VISUAL INPUTS AND MOTOR OUTPUTS AS INDIVIDUALS WALK THROUGH DYNAMICALLY CHANGING ENVIRONMENTS

By

Michael E. Cinelli

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Kinesiology
(Behavioural Neuroscience)

Waterloo, Ontario, Canada, 2006

AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A THESIS

I hereby declare that I am the sole author of 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.

Abstract

Walking around in dynamically changing environments require the integration of three of our sensory systems: visual, vestibular, and kinesethic. Vision is the only modality of these three sensory systems that provides information at a distance for proactively controlling locomotion (Gibson, 1958). The visual system provides information about self-motion, about body position and body segments relative to one another and the environment, and environmental information at a distance (Patla, 1998). Gibson (1979) developed the idea that everyday behaviour is controlled by perception-action coupling between an action and some specific information picked up from the optic flow that is generated by that action. Such that visual perception guides the action required to navigate safely through an environment and the action in turn alters perception. The objective of my thesis was to determine how well perception and action are coupled when approaching and walking through moving doors with dynamically changing apertures. My first two studies were grouped together and here I found that as the level of threat increased, the parameters of control changed and not the controlling mechanism. The two dominant action control parameters observed were a change in approach velocity and a change in posture (i.e. shoulder rotation). These findings add to previous work done in this area using a similar set-up in virtual reality, where after much practice participants increased success rate by decreasing velocity prior to crossing the doors. In my third study I found that visual fixation patterns and action parameters were similar when the location of the aperture was predictable and when it was not. Previous work from other researchers has shown that vision and a subsequent action are tightly coupled with a latency of about 1second. I have found that vision only tightly couples action when a specific action is required and the threat of a collision increases. My findings also point in the same direction as previous work that has shown that individuals look where they are going. My last study was designed to determine if we go where we are looking. Here I found that action does follow vision but is only loosely correlated. The most important and common finding from all the studies is that at 2 seconds prior to crossing the moving doors (any type of movement) vision seems to have the most profound effect on action. At this time variability in action is significantly lower than at prior times. I believe that my findings will help to understand how individuals use vision to modify actions in order to avoid colliding with other people or other moving objects within the environment. And this knowledge will help elderly individuals to be better able to cope with walking in cluttered environments and avoid contacting other objects.

Acknowledgements

Pain is temporary. It may last a minute, or an hour, or a day, or a year, but eventually it will subside and something else will take its place. If I quit, however, it lasts forever.
-Lance Armstrong

In 2003 when I was diagnosed with Leukemia a friend bought me “It’s not about the bike” by Lance Armstrong. I found it to be very motivational because of quotes like the one above. I believe that a positive attitude is everything it can help you get through difficult times. Throughout my ordeal with cancer I learned that you cannot worry about the things you cannot control, you need to look beyond those and enjoy the things you can. Once you have endured and overcome life’s obstacles then good things will happen. I am living proof of this belief, but I could not have done it without the love and support of my wife, Sarah and my family and friends. I would like to thank all the faculty, staff, and students in the Kinesiology department at the University of Waterloo for caring for me and helping me get back on track with my studies. Ironically enough cancer has helped me be a better person because I realized what I had and how precious it was.

In terms of helping me complete this thesis I would like to thank Dr. Fran Allard for filling in as my supervisor to guide me and provide wonderful insights into my work. I would also like to thank Dr. Milad Ishac for helping me to understand concepts and to write computer programming code, but most of all for being a friend. I would also like to thank Sandra Prentice for keeping my research going when I was in the hospital. I especially would like to thank my mom away from home, Ruth Gooding, thanks for “mothering” me when I need your help. But most of all I would like to thank everyone at the University of Waterloo (faculty, staff, and students) who I met over my 11 years there. You have all greatly touched and influenced me and I will always be grateful to you.

To my supervisor, Dr. Aftab Patla

for having faith in me and treating me like a son.

And to my wife, Sarah

for supporting me financially and mentally as I pursued my goal of completing my degree.

CONTENTS

List of Tables

Page

Chapter 2 (Study 1 and 2)

Chapter 3 (Study 3)

Chapter 4 (Study 4)

List of Figures

Page

Chapter 2 (Study 1 and 2)

Chapter 3 (Study 3)

Chapter 4 (Study 4)

CHAPTER 1

WHY I DID WHAT I DID

1.1 Introduction

This thesis has emerged from an intriguing question first proposed by Gibson almost 50 years ago. "The question, then, is how an animal gets about by vision" (Gibson, 1958, p. 183). Gibson (1958) believed that animals (or any locomoting creature) walked to a goal by keeping the focus of expansion on where they wanted to go. He termed this strategy of keeping one's heading in line with the focus of expansion "optic flow". Since the inception this solution of how animals used vision to move about, researchers have attempted to enforce and disprove Gibson's solution to his question. However, the answer to this question is far from being complete and has occupied a large portion of the psychology literature. Researchers from many different disciplines have approached this question from mechanical, neurophysiological, neuropsychological, and cognitive approaches in hopes of adding new insights to the pre-existing knowledge. The goal of my thesis is to understand the movement and visual behaviours of individuals as they navigate through dynamically changing environments.

The motivation behind this thesis was two-fold. First, I wanted to get a better understanding of how well visual perception and action are coupled during locomotor tasks. From the time of Gibson and Crooks (1938) there has been no debate that "locomotion is chiefly guided by vision" (p. 454). Although it is true that the interplay between vision, kinaesthetic and vestibular information is of major importance to the control of locomotion, vision is the only sense that can gather information at a distance. Therefore, vision can be used in a feed forward mode to regulate actions by planning and initiating changes in gait patterns. Lee and Lishman

(1977) stated that vision provides the richest information about the environment and the object or events within it and the movement of body parts relative to the environment. This type of information provided by vision helps individuals to successfully locomote throughout any environment. It is interesting that these claims about vision were made many years ago, while gaze behaviours during locomotion were not well understood until recently. Technological advances have made it possible to analyse individual's gaze behaviours during locomotor tasks. And so, by analysing both movement and gaze behaviours as individuals walked through dynamically changing environments, I aim to understand how well these behaviours are linked to each other.

My second motivation for this thesis was to determine whether the control strategy reported by Lee, Lishman, and Thompson (1982) to describe how individuals adjust movements to contact a target was the same as the one used by participants in my studies. Lee et al. (1982) had long-jumpers approach a take-off board and analysed how they were able to contact the board without stepping over the target. This spatial constraint of target location led to the participants regulating their foot fall position by controlling their flight time in order to be successful. In my studies the task requirements that defined success had both a spatial and temporal component. My first study was used as a foundation for the type of control strategy used by participants as they walked through oscillating doors (opening and closing). In this study, each door oscillated at the same rate for 50cm in each direction such that the maximum aperture was 100cm. The control strategy used in this study will be compared to that used in the Lee et al. (1982) study. Since the subsequent studies also took place in dynamically changing environments (produced by oscillating doors), I assumed that a similar strategy (with slight modifications) would be used in all my studies.

My thesis is comprised of four studies. The first study served to identify how the control strategies are used as individuals walked towards oscillating doors. The second study reduced the time the participants had to respond to the doors in order to determine if another locomotor action parameter emerged. In the second study participants walked towards the doors when they were either closed or opened. When the participants were 2 steps away from crossing the doors, the doors moved. The third study again had oscillating doors; however in this study the doors moved symmetrically or asymmetrically. In this study, visual behaviours were measured in order to determine how visual inputs guided locomotion. In the fourth study the doors oscillated with a constant door aperture width as participants approached the door frame from different eccentricities from the middle of the door frame. This study was used to determine if the same control strategy was used in a slightly different dynamically changing environment and how vision was used to guide locomotion. All these studies are aimed at understanding how vision is used to guide locomotion in dynamically changing environments.

CHAPTER 2

TASK-SPECIFIC MODULATIONS OF LOCOMOTOR ACTION PARAMETERS BASED ON ON-LINE VISUAL INFORMATION DURING COLLISION AVOIDANCE WITH MOVING OBJECTS

Abstract

The objectives of this study were: a) to determine if the control mechanism for interacting with a dynamic real environment is the same as in the virtual reality (VR) studies, b) to identify the action control parameters that are modulated to successfully pass through the changing door aperture, and c) to identify how the task constraints influenced the type of action control parameter modulated. In the first experiment, participants walked along a 14-meter path towards oscillating doors (movement rate=44cm/s and maximum aperture varied 70, 80, or 100cm). Participants, similar to VR studies, primarily made gradual velocity adjustments in order to successfully pass through the doors. The immergence of a locomotor action parameter not seen in VR studies was observed on some trials (i.e. shoulder rotations). In the second experiment, the participants walked along a 10-meter path toward doors that would either move from an open position to a closed position or vice-versa when the participant was only 2 steps away from the doors. The doors' maximum aperture was 90, 110, or 130cm and moved at a rate that ranged between 38-50cm/s. Since gradual velocity adjustments were not possible within the two steps, participants made more shoulder rotations in order to be successful. The magnitudes of these shoulder rotations were proportional to the rate of door movement. The two experiments show that participants use perception to control movement under different task constraints. However, the locomotor action parameters modulated are dependent on the task constraints.

2.1 Introduction

Navigating around a cluttered environment requires the integration of many sensory systems including vision, vestibular, and kinesethic inputs. Vision is the only modality of these three sensory systems that provides information at a distance for proactively controlling locomotion (Gibson, 1958). The visual system provides information about self-motion, about body position and body segments relative to one another and the environment, and environmental information at a distance (Patla, 1998). Efficient use of visual information in the service of real-world, real-time action is the desired goal (Clark, 1999). Gibson (1979) developed the idea that everyday behaviour is controlled by perception-action coupling between an action and some specific information picked up from the optic flow that is generated by that action, such that visual perception guides the action required to navigate safely through an environment and the action in turn alters perception.

One of the first studies to explore visual regulation of action is a study done by Lee et al. (1982) with long jumpers. They found that there was little change in the jumper’s stride length variability until a few steps before the take-off board. They found that stride length variability increased systematically as the runners approach the board while the variability of footfall position decreased rapidly over the last few strides as they approached the take-off board. The decrease in the variability of foot fall location occurred around 4 steps before the take-off board. The authors concluded that this last phase was visually driven and argued that individuals used time-to-contact (TTC) information with the board to modulate their foot placement. The authors believed that in order to be successful it would be better to spread out velocity changes over a longer period of time: the larger the changes required, the earlier they would be initiated.

In the study done by Lee et al. (1982) the analysis was done on the data across trials, Montagne et al. (2000) developed a within trial analysis to identify the control mechanism used to hit the take-off board and correctly perform a jump. They analysed where the jumpers made a stride length adjustment and found that participants made adjustments at different distances from the take-off board. They found a negative correlation between the magnitude of adjustment needed and the step number prior to the take-off board where the change was initiated. The authors concluded that individuals were using perception-action coupling to control movement, initiating an adjustment when a need to do so was perceived. This perceived need to make an adjustment is based on whether or not an individual can successfully complete the task at his or her current state of arrival. We believe that the onset of an adjustment occurs when one's current state is outside the required state (i.e. the state that would afford a safe passage). The amount of change must be within one's physical capabilities such that the further one's current state is from the required state, the earlier the onset of change would occur. Both the study by Lee et al. (1982) and the study by Montagne et al. (2000) show how individuals control their movements in order to successfully make contact with a stationary target.

In a recent study, Montagne et al. (2002) wanted to test if individuals use the same mechanism of control (i.e. perception-action coupling) in a dynamic environment. They had participants walk on a treadmill using virtual reality to simulate walking through hallways. At the end of the hallways were a set of moving doors (oscillating at 1 and 0.5 Hz) with a maximum aperture of 128cm. They calculated the number of trials during which participants passed through the doors when the doors were greater than 75% of the maximum aperture (96cm)when the doors were opening or 87.5% when they were closing. The authors found that the participants made adjustments within the last door cycle, even though visual information about the door movement was available from the start of the trial. In order to pass through the doors, the participants chose to speed up. They accomplished this by decreasing their step duration over the last two steps. They also found that as the task increased in difficulty (0.5Hz to 1Hz), the time when an adjustment (change in velocity) occurred was delayed and success rate decreased. The authors believe that if the task is difficult, too early a change may lead to an improper adjustment. The authors concluded that the control mechanism used by the participants is based on perception-action coupling similar to that used by the long jumpers (Montagne et al., 2000). Therefore, the mechanism of control used by individuals is independent of task constraint.

Recently, Montagne et al. (2003) conducted a study to determine the influence of practice on control. The intent was to understand the process underlying the learning of goal-directed locomotion. They used a set-up similar to that used in previous studies (Buekers et al., 1999; Montagne et al., 2002, 2003). Montagne et al.'s (2003) findings showed that after practice, the participants were able to increase their success rate from 30% to 64.2%. The manner in which the participants were able to do this was by decreasing their current velocity in order to bring themselves within the required state. This was referred to as "funnel-like" control. The "funnel-like" control only became apparent following considerable amounts of practice. In the successful trials, the participants continuously changed their velocity 2 seconds prior to crossing the doors. In these trials, it was believed that the individuals were better able to integrate the cyclical character of the doors to accommodate the future because it is not enough to just know the time it would take to contact the doors; both the current and future state of the doors was important. Therefore, the visual door-cycle properties drive the perception-action coupling cycle in a similar way that the visual information about the position of the take-off board drives the perception-action coupling cycle.

As a natural extension to these studies, we wanted to extend the findings to a real-world dynamic situation to determine how perception is used by individuals to control movement. To address this issue, we used a set-up similar to that used in previous studies by Buekers et al. (1999) and Montagne et al. (2002, 2003); however, we used a real environment rather than virtual reality. The first experiment follows a similar protocol to that used by Buekers et al. (1999) and Montagne et al. (2002, 2003), while in the second experiment, we limited the time available to respond (i.e. 2 steps) and presented only half a cycle (i.e. opening or closing) of door oscillations. We monitored both the velocity profiles of the participants as well as any shoulder rotations to examine how task constraints influence the type of locomotor action parameter modulated.

2.1.1 Experiment 1

In order to meet the first objective we used a real-life set-up that mimicked the salient features of the studies by Montagne et al. (2002, 2003). We used a 14 meter walkway with a set of oscillating doors at the end of the pathway, giving the participants ample opportunity to acquire information and modify their movements. The door oscillation frequency was under 0.5Hz: Montagne et al. (2002) showed that success rate at 0.5Hz was high. Since we used real moving doors, we wanted to minimize the risk of injury. There were two ways to maintain a given door oscillation rate: keep the maximum door aperture constant and change the door velocity or keep the door velocity constant and change the aperture of the doors. Since we were limited to what our step motor could handle, we chose the second option and changed the maximum door apertures (i.e. 70, 80, and 100 cm) with the oscillation rates of 0.314, 0.275, and 0.22 Hz for the three maximum door apertures. Smaller maximum door apertures in this study, while constrained by the set-up, provided similar challenge as higher door oscillation frequencies to the participants to time their passage appropriately.

2.2 Materials and methods

2.2.1 Participants

Five healthy female participants (age ranged from 18 to 20 years) volunteered for the study and gave their informed consent. All participants had normal or corrected-to-normal vision, remained naïve to the purposes of the experiment, and did not report any neurological disorders. Testing procedures were approved by the University of Waterloo’s Office of Research Ethics.

2.2.2 Task and apparatus

The experiment was performed along a 14-meter straight path with a set of sliding doors (each door was 76 cm wide and 2 m high panel made of particle board) placed at the end of the pathway. The doors, suspended from a metal frame, were able to open and close in a horizontal direction by means of a computer controlled step motor. At a distance of 2m past the door frame was a wall. We felt that this distance would be adequate to allow the participants to stop safely after they crossed the doors. An optical switch placed at the start of the path (14 m from doors) triggered the doors to begin their movement (see Figure 1). The maximum aperture of the doors varied between 70, 80, and 100cm; these properties translate into varying door oscillation frequencies of 0.44, 0.55, 0.63 Hz respectively. Once the doors began to move, they continued to oscillate at 44cm/s until the end of the trial. Whole body kinematics and door movement were tracked with an optoelectronic recording system (OPTOTRAK; Northern Digital Inc., Waterloo, Ontario, Canada) at a sampling frequency of 120Hz. Participants were instrumented with six infrared light emitting diodes (IREDs) placed on the following landmarks: left and right ears, spinous process of the 7th cervical vertebrae, left and right spine of scapula (lateral aspect), and spinous process of the 12 thoracic vertebrae. A seventh IRED was placed on the edge of one of the doors to track its movements.

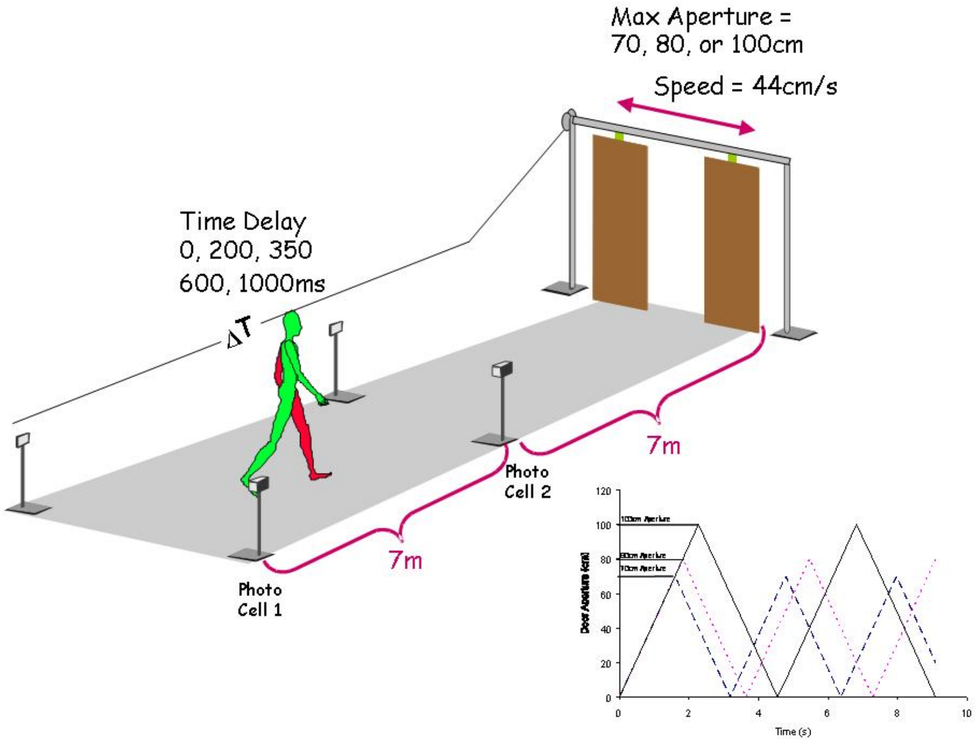

Figure 1- *Experimental set-up: a 14-meter path with oscillating doors at the end of the pathway. Photo cell 1 was used to trigger the doors to oscillate to one of 3 maximum apertures (70, 80, or 100cm) with a random delay (0, 200, 350, 600, or 1000ms) at a speed of 44 cm/s. Photo cell 2 was used to trigger the initiation of kinematic data collection. (Inset) Profiles for each condition showing the door aperture width at any time throughout one cycle.*

2.2.3 Procedure

The instructions given to the participants were, “walk towards the doors at your normal cadence and safely pass through the doors.” The participants performed a total of 60 completely random walking trials. At the start of each trial the doors were open with an aperture of either 70, 80, or 100cm. On 50% of the trials, the doors would oscillate at 44cm/s to one of the three maximum apertures (i.e. 70, 80, 100cm). A random delay of 0, 200, 350, 600, or 1000ms between the optical switch and the door movement was added. Both the uncertainty of the door oscillation and the delay ensured a response based on visual perceptual information rather than response based on memory of previous trials. For the remaining 50% of the trials, the doors remained wide open.

2.2.4 Data Analysis

We used similar data analysis to that used by Montagne et al. (2003). The data were analyzed using the *Predicted Door Aperture at the time of Arrival (PDA)* to allow a trial-by-trial analysis of how the participants controlled their movement while approaching the doors. PDA is a measurement that calculates what the aperture of the doors will be when the participant crosses them given the current walking velocity and distance from the doors. To calculate this, we calculated the Time to Passage at a given instant (TTP) by dividing the distance (d) the participant was from the doors by their instantaneous velocity (v) at that time (TTP=d/v). The second step was to add the elapsed time (T_E) from the start of the trial to TTP; known as travel time (T_T). Therefore, T_T is a predicted indication of the total duration of the trial. This means that if the individual slowed down during a trial, then the total duration of the trial would increase. The last step was to calculate the predicted door aperture at the time of arrival (PDA) at every instant leading up to the successful passage through the doors. In order to calculate PDA, we took the T_T at each instant in time and recorded the door aperture for that time based on the door profile for that trial. For example, if at time 1s (after the doors began to move) the T_T was 4.56s (trial duration from start of door movement), the PDA at this time would be the door aperture at 4.56s after the start of door movement. Therefore, PDA would only change if T_T changed and T_T would change if the participant's velocity changed because TTP would change. Measures on each trial were time-locked to the time when the participant crossed the doors (and filtered at 4Hz), so that the PDA values could be profiled relative to TTP. We also calculated the standard deviations of the PDA values for each participant under each door condition in order to determine the variability of movement as the participant approached the doors. An example of profile of approach velocity and PDA from one participant during one trial is shown in Figure 2.

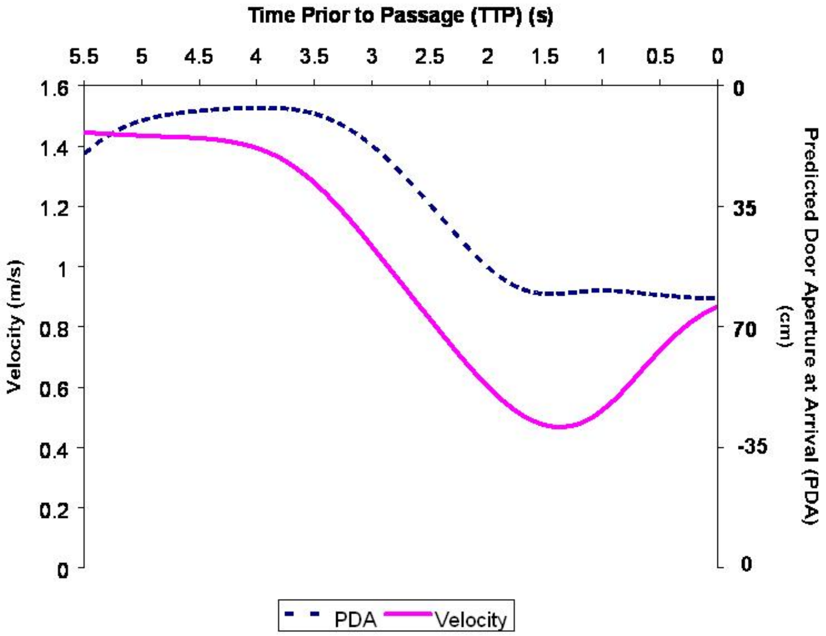

Figure 2- *An example of a time course prior to crossing the doors for both Predicted door aperture at time of arrival (PDA) and the participant's velocity at each instant in time. For this example the maximum door aperture was 70cm. PDA is a measurement that predicts what the door aperture will be at the time of crossing at any time based on the individual's velocity, distance from the doors and state of the doors at that time. For this example the participant had to slow down in order to pass through the doors at a suitable aperture.*

We also analysed when the participants made significant changes in either approach velocity or posture. A velocity adjustment was determined to be the time in which the participants' velocity fell outside 3 standard deviations of their approach velocity for the first 30 seconds of the trial and remained outside 3 standard deviations. Shoulder rotations were measured using the transverse angle of the two IRED markers place on the participant's shoulders. We measured the final shoulder angle at the time of crossing (through the doors) and when, from the start of the trial, a significant change (outside 3 standard deviations) in transverse shoulder angle occurred (Experiment 2).

2.3 Results

None of the participants collided with the moving doors. On average, the participants crossed the doors when the doors were 89.6% (62.7cm) of their maximum aperture at the 70cm condition, 75.6% (60.5cm) of the maximum aperture at the 80cm condition, and 81.4% (81.4cm) of the maximum aperture for the 100cm condition. Figure 3 shows the door aperture magnitude at the time of crossing for all trials for all participants. A one-way ANOVA using the door aperture width at the time of crossing showed that the 70cm and 80cm conditions were significantly different from the 100cm condition ($F_{(4,2)}=119.46$, $P<0.0001$). This is understandable because the 100cm condition has a larger safety margin. The interesting thing would be to analyse the consistency of control for each door aperture condition. In order to analyse the consistency, we conducted a one-way ANOVA of the standard deviation of door aperture at the time of crossing. The post hoc analysis shows that participants crossed the doors at a more consistent door aperture for the 70 and 80cm conditions than the 100cm condition ($F_{(4,2)} = 4.99$, $P = 0.0393$). This shows that the participants were not aiming to pass through the doors when the doors were at their maximum aperture, but rather at some aperture that was greater then the participants' shoulder width (mean of 42cm).

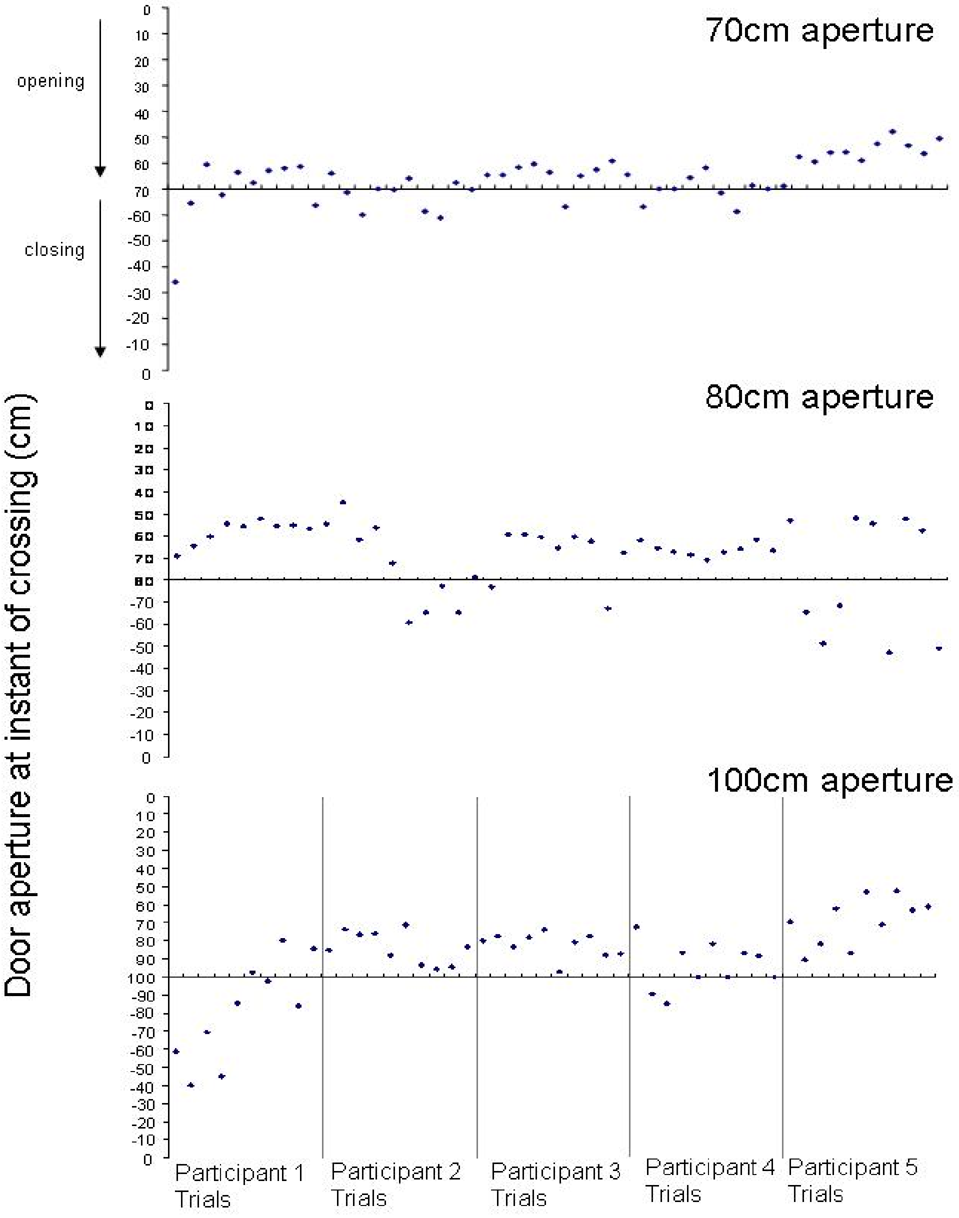

Figure 3- *Door aperture at the time of crossing for each trial performed by each participant in the three test conditions (70cm, 80cm, and 100cm). The solid line indicates maximum door aperture width. Positive values indicate that the participant crossed the doors when they were opening (moving towards maximum aperture) and negative values mean that the doors were closing.*

A two-way Chi-squared analysis revealed that the participants chose to pass through the doors more frequently when the doors were opening rather than when they were closing (Table

1). This, however, was independent of the condition (i.e. 70, 80, or 100cm maximum aperture). This makes sense because the safest time to cross the doors is when the doors are opening towards their maximum aperture. It can be argued that the best approach would be for the participant to pass through the doors just after they were at an aperture width just greater than the participant's shoulder width and on their way to their maximum aperture. This way the participant would have the remainder of the opening time plus the closing time.

Table 1- A comparison across conditions for when the participants decided to pass through the doors. ("opening" = doors were opening to maximum aperture; "closing" = doors were returning from maximum aperture)

Condition	**% of trials with doors opening**	**% of trials with doors closing**
70cm	65	35
80cm	70	30
100cm	78	22

The inset in Figure 1 shows the profiles for one cycle of the door movement for all the conditions (70, 80 and 100cm). These displacement profiles show that there is less time within one cycle that the participant can safely pass through the doors as the maximum aperture decreases from the 100cm condition to the 70cm condition. The PDA profiles for each participant for each trial were calculated. Figure 4 shows examples of PDA profiles for one representative participant for each condition.

