Role of visual information during stair locomotion

by

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AUTHOR'S DECLARATION

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

Vision provides relevant information for safe locomotion in a variety of environments. During stair locomotion visual information may be important to detect step boundaries, transitions between ground level and stairs, handrail location, and potential hazards. Although there is a large body of literature on the role of vision during locomotion there is relatively little focussed on how visual information is used during stair walking. Stairs are related to a significant number of accidents in daily living, and many of these accidents are attributed to visual factors. Therefore, understanding the role of vision during stair walking could provide insight into the mechanisms involved in stair accidents. The purpose of this thesis was to investigate the properties of the visual input used to guide locomotion on stairs. Study 1 was design to describe the gaze patterns during stair locomotion with a specific focus on transitions and handrails. Study 2 investigated the effects of performing concurrent visual and non-visual tasks on walking performance and associated gaze behaviour during stair ascent. Study 3 explored the role of peripheral visual information during visual and non-visual dual tasking. Finally, Study 4 investigated the effects of restricting the lower peripheral visual field to walk on stairs. Studies relied on the measurement in health young adults of: gaze behaviour using an eye tracker, temporal characteristics of walking using foot switches, and reaction time and errors of dual task performance. Overall, the findings of these studies highlight the importance of the lower visual field in guiding stair locomotion and the specific importance for stair transitions. Moreover, foveal vision is not specifically critical to detecting handrails or steps. Results are interpreted in the light of the specialization of the dorsal ventral stream in processing peripheral visual field information. Findings of this thesis provide basic understanding on the role of vision for stair navigation with potential applications in stair-related accident prevention programs and stair design.

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Dedication

This thesis is dedicated to

my mother Alice,
my father Severino,
my sister Silvana, and
my husband Rodrigo.

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Chapter 1

Introduction

The challenge of walking on stairs

1.1 Background

Walking on stairs is a challenging activity of daily living for many individuals, such as older adults and individuals with lower limb and balance impairments, and is related to high incidence of falls. Stair locomotion imposes specific challenges to balance control, precise foot placement on steps, and adaptations in the gait cycle to transition from ground level to stair level.

The literature provides extensive information on the physiological and mechanical demands during stair locomotion. However, the perceptual mechanisms involved during stair walking are still not well understood. Although the importance of visual information during overground walking has been extensively reported in the literature, the current knowledge about the role of vision during stair locomotion is based on how people perceive stair heights , and on observations of video recordings of stair users (Archea, Collins, & Stahl, 1979; Templer, 1992). Therefore, research with a more direct approach on the specific role of vision during stair locomotion may provide important contributions to this field of study.

1.2 Rationale

Stair walking is considered one of the most difficult daily activity tasks (Williamson & Fried, 1996). Stairs are linked to a high incidence of falls in the elderly population, and falls on stairs are associated with injuries that require medical attention even in younger age groups. Interestingly, the first top and bottom steps seem common locations for stair falls (Wild, Nayak, & Isaacs, 1981). However, the current literature is scarce of research on the locomotion in stair transitions, with most studies focusing on the control of locomotion in the mid step region. Additionally, many stair falls are attributed to perceptual errors, which could be a consequence of failing to extract relevant visual information and/or allocating the appropriate executive resources for gait control. However, the visual and executive mechanisms involved in the control of stair locomotion are not well understood. With a better understanding of the visual and executive mechanisms underlying safe stair walking (including locomotion on transitions), this knowledge can be applied in the field of stair design and fall prevention programs. The studies of this thesis are intended to provide basic understanding of the role of vision during stair locomotion. It is anticipated that this work would lead to future work focussed on the application of such knowledge to understanding of challenges faced by older adults or those with physical or cognitive dysfunction.

1.3 Research questions and objectives

This thesis is characterized by four main studies, in which the following research questions are addressed:

Study 1: Gaze behaviour during stair walking

- Where do people look at when they are walking up and down stairs?
- How do people acquire visual information regarding handrails?
- Do transitions between ground level and stairs require unique visual information compared to steady-state stair walking?

Study 2: Effects of dual tasking on gaze behaviour during stair ascent

- Are foveal fixations necessary during stair walking?
- Does the performance of a concurrent visual/non-visual task cause changes in locomotor and gaze behaviours during stair walking?
- Does visual/no-visual dual-tasking have a specific influence on locomotion on transitions?

Study 3: Dual task, stair descent and lower visual field

- Do people need to look down during stair descent?
- Do people use the handrail when dual tasking during stair descent?
- Is the information provided by the lower peripheral visual field sufficient to guide stair descent in a dual task context?

Study 4: Assessing the role of the lower visual field during stair walking

- Does the lower peripheral visual field play a role in guiding stair locomotion?
- Does the lower peripheral visual field play a specific role during walking on transitions vs. middle steps?
- Does the lower peripheral visual field play a specific role during stair ascent vs. descent?

Chapter 2

Literature review

2.1 The challenges of stair locomotion for balance control

Although stair walking is a common everyday activity and we are able to climb stairs from a young age, at the same time, stair walking is a complex locomotor task that imposes challenge to balance control. Compared to ground level walking, stair walking is more challenging given the increased mechanical, spatial, perceptual and executive demands. Additionally, stairs vary in their designs and are present in a variety of environments, which can lead to different levels of challenge (Cavanagh, Mulfinger, & Owens, 1997; Startzell, Owens, Mulfinger, & Cavanagh, 2000, for review). This section provides a brief overview of some of the main factors influencing balance control during stair locomotion that are directly related to the scope of this thesis.

2.1.1 Biomechanical challenges

Biomechanical analysis of stair locomotion has been well documented in the literature in the last 30 years (Andriacchi, Andersson, Fermier, Stern, & Galante, 1980; McFadyen & Winter, 1988; Protopapadaki, Drechsler, Cramp, Coutts, & Scott, 2007; Riener, Rabuffetti, & Frigo, 2002). Stair locomotion is extensively used to assess knee function given its relevance in the daily living activities (Andriacchi, Dyrby, & Johnson, 2003; Brechter & Powers, 2002).Although both stair and level walking share a similar joint moment pattern, the increased moment magnitudes during stair locomotion makes stair walking a highly demanding locomotor task. For instance, stair locomotion causes larger joint angular range of motion and extensor support moment magnitudes in comparison to level walking, with the maximum knee extension moment reaching an increase of three times the knee moment observed during level walking (Andriacchi et al., 1980; McFadyen & Winter, 1988;

Riener et al., 2002). During stair walking, the contact with the step is most often done with the forefoot, which reduces the support surface and increases the demands for balance control (Riener et al., 2002). Additionally, stair ascent and descent also differ from each other, with high generation of energy during ascent and energy absorption during stair descent (McFadyen & Winter, 1988; Protopapadaki et al., 2007; Riener et al., 2002).

2.1.2 Step dimensions and transitions

Stairs differ from each other in dimensions and materials and this variability can have a significant impact on gait parameters and risk for falls. For instance, joint angles, moments, and power patterns increase with increasing staircase inclination (Riener et al., 2002). The stair dimensions present in standard guidelines have been determined by historical architectural traditions rather than experimental approaches (Templer, 1992). However, a psychophysical study showed that the typical step dimensions of 18cm rise vs. 29cm tread is within values for self-selected preferred stair dimensions independently of gender and age (Irvine, Snook, & Sparshatt, 1990).

The assumption that steps are uniform within a staircase seems an important factor for stepping behaviour. On average, the foot clears the step by 2.5cm, however the foot clearance is increased on the first riser and this distance is reduced as individuals walk on the steps (Cavanagh & Higginson, 2003; Hamel, Okita, Higginson, & Cavanagh, 2005; Simoneau, Cavanagh, Ulbrecht, Leibowitz, & Tyrrell, 1991). This reduction in foot clearance in the subsequent steps is attributed to the use of somatosensensory information. Prior to stepping on the first step, visual information is the only sensory input available regarding the step dimensions. When the foot interacts with the first step, somatosensory information, combined with assumption of step dimension constancy, can also be used to guide foot trajectory over the following steps. With uniformity of the steps confirmed within the first few steps, the stride is shortened and the clearance is reduced. This reduction in foot clearance along a stairway is even observed in poor visual conditions, such as darkness and blurriness (Archea et al., 1979; Hamel, Okita, Bus, & Cavanagh, 2005; Simoneau et al., 1991). Therefore, the first transition (floor-to-stair) is unique in terms of providing additional somatosensory information that can be used to modulate the progression during the following steps. Additionally, because foot clears the steps at a very small distance, it should be noted that even minimal variability in step dimensions could be precursor for trips and falls.

Interestingly, most falls during stair walking happen on the first or last step (Wild et al., 1981), which could be related to the challenge of navigating between floor-to-stair and stair-to-floor. Changes in gait pattern must to be performed to allow a fluent transition between over ground walking and stairs (McFadyen & Carnahan, 1997). Additionally, age-related decrements in the ability to regulate body sway during stair-to-floor transition may be a contributor for the high incidence of stair accidents during the last steps in staircases (Lee & Chou, 2007; Sheldon, 1960).

2.1.3 Handrails

Holding a handrail is considered an efficient strategy to increase safety during stair walking, and stair design standards recommend at least one handrail beside stairs (Archea et al., 1979; Fitch, Templer, & Corcoran, 1974; Hall & Bennett, 1956; McGuire, 1971; Sheldon, 1960). Although there is evidence that there are more accidents on stairs with handrails, these accidents tend to cause less serious injuries (Archea et al., 1979). Handrails can provide an extra surface for support, which can reduce the load on the lower extremities and avoid falls after a misstep or slip. Older adults can be seen relying on handrails to pull themselves up and trying to reach for nonexistent handrails following a loss of balance (Archea et al., 1979). In addition, somatosensory information acquired from a light touch of the hands on handrails could also be used to control balance and to monitor the progression on stairs, which has been observed during quiet standing (Jeka, Easton, Bentzen, & Lackner, 1996; Jeka & Lackner, 1994). Given the importance of handrails for safety, the design and provision of adequate handrails are a key factor in any program for stair accident prevention. Unfortunately, the presence of handrails does not guarantee that people will use them: approximately only 1/3 of users hold the handrail to climb up or down stairs (Cohen & Cohen, 2001; Templer, 1992). Despite the lack of handrail use, there is observational estimate that 59% of stair users place themselves within arm's distance of the handrail while walking on stairs (Cohen & Cohen, 2001), which could allow a grasping response in the event of loss in stability. There is evidence that grasping on a handrail can be rapid enough to effectively restore balance in response to a postural perturbation (Ghafouri, McIlroy, & Maki, 2004). Even when the hand is distant from the rail, arm movements can be accurate and fast enough to grasp the handrail with appropriate stabilizing forces (Maki, Perry, & McIlroy, 1998). Although these findings are based on an experiment that had participants being perturbed from a static stepping position (Maki et al., 1998), videotapes of real life stair users seem to confirm the ability to recover balance by quickly holding a handrail (Archea et al., 1979).

2.2 Mechanism of falls on stairs and prevention

Stairs are the most common sites for accidents in homes accounting for more than 27% of domestic accidents (McGuire, 1971). Stair-related injuries increase monotonically with age (Hemenway, Solnick, Koeck, & Kytir, 1994), and approximately one third of all falls requiring medical care happen on stairs (Sheldon, 1960). Estimates are that one in seven people will at some time in her or his life have a stair accident resulting in injuries severe enough to require hospital treatment (Archea et al., 1979). Considering the high incidence and the severity of injuries, it is important to understand the mechanisms involved in stair accidents in order to design efficient fall prevention programs.

A variety of circumstances have been related to stair accidents, such as inadequate light conditions, vertigo, and missing the last step (Sheldon, 1960). Additionally, in a study analyzing video recordings of stair users, behaviours commonly observed preceding a stair accident included change in the focus of attention, movement laterally on the stairway, distraction, change in handrail use, and reaction to another stair user (Archea et al., 1979). It is worth noting, however, that those behaviours occurred only in less than a half of the incidents studied, being unclear the factors triggering the other half of incidents.

There is evidence that falls during stair descent are more frequent than during stair ascent (Fitch et al., 1974; Sheldon, 1960; Svanstrom, 1974; Tinetti, Speechley, & Ginter, 1988). This difference between ascent and descent could be simply because falls during stair descent are more likely to cause injuries requiring medical care compared to stair ascent. However, the high incidence of falls during stair descent could also be associated with a greater challenge for balance control, such as increased movement speed and greater centre of mass-centre of pressure separation in comparison to stair ascent (Zachazewski, Riley, & Krebs, 1993).

In order to better understand stair accidents and create guidelines for safe stairs, Archea et al. (1979) analysed video recordings of stair accidents and proposed a stair use and behaviour model. This model highlights that during the approach to a flight of stairs, the user tends to first look at the flight of stairs as a whole, following by a look at the first several treads; the visual information acquired at this point is used to adjust gait to the riser and tread dimensions. During the approach, visual information about the steps is the only sensory information available to guide stepping behaviour, which leads to a higher step clearance over the first riser (during ascent), or a slower foot drop onto the first tread (during descent). As users initiate to ascend or descend the stairs, they have additional information from the somatosensory system regarding the first step, which can confirm the previous visual input. If somatosensory inputs validate similar step characteristics while negotiating the second step, the idea of uniformity in the stair dimensions is established resulting in reduction in stride length foot clearance. At this point, the somatosensory information reduces the need for visual information and the user can scan around the environment surrounding the stair. This is also the point when the user may become susceptible to tripping on tread or nosing irregularities.

By assuming the importance of perceptual factors for stair safety in their model, Archea et al. (1979) listed a series of recommendations based on the premise that accidents on stairways are caused by human perceptual errors frequently triggered by some defect in the design or construction of stairways themselves. The model and the guidelines highlight the importance of the stair in being the most conspicuous feature in the environment and that visual factors dominate over other sources of information during the early stages of stair negotiation.

2.2.1 Perceptual errors

Perceptual errors refer to inappropriate detection and/or interpretation of relevant sensorial input to guide stair walking and they have been considered the most often cause for stair accidents. Additionally, perceptual errors are associated to multi factors, such as lack of attention to relevant stimuli, illusions, distractions, and misjudgement (Archea et al., 1979; Startzell et al., 2000; Templer, 1992). Any sensorial modality could be source for perceptual errors, however, visual information is most often associated with perceptual errors during in stair navigation. Videotapes of people's behaviour during stair walking suggest that successful stair negotiation was related to: 1) looking at the steps, particularly at the first steps of a stair flight; and 2) looking down at the steps immediately prior to the actual stepping action rather than looking down during the stepping (Archea et al., 1979).

The importance of visual information preceding the stepping action is not surprising given its role in providing information about step characteristics prior to physical contact with the stairs. Although somatosensory information can also be used to guide locomotion after the feet make contact with the steps, visual factors are still believed to be precursors of falls during the entire stairway navigation (Archea et al., 1979; Templer, 1992). In the “Stair behaviour model” proposed by Templer (1992), visual information is required in different phases during stair walking and interruptions of these processes can increase the risk of falls (Figure 2.1). For instance, the initial *conceptual scan* is intended to form a cognitive map of the stairs containing the general stairs configuration, which includes handrail location, step shape, obvious obstructions and hazards. Further in the model, the *step location scan* refers to a fixation on the first step before the actual stepping on the stairs. Additionally, the model also includes *continuous monitoring scans* to search for obstacles and allow appropriate gait changes during the ongoing stair climbing.

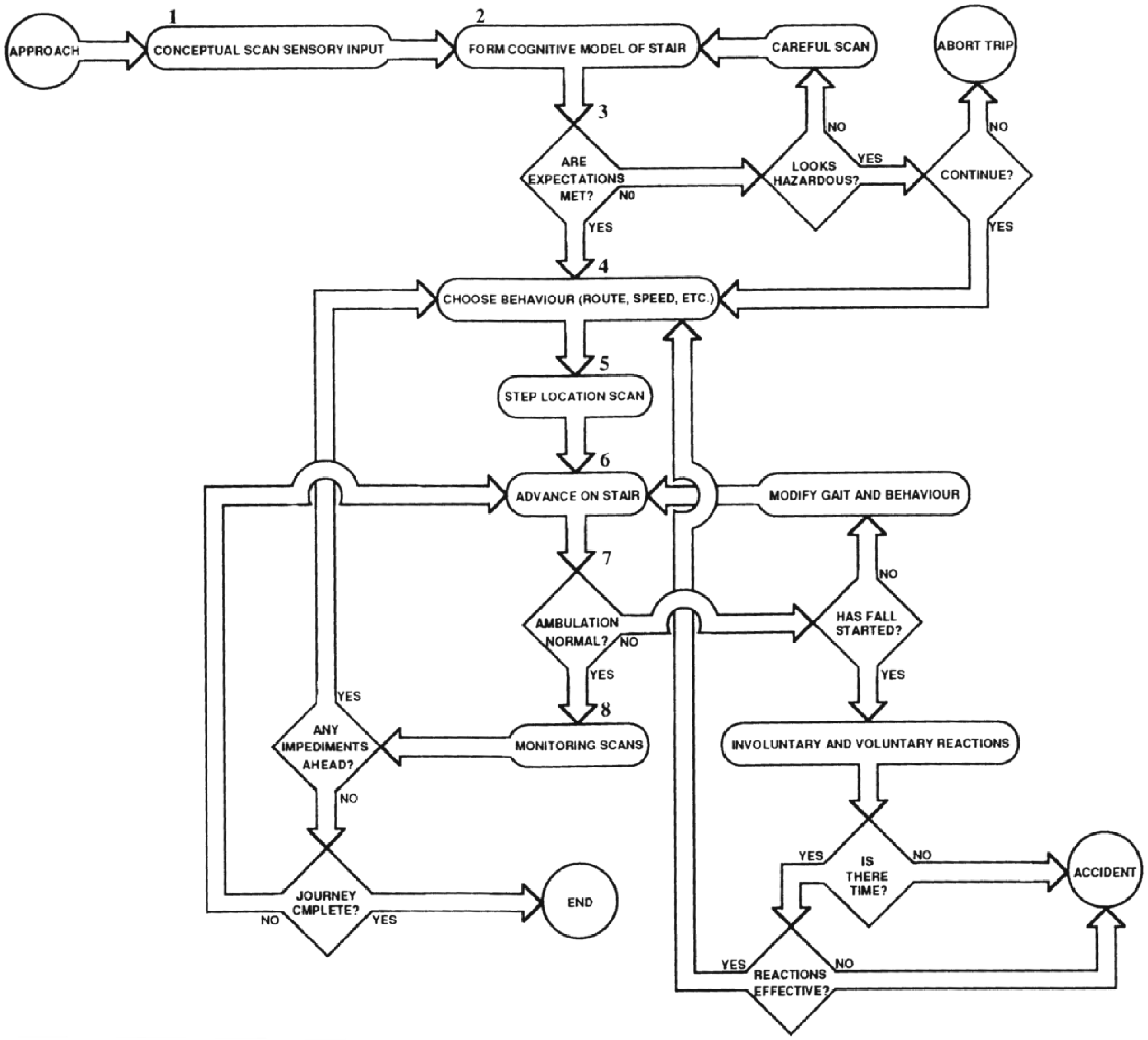

Figure 2.1: Stair behaviour model (reprinted with permission from "The Staircase: Studies of Hazards, Falls, and Safer Design", by John Templer, 1992, p.107, figure 5.19, published by The MIT Press).

Many current findings confirm many of the observations made by Archea et al. (1979) and Templer (1992), such as the reduction in foot clearance during consecutive steps on a staircase (Hamel et al., 2005; Simoneau et al., 1991). However, many inferences regarding gaze behaviour and the role of vision during stair walking are yet to be confirmed. For instance, there is no specific evidence for a general visual scanning during the approach to a staircase, nor a reduction in visual scanning following the navigation on the first few steps as proposed in these models.

2.3 Visual information during stair locomotion

There is no doubt that visual information is important during locomotion. By simply closing our eyes and trying to move around, even in a familiar space, we cannot deny the importance of vision in guiding our behaviour.

The visual system provides rich information that can be used in many ways during locomotion, such as for planning, to guide action and for balance control. Visual information can be used to plan ahead changes in gait pattern for a safe and smooth navigation, as well as to control foot trajectory over obstacles and stepping on targets (Patla, 1998). Additionally, vision provides relevant information for balance control during locomotion, in part by providing a stable frame of reference for upright posture, and dynamic visual information through the use of optic flow (Bardy, Warren, & Kay, 1996).

Despite of the importance of vision for locomotion, only a few studies have investigated the role of vision during stair locomotion and therefore there are still many questions regarding how visual information is utilized to properly adapt our locomotor behaviour to a stair context. The following sections summarize the current knowledge on how vision is used during stair locomotion. As research on vision during stair walking is scarce in some areas, studies regarding vision during other locomotor tasks are also referred to give additional insights into other potential roles for vision during stair locomotion.

2.3.1 Perception of climbability

Vision provides information on the environmental properties of stairs, which allows individuals to adaptively calibrate their own action according to a given situation. By simply having the view of a set of stairs, people can judge if they are able to climb the stairs as well as to perceive both their own maximal and optimal stair riser height for stair climbing (Konczak, Meeuwsen, & Cress, 1992; Meeuwsen, 1991; Warren, 1984). This precise perceptual judgment is related to the concept of affordance, which in general terms refers to the capability of perceiving the functional utility of an object for an individual with certain action capabilities (Gibson, 1979). Therefore, the perception of maximum climbability is linked to the individual's biomechanical constraints. Generally, the stair riser height judged to be optimal has been estimated at approximately 25% of leg length, which corresponds very closely to height related to the minimum energy expenditure for stair climbing (Warren, 1984). However, older adults perceive and select stairs that are significantly lower in riser height than young adults (Cesari, 2005) due to additional constraint factors (other than leg length), such as leg strength and hip flexibility (Konczak et al., 1992). This refined ability to judge step risers shows that visual information provides input on relevant stair properties that can be used to regulate action according the individual's physical characteristics.

2.3.2 Visual impairments

Falls are strongly associated with poor visual function. Low scores in visual acuity, depth perception, contrast sensitivity, and visual field tests are related to fall risk (Lord & Dayhew, 2001). Specifically in terms of stair locomotion, contrast sensitivity was found to be one of the factors significantly associated with stair negotiation speed and handrail use (Tiedemann, Sherrington, & Lord, 2007). In addition, reduced visual conditions affect stair walking. When healthy old individuals walked down stairs under a blurred condition, it caused slower cadence, larger foot clearance and a more posterior foot placement on the step, indicating a safety-oriented adjustment strategy. Under normal visual conditions, gait parameters across multiple steps suggest that safer strategies are adopted only at the beginning of the stairway, with reduced safety margin along the following steps. Differently, when visual conditions are not favourable, the safety strategy is also maintained on subsequent steps (Simoneau et al., 1991). These findings indicate that, although the somatosensory information from the feet might contribute to regulate foot trajectory in the following steps, vision still provides continual visual information for the modulation of locomotor strategies.

Epidemiological studies provide evidence that multifocal spectacle wearers are more likely to fall on stairs (Lord, Dayhew, & Howland, 2002). The lower part of this type of lens is designed for reading at a near distance (40 to 60 cm), which can cause distortion in the image of distant objects is available in the lower visual field, such as stairs and curbs (Johnson, Buckley, Scally, & Elliott, 2007; Lord et al., 2002). It is not surprising, therefore, that multifocal spectacle users show an increased variability in foot clearance, which can lead to trips and falls (Johnson et al., 2007).

Visual field impairments have been also reported as a strong predictor for mobility disability, including difficulty to navigate on stairs (Sakari-Rantala, Era, Rantanen, & Heikkinen, 1998; West et al., 2005). Individuals with visual field loss generally show reduced gait speed and increased number of bumps on objects in the environment (Turano et al., 2004). Individuals with retinitis pigmentosa (which causes visual field loss) seem to rely more on the central vision than healthy controls by directing their gaze to a larger area in the environment and looking down more often to detect obstacles on the floor (Turano, Geruschat, Baker, Stahl, & Shapiro, 2001).

The investigation of the role of the lower peripheral visual field during walking has shown the importance of the visual information acquired from peripheral vision to regulate gait. Generally, restriction in the peripheral visual field (by occlusion or disease) causes compensatory strategies during walking, such as, increased toe clearance over obstacles (Patla, 1998), reduced gait speed (Marigold & Patla, 2008; Turano et al., 2004), reduced step length, and increased downward head tilt (Marigold & Patla, 2008). The peripheral visual field seems to provide enough information to successfully guide the implementation of changes in the limb trajectory during obstacle avoidance, since downward saccades to the obstacle region rarely happen, and when they occur, they are initiated only after following the onset of muscle activity (Marigold, Weerdesteyn, Patla, & Duysens, 2007). Additionally, individuals with peripheral field loss have poorer performance in memory-guided walking to a goal, which demonstrates the importance of the peripheral vision to build and update the spatial representation with the position of goal and landmarks (Turano, Yu, Hao, & Hicks, 2005).

The specific role of the lower visual field during stair walking has not been investigated. There is some evidence that the lower visual field is important to provide visual information to control foot placement during stepping. During a single-step descent task, restriction in the lower visual field caused significant changes in landing behaviour reflecting a safer landing strategy, such as reduction in knee and ankle velocity, and vertical reaction time force (Timmis, Bennett, & Buckley, 2009). These findings from a single step task give some evidence that the visual information from the lower peripheral field might also be used to finely tune foot position during stair walking. However, a single stepping task differs from walking on a full stair flight because it does not include the transition from level walking to the step, it does not require walking on multiple steps consecutively, it does not involve the chance of using handrails as a compensatory strategy, and it prevents the advantages of using dynamic visual information. These differences between single and multiple stepping can potentially give different or additional roles for the peripheral vision during full flight stair walking.

2.3.3 Gaze behaviour

Since (1967), when Yarbus recorded eye movements during scene view, it has been demonstrated that eye movements are linked to the observer's cognitive goals. Currently, gaze behaviour is being studied in a broad range of tasks, including driving, walking, sports, and making tea or sandwiches as an attempt to understand the underling cognitive processes during voluntary movement (Hayhoe & Ballard, 2005; Land, 2006, 2009, for review). With the technological advances in the past few decades, new generation eye-trackers are lightweight, mobile and easier to calibrate, providing opportunities to assess gaze behaviour in real-world activities.

The study of gaze behaviour provides information on eye movements and the relative direction of gaze in the environment. The direction of gaze demonstrates which area in the environment is being viewed by the central vision. The central vision incorporates the fovea, which is the region with highest visual acuity. Between the rapid eye movements (saccades), the eyes have periods when they remain relatively still, which are called gaze fixations. It is during fixations that visual information regarding the environment can be extracted and processed (Land, 2006; Vickers, 2007).

Gaze behaviour is influenced by the goals and specific requirements of the locomotor task. For instance, when people are asked to walk on a hallway and turn at the fifth door on the left, most fixations are directed to the doors on the left side with the fifth door receiving a greater number of fixations than the previous doors (Turano, Geruschat, & Baker, 2003). Gaze fixations are not only linked to the task requirement, but they are also tightly linked in time to the evolution of the task indicating their role in guiding action (Ballard, Hayhoe, & Pelz, 1995; Patla & Vickers, 2003). For example, people consistently fixate two steps ahead in their travel, even when the walk requires precise foot falls on targets on the floors, which corresponds approximately to one second before the start of the actual stepping action on that location (Patla & Vickers, 2003). During this fixation, it is thought that visual information is being acquired to plan the stepping action. This fixation preceding action has also been observed in non-locomotor tasks and called “just in time fixation” (Ballard et al., 1995). For locomotion, the time between the fixation and the actual action seems to be feasible enough to plan the stepping action, as changes in stepping placement can be efficiently implemented within one step cycle (Patla, Prentice, Rietdyk, Allard, & Martin, 1999).

An important question is which type of information is extracted during fixations during locomotion. There is evidence for an optimal point of gaze that fits the spatio-temporal demands of the task. During driving, for instance, drivers keep their direction of gaze on the "tangent point" on the inside of each curve (where the edge of the road reverses direction) from 1-2 s before each bend to approximately 3 seconds into the bend. This point relative to the car's heading predicts the curvature of the road ahead (Land & Lee, 1994). Additionally, there is also evidence that fixations provide the specific visual information relevant for the task. Cinelli et al. (2009) investigated gaze behaviour while people walked through “moving doors”. They found that during the approach, fixations were distributed on the right and left door, and the aperture. However, when participants were in their last steps before crossing, fixations were predominantly directed to the aperture, and variability in gait speed was increased to adjust the walk and successfully cross the doors. Additionally, fixation duration was longer when the doors moved asymmetrically, which was related to a longer time needed to extract and process information during this complex condition. The findings from this study show the role of fixations extracting the relevant information (from the aperture) “just in time” to make the appropriate changes gait speed to perform the task (crossing).

