University of Alberta

Visual Control of Human Gait during Locomotor Pointing

by

Adrian Popescu

A thesis submitted to the Faculty of Graduate Studies and Research

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Faculty of Physical Education and Recreation

Spring 2013

Edmonton, Alberta

Dedication

To the gang in room 32: Tibi, Seba, Misu, Cristi, Vlad, & Florin.

Here is where it all started for me with a springtime dream…

Abstract

Daily locomotor tasks require gait adaptations in order to match various environmental challenges. Healthy individuals rely on vision in order to make proactive gait changes as vision is the sensory modality best suited to provide accurate information about distant environmental constraints. This dissertation was concerned with investigating the adaptive locomotor strategies and the related visual sampling characteristics during locomotor pointing tasks. These goals were achieved by conducting a series of four experiments requiring participants to walk towards and accurately point with the forefoot at distantly located targets without stopping. Young and older healthy participants performed the task in different environmental setups and under various visual sampling conditions.

The results clearly demonstrate that the environmental information was sampled in a predictive manner for planning proactive stepping adjustments during the target approach and for extracting limb position information in relation with the target for fine-tuning the foot trajectory prior to foot-pointing. The results also indicate that discrete visual samples were adequate to complete the tasks. Generally, vision availability amounted to less than half of the trial duration for each trial and the typical sampling strategy consisted of one or two brief visual samples such that vision was available almost all the time during the pointing step. The gaze was deployed towards targets well in advance of the foot-pointing action and it remained anchored there until about the time the foot contacted that particular target.

Participants typically undershot the targets and the likelihood of overshooting the targets significantly changed with the increase in task difficulty and complexity. Older adults prematurely disengaged the gaze from the targets, consequently increasing the likelihood of target overshooting. This may indicate that the older adults need more time to plan and implement gait modulations and could be interpreted as a sign of future, naturally-occurring, and more dramatic changes in visuomotor control during adaptive locomotion.

In conclusion, this work shows the existence of well-preserved yet flexible motor control strategies related to locomotor pointing tasks. With aging, these visuomotor strategies lose their effectiveness and become one of the causes liable for the increase in the rate of falling occurrences for older adults.

Acknowledgements

While completing my doctoral degree I've had a genuine learning experience on many levels. I came in contact with several remarkable people and I can honestly tell that they all contributed to this work you are about to read.

First, I want to express my sincerest gratitude to my supervisor Brian Maraj for his support and gentle guidance in and out the lab: thank you for giving me the liberty to find my own way.

I gratefully appreciate the contribution of my examining committee: professors David Collins, Pierre Gervais, Pierre Baudin, Craig Chapman, and David Westwood (external examiner). Thank you for providing me with sensible advice and constructive comments.

Wonderful people have contributed to this enterprise and I am much obliged to all of them: Zoltan Kenwell for technical advice and instrumentation; Alex Ley for computer programming; Dave McAllindon for the eye tracker integration and computer programming; Florante Macapagal and coworkers for building my experimental setup. Thank you all for generously sharing your expertise and resources with me.

I have had the pleasure to work with and learn from exceptional people: Dr. Keir Pearson, my lab coworkers Caitlin Marchak and Keith Runnalls, as well as the students from the KURT group. Heartfelt thanks.

Fellow graduate students who pawed the way for me Nicoleta Cutsumisu, Tom Wu, Christina Lau, Cameron Bonertz, and Eryk Przysucha. I particularly appreciated your companionship.

All the people volunteering their time to be part of my experiments: I also learned from you to pay it forward, thank you kindly.

Finally, I am especially thankful to my family and friends here and across the ocean. To my mom and dear departed dad: you gave my freedom during confining times; what a privilege. To my sister and her beautiful family: thank you for your support, I miss you all. To my dear friends back home who kept me anchored in reality during trying times on foreign lands: many thanks.

Ioana you imparted me the strength to bring this work to fruition during trying times: I love you.

Table of contents

2. Study one

Intermittent visual information affects motor strategies during locomotor pointing

3. Study two

Locomotor pointing accuracy is affected by target size and intermittent vision

4. Study three

Self-sampled vision and adaptive locomotion: Effects of aging and task complexity

5. Study four

Gaze behaviour and locomotor pointing during biological aging

List of Tables

List of Figures

(continued)

List of Figures (continued)

(continued)

List of Figures (continued)

List of Abbreviations

Abbreviation	Description
|CE|	Absolute constant error (a measure of pointing accuracy)
ANOVA	Analysis of variance (a parametrical statistical technique)
A-P	The anterior-posterior foot pointing outcome measure
CNS	Central nervous system
ETA	Ecological task analysis
F	The symbol for the analysis of variance test (the Fisher test)
FSR	Force sensitive resistor
FV	Full vision condition (vision always available)
HSD	Tukey's honestly significant difference post hoc test
ID	The index of task difficulty
LCD	Liquid crystal display (for goggle lenses)
LED	Light emitting diode (for motion analysis markers)
M	Mean, the arithmetic average for a parametric data set
M-L	The medio-lateral or sagittal foot pointing error outcome measure
OA	Older adults group
P	Raised platform (one post-pointing task experimental condition)
POG	The point of gaze (the line of sight)
PPT	Post-pointing task (following foot pointing)
SV	Self-sampled vision condition

(continued)

List of Abbreviations (continued)

Abbreviation	Description
S	Stair and door (one post-pointing task experimental condition)
SD	Standard deviation (a measure of data dispersion)
STAI-C	The state-trait anxiety inventory for children
STV	Stance vision condition (an intermittent vision allowing vision only during the stance phase of the gait cycle for the pointing foot)
SWV	Swing vision condition (an intermittent vision condition allowing vision only during the swing phase of the gait cycle for the pointing foot)
T	Large target
t	Small target
T1	First target from the starting location
T2	Second target from the starting location
VCTS	The Vision contrast test system chart
VE	Variable error (a measure of pointing consistency)
W	Walking (one post-pointing task experimental condition)
YA	Young adults group

1. Introduction

Locomotion is the process by which animals change their location in space from one position to another. Of the many forms of human locomotion, walking is the typical human gait pattern. Walking can be defined as “a rhythmic displacement of the body parts that maintains the animal in constant forward progression” (Rose & Gamble, 2006; p.1).

Walking is a complex, fundamental motor skill and represents the preferred gait for locomotion. Unless locomotion is performed in ideal conditions (i.e., a flat, non-slippery, unobstructed pathway), the rhythmical nature of the walking gait must change in order to match the characteristics of a cluttered environment. The typical naturally cluttered (a trail in the woods) or artificially rich (a crowded mall) environments impose gait adaptation (i.e., adaptive locomotion). One particular kind of adaptive locomotion is locomotor pointing. This motor task requires accurate foot placement on specific environmental land marks during locomotion. There are many athletic events and daily locomotor tasks for which success depends on the capacity to accurately point at targets while maintaining forward progression largely unaltered (e.g., long jumping or stepping on a dry spot on an icy sidewalk). Regardless of the context, successful interceptive actions must translate sensory information in precise temporal and spatial motor output in a timely manner. Usually, the locomotor pointing event is followed immediately by the execution of another motor task without a temporal interruption. The preceding accurate foot placement dictates the successful accomplishment of the global motor task, which can be artificially separated into a pointing task and post-pointing task (e.g., pointing at the curb in order to step on the sidewalk to continue locomotion or pointing at the take-off board in order to perform the long jump).

Healthy individuals predominantly regulate their gait based on visual information. Vision can provide accurate predictive information related to distant environmental events. That kind of information can be used in a proactive manner to regulate footfall location. Recent research identified gradual changes taking place during biological aging, which degrades a person's capability to perform timely stepping adjustments necessary for adaptive locomotion.

1.1 Adaptive locomotion

On a daily basis, the walking gait pattern must be adapted to match the complex, ever-changing characteristics of the environment. This work will be exclusively concerned with the visuomotor control during adaptive locomotion as opposed to free walking control. Higher motor control centers modulate the stereotypical gait pattern as a function of the information received from various sensory modalities. Above all, vision becomes paramount in planning and guiding locomotion in cluttered environments. The visual system is uniquely equipped to provide accurate and almost instantaneous information at a distance necessary for advanced gait changes in anticipation of distant environmental constraints (i.e., proactive control) (Patla, 1997).

Some locomotor tasks require precise foot placement for implementing avoidance strategies (e.g., step over an obstacle) or for implementing accommodation strategies (e.g., place one foot on dry surface for effective stance support) and are performed under visual control (Patla, 1991). It is often the case that these locomotor strategies are a seamlessly incorporated segment of a more complex movement task for example, crossing the street. While crossing a crowded intersection, individuals often avoid colliding with other pedestrians, scan the area for vehicle traffic, make provisions for optimal support foot placement prior to curb stepping all while maintaining forward locomotion unperturbed (without stopping, suddenly changing direction). Regardless of the context, successful adaptive locomotor strategies relay on efficient visuomotor transformations.

In recent years, the amount of research dedicated to analyzing adaptive locomotion has increased in part because of the technological advances. The role of vision during adaptive locomotion has been investigated by controlling visual information at critical points during locomotion by means of LCD lens goggles (Laurent & Thomson, 1988; Patla, Adkin, Martin, Holden, & Prentice, 1996) or by tracking the point of gaze while negotiating cluttered environments by means of mobile eye-tracking systems (Patla & Vickers, 1997; Chapman & Hollands, 2007).

The walking gait undergoes developmental changes throughout lifespan. Its development begins in infancy and, once achieved, represents a major milestone in the development of fundamental motor skills. The walking pattern will reach adult characteristics around the time a person is eight years old. In typical individuals, the gait remains largely unchanged during adolescence and adulthood.

However, the walking gait pattern begins to change during late adulthood. These changes affect both the free walking gait and the control of adaptive locomotion. There are many factors responsible for this change; for example, the loss of muscle mass, sensory systems deterioration, fear of falling, disease, cognitive disorders etc. (Dionyssiotis, 2012). Free walking becomes "cautious" and is characterized by a reduction in velocity, shorter steps and stride lengths, longer stance and double support times, faster swing, and increased out-toeing and stride width (Craik & Dutterer, 1995; Elble, 1997). Older adults show decreased foot-pointing accuracy and precision (Chapman & Hollands, 2006). They need longer visual samples to maintain stepping accuracy (Patla, 1995) and they tend to shift their gaze away from the ongoing task to the next in order to fixate sooner on future environmental features (Chapman & Hollands, 2010; Di Fabio, Greany, & Zampieri, 2003). These effects worsen in older individuals prone to falling particularly in complex environments (Chapman & Hollands, 2007).

This study will investigate the particular case of locomotor pointing which requires accurate foot placement during locomotion. For example, in order to enter a building, someone must approach a short flight of stairs, optimally position themselves relative to them, change their gait to climb up the stairs, and then reach for the door handle to open the door and pass through it. A complex motor task like this would be routinely performed and typical individuals would carry them out fluently without visibly altering the forward gait progression.

1.2 The functions and roles of vision

In order to better understand how vision regulates locomotion, one must identify the attributes related to a safe and efficient and locomotor control system. According to Patla (1995, 1997) the control system must set up the initial body posture, initiate and terminate locomotion, produce and coordinate rhythmic activation patterns for the muscles, maintain dynamic stability of the body during locomotion, modulate locomotion patterns to implement avoidance or accommodation strategies, guide locomotion toward endpoints not visible from the start, increase fuel efficiency during locomotion, and, ensure the locomotor system's structural stability.

Several of the above-mentioned locomotor control system qualities depend on vision: termination of locomotion, maintenance of dynamic stability, modulation of gait patterns, and guiding locomotion towards endpoints not visible from the starting location. This work's specific aim rests with the role that vision plays in stepping modulation during adaptive locomotor tasks that require foot-pointing at targets embedded at the end of an unconstrained approach.

Due to its trimodal power, vision has a dominant role in locomotor regulation (Lee, 1978). Vision can provide information about the external environment (exteroceptive function); it also can provide information regarding the position and movement of different body parts relative to the body itself (proprioceptive function); finally, vision can provide information about the relative position and movement of the body parts or entire body with regard to the environment (exproprioceptive function). For the particular case of locomotion, vision helps plan a locomotor act relative to the environment. This act is also known as feed-forward control (via exteroceptive and exproprioceptive functions). Vision also controls the locomotion during single-step modulations known as on-line control (via proprioceptive and exproprioceptive functions). Moreover, relative to other sensory systems, vision acts "as an overseer in the control of activity, developing patterns of action and tuning up other perceptual systems and keeping them tuned" (Lee, 1978, p.168).

1.3 Literature Review

1.3.1 Intermittent vision

Typically, other tasks requiring visual attention are routinely performed during locomotion. Anecdotal reports show that vision is often shifted from the ongoing locomotor task to attend a conversation, much like the prey attending both to the chasing predator and the surrounding environment (Thomson, 1980). Such behaviour necessarily imposes brief gaze shifts away from the locomotor task, implying that continuous visual monitoring is not necessary for successful locomotion.

The concept of intermittent visual control has been under scrutiny in the recent past. The empirical support for intermittent visual sampling during locomotion comes from several experimental paradigms.

The seminal work by Lee, Lishman, and Thomson (1982) showed that vision provided the information necessary to make gait adjustments about target location during a long jumping field event. This report constitutes the origin of investigating the control of locomotion during athletic events that impose precise foot placement on targets during full vision availability. The results show a gait pattern consisting of two phases, a pattern that is consistently reproduced across attempts. The initial, accelerative phase is accompanied by an increase in footfall variability (i.e., foot location for each step relative to the take-off board). The second, zeroing-in phase is characterized by the reduction of these cumulative inconsistencies based on the perceived foot-to-target error. These results were replicated for different athletic events regardless of athletes' proficiency levels (Berg, Wade, & Greer, 1994; Bradshaw, 2004; Maraj, 2002; Renshaw & Davids, 2006) and show that visual information is used to pre-plan future footfall locations over several steps preserving the forward progression of locomotion.

Another paradigm employed direct visual manipulation during locomotion in laboratory settings. An ingenious set of six experiments involving visual denial (blind walking) was conducted by Thomson (1983). Participants were able to point accurately (less than one step error) at targets situated at different distances (6 – 21m) provided that the task was accomplished in less than eight seconds. However, two subsequent investigations failed to replicate these findings on account of training protocol, logical fallacy in the argument, and statistical analysis (Elliott, 1986; Steenhuis & Goodale, 1988). The third paradigm utilized intermittent visual sampling during locomotion. In one study vision was denied for a fixed period during either the swing or the stance phase of the pointing foot (Laurent & Thomson, 1988). In a similar vein, Chapman & Hollands (2006a) removed vision corresponding to the dominant limb for the entire period of the gait event. The overall outcome of these studies was that young adults are capable of successfully adapting their gait to maintain foot-pointing accuracy without disrupting the forward locomotor progression.

Finally, a new intermittent visual manipulation was proposed by Patla, Adkin, Martin, Holden, & Prentice (1996). This newer approach gave participants full control over visual sampling by operating a hand-held switch therefore avoiding the previously employed unnatural visual sampling mode (i.e., rigorously controlled intervals). They found that young participants successfully navigate various travel paths, avoid obstacles, and point at different targets en route under self-sampled vision conditions. Regardless of task manipulation, visual requirements never exceeded one visual sample per step or a single, longer sample per stride. The overall visual sample duration increased from 10% (free walking) to 40% (foot prints and obstacle avoidance) of the task duration.

Taken as a whole, these results show that healthy adults have flexible perceptual and locomotor systems and visual resources can be shared. Navigating constraining environments, which require gait adaptation, can be handled in the absence of continuous visual sampling availability. The sampling behaviour closely reflects the environment layout. Visual information is needed most at target proximity. Recent technological progress allowed for eye movement and point-of-gaze (POG) location measurements during locomotion. The next section outlines the major findings to date in this regard.

1.3.2 Gaze behavior

The proactive modulation of the gait pattern is based on advance visual information. Understanding the control of adaptive locomotion requires simultaneous observation of gaze and gait behaviours (Thomson, 1980; Patla, 2004). A limited number of reports are available detailing visuomotor coordination during adaptive locomotion (i.e., synchronized spatio-temporal visual and locomotor parameters). The main challenge was the head-free POG recording during walking. The typical locomotor pointing tasks cover a relatively large space, as participants walk towards preset target locations. This section will provide a chronological review of the related literature that also highlights instrumentation breakthroughs. During the past 20 years, visual parameter recordings evolved from measuring single-dimension eye movements (e.g., horizontal rotation) to naturally occurring combined two-dimensional eye rotation while the resultant POG location was computed for a single plane (typically the floor surface). Procedural limitations notwithstanding, these studies provide a paradigm shift from the indirect account, which examines performance-outcome measures under intermittent vision manipulations, to directly measuring the eye-foot functional relationship during locomotion.

Hollands, Marple-Horvat, Henkes, and Rowan (1995) made a first report investigating the temporal visuomotor coordination aspect during adaptive locomotion. As participants stepped on irregularly spaced raised stepping stones, horizontal eye movements were continuously monitored during the task. Eye movements were recorded using both electro-oculography and infrared reflectometry. Temporal kinematic measures were made via logic circuits for each footfall during walking. The POG spatial location was only inferred and no footfall spatial coordinates were reported. Off-line analysis of saccades and footfall timing data showed that saccades were made towards the next footfall at the end of a stance or during the early swing (i.e., feed-forward control) and POG was anchored (fixated) to the next footfall until 51ms after foot contact took place (i.e., online control).

This proactive stepping control was confirmed in a subsequent study (Hollands & Marple-Horvat, 2001). Participants had to step on consecutive flush stepping stones in a dark environment. The spatial location of the stepping stones was identified via LEDs which were intermittently turned off at random for 500ms to test the effect of target information availability on planning stepping control. The feed-forward interaction between the oculomotor and locomotor control systems was established by the timing between saccade onset and footlift, which was more consistent than the timing between the saccade away and footfall. The premature LEDs disappearance or reappearance prolonged the duration of the stance, but not the swing duration. Additionally, the results showed that the on-line foot control necessary to guide the limb towards targets depends on the specific task constraints. In contrast to the Hollands et al., (1995) study, flush stepping stones here imposed a lesser challenge to preserve dynamic balance during walking, as reflected in the participants' behaviour.

With the introduction of mobile eye-tracking devices, the issue was taken one step further because it was possible to record natural eye rotation data. The possibility of data contamination, resulting from making single-dimension eye rotation recordings (e.g., horizontal) from the naturally occurring combined two-dimensional eye rotation, was eliminated. Patla and Vickers completed two studies (1997; 2003) investigating spatio-temporal aspects of gaze behavior during adaptive locomotion tasks. A split-screen video recording, showing both the walkway with the participants' gaze superimposed (black cursor) and the walking participant, was used to record gaze and stepping parameters. Despite a low temporal resolution (30 Hz) and the lack of spatial foot kinematics data, the feed-forward control mode for stepping was confirmed for obstacle clearance (Patla & Vickers, 1997) and foot-pointing at consecutive footprints (Patla & Vickers, 2003). Moreover, both reports showed that participants typically looked two steps ahead during the walking task and fixated the obstacle one or two steps ahead.

More recently, mobile eye-tracking devices allowed for recording synchronized gaze behavior and spatio-temporal foot kinematics sampling at 120Hz. This technique was employed by Chapman and Hollands (2006, 2007) to observe the relationship between gaze and stepping during adaptive locomotion in older adults. For the first time, foot-pointing outcome measures were reported for accuracy and consistency. Young, older, and older prone-to-falling individuals walked a straight path stepping on two targets (Chapman and Hollands, 2006) or two targets separated by an obstacle (Chapman and Hollands, 2007). Results showed that gaze was deployed in a feed-forward manner and engaged sequentially with each location of interest during locomotion. This gaze fixation sequence was recorded regardless of age or task complexity; however, older adults and particularly older adults at risk for falling, presented with a different gaze strategy that adversely impacted the foot-pointing outcome. An interesting finding was that of premature gaze disengagement with the target. Specifically, older adults shifted their gaze away from the targets before the footfall, while young adults maintained their gaze "anchored" until after their foot landed on target. This effect was exacerbated by the increase of task complexity and for the participants at risk for falling. Moreover, there was a small but significant correlation between the gaze shift away from the targets and the decrease in foot-pointing outcomes (Chapman and Hollands, 2006; 2007). The authors concluded that older adults, especially older adults with a falling history, need more time to process information. As such, they prioritize future adaptive-steps planning over the accurate execution of current adaptive steps.

Overall, visual information is generally used in a predictive manner providing for limb movement planning (feed-forward control), while on-line limb control complements stepping control and depends on imposed task constraints.

Gaze arrives first at the location of interest and is anchored throughout limb movement. For complex tasks requiring a sequence of movements, gaze disengages from one location of interest and moves to the next (saccade away) shortly before or after limb contact. Recent reports indicate that both gaze and the subsequent foot-pointing outcome are influenced by the complexity of the locomotor task and biological aging (Chapman and Hollands, 2006; 2007). Also, premature gaze disengagement with the foot targets, especially for older individuals, negatively impacts the foot-pointing performance outcome.

Similar visuomotor coordination was reported for simple tasks like stepping. Placing the foot on a raised platform, causes a gaze shift towards the platform (downward saccade) before the foot movement initiation. In contrast with young adults, older and healthy individuals have significantly longer saccade-step latencies (Di Fabio, Zampieri, & Greany, 2003). Reports were made for steering as well (Hollands, Patla, & Vickers, 2002). Gaze behaviour related to maintaining and changing the direction of locomotion was observed while participants were visually or verbally cued to initiate steering. The gaze was aligned with the current direction of progression before and after the change in direction. Prior to steering, gaze was realigned with the end point of the travel path and was accompanied by head and, eventually body reorientation.

The main outcome from the above research clearly shows a saccade-step coupling pattern for various locomotor pointing tasks. The saccade-step latency duration between the shift in gaze and the subsequent foot-pointing outcome is affected by aging and environment complexity.

This work introduces a novel technique for deriving a real-time head-free gaze during adaptive locomotion. This technique will use combined head spatial-rotation data and eye rotation data in order to allow for the design of more complex environments that closely resemble real-life encounters. The POG location will be recorded for several scene planes at various spatial orientations, contrasts to previous reports that considered a single physical plane (i.e., the floor surface).

1.3.3 Feed-forward and on-line locomotor control

Vision is best suited to provide rapid and accurate environmental information at a distance, which is used to plan (feed-forward control) and guide (on-line control) stepping in order to meet environmental challenges (Lee, 1978; Patla, 1997). This allows for both timely adjustments to the gait pattern without disrupting the forward progression, as well as fine-tuning the foot trajectory just before pointing with the foot at highly constraining targets during the last step during target approach.

The pioneering study by Lee, Lishman, & Thomson, (1982) observed that the approach phase for long jumping events cannot be automatically reproduced for each attempt even by Olympic-caliber athletes. Based on the footfall pattern (toe to take-off board distance) of each stride up to the take-off event, the authors identified two separate phases. The initial accelerative phase was always followed by a second visually regulated phase during which the accumulated error in footfall variability was systematically reduced. These step adjustments were necessary for landing the take-off foot on the board and were spread over the last strides before this event (i.e., feed-forward control). This feed-forward control strategy was replicated for other field events as well (Berg, Wade, & Greer, 1994; Bradshaw, 2004; Hay, 1988; Maraj, 2002; Renshaw & Davids, 2006).

This strategy was also adopted by young individuals during the performance of lab-based constrained locomotor tasks (Laurent & Thomson, 1988). The task required walking towards and placing the foot on a distant target line under various visual conditions. The footfall variability pattern indicated that stepping adjustments started several steps before the target line location, consistent with feed-forward locomotor control.

A more direct account for this control strategy comes from studies investigating visual sampling requirements and POG recordings during adaptive locomotion. Patla, Adkin, Martin, Holden, & Prentice (1996) found that participants visually sample the environment before arriving at the embedded constraint and not during the "adaptive step" itself. POG location recordings synchronized with foot kinematics indicate that visual information is typically collected two steps in advance (Patla and Vickers, 2003). Comparable findings were reported for obstacle crossing (Patla & Vicker, 1997). Participants fixate on the obstacle during the approach and fixate the future lead foot landing area, not the obstacle, while clearing the obstacle.

Research shows that step modulation can be performed during a single step as well if the accuracy demands are high or if the environment changes suddenly (Perry & Patla, 2001; Reynolds & Day, 2005a; and Reynolds & Day, 2005b). These modulations bring about minute correction during one step (last swing) before the environmental constraint (e.g., foot-pointing).

For example, Reynolds & Day, (2005b) asked participants to step over a matching size, custom-made, exact copy of their own footprint (discrete stepping tasks). Vision removal during the swing phase coincided with a decrease in foot-pointing accuracy. Conversely, if vision was present during the swing, participants made trajectory correction prior to footfall.

Direct evidence for guiding the foot during swing comes from studies investigating the effect of sudden environment changes to stepping control. This is similar to stepping over your pet when it suddenly starts to walk or dropping an object and avoid stepping on it. Reports show that young adults can perform fast adjustments to overcome such challenges, stepping accurately on “jumping targets” which change location mid-swing by making appropriate direction changes during swing without losing balance (Reynolds & Day, 2005a). Similarly, young adults made toe clearance adjustments while stepping over obstacles that changed height unpredictably, and did so without contacting the obstacle (Perry & Patla, 2001).