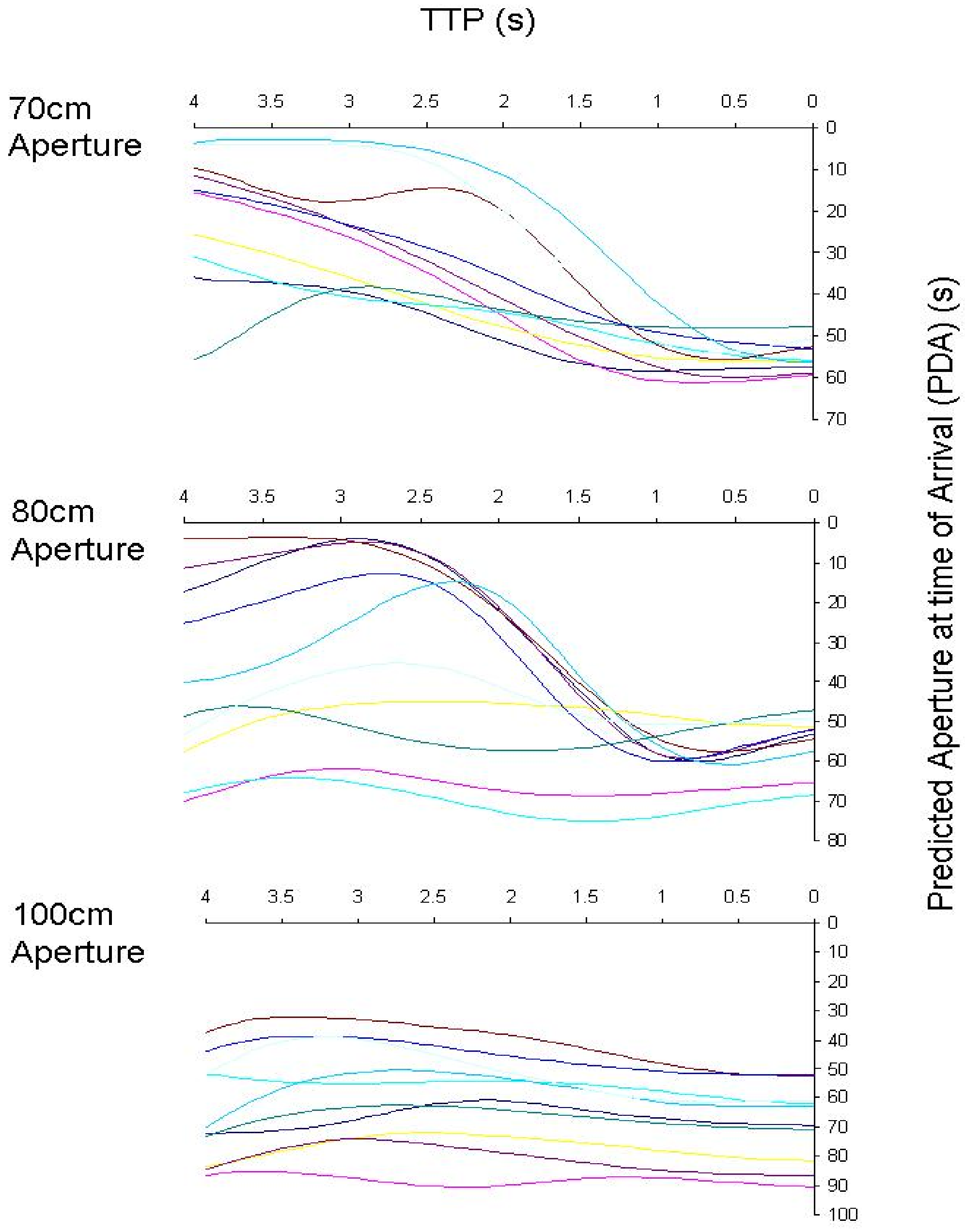

Figure 4- *Time course of the predicted aperture at the time of arrival (PDA) recorded from one representative participant for every trial in each condition. The data were time locked to the time of passage (TTP) and shows the PDA values from 4 seconds prior to crossing the door until TTP. During all the conditions the participants modified their approach velocity and displayed a "funnel-like" approach in order to pass through the doors at an appropriate aperture. An upward movement in the graph signifies acceleration whereas a downward movement signifies a slowing down. Most of the trials show a constant on-line control of locomotion.*

A -way ANOVA was done on the variability in PDA values for each participant at 200ms bins from 5s prior to crossing the doors and the time of passage (TTP) for each door aperture condition. The results showed that there was no main effect for condition ($F_{(2,4)}$= 3.32, P = 0.089), but there was a main effect of time interval bins ($F_{(25,4)}$= 9.78, P< 0.0001). There was an interaction effect between the time interval bins and door aperture condition ($F_{(50,4)}$=1.42, P=0.0482). This meant that the participants were behaving similarly in all the conditions and that the variability was greater for some time intervals than others. We plotted the average values for each condition at each time interval from 5s prior to crossing the door to the Time of Passing (TTP) the doors (see Figure 5). From the figure it appears that at the last three time intervals (0, 0. britsma@ahsmail.uwaterloo.ca2, and 0.4 s) the variability plateaus. In order to determine when the variability stopped decreasing we averaged the variability values for each condition at these three time intervals and determined when the variability values were greater than two Standard Deviations. The times when the variability profiles stopped decreasing were: 1.6s for the 100cm condition, 0.6s for the 80cm condition, and 1.2s for the 70cm condition. Appendix A has the average variability for each participant in each of the door aperture conditions. This “funnel-like” control as the participants approached the doors is similar to that seen in Montagne et al. (2003).

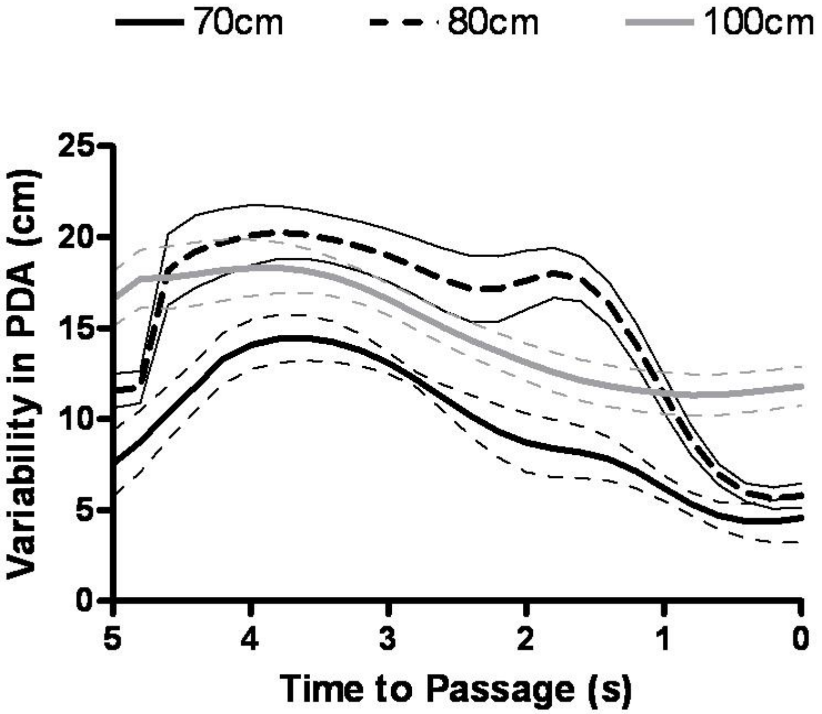

Figure 5- *Time course of predicted aperture at the time of arrival (PDA) variability and Standard Deviations for each condition (70, 80, 100 cm) across all participants. The variability decreases for all conditions as the participants approached the doors. The largest changes in variability occur for the 70cm and 80cm conditions because the level of threat is higher and there is less room for error (narrow maximum aperture).*

Table 2- A comparison between the number of trials in which the participants chose to make a velocity modification and those trials that they chose to make a postural adjustment in order to pass through the doors safely.

Condition	**% of trials with velocity change**	**% of trials with Rotation**
70cm	100	20
80cm	100	41
100cm	82	16

Table 2 shows the percentage of trials when a velocity adjustment was made and the percentage of trials in which a postural modification (rotation of shoulders) was made. Velocity adjustments were more common than shoulder rotations. This velocity adjustment performed by the participants was in the form of slowing down rather than speeding up to pass through the doors safely. Velocity change did not occur as frequently during the 100cm condition. It is interesting to note that the 80cm condition produced the most number of shoulder rotations. These rotations occurred after a change in velocity had already occurred. On average the participants initiated a rotation of their shoulders 0.45 seconds before crossing the doors. Only once was there a postural modification without a change in velocity and this occurred during the 100cm condition. In 50% of the trials when a rotation occurred, the door aperture at the time of crossing was close to or less than 1.3 times the participant's shoulder width, similar to Warren and Whang (1987).

To determine how the participants were controlling their approach velocity as they approached the doors we looked at the time prior to crossing the doors when the participants initiated a change in velocity. This initiation of a change in velocity was the point at which the participant's current velocity fell outside three standard deviations of the initial velocity for that trial. A one-way ANOVA was done to compare the time when an initiation of a change in velocity occurred for each maximum door aperture condition. A change in velocity did not occur for every trial within the 100cm condition, therefore we only analysed those trials in which a change did occur. The results indicated that the time of initiation for the 100cm condition was significantly different than both the 70 and 80cm conditions ($F_{(4,2)}$= 8.97, P = 0.009). The post hoc analysis showed that participants initiated a change in velocity significantly later for the 100cm condition than for either the 70cm or 80cm conditions. Therefore, the participants behaved similarly for the 70cm condition as they did for the 80cm condition. On average the participants initiated a change in velocity 1.6s prior to crossing the doors for the 100cm condition, 3.06s for the 80cm condition and 2.81s for the 70cm condition. To determine if there was a consistent time prior to crossing the doors when the participants would initiate a change in velocity, we looked at the variability (standard deviations) of these times for each participant within a condition. A one-way ANOVA was done using the variability of initiation times for each maximum door aperture condition. The results indicated that the variability of when a change was initiated was not different between conditions: it was wide spread for all the conditions. This means that the participants did not initiate a change in velocity at a particular time prior to crossing the doors. Figure 6 shows a frequency distribution of the time prior to crossing the doors when a change in velocity was initiated.

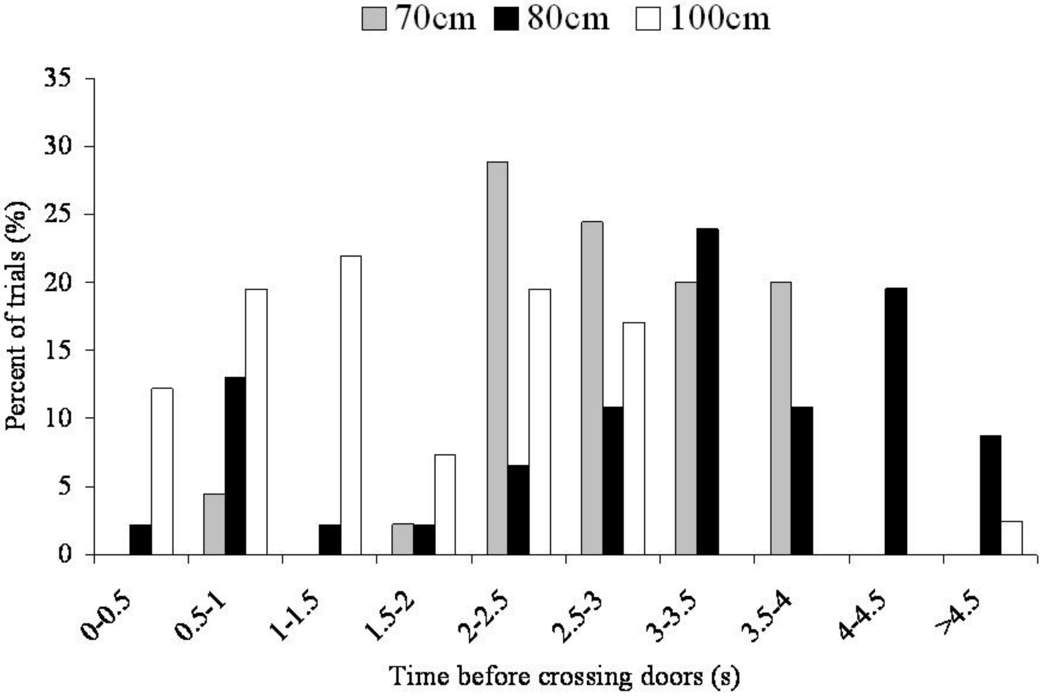

Figure 6- *The number of trials where an initiation in a change in approach velocity occurred for each time prior to passing through the doors (TTP). The distribution of values is spread out over a wide range of times prior to crossing the doors for each of the conditions (70, 80, and 100cm).*

Finally, we looked at the PDA values at the time prior to crossing the doors when a change in velocity was initiated across all participants for each condition. A linear regression analysis was done for each participant and is illustrated in Figure 7. The R^2 values for participants one to five were: 0.543, 0.695, 0.809, 0.802, and 0.587 respectively. The slopes of each regression line were all negative and were significantly different from zero ($P < 0.0001$). This means that the lower the PDA value was (i.e greater difference between the current and required states) the earlier the onset of change in initiation.

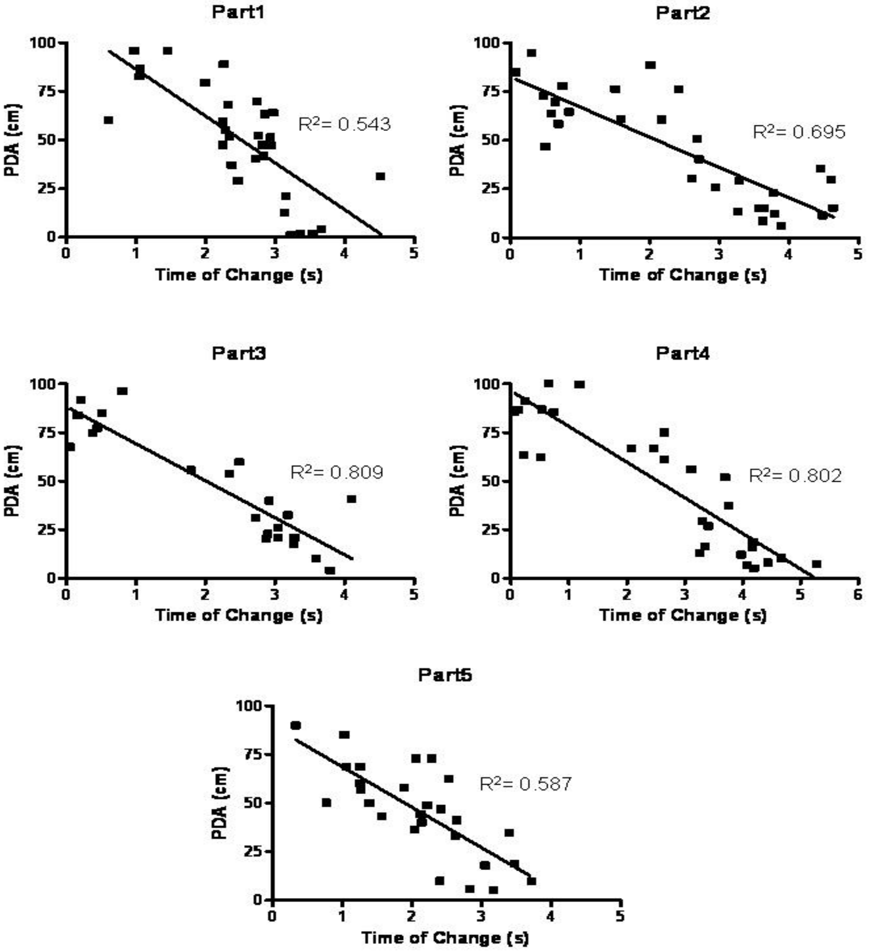

Figure 7- *Relationship between time prior to crossing the door when a change in velocity occurred and the PDA value at that time for each participant (i.e. Part1, Part2, etc.) across the three conditions*

2.4 Discussion

This first study looked at the visual control of locomotion in a dynamically changing environment with different levels of task constraints. The success rate for this experiment was 100%, with no accidental contacts. In previous studies done by Buekers et al. (1999) and Montagne et al. (2002) the success rate was much lower, approximately 30%. In a follow-up study Montagne et al. (2003) had participants practice walking through virtual doors and they were able to increase performance from 30% to 64.2%. In this study the participants increased their success rate by adapting locomotion differently. After practice trials, these participants chose to slow down and view another door cycle in order to pass through the doors, rather than speed up to decrease crossing time. The locomotor modifications were not abrupt, but occurred gradually over time and relied on visual feedback. These changes were “funnel-like”, which was marked by a modification in velocity in order to cross the doors at a time that afforded safety.

There were some significant similarities between the current study and the study done by Montagne et al, (2003). First, both participant groups used perception to guide action. Second, the modification observed was one of decreasing current velocity in order to be successful. Third, the time of initiation of a change in velocity was not consistent across trials. Fourth, there was a decrease in variability in PDA (or Current Arrival Condition) when participants were about 2s away from crossing the doors.

So far, every analysis has proved that there is no difference between the 70 and 80cm conditions and this could be due to any one of three possibilities. The first possibility could be because the participants may have visually perceived the doors in the 80cm condition to be similar to the 70cm condition. The problem with this is that the difference between the current state and the required state in the 80cm condition would be large and the only way to physically adjust this large difference would be to modulate another locomotor action parameter (i.e. shoulder rotation). The second possibility could be that the difference between the two apertures may not be large enough to significantly influence behaviour, given the amount of variability in initiation time in these two cases. The final possibility could be that our criterion for a change in velocity (>3 SDs) is conservative, whereas a weaker criterion (e.g. >2 SDs) could yield earlier initiation times that would be significant. Although we presented three possibilities, we believe the first one is the most probable reason for there to be no difference between the two conditions. One reason why we believe this is because it is evident that the absolute aperture widths of the doors at the time of crossing were similar for both the 70cm and 80cm condition. If a velocity adjustment is not made at the appropriate time, the door aperture would not be a suitable width for straight passage and a postural adjustment would be needed. This is the case in the 80cm condition; incorrect visual perception leads to an incorrect timing of velocity adjustment which led to the doors having a lower aperture. This forced the individual to make a postural adjustment more frequently in order to cross the doors safely (Table 2). This finding highlights the difficulties encountered by the participants in using visual information from a distance in a dynamic environment. If one were to misjudge the passibility of an aperture in a static condition, the consequence would be a gentle bump along the shoulder. In an environment in which the doors were moving, one would want to pass through the doors when the aperture was larger to ensure safety because the consequence of failure may lead to bodily injury.

In this study, the 70cm condition is the most threatening followed by the 80cm condition and finally the 100cm condition. This level of threat is based on the amount of time within one door cycle that an individual could safely pass through the doors. Since the time within a cycle that the doors were passable is limited, the participants changed their velocity in order to safely complete the task when it was perceived to be necessary. Each door cycle within the current study afforded the participants more instances when they would be passable than in the Montagne et al. (2002, 2003) studies. This translated into more time available for the participants to safely bring their current state within the required state if the difference between them was great.

On average the participants in the current study chose to initiate a change in their velocity between 1.6s and 3.06s prior to crossing the doors. Montagne et al. (2002) found that as the task increased in difficulty, a change in velocity would occur later. We found the opposite to be true. The least threatening condition (100cm) resulted in the latest initiation of a change in velocity and the other two conditions resulted in earlier initiations. Ironically, the 80cm condition, although not significantly different from the 70cm condition, had the earliest initiation. We believe that since the time when a safe passage could occur was very large (Figure 1, inset) less of an adjustment was needed to safely perform the 100cm condition because the current state was usually within the required state. In this condition if there was a difference between the current and required states, it would be small and would only require a minor change in velocity. This would account for the delayed initiation of a change in velocity. Again, we believe that the 80cm condition was not perceptually different from the 70cm condition and so participants initially behaved similar for both conditions.

The PDA values at the time of initiation of a change in velocity showed similar trends across all the participants (i.e. earlier initiation when PDA was low). This finding was important because it shows that the initiation of a change in velocity is a function of the degree of error. If there was no relationship between PDA and time of initiation of change in velocity then that would mean that the participants did not make any corrections until they were close to the doors and then used vision to bring them through the doors. However, this is not the case. Instead, the participants continuously used perception to determine if and when an action was necessary.

The participants chose to pass through the doors significantly more frequently when the doors were opening than when they were closing (Table 1), and to do so, they chose to slow down and allow the doors to get to a position where they would be opening at TTP. This response was independent of the condition and clearly a safe strategy. Optic flow information about the current state of the doors and the rate at which one is approaching the doors would allow the participant to respond appropriately.

The PDA values show that as an individual approached the doors, she would change her velocity in order to “fit” through the doors. In order to do this, we believe that as the participants approached the doors they were making continuous perception of current actor-environment fit by comparing the current state of the doors versus the required state of the doors to be passable. If there was a difference between these two events then the participants would modulate their approach velocity until there was no difference between the two. This resulted in the participants using a “funnel-like” approach, as they proceeded to cross the doors. This type of approach relies on perception-action coupling as a mechanism to control movement. Since it takes time for the Central Nervous System to process visual information and produce an action, individuals would want to decrease their approach velocity to allow this processing to take place. Once the participants felt that they could pass through the doors safely, they would increase their approach velocity. However, the participants did not change their velocity at a set distance or time prior to crossing the doors. Therefore, we can say that they were not acting in a feed forward manner, but rather relying on on-line visual feedback to control locomotion. This visual feedback is seen by the decrease in the participants’ velocity standard deviation as they approached the doors.

Unlike the participants in the study done by Lee et al. (1982) who were using spatial parameters to target the take-off board, the participants in our study had to rely on both spatial and temporal parameters in order to be successful. It is possible then that the standard deviation of velocity decreased as the participants approached the doors because they were regulating their velocity based on visually perceived relationship between the cyclic nature of the doors and their proximity to the doors. This means that if the perceived difference between the current state and the require state increases (i.e. low PDA value) as one approaches the doors, a change in behaviour would be required soon in order to complete the task successfully (Figure 7).

The variability in all of the PDA values decreased as one approached the doors (Figure 5). This is similar to what Lee et al. (1982) found for long jump: variability in footfall position during a long jump decreased over the last few strides to the take-off board. The variability in PDA values decreased as the level of threat increased. This low variability shows that the participant is “zeroing in” on passing through the doors at an optimal time. In the 70cm condition there was little room for error and therefore, for a trial to be successful one had to pass through the doors when they were at or close to their maximum aperture.

There were couple of differences between the current experiment and those performed by Montagne et al. (2002 and 2003). The first change was moving from a virtual reality set-up to a real-world environment. This change allows one to use optic flow through actual self motion to control locomotion parameters and allows one to alter the path of locomotion without fear of falling (off the treadmill in the virtual reality set-up) and make shoulder rotations without adversely affecting balance. The smaller door apertures do increase the level of threat; unsuccessful trials may result in harm.

The second change was in the classification of a successful trial. Montagne et al. only considered a trial successful if the participant passed when the doors were between 75% (96cm) whwn opening and 87.5% (116cm) of their maximum aperture on closing. As such, even on trials when the participant did not collide with the doors, the trial would have been considered unsuccessful if the aperture was less than 96cm. In the current experiment, the participants were told to pass through the doors safely. We determined success rate based on whether or not the participant crossed the doors without colliding with them. Unless the participants in the Montagne et al. studies were told to aim for an aperture width of 75% maximum aperture, they would not know why a trial that looked successful resulted in feedback indicating it was not a successful trial. Although Montagne et al. (2002, 2003) do not explain why they chose 75% of maximum aperture as a successful trial, we believe that it was used to serve as an implicit spatiotemporal target similar to the explicit target of the take-off board target in the long jump studies. This criterion could have been used to determine if the participants were aiming to pass through the doors when they were almost at their maximum aperture. Since the success rate, even after extensive practice, was less than perfect, it seems that individuals do not attempt to pass through the doors when the doors are completely open. Instead, individuals seem to pass through the doors just after the aperture is greater than the individual's shoulder width. This was supported by our findings when we analysed the absolute door aperture at the time of crossing.

In the current study there were not only velocity changes, but postural changes were also observed while participants passed through the doors. This behaviour was not seen in previous studies (Buekers et al., 1999; Montagne et al., 2002; 2003). However, in a study done by Warren and Whang in 1987 with participants walking towards various static apertures they found that if the aperture was less than 1.3 times the individual's shoulder width, he or she would rotate his or her shoulders in order to pass through the doors. In this study we found that participants rotated their shoulders even when the door aperture at crossing was greater than 1.3 times their shoulder width. A postural adjustment was not seen in the virtual reality studies for two reasons: first the participants were told that they could change their velocity but not stop to pass through the doors and second, a postural adjustment on a treadmill may result in the participant falling off the treadmill. Our study had different task constraints, one of which was that the participants were simply told to pass through the doors safely. In this study a postural adjustment was not necessary to safely pass through the doors because if the participant missed the optimal time within a door cycle to pass through the doors, the participant could have just waited for the next door cycle to occur. While the option of stopping and waiting for the next door cycle to proceed is available, individuals instead proceeded through the doors with a postural adjustment and maintain their momentum.

The dominating locomotor action parameter modulated in response to the environmental demands in this study was a change in velocity. Although shoulder rotations were observed, they occurred less frequently and were most likely done only when door aperture was misperceived (i.e. 80cm maximum aperture condition). While the parameters modulated in this experiment were different from those found in Montagne et al. (2003), visual control of locomotion was similar.

2.5 Experiment 2

In the previous experiment we found that participants did not aim to pass through the doors when the doors were at their maximum aperture, but when the doors were larger than their shoulder width. This type of behaviour can only be performed when the participants have prior knowledge of the cyclic nature of the doors. We found that velocity modifications are the dominating action parameter change. However, no significant changes in velocity were seen between 1.2 seconds prior to crossing the doors and the time of crossing. While shoulder rotations were seen, they were infrequent. In order to determine if shoulder rotations were simply a consequence of the task or of a misperception of the maximum door aperture, we manipulated task constraints further in this experiment to decrease the possibility of making gradual velocity adjustments. Since in the previous study velocity changes were made gradually over a long period of time, the current study removed the participant's ability to make fine velocity adjustments or have previous knowledge of the cyclic nature of the doors. To do so, we designed an experiment that if and when the doors moved, the participants would be within 1.2 seconds (approximately 2 steps) away from crossing the doors. The previous experiment suggested that the participants were unable to perceptually distinguish the 70cm condition from the 80cm condition. Therefore, to increase safety and elicit a broad range of behaviours, we used maximum door apertures that were different from each other by 20cm. The objective of this second experiment was to identify the dominant action parameter (velocity and/or postural adjustment) modulated to safely pass through the doors.

2.6 **Materials and methods**

2.6.1 Participants

Six healthy participants (mean age of 24 years) participated in the study. All participants had normal or normal-to-corrected vision. Participants' shoulder width ranged from 298mm to 420mm, with the mean shoulder width being 362mm. Informed consent was obtained prior to testing. Testing procedures were approved by the University of Waterloo's Office of Research Ethics.

2.6.2 Task

Participants walked at their normal cadence towards motor-driven sliding doors. Doors moved at a velocity range of 32-50 cm/s (at 2cm/s increments) where one velocity was randomly presented for each trial within each condition. The participants were instructed to pass through the doors to the best of their ability and were allowed to stop in front of the doors if they deemed it necessary. Passage through the doors would therefore imply that the aperture was sufficiently large to permit safe passage.

2.6.3 Apparatus

The door structure was similar to the one used in Experiment 1 and was located at the end of a (ten meter) walkway and positioned two steps ahead of forceplate contact (Figure 8). The step motors were computer driven and allowed for a maximum aperture of 1.5m. Door movement was triggered by forceplate contact two steps prior to the participant crossing the plane of the doors. Vertical force from the forceplate was collected to indicate the time of onset of door movement. Three Optotrak cameras were used to collect kinematic data. Six infrared light emitting diodes (IREDS) were placed on all the same landmarks as in experiment 1. A computer program controlled all aspects of door movement: velocity (32-50cm/s), direction (opening, closing or no) and aperture setting (90, 110, 130cm). Participants also wore headphones to mask the noise of the motor, thereby eliminating the use of auditory cues.

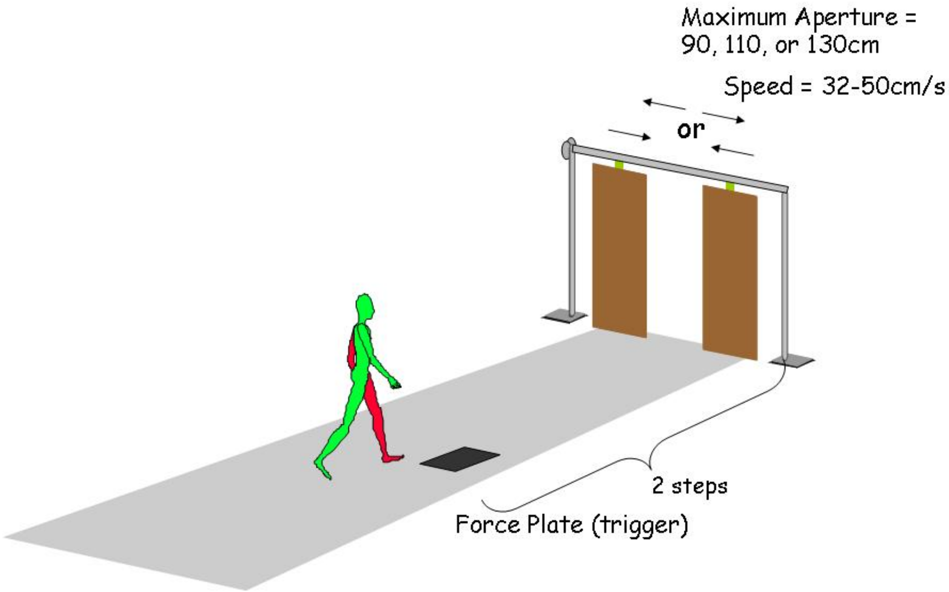

Figure 8- *Experimental set-up: a 10-meter path with moving doors at the end of the pathway. Force plate was used to trigger the doors to move from an open position to a close one or from closed to open. Three maximum apertures were used (90, 110, or 130cm) and they moved at a speed that varied between 32-50 cm/s.*

2.6.4 Procedure

Three conditions (closing, opening, and no movement of the doors) and three aperture settings (90, 110, 130cm) were randomly presented to the participants. In the "closing" condition, the aperture setting was the initial aperture of the doors which then closed to zero. In the "opening" condition, the doors started at zero and opened to the specified aperture setting. In those trials containing "no movement" of the doors, the doors were fixed at the desired aperture setting. A total of 160 trials were collected. Prior to starting the experimental trials, ten control trials with the doors open and ten control trials with the doors closed were collected. Experimental trials consisted of 30 trials for the "opening" condition, 30 trials for the "closing" condition, 60 trials for the “no movement” condition, as well as an additional 20 trials with the doors that remained “closed”. The “closed” and “no movement” trials were used so that the participants could not anticipate the movement of the doors prior to contacting the force plate.

2.7 Results

All trials were successful in the “opening” and “no movement” conditions. In the “closed” trials the participants stopped in front of the doors. The “closing” condition posed the most threat to safety for the participants and had lower success rates. Successful passage through the doors during these conditions occurred on less than half the trials for the 90cm (44%) aperture setting, with successful passage increasing significantly for the 110cm (80%) and 130cm (95%) aperture settings. Of those trials that were unsuccessful in the “closing” condition, the majority of trials occurred as a result of participants choosing not to proceed through the doors. All trials in which participants did not attempt to pass through the doors (44) and those trials in which participants collided with the doors (4) were eliminated from further statistical analysis.

In the trials in which participants successfully passed through the doors, they took less time (sped up) to complete the task when the doors were closing then when they were opening. From the time the participants contacted the force plate until they crossed the doors it took an average of 1.33s to complete the task during the “closing” condition, 1.42s during the “no movement condition” and 1.61s during the “opening” condition.

Since sufficient velocity changes could not always be done to ensure safe passage, participants made shoulder rotations. We measured the transverse shoulder angle at the time when the participants crossed the doors to determine the amount of postural adjustment (i.e.

shoulder rotation) produced by each participant. We compared the shoulder rotation magnitude at the time of crossing for each rate of door movement for each participant. We calculate the slope of the line of the relationship of shoulder angle magnitude versus the rate of door movement rate graph for each condition for each participant and found the values to be different from 0 (i.e. positive slope for the “closing” condition and negative for the “opening” condition). Therefore, we knew that as the rate of door movement changed, so did the magnitude of shoulder rotation. We did a one-way ANOVA of these slopes for the three “closing” conditions. The results showed that in the “closing” conditions all the starting apertures (i.e. 90, 110, 130cm) were significantly different from each other ($F_{(2,5)}= 6.77$, $P=0.019$). However, when a one-way ANOVA was done for the slopes of the three “opening” conditions, the results proved not to be significantly different from each other ($F_{(2,5)}= 0.48$, $P=0.63$). Figure 9 shows the average shoulder rotation magnitudes across all participants at the time of crossing for each condition.