Not many studies that have directly assessed gaze behaviour during stair locomotion, however findings from a recent study reveals that gaze behaviour can be a promising source to understand the use of visual information during stair walking. Zietz and Hollands (2009) studied the gaze behaviour of healthy young and old adults while walking up and down the central 8-steps of and 12-step staircase. They observed that participants spent between 75 and 90% of the time fixating at their future stepping location in the travel path. Moreover, participants looked most frequently three steps ahead, which is one step further than during over ground level walking (Patla & Vickers, 2003). Added to these general observations on gaze behaviour during stair walking, gaze fixations during stair descent showed differences compared to stair ascent: during stair descent, the last gaze fixation on a stair is closer in time to the foot contact with that stair, suggesting that a more up-to-date visual information about stair properties guides stepping movements during descent (Zietz & Hollands, 2009). This study was the first attempt to investigate gaze behaviour during stair walking, and provides the general profile of gaze behaviour during steady-state stair walking. However, many other questions regarding vision and gaze behaviour during stair locomotion remain to be addressed. For example, what are the gaze behaviour characteristics during transitions between stairs and level ground? Is gaze behaviour necessary for grasping responses on the handrail? Does cognitive load play a role on gaze behaviour profiles during stair walking? Do people at risk for falls show different gaze behaviour?

In summary, stair locomotion is a challenging task significantly associated with accidents and falls. Knowledge of the mechanisms involved in the control of stair locomotion is important for stair design and fall prevention programs. As vision is the primary sensory information utilized during stair locomotion, the investigation of eye movements and gaze behaviour can provide relevant information on how people control their steps on stairs. The following chapters detail four studies intended to explore specific aspects of the role of vision during stair ascent and descent in healthy young adults, which provide essential information to guide future studies in older adults focussed on factors contributing to and minimizing fall risk during stair locomotion.

Chapter 3

Study 1 – Gaze behaviour on stairs, transitions and handrails

With kind permission from Springer Science+Business Media: Experimental Brain Research, Where do we look when we walk on stairs? Gaze behaviour on stairs, transitions and handrails, v.209, 2011, 73-83, Miyasike-daSilva V, Allard F, McIlroy WE.

3.1 Overview

Stair walking is a challenging locomotor task and visual information about the steps is considered critical to safely walk up and down. Despite the importance of such visual inputs, there remains relatively little information on where gaze is directed during stair walking. The present study investigated the role of vision during stair walking with a specific focus on gaze behaviour relative to 1) detection of transition steps between ground level and stairs, 2) detection of handrails, and 3) the first attempt to climb an unfamiliar set of stairs. Healthy young adults (n=11) walked up or down a set of stairs with 7 steps (transitions were defined as the two top and bottom steps). Gaze behaviour was recorded using an eye-tracker. Although participants spent most part of the time looking at the steps, gaze fixations on stair features covered less than 20% of the stair walking time. There was no difference in the overall number of fixations and fixation time directed towards transitions compared to the middle steps of the stairs. However, as participants approached and walked on the stairs, gaze was within 4 steps ahead of their location. The handrail was rarely the target of gaze fixation. It is noteworthy that these observations were similar even in the very first attempt to walk on the stairs. These results revealed the specific role of gaze behaviour in guiding immediate action, and that stair transitions did not demand increased gaze behaviour in comparison to middle steps. These findings may also indicate that individuals may rely on a spatial representation built from previous experience and/or visual information other than gaze fixations (e.g. dynamic gaze sampling, peripheral visual field) to extract information from the surrounding environment.

3.2 Introduction

Stairs are related to a high number of accidents and injuries (Sheldon, 1960; Templer, 1992). In comparison to level ground walking, stair navigation imposes additional demands on the control of stability, such as the vertical control of body mass while moving up or down each step, and the coordination for precise foot placement on each step. In order for the central nervous system (CNS) to address the issue of navigation on stairs, vision is considered to play a major role in providing information regarding stair features, such as step characteristics, transitions, and handrails (Archea et al., 1979; Templer, 1992). Although reliance on visual information to guide locomotion has been well documented during over ground walking (Patla, 1997, 1998, 2004; Patla, Adkin, Martin, Holden, & Prentice, 1996; Warren & Hannon, 1990; Warren, Kay, Zosh, Duchon, & Sahuc, 2001) and obstacle avoidance (Berard & Vallis, 2006; McFadyen, Bouyer, Bent, & Inglis, 2007; Mohagheghi, Moraes, & Patla, 2004; Patla & Vickers, 1997; Rhea & Rietdyk, 2007), only a few studies have addressed this issue during stair walking (Simoneau et al., 1991; Timmis et al., 2009; Zietz & Hollands, 2009). Videotapes of stair users suggest that a fall is more likely to occur when a person does not look at the steps prior to start the ascent or descent (Archea et al., 1979), however this assumption about gaze behaviour is based on qualitative observation of head/eye pitch movements recorded by security cameras. Given the paucity of information about the role of vision during stair walking, this study focused on direct, rather than indirect, measurements of gaze behaviour using eye-tracking technology.

Gaze fixation, a common index of gaze behaviour, refers to periods between saccades when gaze is held almost stationary (Land, 2006). Because gaze fixations are considered to represent times when visual information about environment is acquired, they are often used to provide insight into the visual information utilized for movement control. One study that recently investigated gaze behaviour during stair walking found that individuals spent most of the time looking at the steps approximately 3 steps ahead (Zietz & Hollands, 2009). The aforementioned study only investigated navigation on the steps in the middle of a staircase, excluding the transitions between level ground and stairs (e.g. stair-to-floor and floor-to-stair transitions).

Transitions can be specially challenging for balance control as a consequence of changes in gait implemented to accommodate the locomotor pattern to changes in the surface level (Lee & Chou, 2007; McFadyen & Carnahan, 1997). Additionally, the three steps at the bottom and at the top of stairs are reported as the most common location for missteps and stair accidents (Sheldon, 1960; Templer, 1992; Wild et al., 1981). Visual information seems to be particularly important for successful walking on transitions. In stair walking under reduced visual conditions, for instance, a significant reduction in the downward velocity of the foot and walking speed is observed while walking on the first step (Cavanagh & Higginson, 2003). Therefore, considering that visual factors are likely to play an important role while making the transition to and from stairs, the current work was designed to investigate how people acquire visual information about the environment to navigate stairs, with special attention to the issue of transitions.

There are likely several roles for the acquisition of visual information during stair walking. First, visual information may be used to extract specific environmental information to guide immediate action, such as stepping. Visual information about steps, and more specifically transition steps, is probably the most important to guide stair walking. In contrast to transitions, the middle portion of extended stairs may demand less visual guidance, considering that steps are commonly equi-spaced and their dimensions can be predicted based on the first few steps. As a result we expected that individuals would rely on foveal visual information (as gaze fixations) approximately two to three steps prior arriving at the transitions (start and end of the stairs) paralleling the findings in over ground walking, obstacles avoidance and middle section of stairs. In contrast to transitions, we anticipate that individuals would show less gaze fixations directed to the middle stairs.

A potential second role of vision during stair walking is the use of visual information to build a spatial map, which would include more global representation of environmental features, not necessarily related to the immediate action, but useful in possible future action. The construction of a visual spatial map is considered an important element for successful execution of rapid compensatory balance reactions to unexpected perturbations (Maki & McIlroy, 2007). For example, in the control of rapid compensatory grasping reactions, the location of handrails does not require gaze fixations following a perturbation due to the reliance on spatial maps of the environment established prior to the perturbation (Ghafouri et al., 2004). Similarly, a spatial map of a stairway may contain information regarding the location of potential support surfaces (e.g., handrails) that could be used in the event of a sudden unexpected loss of stability requiring rapid corrective movement, such as a grasping response. Considering that information on handrail location is an important visual requirement prior to or during stair walking, in this study, we expected that gaze would be briefly directed to the handrail during the approach phase to the stair supporting the building of its spatial representation.

Of additional importance in the present study is the potential difference in gaze behaviour between familiar and unfamiliar environments. The specific reliance on general feature extraction is likely unique to unfamiliar environments. In order to explore this issue, we prevented participants from viewing the stairs used in this experiment until the start of the first trial. We expected to observe an increased number of fixations and/or fixation time on stair features during the first attempt to climb the stairs compared to the following trials, which could be potentially related to the building of a spatial map during the first trial.

3.3 Methods

3.3.1 Participants

Eleven participants (4 males, 7 females) between 23 and 38 years and height ranging from 1.62-1.85m volunteered to participate in the study. All participants had normal vision or vision corrected to normal with contact lenses. All participants reported no medical condition affecting their balance or ability to traverse stairs. All participants provided written consent prior to participating in the study. This study was approved by the Office of Research Ethics at the University of Waterloo.

3.3.2 Protocol

Participants were asked to approach and walk up and down a set of stairs with 7 steps (Figure 3.1a). The steps were 96 cm wide and had a rise of 18 cm and a tread of 26 cm. A 2.23 m pathway was extended at the bottom step. A lift table (length 2.23 m, width 1.22 m) was positioned at the same level of the top step to provide an elevated walkway. A handrail, at the height of 89 cm from the tread, was placed on one side of the stair (right side ascending/left side descending) and extended along the lift. On the other side, there was a wooden wall along the steps (no handrail was present). Along the sides of the top level, two cables were extended for safety.

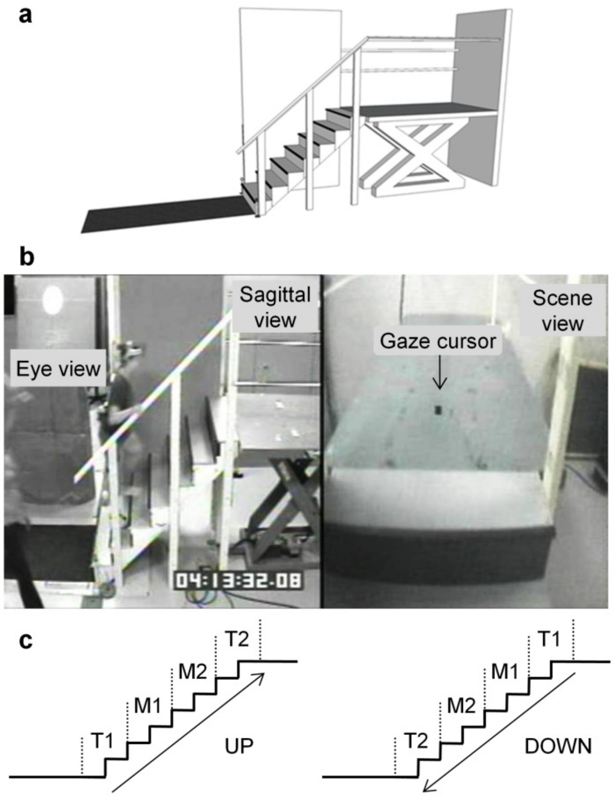

Figure 3.1: (A) Schematic of the experimental stairs (see text for details); (B) Video frame from the video recordings with the sagittal view of the stairs (left), eye view (top left) and scene view from head-mounted camera (right); (C) Gaze location classification for UP (left) and DOWN (right); T1=first transition; M1=first mid step region; M2=second mid step region; T2=second transition

Participants performed 5 trials in each direction (UP and DOWN). Stairs and handrails were kept covered by a tarp until just prior to the start of the first trial. At the beginning of each trial, participants stood at the beginning of the pathway looking straight ahead. The experimenter held a cardboard visual screen in front of the participant's visual field to prevent him/her from being able to view the stairs and handrail. When the trial began, the visual screen was removed and the participant received the command to walk. Participants were instructed to walk on the stairs at their comfortable pace. At the end of each trial, participants remained facing away from the stairs. When the visual screen was repositioned to block the view of the stairs, participants turned around to be ready for the next trial. The participant was asked to stand at one of the three start positions (20 cm apart from each other), randomly assigned in each trial. Stair ascent (UP) and descent (DOWN) were alternated and the starting condition (UP or DOWN) was randomized across participants. Six participants performed their first trial ascending, and five participants descending the stairs (note that participants were able to stand in position to descend the stairs by using the lift table without having them walk up or view the stairs).

A head-mounted eye tracker 5000 (ASL, Bedford, MA, USA) was used to record eye movements and calibrated using the 9 point calibration method with 1° accuracy over the stair area. Briefly, this method requires participants to fixate their gaze on 9 points displayed in a 3 by 3 grid. Each fixation produces a distinct vector between cornea and pupil reflection, which is associated to the coordinates of the respective point providing the line of gaze. Calibration was checked periodically between trials. The eye tracker system provided gaze location represented by a gaze cursor displayed superimposed on the participant's field of view captured by a head-mounted camera (scene view). A video mixer was used to combine the images from the eye tracker system (scene view and eye view), and from a sagittal camera (handrail side), which was digitally recorded at 30Hz; Figure 3.1b). Similar approach was previously used in a locomotor study (Patla & Vickers, 1997).

Footswitches (B&L Engineering, Tustin, CA, USA) were placed inside of participants' shoes under the toe and heel area to provide temporal measurement of their steps. An infrared light switch positioned on the bottom step denoted the time when the foot broke the switch prior to contact with the bottom step. This information was used to synchronize foot switch data relative to location on the stairs. A program written in LabVIEW (National Instruments, Austin, TX, USA) was used to collect footswitch and infrared switch data (240Hz). The same program sent a pulse to the eye tracker system leaving a mark on the video recordings, which allowed synchronization between eye tracker and footswitch data.

3.3.3 Data Analysis

Footswitch data provided time series of foot-contact (FC) and foot-off (FO) for every step, which was used to determine participants' foot stride location with respect to the stairs in the following phases: standing [from when the visual screen was removed to the initial FO]; far approach [from the initial FO to two FC prior the stairs (-2FC)]; near approach [from -2FC to the last FC prior the stairs (0FC)]; first transition [from 0FC to the foot contact on step 2 (2FC)]; first mid steps [from 2FC to foot contact on step 4 (4FC)]; second mid steps [from 4FC to the foot contact on step 6 (6FC)]; and second transition [from 6FC to foot contact out of the stairs (8FC)].

A frame-by-frame analysis of the video recordings was conducted to identify the gaze location along each trial, from the start of the trial (when the visual screen was removed) to the end of stair walking (8FC position). Gaze location was classified in one of the following step regions (Figure 3.1c): (1) *first transition step (T1)*: one tread-length before the stair and step 1; (2) *mid step 1 (M1)*: steps 2 and 3; (3) *mid step 2 (M2)*: steps 4 and 5; (4) *second transition step (T2)*: steps 6 and 7. When not directed to the steps, gaze was classified in one of the following categories: *approaching path* (before the stairs); *path following the stairs*; *end of the path*; *handrail*; or *elsewhere*. An overall measure of gaze behaviour included the total gaze time in each region, expressed as a percentage of the trial duration. Additionally, gaze fixations on stair regions (T1, M1, M2, and T2) were determined when gaze remained stable for 100 ms or longer (3 frames) with maximal deviation of 1 degree of visual angle in each direction, similar to previous locomotion studies (Hollands, Patla, & Vickers, 2002; Patla & Vickers, 1997, 2003). Gaze fixations on step regions were analyzed in terms of *number of fixations* (percentage of the total number of fixations), *mean fixation duration*, and *fixation time* (percentage of the trial duration) for each step region. Each gaze variable was averaged across trials separately for UP and DOWN directions.

To test the hypothesis of increased gaze behaviour on the transition steps we compared the number of fixations, fixation duration, and fixation time across walking direction (UP vs. DOWN) and gaze location (T1, M1, M2, and T2) using a two-way repeated measures ANOVA. When required, data were rank-transformed prior to analysis to address concerns of non-normal distribution. Planned comparisons (Tukey adjustment) were computed to identify difference in the dependent variables between transitions (T1, T2) and mid steps (M1, M2). Tukey post-hoc analysis was performed on significant main effects and interactions. The role of gaze fixations in guiding action in UP and DOWN was analyzed by computing: 1) the percentage of gaze fixations directed to each step region according to participant's stride location (stride location was defined as the stride in which a gaze fixation was initiated); and 2) total gaze time looking ahead against the number of steps looked ahead. To test the hypothesis for gaze in building a spatial representation of handrail location, total gaze time, number of fixations and fixation time on the handrail were calculated for UP and DOWN. Additionally, to find evidence for spatial map built during the early phase of the walking task, total gaze time and fixation time directed on stair features prior to walk initiation were analyzed by a one-way ANOVA with trial number as factor, for each direction. To test the hypothesis for gaze behaviour differences in the first trial, total gaze time and fixation time directed on stair features (steps and handrail) were analyzed by an one-way repeated measures ANOVA with trial number (1,2,3,4, and 5) as a factor, for each direction (UP and DOWN). First trial data was only available from 8 of the 11 participants due to technical problems during the first trial in the other 3 participants. Of these 8 participants, 4 ascended and 4 descended the stairs in their first trial. Significance level was set at 0.05 for all analyses.

3.4 Results

3.4.1 Overall gaze behaviour and gaze fixation characteristics

Gaze fixations (including fixations on stair and non-stair features) covered on average 2.32±0.80s (mean±SD) and 2.82±1.19s of each trial during UP and DOWN, respectively. These values corresponded to 24.8±7.4% and 30.6±11.7% of the time to walk up and down the stairs, respectively. In each trial, participants performed an average of 15.75±5.60 and 17.51±6.64 fixations during UP (range=6-30; mode=16) and DOWN (range=5-31; mode=15), respectively. The average rate of fixations observed during the trials was 1.49±0.50 fixations/s and 1.75±0.68 fixations/s during UP and DOWN, respectively.

As anticipated, participants spent a high proportion of the time gazing on stair features (UP: 60.5%; DOWN: 42.2%; Table 1). Gaze fixations on stair features covered approximately only 1/3 of the total gaze time, in both UP (18.9%) and DOWN (13.7%). However, because most fixations were directed at the stairs this led to the highest total fixation time compared to any other location (e.g., path preceding/following the stairs). The majority of fixations were task-specific given that a small number of fixations were classified as “elsewhere”. Additionally, UP showed significantly higher percentage of fixations (F(1,10)=23.45, P<0.001) and increased fixation time (F(1,10)=9.82, P=0.011) on stairs features compared to DOWN.

Table 3.1: Means (standard deviations) for gaze time, fixation time and number of fixations in different regions for stair ascent (UP) and stair descent (DOWN)

Gaze location	Stair Ascend (UP)			Stair Descend (DOWN)		
	Gaze time (% time)	Fixation time (% time)	Number of fixations (%)	Gaze time (% time)	Fixation time (% time)	Number of fixations (%)
Approach[a]	0	0	0	0.98(2.1)	0.2(0.5)	0.6(1.7)
Stairs	60.5(7.7)	18.9(6.3)	71.6(10.0)	42.2(11.0)	13.7(8.4)	47.6(12.8)
Path[b]	10.7(4.5)	1.6(1.6)	7.7(5.6)	13.2(8.7)	3.3(3.1)	11.3(10.5)
End[c]	19.7(8.7)	3.5(2.2)	17.0(8.9)	23.4(7.9)	8.8(4.2)	26.8(6.0)
Elsewhere	4.1(4.9)	0.6(0.7)	3.6(5.7)	10.9(9.8)	4.3(4.3)	13.7(13.1)

[a] path that precedes the stairs

[b] path that follows the stairs

[c] end of path that follows stairs

3.4.2 Gaze behaviour during first trial

Despite the fact that the details of the stairs were kept from view prior to the start of the first trial, gaze behaviour directed to stair features in the first trial did not differ from subsequent trials during UP and DOWN. Gaze behaviour on stair features was not different across trials comparing total gaze time (UP: F(4,12)=0.28, P=0.88; DOWN: F(4,12)=0.5, P=0.73) and fixation time (UP: F(4,12)=0.94, P=0.475; DOWN:F(4,12)=0.27, P=0.892). Similarly, prior to the onset of walking and after the removal of the visual screen, there was no difference across trials in gaze behaviour on stair features considering total gaze time (UP: F(4,12)=0.99, P=0.44; DOWN: F(4,12)=0.41, P=0.80) or fixation time (UP: F(4,12)=0.86, P=0.51; DOWN:F(4,12)=0.85, P=0.52).

It is worth mentioning that walking time ascending and descending the stairs did not differ significantly across trials (UP: F(4,12)=1.10, P=0.402); DOWN: F(4,12)=1.90, P=0.176). The average walking time to traverse the stairs was 7.02±0.91s for UP and 6.30±0.57s for DOWN.

3.4.3 Gaze Fixations on stair regions

When considering the specific characteristics of gaze fixations on the stair features, a main effect of walking direction (F(1,10)=16.47, P=0.002), and an interaction between gaze location and direction (F(3,30)=3.31, P=0.033) were observed for number of fixations (Figure 3.2 a). Planned comparison revealed that number of fixations on the mid steps (M1 and M2) was significantly larger than on the transition steps (T1 and T2) during UP (P=0.027).

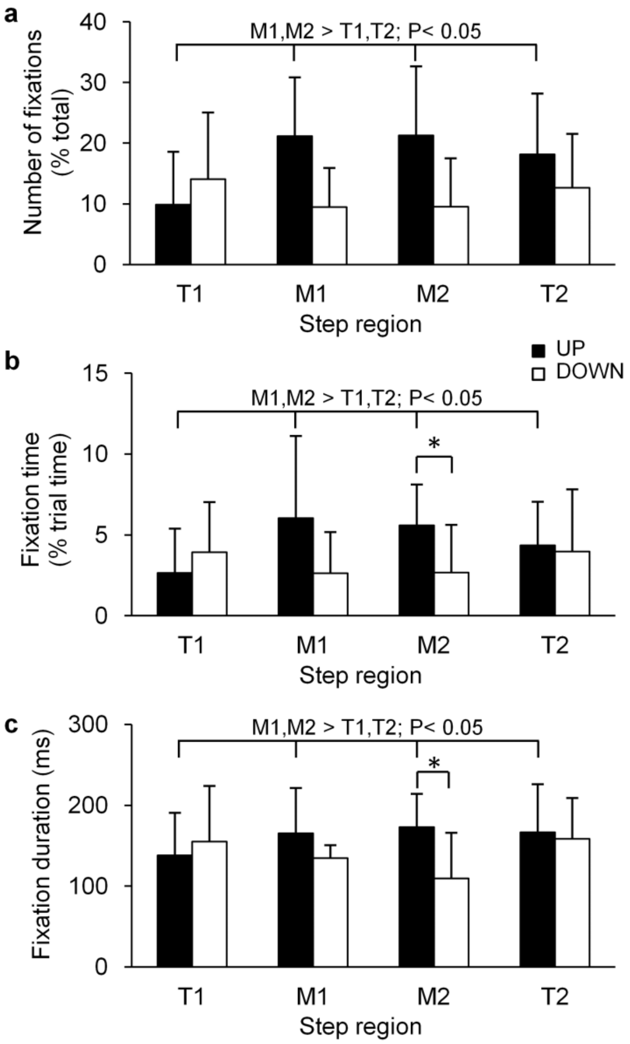

Figure 3.2: (A) Number of fixations on step regions when ascending (UP) or descending (DOWN). (B) Fixation time on steps regions. Fixation time was normalized for each trial by the total time taken to ascend or descend the stairs. (C) Mean fixation duration for fixation on step regions. Planned comparison (M1, M2 vs. T1, T2) indicated in each graph; T1: first transition; M1: first mid step; M2: second mid step; T2: second transition; *p<0.05

For fixation time, there was a significant main effect of walking direction (F(1,10)=6.36, P=0.030) and interaction between gaze location and walking direction (F(3,30)=4.34, P=0.012; Figure 3.2 b). Post-hoc tests evidenced that fixation time on M2 was greater during UP compared to DOWN walking (P=0.037). Planned comparison revealed that, during UP, there was increased fixation on mid steps (M1 and M2) compared to transitions (T1 and T2; P=0.008).

For fixation duration there was a significant main effect for walking direction (F(1,10)=10.11, P=0.010) and an interaction between walking direction and gaze locations (F(3,30)=3.19, P=0.038; Figure 3.2 c). Post-hoc test evidenced that fixation duration on M2 was increased during UP compared to DOWN (P=0.032). Planned comparison showed significant longer fixation duration on the mid steps (M1 and M2) compared to transitions (T1 and T2) during UP (P=0.016).

3.4.4 Gaze behaviour relative to action

Fixations were analyzed relative to the participant's stepping location. Figure 3.3a illustrates the fixation pattern as participants walked along the stair during UP and DOWN tasks, respectively. Colour gradients represent the percentage of fixations that were directed to each location (steps, handrail, and end of path) while participants were walking/standing on the area represented by the stick figure. Note that the sum of percentages does not necessarily equal 100% because some fixations were directed to locations other than the stairs or handrail (Table 1). Fixation behaviour differed from the phase when participants were standing at the beginning of the path prior to walking initiation compared to the subsequent phases when they were actually walking. During standing, there was a higher percentage of fixations directed to the mid step region during UP, and to the end of the pathway during DOWN. However, during walking, a 'look ahead' fixation pattern was observed during both UP and DOWN tasks. In DOWN, fixations were kept within 4 steps of participants' stepping location, whereas in UP fixations tended to be directed between 2 to 4 steps ahead of participants' stepping location. This look ahead pattern can be confirmed in Figure 3.3b, which shows the frequency distribution of steps looked ahead. In UP, gaze was directed 2 to 4 steps (i.e., two strides) ahead for more than 50% of the time, whereas during DOWN, participants had their gaze for approximately 30% of the time directed to each 0 to 2 and 2 to 4 steps ahead (1 and 2 strides).

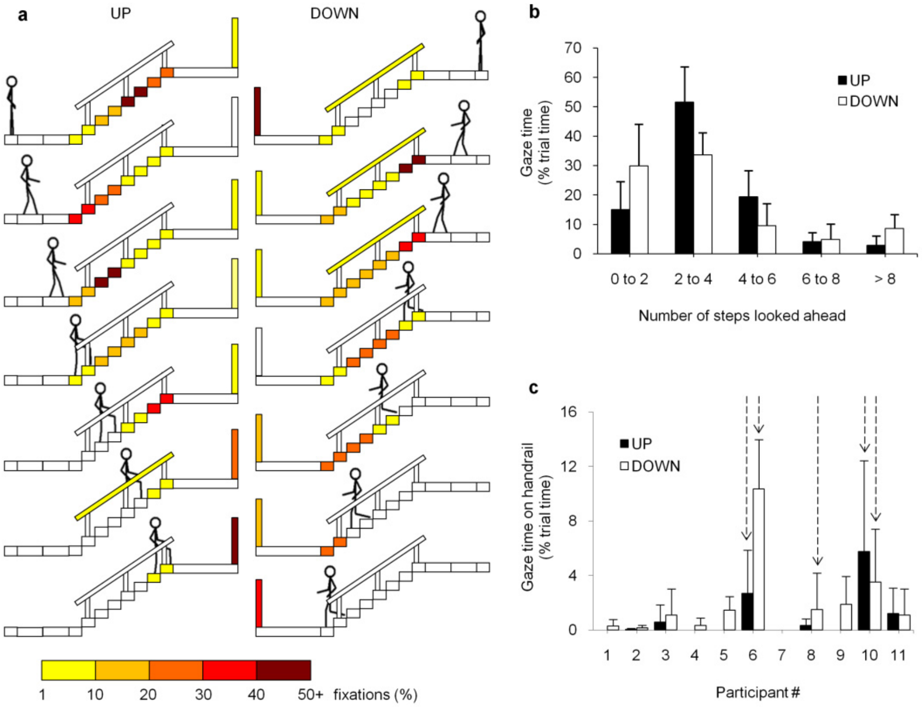

Figure 3.3: (A) Distribution of fixations (%) on stair features relative to participant's stepping location during UP (left) and DOWN (right). Each set of stairs shows the participant's stepping location (stick figure) and the respective percentage of fixations directed from that location on each step region (T1, M1, M2, T2), handrail, and end of the pathway (vertical bar). Note that for the first stairs at the top (in UP and DOWN) participants were standing before walking initiation. Darker colour areas represent the most fixated region; (B) Percentage of time which gaze was directed steps ahead during walking for UP and DOWN; (C) Percentage of time which gaze was directed to the handrail across participants. Dashed arrows indicate when handrail was used. Participants #6 and 10 held the handrail while ascending and descending the stairs, and participant #8 only when descending.