Overall, this evidence indicates the existence of robust yet versatile stepping control strategies. Based on environmental demands, healthy individuals can effortlessly control stepping via feed-forward and/or on-line control to reach the task goal. There are instances where both control mechanisms act in concert. The feed-forward control mechanism would optimally position individuals with regard to the distant environmental constraints while the on-line control strategy would further allow for fine stepping corrections implementation.

The next section will review gait-related changes that occur with aging and affect free-walking and adaptive locomotion.

1.3.4 Aging and adaptive locomotion

Aging, the process occurring with the passage of time, inevitably leads to a loss in adaptability and functional impairment (i.e., biological aging) (Spirduso, Francis, MacRae, 2005). Aging is characterized by changes in neurological, musculoskeletal, and sensory systems, all which play a role in influencing posture and locomotion. In turn, the ability to perform many crucial daily tasks, including locomotion, will be compromised, negatively impacting the quality of life. This process is complex, multifactorial and its full exploration goes beyond the purpose of this dissertation. This work will limit itself to consider only the effects of primary aging on locomotion and more specifically on adaptive locomotion.

Developed countries worldwide suffer from a rapid population aging trend. According to Statistics Canada, the older adults population will double in the next 25 years, from 13.1% in 2005 to 24.5% in 2031, reaching 27.2% in 2056. For the first time in Canadian history, all projection scenarios indicate that by 2015 the older adults will outnumber children (Belanger, Martel, & Caron-Malenfant, 2005; Turcotte & Schellenberg, 2007; Statistics Canada, 2008).

The fact that the free walking gait changes during biological aging is well documented. The older adults adopt a “cautious” gait pattern during free walking: slower progression, with a shorter step and stride lengths, longer stance and double support times, a faster swing, and increased out-toeing and stride width (Craik & Dutterer, 1995; Elble, 1997; Elble et al., 1991; Judge et al., 1996; Prince et al., 1997; Winter et al., 1990). There are significant changes in gait variability magnitude, which is indicative of impaired mobility (Brach et al., 2001; Brach et al., 2008; Gabel & Nayak, 1984; Hausdorff et al., 1997; Owings & Grabiner, 2004a; Owings & Grabiner, 2004b). Stride-to-stride variability is associated with future falling (Maki, 1997) and separates community dwelling fallers from their non-fallers counterparts (Hausdorff, et al., 1997). Older adults show a larger step width variability while walking at self-selected speed (Owings & Grabiner, 2004a; Owings & Grabiner, 2004b) or fast walking (Brach et al., 2001). The overt changes in gait pattern are linked to specific changes in several underlying factors related to locomotion control: sensory deficits, loss of muscle mass, atrophy of the CNS, decreased cognitive ability, fear of falling, etc. (Rose & Gamble, 2006; Spirduso, Frances, & MacRae, 2005).

These changes in older adults’ gait are linked to locomotor disability and falls. Several prospective studies, observing community-dwelling adults age sixty or older, report that 30% or more experience falls each year and that the number of falls increase with age (Blake et al., 1988; Berg et al., 1997; Campbell et al., 1981; Nachreiner et al., 2007; O’Loughlin 1993; Tinetti et al., 1988). Statistics Canada provides more precise statistics for falls as the underlying cause of death.

In the Statistics Canada report, accidental deaths resulting from unintentional injuries were ranked fifth among the leading causes of death in Canada, with 9,506 fatalities (4.1%). Falls, as the underlying cause of death, account for 2,305 cases (a rate of 7.1 per 100,000) (Statistics Canada, 2009, 2010). The number of deaths by falling has a mild but consistent upward trend with aging up to the age of sixty. This trend presents a steeper gradient up to age seventy, followed by a sharp increase afterwards.

However, some age-associated changes to the gait pattern are manifest in the absence of discernible disease, raising the issue of the difficulties encountered when it comes to comparing gait deviation from the "normal" gait descriptors (Elble, 1997). This dissertation is specifically concerned with primary aging effects on adaptive locomotion (i.e., prior to manifest disease onset). As outlined above, adaptive locomotion relies on vision for proactive gait modulation while navigating the environment. The research on the topic of older healthy individuals performing adaptive locomotor tasks reveals changes in visual sampling requirements and subsequent locomotion control output. Related empirical research studies providing support in this regard will be reviewed next.

Chen, Ashton-Miller, Alexander, & Schultz, (1991) reported on an early investigation concerned with the differences in gait patterns between healthy young and older adults during an obstacle avoidance task**.** Participants walked at a comfortable speed down a 4 meter walkway and stepped with the dominant foot over obstacles varying in height from being flush with the floor to standard-stair raiser height. Results showed that the foot clearance and the toe distance over the obstacle were similar for age, gender, and stature, suggesting a common locomotor strategy for obstacle avoidance. No differences were found for the obstacle-free walking gait. However, older adults had a more conservative obstacle-approach strategy: slower crossing speed, shorter step length, and shorter obstacle-heel strike distance. Four older adults stepped on the obstacle showing an increased risk for obstacle tripping with age that was attributed to inattention rather than fatigue.

These findings were followed by an ingenious study designed to investigate locomotor avoidance strategies as a function of time (Chen, Ashton-Miller, Alexander, & Schultz, 1994**).** Healthy young and old participants approached and stepped over a virtual obstacle. A light band (30 mm wide) was projected transversely onto the walkway within a 3 meter region. Gait events information was fed into the computer via conducting strips attached to the soles of each participant's shoes. A computer algorithm predicted the footfall location automatically and selected the light beam location. Results showed that reducing the available response time by 50 to 100 ms would significantly decrease the obstacle avoidance success rate of both experimental groups. Older adults were more likely to contact the obstacle if the available response time ranges between 300-450ms. These results corroborate with more recent findings reported by Chapman & Hollands (2010). They found that older adults engaged in a locomotor pointing task need more time to fixate on distant targets in order to maintain the pointing outcomes as compared with young adults. Target fixation duration of less than 1.5 to 2 seconds would negatively impact the task outcome.

Chapman & Hollands concluded that the older adults need more time to process and transform visual information into accurate stepping movements.

A second line of evidence outlining the differences in visual sampling needs for older adults comes from experiments using the intermittent vision paradigm. Chapman & Hollands, (2006a) employed an intermittent visual sampling paradigm to observe the role of vision during adaptive locomotion. Vision was removed for the entire duration of the stance or swing phase of the gait cycle for the dominant foot using LCD goggles controlled via pressure resistors mounted on the sole of the pointing foot. Participants walked a straight path and placed their foot in three consecutive targets (19 x 42 cm) en route. In contrast to young adults, older adults showed a decrease in foot-pointing accuracy and precision as well as an increase in task failure (i.e., stepping on the edge or outside the target) for the intermittent vision conditions, especially during the swing-only vision condition. In contrast, the young adults maintained target pointing outcome parameters by modifying the locomotor control strategy according to vision availability: increasing the overall stance duration during the intermittent visual conditions prior to targeting or increasing the overall swing duration and approach velocity during swing vision conditions. It was argued, consistent with the hypothesis that visuomotor coordination declines gradually with aging, that the short time frame offered by intermittent vision was insufficient for accurate stepping control during adaptive locomotion.

Two brief reports were made with regard to self-sampled intermittent vision during locomotion for healthy older adults (Patla, 1993, 1995). This approach allows participants full control over the sampling duration and location during the task. Participants were required to walk over two straight travel paths: one unconstrained path (i.e., free walking) and one having evenly distributed footprints (i.e., adaptive locomotion). As expected, intermittent vision was sufficient to complete the tasks. Also the visual demands increased for the constrained footfall path. For the unconstrained path, older adults had similar movement times and the same number of visual samples as their young counterparts (actual data used from Patla et al., 1996). On the other hand, older adults had longer total visual sample durations, as a result of increasing task difficulty by adding footprints. In contrast, young adults took more visual samples en route during the footprints condition. It was argued that the older adults need more time for planning and initiating the appropriate gait adaptation, as it becomes harder to share visual resources and make decisions during locomotion with age.

Finally, a third line of evidence showing differences in visuomotor coordination between young and older adults stems from gaze behaviour measurements during adaptive locomotor tasks. Recent advances in technology have allowed researchers to investigate the coupling between eye movement and step control via infrared oculography (Di Fabio, Zampieri, & Greany, 2003; Greany & Di Fabio, 2008) and eye-tracking systems (Chapman & Hollands, 2006, 2007, and 2010) during adaptive locomotor tasks for older adults.

Eye movements were synchronized with video-based motion data to derive the gaze angle (combined eye vertical rotation and head-pitch angle) and saccade-step latencies during a fast walking obstacle task (Di Fabio, Zampieri, & Greany, 2003). Healthy young people, as well as older people in assisted living facilities took part in this experiment. During the approach participants were cued regarding the lead leg via a stimulus-compatibility paradigm (light arrow and audible tone) for the purpose of disrupting the gait rhythm and revising the motor plan. The task was initiated by looking straight ahead for the visual cue placed at eye level. Results show that, regardless of age, at the cue a downward saccade was generated and used for forward-guiding subsequent footfalls and a vertical saccade was recorded prior to obstacle crossing. However, the older adults had longer obstacle fixations flowing the cue signal and before the obstacle footlift, with some older participants fixating on the obstacle during obstacle stepping. Similar findings were reported by Greany & Di Fabio, (2008) when older individuals classified as at high- and low-risk for falls pointed with the foot at four irregularly-placed consecutive targets during walking. The at-risk older adults demonstrate longer saccade-footlift latencies prior to target pointing as compared with their low-risk counterparts. Overall, this saccade-stepping interaction behaviour was linked to slower central processing times of visual anchors for proactive stepping planning, as well as deficient working memory requiring continuous constraint fixation for on-line foot guidance.

Chapman and Hollands (2006, 2007, and 2010) drafted a series of reports comparing healthy young and older individuals with older at-risk-for-falling individuals performing adaptive locomotor tasks. Gait kinematics data were integrated with eye-tracking data with the purpose of investigating the gaze behaviour and related locomotor control strategies.

It was found that older healthy adults looked at the targets earlier and fixated on them longer and transferred the gaze away from the targets prior to heel contact (Chapman and Hollands, 2006). Similar gaze parameters were recorded when the task complexity changed by adding consecutive and collinear stepping constraints (Chapman and Hollands, 2007). These studies were the first to report two-dimensional stepping accuracy outcome. The results also showed a correlation between premature gaze transfer away from targets (i.e., saccades occurring before footfall) and increased foot-pointing error outcome (Chapman and Hollands, 2006 and 2007).

Similar visuomotor coordination patterns were recorded for the older at-risk participants as well. However, the magnitude of the differences between groups was increased. Overall, the change in visual sampling requirements and the subsequent foot-pointing outcomes suggest changes made with the purpose of overcoming these naturally occurring limitations in locomotor control adaptability (Chapman and Hollands, 2006 and 2007).

An ingenious research paradigm was used to identify the minimum target fixation time necessary for planning and executing adaptive stepping adjustments during locomotor pointing (Chapman & Hollands, 2010). While walking participants had to adjust their gait in order to step over a light emitting diode (LED) presented at various intervals prior to foot-pointing. Results showed that all participants invariably fixate on the target after illumination and maintain fixation until foot-pointing. The necessary fixation time was over one second (approx. one step cycle) for young adults. The fixation time for maintaining similar foot-pointing accuracy levels increased with approximately one second increments for healthy older and older-at- risk-for-falling respectively. Comparable results were previously reported for a target avoidance task as well (Chen, Ashton-Miller, Alexander, & Schultz, 1994**).**

Overall, research evidence shows significant aging effects in visuomotor coordination during adaptive locomotor tasks. In addition, these differences in visual sampling behaviour and related locomotor output are further exacerbated for older individuals with a history of falling. This trend suggests a continuous and progressive deterioration in visuomotor coordination essential for adaptive locomotor tasks. Once the secondary aging effects settle in (i.e., the presence of clinical symptoms of disease), this deterioration trend will become increasingly more abrupt. It seems that older adults plan future steps while executing current stepping adjustments which suggests difficulty in extracting and transforming relevant environment information into precision stepping during adaptive locomotion in a timely fashion (Chapman & Hollands, 2007, 2010; Di Fabio, Zampieri, & Greany, 2003; Greany & Di Fabio, 2008).

Summary

The main findings derived from the adaptive locomotor literature indicate that the perceptual and locomotor control systems are robust and adaptable. The visual sampling requirements are directly linked to the environment layout. Point of gaze data shows that vision is typically used in a predictive manner providing information at a distance for locomotor planning (feed-forward control) while the on-line limb control provides for minute foot trajectory corrections and is dependent on the difficulty imposed by the task constraint. The saccade-step coupling pattern is evident during complex adaptive tasks: gaze disengages from one location of interest and moves to the next in sequential order shortly before or immediately after limb contact. Biological aging also affects the visuomotor coordination and further disruptions were found for older adults prone to falling (i.e., on set of clinical symptoms). Results show that the older adults need more time to process relevant environmental information and implement locomotor adaptive strategies effectively.

The next chapters describe a series of four experiments conducted on adaptive locomotion tasks employing all three paradigms used to investigate the role of vision during locomotor pointing. Healthy young and old individuals performed locomotor pointing tasks of various degrees of difficulty or complexity under full vision or restricted visual sampling conditions.

1.4 Problem statement

In order to investigate the role of vision during adaptive locomotion, researchers either denied the subjects' vision during walking or measured the gaze behavior (fixation spatial location and saccades temporal relation with stepping) while the subject performed various locomotor tasks. To date there is no systematic attempt to classify tasks based on their complexity and/or difficulty, rendering between-studies comparisons difficult. This work would follow the ecological task analysis model (ETA) proposed by Davis & Burton, (1991). The underlying premise of this approach is that there are a number of solutions to a motor task, which are influenced by the interaction between the person performing the task, the nature of the task itself and the environment in which the task is performed. Pursuing this approach, some of the constraints were systematically changed and their effect on gaze behaviour and locomotor control strategies were recorded. Besides describing the control strategies and the associated role of vision, the findings may also be used as relatively simple locomotor tests to identify individuals at risk and subsequently provide them with training to correct adverse gaze-stepping interaction and possibly postpone any adverse psychological and/or physical effects resulting from falling (Young & Hollands, 2010).

1.5 Purpose and working hypotheses

The purpose of this dissertation is to investigate the role of vision during walking and to record the effects of environment characteristics, visual availability, and biological aging[1] on stepping control and foot-pointing outcomes while performing locomotor pointing tasks. Specifically, a set of four studies,

---

[1] This research is only concerned with the biological aging effects on adaptive locomotion. The elderly sample would be independent of disease or functional impairment (i.e., primary aging free of clinical symptoms)

employing all three major research paradigms to date (intermittent vision, self-sampled intermittent vision, and gaze recording), were conducted to further our understanding about the role of vision during adaptive locomotion. The first three studies investigated the effect of intermittent vision on stepping control and the last study examined gaze location and gaze-stepping relation during locomotion. All tasks required participants to walk towards and step on fixed, distant targets flush to the ground without stopping.

In addition, following the ETA conceptual model (Burton & Davis, 1996; Newell, 1986), the individual (age group) and the task constraints (difficulty and complexity) were systematically manipulated. The laboratory environment remained stable during trials while any task manipulation was performed prior to the trial initiation. The task was manipulated independently in terms of difficulty (by means of target size) and complexity (by modifying the post-pointing task). For our purpose, older participants were selected to be free of clinical symptoms (i.e., independent of disease or functional impairment). Based on the assumption that aging will gradually impact locomotor functioning and in order to avoid possible associated confounding factors, the "older group" of individuals were selected around the conventional retirement age of 65 years old. Previous reports recruited advanced-age older individuals (e.g., 68-85 years old as studied by Chapman & Chapman, (2010) and Young & Chapman, (2010); or 84-93 years as studied by Di Fabio, Greany, & Zampieri, (2003)). Our recruitment criterion is in contrast with those reports, but is consistent with the available data on accidental deaths resulting from falling shows an increase change in trend after the age of 60 (see section 2.6.) and, therefore, contributes to reducing the age gap in the research literature.

The first study aimed to replicate and extend previous reports regarding the effect of intermittent vision sufficiency during locomotor pointing. It was hypothesized that vision availability would be reflected in locomotion control strategies and the foot-pointing outcome. Vision was denied as a function of the gait cycle (i.e., vision allowed either during the stance or the swing phase of the pointing foot for each step for the length of the approach).

The second study was prepared as an extension of the first study. The aim was to observe the effect of task difficulty on locomotion control and foot-pointing parameters under gait-cycle related intermittent vision. The task difficulty was manipulated by means of reducing the target size while instructing the participants to maintain a constant approach pace. It was hypothesized that reducing the target size would affect stepping control strategy as well as the foot-pointing outcome. The externally-controlled visual sampling, used to probe the visuomotor control strategies, also tried to replicate typical situations whereby brief attention shifts would direct the gaze away from the ongoing locomotor task (e.g., searching for a street number).

The next two studies considered age as a factor. The differences in gait control between healthy young and healthy older participants were compared. The purpose of the third study was to investigate the effects of task complexity and biological aging on visual sampling requirements during locomotion and the foot-pointing outcome. The participants had full control over visual sampling (i.e., voluntary self-sampled intermittent vision). Task complexity was manipulated by increasing the number of movement components necessary to complete the locomotor task. This was accomplished by adding a post-pointing task (PPT) immediately following the foot-pointing task (i.e., climbing a set of stairs and opening a door). Participants approached and pointed at the center of a target and followed with the post-pointing task without stopping, while allowing themselves visual samples as needed throughout the task. The working hypothesis was that visual sampling and the foot-pointing outcome are affected by the change in task complexity and the participant's age group.

Finally, the last study looked at the differences in gaze behaviour (fixations and saccades) between age groups and observed any associated changes in gaze-stepping interaction and foot-pointing outcome while performing adaptive locomotor tasks of systematically increased complexity. It was hypothesized that task complexity and aging would affect both gaze behaviour and the subsequent foot-pointing outcome.

1.6 Significance

The novel contributions of this dissertation will advance the knowledge on adaptive locomotor control by filling some of the gaps in the extant literature. The experimental task design will enable us to untangle the issue of task manipulations to determine if locomotor pointing tasks can be independently manipulated in terms of difficulty (Study 2) and complexity (Studies 3 and 4), thus allowing for direct comparisons between studies. To my knowledge there is no other published research to provide evidence that the feed-forward locomotor control strategy is preserved in healthy older adults approaching distant embedded targets (Study 3). A novel lab technique would be developed for deriving head-free gaze during locomotion using real-time integration of head and eye rotation throughout the task (Study 4). Finally, a complementary statistical technique was proposed to maintain the inter-subject variability data (i.e., avoiding signed data cancellation) for reporting both foot-pointing and saccade-step latency patterns.

The results generated by this investigation can also have immediate practical applications for both treatment and prevention stand points. It is documented that gait changes with aging are related to falling (Blake et al., 1988; Berg et al., 1997; Tinetti et al., 1988) and such occurrences are accompanied by a decrease in the quality of life (Prince, Corriveau, Hebert, & Winter, 1997). Therefore, the findings can be used to design better rehabilitation protocols closely matching real-life challenges. Such protocols would ensure a seamless transition toward performing daily adaptive locomotor tasks. Moreover, a recent report employed gaze behavior data to identify at-risk individuals and subsequently change the detrimental sampling strategies by training (Young & Hollands, 2010). These encouraging results indicate that a relatively simple gaze behavior test during adaptive locomotion can be employed for screening and identifying at-risk individuals as well as for designing effective intervention protocols. Additionally, the results may be incorporated in the interior design process for retirement homes in an effort to reduce or eliminate fall-associated risks by decreasing the imposed environmental demands on locomotion adaptation.

1.7 Definition of terms

Biological aging is the universal change occurring with the passage of time, independent of disease, leading to loss of bodily systems adaptability (i.e., primary aging).

Feed-forward locomotor control is based on predictive visual information related to distant environmental constraints (e.g., target), allowing for proactive locomotor adjustments spread over several steps based on need.

Foot-pointing error represents the degree of accuracy for locomotor pointing. It is measured separately as the average error in the sagittal plane (A-P error) and frontal plane (M-L error).

Foot-pointing error variability represents the degree of precision for locomotor pointing. It is measured separately as the standard deviation of foot-pointing error values in the sagittal plane (A-P error) and frontal plane (M-L error).

Gaze behaviour represents the resulting consequence of directing vision toward environmental stimuli. The point-of-gaze (POG) was computed in real-time by integrating the head spatial rotation with the eye rotation data (i.e., head-free gaze).

Locomotor pointing represents the motor task of accurately placing specific parts of the foot (i.e., forefoot) about a target (i.e., center of a box).

On-line locomotor control represents the gait modulations occurring immediately before the limb contacts the imposed environmental constraint (e.g., target) and corresponds to the last swing before foot-pointing regardless of vision availability.

Post-pointing task (PPT) represents the motor task occurring immediately after the locomotor pointing task without temporal interruption. The preceding accurate foot placement dictates the successful accomplishment of the global motor task, which can be artificially separated into a pointing task and follow-up goal task (i.e., pointing at the curb and stepping on the sidewalk to continue locomotion).

Task complexity is defined by the number of the linked elements in a motor task. If the number of chained elements is larger, then the task becomes increasingly more complex (i.e., for track and field events, the long jump is less complex than the triple jump).

Task difficulty is defined by the index of difficulty (ID) as described by Fitts' law (Fitts, 1954; reprinted in 1992). The ID is the most commonly used metric to determine the degree of difficulty for a rapid-aiming task. Its mathematical expression is $ID = (\log_2 [2A/W])$, where:

ID = Index of difficulty

A = Amplitude of movement (e.g. last step length before pointing task)

W = Target width

For our purpose, the reduction in target size represented the means to systematically change the ID. The higher the ID, the more difficult the task becomes.

Saccade-step latency represents the temporal difference between gaze transfer away from the target and the foot contact with that target.

Visual sampling represents the time interval during which vision is available to participants. The following parameters are associated with the visual sample: number of visual samples, duration of visual samples, location of visual samples during task, and the total visual sample.

1.8 Organization of the dissertation

The rest of this dissertation, following this brief introductory chapter, is organized into six chapters. Chapter 1 will provide the literature review pertaining to the scope of the dissertation. The topics under scrutiny will cover the functions of vision during adaptive locomotion, the effects of intermittent vision and gaze behaviour during adaptive locomotion, the feed-forward and on-line stepping control, biological effects on stepping control, and, finally, a short description of the putative neural mechanisms involved in visuomotor control.

Each of the following four chapters (Chapters 2-5) will cover one of the four studies carried out to answer the proposed questions related to vision control during adaptive locomotion. Chapter 2 will investigate the effect of intermittent vision (gait-cycle related) during a simple locomotor pointing task. While maintaining the same experimental paradigm, Chapter 3 will record changes in stepping control during intermittent vision while pointing at different target sizes.

The following two studies will consider the effects of task complexity and aging effects on adaptive locomotion. Chapter 4 looks at how task complexity manipulations and biological aging affect visual samples requirements (self-sampled intermittent vision) and stepping control. The last experiment, (Chapter 5) will report findings related to gaze behaviour during locomotor pointing tasks of systematically increased complexity.

The last chapter of the dissertation (Chapter 6) will provide a general discussion of the findings as well as the limitations of the work. The chapter concludes with several recommendations for future research.

1.9 References

Belanger, A., Martel, L., & Caron-Malenfant, E. (2005). Population Projections for Canada, Provinces and Territories 2005-2031. Statistics Canada Ottawa: Minister of Industry.

Berg, W. P., Alessio, H. M., Mills, E. M., & Thong, C. (1997). Circumstances and consequences of falls in independent community-dwelling older adults. *Age and Ageing,* 26, 261-268.

Berg, W.P., Wade, M.G., & Greer N.L. (1994). Visual regulation of gait in bipedal locomotion: revisiting Lee, Lishman, and Thomson (1982). Journal of Experimental Psychology: Human Perception and Performance, 4, 854-863.

Blake, A. J., Morgan, K., Bendall, M. J., Dallosso, H., Ebrahim, S. B. J., Arie, T. H. D., Fentem, P. H., & Bassey, E. J. (1988). Falls by elderly people at home: prevalence and associated factors *Age and Ageing,* 17, 365-372.

Brach, J. S., Berthold, R., Craik, R., VanSwearingern, J. M., Newman, A. B. (2001). Gait variability in community-dwelling older adults. *Journal of the American Geriatrics Society,* 49, 1646-1650.

Brach, J. S., Studenski, S., Perera, S., VanSwearingern, J. M., Newman, A. B. (2008). Stance time and step width variability have unique contributing impairments in older persons. *Gait & Posture,* 27, 431-439.

Bradshaw, E. (2004). Target-directed running in gymnastics: a preliminary exploration of vaulting. *Sports Biomechanics,* 3 (1), 125-144.

Bradshaw, E. J., & Sparrow, W. A. (2000). The Speed-Accuracy trade-off in human gait control when running toward targets. Journal of Applied Biomechanics, 16, 331-341.

Burton, A. W. & Davis, W. E. (1996). Ecological task analysis utilizing intrinsic measures in research and practice. *Human Movement Science,* 15, 285-314.

Campbell, A. J., Reinken, J., Allan, B. C., & Martinez, G. S. (1981). Falls in old age: a study of frequency and related clinical factors. *Age and Ageing,* 10, 264-270.