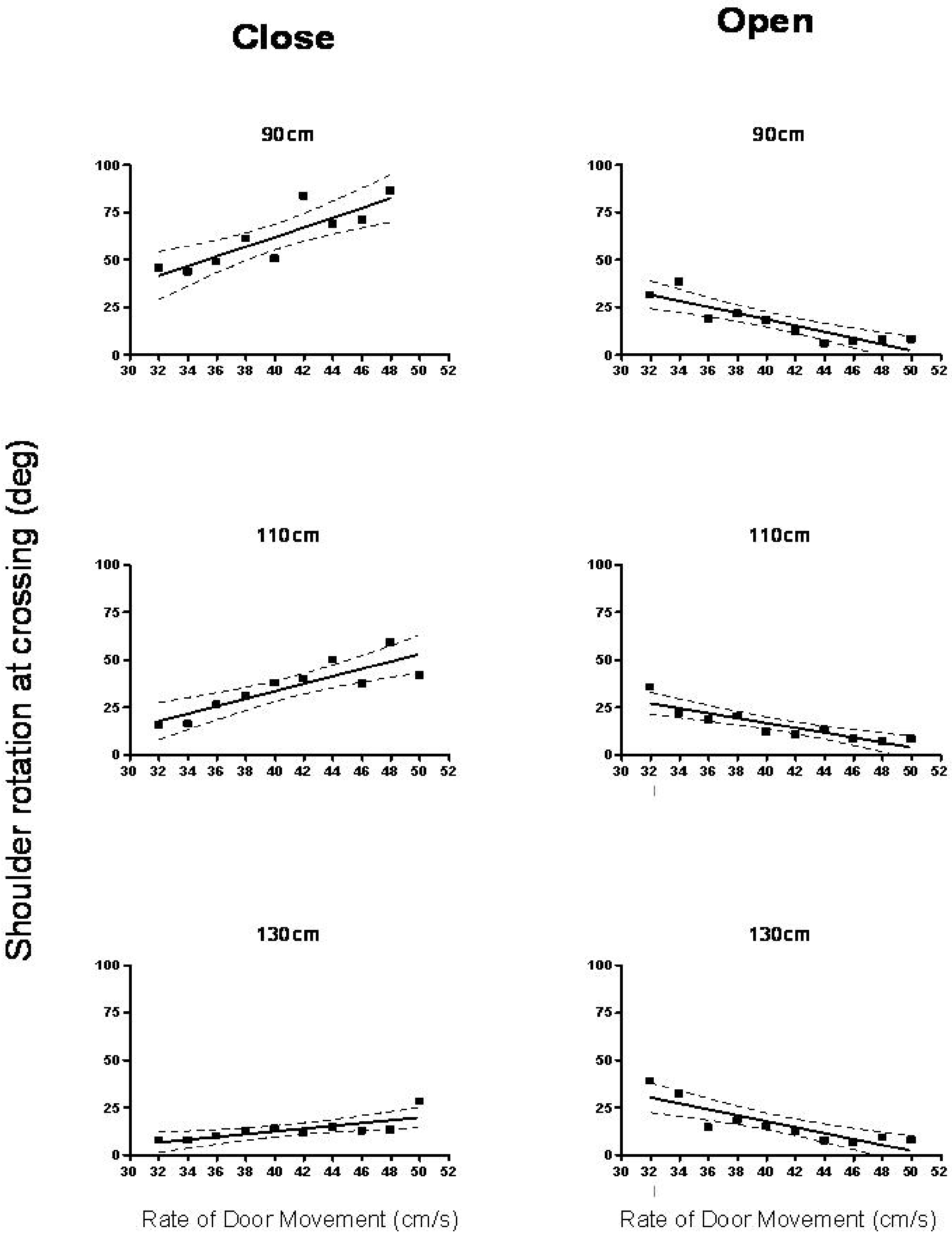

Figure 9- *Average shoulder rotation magnitude of all participants at the time of crossing for each rate of door movement (i.e. 32cm/s, 34cm/s, etc) for each of the six conditions (i.e. close 90cm, close 110cm, etc). The dotted lines indicate the 95% confidence interval and the solid line is the line of best fit.*

Shoulder rotations seem to be the dominant feature in facilitating one's ability to successfully pass through the doors. These shoulder rotations were scaled to the rate of door movement. When the participants rotated their shoulders they decreased their medial-lateral (M/L) shoulder distance and increased their anterior-posterior (A/P) distance. To understand why the participants would do this we measured the participants' M/L shoulder distance at the time of crossing and divided it into the door aperture at that time (i.e. safety margin). This calculation would tell us if the participants wanted to keep the safety margin between the door aperture and their M/L shoulder width constant at the time of crossing. A two-way ANOVA for the "closing" trials using starting aperture and door rate as factors was carried out. A Tukey's post hoc analysis showed that the safety margin at the time of crossing was not significantly different across the different aperture conditions ($F_{(2,5)}= 1.93$, $P= 0.206$). There was a main effect of closing rate as seen in Figure 9 (i.e. the faster rates were significantly different from the slower ones) ($F_{(9,5)}= 5.67$, $P< 0.0001$). However, there were not enough values at the 90cm condition to determine if an interaction was present.

2.8 Discussion

In this experiment participants had to walk along a 10 meter path towards a set of doors that would either move from a closed position to an open one ("opening"), move from an open position to a closed position ("closing") when the participant was 2 steps away from them, or "no movement". The level of threat was clearly greater for the "closing" condition. For the "opening" conditions there was a 100% success rate where as for the "closing" conditions the success rate was significantly lower (44%, 80%, and 95% for 90, 110, and 130cm conditions respectively). It is obvious that the "closing" conditions imposed tighter constraints on changes to gait parameters in order to complete the task successfully. In the trials that were considered unsuccessful, the participants either accidentally contacted the doors or deemed them not to be passable and stopped. Individuals inherently know how much time it takes for them to perform a task (Plumert et al., 2004). If an individual perceives the doors not to be passable he or she would take the safe approach and stop and when there is a misjudgement in perception, a collision occurs. In the most threatening condition (i.e. 90cm closing at a rate of 50cm/s), no one attempted to pass through the doors; all participants stopped.

In the previous experiment we found that the participants did not make any velocity adjustments within 1.2s prior to crossing the doors. This result led us to believe that velocity changes would not or could not occur in this experiment. We restricted the distance between the trigger and the doors in hopes of minimizing gradual velocity change, and see if another action parameter emerges as the primary change for safe passage. Normally the dominant action parameter modification for all task constraint environments is a change in velocity. This change in velocity is usually done over a period of time and is not abrupt. In this experiment we did not give sufficient time for the participants to make on-line velocity adjustments because the distance between the trigger and doors was too short (2 steps). This distance made it physically impossible for individuals to change velocity by a sufficient amount in the time available. However, in the trials in which participants successfully passed through the doors, they took less time (sped up) to complete the task when the doors were closing then when they were opening. The participants sped up in the “closing” condition in an attempt to ensure a safe passage through the doors and decrease the possibility of colliding with the doors. In the “opening” condition, the participants were able to slow down or stop prior to passing through the doors. They did this in order to pass through the doors when they were at an aperture that afforded a safe passage.

These changes in velocity seem to be global changes (i.e. slow down when doors are opening and speed up when the doors are closing). These velocity adjustment was made after the participant triggered the doors to move. Figure 10 shows the velocity profiles for one representative participant for the first trial that the doors closed and for the second time that the doors closed and the same for the “opening” condition. This figure shows that the participant’s velocity prior to the trigger was similar in both trials and that a change in velocity occurred after the doors began to move. This means that the participants were not using an anticipatory control to modulate their velocity, but rather reacting after the doors started to move. Since the doors did not move in a cyclic manner, the participants would not know what the doors were going to do until they actually began to move. The velocity adjustments were not scaled for the various conditions: hence confirming our assertion that no fine control of velocity was possible.

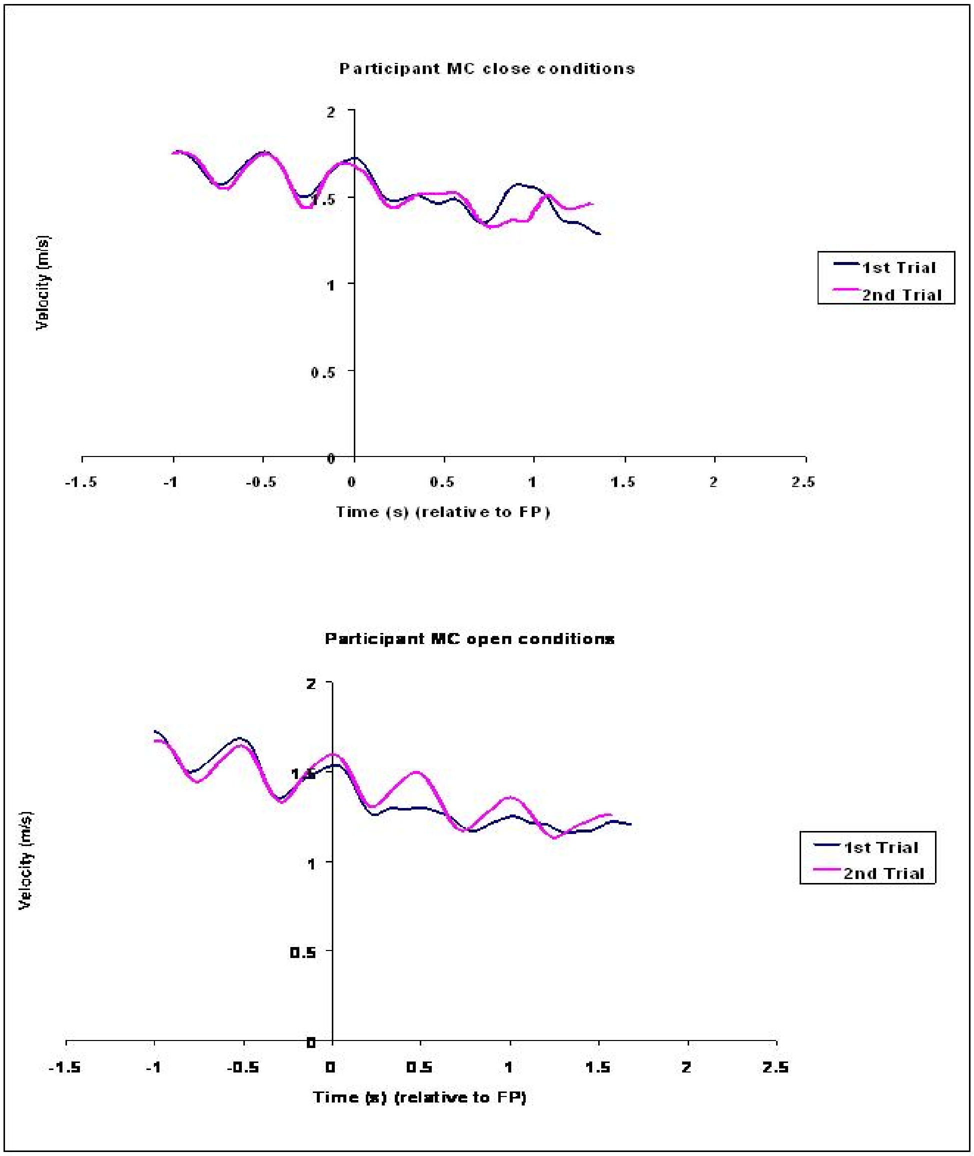

Figure 10- *Representative velocity profiles from one participant prior to door movement and after door movement. Time 0 indicates the time when the doors were triggered to move (i.e. participant made contact with the force plate = FP). The top graph shows the participant's approach velocity for both the first and second time he experienced the doors closing. The bottom graph shows the first and second time he experienced the doors opening. The two trials for each condition were not experienced on consecutive trials. We can see that changes in velocity occurred after the doors had already begun to move in both conditions.*

The results show that when the doors move from a closed state to an open state, the participants rotated their shoulders by the same amount regardless of the doors' maximum aperture. This makes sense since the doors begin at the same position and move to some fixed position. The only difference in the "opening" condition is the rate that the doors move to their maximum aperture. In this case the shoulder rotation magnitude is dependent on the rate of door movement. In the "closing" conditions the doors start at different positions but all end at the same position. In this way it makes sense that shoulder rotations would be dependent not only on the rate of door movement but also the doors' initial aperture. The initial aperture as well as the rate of movement is vital in the behavioural response produced by individuals. In the conditions where the doors began to close, there was a smaller window of time from when the doors were at their maximum aperture to when they reached an aperture equal to that of the participants' shoulder width. This window was smaller for the 90cm condition than the 110cm, which was smaller than the 130cm condition. Individuals, when passing through moving doors, would like the aperture to be larger than their shoulder width at the time of passing. In order to ensure this occurred, the participants rotated their shoulders. In the 90cm condition the participants kept the safety margin constant for the successful trials because there was less room for error than in the 110cm or 130cm conditions. Hence, this explains the lower success rate for the 90cm condition.

In this experiment, the steps prior to the initiation of the door movement are used by vision to prime the nervous system for a certain motor response. Since the environment is static initially, the visual system is able to notify the nervous system if the aperture is not wider than the individual's shoulder width. The motor response in this case would be to decrease one's shoulder width in order to "fit" through the aperture. This decrease in shoulder width can be accomplished by either a rotation or by adducting both shoulders. A shoulder rotation can adversely affect one's heading: the CNS has to ensure that upper body reorientation does not result in path deviation which could cause a collision with doors. Since velocity adjustments observed were not enough to allow for safe passage, participants chose to initiate a shoulder rotation. The time at which the participant initiated a change in shoulder rotations was not different across the different rates of door movement. The interesting thing was that the magnitude of shoulder rotation was scaled to the rate of door movement. This finding suggests that the velocity of shoulder rotation was modulated as a function of door velocity. This is an example of coupling between information parameter (door velocity) and action parameter (shoulder rotation velocity).

2.9 General Discussion

The drive behind the studies 1 and 2 was three-fold. The first purpose was to determine how the control mechanism seen in previous studies (i.e. Montagne et al., 2003) was also used by individuals in our study. The one fundamental difference between our study and the previous ones is that ours was a real-life situation and not a VR setting. Aside from the other differences in methodology between real-life and VR studies, we found that participants still behaved in a similar manner with the immergence of a new locomotor action parameter. Regardless of the environment, whenever there is a dynamically changing environment individuals respond to that environment in an on-line manner. This on-line control is usually dominated by the visual system. The visual system will help the individual determine if a change (i.e. velocity, direction, foot placement, etc) is necessary. The only difference between our study and the VR studies is that we did not need to have the participants practice before they showed this type of control.

The second drive behind the present paper was to identify the action control parameters modulated in order to be successful. Under different task constraints while the visual regulation is similar, the action parameters that are modified, are task-dependent. To test this hypothesis we observed individuals performing tasks with similar objectives (i.e. to safely pass through the doors), but under different task constraints. We found that as the level of threat increased from oscillating doors to a single half cycle, the locomotor action parameters changed from a change in velocity to a shoulder rotation and not the controlling strategy.

The final objective of the present paper was to identify how the task constraints influenced the type of locomotor action parameter modulated. We feel that the parameters of control used are based on the difference between the current state and the required state and also the amount of time available to produce the modulation. A common locomotor action parameter modulation is velocity of locomotion which can be increased and decreased. A decrease in velocity is observed more frequently because we believe it allows an individual more time to process visual information about the environment and produce a safe response, As well reduced momentum minimizes the risk of injury should a collision occur. In the first experiment the doors moved cyclically with the participants having ample time to modulate their actions. A decrease in velocity is also the safest response because an individual would have an easier time stopping if he or she was unable to proceed through the environment safely. An increase in velocity is the appropriate response when a goal-directed action is required within a limited time frame. In the second experiment when the doors continued closing as the participants were close to the doors, they had to increase their velocity in order to pass through safely. The common locomotor action parameter used was a postural adjustment because it quickly changes the required state parameters so that the current state can be brought within the required state effectively.

In summary, visual perception-action coupling is the control mechanism used in meeting environmental challenges during locomotion. The locomotor action parameter modulated is dependent on the task constraints. As the task constraint increases in difficulty, different action parameter changes are recruited. However, this is only true in situations in which the current state can safely be brought closer to the required state. If an individual perceptually believes that a task is impossible, he or she will stop and not proceed. This represents a safe strategy. Collectively these two studies extend our understanding of both how (perception-action coupling) and what changes (velocity, postural) are made to locomotor parameters during travel through complex environments.

CHAPTER 3

MOVEMENT AND GAZE BEHAVIOURS AS INDIVIDUALS WALK THROUGH OSCILLATING DOORS WITH PREDICTABLE AND UNPREDICTABLE APERTURE LOCATIONS

Abstract

Walking through changing environments requires the use of multiple sensory systems in order to properly guide actions. Vision is the most important sensory system because information about the environment can be gathered at a distance and used in a feed forward mode to plan or to initiate a change in gait patterns. Many researchers have found that individuals not only look where they are going, but that vision and action are tightly coupled. We wanted to know where and when participants fixated as they approached and crossed oscillating doors. In this study the participants walked along a 7m pathway towards either symmetrically (coupled) or asymmetrically (uncoupled) moving doors. Here we show that the fixation patterns and location of fixations were random leading up to the doors, however, just prior to crossing the doors the fixations were almost always directed towards the aperture. We also found that the participants passed through the relative middle of the doors when the doors were almost maximally open and in order to do this they usually initiated a change in velocity prior to crossing the doors. Just prior to the participants crossing the doors is the point at which visual information becomes crucial and at that point the participants are attuned to this visual information. Therefore, from the results of the current study, we believe that visual information about the goal is used to guide action. However, when a specific action is required, fixations towards the goal of that action must precede the action.

3.1 Introduction

Walking through a dynamically changing environment may at some point in time require individuals to have to negotiate gaps or apertures to avoid contacting other individuals or objects. The co-ordination idea presented by Clark (1999) suggests that an individual makes real-time adjustments to movements such that the internal perception of the body and physical environment work together. Actions which the environment affords an individual are based on the fit between an individual's physical structure, capacities and skill, and the action-related properties of the environment. This coupling of actions to an environment is known as affordances (Gibson, 1958).

Warren and Whang (1987) found that when participants walked through apertures that were less than 1.3 times their shoulder width they would rotate their shoulders in order to fit through the doors. Montagne et al. (2003) extended this study using oscillating doors in a virtual reality environment and found that after practice participants were able to successfully pass through the doors by slowing down prior to crossing. These studies show perception-action coupling for locomotion and indicate that these skills can be investigated experimentally.

We used a similar experimental setup as Montagne et al. (2003) in order to understand how individuals avoid contacting objects within a dynamically changing environment. We had individuals walk along a path towards real oscillating doors (Study 1). We found that individuals were able to successfully pass through the doors by decreasing their walking velocity prior to crossing the doors and, on some occasions, by rotating their shoulders. The time at which participants initiated a change in velocity indicated when the individual felt that walking at the current velocity would not lead to a successful passage. The argument made from both the Montagne et al. and Cinelli et al. studies was that the controlling mechanism used by individuals to increase success rate was perception-action coupling. The manner in which both research teams demonstrated this was by showing their participants made velocity adjustments so that their ideal state (i.e. passage when the doors were almost maximally opened) was within their safe region (i.e. aperture magnitude was between a minimum, the participant’s shoulder width, and the maximum aperture width) (Fajen 2005). Even though neither study analysed gaze, Montagne et al. (2003) believed that following a change in velocity, vision was guiding action. Montagne et al. (2003) also believed that although vision was available from the start of the trial, individuals were not attuned to it.

Vision is a highly active and intelligent process which uses information efficiently and with little effort in order to perform real-world tasks (Clark, 1999). Vision then is not passive; it does not take “snap shots” of the environment in order to make internal spatial maps. The organization of the ganglion cells within the retina give insights as to how the visual system operates. The richest information comes from the fovea, which is densely packed with both P-type and M-type ganglion cells. There are a lower number of ganglion cells in the peripheral areas of the retina and thus decreased visual acuity. Therefore, the physiology of the retina suggests that there is a benefit to having images fall on the fovea. In order to do this, humans actively move their eyes to redirect their gaze and fixate on objects of interest (Findley and Gilchrist, 2004). If the participant fixates near the object of interest then the image of this object moves across the retina and activates higher visual centers. This is done in order to allow for precise movements by sending information from the dorsal and ventral visual streams to higher cortical centres, namely the motor cortex, to determine if and what type of action is necessary (Fowler and Sherk, 2003).

It is well known that visual information about the environment can be gathered at a distance and used in a feed forward mode to plan or to initiate a change in gait patterns. Patla and Vickers (2003) found that individuals spend most of their time in “travel gaze fixation” mode. This means that the participants directed their gaze at a constant distance ahead in order to acquire information, similar to walking with a flashlight at night. The researchers found that directing gaze about 2m ahead was sufficient to implement a change to step length or width in order to successfully step on a target.

Yarbus (1967) found that when individuals viewed a picture of a forest they spent a great deal of time fixating at the spaces between trees. This type of fixation pattern is important for route planning, where individuals want to look where they are going. Land and Lee (1994) found that individuals in a simulated car steering task fixated on the tangent point of a turn in order to get information about what was ahead. As well, they found that the temporal difference between the direction of one’s gaze and the turning of the steering wheel was about 0.75s. Hollands et al. (1995, 1996) found that individuals produced saccades towards targets just prior to stepping on them in order to control foot placement. All these studies thus indicate that individuals walking through an environment tend to spend the majority of their time fixating on where they are going.

Hollands et al. (2002) found that when individuals had to change direction, their gaze led their heads and bodies in order to maintain alignment with the end-point. Recently, Patla et al. (in press) found that when individuals were asked to walk through a maze of pylons in order to reach a goal, they spent the majority of time prior to initiating gait fixating on the goal. However, during gait the participants gathered information about the environment by spending even larger amounts of time fixating on the goal as well as the travel path.

Fowler and Sherk (2003) found that cats spend about 600ms out of every second fixating (average: 2.5 fixations/s x 247 ms/fixation) on targets placed on a path while the rest of the time is spent shifting gaze to a new location. Humans, like cats, have brief periods of fixation followed by periods of shifting and rarely fixate on irrelevant objects during locomotion (Patla and Vickers, 1997; Hollands et al., 2002; Patla and Vickers, 2003; Fowler and Sherk, 2003) or during everyday tasks (Land and Hayhoe, 2001). Land et al. (1999) found that 95% of all fixations were directed towards task-relevant objects. Turano et al. (2001) found that when individuals walked in an obstacle-free environment 75% of all fixations were either directed towards a goal or in travel gaze mode. The reason there are a majority of fixations directed towards task-relevant objects is because there is a tight coupling between gaze direction and objects being acted on during every day tasks (Land and Lee, 1994; Land and Hayhoe, 2001).

The purpose of the current study was to determine how normally sighted individuals visually sample a dynamically changing environment. Specifically we wanted to know where and when participants fixated as they approached and crossed oscillating doors. The current study follows our previous work using oscillating doors with the addition of monitoring individuals' gaze behaviours. One other addition to our previous protocol is that we had the doors move symmetrically and asymmetrically in order to provide a situation where the aperture was in a predictable location and an unpredictable location respectively. The predictable aperture location could allow vision to be used in a feed-forward or predictive manner.

3.2 Materials and methods

3.2.1 Participants

Six healthy female participants from the University of Waterloo participated in this study (age: 22-32 years). Female participants were used to ensure similar shoulder widths, which ranged between 38 and 42 cm. All participants had normal or corrected-to-normal vision and gave written consent to participate in the study. This study was reviewed and accepted by the Office of Research Ethics at the University of Waterloo.

3.2.2 Apparatus

The door structure was located at the end of a (seven meter) walkway. The doors each measured 200cm high by 76cm wide, were made of particle board and suspended from a steel frame (300 cm wide). The doors were driven independently by two computer generated step motors. Kinematic data were collected using the Optotrak (Northern Digital Inc. Waterloo, ON, Canada) system. A total of ten infrared light emitting diodes (IREDS) were used: two to monitor door position and eight on the participant. The IREDs on the participant were rear-facing; three were in an orthogonal arrangement to represent the torso as a rigid body (i.e. left and right spinous processes of the scapula and 12th thoracic vertebrae), and three were on the head also in an orthogonal arrangement, and one on each heel. Each participant was also instrumented with a Gaze Tracker (Applied Science Laboratories, USA) to monitor gaze location. A computer program controlled all aspects of door movement, velocity (20-40cm/s) and aperture setting (60 or 100cm).

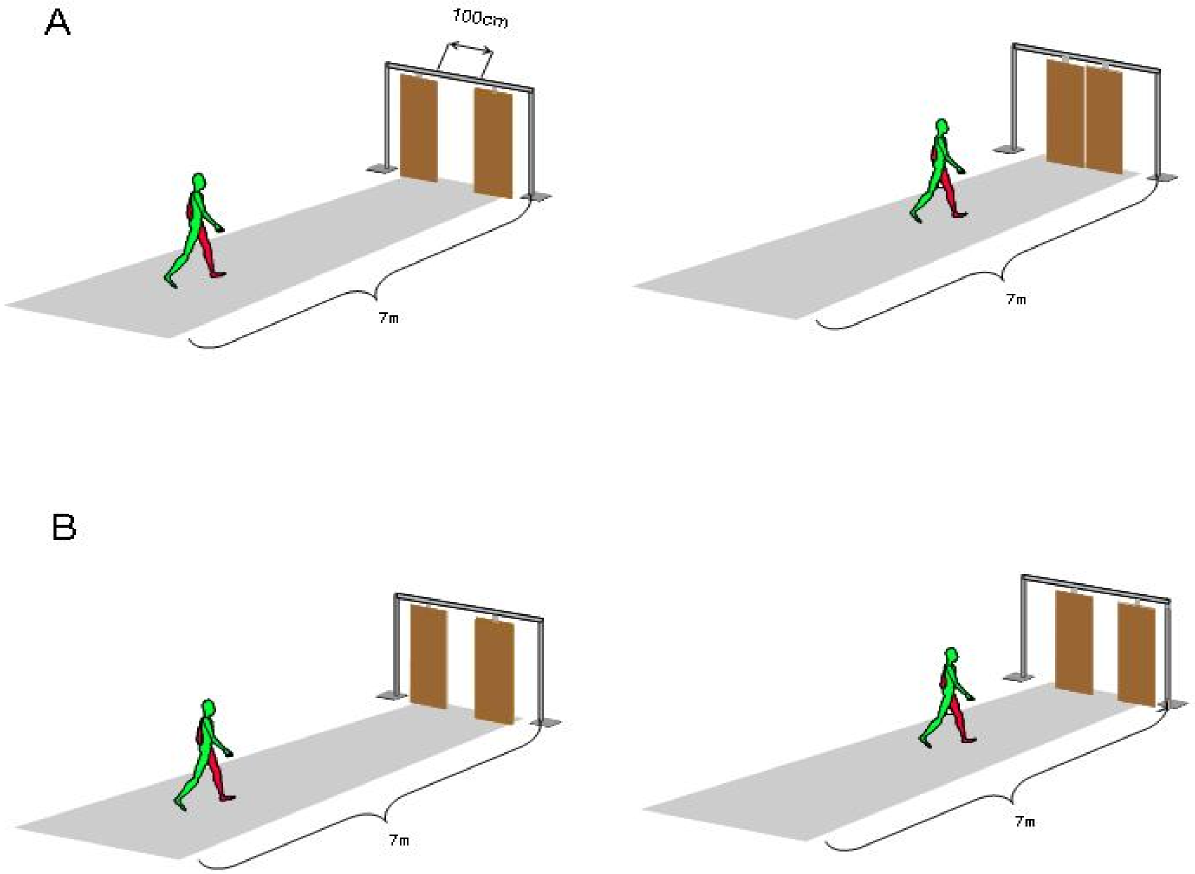

Figure 1- *Experimental setup and conditions. The participants began each trial 7m away from the absolute middle of the doorframe. A) Coupled condition: each door oscillated 50cm in both directions at the same rate (21 to 40cm/s) to produce a maximum aperture of 100cm. B) Uncoupled condition: each door oscillated 50cm in both directions and at a different rate. The faster moving door was always at 40cm/s while the slower moving door varied from 20-38 cm/s.*

3.2.3 Procedure

Participants walked at their normal cadence towards motor-driven sliding doors. The participants were instructed to safely pass through the doors and there was no restrictions on the manner in which they chose to do so. Passage through the doors would therefore imply that the aperture was sufficiently large to permit safe passage. The doors moved in one of two manners; symmetrically (coupled) or asymmetrically (uncoupled). In both conditions each door oscillated 50cm in both directions for a total of 100cm per cycle. In the "coupled" condition the relative middle of the doors was in line with the absolute middle of the door frame where as in the "uncoupled" condition the relative middle of the doors was randomly located along the door frame. Figure 1A is a schematic of the coupled condition to demonstrate when the doors were at their maximum aperture width and when the doors were closed. During the "coupled" conditions each door had a similar velocity that ranged between 21 and 40cm/s with 1 cm/s increments (i.e. 21, 22, 23,…38, 39, 40cm/s) and this provided 20 different conditions. Figure 1B illustrates the "uncoupled" condition and demonstrates how the doors moved as the participants approached the doors. During the "uncoupled" conditions, one door (left or right) always moved at 40cm/s while the other door moved at rates that ranged between 20 and 38cm/s with 2cm/s increments (i.e. 20, 22, 24,…36, 38, 40cm/s). This means that there were ten trials when the left door's velocity was 40cm/s and ten trials when the right door's velocity was 40cm/s) Therefore each participant was exposed to a total of 20 coupled conditions and 20 uncoupled conditions for a total of 40 different conditions. All trials were presented in a random order and each participant experienced each condition once, in order to prevent any learning from taking place.

3.2.4 Data Analysis

The torso IREDs were used to calculate its Center of Mass (COM) position at any given time. From this calculation the location of the participant's COM in the anterior/posterior (A/P) direction and/or the medial/lateral (M/L) directions could be determined. The A/P displacement of the COM was used to determine where the participants were with respect to the doors, but more importantly, to determine the time at which they crossed the doors. The M/L displacement was used to determine the path taken by the participants in order to successfully cross the doors and also to determine the location of the COM with respect to the relative middle of the doors at the time of crossing.

The first derivative of the A/P torso location with respect to time was used to calculate the participant's approach velocity at a given time throughout the trial. For any given trial the time when the participant initiated a change in approach velocity was recorded. This is an important point in time because a change in velocity is thought to be the time when vision guides action. In order to determine when this change occurred, we averaged the first two-seconds of approach velocity for each trial for each participant and calculated the standard deviations of these means. We then searched, from the start of the trial, for when the approach velocity for the current trial fell outside of three standard deviations. In order for this time to qualify as an initiation in a change in velocity, the participant's approach velocity had to remain outside three standard deviations for 100msec. If the participant's approach velocity fell below 10cm/s for more than 100msec, we said that the participant stopped. Following a decrease in velocity or a stop, the time when the participant's velocity continuously increased was the time the participant increased approach velocity to get it back to normal.

The three torso IRED markers on the participant were used to calculate shoulder rotation about the vertical axis (yaw). The three IRED markers on the participant's head were used to calculate head rotation angles in the yaw direction. The average yaw angle magnitudes were calculated for the head and torso for the first two seconds of a trial and the final rotation magnitudes, for the head and torso, at the time of crossing. For the head and torso the final magnitude was subtracted from the average to determine the magnitude change in rotation. In our previous work (Study 1) we found that as the threat of getting hit by the doors increased so did the amount of shoulder rotation at the time of crossing. We used this measurement in order to determine if there was a difference in the amount of rotation at the time of crossing between the coupled and uncoupled conditions.