3.4.5 Gaze behaviour on handrail and handrail use

Compared to the steps, gaze behaviour on the handrail was minimal and varied across participants. Six of the 11 participants revealed some period of gaze fixation on the handrails. Fixations on the handrail were infrequent and widely varied within these participants, accounting on average for only 4.1±3.3% and 5.3±4.0% of all fixations, for UP and DOWN, respectively. Average total fixation time on the handrail was only 0.3±0.4% and 0.4±0.5% of the trial time for UP and DOWN, respectively. Even when the total time that gaze was considered (i.e., including periods of time shorter than 100 ms), only 2 participants (participant # 6 and 10) spent more than 5% of the time gazing to the handrail (Figure 3.3c) and many of the subjects had little to no gaze time towards the handrail.

Importantly, the handrail was rarely used by participants when walking UP or DOWN the stairs. Two participants (participant #6 and 10) used the handrail during both UP and DOWN, and one participant (participant #8) during DOWN only (Figure 3.3c, dashed arrows). These three participants held the handrail in every trial of the respective conditions (UP and/or DOWN). Usually, participants contacted the handrail at the beginning of the stair walking, and their hands either moved from one point to the other on the rail, or slid along the rail, until participants stepped on the last two steps.

For the participants who used the handrail (participants 6, 8 and 10), fixations on the handrail occurred in 48% of the trials. For all other participants who did not use the handrail, only 10% of the trials were characterized by some fixation towards the handrail. When considered across all participants, most fixations on the handrail (12% of all fixations) happened prior to reaching the stair compared to only a few that occurred during the stair walking phase (less than 1%; Figure 3.3c).

3.5 Discussion

This study investigated gaze behaviour during stair walking and, particularly, explored gaze behaviour that may be associated with feature extraction of handrails and stair transitions. This study also focused on characterizing a dual role of gaze fixations on extraction of specific information relative to steps and transitions (to guide immediate action), and in acquiring more general information regarding the environment (to build a spatial map with a specific focus on handrails). This work highlights that timing of gaze fixations on stair features is linked to the immediate action of stair walking. However, in contrast to the predictions, there was no evidence that transitions were a location for more frequent fixation behaviour. In addition, the handrail was rarely fixated and when this occurred, it happened during the approach to the stair for the small number of subjects who tended to use the handrail. Finally, the first walk experienced with a regular set of stairs (with no prior visual information) appeared not to influence gaze behaviour when compared to subsequent repetitions on the increasingly familiar set of stairs.

The results of the current study support the idea that participants used gaze fixations to extract visual information about the environment to control their stepping approximately one or two strides in advance. Overall gaze remained within 4 steps ahead during stair descent and 2-4 steps ahead during stair ascent. These results parallel the gaze behaviour observed during steady-state stair walking (i.e., mid steps), which showed that gaze fixations were directed around 3 steps ahead (Zietz & Hollands, 2009). It is well known that visual information is important for implementation of appropriate gait changes (Cinelli, Patla, & Allard, 2008; Lee, Lishman, & Thomson, 1982; Patla et al., 1999) as well as for heading direction (Warren & Hannon, 1990; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). During gaze fixation events, relevant visual information regarding environmental features is likely extracted to guide immediate action for a successful walking performance. Saccades towards footfall targets are observed just prior the actual step on the target (Hollands, Marple-Horvat, Henkes, &

Rowan, 1995). Similarly, in the presence of obstacles, gaze is directed toward the obstacle area within two steps before the crossing (Patla & Vickers, 1997). Additionally, when walking through apertures, the centre of mass trajectory “follows” the line of gaze within the last 2 seconds before the crossing, which is directed to the centre of the aperture (Cinelli et al., 2008). Therefore, in the present study, the occurrence of gaze fixations approximately three steps ahead in the travel path provides support for the use of fixations to guide action, by extraction of information regarding stair properties (probably step dimensions) relevant for foot placement. Such a relatively fixed gaze position, a few steps ahead in the travel path, may also augment the use of optic flow to control heading direction.

Despite the evidence that restricted visual conditions affect the control of locomotion in transitions between floor level and stairs (Cavanagh & Higginson, 2003), the findings of the current study do not show that transition steps require additional gaze fixations in comparison to mid steps. Two possible explanations may be accounted for the absence of more frequent foveal fixations on transitions. One possible explanation is a lack of environmental complexity and a second possibly related factor is a greater reliance on peripheral versus foveal vision for such task conditions. With respect to complexity, the knowledge that the stairs had regular/predictable step dimensions could contribute to less dependency on extended foveal fixation periods. Gaze behaviour is known to be driven by context complexity and task specificity. During a search task to copy models, for example, gaze fixations increase as a rate of the complexity of the model and dynamic changes in the environment (Aivar, Hayhoe, Chizk, & Mruczek, 2005). In addition, in some locomotor tasks, fixation behaviour is shown to increase when task demands are greater. For instance, when walking over obstacles, the number of fixations on obstacles increases with obstacle height (Patla & Vickers, 1997), and when walking through moving doors, fixations last longer when the doors move asymmetrically than symmetrically (Cinelli et al., 2009). Therefore, gaze behaviour during locomotion seems modulated in accordance with the nature of the visual information that needs to be processed and the relationship to task challenge. Experiments exploring stair walking in more challenging contexts (e.g., uneven steps, higher risers, concurrent stair users, low illumination, dual-tasking) may confirm this trend in the range of fixation behaviour required during walking on transitions and mid stairs.

The reliance on peripheral vision could be a secondary factor contributing to the evenly distributed fixation behaviour across transitions and mid steps. The use of visual information from the peripheral visual field has been reported in many locomotor contexts. For instance, occlusion of the lower visual field leads to a reduction in ankle and knee angular velocity during stepping (Timmis et al., 2009), reduction in gait speed, and an increase in downward head pitch angle during walking on irregular terrains (Marigold & Patla, 2008). Additionally, it was demonstrated that, in an immersive virtual environment with different levels of contrast, reduction in the visual field results in reduction in gait speed, delay in gait initiation, and increased number of contacts with obstacles (Hassan, Hicks, Lei, & Turano, 2007). It is not surprising, therefore, that the use of multifocal spectacles are associated with accidents and difficulty to negotiate steps (Davies, Kemp, Stevens, Frostick, & Manning, 2001; Lord et al., 2002). Thus, the lower peripheral visual field could be providing reliable visual information to guide stair walking in a predictable environment as in the present study, thereby minimizing the need for foveal fixations on transitions.

Under normal environmental conditions, gait patterns are accommodated as people progress on a flight of stairs, reflected by a reduction in foot clearance and increase in walking speed across the steps (Hamel et al., 2005; Simoneau et al., 1991). In the present study, it was anticipated a similar accommodation in gaze behaviour reflected by fewer fixations directed on the mid steps due the predictability of the stairs/environment would be seen. However, participants fixated nearly equally on every stair region prior to stepping on that region; the only moment that a stair section showed significant increased fixation behaviour occurred on the mid steps while participants were standing prior to ascending the stairs. The increase in fixations prior to walking initiation could be due to the construction of the stair spatial representation. However, this gaze behaviour is more likely to be related to the participant's comfortable gaze fixation point. When participants were on level ground prior to ascending the stairs, the mid steps were approximately at comfortable eye level height. Similarly, during stair descent there was a higher number of fixations directed off the stairs (comfortable field of view was located on the surrounding environment at the end of the path following the stairs). Consequently, such fixations were more likely the product of neutral gaze behaviour rather than specific feature extraction of environmental characteristics prior to walk initiation. However, when gait was initiated and participants approached the stairs, gaze behaviour changed to a more action-guiding pattern.

The current findings support the notion of gaze fixation for action in stair locomotion based on the timing of fixations. However, it should be noted that gaze fixations covered a small proportion of the total gaze time, with approximately 2/3 of the total gaze time directed towards the steps not being fixations. In other locomotor tasks, such as walking on foot targets, individuals spent around 13-16% of the time fixating on the foot targets (Patla & Vickers, 2003), which is close to the findings from the present study (19% for ascent and 14% for descent). However, other studies found that people execute around 5 fixations per second while walking on a hallway (Turano et al., 2001), which is higher than the finding from the present study (less than 2 fixations/s). Potential sources for discrepancies could come from the parameters used to define gaze fixations (67ms in Turano et al. 2001 versus 100ms in the present study). Most gait studies report gaze fixations as a percentage of the total fixation time instead of the entire task time, which limits opportunity to compare results. However, the findings from the present study seem to support the idea that individuals spend a considerable amount of the time looking at the stairs but not necessarily fixating. It is possible that, under usual environmental conditions, both gaze fixations and periods shorter than a fixation provide similar information about the environment, with both contributing to a stable frame of reference to use optic flow and exproprioceptive visual information to guide locomotion. This might explain the current results, which reveal that: 1) both gaze fixations and overall gaze were similarly directed within 2-4 steps ahead (Figure 3.3a and b), and 2) participants spent most part of the time looking at the steps but not fixating. Determining the specific importance of foveal fixations on the control of walking over stairs will likely require task conditions that demand gaze fixations elsewhere (e.g. visual dual tasking). At present, the overall low frequency of fixations (100ms or longer) on the stair also suggests that alternative mechanisms may be used under such task conditions to guide behaviour, such as reliance on peripheral vision, shorter fixation periods and/or feed forward control via internal spatial maps.

This study found modest evidence that foveal vision has a role in extracting information to build a spatial representation regarding handrail location. Overall, the handrail was rarely targeted by gaze fixations, which may be associated with the fact that the participants in this study rarely used handrails. The fact that only a few participants held the handrail in this is study is not surprising considering that only 1/3 of stair users hold handrails when climbing stairs (Cohen & Cohen, 2001; Templer, 1992), and young adults are usually less likely to grasp handrails even when balance is perturbed (Maki & McIlroy, 2006). The few fixations on the handrail observed in this study occurred mainly before the participants actually started to walk on the stair (i.e., during the approach phase), suggesting that during the action of stair walking, extraction of information about stepping and steps is prioritized. In the present study, at least for stair descent, fixations on the handrail occurred during the phases prior to stair walking, which could be contributing to the development of such a spatial map. However, considering that fixations on the handrail were very rare and even absent in almost half of the participants, fixations may not be a primary source for determination of handrail location. Alternatively, periods shorter than a single gaze fixation could be enough to acquire and confirm the handrail location coordinates, particularly for a stable/predictable environment, which was the case in the present study. Saccades toward a rail happen when people enter into a new environment and this has been related to extraction of information about environmental features (King, Lee, & Maki, 2007; Lee, Scovil, McKay, Peters, & Maki, 2007). The present study also found that participants briefly gazed at the handrail prior to reaching the steps, which might have contributed to building the spatial map for the handrail. Additionally, two other explanations may account for the limited foveal fixations on the handrail: 1) reliance on remembered spatial map and/or 2) reliance on peripheral field of view. Individuals could rely on a stored representation of stair and handrail dimensions from previous experience since the current stair/handrail was designed based on standard guidelines (e.g. Archea et al., 1979). In addition, extra-foveal information may have been used to build the spatial map (i.e., peripheral vision). Future studies investigating groups that actually rely more on the use of rails to improve balance via mechanical support, such as older adults with balance impairments, will give insightful information on the relationship between gaze behaviour, handrail use, and grasping response.

In this study, there was not a single incident that required a participant to grasp the handrail in order to recover balance. The absence of fixations raises the question of whether participants would have been able to reach to successfully grasp the handrail in the event of an unexpected loss of balance. Grasping a handrail is a common strategy used when balance is disturbed, and the likelihood of recovering balance increases when a handrail is available for grasping (Bateni, Zecevic, McIlroy, & Maki, 2004). Grasping reactions to balance perturbation are quickly initiated limiting the use of foveal vision following the perturbation to guide the initiation of the grasping. Because of the short latency for compensatory grasping responses, spatial information regarding handrail features might be extracted beforehand and used if necessary to guide such fast action. Previous studies have indicated that, in the control of rapid compensatory grasping reactions, the location of handrails does not require gaze fixations following a perturbation due to the reliance on spatial maps of the environment established prior to the perturbation (Ghafouri et al., 2004). The finding from the present study provide complementary evidence that , at least in a “perturbation-free” environment, people are likely to acquire information relative to the handrail location prior to climbing the stairs, which could be used to guide grasping response in the event of loss of balance. However, the reduced gaze fixation behaviour on the handrail observed in this study also suggests that handrail location may be coded by using peripheral visual information.

We did not find a trial effect on the gaze variables analyzed in the present study. Even when participants were prevented from looking at the stair before the start of the first trial, this did not produce an increase in fixation behaviour. Similar gaze behaviour across repeated trials suggests that the CNS did not need augmented visual information even among the most novel of the trials to either build a spatial representation of a flight of stairs or to guide stepping action. As noted previously, it is important to consider that the stairs in the current study followed standard measures, which may have allowed participants to rely on their previous experiences with stair locomotion. Stair climbing is a well-learned task and adults are able to make appropriate perceptual judgments of climbable stairs (Konczak et al., 1992; McKenzie & Forbes, 1992; Warren, 1984). Taking into account that steps in a stairway are typically similar in dimension and the stable gaze behaviour found in this study, inconspicuous step irregularities may not be visually detected and computed to implement appropriate gait adjustments. Further studies should investigate a possible role for foveal information in detecting stair irregularities and its relation with stair accidents.

In summary, the findings of this study give support for the use of both foveal and peripheral vision for stair locomotion. Foveal vision seems to be used a few steps in advance potentially to detect step properties to guide stepping action on the stair in detecting step properties to guide locomotion on stairs. Additionally, peripheral (extra-foveal) information is potentially involved with handrail detection and online control of the limb trajectory. Together, foveal and peripheral visual information can be acquired to guide appropriate gait adaptations for a smooth transition from level ground walking to stairs.

Chapter 4

Study 2 – Effects of dual-tasking on gaze and locomotor behaviour during stair climbing

4.1 Overview

The aim of this study was to investigate the role of foveal vision during stair locomotion and ground-stair transitions. The study exploited a dual task paradigm to influence the reliance of foveal vision during stair ascent. Participants walked on a 7-step staircase under four different conditions: 1) stair walking alone (CONTROL); 2) stair walking fixating on a target at the end of the pathway (TARGET); 3) stair walking while performing a visual reaction time task (VRT); 4) stair walking while performing an auditory reaction time task (ART). Foveal gaze fixations were recorded by an eye-tracker. Step time on each stair step and reaction time behaviour were also calculated. Gaze fixations towards stair features were significantly reduced in TARGET and VRT compared to CONTROL and ART. In spite of reduced fixations, participants were able to successfully ascend stairs and rarely used the handrail. Step time was increased during VRT compared to CNT in all stair steps. Navigating transition steps did not require more gaze fixations than the middle steps. However, reaction time tended to increase during locomotion on transitions suggesting that additional executive challenges are present during this phase. These findings indicate that foveal vision may not be a major source for extraction of visual information regarding stair features. Instead, looking at the steps likely provides a stable reference frame to allow the extraction of visual information regarding step features from the whole visual field.

4.2 Introduction

Many accidents during stair walking are attributed to perceptual errors and distractions (Archea et al., 1979) illustrating the importance of appropriate visual information during stair walking. More generally during walking, gaze is directed to the heading direction which potentially facilitates the use of optic flow to control gait (Cinelli et al., 2009; Hollands et al., 2002; Land & Lee, 1994). Studies on stair locomotion indicate that gaze behaviour is evenly distributed across the steps in a staircase, and that the fixation point is maintained a few steps ahead in the path, which support the importance of keeping foveal vision continuously directed to the stairs to guide immediate stepping (Miyasike-daSilva, Allard, & McIlroy, 2011; Zietz & Hollands, 2009). In spite of this potential role for vision, in everyday life, stair climbing is often performed when the view of the steps is not available. With minimal gait adjustments, people are able to walk on stairs while holding objects (e.g., boxes, laundry basket) that block the close view of the steps suggesting that continuous visual information about the steps may not be essential. Under such conditions, people may require visual information that is sampled intermittently rather than continuously to control locomotion (Patla, Adkin, Martin, Holden, & Prentice, 1996).

In contrast to reliance on foveal vision, either continuously or intermittently, it is possible that gaze behaviour documented in stair-related studies (Miyasike-daSilva et al., 2011; Zietz & Hollands, 2009) may simply be the product of natural gaze tendencies in a familiar task and predictable environment. For example, the larger amount of time that people spend looking at the steps during ascent compared to descent (Miyasike-daSilva et al., 2011) could be the result of the steps being naturally available in the visual field for longer time during ascent than during descent. Consequently, overall gaze behaviour may overestimate the actual requirements for visual information during stair locomotion and have little involvement with specific feature extraction of stair properties to guide stepping.

In order to understand the specific role of foveal vision during stair locomotion, the present study specifically explored the influence of a concurrent visual task (using a dual-task paradigm) requiring gaze fixations to ‘non-stair’ features during stair walking. Such an approach would reveal the specific requirements for foveal vision by examining changes in the performance of the stair walking, gaze behaviour and performance of the secondary visual task. Although this study was designed to explore the role of foveal vision in stair locomotion, the use of a dual-task paradigm will also have a confounding effect due to possible changes in executive function. A growing body of evidence indicates that walking imposes a load on executive function (Yogev-Seligmann, Hausdorff, & Giladi, 2008 for a review). In fact, during dual-task stair walking, young and old adults showed a decrement in a secondary attentional task (i.e., longer voice reaction time to an auditory tone) in order to maintain walking speed similar to single-task stair walking (Ojha, Kern, Lin, & Winstein, 2009). Considering the important interaction between foveal vision demands and executive function during dual-tasking, the present study also addresses the concurrent influence of changes in executive function demands and the role of vision in stair walking. Of specific importance in the present study is the potential importance of foveal vision on transitions regions during stair walking (level ground to first step and last step to level ground). Transitions between level ground and stairs are commonly associated with accidents (Sheldon, 1960; Templer, 1992; Wild et al., 1981). Therefore, the present study may provide insight into the specific control of gaze during locomotion on stair transitions by increasing the complexity of stair walking in a dual-task context.

The current study was designed to determine the specific impact of diverting gaze to another task and the separate influence of the executive challenge of such a task. To distinguish the influences of gaze direction from executive function challenge, stair walking was compared in three dual-task conditions: (1) visual reaction time (gaze fixation and executive challenge), (2) stationary target fixation (gaze fixation but no executive challenge), and (3) auditory reaction time task (no gaze fixation and executive challenge). Overall, it was hypothesized that gaze behaviour towards the stairs would be less frequent when dual-task requires gaze fixations independently of executive challenges (i.e., simple fixation and visual reaction time). However, it was expected that fixations on the steps would be preserved, particularly in the phases preceding the transitions. Additionally, with increasing challenge imposed by the dual-task context, it was expected that individuals would adopt a safer more conservative movement strategy characterized by an increased use of handrails and slower walking speed. It was also anticipated that reaction time would be increased and accuracy decreased while dual tasking specifically during transition phases of stair walking where the visual and executive demands are expected to be greatest.

4.3 Methods

4.3.1 Participants

Fifteen healthy young adults, 8 females, 7 males participated in the study (mean age=26.9±3.3 years, height=169.9±10.4cm). Participants reported no medical condition affecting their balance or ability to traverse stairs and had normal vision or vision corrected to normal with contact lenses. All participants provided written consent prior to participating in the study. This study was approved by the Office of Research Ethics at the University of Waterloo.

4.3.2 Protocol

Participants were asked to approach and walk up a set of stairs with 7 steps (Figure 4.1). The steps were 96.5 cm wide and had a rise of 18 cm and a tread of 25.5 cm. A pathway was extended at the bottom step and a lift table at the same level of the top step provided an elevated walkway. Handrails were placed on each side of the stairs. Participants wore a safety harness attached to a retractable lanyard, which ran along a cable at the ceiling as participants walked on the stairs.

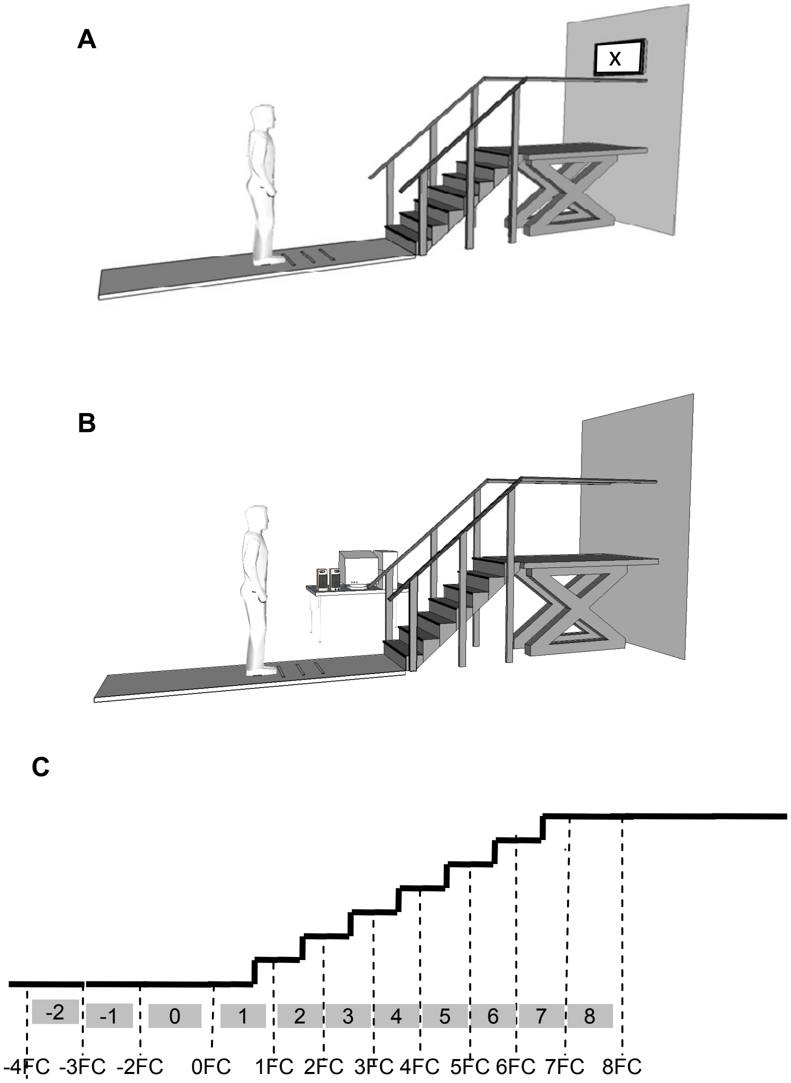

Figure 4.1: Schematics of the experimental setup for TARGET and VRT conditions (A) with the monitor for presentation of visual stimuli. In ART (B), the monitor was occluded and computer speakers emitted the auditory stimuli. (C) Classification scheme for stepping location when ascending the stairs. Steps 0, -1, and -2 represent the steps in the approach. Steps 1 to 8 are the steps on the stairs. Steps 1 and 2 = first transition; Steps 7 and 8 = second transition; FC=foot contact.

Participants were asked to walk up the stairs under four experimental conditions: 1) stair ascent alone with no secondary tasks (CONTROL); 2) Visual target (TARGET): ascent the stairs while fixating on the letter “X” continuously presented on a monitor; 3) Visual reaction time (VRT): stair walking while performing a visual go/no go reaction time task; and 4) Auditory reaction time (ART): stair walking while performing a auditory go/no go reaction time task (Figure 4.1b).

During VRT task conditions the stimuli consisted of the letters “X” or “O” (Figure 4.1A), randomly presented (proportion of occurrence of 3/1) on a computer monitor at the end of the walkway. Each letter was presented for 100ms at random time intervals between 750 and 1250 s. Participants were asked to click on a wireless mouse button every time they saw an “X”. For ART task condition the stimulus comprised of either a high and a low frequency tone randomly emitted by computer speakers (proportion of occurrence: 3/1; stimulus duration:100ms; inter-stimulus interval: 750 to 1250 s). Participants were asked to click the wireless mouse button every time they heard the high tone.

Participants practice the visual and auditory reaction time tasks prior to the walk trials. Prior to each trial, a cardboard visual screen was held by an assistant in front of the participant to prevent him/her from being able to view the stairs and handrails. At the end of each trial, the participant was asked to return to the start position downstairs. Subjects were randomly positioned at 1.5m, 1.75m or 2.0m from the bottom step prior to each trail, to prevent prior plan for approach distance. Participants were instructed to walk at their comfortable pace, and to perform both concurrent secondary task and stair walking at the same time, with no instruction about which task they should prioritize. Participants carried the wireless mouse with their preferred hand during all trials in all four conditions. In CONTROL and ART, the monitor was turned off and occluded. The fixation target and the stimulus for the reaction time tasks were delivered for the entire trial until participants reached the end of the pathway.

Participants performed five blocks of trials. CONTROL was performed in block 1 and 5. The order of the remaining task blocks (TARGET, VRT and ART) was randomly assigned. For CONTROL and TARGET, participants performed 5 trials in each block. For ART and VRT blocks, participant performed 10 trials dual-tasking (reaction time task + stair walking), and 5 trials with the single-task version for the secondary task (reaction time task only). Dual-task and single-task trials were randomly assigned within the VRT and ART blocks. VRT and ART blocks comprised of more trials than in CONTROL and TARGET blocks to allow sufficient number of stimulus-response events across the stairs for data analysis.

4.3.3 Instrumentation and data acquisition

Eye movements were recorded via a head-mounted eye-tracker 5000 (ASL, USA) at 30Hz and digitally recorded. The eye-tracker was calibrated using the 9-point calibration method with 1° accuracy over the stair area. Footswitches (B&L Engineering, USA) were placed inside of participant's shoes to provide foot contact times. An infrared light switch positioned at the bottom step served as a reference to determine foot contact time on approach and stairs. A customized LabVIEW program (National Instruments, USA) was used to collect and synchronize footswitch and infrared switch data. Another customized LabVIEW program was used to control the timing and presentation of the visual and auditory stimuli. The same program recorded the time for each stimulus delivery the mouse button press responses.

4.3.4 Data Analysis

A frame-by-frame analysis of the gaze recordings was conducted to identify gaze location on each step of the stairs. Mean gaze time on the stairs was calculated for each task condition. Gaze fixations required gaze to remain stationary for 67 ms or longer with maximal deviation of 1 degree of visual angle in each direction. The mean number of fixations (percentage of the total number of fixations), mean fixation duration, and mean fixation time (percentage of the trial duration) were calculated for each step and condition.

Footswitch data were used to determine participants' location with respect to the stairs. Step time was calculated from foot contact to foot contact for the last three steps in the approach phase (-2, -1, and 0) and for each step on the stairs (1 to 8; Figure 4.1c). The mean step time was calculated for each task condition. Steps 1 and 2 were defined as first transition and steps 7 and 8 for the second transition.

Reaction time and accuracy were calculated for the auditory and visual reaction time tasks. Reaction times below 200ms were excluded (1.13% of all reaction times across all participants). Accuracy was calculated as the percentage of correct responses. Mean reaction time and accuracy were calculated for each step and condition, noting that only reaction times which the stimulus-response pair fell within the same step (from foot-contact to the next foot-contact) were considered for this calculation.

For each gaze variable (total gaze time, number of fixations, fixation duration, and fixation time), a one-way ANOVA was performed with task condition as the factor. Frequency distribution of fixations directed to the stairs was computed according to participants' stepping location on the stairs in each experimental condition. Step time was assessed using a two-way ANOVA (condition x step number). Reaction times and accuracy were assessed using a one-way ANOVA to examine single-task/dual-task effects. Reaction time and accuracy were further analyzed by two-way mixed ANOVA to evaluate the effect of task (ART, VRT) and step location. Tukey's post-hoc analysis was performed to determine task or step location differences. Significance level was set at 0.05 for all analyses.

4.4 Results

4.4.1 Gaze behaviour

Total time that gaze was directed to the steps was significantly influenced by task conditions (F(3,42)=56.38, $p<0.0001$). The total gaze time was lower for the TARGET and VRT conditions compared to the CONTROL and ART conditions (Figure 4.2a).

Similarly, there were task related differences in total fixation time (F(4,56)=42.92, $p<0.0001$), number of fixations (F(3,42)= 58.03, $p<0.0001$), and fixation duration (F(3, 35)=5.33, $p<0.005$) . The vision conditions, TARGET and VRT, were characterized by reduced fixation time (Figure 4.2b) and number of fixations (Figure 4.2c) compared to ART and the CONTROL. Additionally, fixations were significantly longer during ART compared to all other conditions (Figure 4.2d).