Chapman, G. J., & Hollands, M. A. (2006). Evidence for a link between changes to gaze behavior and risk of falling in older adults during adaptive locomotion. *Gait & Posture,* 24, 288-294.

Chapman, G. J., & Hollands, M. A. (2006a). Age-related differences in stepping performance during step cycle-related removal of vision. *Experimental Brain Research* 174, 613-621.

Chapman, G. J., & Hollands, M.A. (2006b). Evidence for a link between changes to gaze behavior and risk of falling in older adults during adaptive locomotion. *Gait & Posture*, 24, 288-294.

Chapman, G. J., & Hollands, M. A. (2007). Evidence that older adult fallers prioritize planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait & Posture,* 26, 59-67.

Chapman, G. J., & Hollands, M. A. (2010). Age-related differences in visual sampling requirements during adaptive locomotion. *Experimental Brain Research,* 201, 467-478.

Chen, H-C., Ashton-Miller, J. A., Alexander, Neil B., & Schultz, A. B. (1991). Stepping over obstacles: Gait patterns of young and old adults. *Journal of Gerontology: MEDICAL SCIENCES,* 46, 6, M196-M203.

Chen, H-C., Ashton-Miller, J. A., Alexander, Neil B., & Schultz, A. B. (1994). Effect of age and available response time on ability to step over an obstacle. *Journal of Gerontology: MEDICAL SCIENCE,* 49, 5, M1227-M233.

Craik, R. L., & Dutterer, L. (1995). Spatial and temporal characteristics of footfall patterns. In R. L. Craik, & Oatis, C. A. (Eds.) *Gait Analysis. Theory and Practical Applications.* (pp. 143-158). St. Louis, MO: Mosby.

Davis, W. E. & Burton, A. W. (1991). Ecological task analysis: Movement behavior theory into practice. *Adapted Physical Activity Quarterly,* 8, 154-177.

Di Fabio, R. P., Greany, J. F. & Zampieri, C. (2003). Saccade-stepping interactions revise the motor plan for obstacle avoidance. *Journal of Motor Behavior*, 35 (4), 383-397.

DiFabio, R. P., Zampieri, C, & Greany, J. F. (2003). Aging and saccade-stepping interactions in humans. *Neuroscience Letters*, 339, 179-182.

Dionyssiotis. Y. (2012). Analyzing the problem of falls among older people. *International Journal of General Medicine,* 2012:5, 805-813.

Eble, R. J., Thomas, S. S., Higgins, C., & Colliver, J. (1991). Stride-dependent changes in gait of older people. *Journal of Neurology,* 238, 1-5.

Elble, R. J. (1997). Changes in gait with normal aging. In J. C. Masden, L. Sudorsky, & L. Wolfson (Eds.). *Gait disorders of aging. Falls and therapeutic strategies* (pp.93-105). New York: Lippincott-Raven.

Elliott, D. (1986). Continuous visual information may be important after all: A failure to replicate Thomson (1983). *Journal of Experimental Psychology: Human Perception and Performance,* 12 (3), 388-391.

Fitts, P. M. (1992). The information capacity of the human motor system in controlling the amplitude of movement (Reprint). *Journal of Experimental Psychology: Human Perception and Performance: General* 121 (3), 262-269.

Gabell, A. & Nayak, U. S. L. (1984). The effect of age on variability in gait. *Journal of Gerontology,* 39 (6), 626-666.

Greany, J. F., & DiFabio, R. P. (2008). Saccade to stepping delays in elderly at risk for falling. *Aging Clinical and Experimental Research,* 20 (5), 428-433.

Hausdorff, J. M., Edelberg, H. K., Mitchell, S. L., & Goldberger, A. L. (1997). Increased gait unsteadiness in community-dwelling elderly fallers. *Archives of Physical Medicine and Rehabilitation,* 78, 278-283.

Hay, J. G. (1988). Approach strategies in long jump. *International Journal of Sport Biomechanics* 4, 114-129.

Hollands, M. A., & Marple-Horvat, D. E. (2001). Coordination of eye and leg movements during visually guided stepping. *Journal of Motor Behavior,* 33 (2), 205-216.

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, 221-230.

Judge, J. O., Ounpuu, S., & Davis III, R. B. (1996). Effects of age on the biomechanics and physiology of gait. *Clinics in Geriatric Medicine,* 12 (4), 659-678.

Laurent, M., & Thomson, J. A. (1988). The role of visual information in control of a constrained locomotor task. *Journal of Motor Behavior* 20 (1), 17-37.

Lee, D. N. (1978). The functions of vision. In H. L. Pick jr. and E. Saltzman (Eds.). *Modes of perceiving and processing information* (pp. 159-170). Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers.

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

Maki, B. E. (1997). Gait changes in older adults: predictors of falls or indicator of fear? *Journal of the American Geriatrics Society,* 45 (3), 313-320.

Maraj, B. K. V. (2002). Control and co-ordination in the triple jump. In K. Davids, Savelsbergh, G., & Bennett, S. J. (Eds.) *Interceptive actions in sport: Information and movement* (pp. 334-342). New York: Routlege.

Nachreiner, N. M., Findorff, M. J., Wyman, J. F., & McCarthy, M. C. (2007). Circumstances and consequences of falls in community-dwelling older women. *Journal of Women's Health,* 16 (10), 1437-1446.

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade and H. T. A. Whiting (Eds.). *Motor development in children: Aspects of coordination and control* (pp.341-360).Dordrecht, the Netherlands: Martinus Nijhof Publishers.

O'Loughlin, J. L., Robitaille, Y., Boivin, J-F., & Suissa, S. (1993). Incidence of and risk factors for falls and injurious falls among the community-dwelling elderly. *American Journal of Epidemiology,* 137 (3), 342-354.

Owings, T. M. & Grabiner, M. D. (2004a). Step width variability, but not step length variability or step time variability, discriminates gait of healthy young and older adults during treadmill locomotion. *Journal of Biomechanics,* 37, 935-938.

Owings, T. M. & Grabiner, M. D. (2004b). Variability of step kinematics in young and older adults. *Gait and Posture,* 20, 26-29.

Patla, A. (1991). Visual control of human locomotion. In A. E. Patla (Ed). *Adaptability of human gait* (pp. 55-97). Amsterdam: Elsevier.

Patla, A. E. (1993). Age-related changes in visually guided locomotion over different terrains: Major issues. In G. E. Stelmach and Homberg, V. (Eds).

Sensorimotor Impairments in the Elderly (pp. 231-252). The Netherlands: Kulwer Academic Publisher.

Patla, A. (1995) Neurobiomechanical bases for the control of human locomotion. In A. M. Bronstein, Brandt, T., & Woollacott, M. H. (Eds.). *Clinical disorders of balance, posture, and gait* (pp. 19-40). New York: Oxford University Press.

Patla, A. (1997). Understanding the roles of vision in the control of human locomotion. *Gait & Posture 5*, 54-69.

Patla, A. E. (1995). A framework for understanding mobility problems in the elderly. In Craik, R. L., and Oatis, C. A. (Eds.) *Gait Analysis. Theory and Application* (pp. 436-449). St. Louis, MO: Mosby.

Patla, A. E. (2004). Gaze behaviors during adaptive human locomotion: Insights into how vision is used to regulate locomotion. In Vaina, L. M., S. A. Beardsley, and S. K. Rushton (Eds.) *Optic Flow and Beyond* (pp. 383-399). Netherlands: Kluwer Academic Publishers.

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, 3361-3365.

Patla, A., 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, 513-522.

Patla,, A. E., & Vickers, J. N. (2003). How far do we look when required to step on specific locations in the travel path during locomotion? *Experimental Brain Research,* 148, 133-138.

Perry, S. D. & Patla, A. E. (2001). On-line adjustments to body center of mass and limb elevation to suddenly changing obstacle height. In J. Duysens, Smits-Engelsman, B. M., & Kingma, H. (Eds.), *Control of posture and gait* (pp. 485-487). Maastricht, Netherlands.

Prince, F., Corriveau, H., Hebert, R. & Winter, D. (1997). Gait in the elderly. *Gait and Posture,* 5, 128-135.

Renshaw, I., & Davids, K. (2006). A comparison of locomotor pointing strategies in cricket bowling and long jumping. *International Journal of Sport Psychology,* 37, 1-20.

Reynolds, R.F. & Day, L. B. (2005a). Rapid visuo-motor processes drive the leg regardless of balance constraints. *Current Biology,* 15 (2), R48-R49.

Reynolds, R.F. & Day, L. B. (2005b). Visual guidance of the human foot during a step. *Journal of Physiology,* 569 (2), 677-684

Rose, J., & Gamble, J. G. (2006). *Human Waling* (3rd Ed.) Philadelphia, PA: Lippincott Williams & Wilkins.

Spirduso, W. W., Francis, K. L., & McRae, P. G. (2005). *Physical dimensions of aging* (2nd Ed). Champaign, IL: Human Kinetics.

Statistics Canada (2009). Mortality, summary list of causes 2005. Ottawa: Minister of Industry.

Statistics Canada. (2008). Canadian Demographics at a Glance. Ottawa: Minister of Industry.

Statistics Canada: Deaths by cause Chapter XX: external causes of morbidity and mortality Retrieved from http://cansim2.statcan.gc.ca June 23, 2010.

Steenhuis, R. E., & Goodale, M. A. (1988). The effect of time and distance on accuracy of target-directed locomotion: Does an accurate short-term memory for spatial location exist? *Journal of Motor Behavior,* 20 (4), 399-415.

Thomson, J. A. (1980). How do we use visual information to control locomotion? *Trends in Neuroscience,* 3, 247-250.

Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental Psychology: Human Perception and Performance,* 9 (3), 427-443.

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.

Turcotte, M. & Schellenberg, G. (2007). A Portrait of Seniors in Canada. Statistics Canada Ottawa: Minister of Industry.

Winter, D. A., Patla, A. E., & Frank, J. S. (1990). Biomechanical walking pattern changes in the fit and healthy elderly. *Physical Therapy,* 70 (6), 340-348.

Young, W. R. & Hollands, M. A. (2010). Can telling older adults were to look reduce falls? Evidence for a causal link between inappropriate visual sampling and suboptimal stepping performance. *Experimental Brain Research,* 204, 103-113.

Study one

Intermittent visual information affects motor strategies during locomotor pointing[2]

2.1 Introduction

Walking is the preferred mode of locomotion for many of our daily tasks. Natural cluttered environments and artificial, man-made, environments require adaptive locomotion. In typical individuals, gait becomes regulated predominantly via visual information; other sensory modalities have subordinate roles as they cannot provide predictive environmental information at a distance as vision does (Patla, 1997). Vision provides information from the environment to plan movement for feed-forward locomotion control (Patla, Adkin, Martin, Holden, & Prentice 1996; Patla & Vickers, 1997) and information about limb position to fine tune voluntary actions via on-line control (Rietdyk & Rhea, 2006; Reynolds & Day 2005). Support for visually controlled adaptive locomotion also comes from empirical studies involving athletic events (Glize & Laurent, 1997; Lee, Lishman, & Thomson 1982; Hay, 1988; Bradshaw, 2004; Maraj, 2002; Renshaw & Davids, 2006) and mathematical modeling (deRugy, Taga, Montagne, Buekers, & Laurent, 2002)

Vision plays several roles in controlling locomotion; besides modulating gait patterns for adaptive locomotion, it is important for initiation/termination of

---

[2] A version of this chapter has been published. Popescu et al., (2010). *International Journal of Sport Psychology,* 41(3), 313-326.

locomotion, maintaining dynamic stability, and route planning (Patla, 1997). However, other tasks requiring visual attention are routinely performed during locomotion. For instance, conversation often takes place during walking or running, requiring brief gaze shifts away from the ongoing locomotor task. More rigorous, empirical support for intermittent visual sampling during locomotion was provided from three broad experimental paradigms.

The first paradigm comes from investigating the control of locomotion during athletic events requiring precise foot placement on targets during full vision availability. Lee, Lishman, and Thomson (1982) systematically observed the run-up approach to the take-off board for three proficient level long jumping athletes. Contrary to the belief that the run-up was a highly stereotyped gait pattern that can be consistently reproduced, a two-phase approach based on footfall position variability was recorded. The first phase consisted of an initial stereotyped, accelerative phase during which error in footfall variability was accumulated. The stereotyped pattern broke down over the last strides giving way to the visually regulated, zeroing-in phase. If stride length would have been maintained, the target would be missed due to the cumulative effect of small inconsistencies for each stride during the approach run. Recently, the two-phase control strategy was replicated for various athletic events, across gender and proficiency levels (Berg, Wade, & Greer, 1994; Bradshaw, 2004; Hay, 1988; Maraj, 2002; Renshaw & Davids, 2006).

Two new approaches to analyze the footfall position during the long jumping approach events were proposed to quantify the pattern of approach footfall variability. For the long jump approach phase, Glize and Laurent (1997) found that the accumulated spatial error (i.e. footfall variability) fitted a quadratic function. That is, the footfall variability increased up to a point and decreased systematically from there (3 to 4 strides prior to pointing) to meet the take-off board pointing constraints. Recently, a new trial-by-trial analysis method was proposed by Montagne, Cornus, Glize, Quaine, & Laurent (2000). This method provided the means to identify the nature of the control mechanism during adaptive locomotion. Authors found that long jumpers use a continuous perception-action coupling mechanism allowing step length regulation based on need (i.e. the larger the accumulated error the sooner the regulation will be initiated).

The second paradigm, supporting intermittent vision sufficiency during locomotion, employed direct visual manipulation during locomotion in laboratory settings. An ingenious set of six experiments involving visual denial (blind walking) was conducted by Thomson (1983). After 5 seconds of sampling of the static visual environment from the starting position, participants were able to point accurately (i.e. less than one step error) at targets situated at different distances (6 – 21m) provided that the task was accomplished in less than 8 seconds. It was concluded that for distances up to 5m a fixed motor program could control accurate foot placement regardless of elapsed time. For targets beyond 5m and task duration around 8 seconds, a more flexible “mental map” of the environment provides the participant with sufficient information for adaptive locomotion. However, two subsequent investigations failed to replicate these findings on account of training protocol, logical fallacy in the argument, and statistical analysis (see Elliott, 1986; Steenhuis & Goodale, 1988).

The last paradigm utilizes intermittent visual sampling during locomotion. One study manipulated the ambient light as a function of gait events in order to create four visual experimental conditions: full vision, no vision, vision during swing phase, and vision during stance phase of the pointing foot (Laurent & Thomson, 1988). Young adults were instrumented with force sensitive resistors on the sole of their pointing foot. On contact with the ground, the resistors emitted a radio signal capable of switching the light in the experimental room off and on. This manipulation denied vision during the gait cycle as walking and pointing toward a target line with either dominant or nondominant foot. It was found that fixed intervals (lasting 300 ms) of intermittent visual information during the approach phase were sufficient to maintain locomotor pointing accuracy in young adults regardless of visual manipulation. Vision availability during the swing phase of the pointing foot provided the least accurate pointing outcome and the largest approach footfall variability, second only to the no vision condition. During the no vision condition participants made step adjustments to match a “visual map” of the environment rather than following a predetermined motor plan. The required foot adjustments occurred during the last three to four steps (“action units”) regardless of visual manipulation. The footfall variability profile in this study had a strikingly similar profile to that observed in the long jumping events despite the different task constraints.

Chapman & Hollands (2006) employed a similar intermittent visual sampling paradigm. Young and old adults were required to walk and target with the dominant foot towards a series of three targets (19 x 42cm) placed on the ground. Vision was removed for the entire duration of the stance or swing phase of the gait cycle for the dominant foot. Intermittent vision had no significant effect on foot placement accuracy for young adults; however, older adults had difficulties in maintaining foot placement accuracy especially during the swing only vision condition. Accuracy was maintained by increasing the overall stance duration during the intermittent visual conditions prior to targeting or by increasing the overall swing duration and the approach velocity during swing vision condition.

The above mentioned intermittent vision experiments exposed participants to a rigid and unnatural visual sampling mode. This issue was addressed by Patla and colleagues (1996). For this experiment the participants had full control over the number and duration of visual samples. Vision was manipulated with a pair of LCD goggles. The goggles were controlled from a hand-held switch. In contrast with the previous studies, the walking paths were predefined requiring specific foot placement for each step. The overall finding was that intermittent visual sampling was adequate to negotiate various straight or winding walking paths, avoid obstacles, and point at different targets en route. It was shown that the sampling rate increased from 10% duration (no footprints path) to 40% of the total approach duration as a function of difficulty and complexity of the task. A second set of tasks for steering, obstacle avoidance, and stepping on specific footprints made possible identification of visual information use for feed-forward vs. on-line control mode. The analysis of visual samples prior and during the adaptive steps revealed the fact that vision was used predominantly in a feed-forward manner. The intermittent visual sampling indicated an increase for vision demand at target proximity by increasing the sampling frequency. Regardless of task manipulation, visual requirements never exceeded one visual sample per step or a single, longer sample per stride.

The above findings provide strong support for intermittent visual sampling for adaptive locomotion. The present paper will extend the findings of both Laurent and Thomson (1987) and Chapman and Hollands (2006). By combining two constraints, smaller target and less vision availability, the overall task difficulty was increased. While healthy young adults feature flexible perceptual and locomotor systems, we sought to test this further by increasing the overall task difficulty. Our aim was to investigate how intermittent visual information affects motor strategies during locomotion.

2.2 Method

2.2.1 Participants

Six undergraduate university students (3 males and 3 females) with normal or corrected to normal vision volunteered for the study. Participants were independent walkers, free of any neurological or musculoskeletal impairment that could compromise the experiment. The research protocol was approved by the Faculty of Physical Education and Recreation Research Ethics Board and each participant handed in a written informed consent form prior to data collection.

2.2.2 Instruments and task

Two LED markers were attached to the anatomical landmarks of each foot: the anterior-superior aspect of the hallux, and the posterior aspect of the calcaneus. The markers were tracked by a six-camera motion analysis system at a sampling rate of 120Hz (Visualeyez PTI, Burnaby, BC). A pair of Plato LCD goggles (Translucent Technology, Toronto, ON) was utilized to control vision availability. The status of the goggles changed from transparent to translucent (denying vision) as a function of the gait cycle. The status of the goggles was controlled via the input signals sent by two Force Sensitive Resistors (National Instruments, Canada) mounted on the shoe insole under the heel and base of the toes of the dominant (pointing) foot. The task consisted of walking towards and placing the anterior aspect of the pointing foot (big toe) as close as possible to the centerline of the target (Figure 2.1).

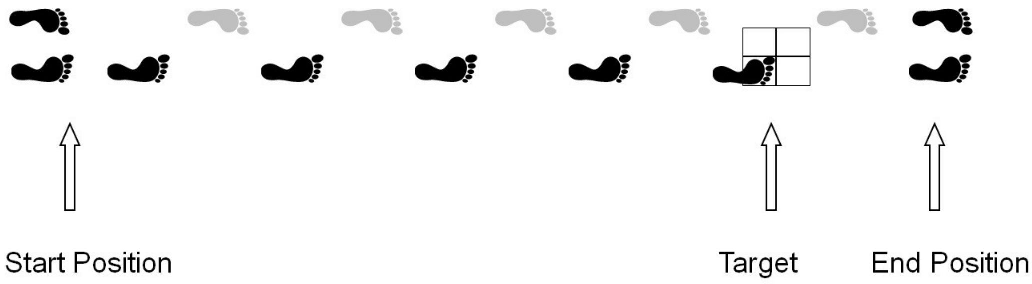


Figure 2.1 Experimental task diagram for the stance vision condition only (right foot depicted during stance; the dark footprints signify vision availability).

2.2.3 Procedure

The target (20x30 cm) was flush to the ground and placed at a distance of approximately 5 meters away from the starting point. During the practice trials preceding data collection, a neutral target location was obtained for each participant by manipulating the starting position such that target will be hit with minimal step adjustments. The center of the target was visibly marked by contrasting color crosshairs. Participants walked at a self selected-pace, stepped on the target placing the dominant forefoot as close as possible to the marked center of the target, and continued their locomotion before stopping for a distance up to 2 m.

Participants had their eyes closed at the starting point. Each trial started with a verbal signal, after which participants opened their eyes, and proceeded walking toward the target. Five trials for each of the three visual conditions were randomly presented. During the full vision condition (FV) vision was always available throughout the approach phase. During the intermittent vision conditions, vision was available for the entire duration of either swing phase of the gait cycle (SWV) or stance phase of the gait cycle (STV) for the pointing foot.

2.2.4 Data analysis

The entire approach footfall variability (foot position for each step relative to the center of the target) was recorded. One step is the event between two consecutive heel contacts with the opposite feet.

A one-way RM ANOVA was conducted on the following dependent variables:

a). Average approach velocity calculated as the ratio between the distance covered by the dominant foot toe marker from the first toe-off to last toe-off before targeting and the time required for this marker to cover the distance;

b). Last step length of the pointing foot prior to pointing;

c). Last step swing duration of the pointing foot prior to pointing;

d).Last step stance duration of the pointing foot prior to pointing;

e). Foot-pointing error on target calculated as the distance between the toe marker of the dominant foot and the center of the target along the anterior-posterior axis;

f). Foot-pointing variability (SD of anterior-posterior error).

Confidence levels were set at $p < 0.05$; Tukey HSD post hoc tests were employed where appropriate.

2.3 Results

2.3.1 Target approach

2.3.1.1 Footfall variability

A 3 (visual condition) x 8 (step rank) RM ANOVA revealed a significant effect for step. Mauchly's test indicated that the assumption of sphericity has been violated $\chi^2 (27) = 58.14$, $p = .001$. The degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .502$). The results showed that the step rank spatial error changed during the approach $F (3.51, 17.56) = 10.35$, $p = .001$, $\eta^2 = .674$. In order to observe how the pattern of footfall evolved during the approach, a separate regression analysis was carried out for each visual condition (Figure 2.2). A cubic regression best fitted the data regardless of visual condition. For the full vision condition $R^2 = .95$, $F(3, 6) = 38.25$, $p = .001$; for the stance vision condition $R^2 = .93$, $F(3, 6) = 38.85$, $p = .001$; and for the swing vision condition $R^2 = .94$, $F(3, 6) = 32.58$ $p = .001$. After initiating the approach, the variability of footfall increased during the approach and was considerably reduced over the last three to four steps before pointing. The most footfall variability was recorded during the stance vision condition (STV) and the least footfall variability occurred during the full vision condition (Figures 2.3).

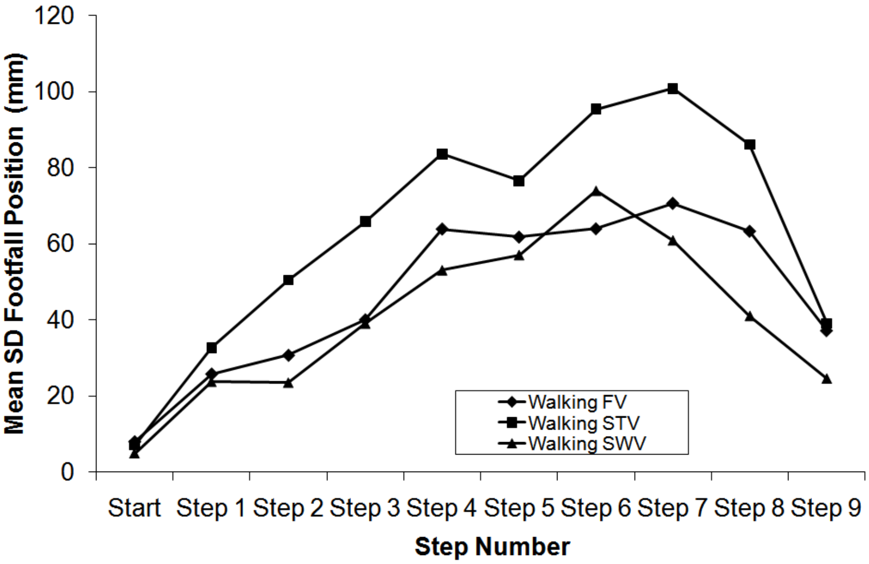


Figure 2.2 Mean approach footfall variability (foot – target position for each step across trials) as a function of visual condition.

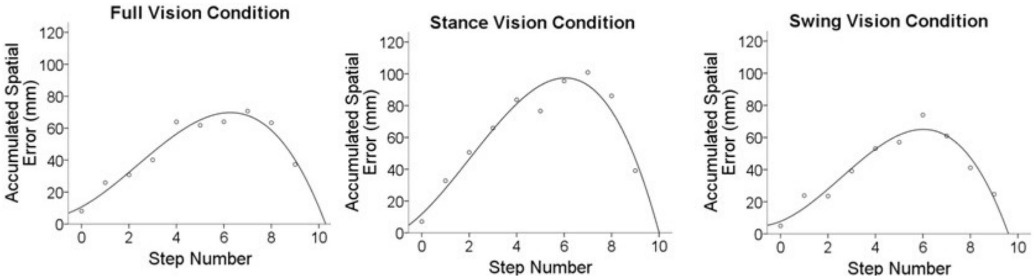


Figure 2.3 The approach footfall variability pattern depicting the accumulated spatial error for each step fitting a cubic regression.