The IREDs on the door edges were used to determine their position at any given time. We used this information to determine the aperture width of the doors at the time of crossing (TOC). We then calculated how close to the middle of the door aperture the participants were at the TOC (% door aperture) by subtracting the position of the COM from the closest door edge (DE) and dividing this value into the door aperture width at the TOC. The equation used to calculate the percentage of door aperture at the TOC was: $\%DA = DA_{TOC} / |COM - DE_c|_{TOC}$ where: DA_{TOC} is the door aperture at the TOC, COM is the center of mass at TOC, and DE_c is the closest door edge to the participant's COM at the TOC. This was done in order to determine the participants' level of control at the time of crossing.

The location of a "fixation" is used by researchers to assume where a participant is attending while fixation duration gives insights to the amount of time needed to process visual information. In the current study, a fixation was defined as the participants' eye angle not exceeding a 1^{o} change for a minimum of 100msec. It is important to take into account the quality of the measurement; no matter what the underlying physiology, it is only possible to detect changes in fixation position that are significantly larger than the measurement noise. Our rational for minimum fixation duration of 100msec was that this time represents the minimum time needed by the nervous system to process visual information (Alpern, 1969; Young, 1970, Yarbus, 1967).

In order to determine where a fixation was located we integrated the Optotrak and Gaze Tracker systems such that the former tracked the participants' head location with respect to the room while the latter tracked the eye position relative to the head. With the combination of the two systems we were able to calculate the fixation location at any point in the room at any time and the duration of each fixation. We then overlaid the fixation location with the door location at the same instant in time to determine where the participant was fixating at that instant in time (i.e. left door, right door or aperture). A frequency count of the number of fixations that occurred at all locations throughout a trial was tallied for each participant. These fixation locations were broken down into two phases: before a change in velocity and after a change in velocity. Since we knew the start and end time of each fixation, we were able to separate out the last fixation to determine not only the location of the last fixation but also the time difference between the start of the last fixation and the TOC. If this last fixation was directed towards where the participant was heading and the latency between the onset of the fixation and the TOC was short, we would know that perception and action were tightly coupled.

3.3 Results

In all the trials collected, only three times were participants hit by the doors. The three collisions occurred during the uncoupled condition and occurred once for three different participants. During the uncoupled conditions one door always moved at a rate of 40cm/s while the other door moved at an unmatched velocity. The door velocities during the “collision” trials were not all the same, the velocity for the door that did not move 40cm/s was 30cm/s for two trials and 34cm/s for the other. These three “collision” trials were removed from all further analyses.

Figures 2 and 3 display representative data from participant SC of both kinematics and gaze behaviours respectively. In Figure 2, each line represents the participant’s COM displacement in the M/L direction for each trial in each condition. Similar graphs for each of the other participants are illustrated in Appendix C. In the coupled condition, the relative middle of the doors was always located at the same location as the absolute middle of the doorframe (i.e. 0 cm in the M/L direction). In the uncoupled condition the relative middle of the doors was not located at the same position as the absolute middle of the doorframe. The COM profiles at the time of crossing (TOC) and the time leading up to the TOC reflect the behaviour of the participants reacting to the behaviour of the doors. In the coupled condition the middle of the aperture was consistent and predictable and so the COM trajectories for all the trials funnel in towards this location whereas the opposite is true for the uncoupled condition.

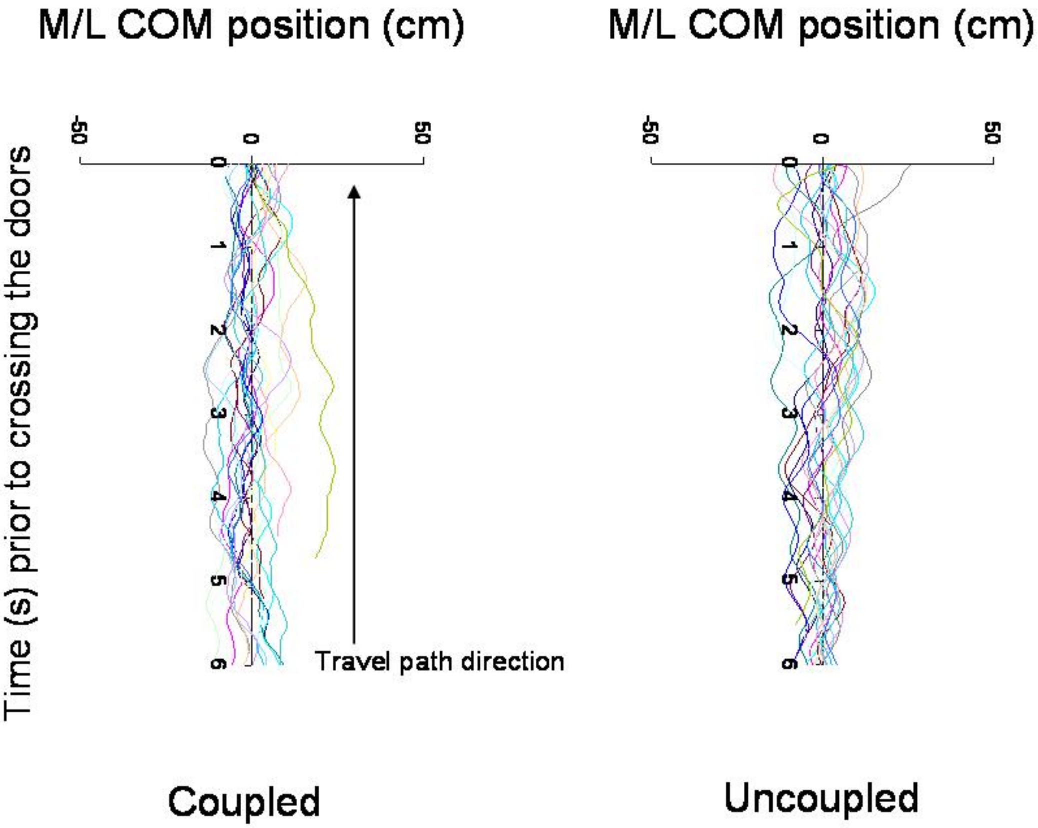

Figure 2- *Examples of one participant's COM trajectories in the M/L direction as they approached and crossed the doors under each of the conditions (i.e. coupled and uncoupled). The y-axis is the time prior to crossing the doors and the x-axis is the position (in cm) of the participant's COM at the time of crossing relative to the absolute middle of the door frame (0cm), such that a positive value indicates a passage to the right of the middle and vice versa for a negative value.*

In Figure 3, each point on the graph displays the location and duration of each fixation for a single coupled and uncoupled trial as participant SC approached the doors. The interesting finding about the location of fixations is the random order in which they occur except for the last one that happens to always be directed towards the aperture. A table of the fixation locations for the first five fixations for each participant under the two conditions is displayed in Appendix D.

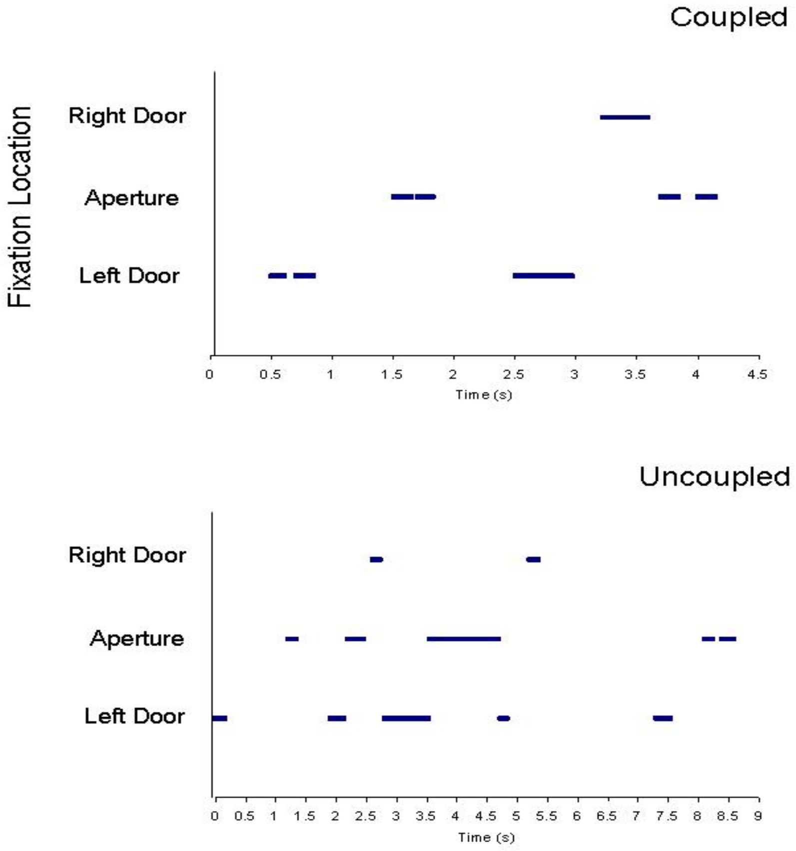

Figure 3- *An example for each condition of one participant's (SC) gaze fixation sequence from the start of a trial to the time of crossing the doors. Outlined are the fixation location along the y-axis and the start and duration of each fixation along the x-axis.*

3.3.1 Velocity adjustments

Table 1a) shows the proportion of trials in which the initial change from steady-state velocity was initiated for each condition. On average, participants decreased their velocities in 67% of the trials in the coupled condition and 95% of the trials in the uncoupled condition. A McNemar Chi Squared test indicated that the uncoupled condition had significantly more trials ($p < 0.05$) with a change in velocity than the coupled condition. Table 1b) shows the proportion of trials in which the participants stopped prior to crossing the doors. Participants stopped in 38% of trials for the uncoupled condition and in only 17% of trials in the coupled condition. There were a significantly higher number of stops ($p < 0.05$) during the uncoupled condition than the coupled condition (using a McNemar test).

Table 1a- Proportion of trials in which each participant slowed down under each condition. The p-values at the bottom compare the coupled to the uncoupled condition

Participant	Coupled	Uncoupled
CSK	0.85	1
EN	0.7	0.85
KD	0.5	1
LE	0.4	0.95
NA	0.8	0.9
SC	0.75	1
Average	0.67	0.95
SD	0.18	0.06
		$p<0.05$

Table 1b- Proportion of trials in which each participant stopped under each condition. The p-value compares the coupled to the uncoupled condition.

Participant	Coupled	Uncoupled
CSK	0.15	0.3
EN	0.45	0.75
KD	0.1	0.2
LE	0	0.35
NA	0.2	0.35
SC	0.1	0.35
Average	0.17	0.38
SD	0.15	0.19
		$p<0.05$

We next compared the time of an initiation of change in velocity and the Time to Cross (TOC) the doors between the coupled and uncoupled conditions and across all the door velocities. A change in velocity was not dependent on door velocity for either condition. Two one-way ANOVAs (i.e. one for the coupled and one for the uncoupled door condition) were run to compare the time when a change in velocity was initiated across the different door velocities. The reason why two ANOVAs were used was because there was a different number of door movement velocities used in the coupled condition than in the uncoupled condition. The results showed no effect of door movement velocity on the time when a change in velocity was initiated for either the coupled ($F_{(19, 5)}$= 0.62, P= 0.874) or the uncoupled ($F_{(9, 5)}$= 0.57, P= 0.814) conditions. The time when a change in velocity was initiated was also not different between the two conditions (i.e. coupled and uncoupled) as shown by a one-way ANOVA. ($F_{(1, 5)}$= 3.17, P= 0.135). However, the time it took the participants to cross the doors from the start of the trial was longer for the uncoupled condition than the coupled condition according to a one-way ANOVA ($F_{(1, 5)}$ = 24.3, P= 0.0044).

3.3.2 Door Aperture at TOC

We averaged the proportion of trials that each participant crossed the doors at each of the aperture ranges. Figure 4 is the average and standard error of these proportions across all the participants. A second order polynomial was used to fit the data in order to observe the trend in the data. The figure shows a plateau in frequency for the coupled condition between apertures of 95 and 100cm whereas in the uncoupled condition the maximum frequency value occurs between apertures of 80 and 85cm. The difference between the coupled and uncoupled conditions shown in Figure 4 is an artefact of fewer instances of 100cm apertures for the uncoupled condition. Interestingly, the average door aperture at the TOC was not different between the coupled and uncoupled condition when collapsed across velocities; by a one-way

ANOVA ($F_{(1, 5)} = 0.21$, $P = 0.663$). The average values were 78cm for the coupled condition and 76cm for the uncoupled condition.

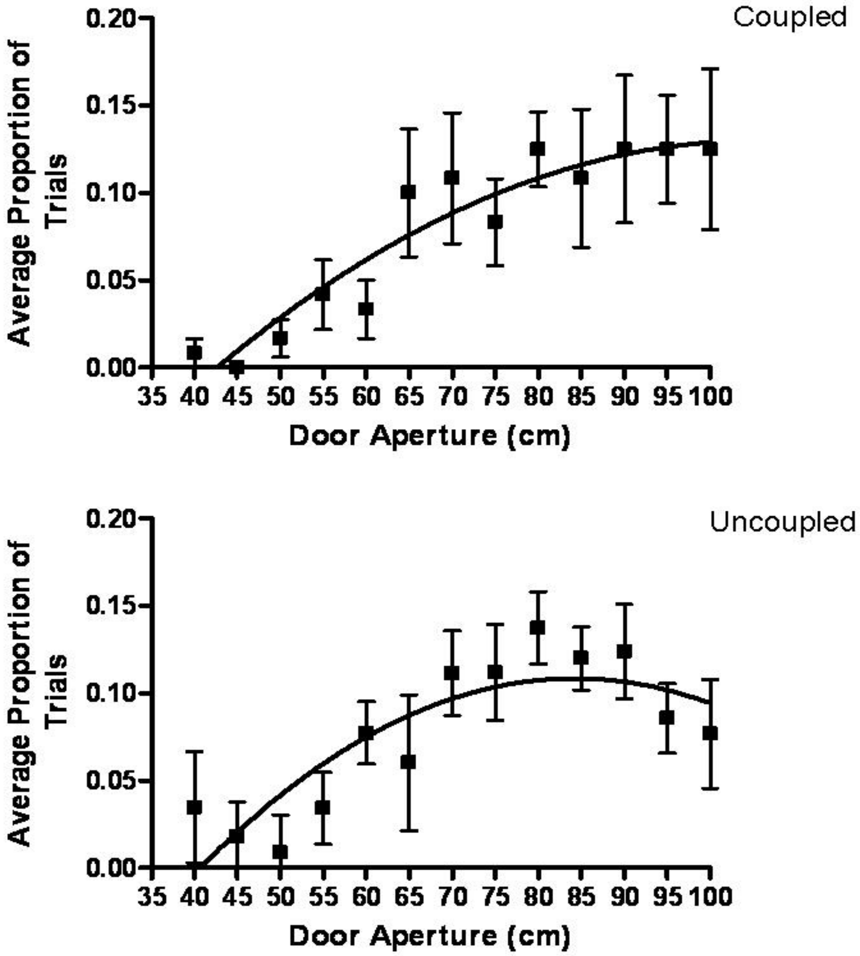

Figure 4- *The average proportion of trials (with standard error bars) that each participant crossed the doors at each of the door apertures (in cm) for both the coupled and uncoupled conditions.*

3.3.3 Center of Mass location at TOC

We were interested in determining how close to the middle of the door aperture participants were at the TOC across conditions. We compared each participant's COM location in the M/L direction relative to the middle of the door aperture at the TOC. Figure 5 shows the average proportion of trials that each participant crossed the doors for each of the relative distances from the middle. For the coupled condition, the participants had on average 75% of the trials in which they passed directly through the middle of the aperture at the TOC. During the uncoupled condition the participants passed directly through the middle of the aperture for about 50% of the trials.

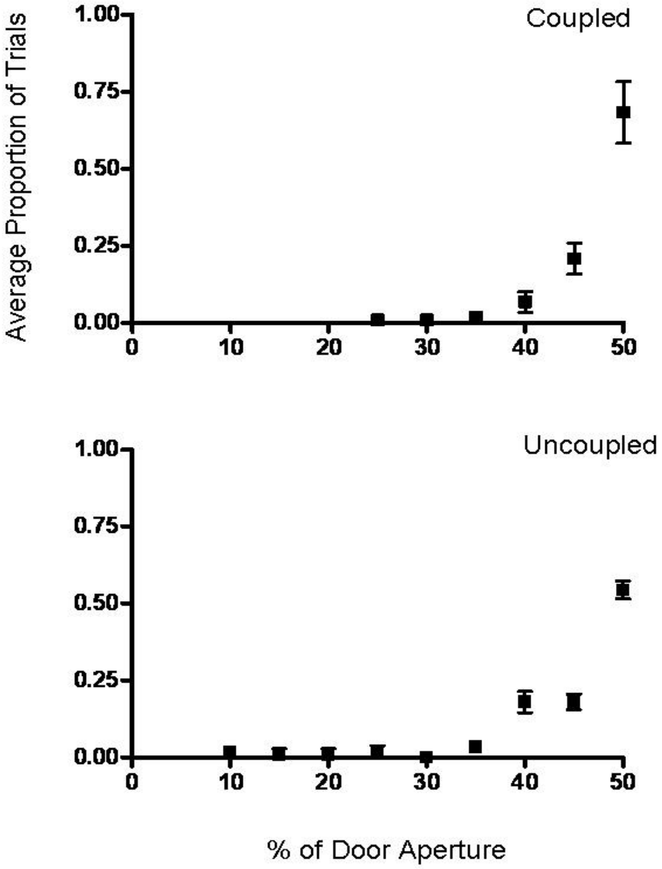

Figure 5- *The relative distance from the middle of the aperture (as a % of door aperture) at the time of crossing under all four conditions. Each data point reflects an average proportion of trials with standard error bars across all participants.*

3.3.4 Variability in Center of Mass location

The variability (using the standard deviation) of the COM location in the M/L direction throughout the trials was compared across conditions. A one-way ANOVA showed that when the doors moved in an uncoupled manner, the location of the participants' COM was more variable in the M/L direction than during the coupled conditions ($F_{(1, 5)}$ =13.20, P=0.015). We then looked at the variability in the COM in the M/L direction across three different time series throughout the uncoupled condition (i.e. initial 2s of each trial, if a change occurred then from time of velocity change to the time of crossing, and if a stop occurred then from time of stopping to the time of crossing). A one-way ANOVA showed that over the initial two seconds of each trial was significantly less variable than the other two time series ($F_{(2, 5)}$ = 8.29, P= 0.0075).

3.3.5 Shoulder and head rotations

We measured the rotation magnitude in the yaw direction for both the head and trunk at the time of crossing. These magnitudes were expressed as a difference between normal yaw movements at the beginning of each trial and yaw at TOC. The average trunk rotation magnitudes changed between 6 and 14 degrees from the start of the trial. We compared the changes in trunk and head rotation magnitudes across conditions separately because we also wanted to know if stopping had an effect on rotation magnitudes. The head rotation magnitudes for the coupled and uncoupled conditions when a stop occurred were compared to when a stop did not occur and the same was done for the trunk rotation magnitudes. In order to analyse these rotation magnitudes we used two two-way ANOVAs (one for the head and one for the trunk). For the trunk there was no main effect of condition (i.e. coupled or uncoupled) ($F_{(1, 5)}$ =1.20, P=0.335) or of whether or not a stop occurred ($F_{(1, 5)}$ =0.52, P=0.512) and there was no interaction effect (P= 0.448, $F_{(1, 1)}$ = 0.68). The same was true for the head rotation magnitudes;

no main effect of condition ($F_{(1, 5)}$ =0.46, P=0.536) or of stopping ($F_{(1, 5)}$ =0.40, P=0.56) and no interaction effect ($F_{(1, 1)}$ = 2.7, P= 0.199). One interesting finding was that the head rotation magnitude (relative to the room coordinates) was less then that of the trunk, indicating that the head was slightly rotated in opposite direction to the trunk, which will be discussed in the discussion.

3.3.6 Fixation Rate and Frequency

There were several instances when the eye did not move more than 1^o throughout the trials. Table 2 displays the average number of fixations per second across all participants for each of the conditions and the proportion of the total number of fixations both before and after a change in velocity. On average the participants made 2.68 and 2.63 fixations/s for the coupled and uncoupled conditions respectively. A one-way ANOVA showed that these values were very similar and therefore, there was no main effect of fixation rate across the two conditions ($F_{(1, 5)}$ = 0.38, P= 0.565). On average 25% of the total fixations during the coupled condition occurred following a change in velocity. However, during the uncoupled condition 35% of the total fixations occurred after a change in velocity.

Table 2- Average and (SD) values under each condition for the number of fixations/second across all participants and the proportion of the total fixations before and after a change in velocity.

CONDITION	**Fixations/sec**	**Proportion of fixations Before a change in velocity**	**Proportion of fixations After a change in velocity**
Coupled	2.68 (0.67)	0.75	0.25
Uncoupled	2.63 (0.6)	0.65	0.35

Fixation periods (i.e. time when the eyes were fixated) occupied between 23 and 85% of each trial. Individually and collectively the participants spent the same amount of time fixating throughout a trial, across the two conditions. A one-way ANOVA showed that there was no significant difference in the overall amount of time spent fixating across the conditions ($F_{(1, 5)}$ = 2.25, P= 0.522). The average amount of time that each participant spent fixating across the different conditions was just over 50% of the trial.

3.3.7 Fixation Durations

Just over 35% of the total number of fixations across all the participants for both the coupled and uncoupled conditions had fixations that were less than 200msec long. Figure 6 shows the proportion of the total number of fixations that had fixation duration within each 50msec time bin for each door condition. The proportion of trials at each time bin decreases exponentially from the first bin (100-149msec) to the last of the equally spaced bins (i.e. 450-499msec). The proportion of trials in the first bin seems to be twice as large as those that are in the second bin and these are twice as large as the proportion of trials in the third bin. The average fixation durations across all the participants' fixations were 206 and 226msec for the coupled and uncoupled conditions respectively. The median fixation durations were calculated and were found to be 167 and 184msec for the coupled and uncoupled conditions respectively. These values are more representative of the fixation durations that occurred most often across the two conditions.

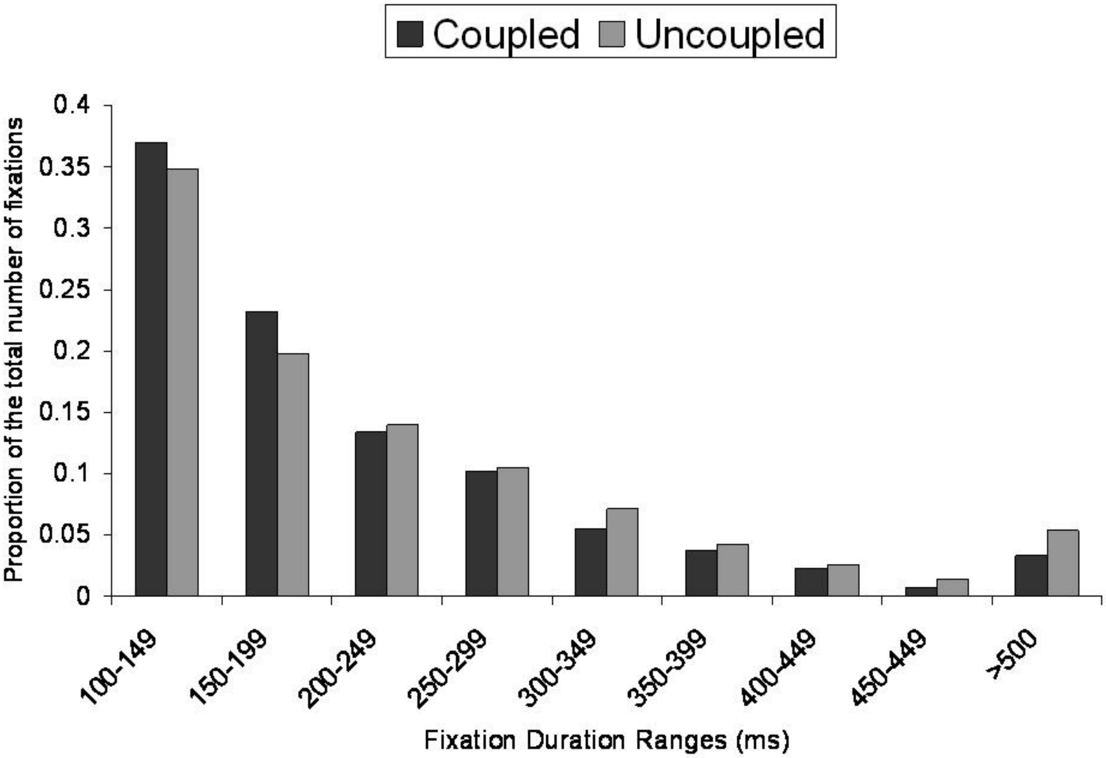

Figure 6*- The duration of fixations across the two conditions. Each bar represents the proportion of all fixations for a given fixation duration. The arrows reflect the median fixation duration values for each condition.*

3.3.8 Fixation Location

Fixation locations were classified into one of two categories with respect to the environment: door (irrespective of left or right) and aperture. Figure 7 shows the average proportion of fixations for each participant under both conditions. The figures were separated into “before” and “after” to distinguish fixation location proportions both before and after a change in velocity. The results will be presented in two sections: before or after a change in velocity.

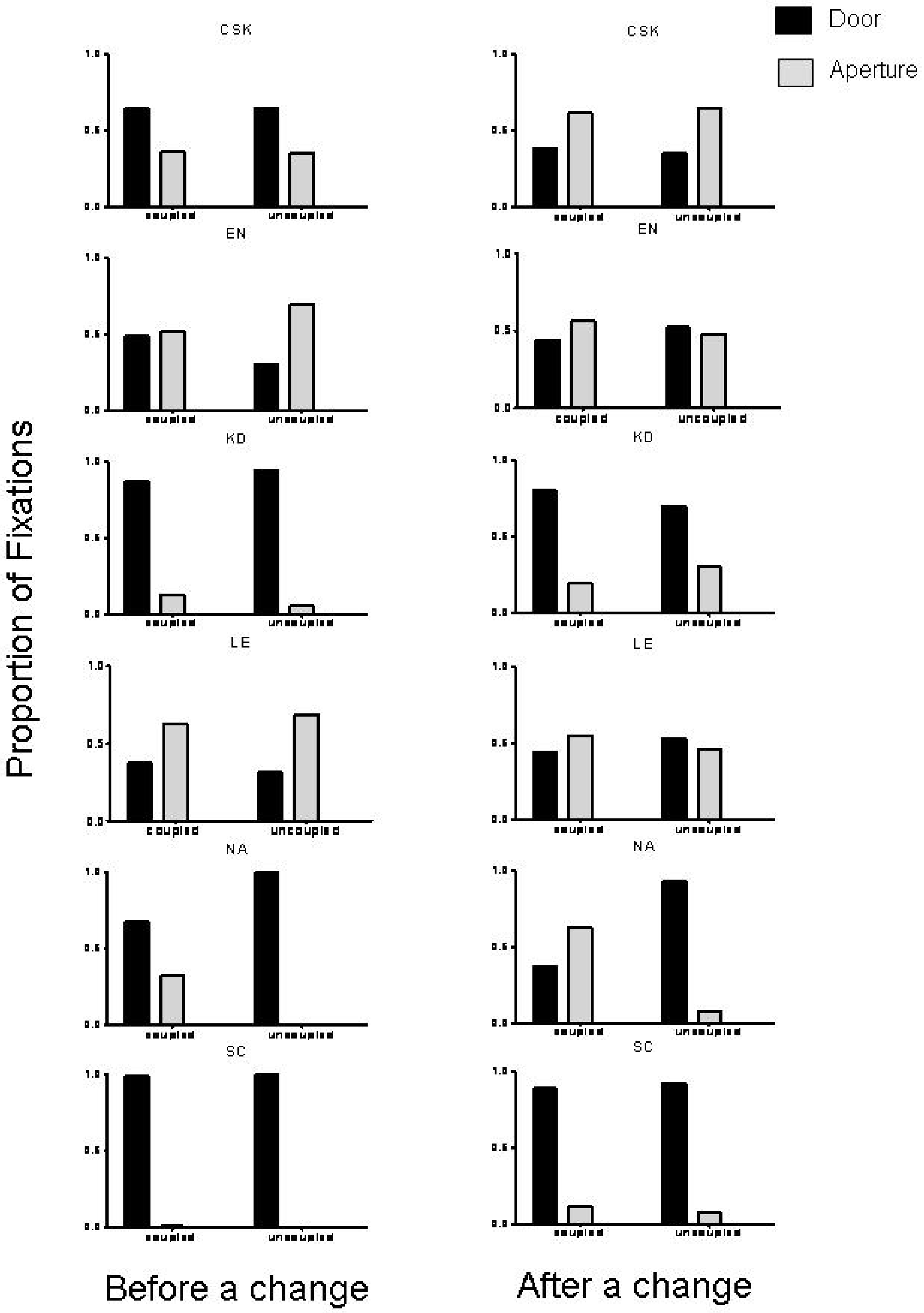

Figure 7- *The proportion of fixations that each participant directed towards either the aperture or one of the two doors. The figures on the left are the proportions before a change in velocity while the figures on the right are the proportion of fixations after a change in velocity*

3.3.8.1 Before a change in velocity

Each participant behaved similarly in the coupled condition as in the uncoupled condition in terms of location of fixations. Four of the participants (CSK, KD, NA, and SC) directed more of their fixations towards the doors than the aperture. The other two participants directed more fixations towards the aperture than the doors.

3.3.8.2 After a change in velocity

Following a change in velocity two of the six participants fixated more at the doors in the coupled condition, whereas in the uncoupled condition the number of participants that directed more of their fixations towards the doors increased to five out of six. Between the two conditions there seems to be a wide spectrum of behaviours across the participants. In going from the coupled to the uncoupled condition: two of the participants (CSK and SC) had similar fixation behaviours, three of the participants (EN, LE, and NA) increased their number of fixations directed towards the doors, and one participant (KD) had an increase in the proportion of fixations directed towards the aperture.

If we look at the location of fixations of the participants collectively, we get a clearer view of the overall fixation behaviours of the participants. Before a change in velocity there is no difference in the proportion of fixations directed towards the doors and the aperture between the coupled and uncoupled conditions. However, the overall proportion of fixations towards the aperture decreases from the coupled and uncoupled condition (Figure 8).