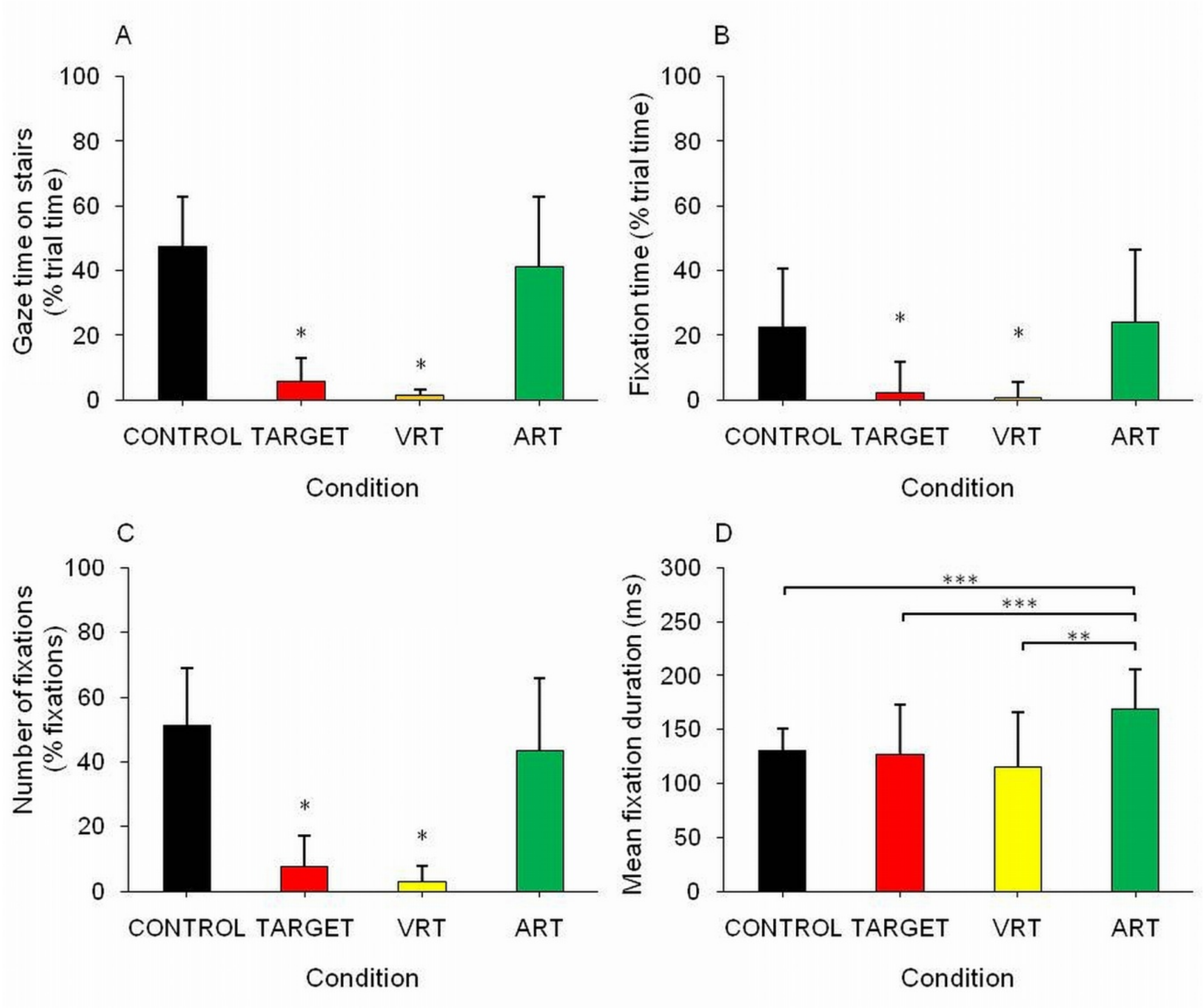

Figure 4.2: Effects of experimental conditions on gaze behaviour for total gaze time (A), fiation time (B), number of fixations (C), and fixation duration (D); ST=stair walking; TARGET= visual fixation target; ART=auditory reaction time; VRT=visual reaction time; *different from CONTROL and ART ($p<0.0001$); **$p<0.01$; ***$p<0.05$.

Figure 4.3a and b display the frequency of gaze fixations directed to any step on the stairs referenced to participants' stepping location. For CONTROL and ART (Figure 4.3a), there was a high number of fixations towards the stairs during the approach and the fixation frequency was progressively reduced as participants continued walking upstairs. For TARGET and VRT, fixation frequency was higher during the approach steps and initial transition (Figure 4.3b). However, it is important to note that the frequency of fixations and the percentage of subjects that performed gaze fixations on the stairs were much lower during TARGET and VRT compared to CONROL and ART conditions.

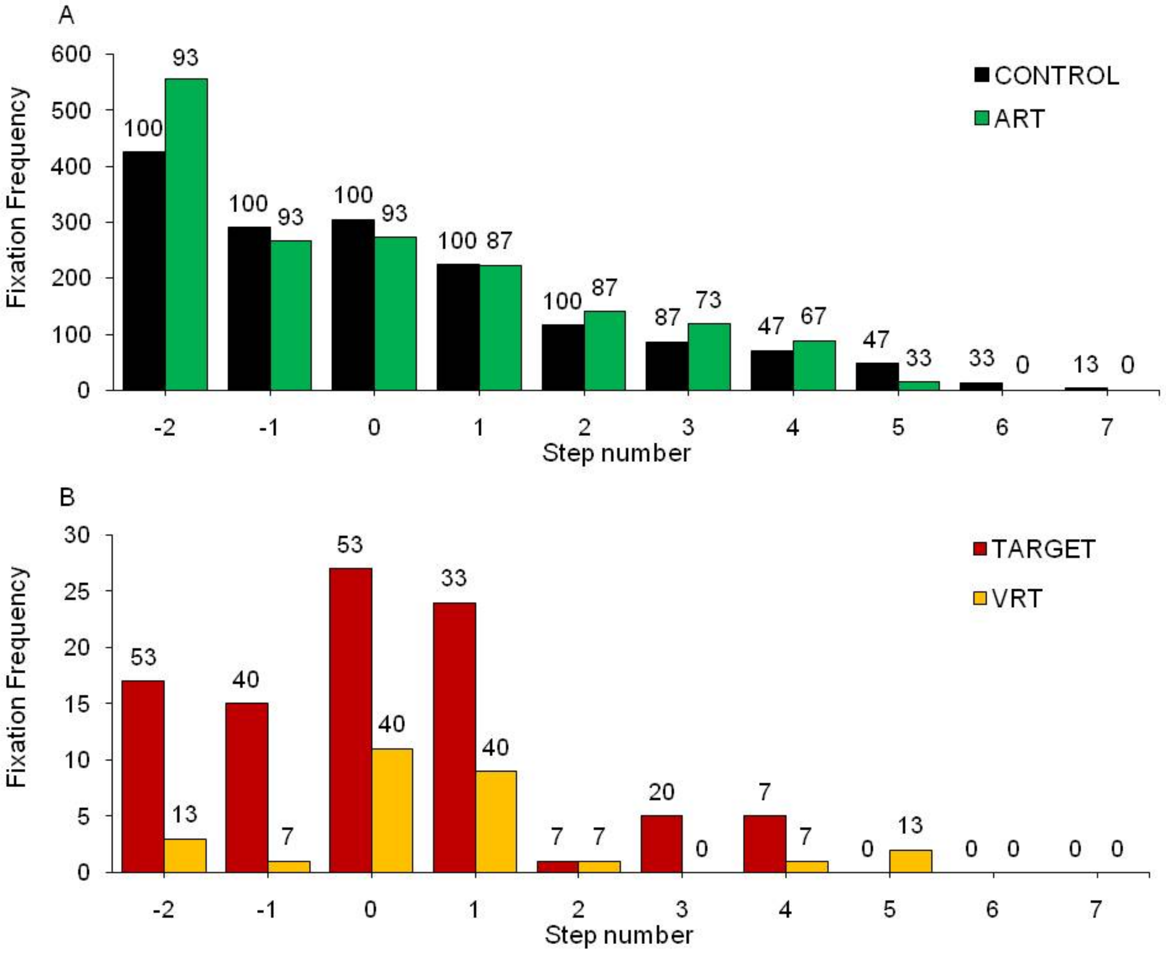

Figure 4.3: Frequency distribution of gaze fixations directed to any stair relative to participants' stepping location (positive step numbers are the steps on the stairs). Frequency represents all fixations observed across participants. Numbers at the top of the bars represent the percentage of participants contributing with fixations. Step "zero" represents the step ending with the last foot contact on the ground prior to the stairs. CONTROL and ART (A), and TARGET and VRT (B) were plotted in two difference graphs due to the large difference in scale; (C) Overall gaze fixation frequency directed on each step by condition. Frequencies represent the summation of all fixations observed across participants.

4.4.2 Locomotor behaviour

The time to walk on the stairs was influenced by task condition (F(3,42)=4.94, p=0.005). Total walk time was significantly increased in VRT (6.64±1.16s) compared to CONTROL (6.01±0.69s; p=0.002), while walk time in ART (6.31±0.67s) and TARGET (6.26±0.93s) showed intermediate values.

Step time was influenced by task condition (F(3,42)=4.82, p=0.0056) and step location (F(9,126)=32.56, p<0.0001). In addition, there was a significant interaction between condition and step (F(27,378)=2.95, 0<0.0001). Overall, step time was longer in VRT compared to CONTROL specifically on steps 1, 2, 4, 5, and 6. ART and TARGET showed intermediated step time values.

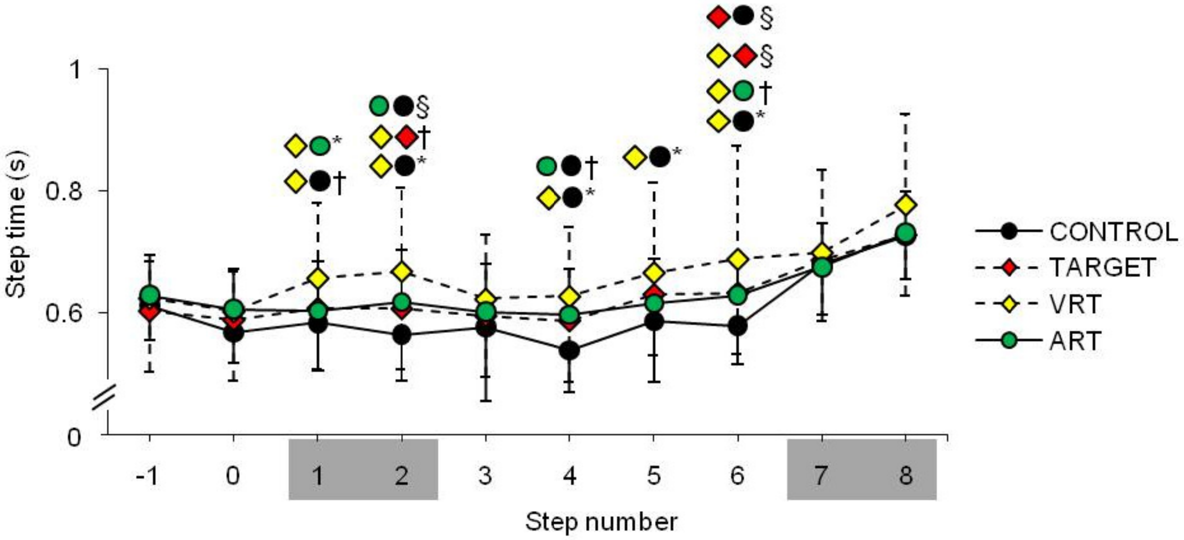

Figure 4.4: Step time across task conditions and step location. Positive step numbers represent step time on the stairs. Steps 1, 2, 7 and 8 represent the transition steps (shaded step numbers). ◇● VRT≠CONTROL; ◇🟢 VRT≠ART; ◇♦VRT≠TARGET; 🟢● ART≠CONTROL; ♦●TARGET ≠CONTROL; §p<0.05;†p<0.01; *p<0.0001.

Handrail use was examined during the different task conditions. Overall, only 3/15 participants contacted the handrail during the experiment. However, all occurrences occurred only in the vision conditions (TARGET or VRT). More specifically handrail contact occurred in TARGET (3 participants in 1, 2, and 5 trials, respectively) and VRT (1 participant in 9 trials) conditions. Interestingly, all the 3 participants used the handrail in their first trial of the task condition. Qualitative inspection of the video recordings from these trials showed that participants contacted the handrail when stepping on the bottom step, and moved their hands (left hand) across the length of the handrail until reaching the last step. Participants did not fixate on the handrails in any trial on this study, regardless of whether they used the handrail.

4.4.3 Reaction time performance

Overall, the performance of the reaction time task was influenced by dual-tasking. Reaction time was significantly longer during dual-tasking compared to single-task for ART (F(1,15)=20.61, p=0.0005; single-task: 319.5±27.0ms; dual-task: 353.3±37.6ms) and VRT (F(1,15)=8.58, p=0.011; single-task: 307.24±23.4ms; dual-task: 324.2±22.4ms). Similarly, accuracy was reduced during dual-task compared to single-task in both ART (F(1,15)=19.92, p=0.0005; single-task: 96.3±3.8%; dual-task: 92.0±3.3%) and VRT (F(1,15)=15.67, p=0.0014; single-task: 96.6±2.8%; dual-task: 91.5±5.4). Reaction time and accuracy did not differ for ART and VRT conditions (p>0.05).

For reaction time, there was a main effect of stepping location (F(10,139)=2.81, p=0.0034) and an interaction condition vs. step (F(10,118)=2.81, p=0.0037). Longer reaction times were observed during locomotion on step 1 in VRT, and steps 7 and 8 in ART. In both VRT and ART, the mid steps (2, 3, 4, and 5) showed reaction times as fast as in the single-task condition. Accuracy was not influenced by step regions (mean: 85.0±11.3%).

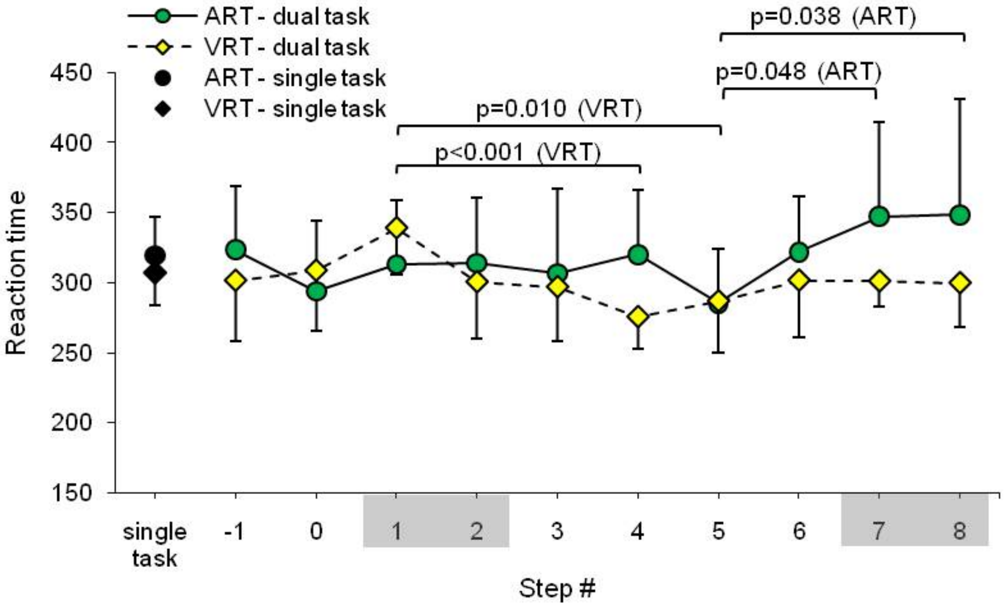

Figure 4.5: Reaction times for auditory and visual reaction time referenced to location on the stairs (step number). Note filled symbols reflect mean single-task performance. Horizontal axis defines the step number in which both reaction time stimulus and response occurred. Positive numbers refer to steps on the stairs. Steps 1, 2, 7 and 8 represent the transition steps (shaded). Single-task performance was obtained from participants standing at the start position and performing the reaction time task alone.

4.5 Discussion

This study investigated gaze behaviour during stair walking under conditions requiring gaze to be fixated away from the stairs. Results showed that gaze fixations on stair features were drastically reduced when a visual task was applied concurrently with stair walking, including in the transition steps. Despite this altered gaze, participants were still able to successfully walk on the stairs with only a few instances of handrail use and modest change in locomotor speed. Locomotor behaviour measured as step time was affected only when dual-tasking involved executive and visual challenged combined. Finally, the small increase in reaction time during locomotion on the transition steps may indicate that executive function and/or visual factors play a role in locomotion on transition steps.

Previous studies demonstrated that individuals spend a significant amount of time looking at the steps during stair walking suggesting that foveal fixations are required to guide locomotion (Miyasike-daSilva et al., 2011; Zietz & Hollands, 2009). However, using a dual-task paradigm, the current study revealed that foveal vision may not be an essential requirement to extract visual information regarding stair properties to control locomotion. When vision is not constrained by a concurrent visual task, there are likely advantages in keeping foveal vision on the steps since the entire visual field can be used to extract relevant visual information. It has been demonstrated, for instance, that peripheral visual information is sufficient to implement alternate foot placement, even when an obstacle suddenly appears in the travel path (Marigold et al., 2007). In the current study, although fixations on the steps were limited during visual dual-task conditions, individuals could still use the lower visual field to extract visual information regarding the steps. During locomotion, when the view of an obstacle is unavailable in the central visual field within two steps and during the crossing, gait changes can still be implemented by using visual information about the obstacle in a feed-forward manner to plan successful obstacle negotiation (Graci, Elliott, & Buckley, 2010). This mechanism could have been used in the present study when vision was diverted from the stairs. However, unlike the work of Graci et al. (2010) visual information could not have been extracted via central vision since participants did not fixate on the stairs even during the approach phase. It is possible that peripheral vision was an alternate source of visual information to guide stair walking when vision is diverted, since the view of the stairs was likely available in the lower visual field as participants approached the stairs. In this context, peripheral visual information likely provided online expproprioceptive information to fine tune limb trajectory on the steps, similarly to studies in obstacle avoidance (Graci et al., 2010; Marigold et al., 2007; Patla, 1998).

While the many observations from this study appear to diminish the potential importance of foveal vision, and may elevate potential role for peripheral vision, we did observe an increase in gaze fixations during the auditory reaction time task compared to the other conditions. One possible explanation for this result is that the auditory task increased executive load leading to a narrowing in the functional attentional visual field (Ball, Beard, Roenker, Miller, & Griggs, 1988). Consequently, foveal information about the steps could have been used to compensate for the lack of peripheral information. However, most of the fixations while performing the auditory task were directed to the last steps in the staircase. The last steps are at a comfortable height for line of gaze and may allow feature extraction of stair properties from the full visual field. It is therefore, possible that these fixations may serve to provide a stable frame of reference to use optic flow and peripheral visual information to guide locomotion rather than as a means to feature extract step characteristics through foveal vision. In a similar way, the monitor that presented the visual stimuli and fixation point may have functioned as a stable frame of reference. Once again, a concern that rises is the interpretation of such gaze fixations in terms of use of foveal information or peripheral information for locomotion.

The present study did not find strong evidence for a specific role of foveal gaze behaviour in locomotion on stair transitions. A minimum amount of fixations was relatively preserved only during the approach to the first transition; however, these fixations were performed for only half of participants. Additionally, it is important to note that gaze was not directed to transitions more often than to other steps. This finding indicates that the transitions do not require additional foveal fixations compared to mid steps. It is possible peripheral visual information is enough to guide stair walking on transitions.

Foveal fixation to an external target implemented in this study had a relatively small effect on walk time suggesting that foveal vision may not be the major source of visual information to guide locomotion on stairs and that peripheral visual field may provide sufficient visual information to guide behaviour. As participants walked up the stairs looking at the computer monitor the view of the stairs was at least partially available in the lower peripheral field. Similarly, the auditory task had a small effect on step time, which is in agreement with previous obstacle avoidance study that found that young adults kept gait parameters, such as gait velocity and stride time, constant while performing an auditory Stroop task (Siu, Catena, Chou, Van Donkelaar, & Woollacott, 2008). However, when a secondary task combining visual and executive requirements was applied, participants walked slower on all step regions. One possible explanation for this finding is that the load in executive function in this condition caused a narrowing in the attentional visual field. Previous studies have shown that the useful visual field reduces when individuals have their central visual field engaged in attentional tasks (Ball et al., 1988; Brabyn, Schneck, Haegerstrom-Portnoy, & Lott, 2001), and this could have been the case for the VRT condition in the current study, which made participants reduce their gait speed.

Concurrent reaction time performance provided additional information on the executive function demands for stair walking. The finding that reaction time was increased in the first transition (VRT) and second transition (ART) suggest that transition may impose additional executive demands compared to the middle steps. The reason for the different effects of VRT and ART on the transitions is still unclear requiring further investigation. However, the fact that the middle steps did not show such increase in reaction time could be associated with an overall reduction of executive/visual challenges in the mid steps as gait accommodates to the step dimensions after negotiating the first few steps. Similar accommodation is observed in gait parameters, such as foot clearance, which is reduced in the mid steps in comparison with the first step (Simoneau et al., 1991).

The current findings indicate that gaze fixations (and foveal vision in general) do not seem to be a requirement for detection of transitions and handrail location. Participants showed few fixations on the transitions when required to fixate on a secondary task and fixations directed to the handrails were not observed in this study. These results support the role of peripheral vision in providing online information for stair walking. Additionally, the fact that the staircase used in this study was built under regular stair design guidelines (e.g., Archea et al., 1979) could had allowed the use of prior experience with stairs as a reference for handrail use and control of walking. Under controlled conditions, such was the context of this study, extra-foveal visual information showed to be appropriate to guide stair walking. Further investigation can contribute to indicate whether foveal vision is required for locomotion on irregular steps or under less optimal visual conditions.

4.6 Conclusion

In a regular set of stairs, young adults are able to successfully control gait with minimal need for foveal vision to be directed to stair features. It is suggested that the peripheral visual information is able to deal with visual requirements for the control of locomotion on stairs, potentially to plan stepping and online control.

Chapter 5

Study 3 – Stair descent and dual-tasking: evidence for a role of peripheral visual field

5.1 Overview

Stairs are related to a significant number of falls in young and old population. The majority of stair accidents are linked to poor stair design in association with a failure by the user to perceive stair physical properties and make appropriate gait adjustments. Considering the importance of vision in extracting information about stair features, the understanding of the role of vision during stair walking can provide insightful information on fall mechanisms, stair design and for the development of fall prevention programs. The purpose of this study was to explore the role of peripheral vision during stair walking. Participants were asked to climb down a regular set of stairs (seven steps) during unrestricted walking (CONTROL), and while performing a concurrent visual reaction time task consisted of clicking on a wireless mouse in response to letter displayed on a computer monitor at the end of the stairway. The monitor was presented in two different locations: at the participants' eye height when they were upstairs (~4m above the ground level) (HIGH); or 0.5m above the ground level (LOW). The monitor location either restricted (HIGH) or facilitated (LOW) the view of the stairs in the participants' lower peripheral visual field. Eye movements were recorded using an eye-tracker and analysed to identify downward gaze shifts. Results showed that, in the presence of a visual task, downward gaze shifts were drastically reduced compared to CONTROL conditions. Gazes shift frequency remained similarly low independently if the visual task facilitated or restricted the use of the lower visual field to extract visual information regarding the stairs. However, individuals largely varied in their gaze behaviour when the visual task restricted the view of the stairs.

Individuals adopted different strategies such as walking slower, using the handrails, and/or looking down. While overall, gait and visual task were not significantly different in the phases prior to transition steps there was an increase in variability between subjects in gaze behaviour and performance in the visual task near locomotion on transitions when the view of the stairs was restricted in the lower visual field. Finally, as well reaction times were increased when the view of the stairs was restricted in the lower visual field and the fastest reaction times occurred in the middle (non-transition steps).

5.2 Introduction

Falls account for approximately 33% of injures in the young adult population, increasing to 60% after the age of 65 (Government of Canada, 2005). A significant number of theses falls is linked to stair accidents. Between 2002 and 2003, 26% of all falls suffered by people aged 65 or older occurred while going up or down stairs (Government of Canada, 2005). Interestingly, a higher percentage of falls happen during descent compared to ascent (Cohen, Templer, & Archea, 1985; Tinetti et al., 1988). The majority of stair accidents are linked to poor stair design in association with a failure by the user to perceive stair physical properties and make appropriate adjustments. Some individuals who fall while walking on stairs report that they had “missed their steps” and tripped, which could be considered a perceptual error (Wild et al., 1981). Not surprising, falls are highly correlated to visual impairments (Lord & Dayhew, 2001). Considering the importance of vision in extracting information about stair features, the understanding of the role of vision during stair walking can provide insightful information on fall mechanisms with applications in stair design and fall prevention programs.

Visual information to guide locomotion can be obtained from both central and peripheral visual fields (Marigold & Patla, 2008; Patla, 1998; Turano et al., 2004; Turano et al., 2005). Visual field loss is commonly associated with mobility deficits and the influence on mobility varies according to the affected region in the visual field (Geruschat, Turano, & Stahl, 1998; Long, Rieser, & Hill, 1990; Turano et al., 2004). For instance, individuals with central field loss report difficulty in tasks requiring detection of elevation changes, such as steps (Szlyk, Fishman, Grover, Revelins, & Derlacki, 1998) and show reduced ability to use optic flow to guide walking (Turano et al., 2005). Loss in the peripheral visual field, such as that caused by retinitis pigmentosa, is related to a significant reduction in gait speed and an increased number of contacts with objects in the environment (Geruschat et al., 1998). In this regard, the lower visual field seems to play a particularly important role during level ground walking. Restriction in the lower visual field while negotiating a multi-surface terrain caused a larger head pitch downwards and reduction in gait speed and step length in young and older adults (Marigold & Patla, 2008). Information acquired from the lower visual field also seems sufficient to modulate foot trajectory during obstacle crossing (Graci, Elliott, & Buckley, 2010). Additionally, during single step descent, the lower visual field seems to provide online information regarding step height to control landing behaviour, since occlusion in the lower visual field is associated to a “cautious landing” behaviour reflected by a reduction in vertical reaction force, knee and ankle angular velocity, and delayed body weight transfer to the leading limb (Timmis et al., 2009).

Although the specific role for the lower visual field in stair walking has not been investigated, there is some evidence suggesting that peripheral vision might play an important role in guiding immediate action on stairs. The preliminary findings from Study 2 of this thesis revealed a reduction of fixation behaviour on stair features when central vision was engaged in a concurrent visual task with little associated impact to locomotor behaviour. These findings indicate that visual information acquired from the peripheral visual field is probably appropriate to guide stair walking. During unrestricted stair walking, the peripheral visual field could provide information about the location/properties of the stairs since the lower visual field can easily “capture” the view of the stairs while walking up or down. Similarly, the lateral visual fields may acquire information on handrail location. If that is the case, a condition for the use of peripheral visual field would be to keep the line of gaze in an optimal location to allow extraction of visual information from extra foveal visual field. Additionally, the ability to rely on peripheral visual field information would provide possible advantages including: 1) reduction in the need to scan large field of view with foveal vision and 2) release of the foveal vision to perform concurrent scan of the environment and to engage executive processes directed towards other tasks.

The purpose of this study was to explore the role of peripheral vision during stair walking. In order to influence gaze direction, a dual task paradigm was conducted concurrently with stair walking. During stair descent individuals performed a concurrent go/no-go reaction time task requiring gaze fixations to “non-stair” targets and allowing influence over the available peripheral vision.. The central visual task was manipulated to restrict (visual stimulus position in a high position) or facilitate (visual stimulus in a low position) the view of the steps in the lower visual field. This manipulation caused a natural restriction of the view of the stairs in the lower visual field, which could cause disruption in locomotor and gaze behaviour during stair descent. It was hypothesized that the lower peripheral field of view is important to navigation of stairs, specifically the transition phases. We anticipated that varied restrictions in lower visual field would lead to differences in gaze behaviour, speed of stair walking and reaction time latency/ accuracy. For gaze behaviour it was hypothesized that, when the dual task limited lower peripheral visual field (visual target in high position), individuals would execute transient downward gaze shifts towards the steps within one stride prior to transition steps. For time to perform stair walking, it was hypothesized that this natural restriction in the lower visual field would result in a more cautious gait including an increase time to walk downstairs and single support time during negotiation with the transition step. Finally, for reaction time performance, it is hypothesized increased latency and reduced accuracy under task conditions that gaze limits the available lower visual field.

5.3 Methods

5.3.1 Participants

Ten healthy young adults (5 females and 5 males) participated in the study (mean age 23.8±3.0 years, height 1.68±0.8 m). Participants were screened for medical condition or history that would affect their balance or ability to traverse stairs. Participants had normal vision or vision corrected-to-normal (with contact lenses), with binocular visual acuity of 20/20 or higher at the Snellen test and mean contrast sensitivity at Mars Letter test of 1.79 ±0.05 log. All participants provided written consent prior to participating in the study. This study was reviewed and accepted by the Office of Research Ethics at the University of Waterloo.