2.3.1.2 Average approach velocity

There was a significant effect of visual condition on the average approach velocity F (2, 10) = 8.07, p = .008, η^2 = .669. The post hoc analysis revealed that there was a significant reduction in approach velocity between the FV condition (M = 0.80 m/s, SD = 0.22) and the SWV condition (M = 0.76m/s, SD = 0.21). It was also revealed a significant reduction in approach velocity between the FV condition and the STV condition (M = 0.75 m/s, SD = 0.20).There was no significant difference between the SWV condition and the STV condition with regard to the average approach velocity (Figure 2.4).

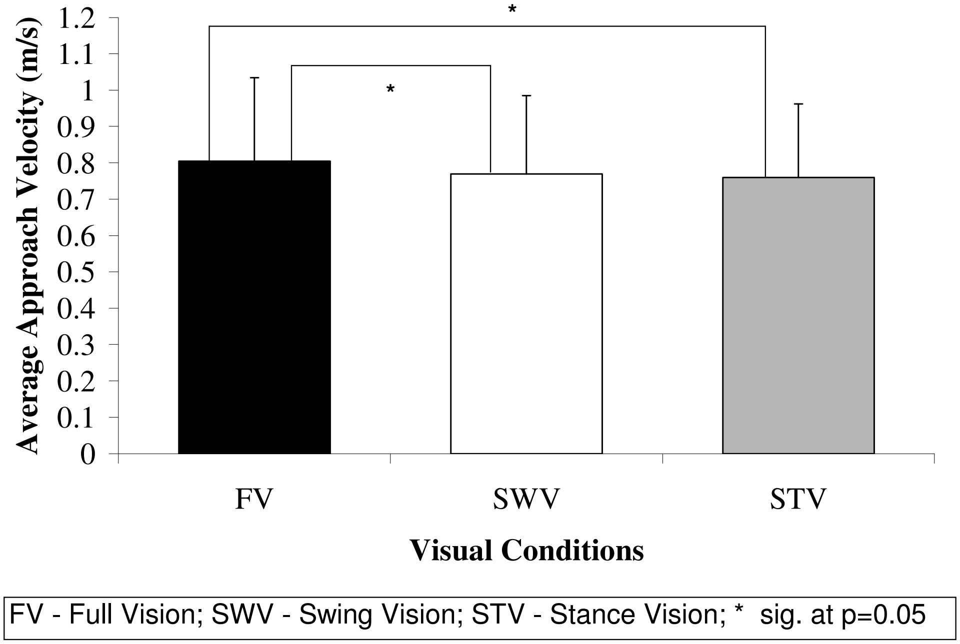


Figure 2.4 Mean and standard deviation of approach velocity as a function of visual condition.

2.3.2 Last step

2.3.2.1 Step length

The results of the ANOVA showed a significant effect of visual manipulation on last step length prior to pointing F (2, 10) = 10.10, p =.004, η^2 =.669. Post hoc analysis indicated that last step length during SWV condition (M = 590.82 mm, SD = 117.21) was significantly longer than during the FV condition (M = 546.42 mm, SD = 132.33). It also indicated that the last step length was significantly longer for the STV condition (M = 606.87 mm, SD = 116.19) as compared to FV condition. The last step length from SWV was not significantly different from the last step STV condition (Figure 2.5).

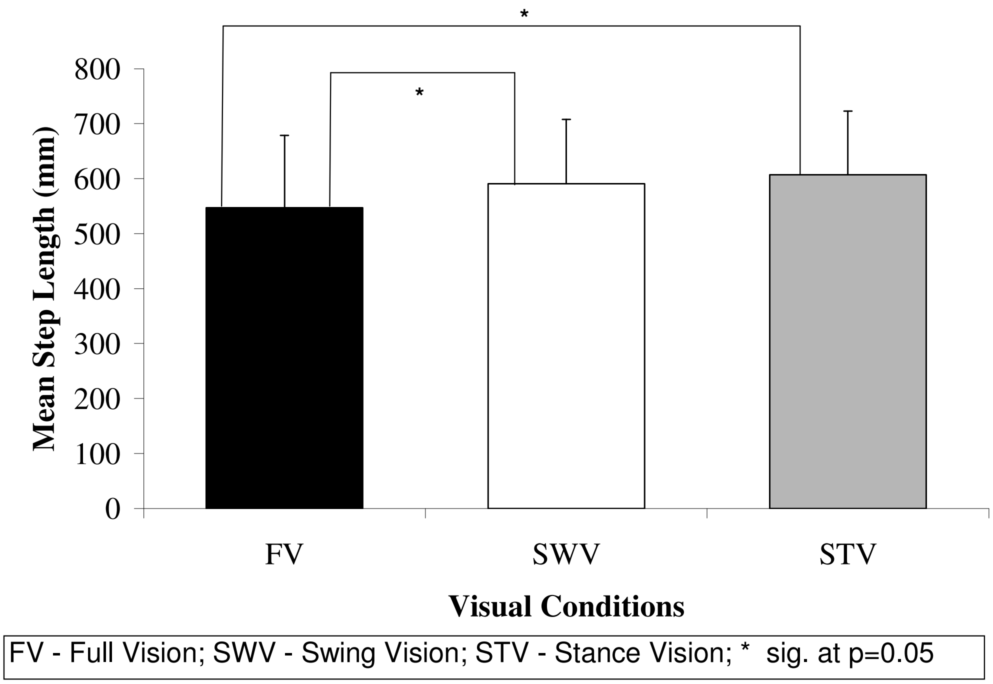


Figure 2.5 Mean and standard deviation of last step length as a function of visual condition.

2.3.2.2 Swing duration

ANOVA revealed that there were significant differences in the mean last step swing duration as a function of visual conditions F (2, 10) = 7.37, p =.001, η^2 =.596. Tukey post hoc comparisons indicated that swing duration was significantly longer for the SWV condition (M= 0.404, SD = .044) as compared to the FV condition (M = 0.384, SD = .040) and swing duration was significantly longer for the STV condition (M = 0.419, SD = .043) as compared to the FV condition. There was no significant difference between the SWV condition and the STV condition with regard to the swing duration of the dominant foot prior to pointing (Figure 2.6).

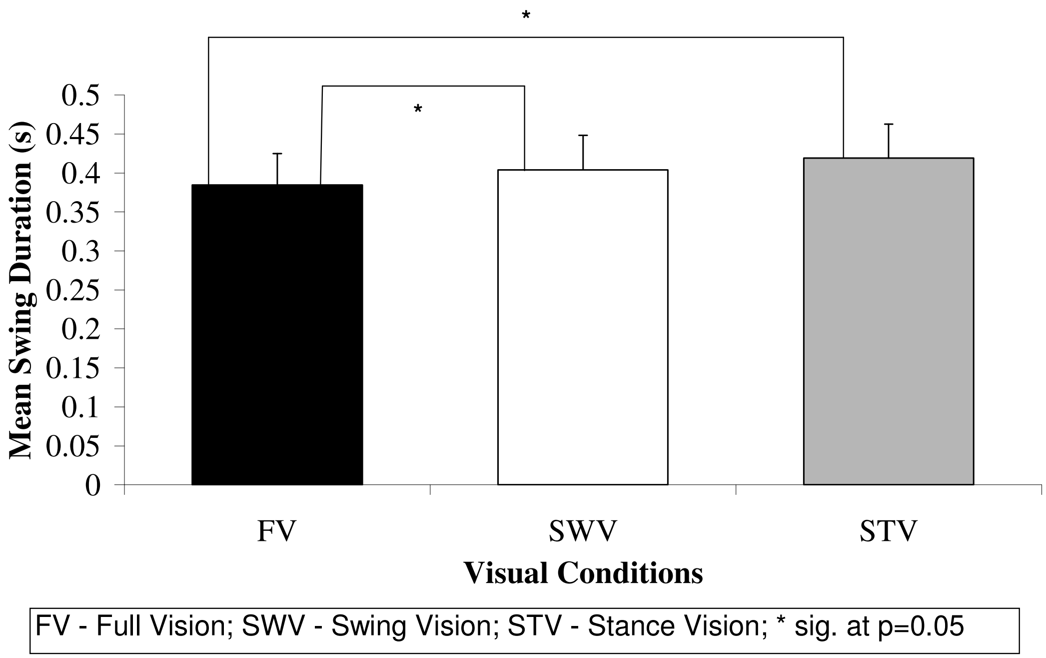


Figure 2.6 Mean and standard deviation of last step swing duration as a function of visual condition.

2.3.2.3 Pointing error (anterior-posterior axis)

On average the target was undershot by the participants regardless of visual manipulation. The error magnitude was not statistically significant F (2, 10) = 1.96, p = .191, $\eta^2 = .282$ (Figure 2.7).

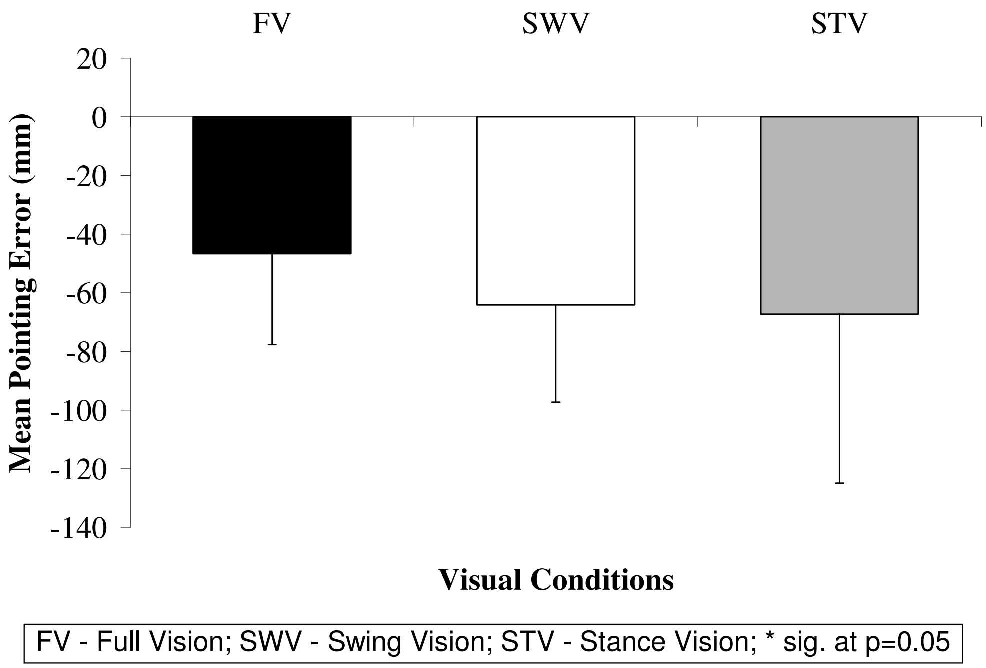


Figure 2.7 Mean and standard deviation of sagittal foot-pointing error as a function of visual condition.

2.4 Discussion

The purpose of this study was to investigate the effect of intermittent visual information on locomotor pointing accuracy. While there was no effect of intermittent vision manipulation on pointing accuracy, there were two different control strategies that emerged, one for the full vision condition and another for the intermittent vision conditions. The strategy for the full vision condition showed a faster approach and shorter step length and swing duration for the last adaptive step. This came in contrast with the strategy for both intermittent vision conditions which had a slower approach followed by longer step length and swing duration for the last adaptive step.

In line with previous research, our study revealed a similar pattern for footfall variability suggesting that after an initial and gradual increase in footfall spatial error, significant footfall adjustments were made during the last three to four steps prior to pointing regardless of the visual condition (Berg et al., 1994; Bradshaw, 2004; Hay, 1988; Lee, et al., 1982; Maraj, 1998; Montagne et al., 2000; Renshaw & Davids, 2006) (Figure 2.2). As participants approach the target and the accumulated error becomes evident, they can benefit from having sampled near the target where foot placement adjustments are required in order to reduce pointing error (Patla et al., 1996). Despite the fact that the participants have a clear view of the target from the starting point (as opposed to the long jumping events) and walk toward the target (as opposed to running at near maximal speed) the essence seems to be represented by the targeting aspect of the task in terms of locomotor strategy. Contrary to the previous findings of Laurent & Thomson (1988), the greatest footfall variability was recorded during the stance vision condition not during swing visual condition. It seems that the increased task difficulty (i.e. smaller target and decreased vision availability) is minimizing the advantage of perceived foot-to-target distance as a reliable gauge for error detection.

The approach velocity was reduced during the intermittent visual conditions as compared to the control, full vision condition. Imposing increased constraints will consequently increase task difficulty. In real-life situations, slowing down will allow more visual sampling and decision-making time necessary to minimize the eventual risk of harm. This was also found for participants performing a serial targeting task, but only during swing vision condition (Chapman & Hollands, 2006). A slower approach could provide more time to sample visual information and to pre-plan future footfalls. Previous studies accounting for gaze behavior showed that young adults sample two steps in advance (Patla & Vickers, 1997, 2003). This feed-forward strategy becomes useful especially during the stance vision condition when no vision is available during the last swing before pointing.

Under both intermittent visual conditions, the last adaptive step was longer and the last swing duration was longer as compared to the full vision condition. Without short and fixed-duration intermittent visual samples during specific gait phases (i.e. stance phase of gait cycle) the outcome movement becomes "clumsy and ill coordinated" (Laurent & Thomson, 1988). It has been previously shown that young adults use vision for planning and guiding movement equally well (Patla, et al., 1996; Patla & Vickers, 1997; Rietdyk & Rhea, 2006; Reynolds & Day 2005). Given the previous research findings and the fact that our study shows last adaptive step modulation prior to the pointing task regardless of vision availability, we infer that the participants used vision for on-line control strategy as well.

Locomotor pointing accuracy was not affected by visual manipulation. Young adults are capable of placing their dominant foot accurately on the center line of a small target despite the increased task demands (i.e. shorter visual samples and smaller target). The footfall pattern during the approach was similar for all three experimental conditions; however, the magnitude of variability was largest during the stance vision condition. The pointing accuracy is consistent with previous research findings (Chapman & Hollands, 2006; Laurent & Thomson, 1988; Patla et al., 1996). Each of these studies had a different task with a varying degree of difficulty and also had different visual manipulations, yet the foot placement remained accurate. For the present study, during all three visual conditions, on average, participants undershot the target. We speculated that the confined laboratory space and the nature of the task may have led to such adaptive behavior (Steenhuis & Goodale, 1988). Overall, the results argue for robust and flexible perceptual and locomotor systems in young adults.

2.4.1 Conclusion

Young adults can safely navigate the environment even if visual information is intermittently sampled. The navigation strategies are flexible and support the idea that most gait adaptations occur in the "near-space zone" (Laurent & Thomson 1988, p.36) where foot placement adjustments and increased visual sampling are necessary. The control strategies are linked to the change in the environment (Gibson, 1986) and depend on the individuals' adaptation capabilities. Future research should address the effects of perceptual variables availability, task difficulty/complexity, and situational factors on adaptive locomotion (Bradshaw & Sparrow, 2000, 2001; Maraj, Allard, & Elliott, 1998; Renshaw & Davids, 2006).

2.5 References

Berg, W.P., Wade, M.G., & Greer N.L. (1994). Visual regulation of gait in bipedal locomotion: revisiting Lee, Lishman, and Thomson (1982). Journal of Experimental Psychology: Human Perception and Performance, 4, 854-863.

Bradshaw, E. (2004). Target-directed running in gymnastics: a preliminary exploration of vaulting. *Sports Biomechanics* 3 (1), 125-144.

Bradshaw, E. J., & Sparrow, W. A. (2000). The Speed-Accuracy trade-off in human gait control when running toward targets. Journal of Applied Biomechanics16, 331-341.

Bradshaw, E. J., & Sparrow, W. A. (2001). Effects of approach velocity and foot-target characteristics on the visual regulation of step length. Human Movement Science 20, 401-426.

Chapman, G. J., & Hollands, M. A. (2006). Age-related differences in stepping performance during step cycle-related removal of vision. *Experimental Brain Research* 174, 613-621.

De Rugy, A., Taga, G., Montagne, G., Buekers, M. J., & Laurent, M. (2002). Perception-action coupling model for human locomotor pointing. *Biological Cybernetics* 87, 141-150.

Elliott, D. (1986). Continuous visual information may be important after all: A failure to replicate Thomson (1983). *Journal of Experimental Psychology: Human Perception and Performance,* 12 (3), 388-391.

Gibson, J. J. (1986). The Ecological Approach to Visual Perception. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Glize, D., & Laurent, M. (1997). Controlling locomotion during the acceleration phase in sprinting and long jumping. *Journal of Sport Sciences,* 15, 181-189.

Hay, J. G. (1988). Approach strategies in long jump. *International Journal of Sport Biomechanics* 4, 114-129.

Laurent, M., & Thomson, J. A. (1988). The role of visual information in control of a constrained locomotor task. *Journal of Motor Behavior,* 20 (1), 17-37.

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

Maraj, B., Allard, F., & Elliott, D. (1998). The effect of nonregulatory stimuli on the triple jump approach run. *Research Quarterly for Exercise and Sport* 69 (2), 129-135.

Maraj, B. K. V. (2002). Control and co-ordination in the triple jump. In K. Davids, Savelsbergh, G., & Bennett, S. J. (Eds.) *Interceptive actions in sport: Information and movement* (p. 334-342). New York: Routlege.

Montagne, G., Cornus, S., Glize, D., Quaine, F., & Laurent, M. (2000). A perception-action coupling type of control in long jumping. *Journal of Motor Behavior* 32 (1), 37-43.

Patla, A. (1997). Understanding the roles of vision in the control of human locomotion. Gait & Posture 5, 54-69.

Patla, A., 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, 513-522.

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, 3361-3365.

Patla, A. E., & Vickers, J. N. (2003). "How far do we look when required to step on specific locations in the travel path during locomotion?" Experimental Brain Research 148, 133-138.

Renshaw, I., & Davids, K. (2006). A comparison of locomotor pointing strategies in cricket bowling and long jumping. *International Journal of Sport Psychology* 37, 1-20.

Reynolds, R.F. & Day, L. B. (2005). Rapid visuo-motor processes drive the leg regardless of balance constraints. *Current Biology,* 15 (2), R48-R49.

Rietdyk, S., & Rhea, C. K. (2006). Control of adaptive locomotion: effect of visual obstruction and visual cues in the environment. *Experimental Brain Research* 169, 272-278.

Steenhuis, R. E., & Goodale, M. A. (1988). The effect of time and distance on accuracy of target-directed locomotion: Does an accurate short-term memory for spatial location exist? *Journal of Motor Behavior,* 20 (4), 399-415.

Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental Psychology: Human Perception and Performance* 9 (3), 427-443.

Study two

Locomotor pointing is independently affected by target size and intermittent vision[3]

3.1 Introduction

Walking is a highly adaptable and complex movement skill. In order to successfully navigate cluttered environments, one has to rely on visual information for gait modulation in order to match the changing environmental demands (i.e., adaptive locomotion). Vision is a unique sensory modality providing accurate predictive environmental information at a distance and almost instantaneously, which allows for proactive locomotor control (Patla, 1997). Adaptive locomotion tasks can be classified into avoidance tasks (stepping over obstacles) and accommodation tasks (placing the foot on specific ground locations also known as locomotor pointing) (Patla, 1991). The typical healthy individual is capable of successfully and seamlessly implementing adaptive locomotor strategies to avoid obstacles or point at targets en route without abruptly disrupting gait's forward progression.

One of the first reports on proactive locomotor control was made by Lee, Lishman, and Thomson (1982). They recorded the approach phase of Olympic-caliber athletes performing a series of long jumps. These tasks require gait adaptation in order to accurately place one foot on a narrow take-off board

---

[3] A version of this chapter has been submitted for publication. Popescu, A. & Maraj, B. *International Journal of Sport Psychology.*

embedded at the end of a runway. It was found that the run-up approach consisted of two phases. The initial accelerative phase built momentum and was always followed by a zeroing-in, visually controlled phase for locomotor pointing. During this second phase vision was used in a feed-forward mode to control stepping in order to overcome the inevitable cumulative footfall errors during the approach towards the take-off board.

More insight regarding the role of visually guided locomotion has come from lab-based intermittent vision experiments. Visual resources are shared during locomotion without threatening the safety and efficiency of locomotion. Brief gaze shifts away from the ongoing locomotor task take place when concurrent tasks require visual attention (e.g., scanning the environment, maintaining eye contact while engaged in conversation). There is empirical support for intermittent visual sampling sufficiency during adaptive locomotion for healthy young adults (Chapman & Hollands, 2006; Laurent & Thomson, 1988; Popescu, Runnalls, & Maraj, 2010).

The representative research paradigm for manipulating visual sampling during adaptive locomotion uses an externally controlled visual sampling protocol linked to the participant’s gait events. As such, vision may be manipulated to be sampled during either the stance or the swing phase of the gait cycle for the pointing foot.

One early report on intermittent vision during locomotor pointing was made by Laurent & Thomson, (1988). Ambient light availability was manipulated to deny vision for fixed amounts of time (i.e. 300ms) on foot contact with the ground during the target approach for the pointing foot. It was shown that brief vision intervals during the approach phase were sufficient for young adults to point accurately at a target line 10 meters away. Similar to long jumping events, feed-forward visual information was used for proactive step adjustments over the last steps prior to foot-pointing.

The pioneering results reported by Thomson and colleagues were successfully replicated and extended recently to incorporate various field events (Bradshaw, 2004; Hay, 1988: Maraj, 2002; Renshaw & Davids, 2006) and confined lab tasks, which varied in their constraining demands (Chapman & Hollands, 2006; Popescu et al., 2010). Overall, the results clearly indicate that vision is used predominantly in a feed-forward manner to control locomotion during adaptive locomotion.

However, visual information may be used equally effectively to guide foot placement (i.e., on-line control) in order to bring about minute correction during one step (last swing) before pointing at the target. The locomotor control system is highly adaptable. Evidence supporting this claim comes from gait investigations in both stable and changing environments. Foot-pointing accuracy stays unchanged if vision is sampled only during the swing phase of the pointing foot when stepping in consecutive targets (Chapman & Hollands, 2006). Moreover, the approach strategy and the last step characteristics change to maximize the windows of vision availability when walking to point at a distant target (Popescu et al., 2010). Even for discrete stepping tasks, when pointing accuracy requirements are high (i.e., stepping over an exact copy of the footprint), lack of vision during swing decreases foot-pointing accuracy (Reynolds & Day, 2005b).

More direct evidence for guiding stepping comes from studies investigating the effect of sudden environment changes to stepping control (i.e., constraint location changes during the pointing step). Reports show that young adults can modify swinging foot trajectory if the target makes an unexpected jump (Reynolds & Day, 2005a) or the obstacle changes its height when the lead limb clears the obstacle (Perry & Patla, 2001).

Everything considered, there is substantial evidence indicating the existence of robust yet versatile stepping control strategies. Young healthy adults can, based on the environmental demands, effortlessly control stepping via feed-forward and/or on-line control to reach the foot-pointing tasks' goal.

The aforementioned experimental tasks varied in terms of difficulty and/or complexity between studies. Researchers used this terminology interchangeably. Participants pointed at the unmarked center of three large targets (43 cm) placed at consecutive steps (Chapman & Hollands, 2006), pointed at a distant target line (Laurent & Thomson, 1988), or pointed at a small target (28 cm) with the center clearly marked, embedded at the end of an unconstrained walkway (Popescu et al., 2010). As the task constraints changed, so did the locomotor control strategy and pointing outcome. The target line was generally overshot for all three visual sampling conditions (full, swing only, or stance only vision), while the approach was less consistent during swing vision conditions (Laurent & Thomson, 1988). The consecutive targets were generally undershot during full vision and stance vision conditions and overshot for the swing vision condition (Chapman & Hollands, 2006). Regardless of the visual manipulation, the marked center of the smaller target was undershot, while the overall approach was slower and the last step was longer for both intermittent vision conditions as compared to the full vision condition (Popescu et al., 2010).

For this reason, direct outcome comparisons between studies must be performed with caution, while taking into account the imposed task demands. In order to dissociate the task difficulty from its complexity and therefore be able to manipulate them independently, we propose the following distinction loosely based on two classic reports in the motor behavior literature. Complexity of a task could be defined by the number of movement segments of the overall task similar to Henry and Rogers (1960) manipulations employed to quantify the response latency for “complicated movements.” This may be accomplished, for instance, by imposing a gait change from walking to stair climbing during task performance. Conversely, task difficulty can be manipulated by making the goal of the task harder to achieve while maintaining the same number of movement components (Fitts, 1954 reprinted 1992).

This study will be concerned with the manipulation of task difficulty aspects only. The most commonly used metric to determine the degree of difficulty for aiming tasks is the index of difficulty (ID) proposed by Fitts (1992). In essence, the higher the index of difficulty, the more difficult the task becomes and the time to complete the aiming task will increase (i.e., movement slows down) in order to keep the accuracy level. This relation between the task index of difficulty and the time required to complete the task is known as Fitts' law. The difficulty index represents the ratio of twice the task distance divided by the target width. The findings reported by Fitts for reciprocal manual aiming tasks have since been extended to discrete aiming tasks (Fitts & Peterson, 1964) as well as locomotor pointing tasks (Bradshaw & Sparrow, 2000; Drury & Woolley, 1995).