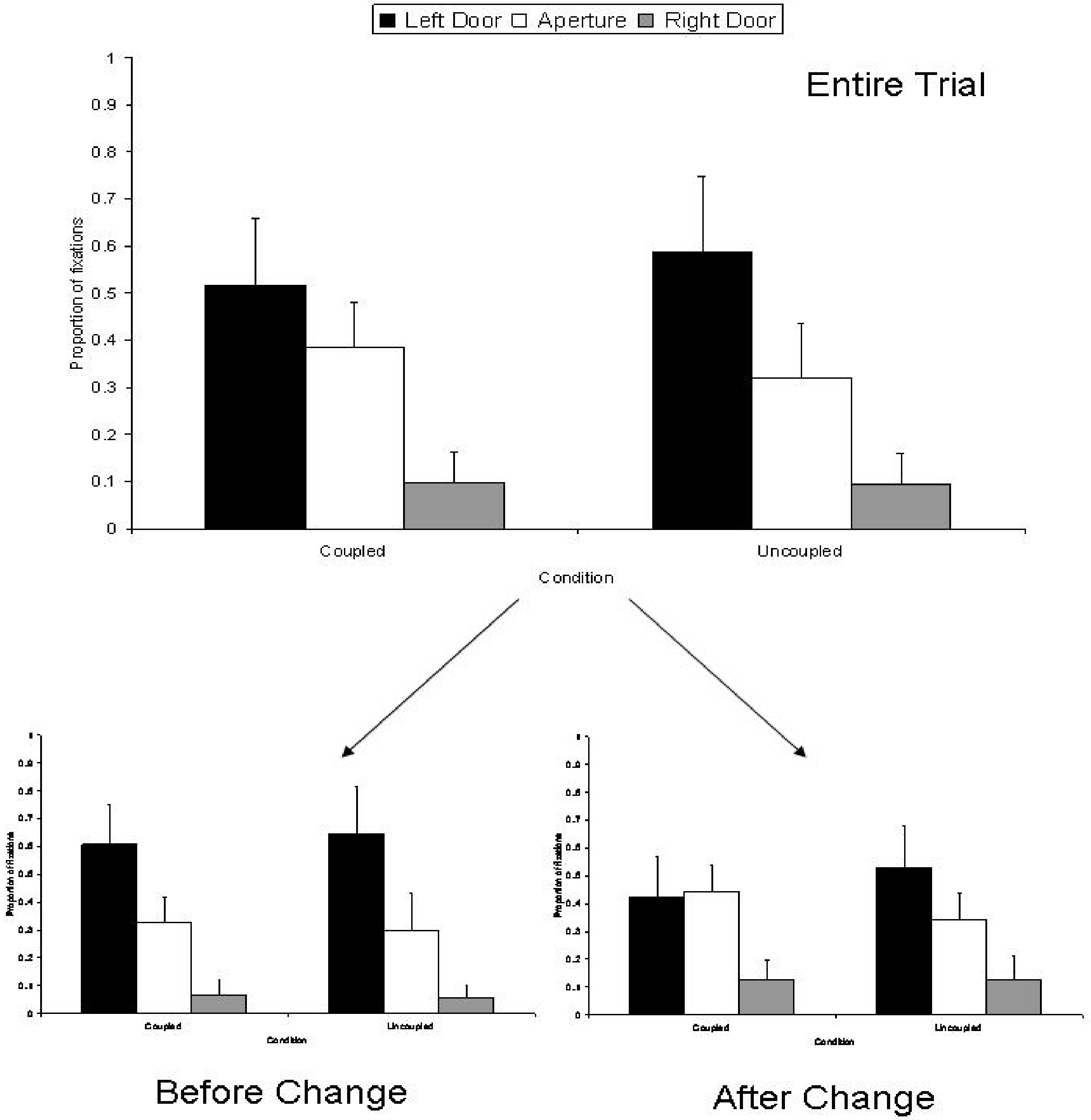

Figure 8- *The top graph shows the overall average proportion of fixations directed towards either door or through the aperture for the entire trial (from start to time of crossing) for both the coupled and uncoupled conditions. The bottom two figures compares the average proportion of fixations directed towards one of the three locations before a change in velocity to after a change in velocity for both conditions.*

3.3.9 Perception-action coupling

In order to determine how tightly coupled perception and action were we analysed fixation location and duration prior to crossing the doors. We were most interested in the latency between the last fixation to a location and the time which the participant crossed the doors. The results indicate that the fixations prior to crossing the doors were almost always directed towards the aperture for both conditions (98%). Table 3 shows the average latency between the start of the last fixation and the time in which the participants crossed the doors. On average this latency was 0.88, and 1.1s for the coupled, and uncoupled conditions respectively. A one-way ANOVA showed that there was not an effect of condition on the latency between the start of the last fixation and the time of crossing the doors ($F_{(1,5)}$ =0.5, P=0.69).

Table 3- Average and (SD) values under each condition for the latency between the start of the last fixation and the time of crossing the doors across all participants. The p-value compares the latencies across the conditions.

CONDITION	Time difference
Coupled	0.88 (0.74)
Uncoupled	1.11 (0.91)

P= 0.6904

3.4 Discussion

Our previous work has shown that when the doors moved in a cyclical fashion, similar to the coupled condition, participants slowed down prior to crossing the doors (Study 1). We also found that following a change in velocity, the participants passed through the doors when the doors were almost maximally opened. Based on the findings, we believed that slowing down was done in order to allow more time to process visual information. In the current study we found similar behaviours by the participants during the coupled condition; they slowed down prior to crossing the doors and they passed through the doors when the doors were close to being maximally opened. The current study was designed to extend the earlier findings in order to determine how vision was used to further process information and to measure if individuals' behaviours were similar when the doors were not moving symmetrically.

In the current study we measured individuals' actions as well as their fixation behaviours as they approached and passed through coupled and uncoupled moving doors. We found two commonalities between the conditions. First, the fixation patterns and location of fixations were random leading up to the doors; however just prior to crossing the doors the fixations were almost always directed towards the aperture (Figure 3). Second, prior to crossing the doors the participants usually initiated a change in velocity (Table 1).

3.4.1 Door Aperture and Position of COM at the Time of Crossing (TOC)

In the current study participants ensured a high level of safety at the TOC by passing through the doors when their aperture width was greater than twice that of the participants' shoulder width (i.e. greater than 80cm). Figure 4 illustrates that for the most part, participants crossed the doors when they were about 95 to100cm wide for the coupled condition and 80 to 85cm wide for the uncoupled condition. This means that during the coupled condition the participants were better at timing their passage to that of the maximum door aperture of 100cm than during the uncoupled condition. Although the time when the doors had an aperture of 100cm would be safest, the participants realized that this might not happen during the uncoupled condition because of the properties of the door movements. During the uncoupled condition, the doors had independent velocities and rarely had an aperture of 90cm or greater. The participants passed through the doors when they were large enough to ensure a safe passage, which tended to be when the aperture was about 80cm wide. Therefore, the difference between the coupled and uncoupled conditions shown in Figure 4 is an artefact of fewer instances of 100cm apertures for the uncoupled condition. Since this was the case, the participants had to have a higher level of precision at the TOC because with 80cm apertures, there was little room for error. Thus, slowing down and stopping more frequently is reflective of the fact that the aperture was deemed impassable more frequently during the uncoupled condition as compared to the coupled condition. By decreasing their walking velocity, the participants were able to view more door cycles and choose to pass when the doors were a suitable aperture.

Regardless of the behaviour of the doors, the participants' level of precision of control remained unchanged. Figure 5 illustrates that under all the conditions the participants passed through the middle or as close to the middle of the doors as possible at the time of crossing (TOC) on the majority of trials, similar to the findings of Duchon and Warren (2002). This high level of precision of control was achieved by the participants slowing down. In order to reach a goal within a cluttered environment, individuals must modify some aspect of locomotion: path direction, velocity or body position. The modification of walking velocity reflected the participants' need for safety. The uncoupled condition was more threatening than the coupled condition because there was an increased probability that the participants would contact the doors. The participants who collided with the doors did so during the uncoupled condition. As well, the number of trials in which a change in velocity occurred was higher in the uncoupled condition versus the coupled condition. This may explain why there were a larger proportion of the total gaze fixations that occurred after a change in velocity during the uncoupled condition as compared to the coupled condition (Table 2).

3.4.2 Action Parameters used to Successfully Cross the Doors

Other previous work showed that when participants were required to pass through static apertures that were slightly larger than their M/L width, the time of an initiated decrease in velocity and the magnitude of change in velocity increased with the level of difficulty (Higuchi et al., 2006). Prior to the current study we had the participants walk normally through static apertures set at different locations with two different widths to determine their behaviour (see Appendix B). In the current study, participants increased the magnitude of change in their walking velocity such that they stopped more frequently when the doors moved in an uncoupled fashion than when they moved in a coupled fashion. That explains why it took longer for the participants to complete the uncoupled conditions. Therefore, in order to maintain similar levels of control across conditions, participants adjusted their magnitude change in velocity according to the level of perceived threat, which could be an effect of aperture size (i.e. Fitts Law).

At TOC the average shoulder rotation magnitudes slightly increased from the start of the trial to further ensure a safe passage. Based on Warren and Whang's (1987) study, we would not have expected there to be shoulder rotations when the door aperture at the TOC was twice as large as the participants' shoulder width. We have previously found that locomotor action parameters available to a participant when passing through moving doors are implemented according to the amount of time available. When the time available to make an adjustment was large, the participants made a change in velocity and as the amount of time to make an adjustment decreased (less than 2 steps), participants made quick postural adjustments in the form of a shoulder rotations because these adjustment required less time to initiate (Study 2). A shoulder rotation directs the COM in a direction that is different than the direction of progression and therefore is less desirable to execute unless the participant feels that it is the only way to ensure safety. The difference between the current study and our previous work is that, in the current study, every trial had a change in shoulder rotation that ranged between 6 and 14 degrees. In our previous work the conditions that had the largest amount of threat (i.e. decreased maximum aperture) caused individuals to produce shoulder rotations. Shoulder rotations could have been an automatic reaction to a high level of perceived threat. The changes in shoulder rotation magnitudes were not large enough to have had a negative effect on intended path direction. Although the shoulders were slightly rotated away from the path of progression, the head angle did not deviate as much in order to keep the path of progression within the participants' central field of view. Therefore, individuals rotated their shoulders to decrease their M/L width, to increase safety, while still being able to fixate ahead at the goal with a great amount of acuity.

3.4.3 Gaze Behaviour during Different Phases

The act of crossing the doors involves 2 phases: (1) approach with unchanged velocity and (2) preparation to cross the doors following a change in velocity. Leading up to the time when the participants crossed the doors, the participants actively moved their eyes to gather information about the environment. A mobile eye in this situation would allow the visual system to combine high resolution with the ability to monitor the entire visual field (Findlay & Gilchrist, 2003). Eyes move to an area of interest, fixate for a short period of time, the visual system extracts the important information to perform a task and then passes it on to the motor system (Land and Furneaux, 1997). This sequence of active movement of the eyes followed by periods of fixation allows the observer to make predictions about future events because the eyes move in a proactive manner and are not reactive.

The most insightful finding from the current study is the break down in proportions of fixations directed towards the doors and aperture both before and after a change in velocity (Figure 7). Interestingly, following a change in velocity more fixations were directed towards the doors in the uncoupled condition than the coupled condition. The participants treated the two conditions similarly before a change in velocity, but not afterwards. The reason for this could be that prior to a change in velocity, the participants used vision to guide them towards the door frame and to pick up features within the environment (i.e. door movement profiles or other objects). Following a change in velocity, more fixations were directed towards the doors in the uncoupled condition. In the uncoupled condition, the location of the aperture is random because of the asymmetry in door movement rates, and the location of the doors is crucial for timing a passage. Since the doors moved independently, it makes sense that more fixations would be directed towards the doors in order to know their perceived direction of movement (Brouwer et al., 2003). The time when both doors move away from each other would indicate a good time to pass through the doors (Study 1).

One suspicious finding was the frequency of gaze fixations directed towards the left door as opposed to the right door (Figure 8). There are three possible reasons for this phenomenon. First, the participants were all habitants of Western world countries and this left-door dominance could be due to cultural adaptations. Since Westerners are used to passing approaching individuals on streets or sidewalks on the right-hand side, they are used to viewing approaching objects in their left field of view. A second explanation is that the participants might have had a dominant hand and thus have a preference for one side as opposed to the other. Although this could be a possibility, we did not test for handedness. The last possibility is that the gaze tracker apparatus might have skewed fixation locations to the left. This last explanation can be dismissed as we checked fixation locations using the Optotrak system during pilot testing.

On average the participants had between 2.5 and 3 fixations per second throughout the trials across the conditions (Table 2). Fixation periods are the time when perception takes place (Findlay & Gilchrist, 2003). Since both the ventral and dorsal streams project to the Frontal Eye Field, it would make sense that gaze shifts in order to scan the environment to locate the next object to be fixated and acted on. On any given trial, the participants spent about 55% of the trial's duration fixating, while the remaining time was spent shifting their gaze to a new location. Although the participants spent the majority of their time during a trial fixating, the majority of fixations were less than 200msec (Figure 6). Fixation durations are dependent on the amount of processing needed (Land and Furneaux, 1997). This means that it only took about 200msec for the visual information to go from the visual cortex along the ventral stream to allow for conscious perception and then communicate with the dorsal stream if an particular action is required (Milner & Goodale, 1995) . Since the fixations were brief and frequent we can assume that it was not likely that participants tracked the movement of the doors as they approached them. Fowler and Sherk (2003) believe that tracking an object would complicate matters, because tracking the doors would not allow the image to move across the retina and stimulate more retinal receptors. Allowing more retinal receptors to be activated would increase activity in the LGN and V1 (Martinez-Conde et al., 2004) and this would provide richer information to travel along both the dorsal and ventral streams in order to allow for appropriate actions to take place.

3.4.4 Perception-Action Coupling

Montagne et al. (2003) argue that visual information may be available to individuals at a distance but they are not attuned to it until about 3m (2s) before crossing the doors. If the participants were not attuned to visual information prior to 2s before crossing the doors, would we have seen any fixations directed towards the doors prior to this time? Fixations towards the doors would indicate that the participants were attending to the position of the doors at the time of fixation. Fixations directed towards the aperture would be used in either a travel fixations mode to direct locomotion or to simultaneously attend to objects (i.e. doors) within one's peripheral field of view. Therefore any fixations on the door that occurred prior to 2s before crossing the doors would indicate that the participants were attuned to the properties of the door. This 2s time coincides with the time when a change in velocity was initiated. We found that the participants had fixations towards the doors and aperture prior to as well as following a change in velocity (Figure 7). As participants approached the doors, fixations directed towards the aperture were used to gather information about travel path direction whereas fixations directed towards the doors (i.e. location) were used to attend to changes in the environment. At a distance there was no set pattern for fixation locations similar to Geruschat et al. (2003). We believe that participants were acquiring information about the environment and visual fixation patterns followed a bottom-up pattern. However, just prior to crossing the doors, fixations were more concentrated towards the door aperture because that is where the participants were heading and so fixation patterns followed a top-down (task-specific) pattern. This finding is similar to Land and Lee (1994) who found that as task demands increased, fixations were tightly bound to task-relevant objects.

Land and Lee (1994) also found that the time difference between a fixation and an appropriate action was about 0.8s. Other tasks such as a stone stepping task have also shown that eye movements to the next target precede stepping on the target by about 1s (Hollands et al., 1995). Both these studies demonstrated that perception and action are tightly coupled in time. We believe that in the current study perception and action are tightly coupled for the time just prior to crossing the doors. At this time the aperture would be the task-relevant object and the task demand to pass through the doors would be greatest at the time prior to crossing the doors (Land and Lee, 1994). The average latency between the start of the fixation and the time of crossing was similar for both the coupled and uncoupled conditions (about 1s) (Table 3). The uncoupled condition had a slightly longer latency than the previous findings and the coupled condition because of the uncertainty in the location of the relative middle of the doors. The latency between the start of the last fixation and the TOC reflects the amount of time between when a decision to cross the doors occurred and when the participants actually crossed the doors. Since the crucial action in this current study was to pass through the doors safely, we believe that perception and action are tightly coupled for this action. Therefore, when a specific action determines the success of the task then vision will guide that action. Fixation at this time increases movement across the retina which leads to more visual areas activated and leads to a successful passage (Fowler & Sherk, 2003).

The question still remains, are individuals attuned to visual information at great distances? When Montagne et al. (2003) used the term “attuned” they could have meant that vision is not tightly coupled with action at great distances. The point at which a change in velocity was initiated has, in the past, been considered the time when perception most tightly influences action (Lee et al., 1982). This is not the case in the current study. Four of the six participants had similar fixation patterns following a change in velocity as they did prior to a change, and only one participant directed more fixations towards the aperture. We believe that this happened because the environment was dynamically changing in the same way from the start of the trial as it did at the end of the trial and so we would not expect the fixation patterns to change. The change in velocity may be more reflective of the participants running out of room between themselves and the doors and the doors not being suitable for safe passage at their current walking velocity rather than the point at which perception tightly coupled action. This could be why participants stopped more frequently in the uncoupled conditions, because the doors were just not suitable for passage until the participant completely ran out of room. If the participants were attuned to visual information from the start of the trial they could have made fine adjustments to their velocity from the start of the trial and not at some point (2s) prior to crossing the doors. From the start of the trial, the visual stimulus (or area of potential threat) was so far from the participant that its behaviour did not directly affect the current state of the participant. Just prior to the participants crossing the doors is the point at which visual information becomes crucial and at that point the participant would be attuned to it.

“Attuned” could also mean conscious perception. In this way one could believe that since there was not a change in movement behaviours during the early stages that individuals were approaching the doors aimlessly, without consciousness. However, in this current study it is difficult to determine whether no change to action occurred because of lack of conscious perception or whether conscious perception determined that no change to the current state was required. It is possible that participants are not attuned to visual information at great distances based on their location of fixations. Prior to a change in velocity, there was no difference in the proportion of fixations directed towards the doors and aperture between the coupled and uncoupled conditions. Following a change in velocity, more participants (5) directed more fixations toward the doors in the uncoupled condition than those who directed a majority of fixations towards the doors in the coupled condition (2). This change in fixation behaviour is because of the nature of movement of the doors. Since the doors moved independently in the uncoupled condition, the location of the aperture and the time when the aperture would be large enough to be passable were unpredictable. Therefore, participants slow down prior to crossing the doors in order to allow further visual processing to increase their precision of control. And it is at this time that individuals become attuned to visual information.

3.5 Conclusions

We have found that changing velocity is only one action parameter used to avoid collisions in a dynamically changing environment. Another strategy used to avoid collisions is a change in body position (i.e. shoulder rotation). The doors provide spatial information necessary to determine if a safe passage is possible. Since the doors were constantly moving, more fixations would need to be directed towards the doors in order to provide updated information about the spatial size of the doors. This spatial information would require fixations so that appropriate information could be directed from the visual cortex to the motor cortex (via the posterior parietal cortex) in order to produce the correct action. Since the doors in the uncoupled condition moved asymmetrically the aperture width and location would be unpredictable therefore the doors would have to be fixated in order to get accurate spatial information. The fixations directed towards the aperture provided information about the location of the goal. Since the participants were successfully able to pass through the middle or very close to the middle of the aperture, their COM in the M/L direction reflected this fixation behaviour. The rate of door movement was always different in each trial but the relative middle of the aperture for the coupled condition was always in the same location. During the uncoupled condition the location of the relative middle of the aperture was variable. This explains why the variability of the COM in the M/L direction was significantly greater in the uncoupled condition especially after a change in velocity. Also within the uncoupled condition the greatest amount of variability in the M/L direction of the COM occurred after a change in velocity. We believe that the participants alternated between fixating on the doors and the aperture in order to determine where the aperture was located and if it was passable. If the aperture was not passable then the participants fixated on the doors to determine where they were located and in which direction (if any) they were moving. This was the case more so in the uncoupled condition because each door moved at a different rate (Figure 7). Therefore, following a change in velocity participants were more attuned to visual information than before a change in order to properly direct their COM to pass through the doors at the safest location possible, the middle of the aperture.

CHAPTER 4

WHAT VISION AND MOVEMENT BEHAVIOURS TELL US ABOUT STRATEGIES USED TO WALK THROUGH A MOVING APERTURE

Abstract

Visually guided actions are performed under the continuous control of vision. Tasks that rely heavily on vision include navigating around obstacles, route planning, and steering towards a goal while avoiding collision with other objects. Two strategies have previously been proposed to explain how individuals steer towards targets; egocentric-direction and optic flow strategies. We wanted to know how individuals use vision to successfully walk through a moving aperture that is a constant width. In this study the participants walked along a 7m pathway towards a door frame at one of five starting locations: either in line with the middle of the door frame or 20, 40, 60 or 80 cm from the middle. The 70cm aperture began in the middle of the door frame and oscillated between the two end posts at one of three velocities (25, 30, or 35cm/s). Here we show that the participants funnelled towards the middle of the door frame regardless of their starting position before passing through the middle of the aperture. The participants' fixations were mostly directed towards the middle of the aperture. We also found that the participants' movements followed their gaze behaviours more closely as they were in close proximity to the door frame (about 2m). We believe that the participants treated the entire door frame as a stationary object, regardless of the moving aperture, and approached the middle of the door frame head on. In this way the participants used neither an egocentric-direction nor an optic flow strategy to steer towards the middle of the aperture. In a real-world setting individuals will use the visual richness of their surroundings and the predictability of movements within the environment to control movement.

4.1 Introduction

Visually guided actions include navigating around obstacles, route planning, and steering towards a goal. These tasks are all performed under continuous control on the basis of visual information (Fajen, 2005). This control of action is necessary in order to successfully execute tasks of daily living (i.e. walking through a crowded mall) as well as sport-specific actions (i.e. a running back carrying the ball towards the line of scrimmage). In both situations, individuals attempt to avoid collision by locating and passing through gaps of appropriate sizes. These gaps may have a consistent width or they may have varying widths; they may be stationary or they may be moving. Here we examine how individuals use vision to successfully walk through a moving aperture that is a constant width. At the start of each trial the middle of the aperture was aligned with the middle of a door frame and then oscillated between the two end posts at one of three velocities (i.e. 25, 30 or 35 cm/s). The participants began each trial seven meters from the door frame at one of five starting locations: either in line with the middle of the door frame or 20, 40, 60 or 80 cm from the middle.

Previously we have observed individuals walking towards oscillating doors with varying aperture size. We found that individuals used vision to determine when to slow down prior to crossing the doors and when they crossed the doors they passed through the middle of the aperture when the aperture was close to its maximum width. Therefore, the individuals appropriately coordinated their movements based on their ability to perceive the behavioural properties of the environment (Turvey, 1992).

Fajen (2005) has considered how individuals successfully complete visually guided tasks. The first component is the ‘ideal state’, which is where an individual should strive to be at each moment in time. The ‘ideal state’ brings the individual to a goal without any further adjustments. An example of this from our previous work passing through oscillating doors is arriving at the doors when the aperture between the doors is at its maximum width.

The second component is the 'safe region' defined by the individual's maximum action capabilities, which separates possible from impossible actions. An example of the safe region from our previous work would be that period of time between when the aperture width was just larger than the individuals' shoulder width and when the doors were at their maximum aperture. As long as the individual can keep the 'ideal state' within the 'safe region' a task will be successful (Fajen, 2005). In the current study we will analyse the behaviours of the participants in order to determine the ideal state and the safe region. The ideal state would be to have the middle of the aperture in line with participants' travel path direction while the safe region will be to keep the middle of the aperture in close proximity to the participants' travel path direction.

Ever since Gibson's (1958) proposal that animals use optic flow to locomote towards objects of interest, many researchers have studied individuals' performance in visually-guided locomotor tasks. Lee et al. (1982) measured how long jumpers approached and successfully contacted the take-off board. Since their participants ran along a straight path towards a spatial target, Lee et al. (1982) used a spatial measurement (i.e. variability in foot fall location) to understand how long-jumpers successfully contacted the take off board. The researchers found that foot fall position variability decreased dramatically over the last four steps prior to contacting the take off board. Lee et al. (1982) believed that these last four steps were visually driven. The assumption was that in the last four steps, vision was used to correct any errors that occurred previously and ensure proper foot positioning. We are also interested in determining if our participants decrease the variability in their ability to adjust their movements in order to safely pass through the aperture.

There has been much debate as to how visual information is used to guide actions successfully. From this debate there have been two strategies that suggest how individuals use vision when walking towards a target: egocentric-direction and optic flow strategy. The egocentric-direction strategy was proposed by Rushton et al. (1998) to explain how individuals walk to targets while wearing visual displacement prisms. The egocentric-direction strategy suggests that individuals walk to targets by rotating their eyes, head, and then the trunk until the angle between their gaze and midline is reduced (Rushton et al., 1998). The optic flow strategy was first introduced by Gibson (1958) to explain how animals steer towards a goal. Optic flow is the pattern of visual motion at the moving eye (Warren et al., 2001). Optic flow-based strategy suggests that participants walk to a goal by changing their path so that the image or goal and the focus of expansion are aligned (Warren et al., 2001).

Rushton et al. (1998) set out to challenge Gibson's thoughts that locomotive heading is guided by optic flow. Rushton et al. (1998) had participants walk to a target while wearing displacement prism glasses. These glasses shifted the perceived egocentric location of the target with respect to the midline of the participant's body. If the participants consistently misperceived the location of an object relative to their body, they would walk in a veering trajectory. The authors found that the trajectories taken by the participants followed a curved path showing that individuals walk towards the perceived location of a target relative to their bodies. In order to determine how the participants arrived at the target the researchers calculated the *target-locomotor direction error* (α). This error was the instantaneous difference between the locomotor direction and the direction of the target, which was shown to be equal to the angular deflection of the prisms.

Warren et al. (2001) challenged the notion that individuals use egocentric-direction to walk towards visually perturbed objects. The researchers had participants walk towards a virtual target and the heading direction was displaced 10^o to the right or left from the actual walking direction. This effect would be similar to that of wearing prisms. The researchers believed that optic flow is used to control locomotion. Warren et al. (2001) tested the optic flow hypothesis by varying the amount of optic flow available to the participants while they walked to a target that was displaced from their heading direction, and monitoring their path to the target. If the participants used egocentric-direction to walk towards the target they would walk in a curved path such that the virtual heading error would be equal to the degree of displacement - 10^o. If the participants used optic flow to walk to the target they would move along a straight path with a heading error that goes to zero. The researchers found that individuals use both egocentric-direction and optic flow to walk to a goal. As the amount of available optic flow information increased, it dominated behaviour and participants walked more of a straight path.

Warren et al. (2001) believed that the reason there was a difference in walking trajectories between their study and that of Rushton et al. (1998) was because prisms distorted optic flow information. Based on this notion, individuals will always use optic flow to guide movement, as long as it is available. The effectiveness of optic flow to guide one to a goal can only be tested in virtual reality environments; it is in this environment that salient features can be removed, added, or distorted in order to determine their importance. The current study does not take place in a virtual environment and so we are unable to manipulate optic flow information available. However, since Gibson first identified optic flow as important for steering control in real world situations, we hope in this study to use walking behaviour to reveal the role of optic flow in walking through a moving aperture.

Fajen and Warren (2003) analysed how individuals steer towards stationary targets at different distances and locations in virtual reality. In their first study, Fajen and Warren (2003) had participants start at the same location every trial but the target was either a) at the same distance away but at a different angular position from the participant or b) at the same angular position from the participant but at different distances. Since the targets were not directly in line with the participant, the researchers determined how individuals walked towards the targets by calculating *target-heading angles (β).* Target-heading angle is the difference between tangent of the individual's walking direction (ϕ) and the instantaneous angle between the participant and the target (ψ). Fajen and Warren (2003) found that participants began to turn towards the goal about 0.5m after it appeared and the participants turned at faster rates with larger initial goal angles. This meant that the participants had completed the turn well before reaching the goal and then followed a straight path for the duration of the trial. Thus the magnitude of the target-heading angles was largest at the start of each trial and half way through the trial the angles decreased to zero and remained there for the duration of the trial. Therefore, individuals in open field situations control their current heading so that it is aligned with the goal (Fajen and Warren, 2003).

Based on these results, Fajen and Warren (2004) analysed how individuals intercept moving targets in virtual reality. One target began either in front of the participants or 20^{o} to the side and began to move (right or left) as the participant walked towards it. The goal of the participants was to walk through the virtual target. Again the researchers calculated the target-heading angle to determine how the participants walked to the target (except in this case the target location dynamically changed). Fajen and Warren (2004) proposed that the participants could use one of two strategies to contact the target; pursuit or interception. In the pursuit strategy individuals align their COM with the target at every instant in time. In the interception strategy individuals align their COM with where the target is going to be at a future time. Basically, if $\beta = 0$ throughout the trial then the participants were using a pursuit strategy and if $\beta > 0$ and is a constant value close to the initial angular difference between the participant and the target then the participants were using an interception strategy. Fajen and Warren (2004) also manipulated background visual information in order to test the behavioural differences of individuals walking to targets under egocentric-direction, local optic flow, and global optic flow conditions. The researchers found that individuals walked to moving targets using an interception strategy under all the different visual information conditions and argue that individuals walk to moving targets using the egocentric-direction of the moving target. In the current study where the goal is to safely pass through a real aperture rather than contact a virtual target we will determine whether participants use a pursuit or interception strategy.

On a behavioural level, it appears as though animals/ individuals are able to steer to a stationary goal by *nulling* the difference between their current state and the ideal state (Fajen, 2005). However, when the target is moving individuals anticipate where the target is heading and use an interception strategy to contact the target. The problem is that the current and ideal states may not be perceptually available to the individual. Gibson (1986) introduced the term *visual kinesthesis,* which is one's ability to rely on optical information about one's movements relative to the environment. Based on this idea, the ideal state can be attainable by acting appropriately in order to generate a certain pattern of optic flow; when flow pattern is not what it should be, ideal and current states are unequal and adjustments must be made (Fajen, 2005). Therefore, in order to null the error the current and ideal states do not have to be estimated, but the observer must act so as to produce a certain flow pattern.

Direction of locomotion is determined by the direction of optic flow on the fovea from the focus of expansion (Lappe and Hoffmann, 2000). Retinal motion during forward movement becomes a combination of radial optic flow and retinal slip induced by eye movement (Lappe and Hoffmann, 2000). Retinal flow is the actual motion pattern seen on the retina during combined self-motion and eye movements. The direction of an individual's gaze during locomotion will strongly affect the patterns of optic flow received (Sherk and Fowler, 2000). Researchers have studied how optic flow is affected when individuals heading to a target do not directly fixate on that target, but at objects in near vicinity along the travel path (Lappe and Hoffmann, 2000; Wann and Swapp, 2000). Wann and Swapp (2000) argue that if the individual is on a correct path to the target, the visual trajectories of the ground elements (i.e. flow line) would be straight. The researchers argue that any animal that routinely fixates on environmental features is aware that curved flow fields arise when it is not walking on a path towards the target and straight ones when it is on the correct path. Wann and Swapp (2000) agree with Gibson's idea that optic flow gives enough information to guide locomotion and they believe that it is accomplished by judging paths rather than judging heading because this simplifies how animals judge locomotor direction. And this is why Wann and Swapp believe we "look where we steer and steer where we walk." (Wann and Swapp, 2000, p.648). Previous research, including our own, has shown that individuals look where they are going (Land and Lee, 1994; Hollands et al., 1995, 1996, 2002; Patla and Vickers, 2003; Cinelli et al, unpublished). In the current study we measured both gaze behaviour and individuals' movements in the hopes of determining if individuals walk where they are looking. Following this analysis we will be able to determine if Wann and Swapp (2000) were correct.

Building on all the previous work done on steering towards goals, the aim of the current study was to determine how participants visually controlled their movements in order to successfully pass through a real-world moving aperture with a constant width. This moving aperture oscillated between two end posts and served as a moving target that individuals had to pass through. Each oscillation was meant to provide a different moving aperture or gap available for individuals to pass through. From this study we wanted to determine what individuals did and how they were successful. We calculated target-heading angles in order to determine if individuals used a pursuit or an interception strategy. The fixation data will help us understand what type of visual information was used and when it was necessary in order for the participants to be successful. The current study aims to understand how vision and action are integrated during a visually-guided task of walking through a moving aperture. This may help us to understand how optic flow and egocentric-direction might both contribute to guiding movement and maybe determine which of the two is more dominant.

4.2 Methods

4.2.1 Participants

Seven healthy female participants from the University of Waterloo participated in this study (age: 20-24 years). Female participants were used to ensure similar shoulder widths, which ranged between 38 and 42 cm. All participants had normal or corrected-to-normal vision and gave written consent to participate in the study. This study was reviewed and accepted by the Office of Research Ethics at the University of Waterloo.