5.3.2 Protocol

Participants were asked to walk down a 7-step staircase at a self selected pace. The steps were 96.5 cm wide and had a rise of 18 cm and a tread of 25.5 cm. A walkway was provided at the bottom step (approximately 3 m long), and at the top step (by a 2.23 vs. 1.22 m lift table). Handrails were present in both sides of the stairs. Along the sides of the top level, two cables were extended providing a guardrail. Participants wore a safety harness attached to a retractable lanyard that ran along a cable above the stairs and walkway. Before the beginning of each trial, the view of the stairs and the handrails was blocked with a visual screen held by an assistant. When a trial started, the screen was removed and participants walked down the stairs at their natural pace, reached the ground level and walked for 3 to 4 more steps before stopping. At the end of each trial, participants were asked to return to the start position upstairs. When the participant reached the start position area, he/she turned around to face the stairs again, the visual screen was set back in front of them, and then they were asked to move to one of the 3 different start points marked on the lift table. The start points were set at 1.2m, 1.4m, and 1.6m from the edge of the first step.

The dual-task comprised of performing a visual go/no-go reaction time task concurrently with stair walking. The visual task consisted of pressing a wireless mouse button in response to a visual stimulus displayed in a flat computer monitor. The stimulus consisted of the letter "X" or "O" randomly presented in the centre of the computer monitor at a proportion of occurrence of 3/1 (X more frequent than O). Stimuli were presented for 100ms at random time intervals between 750 and 1250 s. Participants were asked to click on a wireless mouse button every time they saw an "X". The series of stimulus was delivered during the entire walking. Participants were provided with practice trials for the reaction time task the beginning of the data collection session.

Participants walked downstairs performing the dual task in two different conditions (Figure 5.1). The condition in which the view of the stairs in the lower visual field was facilitated (LOW), the monitor was located downstairs on the walkway following the stairs at 50cm above the ground level. The condition in which the view of the stairs in the lower visual field was restricted (HIGH), the monitor was raised at participants' eye height (~3.5 m above the ground level) when standing at the top of the stairs. The monitor location in HIGH restricted subjects from seeing the steps in their lower peripheral field of view as they walked downstairs, since it required participants to direct their gaze upwards to perform the visual task. Additionally, participants walked downstairs without performing the visual task concurrently (CONTROL), and with no specific information about where they should look. Participants carried the wireless mouse on their preferred hand during all trials (including in CONTROL), which was the right hand for all participants. In both LOW and HIGH conditions, the monitor location allowed participants to perform at least 3 steps after reaching the ground. During the dual task conditions participants were asked to perform both the reaction time and walking at the same time, and no specific instruction was given on which task they should prioritize. No instruction was given on use of handrails. Each participant performed two blocks with 5 stair walking trials in each condition (CONTROL, HIGH, LOW). Participants also performed the visual task in a single task version (reaction time task alone), while standing on the start position upstairs. For HIGH and LOW blocks, three trials (10 seconds length) in the single task version were randomly added in each block. Condition blocks were presented in random order.

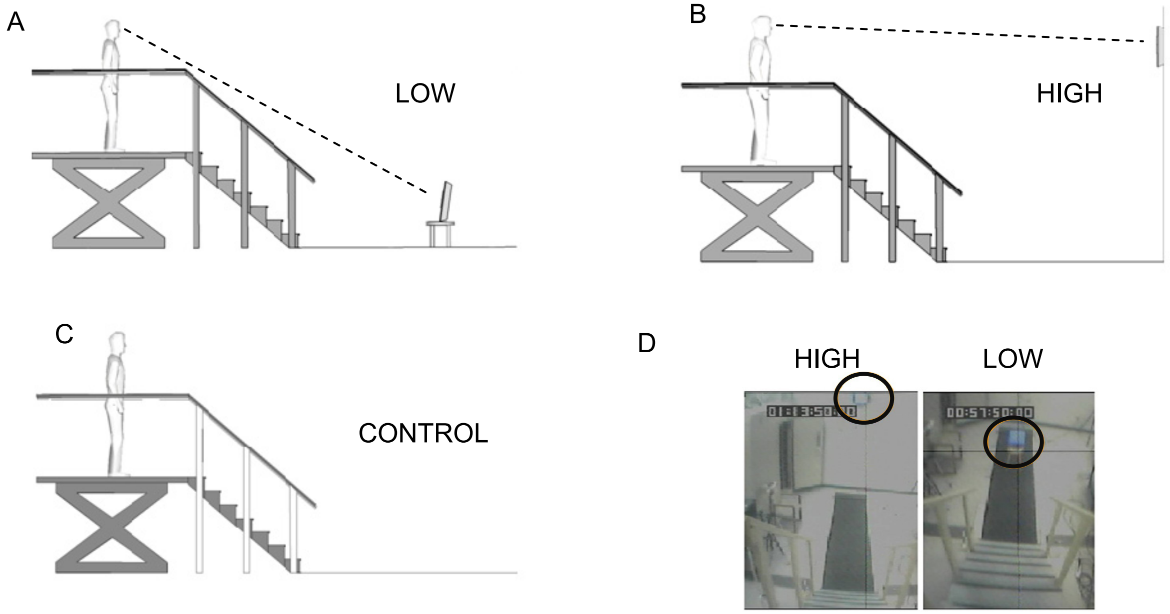

Figure 5.1 Experimental protocol. (A) Dual-task with peripheral vision facilitation (LOW); (B) dual-task with peripheral vision restricted (HIGH); (C) Unrestricted walking (CONTROL); (D) Video frames from head-mounted camera, with participant's view of the monitor (circle) and steps from the top of the stair during HIGH (left) and LOW (right) conditions. Dashed line in A and B illustrates participant's line of gaze oriented towards the monitor.

5.3.3 Instrumentation and data acquisition

A head-mounted eye tracker 5000 (ASL, Bedford, MA, USA) was used to record eye movements at a rate of 60Hz. The eye-tracker was calibrated using the 9 point calibration method with 1º accuracy over the stair area. The eye tracker system provided video outputs of both, the eye view, and the gaze location superimposed on the participant's field of view (scene view). Additionally, a video camera recorded the full-body image of participants walking on the stair, which was used to code handrail use. The images of the eye view, the scene view, and the video camera were digitally recorded.

Footswitches (B&L Engineering, Tustin, CA, USA) placed inside of participant's shoes provided temporal measurement of their steps. An infrared light switch positioned at the bottom step was used to denote the timing prior to contact with the first step. This information was used to synchronize foot contact information with location on the stairs. Footswitch and infrared switch data were collected at 240Hz and recorded using a program written in LabVIEW (National Instruments, Austin, TX, USA).

A custom designed LabVIEW program was used to control the timing and presentation of the visual stimulus for the secondary task. The same program recorded the time for each stimulus delivery and each time that the participants pressed the mouse button.

5.3.4 Data analysis

5.3.4.1 Locomotor behaviour

Footswitch data provided time series of foot-contact and foot-off times for every step for each trial. In combination with the infrared signal prior to contact with the bottom step, footswitch data were used to determine participants' location with respect to the stairs and each step. Participants' stepping location was classified in one of the following categories (Figure 5.2): a) *approach (AP)*, the first foot off (FO) to the last foot contact before the stair (0FC); b) *first transition* (T1), from 0FC to the foot contact on the step 2 (2FC); c) *first mid steps* (MS1), from 2FC to the foot contact on the step 4 (4FC); d) *second mid steps (MS2)*, from 4FC to the foot contact on the step 6 (6FC); g) and *second transition (T2)*, from 6FC to the first foot contact out of the stairs (8FC). Total walk time (from FO to FC8) was calculated per condition per participant. Walk time was also calculated for each stair region (T1, M1, M2, and T2). Single support duration in each step was calculated.

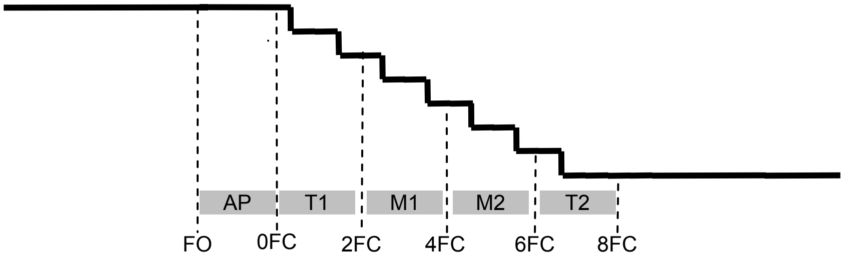

Figure 5.2: Classification scheme for participants' step location when descending the stairs. AP=approach; T1=first transition; MS1=first mid step region; MS2=second mid step region; T2=second transition; FO=initial foot off; -2FC=two foot contacts before stepping on the stair; 0FC= last foot contact before the stair; 2FC=foot contact on the step 2; 4FC =foot contact on the step 4; 6FC= foot contact on the step 6; 8FC=first foot contact out of the stairs.

Handrail use was obtained from the video recordings. The frequency of trials that the handrails were contacted by the participants was determined.

5.3.4.2 Gaze behaviour

A frame-by-frame analysis of the video recordings was conducted to identify gaze shifts downward along each trial, from the start of the trial (when the visual screen was removed) to the end (8FC). A gaze shift downward was defined every time that a downward movement of the eye was detected in the eye view image. For each participant, the percentage of trials per condition in which downward gaze shifts occurred was calculated. Gaze shift duration was calculated as a percentage of trial time.

Additionally, for each gaze shift, the participant's stepping location on the stairs was assessed and the gaze shifts were classified as *approach* (AP), *transition 1* (T1), *mid steps 1* (MS1), *mid steps 2* (MS2), *or transition 2* (T2). The percentage of trials with gaze shifts was computed per condition per step region.

5.3.4.3 Performance in the central visual task

Performance in the reaction time task was assessed by reaction time and accuracy. Accuracy was calculated as the percentage of correct responses. A response was considered correct when participants pressed the mouse button following a "X" stimulus, or did not press the mouse button following the "O". Mean reaction time and accuracy was calculated for each condition. Reaction times below 200 ms were considered an error for anticipation and timing was not included in the calculation of mean reaction time. Additionally, mean reaction time and accuracy was calculated for each step region per condition (only events that stimulus and response fell within the same step region were considered to calculate the means).

5.3.4.4 Statistical analysis

Mean downward gaze shift duration was analyzed by a one-way repeated measures ANOVA with task condition as a factor with three levels (CONTROL, LOW, HIGH). Gaze shift frequency, walk time, reaction time and accuracy were all analyzed using a two-way repeated measures ANOVA with task condition and step region as the two factors. Single support time was analysed using a two-way ANOVA with condition (CONTROL, LOW, HIGH) and specific step location (from -1 to 7) as factors. Post-hoc analysis (Tukey adjustment) was performed to characterize the differences across conditions and step regions. Significance level was set at 0.05 for all analyses.

5.4 Results

5.4.1 Gaze behaviour

As summarized in Table 5.1, gaze behaviour directed to the stairs was reduced in LOW and HIGH as compared to the CONTROL conditions. Specifically, the gaze shifts were shorter in duration, occurring in fewer trials and less frequently. This reduction is evidenced by a significant main effect of experimental conditions on total gaze shift time (F(2,18)=87.88, p<0.0001; Figure 5.3A).

Table 5.1: Gaze shift characteristics across experimental conditions (means±standard deviation).

	CONTROL	LOW	HIGH
# of participants performing gaze shifts	10	7	9
Mean gaze shift duration (ms)	421±50	250±62	274±96
% trials with gaze shifts	60.9±15.6	1.9±1.9	11.8±12.1
Mean number of gaze shifts per trial	6.6±1.6	0.2±2.5	1.2±3.1

For gaze shift frequency, ANOVA evidenced a main effect for condition (F(2,18)=98.73, p<0.0001), step region (F(4,36)=13.18, p<0.0001) and an interaction of condition versus step region (F(8,72)=8.75, p<0.0001). Figure 5.3B shows the frequency of downward gaze shifts with respect to participant's location on the stairs for each condition. Overall, gaze shift frequency was increased in CONTROL compared to LOW and HIGH in all step regions. In CONTROL, the percentage of gaze shifts decreased as participants walked on the stairs. In LOW and HIGH, there was an overall reduction in the percentage of trials with gaze shifts across all step regions. In HIGH, the observed increase in downward shift frequency in step regions prior to transitions (e.g., AP and M2) did not reach statistical significance when compared to the other step regions, however they showed a large standard deviation.

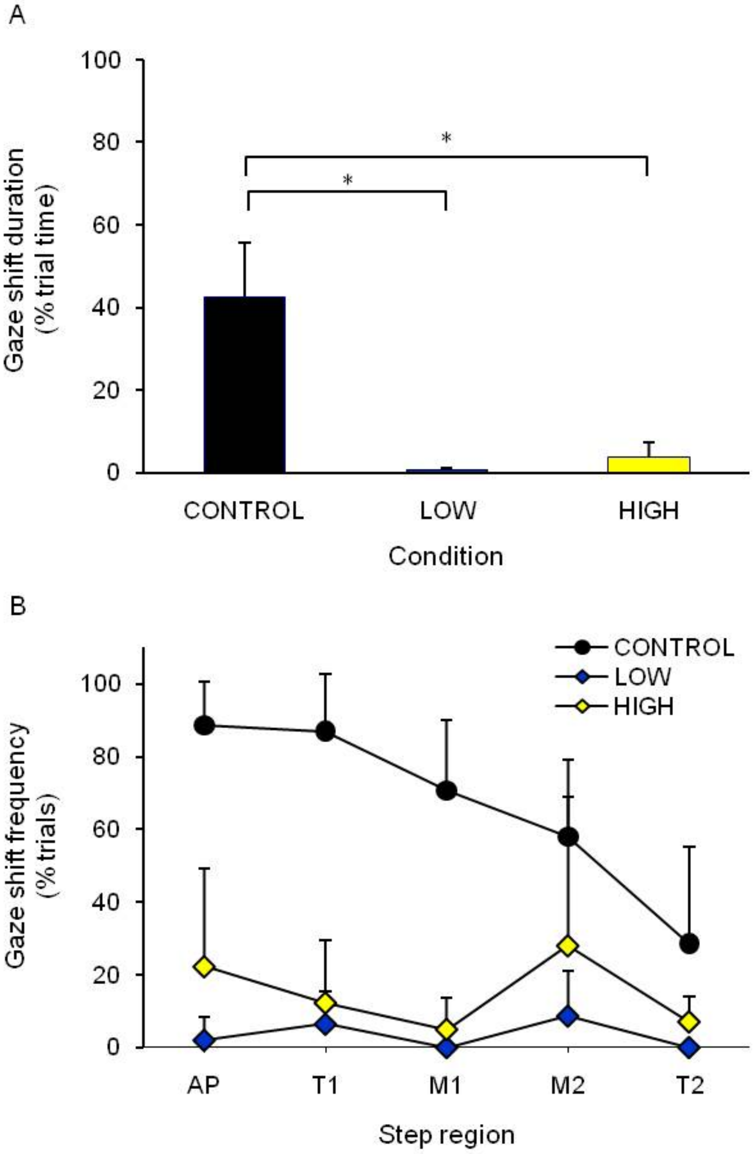

Figure 5.3: (A) Mean gaze shift duration in each condition. (B) Gaze shift frequency in according to participants' stepping location on the stairs in each condition. *p<0.0001

5.4.2 Locomotor behaviour

For walk time, there was a main effect of task condition (F(2,18)=19.83, p<0.0001), step region (F4,36=11.14, p<0.0001) and a condition versus step region interaction (F(8,72=4.2, p=0.0004;

Figure 5.4). Overall, walk time was reduced in LOW and HIGH compared to CONTROL and was slower in the first transition compared to other step regions. In contrast to the differences between control and other tasks, there was no difference in the walk time comparing between the LOW and HIGH tasks.

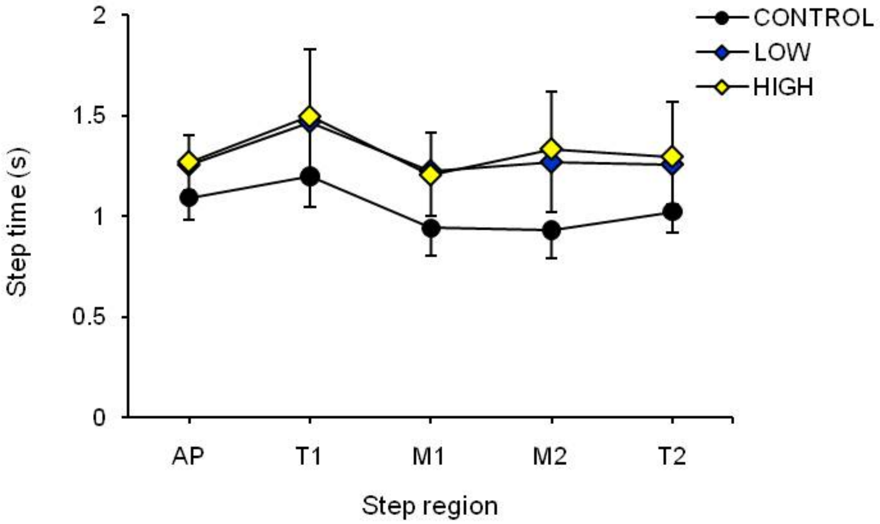

Figure 5.4: Step time (s) for each experimental condition and step region. T1=transition 1; M1=mid steps 1; M2=mid steps 2; T2=transition 2.

Video recordings taken during the experimental trials suggested that some participants performed a “foot search” in order to find the transition step when dual tasking reflected by an increase in the foot swing phase. In order to confirm this observation, the single support time in each step was calculated (Figure 5.5). Similarly to step time, there was a main effect for condition (F(2,18)=17.36, p<0.0001), step (F(6,72)=22.47, p<0.0001), and an interaction between task condition and step location (F(16,144)=5.69, p<0.0001). It was expected that dual-task would increase the single support phase during negotiation with the first and last step. However, single support time was significantly longer in every step in both LOW and HIGH compared to CONTROL (excluding step -1 in LOW, and step 7 in LOW and HIGH). Single support time was also similar between LOW and HIGH (except for step -1). Although the increase in single support time in the transitions was not statistically different from the increase in other steps, it can be observed in Figure 5.5A, a larger standard deviation in the steps “0”, “5”, and “6” during HIGH, which seems to indicate that some participants may have increased single support time but others did not. Figure 5.5B and C show two representative subjects for these cases. Subject S5 (Figure 5.5B) showed very little increase in single support time in all steps when comparing LOW and HIGH vs. CONTROL. Controversially, subject S10 (Figure 5.5C) showed increased single support time in LOW and HIGH compared to CONTROL, particularly in the single support phase preceding the foot contact with the first stair (step “0”) and prior to landing on ground level (steps “5” and “6”).

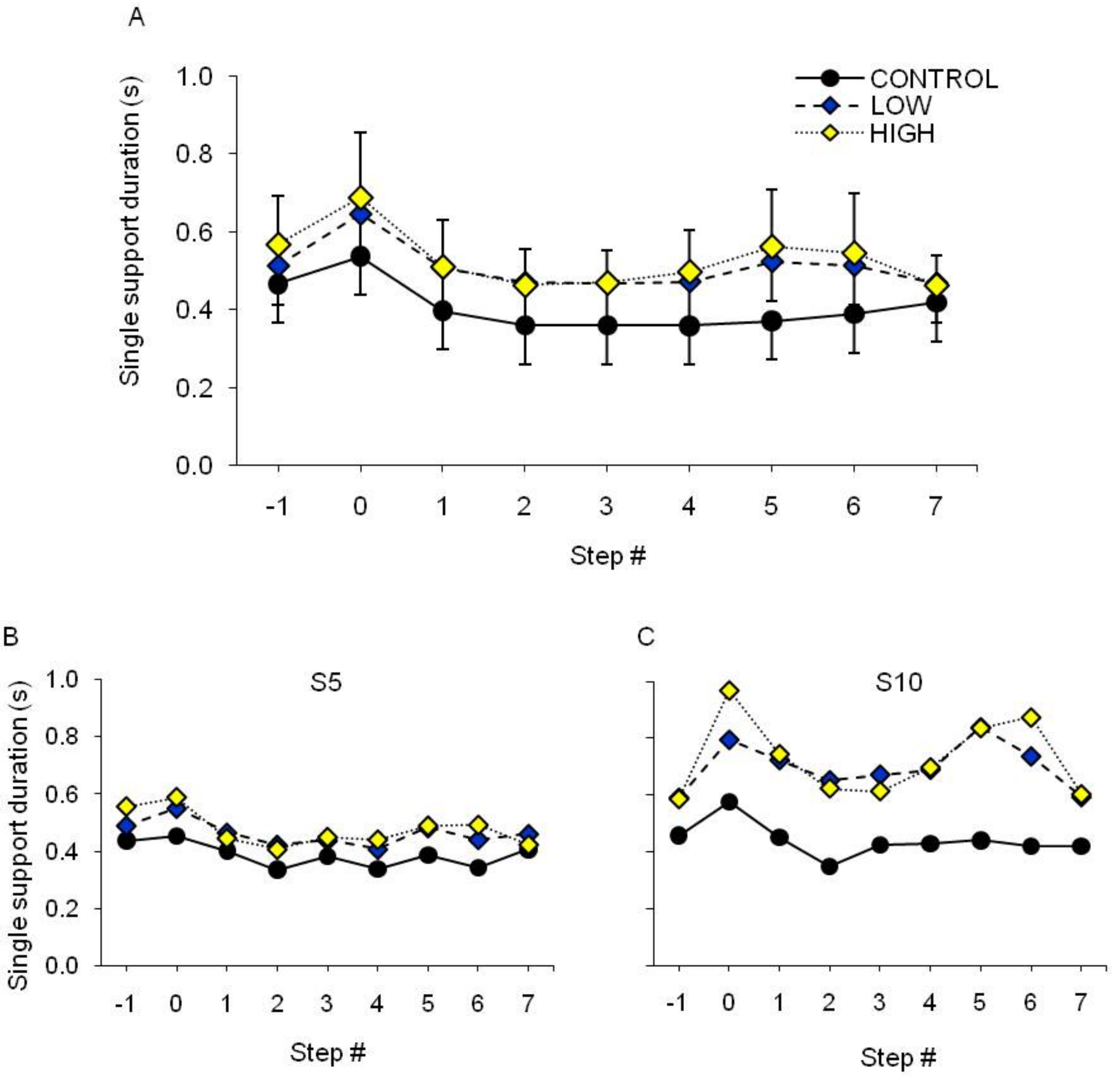

Figure 5.5: Single support time in each step by condition. (A) Average across participants (and standard deviation); (B) Data from a representative subject who showed minimal difference in single support duration across conditions; (C) Data from a representative subject who showed increased difference in single support duration across conditions.

Four of the 10 participants used the handrail at some point in the study. Only one participant held the handrail during CONTROL condition and this occurred in only one trial. In the LOW task, handrail use was increased, with three participants holding the handrail in a total of 25 trials (26% of all trials). The highest handrail use was in HIGH task with 4 participants holding the handrail in 34 trials (34.7% of trials).

5.4.3 Central visual task performance

Table 5.2 shows reaction time and accuracy in the visual task. As expected, dual-task significantly increased reaction time compared to single-task in LOW (F(1,9)=18.34, p=0.002) and HIGH (F(1,9)=32.51, p=0.0003). Similarly, accuracy was significantly reduced during dual-task compared to single-task in LOW (F(1,9)=12.42, p=0.0065) and HIGH (F(1,9)=33.39, p=0.0003).

For reaction time, there was a main effect of task condition (F(1,9)=5.65, p=0.041) and step region (F(4,36)=7.57, p=0.0002; Table 5.2). Specifically reaction time was increased in the HIGH compared to the LOW condition. Additionally, reaction times at the first mid step (M1) showed the fastest reaction times in comparison to all other step regions during dual tasking. There was no significant difference in accuracy comparing between LOW and HIGH conditions (p>0.05), between step regions (p=0.090) and there was no statistically significant interaction between step region and task condition (p=0.072).

Table 5.2: Performance in the reaction time task during dual and single task performance across the different task conditions (HIGH and LOW visual target location). Means±SD for reaction time (ms) and accuracy (% correct responses).

	LOW		HIGH		Total[a]	
	Reaction Time (ms)	Accuracy (%)	Reaction Time (ms)	Accuracy (%)	Reaction time (ms)	Accuracy (%)
Single-task	314±25	91.0±5.3	318±24	89.4±8.9		
Dual-task[a]	337±45*	82.7±15.1	351±48*	80.2±15.2		
Approach	363±42	82.8±5.7	375±48	78.2±10.0	369±44	80.5±8.27
T1	334±42	80.5±10.5	352±52	80.7±13.6	343±37	80.6±11.9
M1	302±28	84.3±16.7	305±41	91.5±10.4	303±34**	87.9±14.0
M2	348±43	75.8±24.2	362±39	71.1±21.3	355±40	73.4±22.3
T2	339±50	90.0±10.4	361±56	79.7±16.2	350±53	84.8±14.3

[a]Means across all step regions in LOW and HIGH; [b] Means across conditions for each step region (approach, T1, M1, M2, T2); *statistical difference between LOW and HIGH (p<0.05); ** statistical difference between M1 and other step regions (p<0.0001).

5.4.4 Individual strategies

Inspection of individual data revealed that participants selected two different walking strategies. Four participants reduced drastically walk speed during the most restricted condition (HIGH), while the other 6 showed only a small reduction in walk speed compared to CONTROL. Table 5.3 shows the descriptive data for these two subgroups. Participants were assigned as “slow walkers” if they showed an increase in walk time larger than 25% in HIGH compared to CONTROL. Handrail was used more often for participants who walked slower (N=3) than faster (N=1). Participants who walked faster in HIGH tended to perform downward gaze shifts more often than slower walkers. In the secondary task performance, three slow walkers showed the lowest dual-task cost in reaction time, while one participant in this group showed higher dual-task cost levels similar to the faster walkers. All slow walkers showed lower dual-task cost in accuracy in LOW, however they appear similar to fast walkers in HIGH.

Table 5.3: Summary of individual data describing locomotor behaviour, gaze behaviour, secondary task performance, and handrail use.

Subject	Locomotion					Gaze			Secondary task										Handrail use		
	Walk time (s)			% change		Gaze shifts (% trials)			Reaction time (ms)			Reaction time dual task cost		Accuracy (%)			Accuracy dual task cost		# trials/total # trials		
	CNT	LOW	HIGH	LOW	HIGH	CNT	LOW	HIGH	Single task	LOW	HIGH	LOW	HIGH	Single task	LOW	HIGH	LOW	HIGH	CNT	LOW	HIGH
< 25% walk time increase																					
S1	4.32±0.6	4.48±0.2	4.41±0.2	3.6	2.0	100	0	10	295±29	324±46	360±46	9.9	22.2	90.6±9.9	90.2±12.0	82.1±14.9	-0.4	-9.4	0/10	0/10	0/10
S2	4.74±0.2	5.14±0.3	5.02±0.3	8.5	6.0	100	30	100	312±22	355±41	342±57	13.9	9.8	93.9±12.6	81.1±15.0	79.4±13.8	-13.6	-17.8	0/10	0/10	0/10
S3	4.57±0.3	5.12±0.2	5.18±0.2	12.2	13.4	100	22	60	312±14	362±43	359±30	15.8	15.1	97.1±4.1	89.2±11.2	95.3±10.0	-8.1	-2.0	0/9	0/9	0/10
S4	4.78±0.2	5.68±0.1	5.44±0.2	18.8	13.8	100	50	100	320±37	351±44	356±63	9.5	11.0	96.2±5.8	80.0±11.9	80.3±6.8	-16.8	-19.9	0/7	0/8	0/10
S5	4.95±0.2	5.56±0.3	5.67±0.1	12.2	14.4	100	0	10	285±20	309±25	348±57	8.2	22.1	94.5±5.1	73.0±16.1	84.2±15.2	-22.8	-14.1	0/9	0/9	0/10
S6	5.94±0.1	6.94±0.3	7.21±0.6	16.9	21.5	100	30	100	331±28	383±59	384±36	15.4	15.8	91.2±8.6	80.3±13.2	80.8±14.0	-11.9	-13.0	0/8	7/10	7/10
> 25% walk time increase																					
S7	4.75±0.5	6.24±0.1	6.55±0.6	31.5	37.9	100	10	67	326±22	333±46	338±40	2.2	3.7	84.9±12.5	86.5±8.5	72.2±14.5	1.8	-14.7	0/10	0/10	0/9
S8	3.84±0.3	5.62±0.2	6.27±0.2	46.4	63.3	100	0	20	373±28	377±43	386±27	1.2	3.5	89.4±9.4	89.4±10.2	68.6±19.9	0.0	-23.3	1/10	0/10	10/10
S9	4.68±0.7	6.43±0.5	7.67±0.6	37.4	63.8	100	10	0	305±19	349±30	379±46	14.7	24.3	94.9±6.2	90.7±10.0	85.0±7.3	-4.4	-10.9	0/10	10/10	10/10
S10	4.73±0.3	7.85±0.6	8.05±1.6	65.8	69.9	100	10	22	300±19	308±29	301±38	2.6	0.3	92.1±9.2	90.2±11.7	77.2±14.6	-2.1	-16.6	0/10	8/10	7/9

[1] Dual task cost was calculate as the percentage of change in performance in the dual task (DT) condition compared to single task (ST) performance as: $DTcost = ((ST - DT)\ 100/)/DT$

The classification as “slow walkers” and “fast walkers” was able to account for the variability found in the group analysis. Figure 5.6 illustrates individual data for gaze, locomotion, and visual task variables in the HIGH task condition. Large gaze shift variability prior to transitions in HIGH could be explained by the considerable variation between fast walkers in this variable (Figure 5.6A). For instance, during M2, half of the fast walkers performed gaze shifts in most of the trials (N=3), one participant looked down for only one trial (S3) and the remaining two participants did not perform gaze shifts in any trial. Large variation in gaze behaviour could also be observed in the approach phase. Slow walkers showed very low frequency or absence of gaze shifts throughout all step regions.