Bradshaw & Sparrow (2000) employed tasks similar to the approach phase of a long-jumping event. One task consisted of running towards and stepping with one foot on a take-off board. The task index of difficulty was increased by changing the ratio between approach distance and the target width. For the eight-meter approach distance, participants slowed down consistently for each of the four tested target dimensions (44, 38, 33, and 29 cm). Conversely, no trade-off between approach speed and target accuracy was found for the twelve-meter approach and the four target sizes (43, 50, 57, and 65 cm). These results suggest that, at least for narrow targets, the index of difficulty is a valid metric for manipulating pointing tasks, and such changes in task difficulty will be reflected in stepping control.

Stepping in consecutive targets with alternate steps during walking conforms to Fitts' law as well (Drury & Woolley, 1995). The report found that foot-pointing at targets during typical walking shows a speed-accuracy trade-off for target widths below 30 cm. Here the time to complete the task was the pointing foot swing duration and the distance to target was the step length. It was concluded that for narrow targets, imposing high accuracy constraints, vision becomes a necessary condition for accurate stepping control.

The above findings are conducive to hypothesizing that task difficulty and task complexity parameters can be independently and systematically manipulated, leading to adaptive locomotion protocols that closely match real-life challenges. If correct, this assumption may lead to finding a metric for rating various adaptive locomotor tasks in terms of difficulty and/or complexity, providing for meaningful comparisons between studies. Moreover, results may be utilized for applied purposes such as improving interior design for retirement houses to minimize or alleviate the risk of falling for older adults (prevention by decreasing task demands), and designing better adaptive locomotion rehabilitation protocols (treatment) to ensure seamless transfer to real-life locomotion challenges.

Therefore, the aim of this study was to investigate whether locomotor pointing is affected by changing the task difficulty while operating under intermittent visual sampling (simulating brief visual disruption during real life locomotion). We used intermittent vision sampling to probe the visuomotor control strategies and the systematic manipulation of target size to observe the effect of task difficulty on foot-pointing. It was expected that the increase in task difficulty would be reflected in locomotor control strategies and the foot-pointing outcome.

3.2 Method

3.2.1 Participants

Ten undergraduate students, independent walkers with normal or corrected-to-normal vision, volunteered for the study. Participants were free of any neurological or musculoskeletal impairment that could compromise the protocol. The research protocol was approved by the Faculty of Physical Education and Recreation Research Ethics Board. Each participant handed in a written informed consent form prior to data collection.

3.2.2 Procedure

Two square targets, a large (T) and a small target (t) with the side size of 28 cm and 20 cm respectively, were flush to the ground and placed approximately five meters away in a straight line from the starting point. To ensure that each participant could precisely identify the center of the target, the center location was visibly marked by contrasting crosshairs, thus eliminating one possible confounding variable (i.e., estimating the pointing location). The approach distance was set to seven steps by changing the starting position location for each participant to ensure consistent target pointing with minimal step adjustments while accounting for variations in step length between participants. One step was defined as the event between two consecutive heel contacts with opposite feet. Three visual conditions were employed: full vision (FV), vision during the swing (SWV), and vision during the stance (STV). During the intermittent visual conditions, vision was available for the entire duration of the swing or stance phase for the pointing foot. The two target sizes and the three visual conditions were randomly presented.

During practice trials, the walking pace was monitored for consistency (no disruptions, consistent approach velocity) and participants chose the foot that was most comfortable to point with. Subsequently, the same foot was used for target-pointing throughout the experimental trials. Participants briefly waited with their eyes closed at the starting position. Following a verbal command, they opened their eyes and walked at a self-selected pace towards the target. They were instructed to point at the center of the target without slowing down or stopping and continue to walk past the target before stopping for about one and a half meters. Thirty trials were collected, five for each target and visual condition.

3.2.3 Instruments and task

Foot LED markers were tracked by a six-camera motion analysis system (Visualeyez PTI, Burnaby, BC) recording at 120 Hz. The markers were placed on the corresponding anatomical landmarks of the anterior-superior aspect of the hallux, and the posterior aspect of the calcaneus. Vision availability was manipulated using a pair of Plato LCD goggles (Translucent Technology, Toronto, ON). Two Force Sensitive Resistors (FSRs) (National Instruments, Canada) were used to control the status of the goggles. The FSRs were mounted on the shoe insole under the heel and base of the toes of the pointing foot. The resulting electrical signal generated during stepping changed the status of the goggles from transparent to translucent as a function of the gait events. The task consisted of walking towards and pointing with the anterior aspect of the dominant foot (big toe) as close as possible to center of the target (Figure 3.1)

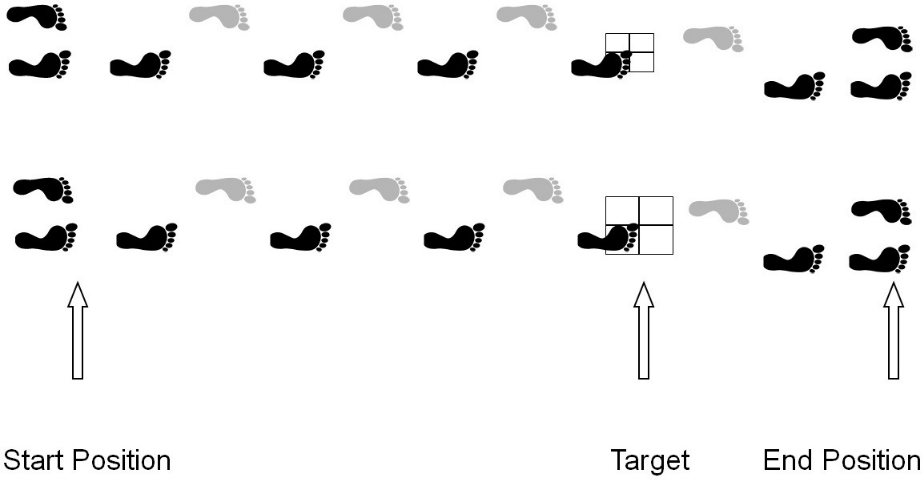


Figure 3.1 Experimental task diagram for the stance vision condition only, for both the large and the small target (right foot depicted during stance and the dark footprints signify vision availability).

3.2.4 Data analysis

Data was reduced using a custom written MATLAB program (The MathWorks, Inc. Natick, MA) and statistically analyzed using STATISTICA for Windows (StatSoft, Inc., Tulsa, OK). The gait events were manually identified and one step was defined as the event between two consecutive heel contacts with the opposite feet. The entire approach anterior-posterior footfall variability (distance between the toe marker positions for each foot during stance relative to the center of the target across trials) was recorded. Separate regression analyses were carried out for each condition to assess the approach pattern (Glize and Laurent, 1997). A two-way RM ANOVA with 2 (target size) x 3 (visual condition) was conducted on the following dependent variables: last step kinematics (step length, step width, stance and swing duration) and approach velocity (distance from second toe off to last toe off before pointing at the target divided by the time necessary to cover this distance). The foot-pointing outcome parameters for both the anterior-posterior (A-P) and the medio-lateral (M-L) aspects were derived from the pointing foot marker position relative to the center of the target: absolute pointing error (|CE|), variable error (VE), and signed error (Schutz, 1977). To establish the signed foot-pointing error pattern while preserving the inter-subject variability, a hierarchical loglinear analysis with backward elimination was used for categorical data (number of occurrences for overshooting and undershooting the target) and the significant differences were tested with Pearson Chi Square statistics. All variability data (standard deviation) was log transformed prior to data analysis. Confidence levels were set at $p < 0.05$ and Bonferroni post hoc tests were employed where appropriate. Only statistically significant results will be reported in the next section.

3.3 Results

3.3.1 Target approach

3.3.1.1 Footfall variability

A 2 (target size) x 3 (visual condition) x 7 (step number) RM ANOVA revealed a significant effect for step number. Mauchly's test indicated that the assumption of sphericity has been violated $\chi^2(27) = 71.43$, $p = .001$. The degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .450$).

The results indicate a main effect for step number $F(3.15, 38.35) = 17.96$, $p = .001$, $\eta^2 = .666$. This showed that the variability magnitude for the steps changed during the approach. In order to observe the approach pattern, separate regression analyses were carried out for each experimental condition**.**

For the large target conditions: full vision condition, a quadratic regression line had $R^2 = .708$, $F(2, 5) = 6.05$, $p = .046$; for the stance vision condition, a quadratic regression line had $R^2 = .909$, $F(2, 5) =25.05$, $p = .002$; and for the swing vision condition, the quadratic regression showed $R^2 = .904$, $F(2, 5) = 23.62$, $p = .003$. Regarding the small target conditions: for the full vision condition, a quadratic regression line fitted the data with $R^2 = .958$, $F(2, 5) = 56.33$, $p = .001$; for the stance vision condition, a quadratic regression line had $R^2 = .961$, $F(2, 5) = 61.25$, $p = .001$; and for the swing vision condition, the quadratic regression line showed $R^2 = .932$, $F(2, 5) = 34.40$, $p = .001$.The overall pattern of variability for each footfall shows an increase during the approach, followed by a sharp and consistent decrease over the last steps before pointing (Figure 3.2).

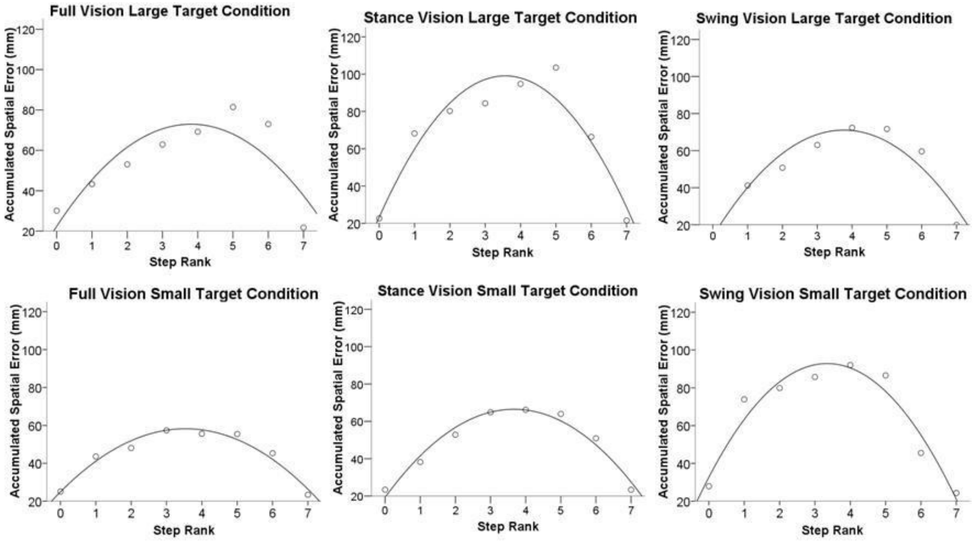


Figure 3.2 Accumulated spatial error during the target approach for the experimental conditions. The spatial error represents the footfall variability standard deviation (foot – target position for each step across trials).

3.3.2 Pointing error

3.3.2.1 A-P foot-pointing error (absolute values)

The results of the analysis showed a significant main effect for target size F (1, 9) = 6.34, p = .033, $\eta^2 = .413$. A larger absolute error was recorded for the small target (M = 22.07 mm, SD = 4.64) as compared to the large target (M = 17.06 mm, SD = 7.88) (Figure 3.3).

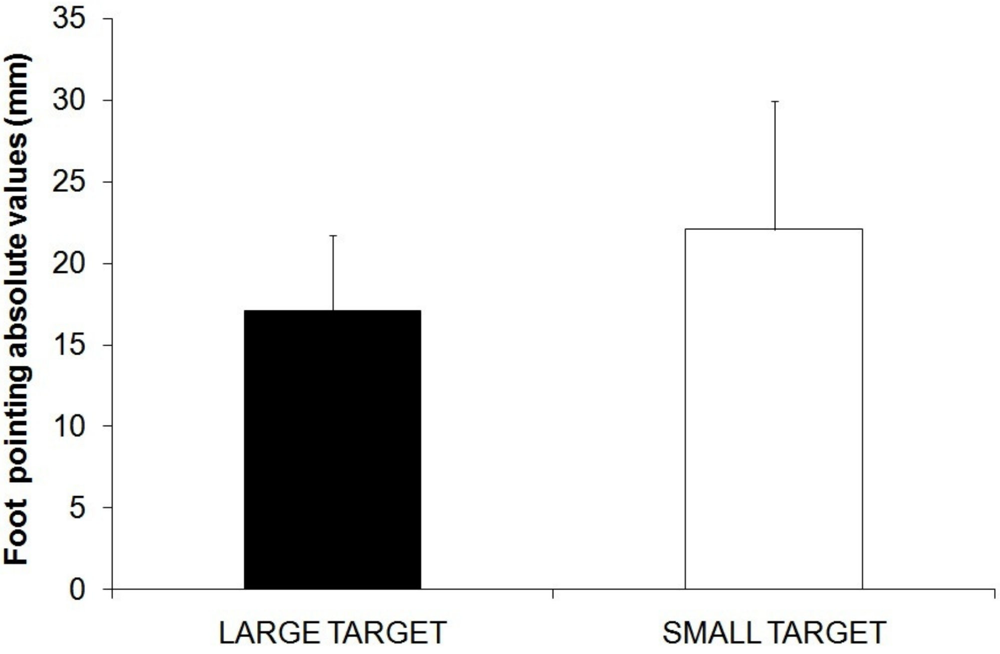


Figure 3.3 Anterior-posterior foot-pointing error as a function of target size.

3.3.2.2 A-P foot-pointing error (signed values)

The three-way loglinear analysis Target size x Visual condition x Pointing produced a final model that retained the target by pointing interaction as significant factor contributing to the model. The goodness-of-fit test for this model was Pearson χ^2 (8) = 7.67, p = .466, indicating that the expected values were not different from the observed data. Consequently, data was collapsed to retain only this significant interaction. The target-by-pointing interaction was significant Pearson χ^2 (1) = 3.89, p = .049. The interaction indicates that the ratio of overshooting and undershooting the target was different for each target. The odds ratio calculations show that participants are 1.5 times more likely to overshoot the small target as compared to the large target (Figure 3.4).

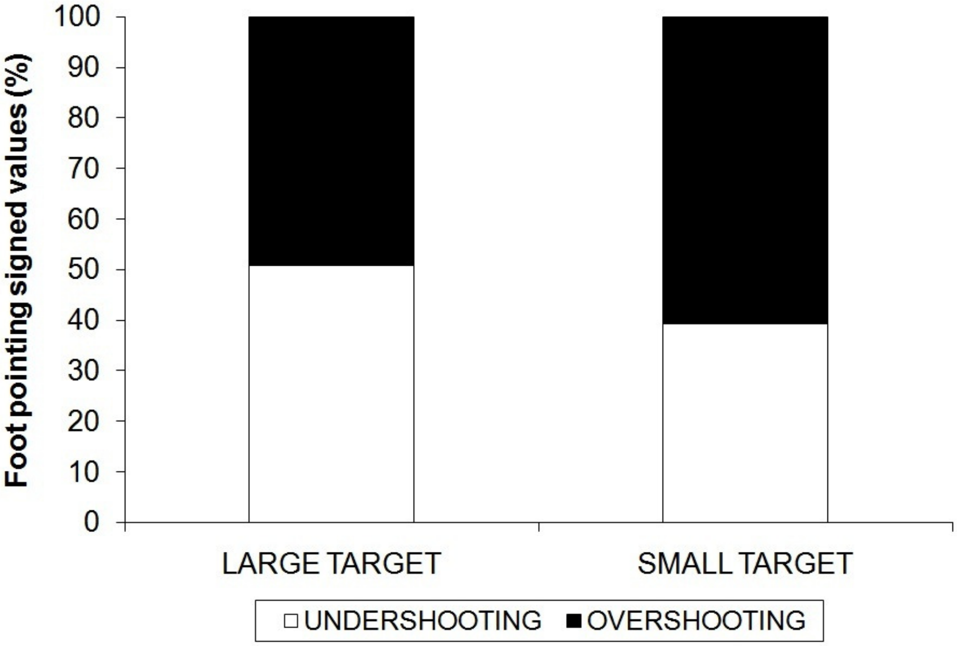


Figure 3.4 Anterior-posterior foot-pointing pattern as a function of target size (signed values).

3.3.2.3 M-L foot-pointing error (absolute values)

There was a significant main effect for vision F (1, 9) = 4.68, p = .023, η^2 = .342. The post hoc test indicated a significantly larger error for the STV condition (M = 13.66 mm, SD = 7.32) as compared to the SWV condition (M = 9.79 mm, SD = 4.58) (Figure 3.5).

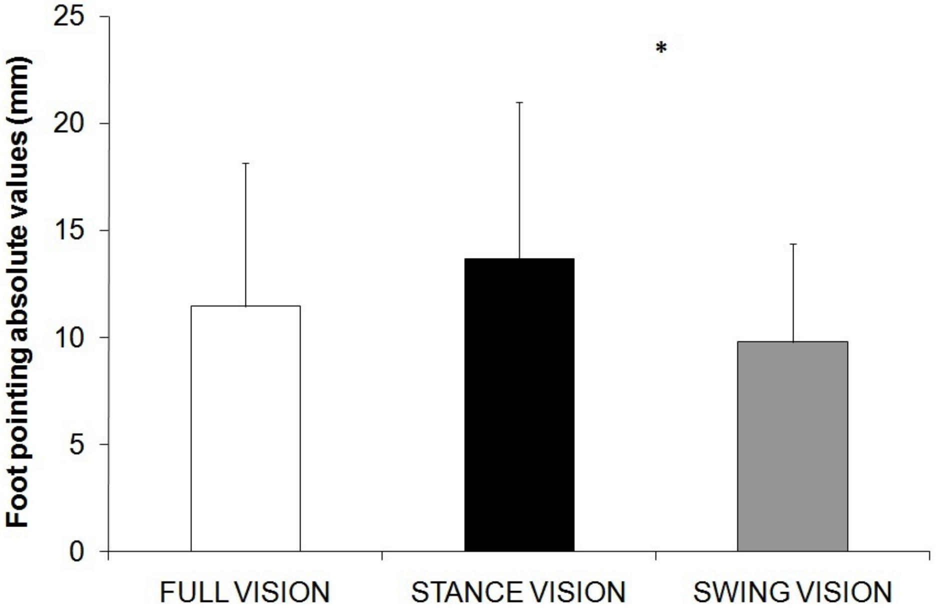


Figure 3.5 Medio-lateral foot-pointing error as a function of visual condition.

3.3.2.4 M-L foot-pointing error variability (absolute values)

A significant main effect for the visual condition was found F (1, 9) = 4.30, p = .030, $\eta^2 = .324$. The post hoc test indicated a significantly larger error variability for the STV condition (M = 7.87 mm, SD = 3.23) as compared to the SWV condition (M = 6 mm, SD = 3.34). No difference was recorded between the FV and STV conditions or between the FV and STV conditions. The analysis also revealed a significant visual condition by target size interaction F (1, 9) = 5.02, p = .018, $\eta^2 = .358$. The post hoc test indicated a larger error variability for the STVT condition (M = 8.47 mm, SD = 2.91) as compared to the FVT condition (M = 4.85 mm, SD = 1.41) and a larger error variability for the STVT condition (M = 8.47 mm, SD = 2.91) as compared to the SWVT condition (M = 5.51 mm, SD = 3.55) (Figure 3.6).

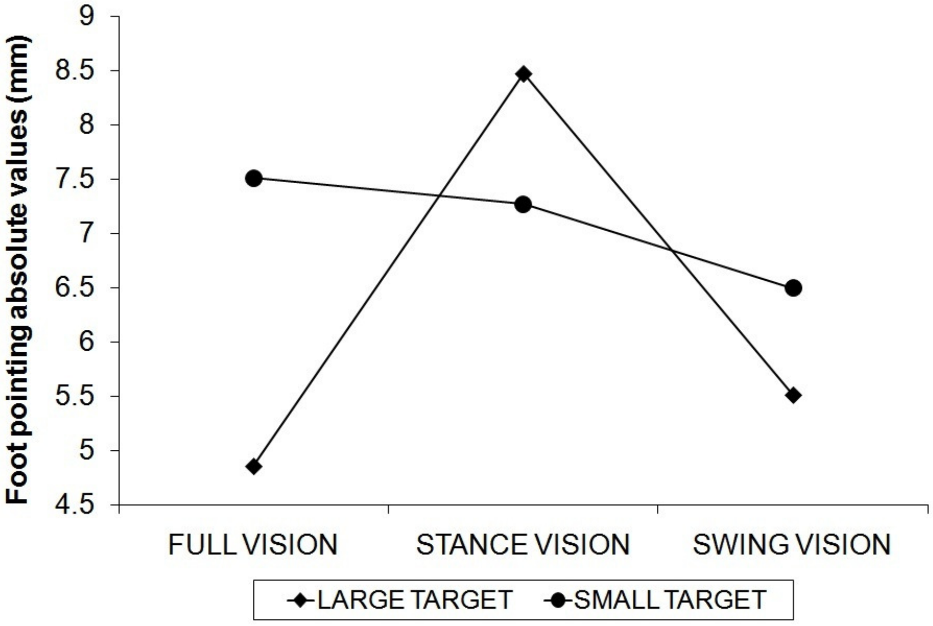


Figure 3.6 Medio-lateral foot-pointing error variability (SD) as a function of visual condition and target size.

3.4 Discussion

This study investigated the effect of task difficulty on stepping control and foot-pointing outcome during adaptive locomotion under intermittent vision. Task difficulty was manipulated by reducing the target size and vision was sampled as a function of the pointing foot gait events. The outcome of the experiment was consistent with the hypothesis. The small target pointing imposed increased difficulty demands and resulted in larger absolute pointing errors regardless of vision availability. In addition, the odds of target overshooting significantly increased for the small target pointing in the direction of walking progression. Regardless of the experimental conditions, vision was used mainly in a feed-forward mode to control stepping.

3.4.1 The target approach

Vision provides distant environmental information and allows for changing gait parameters in advance of reaching critical locations (i.e., proactive locomotor control). Typically, the required stepping adaptation would be dispersed over several steps when negotiating nested task constraints located at the end of an unconstrained approach (Laurent & Thomson, 1988; Lee et al., 1982; Maraj, 2002; Renshaw & Davids, 2006; Popescu, et al., 2010). Our results are consistent with these reports despite matching the approach distance with the participant's step length before data collection. The naturally occurring cumulative effect of small inconsistencies for each step during approach in the direction of progression became evident, and stepping corrections were needed for landing the foot on the target without disrupting the gait pattern (i.e., to preserve the dynamic balance and the pace). The footfall variability pattern for each step during the approach shows step adjustments over several consecutive steps at target proximity regardless of visual manipulation or task difficulty. This clearly shows that brief visual samples during the approach are sufficient for future footfall planning while maintaining the rate of forward progression largely unaltered. This timely, consistent, and progressive reduction in accumulated error optimally positioned each participant with regard to the task goal for the pointing step.

3.4.2 The pointing step

3.4.2.1 A-P foot-pointing error

Large stepping corrections occurred during the last swing before foot-pointing. Due to task design, participants faced the effect of cumulative errors in the sagittal direction. In line with previous reports, pointing accuracy was not affected by intermittent vision sampling (Chapman & Hollands, 2006; Laurent & Thomson, 1988; Popescu et al., 2010). We infer that stepping control in the sagittal direction was performed largely in a feed-forward manner since stepping adjustments were made before the last pointing step and vision availability during the last swing prior to foot-pointing did not affect (improve) the pointing outcome.

Most importantly, a significant increase in the mean absolute pointing error as well as a pointing pattern reverse was recorded for the small target. The temporal parameters recorded for the last step (pointing foot swing duration and non-pointing foot stance duration respectively) were similar across conditions and were linked with an increase in absolute pointing error. This is consistent with the speed-accuracy trade-off reported for discrete foot-pointing tasks (Bradshaw & Sparrow, 2000; Drury & Woolley, 1995).

Previous literature reports averaged signed values across subjects for pointing errors. As such, when outcome values are pooled together, it is possible that few large values may cancel out the majority of the other values, thus obscuring the actual pointing pattern (Schutz, 1977). Therefore, we conducted a separate analysis to investigate more closely the pattern of foot-pointing for signed error values while preserving the inter-subject variability. It has also been argued that the nature of the adaptive locomotor task (i.e., the environmental demands) dictates the typical pattern of foot-pointing outcomes (Steenhuis & Goodale, 1988). For instance, stepping too close to an icy patch will increase the chance of stepping on it and slipping. The expected behavior would therefore be to increase the safety margin by undershooting the icy patch. For similar locomotor pointing tasks, undershooting the target was the preferred pointing behavior (Chapman & Hollands, 2006; Popescu et al., 2010). Our results show that the small target was more likely to be overshot in contrast with the large target. Such strategy seems inappropriate, since overshooting the target has a detrimental effect by blocking the sight of the target centre during the last swing. Therefore, the possibility of making corrections during the last swing phase will not include the visual information necessary to guide the foot before landing.

3.4.2.2 M-L foot-pointing error

In contrast to the sagittal pointing direction, the side-to-side stepping had no cumulative effect during target approach since the path followed a straight line. Only the visual manipulations affected foot-pointing outcomes, while the target size had no effect on pointing outcomes. When vision was available during the last swing, the mean absolute pointing outcome (accuracy) and pointing variability (consistency) were significantly reduced. The same trend, although without reaching statistical significance levels, was recorded during the full vision condition as compared to the stance vision condition (blind pointing). Low statistical power may explain this lack of significance. These results corroborate previous reports despite the differences in pointing task layout (Chapman & Hollands, 2006).