4.2.2 Apparatus

The door structure was located at the end of a seven meter walkway. The doors each measured 200cm high by 76cm wide, were made of particle board and suspended from a steel frame (300 cm wide). The doors were driven independently by two computer generated step motors. Kinematic data collected using the Optotrak (Northern Digital Inc. Waterloo, ON, Canada) system. A total of 9 infrared light emitting diodes (IREDS) were used: two to monitor door position, one to locate the absolute middle of the door frame, and six on the participant. The IREDs on the participant were rear-facing; three were in an orthogonal arrangement to represent the torso as a rigid body (i.e. left and right spinous processes of the scapula and 12th thoracic vertebrae), and three were on the head also in an orthogonal arrangement. Each participant was also instrumented with a Gaze Tracker (Applied Science Laboratories, USA) to monitor gaze location. A computer program controlled the velocities at which the doors moved (i.e. 25, 30, and 35 cm/s).

4.2.3 Procedure

Participants walked at their normal cadence towards motor-driven sliding doors, seven meters away. The participants began each trial at one of five locations: in line with the middle of the aperture, 20cm or 80cm to the left of the middle, and 40cm or 60cm to the right of the middle (Figure 1). Since all participants had shoulder widths of about 40cm, these distances from the middle represented 0.5, 1, 1.5, and 2 shoulder widths away from the middle. The participants were instructed to walk through the aperture without stopping prior to crossing. The doors began each trial with the inside edges of each door located 35 cm from the absolute middle of the door frame. This 70cm aperture remained constant throughout the trial. The aperture shifted along the door frame either from the center position towards the right post and then towards the left post and back again or vice versa. The aperture moved at one of three velocities: 25, 30, or 35cm/s. At each of the starting positions the participants would experience each movement velocity twice, once when the aperture moved right to left and once when it moved left to right. Therefore, each participant would have six trials at each starting position. This produced 30 different conditions all of which were presented in a random order and each participant experience each condition once, in order to prevent any adaptations from taking place.

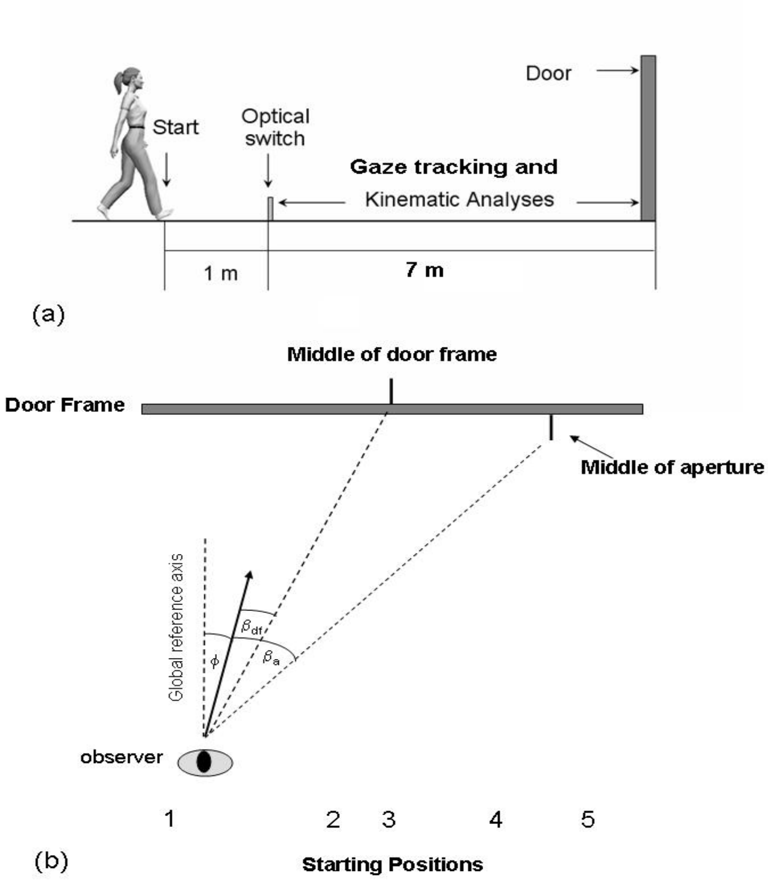

Figure 1- *a) Sagittal view of the experimental set-up. The participants began walking for a distance of 1m before the aperture began to move. Movement and gaze behaviours were collected when the aperture began to move (i.e. 7m). b) Bird's eye view of the experimental set-up. Displayed are the five starting positions: relative to the middle of the door frame (3), 2 was 20cm, 4 was 40cm, 5 was 60cm and 1 was 80cm from the middle. The global reference axis is used to define the observer's direction of locomotion (*ϕ*), and to calculate the variables used to describe the strategy used by the participant to walk to the moving aperture.*

4.2.4 Data Analysis

4.2.4.1 Difference between the Center of Mass (COM) and the relative middle of the aperture

The absolute difference between the COM and the relative middle of the aperture was calculated from the time of crossing the doors back to the start of the trial by 100msec intervals. All the conditions and starting positions for each of the participants were grouped together and treated similarly. The data from each participant was treated separately and time locked to the time of crossing the doors. The variability (standard deviation) in the difference between the COM and the middle of the aperture at each time interval from the time of crossing back to the start of the trial for each participant was calculated. In order to calculate when the variability began to significantly decrease we averaged the variability in the first second of the trial and then found the time when the variability values for the entire trial fell outside of two standard deviations and remained there.

These absolute differences for each trial from four seconds prior to crossing the doors to the time of crossing were then grouped into their respective starting positions. Average difference between the position of the COM and the middle of the aperture for each starting position was then calculated. We believed that the participants would aim to pass through the middle of the doors at the time of crossing. Based on this belief, we were interested in finding the time prior to crossing the doors when this difference between the COM and middle of aperture was similar. In order to determine this time we first calculated the average and standard deviation of the average difference between the COM and the middle of the aperture over the last one second prior to crossing the doors. We then found the time from the time of crossing the doors when the average difference fell outside of two standard deviations and remained there.

4.2.4.2 Difference between the COM and the absolute middle of the door frame

This calculation was similar to the previous except that the absolute position of the middle of the door frame was used instead of the relative middle of the aperture. The absolute difference between the COM and the absolute middle of the door frame was calculated from the time of crossing the doors back to the start of the trial by 100msec intervals. The data was separated into the different starting positions. The data from each participant was treated separately and time locked to the time of crossing the doors and averaged. Again, we were interested in finding the time prior to crossing the doors when the difference between the COM and middle of the door frame was similar. In order to determine this time we again calculated the average and standard deviation of the average difference between the COM and the middle of the door frame over the last one second prior to crossing the doors. We then found the time from the time of crossing the doors when the average difference fell outside of two standard deviations and remained there.

4.2.4.3 Target-heading angle

This calculation was similar to Fajen and Warren (2003, 2004). We used the anterior/ posterior (A/P) and M/L position (i.e. x and z respectively) of the participants' COM at each instant in time. The x and z coordinates were filtered using a 2nd order, dual pass filter with a 0.6Hz cut-off frequency similar to Fajen and Warren (2003, 2004), to reduce the stride to stride oscillations. The filtered data were used to compute each participant's direction of motion (heading, ϕ) in terms of the global coordinate axis (see Figure 1b) for each frame according to the following equation:

$\phi_i = \arctan (x_i - x_{i-1} / z_i - z_{i-1})$, Where x_i and z_i are the COM coordinates on the *i*th frame. The direction of the middle of the door frame (ω) and the middle of the aperture (ψ) with respect to the global reference axis were computed from the following equation:

$\omega_i = \arctan(dfX - x_i / dfZ - z_i)$ and $\psi_i = \arctan(aX_i - x_i / aZ_i - z_i)$,

where dfX and dfZ are the coordinates of the middle of the door frame and aX_i and aZ_i are the coordinates of the middle of the aperture on the *i*th frame. The target-heading angle between the participant's COM and the middle of the door frame was computed as $\beta_{df} = \phi - \omega$. The target-heading angle between the participant's COM and the middle of the aperture was computed as $\beta_a = \phi - \psi$. In order to calculate the average target-heading angles at each starting position, the trials were time locked (normalized) to the time of crossing the doors and every 100ms prior to crossing the doors were averaged.

4.2.4.4 Fixation Locations

In order to determine where a fixation was located we integrated the Optotrak and Gaze Tracker systems such that the former tracked the participants' head location with respect to the room while the latter tracked the eye position relative to the head. With the combination of the two systems we were able to calculate the horizontal and vertical fixation location at any point in the room at any time. We plotted the absolute coordinates of each fixation in order to determine the location of each fixation with respect to the door frame. We then overlaid the fixation location with the location of the doors at the same instant in time to determine where the participant was fixating at that instant in time (i.e. left door, right door or aperture). This was done in order to determine the number of fixations directed towards each of the relative locations (i.e. left door, aperture, and right door).

4.2.4.5 Cross correlation

A cross correlation was used to determine the time at which the greatest correlation occurred between each participant’s COM in the M/L direction and the horizontal location of gaze. The horizontal location of gaze was held constant while the location of the COM in M/L direction was moved back and forth in order to locate the greatest correlation value.

4.2.4.6 Steering Control

Head and trunk rotations about the vertical axis (yaw) were calculated throughout each trial. In order to determine the manner in which participants steered towards the aperture (goal) the time difference between the onset of head and trunk rotation as well as a change in COM in the M/L direction for each trial were compared. To determine the onsets of these movements, first the average head and trunk rotation magnitudes as well as average position of the COM in the M/L direction were calculated for the first two seconds of each trial. Second, the time (from the start of the trial) when each of the values fell outside two standard deviations and stayed there for 100msec was reported as the time when there was a significant change. Third, these times of initiation were grouped into the five different starting positions and the time (from the start of the trial) when significant head and trunk rotations were initiated were each subtracted from the time when a change in travel path was initiated. Negative values meant that the head and trunk rotations occurred prior to a change in travel path.

4.3 Results

Our previous work (Study 3) has shown that when individuals walk through an aperture (static or dynamic) they tend to walk through the middle of the opening. Based on this finding we wanted to know how individuals approach and pass through a moving aperture of fixed width. In order to do so we calculated the absolute difference between the location of the participants' Center of Mass (COM) in the medial/ lateral (M/L) plane and the location of the relative middle of the aperture. Since our previous findings showed that regardless of the movement of the doors individuals always attempt to pass through the relative middle of the doors, we collapsed the data over all velocities and starting positions. Figure 2 shows the variability values for each participant from four seconds prior to crossing the doors to the time of crossing the doors. The amount of variability decreased as the participants approached the doors. From the start of the trial, the time when the variability was below two standard deviations from the mean of the first second of the trail and remained there was identified as the time when a significant decrease in variability occurred. The time prior to crossing the doors when variability significantly decreased for each participant is as follows: BS=2.3s, KC=2.3s, KY=2.7s, LS=2.2s, PS=2.9s, TD=2.9s, TR=2.2s. The average time when the variability significantly decreased across the participants was 2.5s prior to crossing the doors.

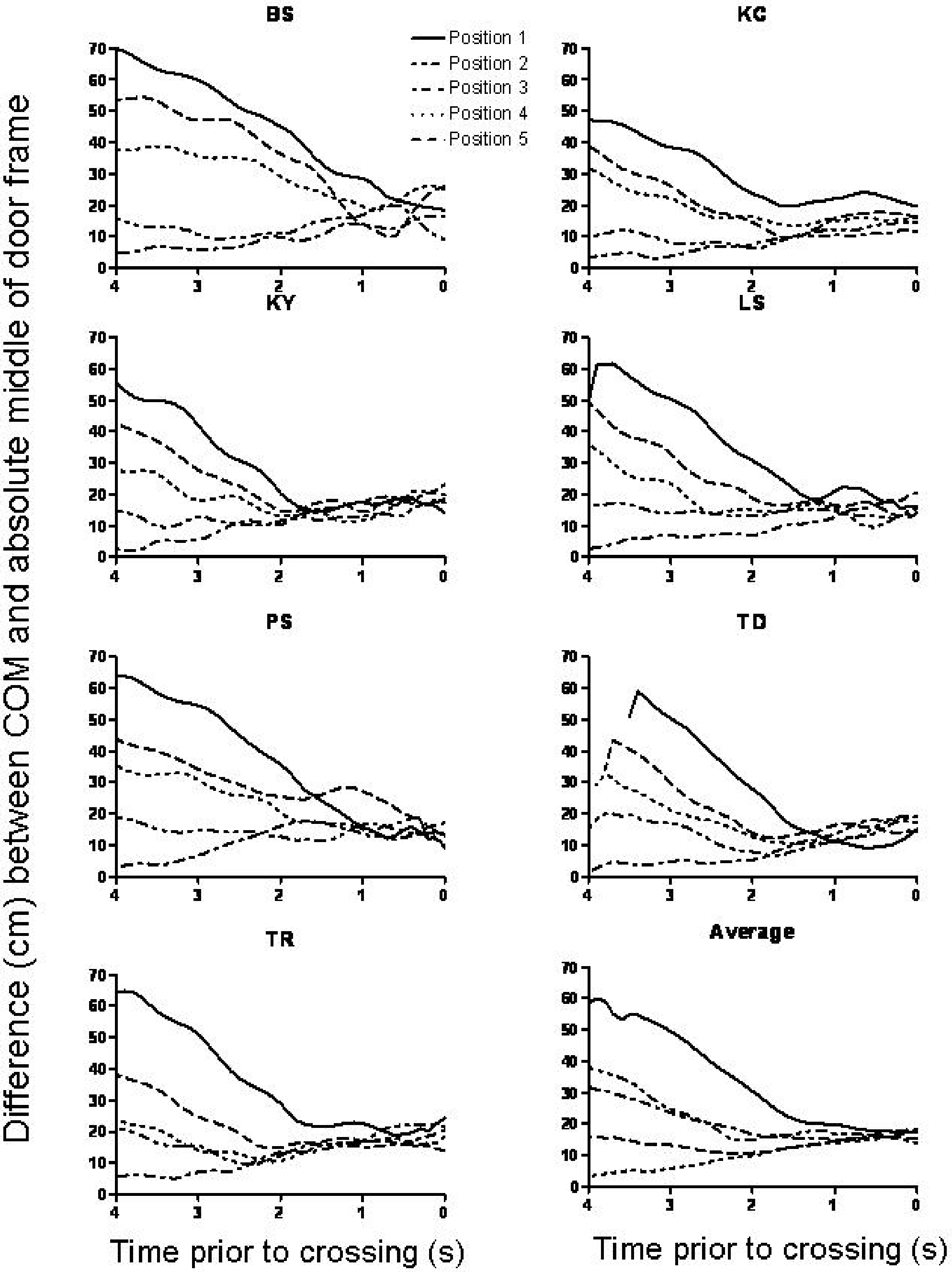

Figure 2*- The variability (standard deviation) in the difference between each participant's COM in the M/L direction and the horizontal location of the middle of the aperture as the time before crossing the door decreased (i.e. approaching the door frame).*

We also looked at the average difference between the COM location and the location of the middle of the aperture for each participant at each of the five starting positions, as shown in Figure 3. On average each participant decreased the difference between their COM and the location of the middle of the aperture as they approached the doors. This effect is known as funnelling. We then determined the time when the COM – mid-aperture difference was similar in size to this difference at the time of crossing. Table 1 a) displays the times for each participant at each starting location when the difference between their COM and the middle of the aperture were similar to the time of crossing. On average, this occurred 1.37 s prior to the participants crossing the doors (i.e. Position 1= 1.31, Position 2= 1.33, Position 3= 1.47, Position 4= 1.43, and Position 5= 1.29).

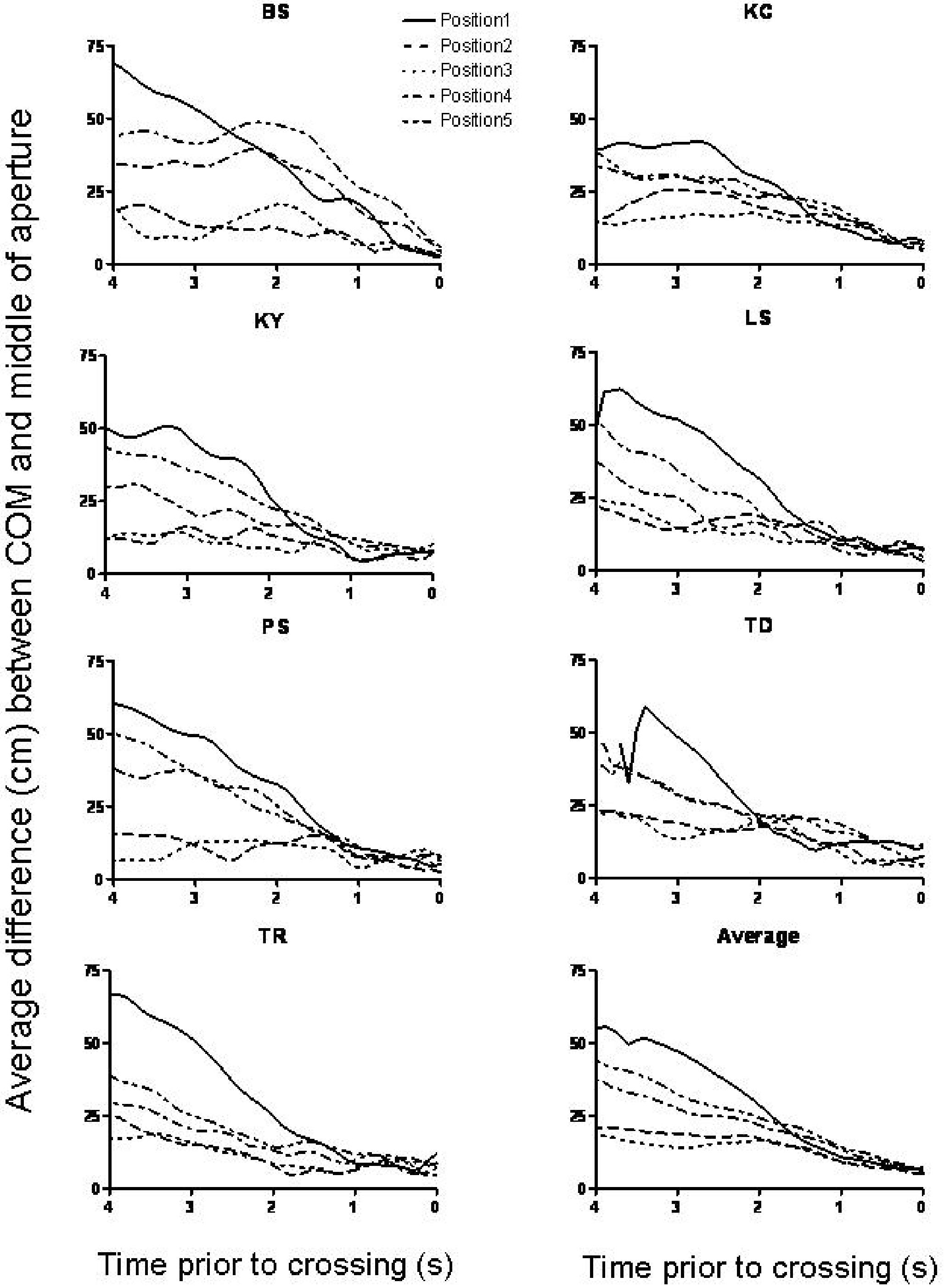

Figure 3- *The average difference (for each participant) between the participants' COM in the M/L direction and the horizontal location of the middle of the aperture as they approached the door frame.*

Table 1a)- Time (s) of change prior to crossing the doors when the difference between the Relative middle of the aperture and the COM fell outside 2 standard deviations for each participant

Participants	Position 1	Position 2	Position 3	Position 4	Position 5
BS	1.5	1.1	1.2	1.1	1.3
KC	1.2	1.1	1.2	1.1	1.7
KY	1.2	1.2	1.1	1.3	1.1
LS	1.2	1.2	1.9	1.6	1.1
PS	1.2	1.2	1.7	1.1	1.1
TD	1.7	1.1	1	1.5	1.3
TR	1.2	2.4	2.2	2.3	1.4
Average	**1.31**	**1.33**	**1.47**	**1.43**	**1.29**
SD	0.20	0.48	0.46	0.43	0.22

Table 1b)- Time (s) of change prior to crossing the doors when the difference between the Absolute middle of the door frame and the COM fell outside 2 standard deviations for each participant

Participants	Position 1	Position 2	Position 3	Position 4	Position 5
BS	1.1	N/A	N/A	2	1.6
KC	2.2	N/A	N/A	2.1	2.5
KY	2	N/A	N/A	3.4	2.6
LS	1.7	N/A	N/A	2.8	2.1
PS	1.1	N/A	N/A	2	2.8
TD	1.4	N/A	N/A	3	2.3
TR	1.9	N/A	N/A	3.4	2.5
Average	**1.63**	**N/A**	**N/A**	**2.67**	**2.34**
SD	0.44	N/A	N/A	0.63	0.40

Table 1c)- Time (s) difference between the change in A and B

Participants	Position 1	Position 2	Position 3	Position 4	Position 5
BS	0.4	N/A	N/A	-0.9	-0.3
KC	-1	N/A	N/A	-1	-0.8
KY	-0.8	N/A	N/A	-2.1	-1.5
LS	-0.5	N/A	N/A	-1.2	-1
PS	0.1	N/A	N/A	-0.9	-1.7
TD	0.3	N/A	N/A	-1.5	-1
TR	-0.7	N/A	N/A	-1.1	-1.1
Average	**-0.31**	**N/A**	**N/A**	**-1.24**	**-1.06**
SD	0.57	N/A	N/A	0.43	0.46

The idea behind having the participants start at different locations was to prevent walking up the middle of the pathway towards the middle of the doorframe and slowing down enough for the aperture to line up with their travel path direction. At each of the five starting positions the participants could have walked in a straight line and been able to pass through the doors at some point. In order to determine whether this strategy was used, the average position of the COM in the M/L direction with respect to the absolute middle of the door frame was calculated for each participant at each starting location. Figure 4 shows the average position of the COM with respect to the absolute center of the doors as the participants approached the doors. Interestingly, the participants all funnelled towards the middle of the door frame from all the starting locations.

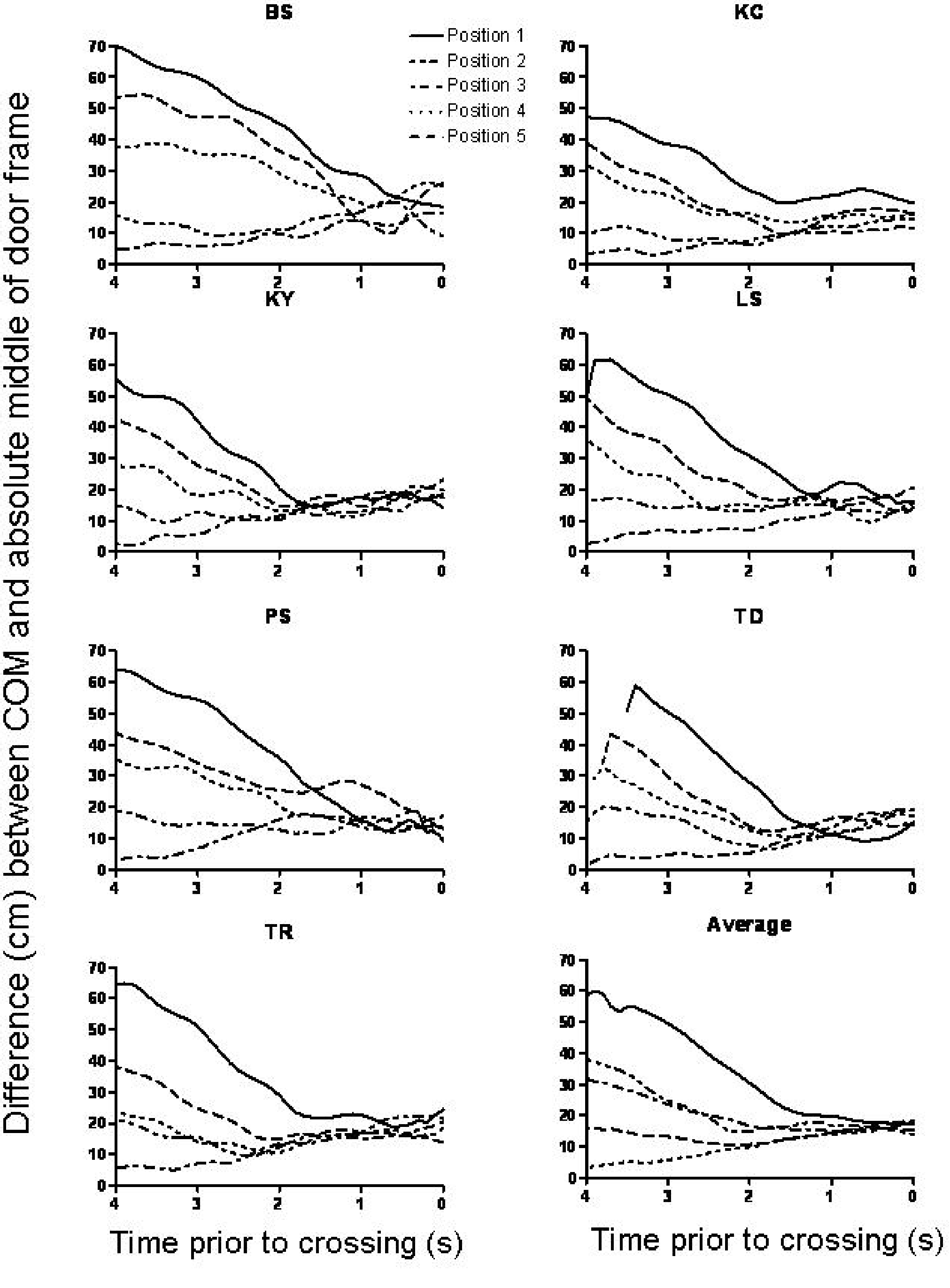

Figure 4- *The average difference (for each participant) between the participants' COM in the M/L direction and the location of the middle of the door frame as they approached the door frame.*

The times prior to crossing the doors when the difference between the participants' COM and absolute middle of the doors became similar to that at the time of crossing is shown in Table 1 b). Since the starting positions 2 and 3 were close to and in line with the middle of the door frame there was no significant change from the start of the trial to the time of crossing. On average the time prior to crossing the doors when this occurred was about 2.21s. (i.e. Position 1= 1.63, Position 4= 2.67, and Position 5= 2.34). From Figure 4 it appears as though at one second prior to crossing the doors all the participants seem to make fine adjustments in order to pass through the middle of the doors. A paired t-test comparing the final COM position in the M/L direction at the time of crossing for each trial within each participant to the location of the absolute middle of the door frame was used to determine if the location of the final COM position was similar for that participant across all trials. The results from the t-test showed that for six of the seven participants, the final position of the COM in M/L direction was not significantly different from the middle of the door frame (BS: p=0.732, KC: p=0.608, KY: p=0.886, LS: p=0.323, PS: p=0.036, TD: p=0.100, TR: p=0.367).

For each trial at each starting location the time when the difference between each participant's COM and the middle of the aperture was similar to the time of crossing was subtracted from the time when the difference between the COM and the middle of the door frame was similar to the time of crossing. This was done in order to determine which event took place first: participants funnelling towards the middle of the pathway or positioning themselves in line with the middle of the door frame. The results in Table 1c) show these differences. A positive value meant that the participants were in line with the middle of the aperture and then funnelled towards the middle of the pathway. On average the results show that for each starting position the participants funnelled towards the middle of the pathway prior to finding the location of the middle of the aperture. The average time differences across the participants for the different starting positions were as follows: Position 1= -0.31s, Position 4= -1.24s, and Position 5= -1.06s.

The difference between the participants' COM and either the middle of the door frame or the middle of the aperture were used to determine what the participants were doing. In order to determine how the participants were doing what they were doing, target-heading angles were calculated. The average target-heading angle for each participant at each starting position for the angle between the participants' COM and the middle of the door frame is plotted in Figure 5. These angles were very close to zero for all participants at all starting locations. This means that each participant faced and walked towards the middle of the door frame from the start of the trial on each trial. The average target-heading angle for each participant at each starting position for the angle between the participants' COM and the middle of the aperture is plotted in Figure 6. These angles fluctuated between -1 and 1 degree for each participant from each starting position, but were not equal to zero throughout the trial. If the target-heading angle was greater than zero and constant then participants would have been using an interception strategy as seen in the study by Fajen and Warren (2004). The participants in the current study, however, used neither a pursuit nor interception strategy.