Figure 5.6B shows percent of change in stride duration in HIGH compared to CONTROL (positive values indicate that the stride duration in that phase was increased). Overall, fast walkers were less likely to slow down throughout all step regions, while slow walkers did slow down in all step regions.

Figure 5.6C shows individual data for dual task cost on accuracy in the reaction time task in each step region comparing slow and fast walkers in the HIGH condition. In M2, dual task cost largely varied between participants. This variation in M2 across participants accounted for the large standard deviation in accuracy in this step region compared to the other steps.

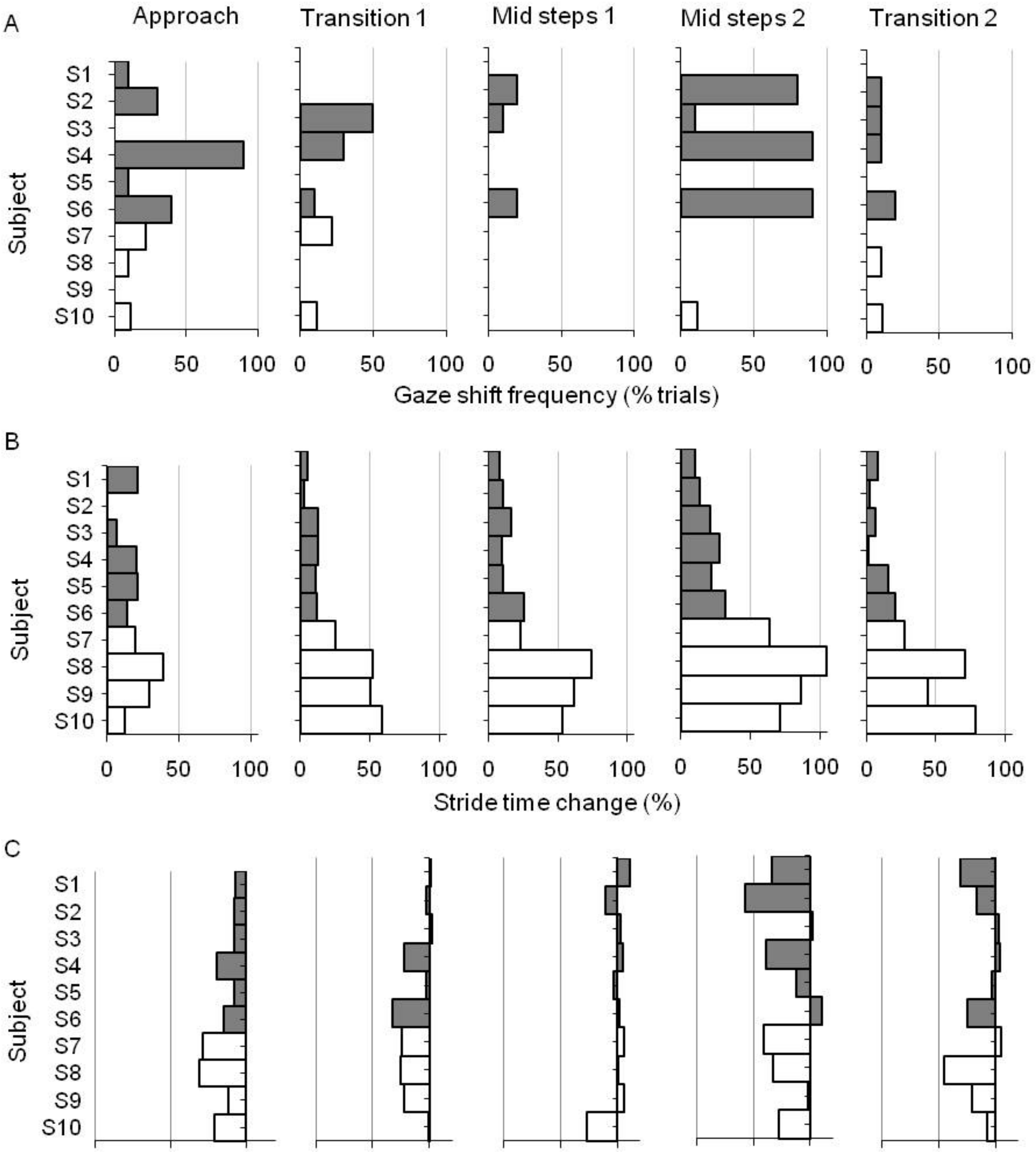

Figure 5.6: (A) Frequency of trials with gaze shifts in each step region during the HIGH condition for each subject; "fast walkers" in grey bars and "slow walkers" in white bars. (B) Mean walk time in each step region for fast and slow walkers. (C) Dual-task cost in accuracy for the secondary task in each step region in the HIGH task condition.

5.5 Discussion

The aim of this study was to probe the potential role of the lower visual field during stair walking. The line of gaze was manipulated by presenting a visual reaction time task in two different locations, which naturally facilitated or limited the view of the stairs in the lower visual field during stair descent. Results showed that, in the presence of a visual task, downward gaze shifts were drastically reduced compared to unrestricted or control conditions. Gaze shift frequency remained similarly low independently if the visual task facilitated or restricted the use of the lower visual field to extract visual information regarding the stairs. However, individuals largely varied in their gaze behaviour when the visual task restricted the view of the stairs. In support of the hypotheses to deal with the dual task conditions, individuals adopted different strategies such as walking slower, using the handrails, and/or looking down. While overall, gait and visual task were not significantly different in the phases prior to transition steps there was some indirect support for the potential unique importance of lower visual field in transition phases. This included the increase in variability between subjects in gaze behaviour near locomotion on transitions, where the view of the stairs was restricted in the lower visual field. Finally, reaction times were increased when the view of the stairs was restricted in the lower visual field and the fastest reaction times occurred in the middle (non-transition steps).

5.5.1 Role for lower visual field

In a previous study, Rosenbaum (2009) recorded people walking down a staircase in a public venue and reported that the last look down occurred approximately in the third or fourth step from the bottom, which he suggested to be triggered by the disappearance of the view of the stairs from the visual field. In agreement with these qualitative observations, the present study also found a reduction in looks down in the last steps under unrestricted walking (CONTROL condition).

In the presence of a concurrent visual reaction time task, participants drastically reduced the time looking down independently whether the line of gaze was high or low. Considering that the human lower visual field extends for more than 60 degrees inferiorly from the midline (Millodot, 2008), the view of the steps in the lower visual field was potentially facilitated when the line of gaze was directed to the monitor located downstairs, which minimized the need for additional looks down in the middle of the stairs. Studies have shown that peripheral visual information is appropriate to implement changes in gait (Graci et al., 2010; Marigold & Patla, 2007; Timmis et al., 2009). In the case when the monitor was elevated, the large variability in the phase preceding the last transition (i.e., 3-4 steps from the bottom) suggests that at least some participants looked down possibly to regain the view of the steps within the lower visual field, similar to the last look reported by Rosenbaum (2009). For those participants who rarely looked down, there are three possible explanations for their behaviour. First, it is possible that they were able to infer information regarding stair features, since a specific restriction in the peripheral visual field was not applied in the current study (e.g., occluding glasses). In fact, some participants reported that they used the view of the handrails (in the peripheral vision) as a “cue” to know where the beginning and the end of the stairs were. Second, taking into account the size of the human visual field, participants may have had a view of the first steps in the visual field while fixating in the monitor mounted on the wall; however, as participants walked down, the view of the stairs became less available since the line of gaze became relatively higher. Finally, it is possible that in the last few steps, individuals could make use of a stored representation of the stairs, considering that people can use memory of environmental layout to guide walking within short periods of time (Thomson, 1980). Future studies investigating the use peripheral visual information during locomotion will confirm the use of extra-foveal visual information. Nevertheless, the present study demonstrated a reduction in downward gaze shifts during dual-tasking in stair descent. This reduction indicates that gaze fixations can be minimized during stair walking, and supports the notion that the lower peripheral vision can provide relevant visual information to control stair walking. Future studies investigating the range of peripheral vision for stair walking in more controlled conditions will provide substantial information of this role.

5.5.2 Locomotor strategy

Individuals dealt with the dual-task context by adopting two main strategies. First, all participants slowed walking speed to some degree during dual-tasking independent of whether the view of the stairs was facilitated or not. Reduction in gait speed is common during dual-tasking in more challenging locomotor conditions, such as obstacle avoidance, which is thought to be related to the increased executive requirements under more complex conditions (Siu et al., 2008). Handrail use was a second strategy more likely used during dual-tasking. In the present study, less than half of participants adopted this strategy, a rate slightly above the general handrail use frequency in the young population, which is approximately 1/3 of stair users (Cohen & Cohen, 2001). The current results reveal that even in more challenging situations such as dual-tasking, holding a handrail is still not a predominant strategy by young adults.

In the present study, the transitions were not characterized by a specific change in walk time compared to the other step regions. This could be interpreted as transitions and mid steps having similar requirements in terms of executive load, and consequently, similar strategies could be used to compensate for the dual-task challenge. It should be considered, however, that at the top of the stairs, participants were likely able to see the first steps in the lower visual field, even when looking at the monitor mounted high on the wall, which might have reduced the uncertainty regarding the beginning of the stairs and the need for major changes in gait speed. Additionally, the fact that participants widely varied in the degree they reduced gait speed prior to the second transition due to individual preferences, may have contributed to the lack of effect of transitions on walk time. Future studies with more controlled restriction conditions will be able to confirm specific requirements when walking on transition steps as well as different alternate strategies.

5.5.3 Visual dual-task

Longer reaction times were observed when walking downstairs, which was probably an effect of prioritizing locomotion and balance control over the visual task, a common strategy adopted by healthy individuals while dual-tasking (Yogev-Seligmann et al., 2008). When the visual task restricted the view of the stairs in the lower visual field (HIGH), even longer reaction times were observed, which could be linked to the additional challenge imposed by a restricted lower visual field of view. More specifically, there could have been a change in the functional field of view referring to the total visual field area in which a stimulus can be detected (Ball et al., 1988). When the central vision is engaged in an attentional visual task, the detection of stimuli in the peripheral visual field is reduced (Ball et al., 1988; Brabyn et al., 2001). The narrowing in the functional visual field is well established in a range of visual tasks involving visual function assessment, relationship with driving skills, and aging effects (Ball et al., 1988; Brabyn et al., 2001; Rogé, Pébayle, Campagne, & Muzet, 2005). However, there is less information on the relationship between functional visual field and activities requiring balance control, such as locomotion where visual information gathered from peripheral visual field is crucial. Future studies associating the concept of functional visual field and tasks challenging balance control will be able to explore the limits of the peripheral visual information in more complex contexts.

Interestingly, the shortest reaction times occurred during walking in the mid steps. Possible explanations for this result are the reduction in executive requirements to control gait in the middle steps by using knowledge gained from the interaction with the first steps and reliance on somatosensory information and a stored representation of the stairs. The highly predictable step-to-step distances surely permits a greater reliance on stored representation of the expected distances and reduced reliance on visual information. The distance in which the foot clears the steps reduces along successive steps on a staircase, which is associated with an accommodation of foot trajectory to the steps dimension, assuming that the steps are similar within a staircase (Hamel et al., 2005). This accommodation process could also reduce visual attentional demands in the mid steps, which contributed to improvement in the visual task.

Although the phases prior to transition steps did not significantly increase reaction times and accuracy, it is interesting to note that participants widely varied in accuracy prior to the last transition. This could mean that, at least in some people, there was a shift in attention to gait at the end of the stairs, as a tentative to detect the end of the stairs. This need to switch attentional resources to gait might be associated with increased downward gaze shifts performed for a few participants (e.g., foveal gaze transiently diverted from the stimulus). It is possible that in the case of participants who did not perform gaze shifts, they could also be switching attentional resources to the peripheral visual field without an associated gaze shift.

5.5.4 Individual differences

The fact that participants did not receive explicit instruction on which task they should prioritize allowed them to use different strategies to find a solution to walk while dual tasking and with the view of the stairs restricted. Some participants chose to preserve locomotor behaviour and reduce the performance in the reaction time task while others chose to preserve the performance in the reaction time task to the detriment of walking speed. The reduction in gait speed was associated with handrail use in order to increase safety on the stairs. Interestingly, individuals who employed a more cautious strategy exhibited this strategy whether or not the view of the stairs was facilitated. When participants chose to maintain walking speed, they tended to perform more gaze shifts downwards, which in some cases had an effect on the reaction time performance. In other cases, participants seemed to find a balance point between the two tasks minimizing large performance decrements in both tasks. In real world activities, this broad range of strategies is likely to happen, and possibly related to individuals perception of threat in the task. Future studies investigating individual differences will shed light into understanding challenges for balance control under dual task conditions in everyday life activities and the factors that influences locomotor strategies.

5.6 Conclusions

In the presence of a central visual task people do not look down as often when walking downstairs, which supports the use of peripheral visual information to guide stair walking. To deal with dual task conditions, individuals adopt different strategies such as walking slower, using the handrails, and looking down. Walking on the mid steps of a staircase seems to require less from executive function, whereas visual attention seems to be required to detect the last transition via gaze shifts or overt visual attention towards the peripheral vision.

Chapter 6

Study 4 – The role of the lower visual field in stair climbing

6.1 Overview

Locomotion on stairs is challenging for balance control, and is related to a significant incidence of falls. The visual system provides relevant information to guide locomotion and there is evidence that information from the peripheral visual field is specifically important to guide locomotion. The present work focused on the role of peripheral vision for walking on stairs. Healthy young adults (n=12) were asked to walk up and down a 7-step staircase while wearing customized goggles, which restricted the lower visual field (LVF). Three visual conditions varying LVF restriction were tested: full visual field (FULL VISION); 30º (MILD), and 15º (SEVERE) of lower visual field available. Step time, head pitch angle and handrail use were measured during approach, transitions (two steps at the top and bottom of the stairs) and middle step phases. Transient pitch head angles increased with LVF restriction, while walk speed decreased and handrail use increased. Stair descent appeared to be more impaired by occlusion than stair ascent, showing larger increases in head pitch angles and slower walk times. LVF restriction showed greater influence on walk time and head angle during the approach to the first transition compared to other stair regions. This study provides evidence for the use of lower visual field information to guide stair walking and its particular importance when negotiating the first few steps of a staircase. Restriction in lower visual field information during stair walking results in more cautious locomotor behaviour such as walking slower and using the handrails.

6.2 Introduction

Visual inputs provide important information to guide action and there is evidence that information from the peripheral visual field is specifically important to guide movements such as locomotion. Restriction in the lower visual field has been related to a reduction in gait speed and increase in downward head movements during walking to compensate for the reduction in peripheral visual information (Geruschat et al., 1998; Marigold & Patla, 2008; Patla, 1998). Additionally, information acquired from the lower visual field seems appropriate to control stepping reactions in response to balance perturbation (Zettel, Holbeche, McIlroy, & Maki, 2005) and implement changes in gait to avoid obstacles (Marigold et al., 2007), without the need for initial redirection of gaze towards the obstacle region or landing area.

Previous studies have attempted to determine the minimum visual field required to walk under different contexts such as natural environments, in-laboratory walking courses, and virtual environments. In such studies, walking performance is commonly assessed by global variables such as contact/collisions with objects in the environment or walking speed. Overall, these studies have shown that loss in the central 21° of visual field and the lower visual field (radius 58°) is associated with a reduction in gait speed and contact/collisions with objects in the environment tested in individuals with simulated and actual visual field loss (Hassan et al., 2007; Lovie-Kitchin, Mainstone, Robinson, & Brown, 1990).

The present work focused on the role of peripheral vision for the control of walking on stairs. Considering the apparent importance of the lower visual field information during the performance of level ground locomotor tasks, information from the peripheral visual field is likely very important during stair walking where foot placement is more constrained. Although the role of the peripheral visual field information has not been specifically investigated during stair walking, there is some indirect evidence that supports this view. First, central visual information about the steps does not seem to be a requirement for stair ascent/descent as demonstrated in the Studies 2 and 3 of this thesis, where individuals were able to successfully walk with minimal foveal fixations on the stairs. Second, from Study 3, the view of the stairs in the lower visual field seems adequate to guide stairs walking. Study 3 revealed that gaze shifts downwards rarely occur when the view of the stairs is available in the lower visual field. A potential benefit of relying on peripheral visual information to control stair walking is the release of the central vision for the performance of another concurrent task or acquisition of more specific information regarding navigation.

The present study investigated the role of the lower visual field (LVF) during stair ascent and descent. Two different levels of restriction in the LVF were applied in this study (mild and severe LVF restriction). It was expected that locomotor behaviour would be more affected during descent compared to ascent, observed by increased handrail use, reduction in gait speed, and increase in head tilt. For the restriction levels in the LVF, it was expected that the mild level restriction would have no effects on locomotion and head tilt. However, it was hypothesized that the severe restriction in the LVF would cause compensatory strategies in order to extract enough online visual information during stair walking marked by an increase in head angle (to redirect gaze). Additionally, locomotor behaviour was expected to be influenced by the severe restriction in the LVF including a reduction in walking speed and increased handrail use. Finally, it was expected that the severe restriction in the LVF would have a stronger effect during the transition to stairs, demonstrated by increased head tilt, reduction in gait speed, and handrail reaching movement during the approach to the transition and during the transition.

6.3 Methods

6.3.1 Participants

Twelve healthy young adults (6 females and 6 males) participated in this study (mean age=29.7±3.1 years, height=168.1±6.5cm). Participants were free of any medical condition affecting their balance or ability to traverse stairs. All participants showed normal vision or vision corrected to normal with contact lenses in terms of visual acuity (Snellen test) and contrast sensitivity (Mars Letter test). This study received Ethics approval from the Office of Research Ethics at the University of Waterloo and all participants provided written consent to participate in the study.

6.3.2 Protocol

Participants were asked to walk up and down the 7-step staircase used in the previous studies. Handrails were present in both sides of the stairs. A walkway was extended at the bottom step (approximately 3 m long), and at the top step (by a 2.23 vs. 1.22 m lift table). Participants wore a safety harness attached to a retractable lanyard running along a cable above the stairs and walkway. At the beginning of each trial, participants were asked to look straight ahead and keep a comfortable head and gaze line. Participants alternately walk up and down the stairs at their self-selected pace; participants walked for at least 3 steps before reaching the stairs and following the stairs. At the end of a trial, participants were asked to turn around and get in position for the next trial, at one of 5 different start points marked on floor. The starting points varied by 20cm from each other, at a distance from the stairs that required a minimum of 3 steps before reaching the first stair-step.

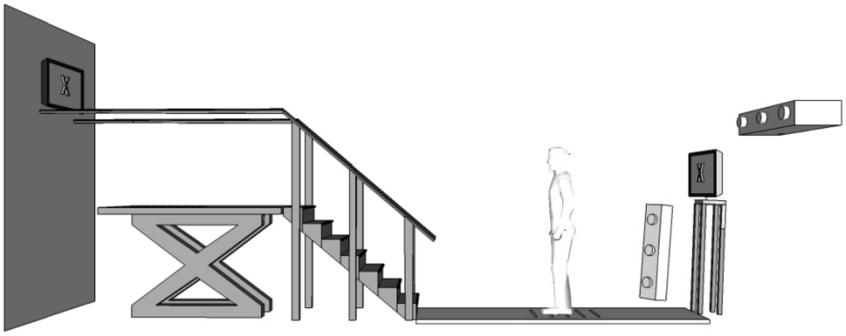

Figure 6.1: Schematic of the experimental setup (details in the text).

Three visual conditions were tested: 1) full visual field (FULL VISION); 2) mild occlusion consisting of more than 30º of lower peripheral visual field available (MILD), and 3) a more severe occlusion, with less than 15º of lower peripheral visual field available (SEVERE). Visual occlusion was applied by having participants wearing customized safety goggles with the lens covered with adhesive paper at the level of the desired occlusion. An arc perimeter was used to set the occlusion levels. Participants were asked to sit in front of the arc perimeter with head constrained by a chin rest. Participants fixated on the central point in the arc perimeter and slowly moved a piece cardboard on the surface of the safety goggles until they were able to see a mark at 15º and 30º below the central point in the perimeter, respectively. The position of the cardboard was tested 3 times for each occlusion level and the average of the three measures was used to set the occlusion during the experimental trials. During the FULL VISION condition, participants wore the same clear safety goggles without occlusion. Participants performed 5 trials in each walk direction (including ascent and descent) in each level of occlusion. Stair walking trials were alternated between ascent (UP) and descent (DOWN). Blocks of trials for each occlusion level were randomly presented across subjects.

In order to avoid consistent downward head positions with occlusion and to better reveal head pitch instances, half of the trials required that participants look at a visual target displayed in a monitor screen during stair walking (FIX). One computer monitor was placed at each end of the pathway (i.e., upstairs and downstairs) at 3 m from the stairs and at 1.5m height. In the other half of trials, participants had no specific instruction on where to gaze (FREE). In summary, each participants performed a total of 60 trials, with 5 trials in each condition combining stair direction (UP and DOWN), visual field (FULL VISION, MILD, SEVERE), and gaze (FIX and FREE).

6.3.3 Data acquisition and analysis

Footswitches (B&L Engineering, Tustin, CA, USA) were placed inside of participant's shoes to provide temporal measurement of their steps. An infrared light switch positioned at the bottom step was used to denote the timing just prior to contact with the bottom step. Footswitch and infrared switch data were collected at 240Hz and recorded using a program written in LabVIEW (National Instruments, Austin, TX, USA). Footswitch data provided time series of foot-contact and foot-off times for every step for each trial. In combination with the infrared signal prior to contact with the bottom step, footswitch data were used to determine participants' stepping location with respect to the stairs. Participant's location was classified in one of the following categories (Figure 6.2) : a) approach (AP), from two steps (-2FC) to the last foot contact before the stair (0FC), d) first transition (T1), from 0FC to the foot contact on the step 2 (2FC); e) first mid steps (MS1), from 2FC to the foot contact on the step 4 (4FC); f) second mid steps (MS2), from 4FC to the foot contact on the step 6 (6FC); g) and second transition (T2), from 6FC to the first foot contact out of the stairs (8FC).

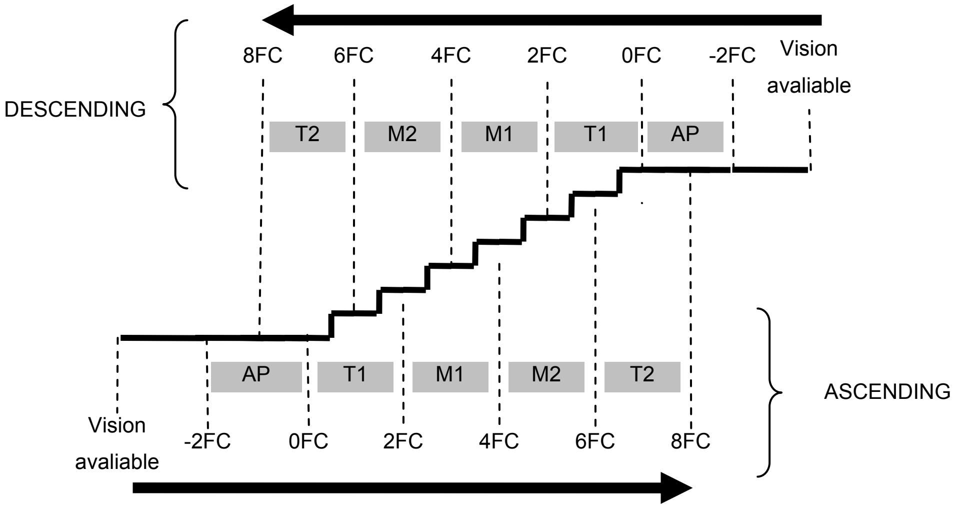

Figure 6.2: Classification scheme for participant's location when ascending and descending the stairs. Top of the figures shows location for stair descent and bottom for stair ascent. AP = approach; T1 = first transition; M1 = first mid step region; M2 = second mid step region; T2=second transition; -2FC=two foot contacts before stepping on the stair; 0FC= last foot contact before the stair; 2FC=foot contact on the step 2; 4FC =foot contact on the step 4; 6FC= foot contact on the step 6; 8FC=first foot contact out of the stairs.

Walk time was calculated from -2FCto 8FC, as well as for each step region (AP, T1, MS1, MS2, T2). Additionally handrail use was obtained from the video recordings. The frequency of trials that handrail was held per condition was calculated.

Head movement was recorded by an Optotrak system (3020, Northern Digital, CA). Clusters of active markers were mounted on two plates. The plates were attached on a head frame at the forehead (3 markers) and at the back of the head (4 markers). Markers were collected at 120Hz and filtered at 2Hz. Pitch head angle was calculated using Cardan angle rotation sequence. Head pitch angle was calculated relative to reference vertical line in the experiment coordinate system. Head angle during the trials was normalized by the head angle during quiet standing, with the participant looking comfortably straight ahead. Therefore, a positive normalized head angle represented greater head pitch and a negative value will give a reduced head tilt. The mean and maximum head angle was calculated per participant and per condition.

Walk time, mean head angle, maximum head angle, and head angle variability were analyzed by a 3-way repeated-measures ANOVA with direction (UP vs. DOWN), visual occlusion (FULL VISION, MILD, SEVERE), and visual target (FREE vs. FIX) as factors. Provided that this analysis showed similar trend for all variables between FREE and FIX (details in Results session), walk time, mean and maximum head angle, and head angle variability in FREE were independently analysed by a three-way ANOVA with occlusion (FULL VISION, MILD, SEVERE), stair direction (UP, DOWN), and stair region (AP,T1, M1, M2, and T2) as factors. FREE was selected as opposed to FIX because it provided a more ecologically relevant condition. Additionally, a 3-way ANOVA was computed for the percentage of trials with handrail use with direction, occlusion and stair region as factors. Post-hoc analysis (Tukey adjustment) was performed to characterize the differences in gaze behaviour across visual conditions and walking direction. Significance level will be set at 0.05 for all analyses.

6.4 Results

6.4.1 Locomotion

For the overall time spent to walk on the stairs, there was a significant main effect for occlusion ($F(2,22)=22.86$, $p<0.001$) and direction vs. occlusion interaction ($F(2,22)=5.12$, $p=0.0149$; Figure 6.3). Stair walking time significantly increased as occlusion level increased for both walking UP and DOWN. Walk time was moderately shorter in DOWN compared to UP only in the full vision condition.