Indeed, young participants can use on-line stepping control to compensate for target location change or to guide the foot to highly constraining locations (Reynolds & Day, 2005a; Reynolds & Day, 2005b). The reduced pointing accuracy and increased consistency for the medio-lateral pointing component during the swing vision condition could be taken as evidence of on-line corrections. Previous studies looked at swing trajectory kinematics to infer on-line stepping control, but the findings were inconclusive (Chapman & Hollands, 2006). Others found that foot heading trajectory was consistently modified prior to foot contact for a one single step task (Reynolds & Day, 2005b). However, owing to the experimental task we cannot exclude that pointing outcomes were also the result of advance planning permitted by a long and unconstrained approach. Moreover, this study considered only discrete kinematic variables as dependent measures, which can only provide indirect accounts for on-line foot control. More research is warranted to clarify the effect of task demands for on-line stepping control under increased dynamic balance challenges such as those imposed by locomotion.

The pointing outcomes imply a separation in stepping control for the sagittal and medio-lateral pointing aspects. Our results show similarities with the proposal that balance control (related to the medio-lateral component) and stepping pattern control (linked to the sagittal aspects) may be independently regulated (Gabell & Nayak, 1984). The authors recommend a balance control mechanism for walking (for step width and double support duration) and a separate control mechanism for gait patterning (for step length and step time). Recently, Brach, Perera, Studenski et al. (2008) have linked cognitive processing capability (planning and execution) with the motor control of gait patterning and sensory deficits (including vision) to balance control. Consistent with these reports, our results show that for healthy individuals, visual manipulations during adaptive locomotion were reflected exclusively in the medio-lateral pointing component.

3.4.3 Meaningful significance

The recorded pointing error magnitudes are rather small, but consistent with previous reports for locomotor pointing tasks during intermittent vision conditions (Chapman & Hollands, 2006; Laurent & Thomson, 1988; Popescu et al., 2010). First, the small error magnitude may be resting with the fact that the present protocol was less stringent and does not sufficiently challenge the participants to show larger or more consistent pointing behavior (i.e., more undershooting interspersed with few overshooting pointing outcomes). That is to say, the consequences for overshooting targets flush to the ground are merely theoretical in comparison to overshooting the edge of a ground hole while walking**.**

Second, small and statistically significant differences in pointing errors raise the question of functional significance for daily adaptive locomotor tasks. Young and healthy individuals can easily adjust for eventual errors in foot placement during walking due to flexible perceptual and locomotor systems. However, losing locomotor adaptability during biological aging can result in dire consequences. Prospective cohort studies investigating free walking changes in gait variability for older adults point toward significant functional impact linked to minute gait changes. For instance, doubling the likelihood of falling during future walks is associated with 0.017 m variability in stride length, a 0.016 m/s change in step velocity, or 0.7% variability in double support duration (Maki, 1997). Preliminary criteria for meaningful change in gait variability for older adults were reported by Brach, Perera, Studenski et al., (2010). Gait variability changes of 100 ms for stance and swing time and 25 mm for step length are related to increased walking difficulty and decreased walking distance.

3.4.4 Conclusion

Young adults use brief periods of visual sampling for proactive stepping control to initiate and partition gait adaptations over several steps before pointing at distant targets, thus preserving gait largely unaltered. Reduced target size decreases pointing accuracy and adversely affects the foot-pointing pattern in the direction of progression, irrespective of vision availability. On the other hand, a lack of visual information during the pointing step decreases pointing accuracy and precision in the medio-lateral direction. Results also suggest that foot-pointing tasks may be manipulated by changing the difficulty of the task alone. Future research should look more closely at finding a metric to quantify task difficulty for locomotor pointing tasks, as the index of difficulty could be a promising lead. Practical applications may lead to fall prevention via better interior design and highly transferable rehabilitation protocols towards real-life locomotor challenges.

3.5 References

Bradshaw, E. J. (2004). Target-directed running in gymnastics: A preliminary exploration of vaulting. *Sports Biomechanics,* 3, 125-144.

Bradshaw, E, J. & Sparrow, W. A. (2000). The speed-accuracy trade-off in human gait control when running towards targets. *Journal of Applied Biomechanics,* 16, 331-341.

Brach, J. S., Studenski, S., Perera, S., VanSwearingern, J. M., Newman, A. B. (2008). Stance time and step width variability have unique contributing impairments in older persons. *Gait & Posture,* 27, 431-439.

Brach, J. S., Studenski, S., Perera, S., VanSwearingern, J. M., Newman, A. B. (2010). Meaningful change in measures of gait variability in older adults. *Gait & Posture,* 31, 175-179.

Chapman, G. J., & Hollands, M. A. (2006). Age-related differences in stepping performance during step cycle-related removal of vision. *Experimental Brain Research*, 174, 613-621.

Drury, C. G. & Woolley, S. M. (1995). Visually-controlled leg movements embedded in a walking task. *Ergonomics,* 38, 4, 714-722.

Fitts, P. M. (1992). The information capacity of the human motor system in controlling the amplitude of movement (Reprint). *Journal of Experimental Psychology: Human Perception and Performance: General* 121 (3), 262-269.

Fitts, P. M. & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology,* 67 (2), 103-112.

Gabell, A. & Nayak, U. S. L. (1984). The effect of age on gait variability. *Journal of Gerontology,* 39 (6), 662-666.

Glize, D., & Laurent, M. (1997). Controlling locomotion during the acceleration phase in sprinting and long jumping. *Journal of Sport Sciences,* 15, 181-189.

Hay, J. G. (1988). Approach strategies in the long jump. *International Journal of Sport Biomechanics,* 4, 114-129.

Henry, F. M., & Rogers, D. E. (1960). Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly* 31(3), 448-458.

Laurent, M., & Thomson, J. A. (1988). The role of visual information in control of a constrained locomotor task. *Journal of Motor Behavior,* 1, 17-37.

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

Maki, B. E. (1997). Gait changes in older adults: predictors of falls or indicator of fear? *Journal of the American Geriatrics Society,* 45, 313-320.

Maraj, B. K. V. (2002). Control and co-ordination in the triple jump. In K. Davids, Savelsbergh, G., & Bennett, S. J. (Eds.) *Interceptive actions in sport: Information and movement* (pp. 334-342). New York: Routlege.

Schutz, R. (1977). Absolute, constant, and variable error: Problems and solutions. In Mood, D. (Ed.) *The measurement of change in physical education: Proceedings of the Colorado Measurement Symposium* (pp. 82-100). Boulder, CO.

Patla, A. (1991). Visual control of human locomotion. In A. E. Patla (Ed). Adaptability of human gait. North-Holland: Elsevier Science Publishers B. V.

Patla, A. (1997). Understanding the roles of vision in the control of human locomotion. *Gait & Posture,* 5, 54-69.

Perry, S. D. & Patla, A. E. (2001). On-line adjustments to body center of mass and limb elevation to suddenly changing obstacle height. In J. Duysens, Smits-Engelsman, B. M., & Kingma, H. (Eds.), *Control of posture and gait* (pp. 485-487). Maastricht, Netherlands.

Popescu, A., Runnalls, K., & Maraj, B. K. V. (2010). Intermittent visual information affects motor strategies during locomotor pointing. *International Journal of Sport Psychology,* 41, 313-326.

Renshaw, I., & Davids, K. (2006). A comparison of locomotor pointing strategies in cricket bowling and long jumping. *International Journal of Sport Psychology,* 37, 1-20.

Reynolds, R. F., & Day, B. L. (2005a). Rapid visuo-motor processes drive the leg regardless of balance constraints. *Current Biology* 15 (2), R48-R49.

Reynolds, R. F., & Day, B. L. (2005b).Visual guidance of the human foot during a step. *Journal of Physiology,* 569.2, 677-684.

Steenhuis, R. E., & Goodale, M. A. (1988). The effects of time and distance on accuracy of target-directed locomotion: Does an accurate short-term memory for spatial location exist? *Journal of Motor Behavior,* 20 (4), 399-415.

Study three

Self-sampled vision during adaptive locomotion: The effects of age and task complexity

4.1 Introduction

A wide range of adaptive locomotor tasks are flawlessly performed by able body individuals on a daily basis. Free walking stepping is under pre-planned ballistic-control, but precise footfall location selection necessary for cluttered environments navigation (e.g., stepping on targets smaller than the foot size would impose a visually-controlled stepping strategy (Drury & Woolley, 1995). The typical man-made environment requires momentary locomotor adaptations in order to avoid obstacles or step on safe surfaces (locomotor pointing) while constantly maintaining forward progression.

Vision is the best suited sensory modality to provide almost instantaneous predictive environmental information at a distance necessary for stepping control (Patla, 1997). Vision is paramount for planning (i.e. feed-forward control) and guiding stepping (i.e. on-line control) in challenging environments. Research findings indicate that visual information is used primarily to pre-plan future steps in order to best position the individual with regard to a distant constraint in stable environments (Laurent & Thomson, 1988; Popescu, Runnals, & Maraj, 2010). At the same time, should environmental features suddenly change, fine-tuning adaptive strategies can be implemented during a single step (i.e. swing phase) to accommodate for a sudden target location change (Reynolds & Day, 2005a), obstacle height change (Perry & Patla, 2001), or highly constraining foot-pointing tasks toward stationary targets in need for fine foot trajectory control (Reynolds & Day, 2005b).

It was recognized that vision sampled intermittently during locomotion provides sufficient information for gait adaptation in healthy individuals akin to scanning distant environmental features by temporarily shifting one's gaze from the ongoing locomotor task. One explanation for intermittent vision sufficiency draws on mammalian evolutionary adaptations. Both the predator and the prey must share visual resources between their own locomotion control, relevant environmental features, and knowledge of the opponent's spatial location (Thomson, 1980; Patla, 1995a). Recently, empirical research reports confirmed the intermittent vision sufficiency hypothesis. Two major research paradigms were employed to test intermittent vision effects on stepping control: external (gait-cycle related) versus internal (voluntary) visual sampling control.

The frequently employed technique of investigation was the gait-cycle related visual manipulation during which vision is sampled at regular intervals based on the participants' gait events: visual samples occur either during the stance or the swing phase of the pointing foot for each step during walking. Regardless of the environmental layout, young and healthy individuals can effectively use brief visual samples to adapt their locomotor strategy while accurately pointing at targets with their feet during walking (Laurent & Thomson, 1988; Chapman and Hollands, 2006a; Popescu, et al., 2010).

A chief limitation of this inflexible intermittent vision sampling is its departure from the real-life visual sampling behavior. Intuitively, there should be an interrelation between the environment layout (complexity) and the imposed visual sampling demands. While reducing visual sampling to specific and repetitive intervals provided valuable insights to adaptive locomotor control, it automatically introduced limitations with regard to external validity. There are outstanding questions that cannot be answered using the external visual sampling technique: for example when, where, and for how long is vision necessary to ensure safe and efficient adaptive locomotion. The necessary paradigm change to answer these questions is that visual sampling must become a dependent variable thus giving participants full control over the sampling intervals (i.e., voluntary self-sampling control).

To date, a single published report employed this internal visual control paradigm for adaptive locomotor tasks. Patla, Adkin, Martin, Holden, & Prentice (1996) investigated the visual sampling characteristics in young adults while navigating environments varying in difficulty and complexity under voluntary visual sampling. Sampling behavior was monitored as participants walked on predefined paths (i.e. stepping on footprints) avoiding obstacles on route.

In contrast, the second set of tasks had an unconstrained approach and closely monitored visual sampling characteristics prior to (i.e. feed-forward control) and during the swing phase (i.e. on-line control) for steering, stepping over an obstacle, or footprint pointing. Participants wore LCD goggles controlled via a hand-held switch independent of gait events. Vision was sampled as needed during locomotion. Results indicated that intermittent visual sampling was adequate for all these tasks. While there was no privileged step-phase location when vision became critical, visual requirements never exceeded one visual sample per step or a single and longer visual sample per stride. The sampling duration changed from 10% (control condition) to 40% of the overall approach duration as a function of changing the task difficulty and complexity. Visual demands increased at target proximity and were met by increasing the sampling frequency, not sample duration. Finally, vision was used predominantly in a feed-forward manner for planning and initiating stepping trajectory as was expected for stable, unchanging environments.

Recent research has turned toward investigating the relationship between visual sampling and adaptive locomotor control in the older adults. However, the available information on older adults visual sampling needs during adaptive locomotion is limited. In general, the reports indicate differences between age groups in terms of both visual sampling needs as well as stepping control and foot-pointing outcomes.

One report makes direct comparisons between healthy young and older individuals pointing with the foot at large consecutive targets under gait-cycle related visual sampling (Chapman & Hollands, 2006a). Participants wore LCD goggles controlled via pressure resistors mounted on the sole of the pointing foot to remove vision for the entire duration of either the stance or swing phase of the gait cycle for the pointing foot. In contrast to young adults, older adults showed a decrease in foot-pointing accuracy and precision as well as an increased task failure (i.e. stepping on the edge or outside the target) for the intermittent vision conditions. It was argued, advance stepping planning notwithstanding, that the short time frame offered by intermittent vision was insufficient for accurate stepping control during locomoton. This is consistent with the hypothesis of gradual visuomotor coordination decline with ageing.

Related to the aforementioned study by Patla et al. (1996) on voluntary visual sampling, two brief reports outlining preliminary results concerning healthy older individuals were made (Patla 1993, 1995b). Only two conditions, identical with the Patla et al. (1996) study, were employed. Older participants had to walk two straight paths: one with evenly distributed footprints and the other without footprints (free walking). As expected, intermittent vision was sufficient to complete the task uneventfully, and the visual demands increased for the experimental condition as compared to the control condition. Compared to young adults (data reported in Patla et al., 1996) the older adults had a similar trial completion duration and number of visual samples per trial during the free walking condition. Differences between age groups were recorded for the experimental condition (i.e. stepping on footprints). Older adults had longer cumulative visual samples duration per trial while reducing the number of individual visual samples. It was argued that the older adults need longer times for planning and initiating the appropriate gait adaptation as it becomes harder to share visual resources and make decisions during adaptive locomotion.

Overall, young and healthy individuals successfully handle adaptive locomotion under intermittent visual conditions in various environmental set ups.

They have adaptable perceptual and motor systems allowing for suitable changes in locomotor control strategies to successfully match environmental demands (Chapman & Hollands, 2006a; Patla et al., 1996; Popescu, et al., 2010). In contrast, the few existing reports indicate that healthy older adults have stepping control difficulties under brief externally controlled visual conditions and choose strategies allowing for longer visual samples for successful task completion, thus allowing more time for planning and implementing gait adaptation (Chapman & Hollands, 2006a; Patla, 1995b).

Therefore, to fill the existing literature gap, this study had two foci. The first was to document the task complexity effect on visual sampling, answering the question of when and for how long vision is necessary to successfully complete the task. The second goal was to make direct comparisons between age groups regarding the visual sampling characteristics and stepping adaptation during adaptive locomotion including the foot-pointing error measurements. We anticipate finding that participants, regardless of age group, would have similar visual sampling characteristics. Furthermore, we hypothesize that task complexity and age would decrease foot-pointing accuracy and consistency as well as increase the likelihood of target overshooting.

4.2 Method

4.2.1 Participants

Sixteen healthy participants, eight young adults (M = 22.62 years, SD = 3.11) and eight older adults (M = 62.5 years, SD = 3.85), all independent walkers with normal or corrected-to-normal vision, volunteered to participate. Participants were free of any neurological or musculoskeletal impairment that could compromise the protocol. The following tests were employed to screen the participants and control for the associated confounding factors: the “Snellen” chart for testing static visual acuity (Precision Vision, La Salle, IL)[4], VCTS 6500 chart (Ginsburg, 1984) for testing visual contrast sensitivity, the “Mini-Mental State” questionnaire (Folstein, Folstein, & McHugh, 1975) for cognitive functioning, the Timed “Up & Go” test (Podsiadlo & Richardson, 1991) for functional mobility, and the STAI-C questionnaire (Spielberger et al., 1973; Rankin, Gfeller, & Gilner, 1993) for state anxiety. The results are summarized in Table 4.1. The research protocol was approved by the University of Alberta Research Ethics Board and each participant provided a written informed consent form prior to data collection.

---

[4] Participants with single vision corrective eyeglasses or contact lenses were accepted

Table 4.1 Participants' characteristics

Characteristics	Young Adults		Older Adults		
Age (years)					
Mean	22.62 ± 3.11		62.5 ± 3.85		
Range	21 - 28		59 - 68		
Visual acuity (Snellen chart)					
Range	20/16 - 20/20		20/20 - 20/30		
Functional mobility (Timed "Up & Go" test)					
Mean	7.53 ± 0.76		8.48 ± 0.73		
Range	6.2 - 8.5		7.80 - 9.5		
Cognitive functioning (Mini-Mental State)					
Mean	30 ± 0		29.5 ± 1.06		
Range	30 - 30		27 - 30		
State anxiety (STAI-C)					
Mean	29.87± 2.64		27.37 ± 2.44		
Range	27 - 34		24 - 30		
Visual contrast (VCTS chart)					
Spatial Frequency	1.5	3	6	12	18
Young Adults					
Mean	6.5 ± 0.53	6.5 ± 0.53	6.75 ± 0.70	6.62 ± 0.74	5.87 ± 0.64
Range	6 to 7	6 to 7	6 to 8	6 to 8	5 to 6
Old Adults					
Mean	6 ± 0.53	6.37 ± 0.51	6 ± 0.53	5.87 ± 0.64	5.12 ± 0.35
Range	5 to 7	6 to 7	5 to 7	5 to 7	5 to 6

4.2.2 Instruments and task

Foot LED markers were tracked by a six-camera motion analysis system (Visualeyez PTI, Burnaby, BC) recording at 120Hz. The markers were placed on the corresponding anatomical landmarks of the anterior-superior aspect of the hallux, and the posterior aspect of the calcaneus. Vision availability was manipulated using a pair of Plato LCD goggles (Translucent Technology, Toronto, ON). Participants controlled the visual samples from a hand-held momentary switch at will. The switch was hosted in a hollow tube (10 cm x 1.75 cm) and connected to the LCD goggles with a 50 cm flexible wire. Pressing the switch would change the status of the goggles from translucent to transparent and they would remain transparent until the switch was released. Task complexity was manipulated by increasing the number of movement components performed during each trial, utilizing the work of Henry and Rogers (1960) for guidance. Participants had full control over vision availability throughout the task and were instructed to use vision only when needed. The task consisted of walking towards and placing the anterior aspect of the dominant foot (big toe) as close as possible to the centerline of the target before proceeding with the post-pointing task (PPT) (Figure 4.1).

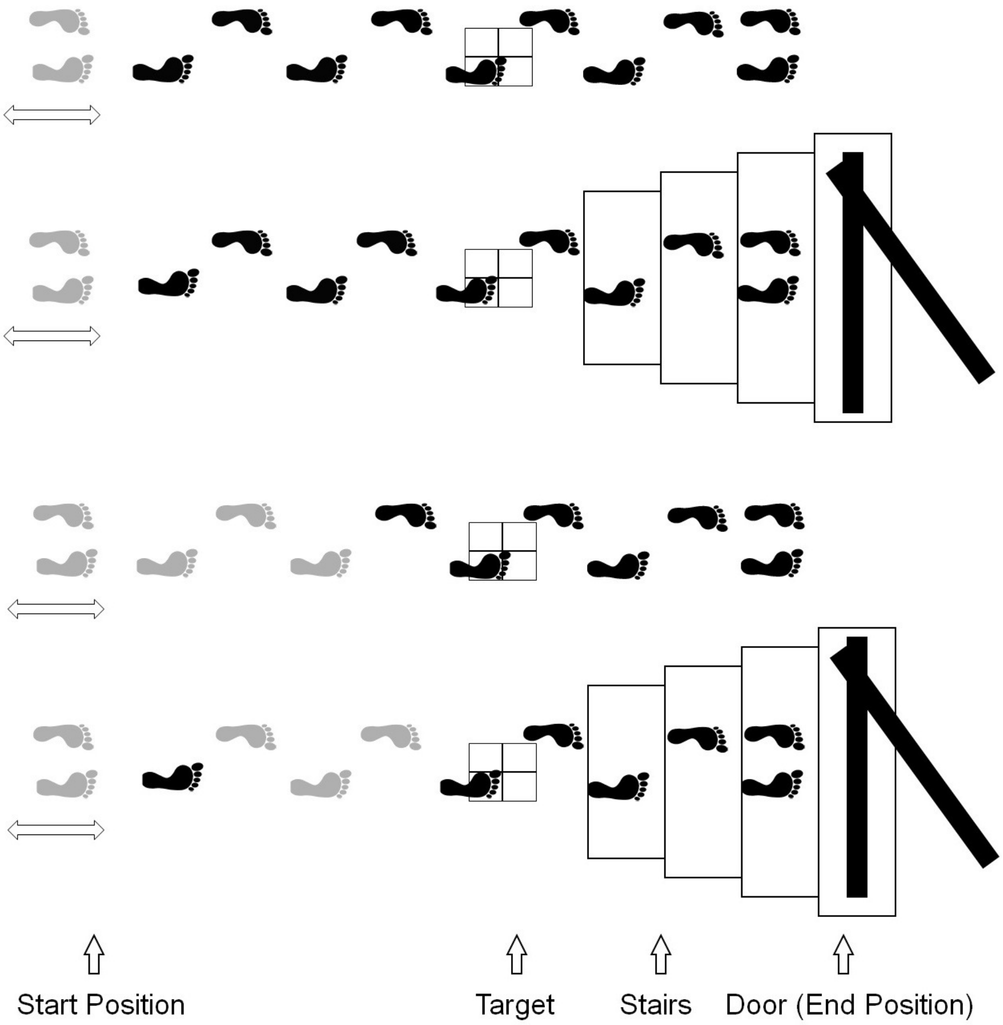


Figure 4.1 Experimental task diagram (dark footprints signify vision availability; the full vision conditions are shown at the top).

4.2.3. Procedure

One square target (28 x 28 cm), flush to the ground, was placed approximately five meters away from the starting location. The distance to the target was changed such that each participant took five steps to cover it. The center of the target was visibly marked by contrasting crosshairs to eliminate one possible confounding variable (i.e., target center location). Before data collection, the “neutral” target location was determined for each participant such that consistent target pointing was accomplished with minimal step adjustments. The approach distance to the target was set to five steps for each participant. During data collection the starting position was randomly changed from a neutral to a forward or backward displaced position by 10 cm to ensure target position unpredictability and the need for visual guidance during the foot-pointing event. There were two PPT conditions, walking continuation (control condition) or climbing up a set of four stairs and opening a door (experimental condition). The distance between the target and the PPT was set at 1 ½ step lengths for each participant. The two visual conditions were full vision and self-sampled vision. The combination between visual sampling and PPT complexity resulted in four experimental conditions: full vision with target (FVT), sampled vision with target (SVT), full vision with stairs and door (FVS), and sampled vision with stairs and door (SVS). The order of presentation between conditions was counterbalanced across participants. There was no restriction on pointing foot selection. Participants decided on the pointing foot during the practice trials. Subsequently they maintained the same foot for pointing throughout the data collection session.

Sufficient practice trials were allowed before each condition to ensure a comfortable and consistent walking pace. As a precautionary measure, an assistant shadowed the participant during the trials. At the starting location, the goggles were always set on translucent mode (no vision). Following a verbal command, participants manipulated the goggles as needed while walking at a self-selected pace toward the target. They stepped on the target, pointing with the forefoot at the center and continued with the PPT before stopping. A total of 36 trials per participant were collected: three trials for each target location and each experimental condition.

4.2.4 Data analysis

Data were reduced using a custom-written MATLAB program (The MathWorks, Inc., Natick, MA) and the gait events were manually identified using a graphical input function. One step was defined as the event between two consecutive heel contacts with the opposite feet. The approach footfall variability (toe marker position for each step relative to the center of the target) was recorded. Separate regression analyses were carried out for each condition to assess the approach footfall pattern (Glize and Laurent, 1997).

The statistical analysis was carried out using STATISTICA for Windows (StatSoft, Inc., Tulsa, OK). A mixed ANOVA design with 2 (age) x 2 (visual condition) x 2 (PPT) with repeated measures on the last two factors was conducted on the spatio-temporal gait events (step length and width, stance and swing duration), approach velocity (from second toe off to last toe off before pointing at the target), and foot-pointing error (absolute constant error and variable error for the anterior-posterior (A-P) and medio-lateral aspects (M-L). The absolute constant error measure was used in order to alleviate the possibility of underestimating the average bias between group means as a consequence of signed values additions (Schutz, 1977). Standard deviation data was log transformed prior to data analysis. Confidence levels were set at $p < 0.05$; Bonferroni post hoc tests were employed where appropriate. In order to establish the overshooting vs. undershooting foot-pointing pattern, a hierarchical loglinear analysis was conducted on the resulting categorical data. This statistic was employed to preserve the trial-by-trial foot-pointing pattern knowing that the typical constant error computation for signed values is prone to obscuring the effects due to signed values data cancelling each other out in the process. The visual sampling parameters were reported as percentages: total visual sample duration, number of visual samples per trial, and visual samples per step. Only statistically significant results will be reported in the next section.

4.3 Results

4.3.1 Visual sampling parameters

4.3.1.1 Vision availability

Similar overall visual sample durations during the approach were recorded irrespective of experimental manipulations or age. Regardless of task complexity, on average, participants used vision for less than half of the approach duration (40% young adults and 43.5% older adults) (Table 4.2).