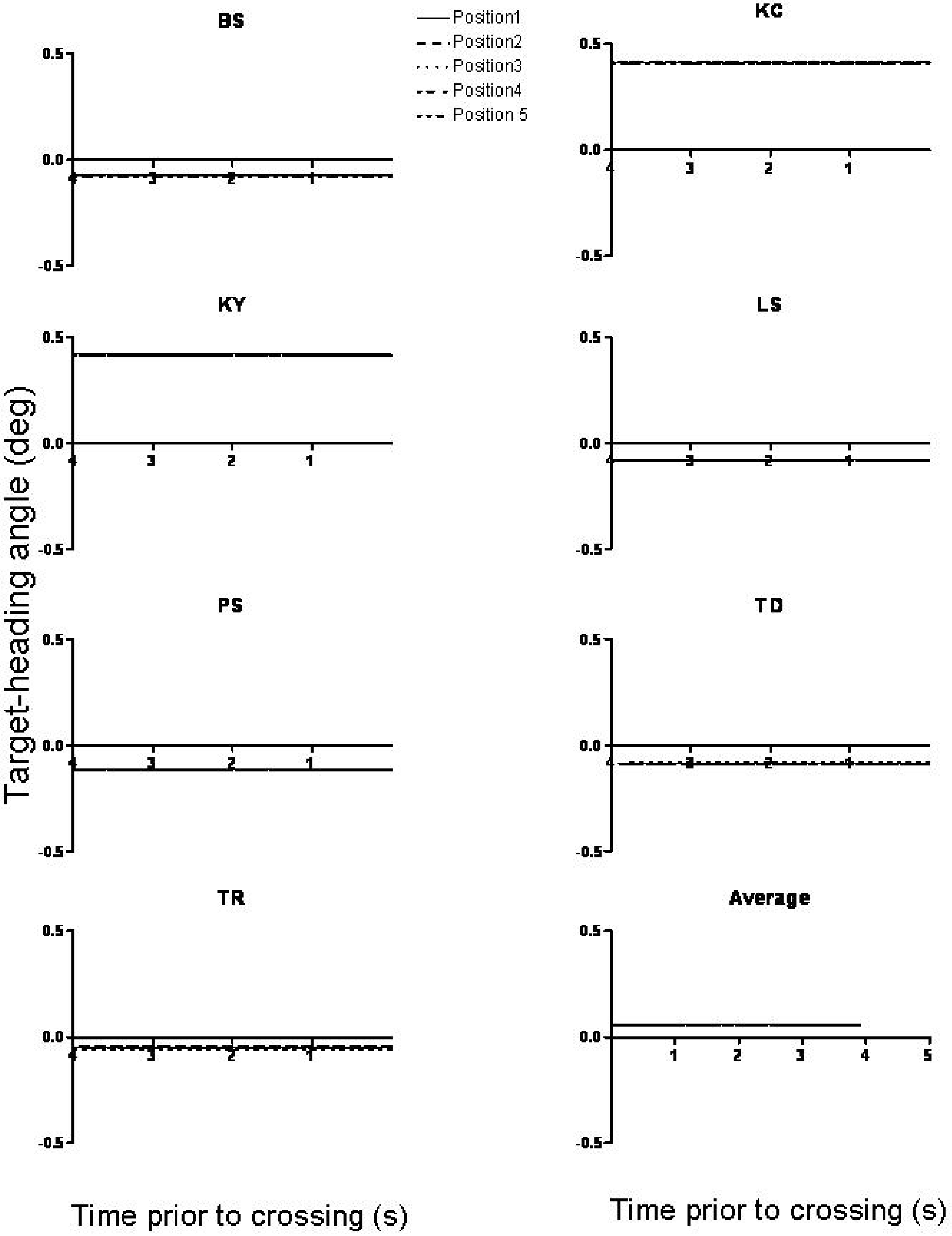

Figure 5- *Target-heading angles (β_{df}) between each participant's heading direction and the location of the middle of the door frame.*

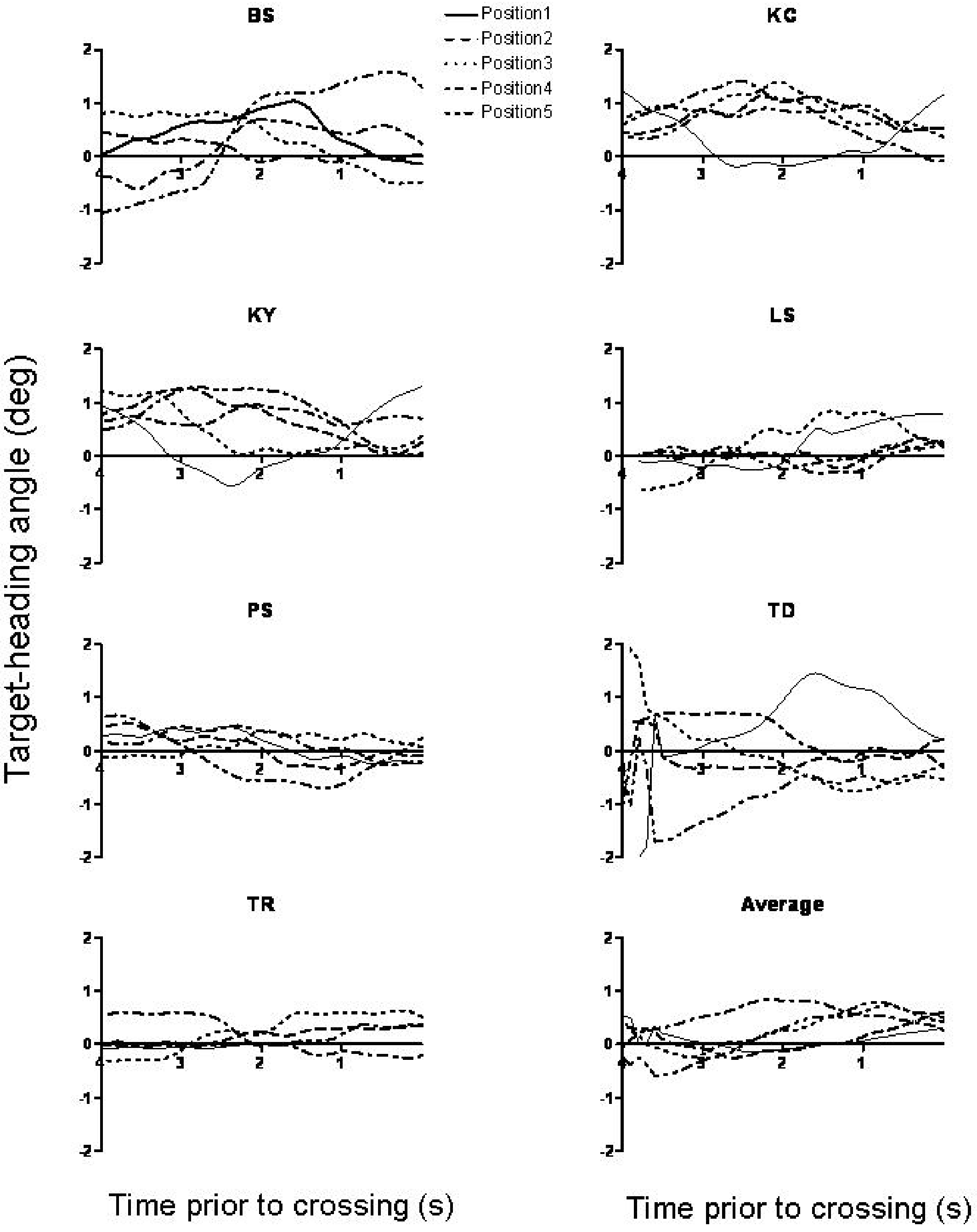

Figure 6- Target-heading angles (β_a) between each participant's heading direction and the location of the middle of the aperture.

Table 2- Proportion of total fixations directed towards each of the relative locations.

Participant	Left Door	Aperture	Right Door
BS	0.07	0.52	0.40
KC	0.16	0.79	0.04
KY	0.11	0.84	0.05
LS	0.61	0.36	0.04
PS	0.01	0.72	0.28
TD	0.38	0.56	0.06
TR	0.68	0.31	0.02
Average	**0.29**	**0.59**	**0.13**
SD	0.27	0.21	0.15

Fixation locations could give insights as to where individuals are directing their attention. Figure 7 demonstrates the absolute coordinates for all the fixations of each participant over all the trials. It is interesting to note that overall, 17% of fixations are directed approximately (+/- 10cm) towards the middle of the door frame (i.e. coordinates (0, 0)). The individual proportions of fixations directed towards the middle of the door frame for each participant were as follows: BS= 0.16, KC= 0.23, KY= 0.19, LS= 0.16, PS= 0.14, TD= 0.17, TR= 0.12. At each of the fixations the relative location of the fixations were also analysed. Table 2 showed the proportions of fixations that each participant directed towards each of the relative locations. Overall, the majority of fixations (59%) were directed towards the middle of the aperture.

A cross correlation between the participants' COM location in the M/L direction and the location of their gaze in the horizontal direction was done for each trial. There were two cross correlations done: one for the entire trial (i.e. from start to time of crossing) and one for the last two seconds prior to crossing the doors. Table 3a) shows the average time shift and average correlation values for each participant over the entire trial. The average the cross correlation values across all participants was 0.525 with an average time shift of about 1.07 seconds. Since the participants funnelled their movements towards the middle of the pathway at about two seconds prior to crossing the doors and because the variability in the difference between the participants' COM and the middle of the doors decreased around two seconds prior to crossing the doors, we decided to run another similar cross correlation for the last two seconds of data. The results in Table 3b) illustrate the average correlation values and the average time shift for each participant for the last two seconds prior to crossing the doors. The overall average across the participants shows that on average the cross correlation values were 0.695 with a time lag of about 0.54 seconds.

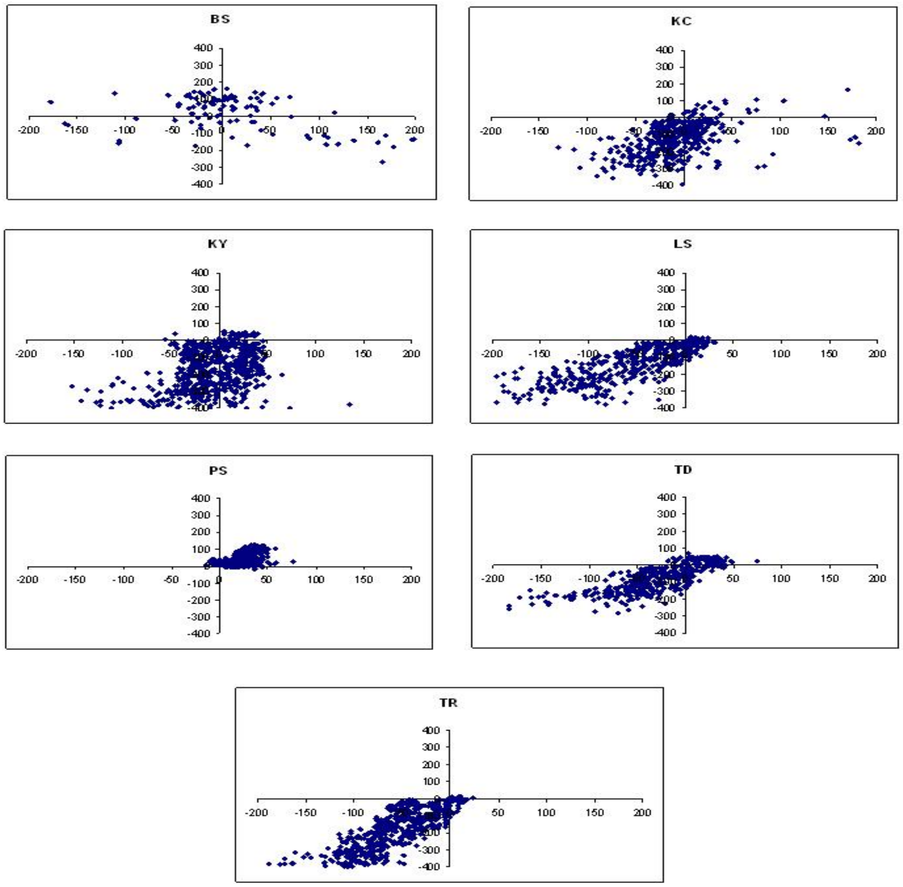

Figure 7- *Location of each fixation with respect to the absolute middle of the door frame for each participant throughout all the trials. The coordinates 0,0 are the mid-point of both the horizontal and vertical distances of the door frame.*

Table 3a- The average correlation values and average time shift for each participant over the entire trial.

Participant	Correlation value	Time difference (s)
BS	0.427	0.924
KC	0.492	0.739
KY	0.566	0.957
LS	0.718	1.333
PS	0.416	1.596
TD	0.467	0.967
TR	0.588	0.952
Average	0.525	1.067
S.D.	0.107	0.293

Table 3b- The average correlation values and average time shift for each participant for the last 2s of each trial.

Participant	Correlation value	Time difference (s)
BS	0.499	0.507
KC	0.670	0.433
KY	0.755	0.201
LS	0.684	0.446
PS	0.652	0.962
TD	0.677	0.728
TR	0.677	0.481
Average	0.659	0.537
S.D.	0.078	0.242

The difference in onset times for head and trunk rotations and change in travel path proved to be very different both within participants and across participants at each of the different starting positions (Table 4). In terms of head and trunk rotations, the head did not always have a significant rotation prior to a rotation in the trunk. There seems to be no consistency in the manner in which the participants steered towards the aperture. There was one subtle consistency, for the most part each participant changed travel path direction (COM) prior to having a significant onset of trunk rotation.

Table 4- The difference in onset times of trunk and head rotations from a change in travel path (COM) for each participant at each of the starting positions (P1 to P5).

	P1		P2		P3		P4		P5	
	Trunk-COM	Head-COM	Trunk-COM	Head-COM	Trunk-COM	Head-COM	Trunk-COM	Head-COM	Trunk-COM	Head-COM
BS	0.2	0.71	0.927		0.187	1.188	-0.106	-0.804	0.167	0.261
KC	1.473	1.510	1.104	-2.142	2.483	-1.311	1.580	0.258	0.097	0.200
KY	0.731	0.194	0.737	1.053	0.519	-1.154	-0.367	-0.183	0.142	0.258
TR	1.139	-0.283	0.173	-0.477	0.692	0.350	-0.242	0.317	1.347	0.886
LS	0.690	-0.097	1.247	-1.030	1.500	0.764	0.628	-0.887	0.567	-0.139
PS	0.567	0.690	0.908	0.033	1.086	0.677	0.000	0.113	1.237	1.320
TD	0.458	-0.410	0.825	1.367	0.694	1.157	-0.190	0.172	0.536	0.367
Average	0.751	0.331	0.846	-0.199	1.023	0.238	0.186	-0.145	0.585	0.450
SD	0.428	0.682	0.342	1.313	0.768	1.046	0.694	0.505	0.520	0.489

4.4 Discussion

The purpose of the present study was to determine how individuals pass through a moving aperture and how visual information is used to guide such movements. Visually controlled locomotion requires a multi-level analysis. Loomis and Beall (1998) have outlined three levels of control: first, individuals must formulate a plan of action, which involves perception and cognition. Second, individuals must assess the environmental layout and plan a detailed path of travel. Third, individuals must regulate their speed and direction necessary for staying on the path. We found that regardless of the starting position, all participants funnelled towards the middle of the door frame before passing through the aperture. This would be consistent with the findings of Andersen and Enriquez (2006) who believed that an allocentric rather than egocentric frame of reference is more useful to control steering during locomotion. It seems as though the participants in our study adjusted their velocity so that the middle of the door frame and the middle of the aperture would be in similar locations at the time of crossing.

4.4.1 Location of COM in the M/L direction

The main objective of the participants was to pass through the moving aperture. This meant that they had to direct their COM through the aperture at the time of crossing. The manner in which the participants did this was very interesting. First, the variability in the difference between the location the participants' COM in the M/L direction and the middle of the aperture decreased as the participants approached the doors. The large discrepancy between the COM and the middle of the aperture that was present at the beginning of the trial was corrected by the time the participants were about 2s away from crossing the doors. This finding was similar to that of the foot fall position of long jumpers as they approached the take-off board in a study done by Lee et al. (1982), who claim that at this time action becomes visually driven. Our finding as well as that of Lee et al. (1982) both show that the variability decreased in the final stages leading to the target. Lee et al.'s (1982) spatial finding of when variability decreased (i.e. last four steps) may be equal to our temporal finding (i.e. 2.5 seconds prior to crossing). And so, at two seconds prior to crossing the doors, vision directly affects action in order to reduce the discrepancy between the COM and the middle of the aperture to successfully perform the task.

Second, the average difference between the location of the participants' COM in the M/L direction and the middle of the aperture decreased as the participants approached the doors. This makes sense since the participants had to pass through the aperture in order to be successful. This average difference consistently decreased until about 1.3s prior to crossing the doors (Table

1a) at which point the difference plateaus. Fajen (2005) would view this as the participants continuously making adjustments in order to bring their ideal state within the safe region. Once the ideal state was well within the safe region, further adjustment was unnecessary.

Interestingly, the difference between the COM and the middle of the door frame also decreased as the participants approached the door. This result suggests that the participants were funnelling their movements to a position in line with the middle of the door frame from each starting position. Based on these results it may be that participants just walked so that they were in line with the middle of the door frame. This type of funnelling occurred until the participants were about 2s from crossing the doors (Table 1b). Regardless of the starting position the participants were drawn towards the middle of the door frame. Why would the participants choose to adopt this behaviour? Even though the aperture was equally passable when it was at any location along the door frame, participants chose to move towards the middle of the door frame and then make fine adjustments. It could be that the right and left end posts of the door frame (i.e. turning points of the door) were viewed as obstacles that hindered success rate. If this were the case then each post would repel the participants equally to form a corridor and force them to walk towards the middle of the door frame (Patla et al., 2004; Warren, 2006). If this were true the participants would pass through the doors when the aperture was aligned with or close to the middle of the door frame. From the results we see that this is the case, the participants pass through the aperture when it was relatively close to the middle of the door frame.

We have shown that the participants not only aimed to pass through the middle of the aperture, but they did so by walking towards the middle of the door frame. The timing of these two events helps to explain how participants successfully passed through the aperture. On average, participants funnelled towards the middle of the pathway 0.3-1.24s prior to aligning their COM to the middle of the aperture (Table 1c). Therefore, participants got themselves to the middle of the pathway first then dealt with passing through the middle of the aperture; by doing this all conditions were treated in a similar manner. The participants were in line with the middle of the door frame at about the same time as the variability in the difference between the COM and the middle of the aperture significantly decreased (2s prior to crossing the doors). Following this time the difference between the participants' COM and the middle of the aperture was reduced as was the variability. We believe that the aperture movement or location did not drive the participants' actions until they were in the middle of the pathway. At this point, they used egocentric-direction to guide their movements in order to pass through the aperture. Therefore, behaviour in our study was serial; get to the middle of the pathway then pass through the doors.

4.4.2 Target-heading angle

We know what the participants did in order to pass through the aperture, but we wanted to know how they did what they did. Previous work by Fajen and Warren (2004) using a similar paradigm found that individuals walk towards a moving target using an interception strategy – by walking ahead of the target. We were unable to replicate this finding using our experimental protocol. Based on what the participants did in order to pass through the aperture, we believe that they used neither a pursuit nor an interception strategy.

Calculating the target-heading angle (Fajen and Warren, 2004) is an excellent way to determine if the participants used a pursuit or interception strategy. If the angle between the participant and the middle of the aperture is greater than zero (i.e. $\beta_a > 0$) for the entire trial, then the participants are using the interception strategy. If the angle is equal to zero, then the participants are using the pursuit strategy. As it turns out, β_a angle fluctuated between 1 and -1 for each participant at each starting location. Therefore the participants used neither a pursuit nor an interception strategy to pass through the aperture. These β_a angles are merely a by-product of the participants' desire to walk towards the middle of the door frame because as they walk towards the middle of the door frame the aperture oscillates resulting in a target-heading angle that also oscillates. On the other hand, the heading angle between the participants' COM and the middle of the door frame (β_{df}) was consistently very close to zero for every participant, on every trial. This means that the participants systematically zeroed in on the middle of the door frame and walked towards it from all the different starting locations.

Fajen and Warren (2004) found that participants always used the interception strategy in order to contact a moving target in virtual reality. The main reason we believe that our participants did not show an interception strategy, but instead used a *zeroing* strategy is because of our task constraints. We had real, physical oscillating doors with a 70cm aperture that created the target for participants to pass through. Although our study and the study by Fajen and Warren (2004) had targets moving in the frontal plane, our target oscillated and theirs did not. The other crucial difference was that the latter study had a target present where as our target was empty space. Walking towards a target allows an observer to use local optic flow information because the motion pattern defined by the target's texture specifies the observer's heading (Warren and Saunders, 1995). This is not true of empty space. Fixations towards empty space with objects on either side of the space could be used to guide motion or they could also allow for simultaneous awareness of events in one's peripheral field of view. It is difficult to determine from the current study which of these two possibilities the participants were using. The only commonality between the two studies is that there is a stationary background and objects moving in the foreground providing global optic flow. The difference in the two studies is that Fajen and Warren's target provided the global optic flow where as in our study the object that needed to be avoided provided the global optic flow. The participants' direction of heading is specified by the global optic flow from the stationary background which provides information for the target-heading angle (Fajen and Warren, 2004). Gibson (1958) believed that this type of optic flow, where the background is stationary and the image of a target expands on the retina, could be used to steer to a goal or target.

The reason we observed behaviours that were serial can be explained by the environmental layout. Our entire door frame could have been viewed initially, by the participants, as one stationary object. In this way the participants could have used global optic flow to steer towards the target. Walking through complex environments requires the use of optic flow and scene layout information. When steering towards a stationary target, individuals tend to steer so that they are aligned with the middle of that object (Higuchi et al., 2006; Duchon and Warren, 2002). Following this behaviour the participants had to pass through the moving aperture.

We used a target that was a two-dimensional space and is best intercepted at an angle perpendicular to its movement, where as the virtual target used by Fajen and Warren (2004) was a three-dimensional cylinder which could be intercepted at any angle. Therefore, the participants in our study would want to take on the aperture "head on" because attempting to pass through the doors from an angle increases the chances of getting hit by the doors. This constraint was not present in the Fajen and Warren (2004) study because in virtual reality there is no threat of making contact with the target.

4.4.3 The effect of vision on action

Previous research has shown that individuals look where they are going (Land and Lee, 1994; Hollands et al., 1995, 96; Wann and Swapp, 2000; Hollands et al.,2002; Patla and Vickers, 2003). We wanted to know if individuals passing through the apertures go where they look. In order to answer this question we cross correlated the location of the COM with gaze behaviours. Using data for the entire trial the correlation values were moderate (i.e. 0.525) with a latency of about 1s. This means that action loosely followed vision after about 1s and therefore, individuals did not always go where they were looking. We believe that the cognitive system drove individuals towards the middle of the pathway in order to make each trial perceptually similar. Regardless of the starting position or the movement of the doors, the participants were going to walk towards the middle of the door frame (i.e. auto pilot). Overall throughout all the trials, the majority of fixations were directed towards the middle of the door aperture. Amazingly these fixations were also close to the middle of the doorframe. It could be possible that the participants' fixations were used to direct their walking because the fixations were in the general location of where the participants walked, but also their fixations were used to attend to the location of the aperture. When the participants walked towards the middle of the door frame and fixated ahead they did so that the visual system could detect changes in the movement of the aperture and the direction of movement (Wann and Swapp, 2000). Walking towards the middle of the door frame places the entire door frame within one's central visual field and any movement of objects would increase radial flow and this in turn would stimulate areas MT and MST in the extra-striate cortex in order to detect direction of movement (Bremmer et al., 2000).

In this case the participants could be attending to where they were going, and using the movement of the doors in their periphery to determine movement direction. The movement of objects in the peripheral field of view increase peripheral radial retinal flow. Peripheral radial retinal flow can be processed with little or no attentional allocation (Wann et al., 2000). The fact that the participants alternated their gaze between the aperture and other features in the environment, they could still attend to where they were going and look elsewhere (Land, 1998). This type of behaviour would allow the participants to walk towards the middle of the door frame while knowing the movement direction of the aperture. Walking towards the middle of the door frame would reduce one's cognitive load because the participant would not have to worry if they were in a location that would allow safe passage and could also locate the middle of the doors. Instead the participants would only have to modify their velocity until the aperture was in close proximity to where they were (middle of door frame) to be passable. We saw this in the final 2s of each trial because action followed vision more closely. A cross correlation of the location of the participants' COM and the location of gaze was moderate to good (i.e. 0.66) with an average delay of about 0.5s. Therefore, in the last 2s of each trial participants walked where they were looking.

4.5 Conclusion

Overall, vision was used initially by the participants to look where they were heading and as the proximity to the aperture increased the participants walked where they were looking. Initially the participants treated the entire door frame as a stationary object and walked towards the middle of the door frame. It is difficult for us to say with certainty that the participants completely used the optic flow or egocentric-direction strategy to guide locomotion. Instead we believe with the richness of visual information in the environment that the participants used a combination of the two strategies. We did not find a consistent sequencing of head, trunk and

COM (Table 4) when the participants changed their heading direction as seen in other steering studies (Grasso et al., 1996; Grasso et al., 1998; Hollands et al., 2002; Hicheur et al., 2005). However in the last 2s of each trial the difference between the participants' COM and the middle of the aperture is reduced and there is a stronger cross-correlation between gaze location and direction of motion. Since the participants are about 1-2 strides away from crossing the doors when a change in velocity occurred, they may be reducing their velocity enough so that the middle of the aperture will be in close proximity to where they will be when they reach the door frame. This would be the ideal state for the participant. As long as the ideal state is within the safe region the participants may or may not have to make adjustments to their movement in order to safely pass through the middle of the doors. This would be considered an interception strategy except that the participants are taking advantage of the fact that the aperture will oscillate towards the middle of the door frame.

CHAPTER 5

WHAT I HAVE LEARNED FROM MY STUDIES

5.1 General Discussion

The general purpose of the experiments in this thesis was to get a better understanding of how visual perception is used to help guide appropriate actions to successfully navigate through dynamically changing environments. In the first study participants approach oscillating doors which moved in reciprocal directions to each other. Each door opened and closed at a constant rate of 22cm/s and had maximum apertures of 70, 80, or 100cm. The participants passed through the doors when they were close to their maximum aperture width. In order to do so, the participants initiated a change in velocity prior to crossing the doors to allow the doors to reach a state that would be passable at the projected time of crossing (TOC). This change in velocity occurred later for the largest aperture than for the smaller, more threatening apertures.

In the second study, participants approached doors that were either maximally opened (i.e. 90, 110, or 130cm) or completely closed at the start of each trial. When the participants were two steps from crossing the doors, the doors began to move. There was not sufficient time for the participants to make on-line velocity adjustments because the distance between the trigger and doors was too short (2 steps). In this study the dominant action parameter observed was an increase in shoulder rotations as the threat of being hit by the doors increased.

The conclusion from these studies was that action parameters were initiated because the participants perceived their ideal state to be outside of or on the boarder of the safe region and realized that some sort of behaviour change was needed to ensure safety. The type of action parameter (adjustment) initiated was dependent on the time available. Since velocity adjustments take time to produce, they were used when there was time available to do so. However, when time was limited (i.e. less than 2 steps) a fast adjustment was required and therefore, a postural adjustment was initiated. As the threat of colliding with the doors increased, modifications that take less time to initiated (i.e., shoulder rotations) were seen.

In the third study, eye movements were monitored while participants approached doors that were oscillating as in the first study. The difference in the movement of the doors in the third study was that they moved independently of each other and each door had a maximum aperture distance of 50cm. On half the trials each door moved at the same rate (coupled) such that the middle of the aperture was inline with the middle of the door frame. On the other half one door moved at a faster rate than the other (uncoupled) such that the middle of the aperture was randomly located at some point along the door frame. The results showed that under both door movement conditions, the participants passed through the middle of the aperture, when the aperture width was close its maximum. Again the dominant behaviour in this study to increase the level of safety was a change in velocity prior to crossing the doors. Interestingly, visual fixation behaviours prior to changes in velocity were similar between the two conditions, but following a change in velocity, the participants spent more time fixating on the doors than on the aperture in the uncoupled condition. Fixations while participants approached the door frame were random, but the last fixation prior to crossing the doors was almost always directed toward the middle of the aperture. In this case, fixations were directed towards where the participants were heading immediately following the fixation. The main conclusion from this study was that perception directly guided action in a top-down manner when the action was crucial to the success of the trial.

In the fourth and final study the participants' eye movements were recorded while they approached the door frame from one of five different positions as the doors oscillated between the two end posts with a constant aperture width of 70cm. At the start of each trial, the middle of the aperture was in line with the middle of the door frame, so that the participants could not anticipate its movement direction, and began to move (either right or left) at one of three different velocities. All the participants funnelled towards the middle of the door frame from each of the starting locations before passing through the aperture. The target-heading angle revealed that the participants treated the entire door frame like a stationary object and walked towards the middle of the door frame. Variability in the difference between the location of participants' COM and the middle of the aperture revealed that the participants began directing their movements towards the middle of the aperture about 2.5s prior to crossing the doors. The gaze data in combination with the movement data from the participants in the last 2s prior to crossing the doors showed that the participants closely directed their movements towards where they were looking. The conclusion from this study was that the strategy used by the participants was to direct their movements so that all situations were similar and in the final stages prior to crossing the doors the perceptual system controlled task-specific, fine movements.

5.2 Actor-environment interaction

Gibson (1979) first stated that control of movement lies in the relationship between the actor and its environment. The manner in which an actor controls movement is dependent on the environment. Warren (2006) believes that biology makes the most of the regularities of the entire actor-environment relationship as a means of ordering behaviour, thus behaviour is constrained by the structure of environment, biomechanics of the body, perceptual information about the state of the agent-environment system, and the task demands. The manner in which individuals are able to reach their goal or target is by appropriately adapting their behaviours to existing constraints. Behaviour must be stable, so as to resist perturbations and behaviour must also be flexible so that it can be modulated to current environmental conditions or task demands (Warren, 2006).

The participants in the four studies adjusted their behaviours based on the constraints within their environmental settings. In order to do so, the participants had to use perception to take advantage of the physical constraints of the environment and maintain stability. The manner in which individuals maintain stability is by producing low-dimensional action patterns (Warren, 2006). Low-dimensional action patterns are simple changes made to ongoing actions. They are a product of perceptual information integrated within the cortex and the production of an appropriate adaptive behaviour. Within the four experimental protocols there were only a few possible adaptive behaviours that the participants could employ in order to achieve their goal. Consistently throughout the studies the participants slowed down prior to crossing the doors when there was a perceived threat of colliding with the doors, based on their current walking velocity. Only in situations when the temporal constraints to the environment changed did the participants use other adaptive behaviours. These adaptive behaviours included postural adjustments when the doors did not oscillate and a change in travel path direction when the goal was not in line with heading direction. According to Fajen (2005) the adaptive behaviours displayed in the four studies were visually guided and were initiated in order to get the ideal state within the safe region. The adaptive behaviours produced by the participants in the four studies must have incorporated cognitive factors (goals), perceptual information, body biomechanics, and environmental properties.

5.3 Task requirements

The main drive behind my first two studies was to determine if performance looked similar in a visually-guided locomotion task with a temporal component as it does with a task which requires spatial precision. Lee et al. (1982) measured footfall position of long jumpers as they approached the take-off board. This long jumping study was a spatial task in which the location of each footfall position was important. The amount of time that it took to reach the spatial target was not important because the target was static. In this study the controlled variable was the stride length and the accuracy in the location of each footfall position was crucial to success of the trial. In the study done by Lee et al. (1982) perception of the location of the target relative to the participants was used to control stride length, thus footfall position.

Based on Lee et al.'s (1982) method of analysing how individuals control locomotion, I set out to see if a similar method of control was used by my participants in the first study. Unlike the Lee et al. (1982) study, this study had an important temporal component. In this study the time of arrival at the oscillating doors was very important because the goal of the task was to arrive at the doors at a time when the aperture was sufficiently large for a safe passage. The participants had to pass through the doors when the aperture between them was greater than their shoulder widths, thus the temporal component as well as the spatial component was very important to the success of the task. In my study the participants had to use perception about their proximity to the doors, their shoulder widths, and the time when the door aperture would be large enough to allow a safe passage to control their rate of movement (i.e. velocity). In order to be successful, the participants had to control the temporal component of the task (i.e. velocity). Similar to the study of Lee et al. (1982) whose participants decreased variability in footfall position four steps prior to crossing the doors; my participants decreased the variability in the

Predicted Door Aperture at the time of crossing. Although the participants in my first study were using perception to guide action, the strategy used to control movement was different from that used by Lee et al. (1982). When the participants were close to the doors they used vision to determine when and how much a velocity adjustment was needed to bring their ideal state with in the safe region.

In my second study I did not allow the doors to oscillate; this put a constraint on the temporal component of the task. This again was a task that had both a spatial and a temporal component. The balance in the effects of the spatial component and the temporal component changed from when the doors were closing as to when they were opening. When the doors were closing there was a greater spatial constraint and when they were opening there was less of a spatial constraint. When the doors were opening the temporal component (i.e. velocity) of the task was still controlled to allow a safe passage. When the doors were closing, the temporal component could not be adjusted in the time available and so a quick spatial adjustment (shoulder rotation) was initiated. From my first two studies I can conclude that when the pendulum of the task requirements swings from a spatial task to a spatio-temporal task the controlled variable changes from a spatial component to a temporal one.

The idea behind my fourth study was primarily based on Lee et al.'s (1982) study. Whereas Lee et al. (1982) had a stationary target that individuals had to contact, I wanted to have a target that was moving. Even though the task shifted from one with a spatial component to one with a spatial and temporal component, a spatial measurement best described how participants passed through the middle of the aperture. It did not matter when the participants reduced the difference between their COM and the middle of the aperture as long as they did so prior to crossing the doors. In this study the participants' only concern was to adjust their velocity such that their COM and the aperture arrived at the same location at similar times; they did not have to worry about when the aperture would be large enough to be passable. In this study the participants had to control both direction and velocity. However, velocity became more important as the participants' proximity to the door frame increased (i.e. about 2s prior to crossing the doors). The participants had to adjust their velocity enough so that the distance between them and the aperture decreased to zero. In the last 2s prior to crossing the doors, the participants were treating the aperture like a stationary target (Fajen and Warren, 2003). The last 2s of each trial in my fourth study were similar to the last four steps prior to the take off board in Lee et al.'s (1982) study in that at this time both tasks were visually driven. The long jumpers used vision to determine their distance to the take-off board and controlled their flight time appropriately. In my study, the participants used vision to determine how much they should adjust their velocity so that their paths and the path of the moving aperture would meet.