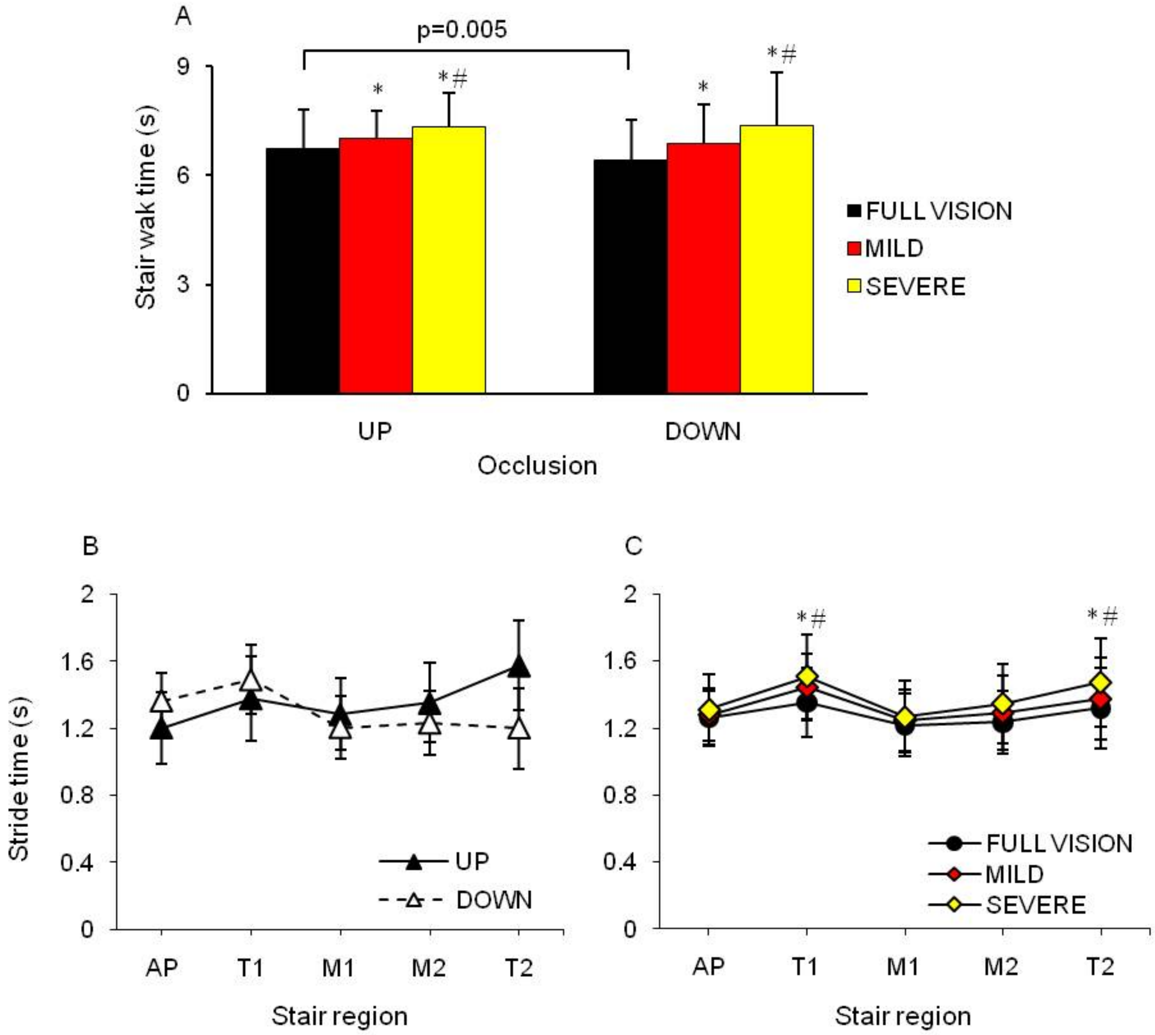

Figure 6.3: (A) Stair walk time across for UP and DOWN in each occlusion condition. (B) Stride time in each stair region for UP and DOWN. (C) Stride time in each stair region according to occlusion condition. FULL VISION: no vision occlusion; MILD: 15º occlusion; SEVERE: 30º occlusion; *denotes significant difference compared to the respective FULL VISION condition ($p<0.05$); #significant difference compared to respective MILD condition ($p<0.05$).

For stride time in the FREE gaze condition, there was a main effect for direction (F(1,11)=9.39, p=0.0108), occlusion (F(2,22)=12.62, $p<0.001$) and stair region (F(4,44)=14.74, $p<0.0001$). In addition, there was a significant interaction between direction and step region (F(4,44)=61.64, $p<0.0001$; Figure 6.3b), and between occlusion and step region (F(8,88)=4.84, $p<0.0001$; Figure 6.3c). Overall, the stride time was longer in SEVERE vision and in the transition regions. The interaction between direction and step region revealed that stride time was increased during the approach and first transition in DOWN, and in the last transition in UP (Figure 6.3b). For occlusion level, SEVERE significantly increase stride time in T1 and T2 compared to FULL VISION and MILD conditions (Figure 6.3c).

6.4.2 Head angle

For mean head tilt angle, there was a main effect for direction ($F(1,11)=97.43$, $p<0.0001$), occlusion ($F(2,22)=25.78$, $p<0.0001$), and gaze ($F(1,11)=6.03$, $p=0.032$; Figure 6.4a), and an interaction between direction and occlusion ($F(2,22)=3.93$, $p<0.035$; Figure 6.4b). As might be expected, the mean head angle was increased in DOWN compared to UP conditions and during the FREE condition compared to FIX gaze condition. Mean head angle also increased with occlusion level though there was no statistical difference in mean head angle between SEVERE and MILD in DOWN condition.

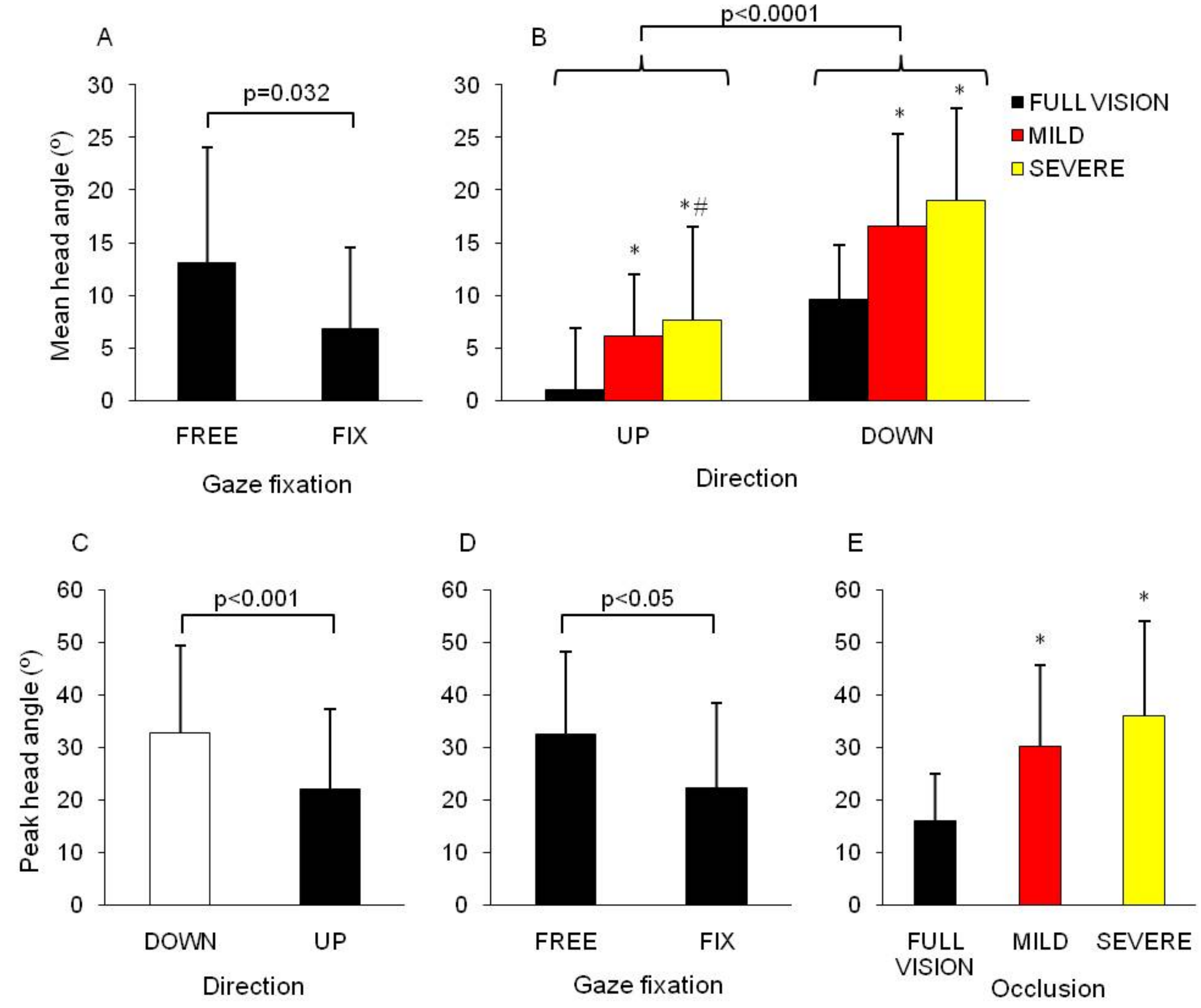

Figure 6.4: (A) Mean head angle as a function of gaze fixation. (B) Mean head angle across walk direction and occlusion. (C) Peak head angle as a function of stair walk direction. (D) Peak head angle as a function of gaze. (E) Peak head angle as a function of occlusion level. (FULL VISION: no vision occlusion, MILD: 15º occlusion; SEVERE: 30 occlusion; FREE: no visual target; FIX: visual target; UP: stair ascent; DOWN: stair descent; *significant different from FULL VISION in the respective walk direction, p<0.001; # significant different from MILD in the respective walk direction, p<0.05).

Peak head angle followed a similar pattern to mean head angle. For peak head angle, there was a main effect for direction (F(1,11)=31.41, p=0.0002), gaze (F(1,11)=8.33, p=0.015), and occlusion (F(2,22)=32.85, p<0.0001). Peak head angle was larger during DOWN compared to UP (Figure 6.4c), and during FREE compared to FIX (Figure 6.4d). Additionally, peak head angle was significantly lower in FULL VISION compared to MILD and SEVERE (Figure 6.4e).

Importantly while FIX condition produced head angles with smaller magnitudes than FREE, there was no interaction between FIX/FREE and direction of walking or degree of occlusion. As a result, the following analysis considered head angles only in FREE to investigate the differences across step regions (noting that head angles in FIX showed similar trend).

For mean head angle in each step region, there was a main effect for direction ($F(1,11)=89.96$, $p<0.0001$), occlusion ($F(2,22)=20.54$, $p<0.0001$) as expected from the previous analysis. In addition there was a significant difference related to step region ($F(4,88)=25.06$, $p<0.0001$), and an interaction between direction vs. step region ($F(4,44)=27.15$, $p<0.0001$) and occlusion vs. step region ($F(8,88)=9.97$, $p<0.0001$). Overall, mean head angle was increased in DOWN compared to UP in all step regions excluding T2 (Figure 6.5A). Mean head angle decreased in all step regions in DOWN, while it decreased from AP to M1in UP. Additionally, although mean head angle remained the same in FULL VISION both occlusion levels (MILD and SEVERE) resulted in larger mean head angle across all step regions excluding T2 (Figure 6.5B).

For peak head angle across step regions there was a main effect for direction ($F(1,11)=76.03$, $p<0.0001$), occlusion ($F(2,22)=25.29$, $p<0.0001$) and step region ($F(4,88)=35.59$, $p<0.0001$). Similar to mean head angle, there were interactions between direction and stair region ($F(4,44)=14.45$, $p<0.0001$) and occlusion and step region ($F(8,88)=14.22$, $p<0.0001$). Larger peak head angle was observed in DOWN compared to UP in all step regions excluding T2 (Figure 6.5C). Peak head angle decreased in every stair region in DOWN, while it decreased from AP to M1 while walking UP. Peak head angle was similar across all step regions in FULL VISION (Figure 6.5D). In comparison to

FULL VISION, both occlusion levels (MILD and SEVERE) resulted in larger peak head angles across all stair regions. The largest peak angles occurred in the SEVERE occlusion condition.

For head angle variability, there was a main effect for occlusion ($F(2,22)=12.87$, $p<0.001$), step region ($F(4,88)=9.96$, $p<0.0001$), and an interaction between occlusion and stair region ($F(4,44)=4.97$, $p<0.0001$). While head angle variability remained constant across all step regions in FULL VISION, it showed a significant increase in SEVERE occlusion at the approach and initial transition phases, and in the transition phase for the MILD occlusion (Figure 6.5E).

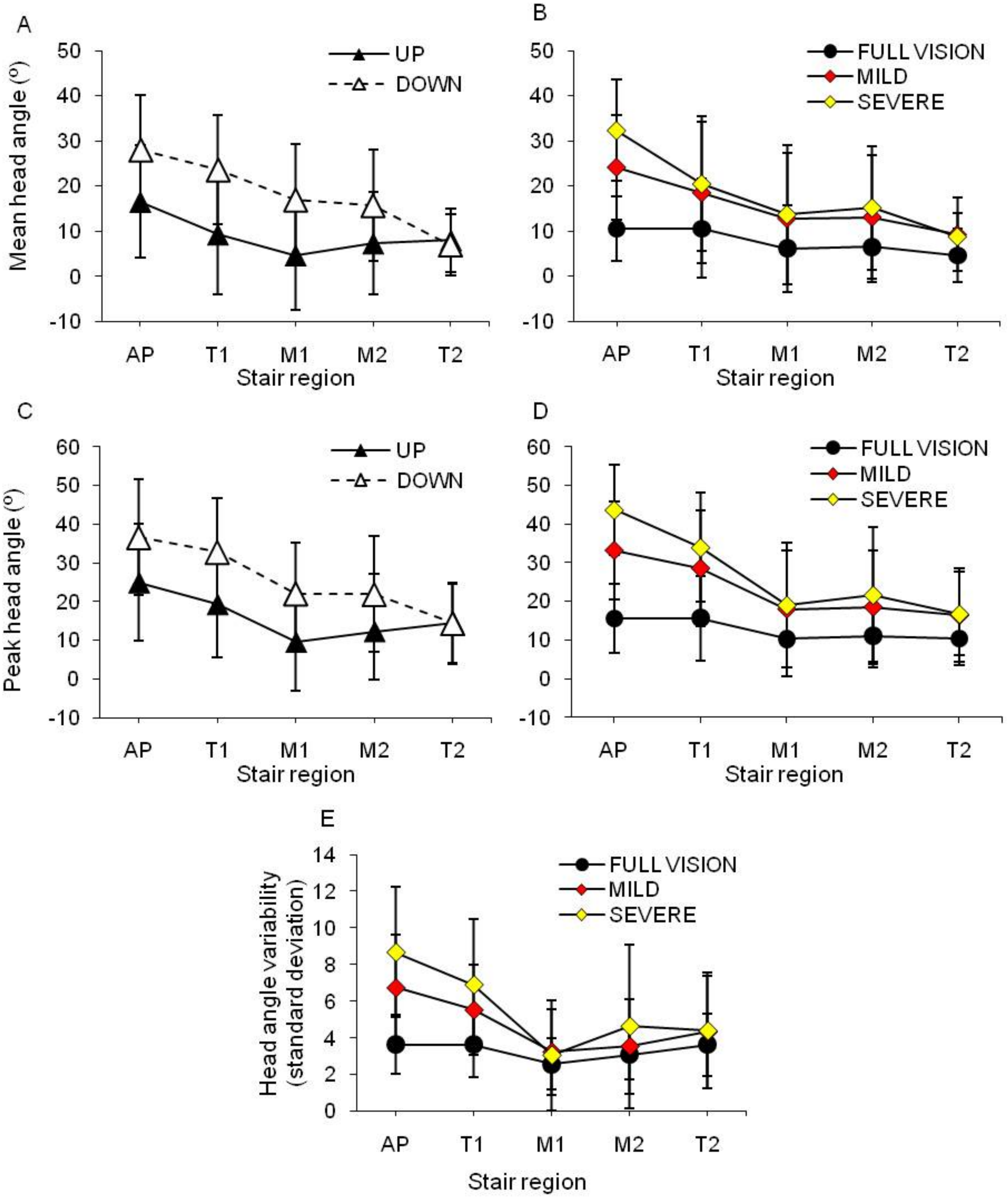

Figure 6.5: Mean head angle in each stair region according to stair walking direction (A) and in the three levels of occlusion (B). Peak head angle in each stair region according to stair walking direction (C) and in the three levels of occlusion (D). Head angle variability in each occlusion level by stair region (E); FULL VISION: no vision occlusion, MILD: 15º occlusion; SEVERE: 30º occlusion; FREE: no visual target; FIX: visual target; UP: stair ascent; DOWN: stair descent; AP: approach phase; T1: first transition; M1: mid steps 1; M2: mid steps 2; T2: second transition.

6.4.3 Handrail use

Handrail use was significantly affected by occlusion (F(2,22)=4.78, p=0.019), with increased handrail use in both MILD and SEVERE occlusions. The greatest degree of use was in walking DOWN the stairs with the SEVERE occlusion. Table 6.1 details the increased prevalence of handrail use and greater number of involved participants with increases level of occlusion and between direction and gaze conditions.

Table 6.1: Summary of handrail use. Total number of trials with handrail use and respective percentage of trials were calculated across all participants according to stair direction, occlusion level and gaze task. The number of participants who contacted the handrails for each condition is also shown.

	UP			DOWN		
	FULL VISION	MILD	SEVERE	FULL VISION	MILD	SEVERE
FREE						
Number of trials	19	28	29	18	27	39
Percentage of trials (%)	32.2	48.3	49.2	31.0	47.4	66.1
Number of participants	4	6	6	4	6	8
FIX						
Total number of trials	24	33	38	32	33	40
Percentage of trials	40.7	56.9	65.5	56.1	56.9	66.7
Number of participants	5	7	8	7	7	8

6.4.4 Adverse events during the experiment

During the experiment, there was no occurrence of any trial in which a participant lost her/his balance requiring the use of the harness to stop a fall. However, there were a few trials where participants interrupted the stair walking, which was possibly linked to the restriction in the lower visual field. Table 6.2 summarizes the occurrence of these trials. It can be observed that most of the events occurred in DOWN and under some level of occlusion. In many trials participants reported they were “expecting one more step” and it could be observed in the video recordings a respective trajectory of the foot landing on the ground as it was reaching a stair step. In addition to these trials in which there was clear evidence of a disruption to walking and likely some degree of instability, there were also some trials that were characterized by unusual foot contacts that did not result in apparent interruption of walking. These were most commonly seen as the heel making contact with the edge of the step during the swing phase. This heel contact on the edge of the step was observed in the video recordings and confirmed by the footswitch data. From the 25 heel contacts on the step edge observed, 5 were in FULL VISION, 5 trials in MILD and 15 trials in SEVERE. In all this 25 trials, there was no apparent loss of balance or interruption of the alternate stair climbing pattern.

Table 6.2: Summary of trials with observed events causing interruption of alternate gait pattern.

Direction	Occlusion	Gaze	Participant	Event
UP	SEVERE	FIX	S3	Expected an extra step at the bottom
	MILD	FREE	S2	Instability backwards at the first step
DOWN	FULL VISION	FREE	S8	Missed the last step
		FIX	S10	Missed the last step
	MILD	FREE	S8	Missed the last step
		FIX	S10	Stopped walking prior to first step and reached for the handrail
			S11	Expected an extra step at the bottom
	SEVERE	FREE	S1	Expected an extra step at the bottom
			S6	Did not expected the last step (participant thought having reached the last step at step# 5-6)
		FIX	S3	Stopped walking prior to the first step to look down
			S7	Expected an extra step at the bottom

6.5 Discussion

The aim of this study was to investigate the role of the lower visual field in stair locomotion. Young healthy adults walked upstairs and downstairs, with the lower visual field occluded to a varying degree. Overall the study revealed changes in behaviour (head pitch angles, walking speed, handrail use and unusual events) that were associated with the degree of occlusion and reinforced the importance of the lower visual field for stair walking. It was found that pitch head angles increased with occlusion, while walk speed decreased and handrail use was increased. Stair descent appeared to be more disrupted by occlusion than stair ascent, showing a larger increase in head pitch angles and walk time. Finally, occlusion of the lower visual field showed a greater effect on walk time and head angle in the approach to the first transition compared to other stair regions.

The present findings indicate the role of visual information acquired from the lower visual field for stair locomotion. When lower visual information is restricted, individuals walked more cautiously on the stairs by reducing gait speed and using the handrail. Such cautious locomotor behaviour has been reported when peripheral visual information is restricted during other locomotor tasks, such as walking avoiding obstacles (Geruschat et al., 1998) and on irregular terrains (Marigold & Patla, 2008). Interestingly, stair descent was more affected by lower visual field occlusion than stair ascent. A possible cause for this finding is that lower visual field restriction during stair descent is more likely to remove a greater amount of the steps in the visual field, differently from stair ascent, in which the stairs (or at least some steps) is likely to fill the field of view when an individual approaches the stairs. The greater effect of lower visual field restriction in stair descent may also relate to the greater incidence of accidents during stair descent compared to ascent reported in the literature (Cohen et al., 1985; Tinetti et al., 1988).

Although a number of studies have evidenced the importance of the peripheral visual field during over ground walking, it is has not been well established the extent of field of view that is required. For safe driving, for instance, a minimum of 15º degrees above and below fixation point is required (Canadian Ophthalmological Society, 2000). Additionally, in a virtual environment, it was shown that a visual field raging from 11 to 32º is required for efficient navigation under a wide range of contrast levels (Hassan et al., 2007). In the present study, even a mild occlusion level (i.e., at least 30º of the lower visual field available) caused changes in head angle and locomotor behaviour, suggesting that a larger lower visual field is necessary to guide locomotion in natural environments, particularly in stair walking. Although in this study, the occlusion varied approximately ±5º between individuals and the capacity to see the stairs in the lower visual field also depends on individuals' height (which changes the height of the line of gaze), head pitch increased approximately between 10 and 15 degrees to compensate both levels of occlusion. Therefore, the severe restriction generally did not cause larger head angle than the mild level of restriction. Possibly this degree of change in head angle allowed participants to use peripheral visual information regarding the steps and at the same time minimized the change in head posture relative to gravity. During locomotion, head is actively stabilized in order to provide a stable gravitational reference for the vestibular system maximizing otolithic signal for estimate of head linear movement (Pozzo, Berthoz, & Lefort, 1990). Consequently, large changes in head posture were likely avoided during stair walking to reduce ambiguous signal between head rotation and translation.

The present findings also highlight the importance of peripheral visual information about the stairs for locomotion on transitions. When the lower visual field is restricted, gait speed is reduced in the transitions to and from stairs. Similar changes are observed in other locomotor tasks when the lower visual field is restricted (Graci et al., 2010; Rhea & Rietdyk, 2007). In the context of stair walking, the lower visual field provides information about the steps as well as about the near ground relative to the lower limbs. The larger increase in head pitch within two steps of entering the stairs and in the first transition indicates the importance of the lower visual field information to deal with the first steps in staircase. The fact that gait speed and head angles were less affected in the mid steps by the lower visual field restriction potentially indicates that the interaction with the first steps in a staircase provides enough information (e.g., proprioceptive information) about step configuration that helps to reduce the requirements for visual information when negotiating subsequent steps. Interestingly, restriction in the lower visual field had a smaller effect in the transition from stairs to level ground (second transition) in comparison to the first transition. One possible reason for this lack of effect of lower visual field restriction in the second transition was the fact that some participants may have counted their steps on the stairs in this repeated trial experiment. Of the 12 participants in the experiment, 3 participants declared they counted their steps every trial, while other three mentioned they counted sometimes and one participant admitted counting steps after a misstep (in the first block of trials). Anecdotally this reliance on counting is also a strategy used when individuals traverse stairs in the dark. Additionally, the fact that the stairs used in the present study had only 7 steps, may have contributed to use visual memory to control stepping throughout the entire staircase. Visual information seems to be retained for at least 4 strides (8 steps) and used to control obstacle crossing and for around 8 seconds to step on targets (Mohagheghi et al., 2004; Thomson, 1980), which suggest that similar visual stored representation of the stair could have been used.

In summary, this study showed evidence for the use of lower visual field information to guide stair walking and its particular importance when negotiating the first few steps in a staircase. Restriction in lower visual field information during stair walking results in more cautious locomotor behaviour such as walking slower and using the handrails.

Chapter 7

General Discussion

The motivation of this thesis was to gather a better understanding on the role of vision during locomotion specifically in stair walking. Stair walking is a challenging task, requiring precise foot placement and balance control demands. These increased demands could potentially create a scenario to reveal in more depth the relevance of visual information during locomotion and importantly provide understanding that might address the high prevalence of falls that occur on stairs, particularly within the top and bottom steps (transitions). From the experiments described in this thesis, it was observed that healthy young adults consistently look down to the steps but rarely look at the handrails (Study 1). Interestingly, when people are challenged during stair walking to perform a concurrent visual task (Study 2 and 3), they drastically reduce the time they look at the steps, giving an indication that they may monitor the steps through peripheral vision rather than foveal vision. This is finally confirmed in Study 4 where individuals had a need to increase head movements downwards when they had peripheral vision occluded. Generally, manipulation of dual-tasks and visual field occlusion required participants to reduce gait speed, use the handrails and decrease performance in the secondary task. Importantly, these studies also revealed differences between subjects showing that even among young adults, individuals have individualized strategies to solve control challenges.

7.1 Contributions for the understanding of the role of visual information during locomotion

7.1.1 Stairway models

In the stair behaviour models proposed by Archea et al. (1979) and Templer (1992), vision has an important role during stair walking (Figure 2.1). For instance, when approaching a staircase it is suggested that individuals perform a "conceptual scan" to form a cognitive model of the stairs, and "close-up fixation looking down on the first step" (Templer, 1992). Results from this thesis could support the idea of a conceptual scan occurring prior to stair ascent since during unconstrained stair walking, the line of gaze is directed to the stairs ahead, and generally people look down within three steps to reach the stairs. However, the experiments in this thesis also demonstrated that people do not often look in advance to the steps during stair descent nor while performing a concurrent visual task when walking up or down. Indeed some people do not foveate directly onto the steps whatsoever, suggesting that the first step location and general properties of stairs could be determined by peripheral vision.

Considering a main purpose for the conceptual scan is to detect potential hazards and peculiarities in a staircase, it is possible that under very predictable environment and standard staircases (such was the case in this thesis), these conceptual scans can be as short as a snapshot of the environment, and visual information is acquired from the visual field as a whole rather than from active foveal visual scan. People are able to detect global features in a scene ("scene gist") from glances as short as 26ms, such as categorizing natural scenes (Rousselet, Joubert, & Fabre-Thorpe, 2005). Additionally, environmental information via peripheral visual field seems plausible since objects requiring large-scale integration of features (e.g., buildings) tend to activate retinotopic visual areas that overlap the peripheral visual field representation (Levy, Hasson, Avidan, Hendler, &

Malach, 2001). Possibly, peripheral visual information is effective enough for detection of the first step. In the case of any detected abnormal characteristics of the stairs (e.g., differences in step dimensions, another stair user, low light level, etc) prolonged visual scanning including gaze fixations would probably be observed. It is also possible that in more challenging situations, such as low contrast or illumination there may be a greater reliance on foveal feature extraction. Based on the present findings, it seems fair to say that during stair walking under conventional conditions there is limited need for gaze fixations. An advantage to this strategy is that saccades to a target location take longer to be performed when eyes are engaged in a fixation (Kingstone & Klein, 1993). By not keeping eyes fixating during stair walking, faster saccades could be generated if any unexpected variable detected in the visual field requires redirection of foveal vision for additional visual processing.

7.1.2 Role of peripheral vision in stair walking

Using peripheral vision to control locomotion has its advantages. First, compared to foveal vision, peripheral vision can cover a wider area in the environment in which global environmental information can be acquired. Tatler et al. (2005) demonstrated that when looking at real-world scenes (rooms mimicking a kitchen, office, etc), object presence in the scene, colour of objects can be encoded via peripheral vision (no direct fixation on the object), which could certainly be important in detecting stair edges. Second, the dynamic visual information regarding the near ground provided by the lower visual field during walking likely contributes to regulation of foot trajectory for appropriate foot placement in the stairs, similarly to other locomotor tasks (Lee et al., 1982; Patla & Greig, 2006). For stair walking, this source of information seems particularly crucial to navigate the first steps on the stairs. Finally, using peripheral vision to control locomotion in the near space allows the use of foveal vision in other tasks or to scan the imminent space. The use of the lower visual field to control locomotion likely relates to the fact that gaze is directed a few steps ahead, when foveal vision is not engaged in a concurrent task. Considering that lower visual field information can be used to guide quick stepping reactions in response to balance perturbation (Zettel et al., 2005), it seems plausible its role in a regular and predictable set of stairs.