4.3.1.2 Visual sample per step during the approach

Regardless of age and experimental manipulation, the number of visual samples increased during the approach. The sum total of visual samples at target proximity shows that, with few exceptions, almost every trial had vision available during the penultimate step (92.33%) or the last step (90.59%) (Table 4.2).

4.3.1.3 Visual sample per trial during the approach

The dominant visual strategy was the use of one visual sample (22.98% for young adults and 25.28% for older adults) or two visual samples (17.41% for young adults and 18.81% for older adults) during the approach. The use of three or more brief visual samples was sparingly recorded (Table 4.2).

Table 4.2 Visual sample parameters (for the sampled-vision trials only)

	Young		Older	
	Walk	Stairs	Walk	Stairs
Visual samples overview				
Total Visual Sample (s)[1]	1.29 ± 0.28	1.35 ± 0.30	1.35 ± 0.50	1.36 ± 0.55
Mean Visual Sample (s)[2]	0.91 ± 0.32	1.09 ± 0.30	0.79 ± 0.33	0.71 ± 0.29
Percent Visual Sample[3]	0.39 ± 0.07	0.41 ± 0.08	0.43 ± 0.08	0.44 ± 0.18
Visual samples per step rank (%)[4]				
First step	7.31	5.92	9.05	10.45
Second step	5.92	2.09	11.14	10.45
Third Step	12.19	9.75	14.63	13.93
Fourth Step	21.60	23.34	24.39	22.99
Fifth Step	22.29	22.64	23.34	22.29
Visual samples per trial (%)				
One Sample	13.58	17.07	9.4	8.71
Two Samples	9.05	8.01	8.36	10.8
Three Samples	2.43	0.34	3.13	2.09
Four Samples	0	0	2.43	1.39
Five Samples or more	0	0	1.39	1.74
Discarded trials[5]				
No vision during the last swing	5	2	1	2
Part vision during the last swing	3	5	4	4
Full vision for the entire trial	0	0	0	2
No data recorded	0	1	0	0

Note

[1] *Total duration of visual samples in seconds*

[2] *Algebraic mean of visual samples in seconds*

[3] *Ratio between total visual sample duration and trial duration*

[4] *Regardless of other visual samples during the same trial*

[5] *Randomly occurrences for participants and trials*

4.3.1.4 Visual sampling strategy during the approach

The initiation of the visual samples differed between participants and between trials. However, having one, two, or three visual samples during the approach covered 93.02% of the various sampling strategies. Within these three strategies, the single visual sample was initiated[5] during the third or fourth step in a proportion of 87.85%. Regarding the two visual sample strategy, the most prevalent behaviour was the initiation of samples to occur during the first and fourth step or second and fourth step (64.42%). This strategy was followed by the visual sample initiation at the first and third step (19.23%). Finally, for the use of three visual samples, 11 different strategies were identified. Most notably, the environment was sampled before gait initiation in over half of the trials (52.14%). The two most frequent strategies were those with visual samples before gait initiation, at step three, and at step four (17.39%); or starting at the first step, third step, and fourth step respectively (17.39%) (Table 4.3).

---

[5] Once initiated, the visual sample was available until the trial ended to include the last step as well.

Table 4.3 Percent of visual samples initiation during the approach

	Young Adults		Older Adults		Total
	Target	Stairs & Door	Target	Stairs & Door	
One Visual Sample					
Step Rank					
1	1.42	0	0	1.42	2.85
2	0.71	2.14	1.42	3.57	7.85
3	13.57	11.42	7.85	2.85	35.71
4	12.14	20	10	10	52.14
5	1.42	0	0	0	1.42
Two Visual Samples					
Step Rank					
1, 2	0.96	0	0	0	0.96
1, 3	0	0.96	10.57	7.69	19.23
1, 4	9.61	13.46	6.73	15.38	45.19
1, 5	2.88	0.96	0	0	3.84
2, 4	6.73	1.92	4.8	5.76	19.23
2, 5	0	0	0	0	0
3, 4	1.92	1.92	0	0.96	4.8
3, 5	1.92	2.88	0.96	0	5.76
4, 5	0.96	0	0	0	0.96

(continued)

Table 4.3 Percent of visual samples initiation during the approach (continued)

	Young Adults		Older Adults		Total
	Target	Stairs & Door	Target	Stairs & Door	
Three Visual Samples					
Step Rank[1]					
0, 1, 4	0	4.34	4.34	0	8.69
0, 2, 4	8.69	0	0	0	8.69
0, 2, 5	4.34	0	0	0	4.34
0, 3, 4	4.34	0	8.69	4.34	17.39
0, 3, 5	0	0	4.34	0	4.34
0, 4, 5	4.34	0	0	4.34	8.69
1, 2, 3	0	0	4.34	0	4.34
1, 2, 4	4.34	0	0	0	4.34
1, 3, 4	4.34	0	8.69	4.34	17.39
1, 3, 5	0	0	8.69	0	8.69
2, 3, 4	0	0	4.34	8.69	13.04

Note

[1] *Step rank zero means that the visual sample occurred before the "GO" command but prior to first toe off*

4.3.2 Stepping parameters

4.3.2.1 Target approach

4.3.2.1.1 Footfall variability

A 2 (age) x 2 (visual condition) x 2 (task complexity) x 8 (step rank) RM ANOVA for footfall position in the direction of progression revealed a significant main effect for vision F (1, 14) = 5.83, p = .030, $\eta^2 = .294$. It also revealed a main effect for task complexity F (1, 14) = 5.63, p = .032, $\eta^2 = .287$. Finally, the analysis revealed a main effect for step rank. The Mauchly's test indicated that the assumption of sphericity has been violated χ^2 (14) = 27.34, p = .019. The degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .699$), F (3.49, 48.95) = 63.94, p = .001, $\eta^2 = .820$.

These results showed that the step rank spatial error changed during the approach. The footfall pattern for each step during the approach was further analyzed to observe the accumulated spatial error pattern during target approach. Separate regression analyses were carried out for each experimental condition. For each of the four experimental conditions a quadratic function was found to fit the data. For the FVT condition, the quadratic regression had $R^2 = .975$, F (2, 3) = 59.27 p = .004; for the FVS, it had $R^2 = .971$, F (2, 3) = 50.81 p = .005; for the SVS condition, it had $R^2 = .905$, F (2, 3) = 14.27 p = .029; and for the SVS condition, it had $R^2 = .991$, F (2, 3) = 166.67 p = .001. Overall, the variability for each footfall increased during the approach and was considerably reduced over the last two steps before pointing (Figure 4.2).

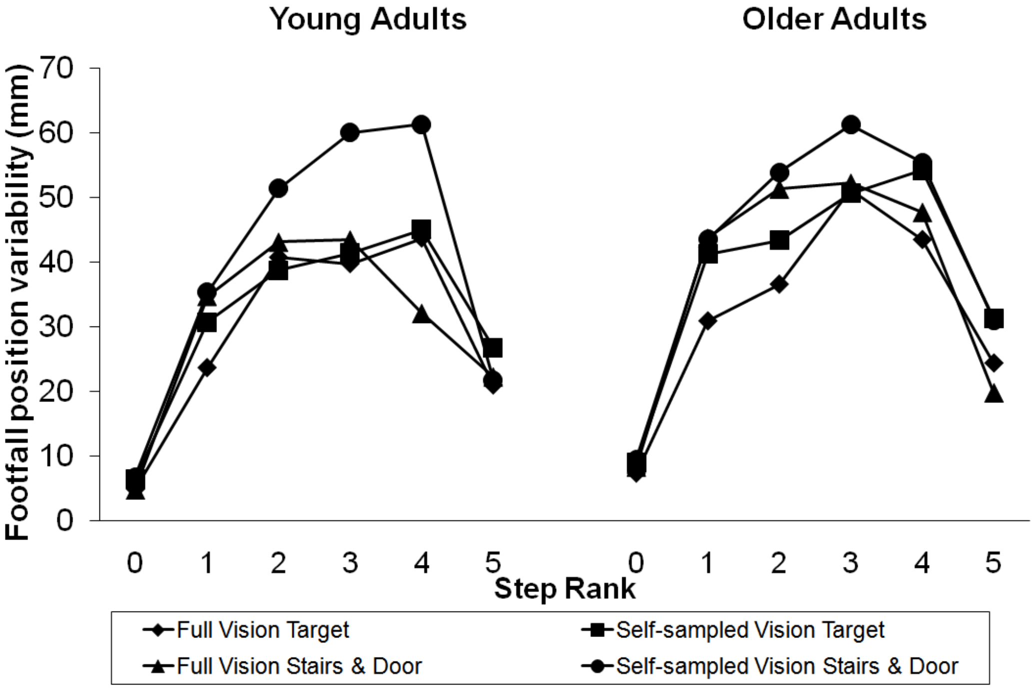


Figure 4.2 Mean approach footfall variability profiles (foot – target position for each step across trials) as a function experimental condition.

4.3.2.1.2 Velocity variability

The analysis indicated a significant age by vision by task interaction F (1, 14) = 8.86, p = .01, η^2 = .388. Bonferroni's post hoc test indicated that older adults had a significantly smaller velocity variability for the FVS condition (M = 0.067 m/s, SD = 0.032), as compared to the SVS condition (M = 0.126 m/s, SD = 0.079) (Figure 4.3).

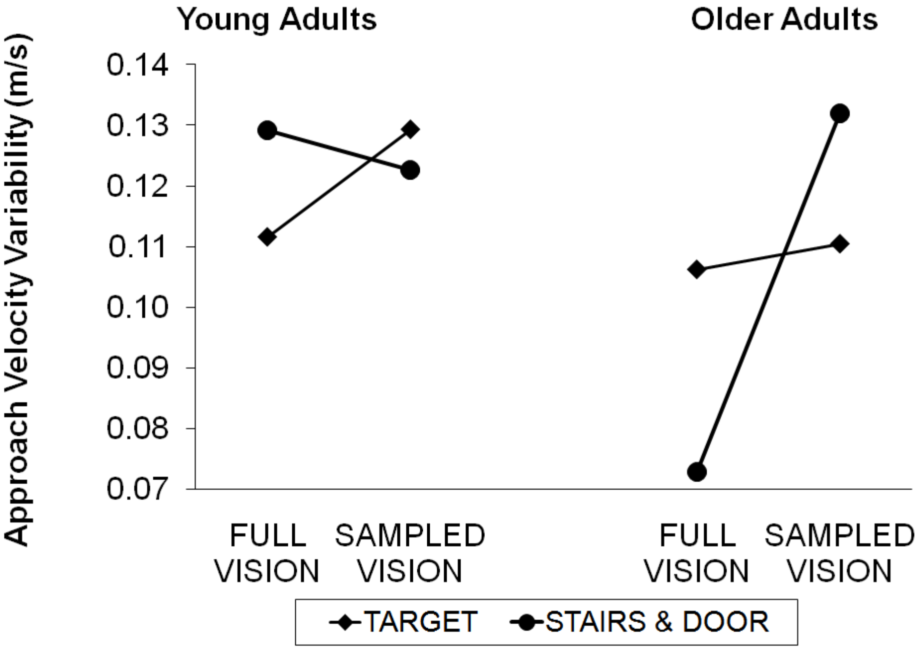


Figure 4.3 Approach velocity variability (SD) during target approach.

4.3.2.2 Last step

4.3.2.2.1 A-P foot-pointing error variability (absolute values)

The statistical analysis showed a significant vision by task complexity interaction F (1, 14) = 6.63, p = .022, η^2 = .321. Bonferroni's post hoc test indicated significantly decreased variability for the SVS condition (M = 16.51mm, SD = 6.69) as compared to the SVT condition (M = 24.80 mm, SD = 10.27) (Figure 4.4).

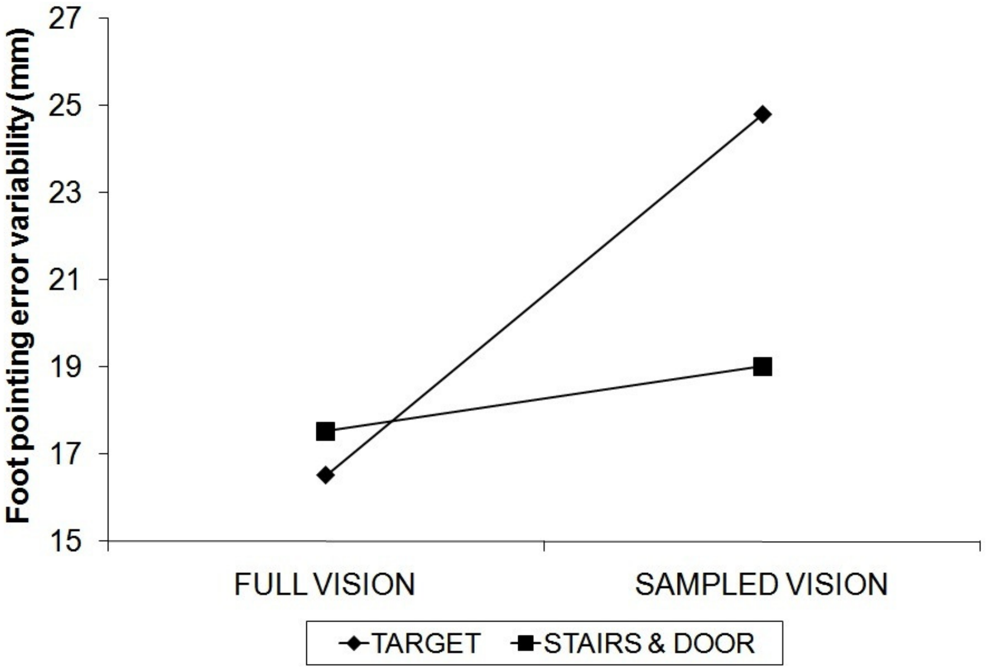


Figure 4.4 Anterior-posterior foot-pointing error variability (VE).

4.3.2.2.2 A-P foot-pointing error (signed values)

The four-way loglinear analysis produced a final model that retained the age by pointing interaction as the only significant factor. The goodness-of-fit for this model was $\chi^2(10) = 5.39$, $p = .863$, indicating that the expected values were not different for the observed data. As such, data was collapsed across vision and task complexity conditions. The age by pointing interaction was significant Pearson $\chi^2(1) = 28.84$, $p< .001$. The interaction indicates that the ratio of undershooting or overshooting the target was different for young and older adults. The odds ratio computations showed that young adults were 2.54 times more likely to undershoot the target as compared to older adults (Figure 4.5).

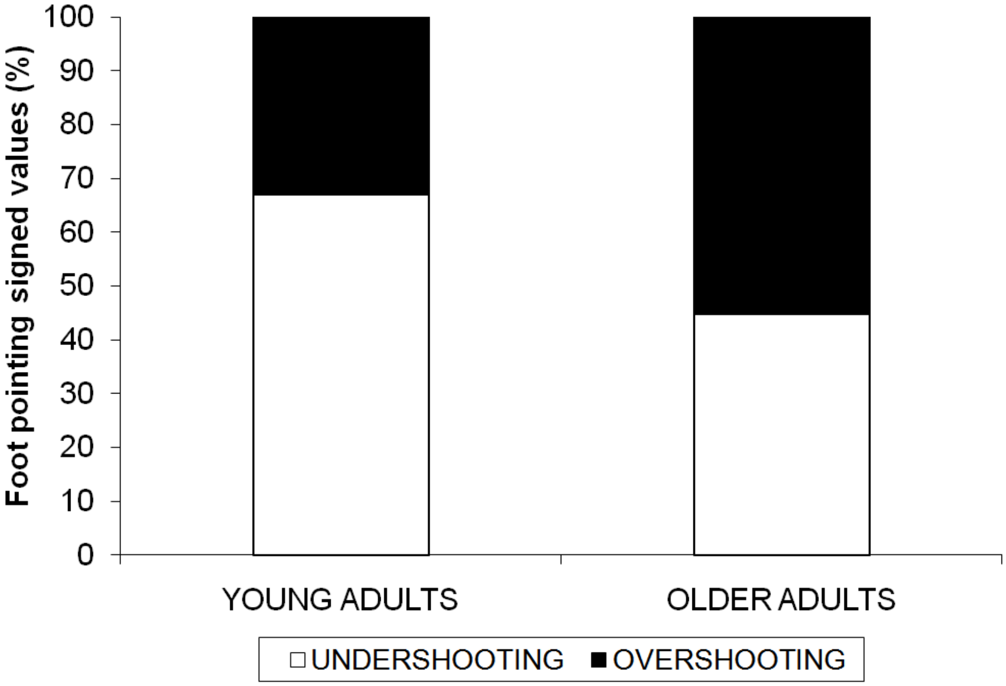


Figure 4.5 Anterior-posterior foot-pointing pattern as a function of age.

4.3.2.2.3 M-L foot-pointing error (absolute values)

The analysis indicated a main effect for task complexity F (1, 14) = 9.99, p = .007, $\eta^2 = .417$. More accurate side-to-side pointing was recorded during the stairs and door condition (M = 7.47 mm, SD = 6.01) as compared to the target condition (M = 10.07 mm, SD = 7.65).

4.3.2.2.4 M-L foot-pointing error variability (absolute values)

There was a significant main effect for vision F (1, 14) = 9.39, p = .008, $\eta^2 = .402$. Increased medio-lateral error variability was recorded during the SV condition (M = 14.50 mm, SD = 7.17) as compared to the FV condition (M = 9.04 mm, SD = 3.06). There was also a significant main effect for task complexity F (1, 14) = 7.90, p = .014, $\eta^2 = .361$. Less variability was recorded during the stairs and door condition (M = 10.79 mm, SD = 5.11) as compared to the target condition (M = 12.75 mm, SD = 6.93).

4.3.2.2.5 M-L foot-pointing error (signed values)

The four-way loglinear analysis Age x Visual Condition x Task Complexity x Pointing Error provided a backward elimination model retaining the age by pointing interaction as the only contributing factor. The goodness-of-fit test for this model was Pearson χ^2 (10) = 3.37, p = .971, indicating that the expected values did not differ from observed data. Consequently, data was collapsed to retain only the significant interaction. The age by pointing interaction was significant, Pearson χ^2 (1) = 16.71, p< .001. The interaction indicates that the ratio between medially and laterally target pointing was different for young and older adults. Based on the odds ratio calculations, older adults were two times more likely than young adults to point medially at targets (Figure 4.6).

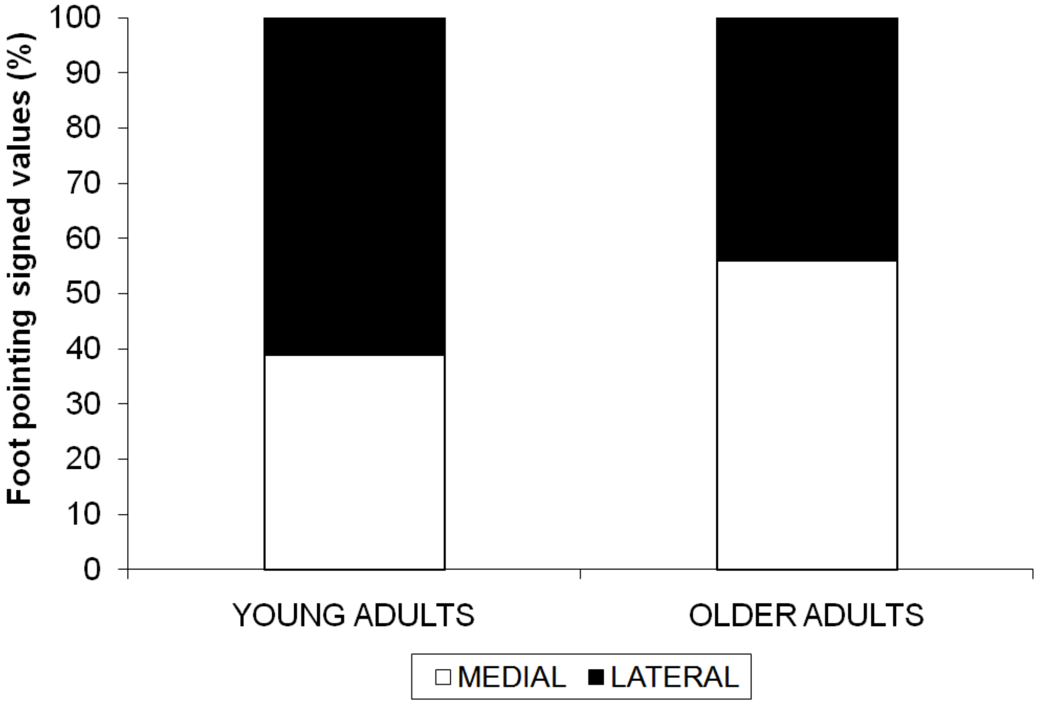


Figure 4.6 Medio-lateral foot-pointing pattern as a function of age.

4.3.2.2.6 Step length

The analysis indicated a significant main effect for vision F (1, 14) = 25.74, p = .001, η^2 = .648. A longer step length was recorded for the SV condition (M = 736.42 mm, SD = 59.19) as compared to the FV condition (M = 687.70 mm, SD = 59.90).

4.3.2.2.7 Step swing duration

There was a significant main effect for vision F (1, 14) = 6.03, p = .028, η^2 = .301. The swing duration recorded during the SV condition (M = 0.526 s, SD = 0.052) was significantly longer than that recorded during the FV condition (M = 0.507 s, SD = 0.043).

4.3.2.2.8 Step width

The analysis showed a significant main effect for task complexity F (1, 14) = 6.01, p = .028, $\eta^2 = .301$. The step recorded for the stairs and door condition (M = 128.44 mm, SD = 43.05) was wider than that recorded for the target condition (M = 118.23 mm, SD = 48.90).

4.3.2.2.9 Step width variability

The analysis indicated a significant main effect for vision F (1, 14) = 41.39, p < .001, $\eta^2 = .747$. Step width was more consistent during the FV condition (M = 31.29mm, SD = 12.77) than it was during the SV condition (M = 49 mm, SD = 13.47).

4.4 Discussion

This study investigated how aging and task complexity affected visual sampling strategies and stepping control during a locomotor pointing task. To our knowledge, this is the first study to report on foot-pointing parameters under self-sampled visual conditions and make direct comparisons between young and older participants. Participants walked at a self-selected pace to point with the foot at one target while controlling visual sampling availability based on need throughout the task. As anticipated the visual sampling characteristics were similar but the foot pointing outcome was significantly different between the age groups. An unanticipated effect was that the increase in task complexity (PPT present) proved beneficial for the foot-pointing outcome.

4.4.1 Visual sampling

Self-sampled intermittent vision was sufficient for successfully accomplishing the task regardless of experimental conditions. Moreover, vision was necessary for less than half of the overall trial duration, independent of age and PPT complexity consistent with previous reports by Patla et al., (1996) and Patla (1993; 1995). The experimental setup was meant to mimic similar daily encountered adaptive locomotor tasks. We do not exclude the possibility that part of the expected task complexity effects on visual sampling were masked while performing such well-rehearsed locomotor tasks. Furthermore, although the PPT required a change in gait pattern (walking to stair climbing) the distance between the target and the PPT was far enough to allow healthy participants sufficient time to implement the gait adaptation without impinging on the foot-pointing task. With the exception of steering, stepping control strategies can be implemented in one step cycle (Patla, 1997). Unlike older adults prone to falling, healthy older adults seem proficient in implementing serial adaptive strategies consistent with previous reports (Chapman & Hollands, 2007).

Visual samples were consistently initiated during the penultimate or the last step prior to foot-pointing. Once initiated, the visual sample continued uninterrupted until task completion during the PPT. Specifically, participants had vision available from the pointing step onward for both visual conditions. It was shown before that the presence of environmental constraints is accompanied by a corresponding increase in visual sampling needs (Patla et al., 1996).This is also corroborated by recent findings in gaze behaviour. Chapman & Hollands (2010) found a sharp decrease in foot-pointing outcome parameters as a consequence of brief target fixation periods amounting to less than one step cycle prior to foot contact. In addition, this timely visual sampling initiation prior to the pointing step coincided with a marked decrease in footfall variability optimally positioning participants for the foot-pointing task (see next section).

Less consistent was the overall visual sampling strategy. The majority of trials were accomplished with a single visual sample (at target location) or two visual samples (at trial initiation and target location), leaving the mid-section of the approach without vision. Healthy young participants are able to maintain a straight walking path for a brief time period without visual feedback (Patla, 1998; Thomson, 1983). There were exceptional instances where three or more samples per trial were recorded. Occasionally, three older participants employed more than two visual samples during the task, without a consistent pattern however. This may indicate substantial change in visual sampling needs for the older adults during adaptive locomotion. We reserve our judgment and suggest that more research must be conducted to investigate such occurrences in light of recent reports revealing unsafe gaze strategies resulting in detrimental foot-pointing outcomes (see Chapman & Holland, 2007, 2010).

Approximately half of the participants maintained the same sampling strategy throughout the entire session (number of samples and their location). Older participants changed the sampling strategy twice as frequently as their young counterparts. Since foot-pointing accuracy (absolute magnitude) and precision (variability) did not change as a function of age, this sampling variation argues for locomotor control adaptability and the fact that healthy individuals, regardless of age, find different solutions in response to the same task goal. As argued previously, the visuomotor transformations for adaptive locomotor tasks are made "de novo" for each trial attempt as opposed to being preplanned and run from memory (Patla & Vickers, 2003). This represents an optimal locomotor strategy because in real-life the environment can change unexpectedly and, as a result, it is unproductive to preplan entire locomotor sequences and run them without preserving the capability for gait alteration.