From all my studies I have learned that whether the task has a spatial component or both a spatial and temporal component, vision is used to guide action in the final stages of a task. Vision is used to bring one's actions within the safe region and by doing so, minimal or no adjustments will be needed to ensure success. However, in tasks with stationary targets the control structure used to reach the target should have a spatial component where as a moving target must have a control structure with a temporal component to ensure success.

5.4 Vision and Locomotion

> "Vision is a biologically basic function, and if that can be accounted for then the problem of human space perception may appear in new light. The question, then, is how an animal gets about by vision." (Gibson, JJ, 1958, p. 183)

Until recently, little has been known about eye movements during locomotion mainly because of the lack of technology. In my last two studies I monitored gaze behaviours of individuals as they approached dynamically changing environments in order to get a better understanding of how vision controls locomotion. Many researchers have found that individuals look where they are going or planning on going (Yarbus, 1967; Land and Lee, 1994; Hollands et al., 1995, 1996, 2002; Patla and Vickers, 2003; Wilkie and Wann, 2003). The idea behind looking where you are going is that individuals can plan locomotor changes in advance in order to allow sufficient time to implement the strategy. This seems to be true when the objects within one's environment are stationary and there is no temporal demand on one's movement. In my third study the fixation patterns at the beginning of the approach (from great distances) were used to perceive door location in order to identify time of potential threat and heading direction. As the participants were about to cross the doors, fixations were directed towards the middle of the aperture in order to negotiate the tight fit and allow precise movements. In comparison to stationary objects, fixation patterns in dynamic situations are directed towards where one is heading just prior to a critical movement.

Fixation patterns are made to task-relevant objects just prior to the motor act that they mediate by a fraction of a second (Land and Hayhoe, 2001). In my third study I found that fixations to the middle of the aperture preceded passage by about 1s. Prior to this last fixation, fixation locations were random and had no obvious relationship the outcome of the trial. During locomotion fixations occur frequently over short periods of time and are usually separated by gaze shifts. I found similar results to Fowler and Sherk (2003); about 60% of a trial duration is spent fixating with about 2.5 fixations/s and an average fixation duration of 247msec. If fixation locations are assumed to be where one is attending, then based on the fixation patterns seen in my studies, vision is used to analyse the manner in which the environment is changing. The participants walked in a direction that was perpendicular to the movement of the doors. When the participants fixated ahead, the movement of the doors across the retina gave an indication of the direction of door movement and possibly the rate of door movement. Since vision is chiefly used to determine the dynamics of the environment, then other sensory systems such as the vestibular system and the proprioception from the bottoms of individuals' feet may be used to direct movement.

Vision has been shown to direct movement in dynamically changing environments when individuals must intercept a moving target. An individual's direction of gaze during locomotion strongly affects the pattern of optic flow that the individual sees (Sherk and Fowler, 2000). If one directs gaze straight ahead, then the rate of expansion of centrally located stationary objects on the retina gives an indication of the time to contact that object and the movement of peripheral stationary objects across the retina give an indication of rate of self motion. While optic flow can be used to guide movements by keeping the difference between the focus of expansion and body orientation to zero (Warren et al., 2001), it is also possible that individuals can use egocentric-direction to control movements (Rushton et al., 1998). It could be that in all the studies as the participants walked towards the door frame they received better time-to-contact judgement of the aperture from the retinal image expansion of the door frame along with information about rate of self-motion and direction of movement of the doors. The combination of all the perceptual information helped the participants control locomotion in order to be successful. Each different aspect of vision is projected to different areas of the visual cortex and all areas of the visual cortex contribute to visual guidance of locomotion.

5.5 Real-world versus virtual reality environments

Most of the recent work that has analysed locomotion during visually-guided tasks has been done in virtual reality (VR) environments. The benefit of conducting a study in a VR environment is that a researcher can manipulate visual features of the environment that would otherwise not be possible in a real-world setting. These manipulations help researchers understand how certain visual features affect the control of locomotion. For example, researchers can have participants walk to a target in an environment that is visually impoverished and then perform the same task in a visually-rich environment and compare the differences in behaviours in order to determine the effects of optic flow. The other up-side to VR environments is that researchers can place individuals in many different environments and perform many different tasks without the threat of causing any physical harm to the individual. For example, researchers could measure kinematics or muscle behaviour of individuals as they walk along a cliff without really being on a cliff's edge. With VR, researchers have been able to further understand how visually-guided actions are controlled in many different situations and settings.

Two of my studies had direct influences from previous VR studies. My first experimental protocol stemmed from studies done by Montagne et al. (2002, 2003). The similarities between my study and those of Montagne et al. (2002, 2003) are that participants approached oscillating doors head-on from a distance greater than 7m, the participants were allowed to control their own walking velocity, and the rate of the treadmill movement in Montagne et al.'s (2002, 2003) studies was linked to the rate at which the scene display changed in order to produce veridical self-motion information. Aside from the differences in classification of successful trials there were differences between my study and that of Montagne et al. (2002, 2003). The first difference was my participants physically walked towards the doors and therefore received information from multiple sensory systems, while Montagne et al.'s (2002, 2003) study had participants on a treadmill with limited vestibular information and reduced proprioceptive information (walking on a automatic treadmill should not require the same propulsion forces as walking on the ground). This VR feature allowed the researchers to understand how vision, not any other sensory systems, can control locomotion. Although a VR environment reduces the risk of an individual making physical contact with the door, a big difference was that my participants could make not only velocity adjustments, but postural adjustments and also change direction of motion. Montagne et al.'s (2002, 2003) participants could only adjust velocity because if they did make any other adjustment they would fall off the treadmill. In this way Montagne et al. (2002, 2003) controlled both visual information and they constrained the responses available to the participant.

My fourth study was directly influenced by the VR study done by Fajen and Warren (2004); in both studies participants had to approach a target that was moving while walking on flat ground. The main difference, and benefit of a VR environment, between the studies was that the amount of optic flow information available to the participants as they approached the target could vary from trial to trial in order to determine the effects of optic flow on controlling locomotion. Not only were Fajen and Warren able to manipulate the level of optic flow available to the participants, but they were also able to manipulate the type of optic flow, global and local. The other difference between the two studies was that in my study there was the doorframe with end posts that the target oscillated between and the Fajen and Warren (2004) study had a target in space that looked like it would continually move to infinity unless the participant intercepted it. This difference may have been the reason for the participants in the Fajen and Warren (2004) study using an interception strategy to arrive at the moving target where as my participants used a zeroing strategy.

In conclusion, VR environments can be very powerful research tools. The best VR environments are those which are very life-like (i.e. one that has the individual fully immersed in the environment and the environment changes as the individual physically walks through the environment). One of the benefits of using one of these VR environments is the ability to break the laws of optics and physics or disconnect physical reality as specified by an individual's body senses from the world he/she sees. VR offers a unique research tool that allows the behavioural neuroscientist an opportunity to address unanswerable questions. Some applications include: modifying human behaviour (i.e. simulators), enhance human abilities (i.e. tele-operations), and rehabilitate patients with motor control deficits. These applications increase knowledge with reducing cost, injury, and time. The down-side to VR environments is that the visual manipulation in some situations is so far from reality that the participants behave as "best" as they can and not how they normally would because the environment lacks ecological validity.

Both VR and real-world studies take place in controlled settings. Real-world studies are great for measuring behaviours because individuals are physically interacting with the environment in a similar manner that they would every day. The problem with real-world studies is that most are done in stale environments that break down a series of behaviours to one single feature and then try to extrapolate the results to other events without taking into consideration cognitive influences and capabilities as well as perceptual influences. The other problem with real-world behavioural studies is that features within the environment are meant to simulate other features in the environment and this may also decrease ecological validity. The best way to measure individuals' behaviours is by observing analysing their behaviours in their natural environments. The down-side to field studies is that it is difficult to control the environment. Therefore, life-like VR environments provide a happy medium between field studies and real-world laboratory settings.

5.6 Future research ideas

From my studies, I have been able to describe consistencies in the behaviours of young healthy humans while walking in dynamically changing environments. The first consistency is that when a temporal component is added to a task, the controlled variable will have a temporal component to it. The second consistency is that individuals become attuned to visual information to guide action just prior to when a precise movement is needed. The third one is that if individuals are asked to walk through an aperture, whether it is static or not, they will pass through the aperture as close to the middle as possible. The last one is that individuals will approach a moving target that oscillates between two visible end-points by walking towards the mid-point between the two end-points before arriving at the target.

One other idea for future research, while still maintaining the real-world flavour, is to come to some understanding of what drives the four consistencies described in this thesis. My previous experimental protocols could be repeated with a similar population, but have the participants perform the tasks under an egocentric visual condition by blacking out the entire room except the oscillating doors. The movement behaviours would be compared to my previous results and any differences would be accounted for by the differences in visual information available to the participants. The gaze behaviours would also give insights as to the sequencing of eye, head, and trunk movements in visually impoverished environments. One other way to test the consistencies that I have found in this thesis would be to use a life-like VR environment similar to the one used by Warren. In this environment I would simulate a busy train station (i.e. with people walking about and stationary objects that needed to be avoided) and measure individuals' behaviour as they performed tasks such as walking from one platform to another or getting on to a train just before it left the station. I would be able to compare individuals' behaviours in this setting to those in my thesis.

Based on the consistencies just described, I now have solid grounds to study how clinical populations handle these tasks. The clinical populations that I would use under any of my experimental protocols would either have motor deficiencies or visual impairments. An example of a population with motor deficiencies would be individuals with Parkinson's disease. Parkinson's individuals are known to freeze when walking through doorways only when they cannot perceive what is on the other side of the doorway and they also have reduced movement magnitudes. I think it would be very interesting to monitor gaze and movement behaviours of Parkinson's individuals as they walk through oscillating doors. Gaze behaviours could give insights as to why Parkinson's patients may freeze while movement behaviours may give insights into why they are not successful or how they control behaviours in order to be successful. Patients with visual impairments would have either reduced visual fields to specific areas or decreased visual acuity. Monitoring patients with visual impairments and analysing movement behaviours would give insights into the necessity of specific visual information to the control of locomotion.

Appendix A

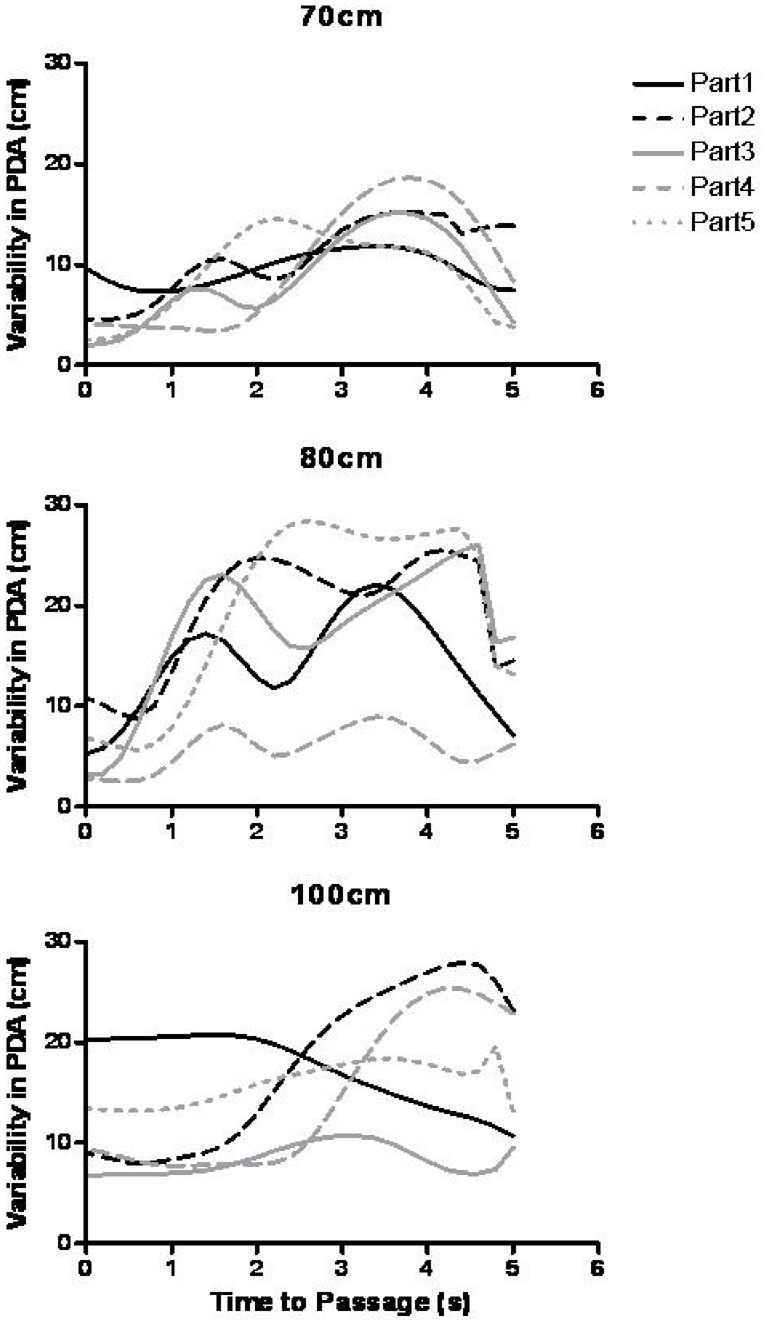

Figure A-1: *The average variability in PDA for each participant under each door aperture condition.*

Appendix B- Gaze behaviours and actions associated with passing through static doors.

B.1 Introduction

The static door conditions (i.e. 100cm and 60cm) served as control trials in order to get baseline data for how participants behaved with static apertures. The two aperture widths, 100cm and 60cm, were used to reflect two extreme conditions within the dynamic conditions used in the current study. The 100cm condition reflected the greatest possible aperture that could occur during the dynamic conditions. The 60cm condition was chosen because from Warren and Whang's (1987) study, it was a width that is passable without shoulder rotations (i.e. slightly larger than 1.3 times the participants' shoulder width). Also our previous work (Study 3) has shown that 60cm reflects the lower limit in which individuals will frequently choose to pass through sliding doors.

B.2 Methods

Participants and apparatus were the same as in study 3.

B.2.1 Procedure

Participants walked at their normal cadence towards static doors with a maximum aperture of either 60 or 100cm. The participants were asked to perform five trials for each of the apertures. The five trials were as follows: the position of the doors were adjusted such that the center was either directly in front of the participant or shifted to the right or left by 11cm for the 100cm aperture or by 15cm for the 60cm aperture.

B.3 Results

In these static conditions (i.e. 100cm and 60cm) there were, on average, 47% of the trials in which a decrease in velocity was initiated during the 100cm condition and 67% during the 60cm condition. A McNemar Chi Squared test showed that there were significantly more trials

($p<0.05$) in which a decrease in velocity occurred for the 60cm condition than for the 100cm condition.

We compared each participant's COM location in the M/L direction relative to the middle of the door aperture at the TOC. On average the participants had 3 of 5 trials in which they passed directly through the middle of the doors and on the other 2 trials they passed about 5cm away from the middle. For the 60cm condition on average the majority of trials (~80%), the participants passed either directly through the middle or within 6cm from the middle.

On average the participants made 2.47 and 2.93 fixations/s for the 100cm and 60cm conditions respectively. The median fixation durations were calculated and were found to be 150msec for both the 100cm and 60cm conditions. The average latency between the start of the last fixation and the time in which the participants crossed the doors was 0.98 and 0.76 for the 100cm and 60cm conditions respectively.

B.3.1 Fixations before a change in velocity

All participants had similar proportions of fixations directed towards the doors and aperture for both the 100cm and the 60cm conditions. Three participants (CSK, EN, and LE) directed a larger proportion of their fixations towards the aperture than the doors. Two participants (KD and SC) had a larger proportion of fixations directed towards the doors than the aperture. Only one participant (NA) had equal proportion of fixations directed towards the doors and aperture.

B.3.2 Fixations after a change in velocity

All participants differed in their fixations for the 100cm and 60cm conditions. In the 100cm condition, all participants fixated towards the aperture more so than towards the doors. There were very few fixations directed towards the doors at this time. In the 60cm condition, four participants (CSK, EN, KD, and LE) had more fixations directed towards the aperture than the doors and two participants (NA and SC) fixated towards the aperture and the doors the same amount. During the 60cm condition, four of the six participants (CSK, EN, LE, and NA) had similar proportions both before and after a change in velocity. The other two participants dramatically increased their number of fixations towards the aperture.

B.4 Discussion

Although the relative middle of the doors was shifted for each trial, the participants still passed through close to the relative middle of the aperture (Figure 5). The participants were not told to locate and pass through the relative middle of the aperture, just to pass through the doors. We believe that by behaving like this the participants were increasing their level of safety. Humans and honeybees steer down the middle of a passageway by equating the speed of optic flow but they also take advantage of the equalization of splay angles (Duchon & Warren, 2002). Participants maintained equal safety margins on both sides of their body when they passed through the middle of the aperture at time of crossing (TOC). This equalization of safety margins ensured greater safety at the TOC.

The fixation locations throughout the static trials give insights as to how vision was used to control locomotion (Figure 7). For the 100cm condition it would make sense that individuals would spend more time fixating towards the aperture after a change in velocity because the aperture was large and of little threat. The individuals then were most concerned with finding the middle of the aperture and passing through it. In the 60cm condition the aperture was narrow with a smaller safety margin. Thus this condition presented more of a challenge to the participants. It would be apparent that this condition would require more fixations directed towards the doors in order to develop a spatial representation of the doors’ location relative to the participants' M/L dimensions. The aperture location in both conditions is still very important because it directs where an individual must walk in order to successfully pass through the doors (goal). This would agree with Rushton et al. (1998) that fixations towards a goal can be used to track one's heading during goal-directed locomotion. The last fixation prior to crossing the doors was always located towards the aperture and this speaks to this desire to successfully complete the task and pass through the relative middle of the aperture.

Appendix-C

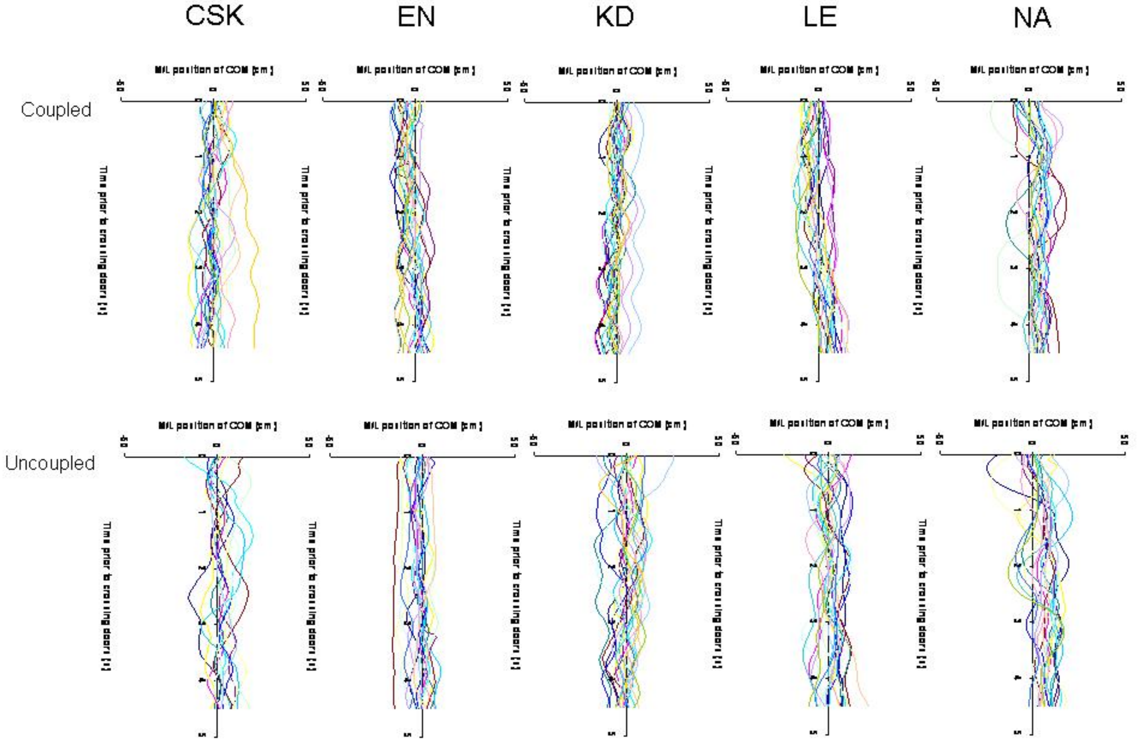

Figure C-1: *M/L position of COM over time for each trial of each participant for both the coupled and uncoupled conditions.*

Apendix D- The number of trials that had fixations directed towards each location for each fixation number

		Coupled			Uncoupled		
Participant	Fixation #	Left Door	Aperture	Right Door	Left Door	Aperture	Right Door
CSK	1	14	5	1	16	3	1
	2	9	10	1	9	10	1
	3	14	6	0	12	7	1
	4	10	10	0	10	10	0
	5	11	8	1	16	4	0
EN	1	18	2	0	15	5	0
	2	13	7	0	5	14	1
	3	6	14	0	12	8	0
	4	5	15	0	10	9	1
	5	6	14	0	6	13	0
KD	1	20	0	0	20	0	0
	2	16	4	0	17	3	0
	3	14	5	0	15	5	0
	4	13	6	0	16	4	0
	5	11	6	0	12	8	0
LE	1	0	14	6	0	15	5
	2	0	9	11	0	7	13
	3	0	10	10	0	12	8
	4	0	12	8	0	8	12
	5	1	11	8	0	13	7
NA	1	20	0	0	18	0	1
	2	16	4	0	16	3	0
	3	15	5	0	10	8	1
	4	12	8	0	10	8	1
	5	10	8	0	13	4	1
SC	1	20	0	0	20	0	0
	2	19	1	0	18	2	0
	3	17	2	0	12	6	0
	4	13	4	0	10	3	0
	5	9	4	0	7	3	0

References:

Alpern, M. Types of Movement, H. Davson (Ed.) The Eye (vol.3, 2nd ed), Academic Press, New York, 1969.

Andersen, G.J. and Enriquez, A. (2006). Use of landmarks and allocentric reference frames for the control of locomotion. Visual Cognition, 13(1), 119-128

Bremmer, F., Duhamel, J.R., Hamed, S.B., and Graf, W. (2000). Stages of self-motion processing in primate PPC. Int. Review of Neurobiology, 44, 173-198

Brouwer, A.M., Middelburg, T., Smeets, J.B.J., and Brenner, E. (2003). Hitting moving targets. Experimental Brain Research, 152, 368- 375

Buekers, M., Montagne, G., de Rugy, A., Laurent, M. (1999). The regulation of externally paced human locomotion in virtural reality. Neuroscience Letters, 275, 171-174

Clark, A. (1999). An embodied cognitive science. Trends in Cognitive Sciences, 3(9), 345-51

Duchon, A.P. and Warren, W.H. (2002). A visual equalization strategy for locomotor control: Of Honeybees, Robots, and Humans. Psychological Science, 13(3), 272-278

Fajen, B.R. (2005). Perceiving possibilities for action: On the necessity of calibration and perceptual learning for the visual guidance of action. Perception, 34(6), 717-40

Fajen, B.R. and Warren, W.H. (2003). Behavioral Dynamics of Steering, Obstacle Avoidance, and Route Selection. J Exp. Psych: Hum. Per. Perform., 29(2), 343-362

Fajen, B.R. and Warren, W.H. (2004). Visual guidance of intercepting a moving target on foot. Perception, 33, 689-715

Findley, J.M. and Gilchrist, I.D. (2004). Active vision: the psychology of looking and seeing. Oxford: Oxford University Press

Fowler, G.A. and Sherk, H. (2003). Gaze during visually-guided locomotion in cats. Behavioural Brain Research, 139. 83-96

Geruschat, D.R., Hassan, S.E., and Turano, K.A. (2003). Gaze behaviour while crossing complex intersections. Optometry and Vision Science, 80(7), 515-528

Gibson, J.J. (1958). Visually controlled locomotion and visual orientation in animals. British Journal of Psychology, 49, 182-194

Gibson, J.J. (1979). The ecological approach to visual perception. Boston: Houghton Mifflin

Gibson, J.J. (1986). The ecological approach to visual perception, Hillsdale, NJ: Houghton Mifflin

Gibson, J.J. and Crooks, L.E. (1938). A theoretical field analysis of automobile driving. American Journal of Psychology, 11, 453-471

Grasso, R., Glasauer, S., Takei, Y., and Berthoz, A. (1996). The predictive brain: anticipatory control of head direction for the steering of locomotion. Neuroreport, 26, 1170-1174.

Grasso, R., Prevost, P., Ivanenko, Y.P., Berthoz, A. (1998). Eye-head coordination for the steering of locomotion in humans: an anticipatory synergy. Neuroscience Letters, 253, 115-118.

Hicheur, H., Vieillendent, S., and Berthoz, A. (2005). Head motion in humans alternating between straight and curved walking path: Combination of stabilizing and anticipatory orienting mechanisms. Neuroscience Letters, 383, 87-92

Higuchi, T., Cinelli, M.E., Greig, M.A., and Patla, A.E. (2006). Locomotion through apertures when wider space for locomotion is necessary: adaptation to artificially altered body dimensions. Experimental Brain Research

Hollands, M.A., Marple-Hovat, D.E. (1996). Visually guided stepping under conditions of step cycle related denial of visual information. Experimental Brain Research, 109, 343-56

Hollands, M.A., Marple-Hovat, D.E., Henkes, S., and Rowan, A.K. (1995). Human eye movements during visually guided stepping. J Motor Behavior, 27, 155-163.

Hollands, M.A., Patla, A.E., Vickers, J.N. (2002). "Look where you're going!": gaze behaviour associated with maintaining and changing the direction of locomotion. Experimental Brain Research, 143, 221-230.

Land, M.F. (1998). The visual control of steering. In: Vision and Action (eds Harris LR & Jenkin K) 163-180. Cambridge University Press

Land, M.F. and Furneaux, S. (1997). The knowledge base of Oculomotor system. Philosophical Transactions: Biological Sciences, 352(1358), 1231-1239.

Land, M.F. and Hayhoe, M. (2001). In what ways do eye movements contribute to everyday activities? Vision Research, 41(25-26), 3559-3565.

Land, M.F. and Lee, D.N. (1994). Where we look when we steer. Nature, 369, 742-744

Land, M.F., Mennie, N., and Rusted, J. (1999). The roles of vision and eye movements in the control of activities of daily living. Perception, 28, 1311-1328

Lappe, M. and Hoffmann, K.P. (2000). Optic flow and eye movements. Int. Review of Neurobiology, 44, 29-47

Lee, D. N. and Lishman, R. (1977). Visual control of locomotion. Scandinavian Journal of Psychology, 18, 224-230

Lee, D.N., Lishman, J.R., and Thompson, J.A. (1982). Regulation of gait in long jumping. Journal of Experimental Psychology Human Perception and Performance, 8(3), 448-459

Loomis, J.M. and Beall, A.C. (1998). Visually controlled locomotion: Its dependence on optic flow, 3D space perception and cognition. Ecological Psychology, 10(3-4), 271-85

Martinez-Conde, S., Macknik, S.L., and Hubel, D.H. (2004). The role of fixational eye movements in visual perception. Nature Reviews/ Neuroscience, 5, 229-240

Milner, A.D. and Goodale, M.A. (1995). The visual brain in action. Oxford: Oxford University Press

Montagne, G., Buekers, M., Camachon, C., de Rugy, A., and Laurent, M. (2003). The learning of goal-directed locomotion: A perception-action perspective. The Quarterly Journal of Experimental Psychology, 56A(3), 551-567

Montagne, G., Buekers, M., de Rugy, A., Camachon, C., and Laurent, M. (2002). Control of human locomotion under various task constraints. Experimental Brain Research, 143, 133-136.

Montagne, G., Cornus, S., Glize, D., Quaine, F., and Laurent, M. (2000). A perception-action coupling type of control in long jumping. Journal of Motor Control, 22(1), 37-43

Patla, A.E. (1998). How is human gait controlled by vision? Ecological Psychology, 10(3-4), 287-302

Patla, A.E. and Vickers, J.N. (1997). Where and when do we look as we approach and step over an obstacle in the travel path? Neuroreport, 8, 3661-5.

Patla, A.E. and Vickers, J.N. (2003). How far ahead do we look when required to step on specific locations in the travel path during locomotion. Experimental Brain Research, 148, 133-38

Patla, A.E., Tomescu, S.S., and Ishac, M.G. (2004). What visual information is used for navigation around obstacles in a cluttered environment? Can J Physiol Pharmacol., 82(8-9), 682-92

Patla, A.E., Tomescu, S.S., Grieg, M.A., and Novak, A. (2006). Gaze fixation patterns during goal-directed locomotion while navigating around obstacles and a new route-selection model.

Plumert, J.M., Kearney, J.K., Cremer, J.F. (2004). Children’s perception of gap affordances: Bicycling across traffic-filled intersections in an immersive virtual environment. Child Development, 75(4), 1243-1253.

Rushton, S.K., Harris, J.M., Lloyd, M.R., and Wann, J.P. (1998). Guidance of locomotion on foot uses perceived target location rather than optic flow. Current Biology, 8(21), 1191-94

Sherk, H. and Fowler, G.A. (2000). Optic flow and the visual guidance of locomotion in the cat. Int. Review of Neurobiology, 44, 141-170

Turano, K.A., Geruschat, D.R., Baker, F.H., Stahl, J.W., and Shapiro, M.D. (2001). Direction of gaze while walking a simple route: persons with normal vision and persons with retinitis pigmentosa. Optometry and Vision Science, 78(9), 667-75

Turano, K.A., Yu, D., Hao, L., and Hicks, J.C. (2005). Optic-flow and egocentric-direction strategies in walking: Central vs peripheral visual field. Vision Research, 45, 3117-32

Turvey, M.T. (1992). Affordances and prospective control: An outline of the ontology. Ecological Psychology, 4, 173-187

Wann, J.P. and Swapp, D. (2000). Why you should look where you are going. Nature Neuroscience, 3(7), 647-8

Wann, J.P., Swapp, D., and Rushton, S.K. (2000). Heading perception and the allocation of attention. Vision Research, 40, 2533-43

Warren, W.H. (2006). The dynamics of perception and action. Psychological Reviews, 113(2), 358-389

Warren, W.H. and Saunders, J.A. (1995). Perceiving heading in the presence of moving objects. Perception, 24, 315-331

Warren, W.H. and Whang, S. (1987). Visual guidance of walking through apertures: body-scaled information for affordances. J. Experimental Psychology Human Perception and Performance, 13(3), 371-383

Warren, W.H., Kay, B.A., Zosh, W.D., Duchon, A.P., and Sahuc, S. (2001). Optic flow is used to control human walking. Nature Neuroscience, 4(2), 213-16.

Wilkie, R and Wann, J.P. (2003). Controlling steering and judging heading: retinal flow, visual direction, and extraretinal information. J Exp Psychol Hum Percept Perform., 29(2), 363-78

Yarbus, A.L. (1967). Eye Movements and Vision, New York: Plenum Press

Young, L., Recording eye psition, M. Clynes & M. Milsum (Eds.), Biomedical Engineering Systems, McGraw Hill, New York, 1970.