7.1.3 CNS control mechanism for visual information to control locomotion

Information gathered from central and peripheral vision is thought to be processed via two different visual systems (Milner & Goodale, 2006; Milner & Goodale, 2008): 1) ventral stream, considered the vision for perception system; and 2) dorsal stream, the vision-for-actions system. The table below summarizes the main characteristics for both systems.

Table 7.1: Ventral and dorsal stream pathways and main functions (Milner & Goodale, 2006; Milner & Goodale, 2008).

	Ventral stream	Dorsal stream
Other names	Vision-for-perception, what stream	Vision-for-action, where pathway
Neural path	From occipital lobe (primary visual cortex (V1) through the temporal lobes	From the occipital lobe to the top of the posterior parietal cortex
Functions	Cognitive processing of information and higher executive processes	Orienting gaze and sustaining attention at one location
	Assign meaning to objects and events	Rapid processing and updating of information for orientation in space and movement
	Guides the anticipation and planning of actions – takes more time	Parietal lobes appear to contain the master map of locations that we use for navigating and for controlling our orientation in space

Central vision is represented more densely in the parvocellular layers at the LGNd, which cells synapse on layers of V1 that project largely to the ventral stream. Receptive fields are more likely to include foveal regions than peripheral regions, which leads to a cortical magnification of the fovea in the ventral stream, but not necessarily in the dorsal stream. On the other hand, parvocellular density declines more rapidly with eccentricity than magnocellular density (Azzopardi, Jones, & Cowey, 1999). Interestingly, there is some overlap between the two systems. The magno-dominated pathways synapse on layers of V1 that project to both ventral and dorsal extrastriate areas (Milner & Goodale, 2006). By projecting to both systems possibly contributes for engagement of foveal vision in the event of any unexpected feature detected in the peripheral visual field requiring higher level of processing. At the same time, dorsal stream sub-areas, such as the parieto-occipital cortex, have receptive fields that represent central and peripheral visual fields relatively evenly (Colby, Gattass, Olson, & Gross, 1988), which may also justify the use of foveal vision for action.

The lower visual field seems specifically important to locomotor tasks. In comparison to the upper visual field, the lower visual field shows increased visuomotor performance, which is in part attributed to increased retinal ganglion cell density in the superior hemiretina projecting more strongly to the dorsal stream (Danckert, Sharif, & Goodale, 2001; Danckert & Goodale, 2001). Although this lower visual field specialization has been investigated only in upper limb movements, it is possible that it is also an important contributor to the control of walking.

7.2 Limitations

The four studies of this thesis focused on healthy young adults, therefore, one must be cautious about generalizing the present finding to other populations such as older adults and individuals with balance or mobility impairments. Most importantly, individuals within the same cohort may also very between each other (e.g., Study 3), therefore individual differences should also be considered.

The experiments of this thesis were conducted using a 7-step staircase with standard dimensions as recommended for home stairs (Archea et al., 1979). Considering that stairs may broadly vary, other factors such as stair dimensions, environmental conditions (illumination, indoor/outdoor), concurrent stair users, length of stairs may contribute to different results. Of particular interest would be to explore locomotion on stairs in the presence of step irregularities, such as in step dimensions (height and depth), which would give interesting insight on the limits of visual information (and in the peripheral visual information) to control stair walking and possible relation to fall risk.

Three studies in this thesis investigated gaze behaviour related to stair features by using an eye tracker. Although eye trackers provide relatively reliable measure for gaze behaviour (Patla & Vickers, 1997), limitation of this method should be considered. For instance, gaze behaviour analysis is restricted to the useful visual field range provided by the device (approximately 30° of visual field). Additionally, recordings of eye movements in a natural task in which the participant is moving could create oscillation in the gaze cursor with effects on the precision of gaze location estimation, particularly when gaze is directed to boundaries of distinct areas of interest (e.g., border between transition and mid step region). Additionally, this approach does not estimate the exact eccentricity of objects in the visual field, which limits the interpretation of the extent of the visual field necessary for stair locomotion. Future studies should look at the precision of the peripheral visual field (at different eccentricities) to detect stair features and particularly stair irregularities.

7.3 Future directions

The studies of this thesis provided basic understanding on the visual mechanisms used by young adults during stair locomotion and the particular role of peripheral visual information for stair locomotion. Future studies exploring visual field function in more challenging context and in different populations will provide additional insight in theses mechanisms.

One possible follow-up study would be to investigate age-related changes in the use of lower visual field information during stair locomotion. Previous studies have shown that with aging, locomotion is affected when a concurrent task is performed, which is related to the load in executive function (Yogev-Seligmann et al., 2008). Additionally, in visual field studies, it is been demonstrated that loss in the visual field is associated with mobility difficulties (increased contacts with objects and reduction in gait speed) (Turano et al., 2004). Older adults tend to rely more on central vision to guide walking (and stair walking) compared to young adults (Zietz & Hollands, 2009). Therefore, it is possible that dual tasking affects locomotion because of executive load or inability to use peripheral visual information, or a combination of both. To test these alternatives, an experiment could be designed in which young and older adults would walk performing a current visual task. The visual task would be manipulated in two levels: 1) executive load, and 2) environmental location. Stairs could also be used here as locomotor task. If the decrements in dual tasking are due to executive load (and narrowing in the functional visual field), even when the visual task location optimize the extraction of peripheral visual information for locomotion, significant decrement in walking performance would be observed. If there is an inability to use peripheral visual information, performance in the locomotor task will be similarly degraded independently of visual task executive load. Possible age-related differences could be found, such as that locomotion in older adults is more affected by the visual task, as they are thought to rely more on central vision to guide locomotion than young adults do. Global locomotor measures, such as walk speed and handrail use could be assessed as well as more specific measures, such as foot clearance on the steps. Gaze behaviour measures could be used to control gaze direction and provide information on eccentricity for stair features in the visual field (a recent approach proposed by Scovil and colleagues (2009).

7.4 Implications

The findings of this thesis reveal the importance of peripheral visual information during stair locomotion and this in turn may have potential implications in the field of stair design and fall prevention programs. In stair design, for instance, building codes (e.g., the Ontario Building Code, 1997) could include recommendations for stair building taking into account characteristics that optimize the use of peripheral visual information (e.g., steps and handrails with high contrast). As well, fall prevention programs could use this information in order to better instruct individuals to maximize the use of peripheral visual information about the steps during stair walking (e.g., gaze line downwards). Although such interventions still need to be tested in order to confirm their utility in reducing stair accident incidence, they appear to be feasible given the findings of this thesis.

The results of this thesis also demonstrated that by using contexts that are more challenging during stair locomotion, including dual-tasking and visual field occlusion, it was possible to influence the role of visual contributions. This has implications to the potential differences in the role of vision during more natural task conditions when distraction and concurrent task performance are common. The use of such methods in clinical settings could possibly contribute to assessment of safety and behaviour on stairs.

7.5 Conclusions

This thesis investigated the role of vision during stair walking. Stair locomotion in healthy young adults was assessed under different conditions including dual-tasking and visual field occlusion. It was observed that peripheral visual information plays a particularly important role in guiding stair walking including navigation on transitions between ground and stairs. Visual input from the lower visual field seems specifically important to guide locomotor behaviour during stair walking. The findings of this thesis may potentially contribute for the field of stair design and fall prevention programs.

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Bibliography

Aivar, M. P., Hayhoe, M. M., Chizk, C. L., & Mruczek, R. E. B. (2005). Spatial memory and saccadic targeting in a natural task. *Journal of Vision*, *5*(3), 177-193.

Andriacchi, T. P., Dyrby, C. O., & Johnson, T. S. (2003). The use of functional analysis in evaluating knee kinematics. *Clinical Orthopaedics and Related Research*, *410*, 44-53.

Andriacchi, T., Andersson, G., Fermier, R., Stern, D., & Galante, J. (1980). A study of lower-limb mechanics during stair-climbing. *Journal of Bone and Joint Surgery Am*erican, *62*(5), 749-757.

Archea, J., Collins, B. L., & Stahl, F. I. (1979). *Guidelines for stair safety*. Washington, DC: National Bureau of Standards. Retrieved from http://openlibrary.org/b/OL4062675M/Guidelines-for-stair-safety

Azzopardi, P., Jones, K. E., & Cowey, A. (1999). Uneven mapping of magnocellular and parvocellular projections from the lateral geniculate nucleus to the striate cortex in the macaque monkey. *Vision Research*, *39*(13), 2179-2189.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: expanding the useful field of view. *Journal of the Optical Society of America A*, *5*(12), 2210-2219.

Ballard, D. H., Hayhoe, M. M., & Pelz, J. B. (1995). Memory representations in natural tasks. *Journal of Cognitive Neuroscience*, *7*(1), 66-80.

Bardy, B., Warren, W., & Kay, B. (1996). Motion parallax is used to control postural sway during walking. *Experimental Brain Research*, *111*(2), 271-282.

Bateni, H., Zecevic, A., McIlroy, W. E., & Maki, B. E. (2004). Resolving conflicts in task demands during balance recovery: does holding an object inhibit compensatory grasping? *Experimental Brain Research*, *157*(1), 49-58.

Berard, J., & Vallis, L. (2006). Characteristics of single and double obstacle avoidance strategies: A comparison between adults and children. *Experimental Brain Research*, *175*(1), 21-31.

Brabyn, J., Schneck, M., Haegerstrom-Portnoy, G., & Lott, L. (2001). The Smith-Kettlewell Institute (SKI) longitudinal study of vision function and its impact among the elderly: an overview. *Optometry and Vision Science*, *78*(5), 264-269.

Brechter, J. H., & Powers, C. M. (2002). Patellofemoral joint stress during stair ascent and descent in persons with and without patellofemoral pain. *Gait & Posture*, *16*(2), 115-123.

Canadian Ophthalmological Society Working Group on Driving Standards (2000). Canadian Ophthalmological Society recommendations for driving standards and procedures in Canada. *Canadian Journal of Ophthalmology*, *35*(4), 187-191.

Cavanagh, P. R., Mulfinger, L. M., & Owens, D. A. (1997). How do the elderly negotiate stairs? *Muscle & Nerve. Supplement*, *5*, S52-55.

Cavanagh, P. R., & Higginson, J. S. (2003). What is the role of vision during stair descent? In A. Jeffrey, Owens, D. Alfred, & Harvey, Lewis O., Jr. (Eds.), *Visual perception: The influence of H. W. Leibowitz*, Decade of behavior. (pp. 213-242). Washington, DC, US: American Psychological Association.

Cesari, P. (2005). An invariant guiding stair descent by young and old adults. *Experimental Aging Research*, *31*(4), 441-455.

Cinelli, M. E., Patla, A. E., & Allard, F. (2008). Strategies used to walk through a moving aperture. *Gait & Posture*, *27*(4), 595-602.

Cinelli, M. E., Patla, A. E., & Allard, F. (2009). Behaviour and gaze analyses during a goal-directed locomotor task. *The Quarterly Journal of Experimental Psychology. Section A, Human Experimental Psychology*, *62*(3), 483-499.

Cohen, H. H., Templer, J., & Archea, J. (1985). An analysis of occupational stair accident patterns. *Journal of Safety Research*, *16*(4), 171-181.

Cohen, J., & Cohen, H. H. (2001). Hold on! An Observational Study of Staircase Handrail Use. *Human Factors and Ergonomics Society Annual Meeting Proceedings*, *45*, 1502-1506.

Colby, C. L., Gattass, R., Olson, C. R., & Gross, C. G. (1988). Topographical organization of cortical afferents to extrastriate visual area PO in the macaque: a dual tracer study. *The Journal of Comparative Neurology*, *269*(3), 392-413.

Danckert, J., Sharif, N., & Goodale, M. (2001). Intercepting moving targets in the upper and lower visual fields. *Journal of Vision*, *1*(3), 319a.

Danckert, J., & Goodale, M. A. (2001). Superior performance for visually guided pointing in the lower visual field. *Experimental Brain Research*, *137*(3), 303-308.

Davies, J. C., Kemp, G. J., Stevens, G., Frostick, S. P., & Manning, D. P. (2001). Bifocal/varifocal spectacles, lighting and missed-step accidents. *Safety Science*, *38*(3), 211-226.

Fitch, J. M., Templer, J., & Corcoran, P. (1974). The dimensions of stairs. *Scientific American*, *231*, 82-90.

Geruschat, D., Turano, K., & Stahl, J. (1998). Traditional measures of mobility performance and retinitis pigmentosa. *Optometry and Vision Science*, *75*(7), 525-537.

Ghafouri, M., McIlroy, W. E., & Maki, B. E. (2004). Initiation of rapid reach-and-grasp balance reactions: is a pre-formed visuospatial map used in controlling the initial arm trajectory? *Experimental Brain Research*, *155*(4), 532-536.

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

Government of Canada, P. H. A. O. C. (2005). Technical Reports: Injury Resulting from Falls Among Canadians Age 65 and Over - Report on Seniors' Falls in Canada - Public Health Agency of Canada. Retrieved March 19, 2010, from http://www.phac-aspc.gc.ca/seniors-aines/publications/pro/injury-blessure/falls-chutes/tech/injury-blessures-eng.php

Graci, V., Elliott, D., & Buckley, J. (2010). Utility of peripheral visual cues in planning and controlling adaptive gait. *Optometry and Vision Science*, *87*(1), 21-27.

Hall, N. B. J., & Bennett, E. M. (1956). Empirical assessment of handrail diameters. *Journal of Applied Psychology*, *40*(6), 381-382.

Hamel, K. A., Okita, N., Bus, S. A., & Cavanagh, P. R. (2005). A comparison of foot/ground interaction during stair negotiation and level walking in young and older women. *Ergonomics*, *48*(8), 1047-1046.

Hamel, K. A., Okita, N., Higginson, J. S., & Cavanagh, P. R. (2005). Foot clearance during stair descent: effects of age and illumination. *Gait & Posture*, *21*(2), 135-140.

Hassan, S. E., Hicks, J. C., Lei, H., & Turano, K. A. (2007). What is the minimum field of view required for efficient navigation? *Vision Research*, *47*(16), 2115-2123.

Hayhoe, M., & Ballard, D. (2005). Eye movements in natural behavior. *Trends in Cognitive Sciences*, *9*(4), 188-194.

Hemenway, D., Solnick, S. J., Koeck, C., & Kytir, J. (1994). The incidence of stairway injuries in Austria. *Accident Analysis & Prevention*, *26*(5), 675-679.

Hollands, M. A., Marple-Horvat, D. E., Henkes, S., & Rowan, A. K. (1995). Human eye movements during visually guided stepping. *Journal of Motor Behavior*, *27*(2), 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*(2), 221-230.

Irvine, C., Snook, S., & Sparshatt, J. (1990). Stairway risers and treads: acceptable and preferred dimensions. *Applied Ergonomics*, *21*(3), 215-225.

Jeka, J. J., Easton, R. D., Bentzen, B. L., & Lackner, J. R. (1996). Haptic cues for orientation and postural control in sighted and blind individuals. *Perception & psychophysics*, *58*(3), 409-423.

Jeka, J. J., & Lackner, J. R. (1994). Fingertip contact influences human postural control. *Experimental Brain Research*, *100*(3), 495-502.

Johnson, L., Buckley, J. G., Scally, A. J., & Elliott, D. B. (2007). Multifocal spectacles increase variability in toe clearance and risk of tripping in the elderly. *Investigative Ophthalmology & Visual Science*, *48*(4), 1466-1471.

King, E., Lee, T., & Maki, B. (2007). Does peripheral vision contribute to online control of grasping reactions evoked by an unexpected perturbation when walking in an unfamiliar environment? (p. 84). Presented at the 18th ISPGR Conferece, Vermont, USA. Retrieved from http://ispgr.org/conferences/vermont-2007/abstracts-online/index.html

Kingstone, A., & Klein, R. (1993). Visual Offsets Facilitate Saccadic Latency: Does Predisengagement of Visuospatial Attention Mediate This Gap Effect? *Journal of Experimental Psychology: Human Perception and Performance*, *19*(6), 1251-1265.

Konczak, J., Meeuwsen, H. J., & Cress, M. E. (1992). Changing affordances in stair climbing: the perception of maximum climbability in young and older adults. *Journal of Experimental Psychology. Human Perception and Performance*, *18*(3), 691-697.

Land, M. F., & Lee, D. N. (1994). Where we look when we steer. *Nature*, *369*(6483), 742-744.

Land, M. F. (2006). Eye movements and the control of actions in everyday life. *Progress in Retinal and Eye Research*, *25*(3), 296-324.

Land, M. F. (2009). Vision, Eye Movements, and Natural Behavior. *Visual Neuroscience*, *26*(01), 51-62.

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

Lee, H., & Chou, L. (2007). Balance control during stair negotiation in older adults. *Journal of Biomechanics*, *40*(11), 2530-2536.

Lee, T., Scovil, C., McKay, S., Peters, A., & Maki, B. (2007). Age-related differences in reach-to-grasp reactions and associated gaze behavior evoked by unexpected perturbation when walking in an unfamiliar environment (p. 94). Presented at the 18th ISPGR Conferece, Vermont, USA. Retrieved from http://ispgr.org/conferences/vermont-2007/abstracts-online/index.html

Levy, I., Hasson, U., Avidan, G., Hendler, T., & Malach, R. (2001). Center-periphery organization of human object areas. *Nat Neurosci*, *4*(5), 533-539.

Long, R. G., Rieser, J. J., & Hill, E. W. (1990). Mobility in individuals with moderate visual impairments. *Journal of Visual Impairment & Blindness. Vol 84(3)*, 111-118.

Lord, S. R., Dayhew, J., & Howland, A. (2002). Multifocal Glasses Impair Edge-Contrast Sensitivity and Depth Perception and Increase the Risk of Falls in Older People. *Journal of the American Geriatrics Society*, *50*(11), 1760-1766.

Lord, S. R., & Dayhew, J. (2001). Visual risk factors for falls in older people. *Journal of the American Geriatrics Society*, *49*(5), 508-515.

Lovie-Kitchin, J., Mainstone, J., Robinson, J., & Brown, B. (1990). What areas of the visual field are important for mobility in low vision patients? *Clinical Vision Sciences*, *5*(3), 249-263.

Maki, B. E., & McIlroy, W. E. (2006). Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. *Age and Ageing*, *35 Suppl 2*, ii12-ii18.

Maki, B. E., Perry, S. D., & McIlroy, W. E. (1998). Efficacy of handrails in preventing stairway falls: a new experimental approach. *Safety Science*, *28*(3), 189-206.

Maki, B. E., & McIlroy, W. E. (2007). Cognitive demands and cortical control of human balance-recovery reactions. *Journal of Neural Transmission*, *114*(10), 1279-1296.

Marigold, D. S., & Patla, A. E. (2007). Gaze fixation patterns for negotiating complex ground terrain. *Neuroscience*, *144*(1), 302-313.

Marigold, D., & Patla, A. E. (2008). Visual information from the lower visual field is important for walking across multi-surface terrain. *Experimental Brain Research*, *188*(1), 23-31.

Marigold, D., Weerdesteyn, V., Patla, A. E., & Duysens, J. (2007). Keep looking ahead? Re-direction of visual fixation does not always occur during an unpredictable obstacle avoidance task. *Experimental Brain Research*, *176*(1), 32-42.

McFadyen, B. J., & Carnahan, H. (1997). Anticipatory locomotor adjustments for accommodating versus avoiding level changes in humans. *Experimental Brain Research*, *114*(3), 500-506.

McFadyen, B. J., & Winter, D. A. (1988). An integrated biomechanical analysis of normal stair ascent and descent. *Journal of Biomechanics*, *21*(9), 733-744.

McFadyen, B., Bouyer, L., Bent, L., & Inglis, J. (2007). Visual-vestibular influences on locomotor adjustments for stepping over an obstacle. *Experimental Brain Research*, *179*(2), 235-243.

McGuire, M. C. (1971). Preventive measures to minimize accidents among the elderly. *Occupational Health Nursing*, *19*(4), 13-18.

McKenzie, B. E., & Forbes, C. (1992). Does vision guide stair climbing? A developmental study. *Australian Journal of Psychology*, *44*(3), 177-183.

Meeuwsen, H. J. (1991). Variables affecting perceptual boundaries in bipedal stair climbing. *Perceptual and Motor Skills*, *72*(2), 539-543.

Millodot, M. (2008). *Dictionary of Optometry and Visual Science*. Elsevier/Butterworth-Heinemann.

Milner, A. D., & Goodale, M. A. (2006). *The visual brain in action*. Oxford, Oxford University Press.

Milner, A. D., & Goodale, M. (2008). Two visual systems re-viewed. *Neuropsychologia*, *46*(3), 774-785.

Miyasike-daSilva, V., Allard, F., & McIlroy, W. E. (2011). Where do we look when we walk on stairs? Gaze behaviour on stairs, transitions, and handrails. *Experimental Brain Research*, *209*(1), 73-83.

Mohagheghi, A., Moraes, R., & Patla, A. E. (2004). The effects of distant and on-line visual information on the control of approach phase and step over an obstacle during locomotion. *Experimental Brain Research*, *155*(4), 459-468.

Ojha, H. A., Kern, R. W., Lin, C. J., & Winstein, C. J. (2009). Age affects the attentional demands of stair ambulation: evidence from a dual-task approach. *Physical Therapy*, *89*(10), 1080-1088.

Ontario. Ministry of Municipal Affairs and Housing. (1997). *Ontario Buiding Code 1997*. Toronto.

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

Patla, A. E., Adkin, A., Martin, C., Holden, R., & Prentice, S. (1996). Characteristics of voluntary visual sampling of the environment for safe locomotion over different terrains. *Experimental Brain Research*, *112*(3), 513-522.

Patla, A. E., & Greig, M. (2006). Any way you look at it, successful obstacle negotiation needs visually guided on-line foot placement regulation during the approach phase. *Neuroscience Letters*, *397*(1-2), 110-114.

Patla, A. E., Prentice, S. D., Rietdyk, S., Allard, F., & Martin, C. (1999). What guides the selection of alternate foot placement during locomotion in humans. *Experimental Brain Research*, *128*(4), 441-450.

Patla, A. E., & Vickers, J. N. (1997). Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport*, *8*(17), 3661-3665.

Patla, A. E., & 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*(1), 133-138.

Pozzo, T., Berthoz, A., & Lefort, L. (1990). Head stabilization during various locomotor tasks in humans. *Experimental Brain Research*, *82*(1), 97-106.

Protopapadaki, A., Drechsler, W. I., Cramp, M. C., Coutts, F. J., & Scott, O. M. (2007). Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. *Clinical Biomechanics*, *22*(2), 203-210.

Rhea, C. K., & Rietdyk, S. (2007). Visual exteroceptive information provided during obstacle crossing did not modify the lower limb trajectory. *Neuroscience Letters*, *418*(1), 60-65.

Riener, R., Rabuffetti, M., & Frigo, C. (2002). Stair ascent and descent at different inclinations. *Gait & posture*, *15*(1), 32-44.

Rogé, J., Pébayle, T., Campagne, A., & Muzet, A. (2005). Useful visual field reduction as a function of age and risk of accident in simulated car driving. *Investigative Ophthalmology and Visual Science*, *46*(5), 1774-1779.

Rosenbaum, D. A. (2009). Walking down memory lane: where walkers look as they descend stairs provides hints about how they control their walking behavior. *The American Journal of Psychology*, *122*(4), 425-430.

Rousselet, G., Joubert, O., & Fabre-Thorpe, M. (2005). How long to get to the “gist” of real-world natural scenes? *Visual Cognition*, *12*(6), 852-877.

Sakari-Rantala, R., Era, P., Rantanen, T., & Heikkinen, E. (1998). Associations of sensory-motor functions with poor mobility in 75- and 80-year-old people. *Scandinavian Journal of Rehabilitation Medicine*, *30*(2), 121-127.

Scovil, C., King, E., & Maki, B. (2009). Determining the Visual Angle of Objects in the Visual Field: An Extended Application of Eye Trackers. *Biomedical Engineering, IEEE Transactions on*, *56*(3), 910-912.

Sheldon, J. H. (1960). On the Natural History of Falls in Old Age. *British Medical Journal*, *2*(5214), 1685–1690.

Simoneau, G. G., Cavanagh, P. R., Ulbrecht, J. S., Leibowitz, H. W., & Tyrrell, R. A. (1991). The Influence of Visual Factors on Fall-related Kinematic Variables During Stair Descent by Older Women. *Journal of Gerontology*, *46*(6), M188-195.

Siu, K., Catena, R., Chou, L., Van Donkelaar, P., & Woollacott, M. (2008). Effects of a secondary task on obstacle avoidance in healthy young adults. *Experimental Brain Research*, *184*(1), 115-120.

Startzell, J. K., Owens, D. A., Mulfinger, L. M., & Cavanagh, P. R. (2000). Stair negotiation in older people: a review. *Journal of the American Geriatrics Society*, *48*(5), 567-580.

Svanstrom, L. (1974). Falls on stairs: an epidemiological accident study. *Scandinavian Journal of Social Medicine*, *2*(3), 113-120.

Szlyk, J. P., Fishman, G. A., Grover, S., Revelins, B. I., & Derlacki, D. J. (1998). Difficulty in performing everyday activities in patients with juvenile macular dystrophies: comparison with patients with retinitis pigmentosa. *British Journal of Ophthalmology*, *82*(12), 1372-1376.

Tatler, B. W., Gilchrist, I. D., & Land, M. F. (2005). Visual memory for objects in natural scenes: from fixations to object files. *The Quarterly Journal of Experimental Psychology. Section A, Human Experimental Psychology*, *58*(5), 931-60.

Templer, J. (1992). *The staircase: studies of hazards, falls, and safer design*. Cambridge, MA: MIT Press.

Tiedemann, A. C., Sherrington, C., & Lord, S. R. (2007). Physical and psychological factors associated with stair negotiation performance in older people. *Journal of Gerontology, Medical Sciences*, *62*(11), 1259-1265.

Timmis, M., Bennett, S., & Buckley, J. (2009). Visuomotor control of step descent: evidence of specialised role of the lower visual field. *Experimental Brain Research*, *195*(2), 219-227.

Tinetti, M. E., Speechley, M., & Ginter, S. F. (1988). Risk factors for falls among elderly persons living in the community. *The New England Journal of Medicine*, *319*(26), 1701-1707.

Turano, K. A., Geruschat, D. R., Baker, F. H., Stahl, J. W., & 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., Broman, A. T., Bandeen-Roche, K., Munoz, B., Rubin, G. S., & West, S. (2004). Association of visual field loss and mobility performance in older adults: Salisbury Eye Evaluation Study. *Optometry and Vision Science*, *81*(5), 298-307.

Turano, K. A., Geruschat, D. R., & Baker, F. H. (2003). Oculomotor strategies for the direction of gaze tested with a real-world activity. *Vision Research*, *43*(3), 333-346.

Turano, K. A., Yu, D., Hao, L., & Hicks, J. C. (2005). Optic-flow and egocentric-direction strategies in walking: Central vs peripheral visual field. *Vision Research*, *45*(25-26), 3117-3132.

Vickers, J. N. (2007). *Perception, cognition, and decision training*. Human Kinetics.

Warren, J., & Hannon, D. J. (1990). Eye movements and optical flow. *Journal of the Optical Society of America A*, *7*(1), 160-169.

Warren, W. H. (1984). Perceiving affordances: visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(5), 683-703.

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature Neuroscience*, *4*(2), 213-216.

West, S. K., Munoz, B., Rubin, G. S., Bandeen-Roche, K., Broman, A. T., & Turano, K. A. (2005). Compensatory strategy use identifies risk of incident disability for the visually impaired. *Archives of Ophthalmology*, *123*(9), 1242-1247.

Wild, D., Nayak, U. S. L., & Isaacs, B. (1981). Description, classification and prevention of falls in old people at home. *Rheumatology*, *20*(3), 153-159.

Williamson, J. D., & Fried, L. P. (1996). Characterization of older adults who attribute functional decrements to "old age". *Journal of the American Geriatrics Society*, *44*(12), 1429-1434.

Yarbus, A. (1967). *Eye movements and vision*. New York: Plenum Press.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders*, *23*(3), 329-342.

Zachazewski, J. E., Riley, P. O., & Krebs, D. E. (1993). Biomechanical analysis of body mass transfer during stair ascent and descent of healthy subjects. *Journal of rehabilitation research and development*, *30*(4), 412-422.

Zettel, J. L., Holbeche, A., McIlroy, W. E., & Maki, B. E. (2005). Redirection of gaze and switching of attention during rapid stepping reactions evoked by unpredictable postural perturbation. *Experimental Brain Research*, *165*(3), 392-401.

Zietz, D., & Hollands, M. (2009). Gaze behavior of young and older adults during stair walking. *Journal of Motor Behavior*, *41*(4), 357-365.