4.4.2 Feed-forward stepping control during approach

Our results show, for the first time, that the feed-forward stepping control strategies are preserved in healthy older adults and apply under self-sampled visual conditions as well. A typical two-phase approach pattern, as measured by the footfall variability pattern, was recorded given the task requirements. The small and cumulative footfall inconsistencies in the direction of progression were reduced over the last two steps before the foot-pointing. The advantage of proactive locomotor control — that is, spreading the step adjustments over several steps — maintained gait pattern largely unchanged while optimally positioning the participant in regard to the target for final foot-pointing adjustments during the last swing. Our results provide strong support for the feed-forward control strategy predominantly employed while navigating stable environments regardless of visual constraints. This adaptive locomotor control pattern is robust and consistent, spanning across tasks, gait type, and visual feedback conditions (Glize and Laurent, 1997; Laurent & Thomson, 1988; Lee, Lishman, & Thomson 1982; Patla et al, 1996; Popescu, et al, 2010).

4.4.3 Last step on-line control and foot-pointing outcome

Two pointing step control strategies emerged as a function of visual condition regardless of age group and task complexity. In contrast with the full vision condition the self-sampled visual condition had a longer swing duration as well as an increased step length and step width. This is consistent with previous reports showing last step modulations prior to target pointing if gait-cycle related intermittent vision was used to manipulate visual sampling (Chapman & Hollands, 2006a; Popescu et al., 2010). With few exceptions, during the pointing step all trials had visual information available for pointing foot guidance regardless of visual condition. We argue that the increase in footfall variability accumulated during the “blind” middle portion of the approach and the highly constraining foot-pointing task demanded marked step modulations prior to foot-pointing for the self-sampled vision condition. Healthy young participants have flexible perceptual and locomotor systems maximizing the advantage of vision availability at target vicinity to effectively modulate their pointing step. Our results show that similar pointing step control strategies are preserved in healthy older adults as well.

The nature of the task imposed stepping modulations mostly in the direction of locomotion progression (i.e., A-P direction) due to the cumulative nature of footfall inconsistencies during the target approach. The largest step modulations, regardless of visual condition, occurred during the last step prior to pointing (Figure 2). This strongly suggests the possibility of on-line stepping control at least for the self-sampled visual condition due to the "blind" approach midsection. However, due to design limitations, we cannot attribute last step modulation solely to on-line stepping control, since step pre-planning was possible before reaching the target location. Typically, for stable unchanging environments locomotion operates predominantly under feed-forward control (Laurent & Thomson, 1988; Patla, 1998; Patla et al, 1996). Nevertheless, due to the constraining foot-pointing task (i.e., pointing at a marked target center), the need for precise foot guidance during the last swing prior to foot-pointing is likely taking place.

There were no differences in foot-pointing outcomes for the absolute A-P pointing component consistent with other reports (Chapman & Hollands, 2006b; Popescu et al., 2010). As anticipated foot-pointing outcome parameters did change in the presence of the PPT which affected only the medio-lateral foot-pointing component. Contrary to our expectations, the presence of a more structured environment, while imposing a gait change, in fact benefitted participants regardless of age or visual condition. We speculate that such finding could be explained by the fact that the task had a collinear design (target center and PPT structure) providing participants with more cues towards a better positioning for the pointing task. Another possible explanation for this outcome may be the fact that an increased error in foot placement at this location during the task (i.e., just before stepping on the first stair) could increase the likelihood of tripping and falling. More testing employing offset target locations during locomotor pointing are needed to confirm this supposition. The pattern of foot-pointing (signed values) will be discussed in the next section.

4.4.4 Older participants

Marked differences were recorded with regard to the pointing pattern between young and older adults. The results reveal that older adults overshoot the target twice as often as young adults. Overshooting the target is detrimental for this particular task since the overshooting foot would block the view of the target center limiting the visual information availability necessary for guiding the foot during the terminal portion of the swing (i.e., on-line control). Therefore, for comparable foot-pointing tasks, the desired behaviour would be to undershoot the target, which would allow for foot guidance on target (Laurent & Thomson, 1988; Popescu et al., 2010).

Similarly, the foot-pointing pattern in the M-L direction indicates that older adults had a tendency to point medially at the target (i.e., narrow step). The negative connotation for such strategy could be that it may impact the dynamic balance and consequently compromise the immediately following constrained steps, which might result in a trip and/or fall. Because the current task was not designed to challenge the M-L foot-pointing component (i.e., shifting the target to the side) and no dynamic balance data was recorded, we hesitate to attribute any functional significance to these findings (see also Chapman & Hollands, 2010).

Although absolute pointing error magnitude was not affected by the experimental manipulations, the changes in the foot-pointing pattern between healthy young and older adults could indicate deficient stepping control for the older adults in the absence of discernible disease (Elble, 1997). Such findings support previous reports regarding marked differences between the high and low-risk for falling older adults, in that detrimental foot-pointing outcomes were predominantly present in the high-risk group (Chapman & Hollands, 2007). Despite the fact that both age groups adopted sampling strategies allowing for vision at the target proximity, it could be that the older adults preserve a well-learned but inadequate visual sampling behavior. Previous reports, with an older sample of participants, showed that these individuals need longer times to plan and initiate the appropriate gait adaptation as it becomes harder to share visual resources and make decisions during ongoing locomotion (Patla, 1995; Chapman & Hollands, 2006a).

4.4.5 Dual-task limitation

Although the task was successfully accomplished regardless of the visual condition (full or sampled), there may be subtle effects introduced by the dual-task nature of performing adaptive locomotion while self-selecting visual samples. Individuals benefit from sampling at particular locations during brief duration tasks such as manual aiming while concurrently operating a switch to self-select visual samples (Hansen, Cullen, & Elliott, 2005). As the results show, our task allowed sufficient time to implement or modify the sampling strategy during the task. Consistent with Patla et al. (1996), our rationale was that the voluntary self-sampling vision protocol bears a closer resemblance to the natural visual sampling behavior found outside the confines of the laboratory environment. Nevertheless, the dual-task nature of such experimental protocols must be factored into results interpretation and the subsequent functional significance attributions.

4.4.6 Conclusion

The results demonstrate that intermittent self-sampled vision is sufficient during adaptive locomotion for healthy young and older adults. Different visual sampling strategies amounted to overall vision availability of less than half of the approach duration. This is the first study to show that the typical feed-forward stepping control remains intact in healthy older adults under full and intermittent, self-sampled vision. This strategy allows dissipating stepping modulation over several steps while maintaining the forward progression largely unaltered. Older adults had different pointing patterns compared to young adults, resulting in target overshooting. In relation with previous reports having much older or prone to falling participants, these findings may indicate an intermediate stage indicating more dramatic future changes in stepping control for aging individuals.

4.5 References

Chapman, G. J., & Hollands, M. A. (2006a). Age-related differences in stepping performance during step cycle-related removal of vision. *Experimental Brain Research* 174, 613-621.

Chapman, G. J., & Hollands, M. A. (2006b). Evidence for a link between changes to gaze behaviour and risk of falling in older adults during adaptive locomotion. *Gait & Posture*, 24, 288-294.

Chapman, G. J. & Hollands, M. A. (2007). Evidence that older adult fallers prioritize the planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait & Posture,* 26, 59-67.

Chapman, G. J., & Hollands, M. A. (2010). Age-related differences in visual sampling requirements during adaptive locomotion. *Experimental Brain Research,* 201, 467-478.

Elble, R. J. (1997). Changes in gait with normal aging. In J. C. Masden, L. Sudorsky, & L. Wolfson (Eds.). *Gait disorders of aging. Falls and therapeutic strategies* (pp. 93-105). New York: Lippincott-Raven.

Folsten, M. F., & Folsten, S. E., & McHugh, P. R. (1975). “Mini-Mental State” A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research,* 12, 189-198.

Ginsburg, A. P. (1984). A new contrast sensitivity vision test chart. *American Journal of Optometry and Physiological Optics,* 61, 403-407.

Glize, D., & Laurent, M. (1997). Controlling locomotion during the acceleration phase in sprinting and long jumping. *Journal of Sport Sciences,* 15, 181-189.

Hansen, S., Cullen, J. D., & Elliott, D. (2005). Self-selected visual information during discrete manual aiming. *Journal of Motor Behavior,* 37 (5), 343-347.

Laurent, M., & Thomson, J. A. (1988). The role of visual information in control of a constrained locomotor task. *Journal of Motor Behavior* 20(1): 17-37.

Lee, D. N. (1978). The functions of vision. In H. L. Pick jr. and E. Saltzman (Eds.). *Modes of perceiving and processing information* (pp. 159-170). Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers.

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

Patla, A. (1997). Understanding the roles of vision in the control of human locomotion. Gait & Posture 5, 54-69.

Patla, A. E. (1993). Age-related changes in visually guided locomotion over different terrains: Major issues. In Stelmach, G. E. and Homberg, V. (Eds). *Sensorimotor Impairments in the Elderly* (pp. 231-252). The Netherlands: Kulwer Academic Publisher.

Patla, A. E. (1995a). Neurobiomechanical bases for the control of human locomotion. In Bronstein, A. M., Brandt, T, and Woollacott, M. H. (Eds).

Clinical disorders of balance, posture, and gait. (pp. 19-40).New York: Oxford University Press.

Patla, A. E. (1995b). A framework for understanding mobility problems in the elderly. In Craik, R. L., and Oatis, C. A. (Eds.) *Gait Analysis. Theory and Application* (pp. 436-449). St. Louis, MO: Mosby.

Patla, A., 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, 513-522.

Patla, A. E., & Vickers, J. N. (2003). How far do we look when required to step on specific locations in the travel path during locomotion? *Experimental Brain Research* (148), 133-138.

Perry, S. D. & Patla, A. E. (2001). On-line adjustments to body center of mass and limb elevation to suddenly changing obstacle height. In J. Duysens, Smits-Engelsman, B. M., & Kingma, H. (Eds.), *Control of posture and gait* (pp. 485-487). Maastricht, Netherlands.

Podsiadlo, D., & Richardson, S. (1991). The Timed “Up & Go”: A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society,* 39, 142-148.

Popescu, A., Runnalls, K., & Maraj, B. K. V. (2010). Intermittent visual information affects motor strategies during locomotor pointing. *International Journal of Sport Psychology,* 41 (3), 313-326.

Rankin, E. J., Gfeller, J. D., & Gilner, F. H. (1993). Measuring anxiety states in the elderly using the state-trait anxiety inventory for children. *Journal of Psychiatric Research,* 27, 1, 111-117.

Reynolds, R. F., & Day, B. L. (2005a). Rapid visuo-motor processes drive the leg regardless of balance constraints. *Current Biology* 15 (2), R48-R49.

Reynolds, R. F., & Day, B. L. (2005b).Visual guidance of the human foot during a step. *Journal of Physiology,* 569.2, 677-684.

Schutz, R. (1977). Absolute, constant, and variable error: Problems and solutions. In Mood, D (Ed.) *The measurement of change in physical education: Proceedings of the Colorado Measurement Symposium (pp. 82-100).* Boulder, CO.

Spielberger, C. D., Gorshuch, R. L., Lushene, R., Vagg, P. R., and Jacobs, G. A. (1973). State-Trait Anxiety Inventory for Children. Consulting Psychologist Press Inc. & Mind Garden Inc.

Thomson, J. A. (1980). How do we use visual information to control locomotion? *Trends in Neuroscience,* 3, 247-250.

Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental psychology: Human Perception and Performance,* 9 (3), 427-443.

VCTS application manual (1988). VISTECH Consultants, Inc., Dayton, OH. Retrieved on April 2nd, 2009 from http://www.agingeye.net/cataract/Vistech2.pdf

Study four

Saccade-step latency during locomotor pointing: The effects of age and task complexity[6]

5.1 Introduction

Precise limb-positioning tasks benefit greatly from visual information necessary to plan and guide limbs to specific spatial locations (Elliott, Hansen, Grierson, Lyons et al., 2010; Patla, 1997). Both aiming with the hand (reaching) and pointing with the foot (stepping on specific locations) during adaptive locomotion share evolutionary and neurophysiologic similarities. Some mammalian species use their forelimbs for both object manipulation and precise arboreal locomotion, whereas in adult humans, the upper limbs have been freed from their locomotion role (Georgopoulos & Grillner, 1989).

Many aiming or foot-pointing activities are performed on a daily basis: dialing a phone number, reaching for a cup of coffee, or stepping on a dry spot while walking on icy sidewalk. Such tasks are performed rather fast and the outcomes are accurate owing to the coordinated eye and limb movements with regard to the target object. The coordination between the eye and the limb motor control systems (visuomotor coordination) was the object of investigation for researchers during the recent past as technological advances allowed for

---

[6] A version of this chapter has been submitted for publication. Popescu, A. & Maraj, B. *Human Movement Science.*

simultaneous recording of head-free gaze and limb movement (Chapman & Hollands, 2007; Helsen, Elliott, Starkes, & Ricker, 1998; Johansson, Westling, Backstrom, & Flanagan, 2001; Patla & Vickers, 2003).

Originally, the typical experimental setup for gaze recording during manual aiming tasks was to immobilize the head movement by means of a bite bar, and measure eye movements only as the hand aimed at targets (Goodale, Pelison, & Prablanc, 1986). Typically, eyes begin moving sooner than the hand, and the gaze tends to undershoot the target with a primary saccade while the hand is still in midflight. The first report on head-free gaze and hand coordination was made by Helsen et al., (1998). Here, the point of gaze (POG) was computed from combined free head movements (constrained to a $1m^3$ spatial area) and eye rotation relative to the head. The POG temporal and spatial parameters were synchronized with limb kinematics during a discrete manual aiming task. Results showed that saccades were directed towards the target and they were initiated well in advance of hand movement, thus providing information for limb guidance. The eye fixates on the target vicinity (2^0-3^0) or the target itself (with one or two corrective saccades) until limb movement termination. A trademark visuomotor coordination was noted during single-target aiming movements. Specifically, the end of the first saccade coincides with the peak acceleration of the hand (temporal feature), and peak velocity of the hand coincides with 50% of the movement amplitude (spatial feature).

One aspect of gaze-hand coordination that caught researchers’ attention became known as gaze anchoring. For tasks involving a sequence of movements, the POG is rapidly directed towards the first location of interest and remains engaged (fixated) until about hand arrival before jumping to the next location. Such proactive gaze behavior was reported for sequential aiming tasks (Wilmut, Wann, & Brown, 2006; Neggers & Bekkering, 2002) and object manipulation (Johansson, Westling, Backstrom, & Flanagan, 2001) as well as more complex tasks such as making tea or sandwiches (Land & Hayhoe, 2001; Land, 2009).

Overall, the results show that gaze was deployed towards the next target/object in the sequence almost exclusively, gaze preceded limb movement (i.e. feed-forward control), hand contact sites were obligatory POG targets, and gaze was disengaged (i.e., saccading away) shortly before or at hand contact. Depending on task duration, this premature gaze shift towards the next location in the sequence ranges between 200ms for sequential aiming (Wilmut et al., 2001) and 600ms for manipulative tasks (Land & Hayhoe, 2001). This feed-forward, proactive limb control modality maintains fluent, continuous movements without affecting limb endpoint accuracy. Researchers proposed a short-term memory buffer to store target/object spatial location representation. Healthy individuals successfully perform memory-driven aiming/reaching tasks during proactive visual sampling.

Walking is the predominant form of locomotion and it is integrated in many instrumental activities of daily living such as housework and shopping. Walking is a complex motor skill: the automatic and rhythmic limb pattern must be adapted in response to complex environments (i.e., adaptive locomotion). Vision is best suited to provide rapid and accurate environmental information at a distance, which is used to plan (feed-forward control) and guide (on-line control) stepping in order to meet environmental challenges (Lee, 1978; Patla, 1997). In order to understand the control of adaptive locomotion, both gaze and gait must be simultaneously observed (Thomson, 1980; Patla, 2004). In comparison to manual aiming literature, to date, fewer reports are available detailing visuomotor coordination during adaptive locomotion. The main challenge was the head-free POG recording during walking. In contrast to manual aiming, which requires only a small spatial volume in which the head can freely rotate, typical locomotor pointing tasks cover a much larger space, as participants walk towards preset target locations.

The first report investigating the temporal visuomotor coordination aspect during adaptive locomotion was made by Hollands, Marple-Horvat, Henkes, and Rowan (1995). Horizontal eye movements were continuously monitored while participants stepped on 18 raised and irregularly spaced stepping stones. Eye movements were recorded using both electro-oculography and infrared reflectometry. Temporal kinematic measures were made via logic circuits for each footfall during walking. Although POG spatial location was only inferred and no footfall spatial coordinates were reported, off-line comparison of saccades and footfall timing data showed that saccades were made towards the next footfall at the end of a stance or during the early swing (i.e., feed-forward control) and POG was anchored (fixated) to the next footfall until 51ms after foot contact took place (i.e., online control).

This feed-forward stepping control was confirmed in a subsequent study constraining participants to step on flush stepping stones in a dark environment (Hollands & Marple-Horvat, 2001). The location of the stepping stones was identified via LEDs. They were intermittently turned off at random for 500ms to test the effect of target information availability on planning stepping control. The timing between saccade onset and footlift was more consistent compared to the timing between saccade away and footfall, indicative of a feed-forward interaction between the oculomotor and locomotor control systems. The premature LEDs disappearance or reappearance prolonged the duration of the stance, but not the swing duration. The on-line limb control (foot guidance) seems dependent on the task constraints. The flush stepping stones imposed a lesser challenge during walking. Consequently, foot guidance towards targets was not needed to preserve dynamic balance during walking.

Despite the inherent limitations, these studies provide a shift from the previous research paradigms testing visuomotor coordination during adaptive locomotion. Henceforward, direct means for investigating the eye-foot functional relationship replaced the formerly indirect account for examining the role of vision for locomotion control (via performance-outcome measures under intermittent vision manipulations).

With the introduction of mobile eye-tracking devices, the issue was taken one step further as natural eye rotation data recording was possible. As such, the likelihood of data contamination, resulting from making single-dimension eye rotation recordings (e.g. horizontal) from the naturally occurring combined two-dimensional eye rotation, was eliminated. Two reports were made by Patla and Vickers (1997; 2003) investigating spatio-temporal aspects of gaze behavior during adaptive locomotion tasks. A split-screen video recording, showing both the walkway with the participants' gaze superimposed (black cursor) and the walking participant, was used to record gaze and stepping parameters. Despite a low temporal resolution (30 Hz) and the lack of spatial foot kinematics data, the feed-forward control mode for stepping was confirmed for obstacle clearance (Patla & Vickers, 1997) and foot-pointing at consecutive footprints (Patla & Vickers, 2003). Moreover, both reports indicate that participants typically look two steps ahead during walking and fixate the obstacle one or two steps ahead.

In recent years, the mobile eye-tracking technique was further improved, rendering researchers capable of recording synchronized gaze behavior (saccades and fixations) and spatio-temporal foot kinematics sampling both data streams at 120Hz. This high frequency sampling allowed for precise timing recording and fine discrimination between gaze events and stepping. In a series of experiments, Chapman and Hollands (2006, 2007) observed the relationship between gaze and stepping during adaptive locomotion in older adults. These reports provided, for the first time, foot-pointing outcome measures for accuracy and consistency. Young, older, and older prone-to-falling individuals walked a straight path stepping on two targets (Chapman and Hollands, 2006) or two targets separated by an obstacle (Chapman and Hollands, 2007). Results showed that gaze was deployed in a feed-forward manner and engaged sequentially with each location of interest during locomotion. This gaze fixation sequence was recorded regardless of age or task complexity; however, older adults and particularly older adults at risk for falling, presented with a different gaze strategy that adversely impacted the foot-pointing outcome. An interesting finding was that of premature gaze disengagement with the target. Specifically, older adults shifted their gaze away from the targets before the footfall, while young adults maintained their gaze “anchored” until after their foot landed on target. This effect was exacerbated by the increase of task complexity and for the participants at risk for falling. Moreover, there was a small but significant correlation between the gaze shift away from the targets and the decrease in foot-pointing outcomes (Chapman and Hollands, 2006; 2007). Authors concluded that older adults, especially older adults with a falling history, need more time to process information; therefore, they prioritize future adaptive steps planning over the accurate execution of current adaptive steps.

Overall, technological advancements during past decades provided investigators the means to produce empirical evidence supporting the shared similarities between manual aiming and foot-pointing as outlined by Georgopoulos & Grillner (1989). Despite the differences between limb inertial parameters and task constraints (dynamic balance during walking), some commonalities emerged. Vision is used predominantly proactively (feed-forward control), providing information necessary for limb movement planning while on-line limb control is dependent on imposed task constraints. Gaze arrives first at the location of interest and is anchored throughout limb movement. Typically, for complex tasks requiring a sequence of movements, gaze disengages from one location of interest and moves to the next (saccade away) shortly before or after limb contact. Such gaze behavior helps planning the next action in a sequence maintaining the overall movement fluency, without affecting the outcome of the current ongoing sub-movement execution. However, recent reports indicate that both gaze and the subsequent foot-pointing outcome are influenced by the complexity of the locomotor task and biological aging (Chapman and Hollands, 2006; 2007). Also, premature gaze disengagement with the foot targets, especially for older individuals, negatively impacts the foot-pointing performance outcome.

Although recent progress has been made in the investigation of visuomotor coordination during adaptive locomotion, gaze recordings were confined to eye movement alone which indirectly constrained the task design to a single spatial plane (the floor surface). Gaze parameters may be computed by incorporating free head rotation into the algorithm, subsequently extending task design to more elaborate, similar to real-life environments. The findings can be extrapolated, for instance, to better the retirement house design in an effort to curb the risks associated with tripping and falling in the older adults. Therefore the aim of this study was to investigate differences in gaze behavior between young and older healthy adults and to observe associated changes in stepping control while performing ecologically valid adaptive locomotor tasks of systematically increased complexity. We were interested to observe how planning a contiguous post-pointing task (PPT) requiring a change in gait impinges on the current execution of a foot-pointing task. A second goal was to implement a novel technique for deriving head-free gaze during adaptive locomotion in order to alleviate any ambiguities related to head-free gaze measurement. Real-time POG was derived by combining both head spatial rotation with eye rotation throughout the task. Moreover, POG spatial location was derived by predefining several areas of interest (e.g., the targets) located within various scene planes with different spatial orientation covering the entire task layout.

5.2 Method

5.2.1 Participants

Eighteen volunteers, nine young adults (YA) (mean age 22.44 ± 1.92) and nine older adults (OA) (mean age 62.4 ± 3.71), independent walkers with normal or corrected-to-normal vision, participated in this study. Participants were free of any neurological or musculoskeletal impairment that could compromise the experiment. The following tests were employed to screen the participants and control for any associated confounding factors: visual acuity with the "Snellen" chart for static visual acuity (Precision Vision, La Salle, IL)[7], visual contrast sensitivity with the VCTS 6500 chart (Ginsburg, 1984), cognitive functioning with the "Mini-Mental State" questionnaire (Folstein, Folstein, & McHugh, 1975), and functional mobility employing the Timed "Up & Go" test (Podsiadlo & Richardson, 1991). The screening test results are summarized in Table 5.1. The research protocol was approved by the University of Alberta Research Ethics Board and participants gave written informed consent before data collection.

---

[7] Participants with single vision corrective eyeglasses or contact lenses were accepted

Table 5.1 Participants' characteristics

Characteristics	Young Adults	Older Adults
Age (years)		
Mean	22.44 ± 1.92	62.4 ± 3.71
Range	20 - 26	59 - 68
Visual acuity (Snellen Chart)		
Range	20/16 - 20/30	20/16 - 20/25
Functional mobility (Timed "UP & GO")		
Mean	7.47 ± 0.77	8.04 ± 0.69
Range	5.8 - 8.2	6.5 - 9
Cognitive functioning ("Mini-Mental State")		
Mean	30 ± 0	29.7 ± 1.06
Range	30 - 30	27 - 30

Visual contrast (VCTS Chart)					
Spatial Frequency	1.5	3	6	12	18
Young Adults					
Mean	6.6 ± 1.11	6.7 ± 0.66	6.88 ± 0.78	6.88 ± 0.78	6.44 ± 1.13
Range	6 to 9	6 to 8	6 to 8	6 to 8	4 to 8
Older Adults					
Mean	6.11 ± 0.6	6.55 ± 0.52	6 ± 0.5	5.55 ± 1.13	5.11 ± 0.92
Range	5 to 7	6 to 7	5 to 7	3 to 7	3 to 6

5.2.2 Instruments and task

Kinematics data were recorded with a six-camera motion analysis system (Visualeyez PTI, Burnaby, BC). LED markers were placed on the corresponding anatomical landmarks of the anterior-superior aspect of the hallux, and the posterior aspect of the calcaneus for both feet.

Gaze data was recorded via a high-speed monocular head-mounted mobile eye tracking system (HS-H6, Applied Science Laboratories, Bedford, MA). A set of four LED markers, placed on a 10 x 10 cm rigid body, were attached to the eye tracker headband posterior to the participants' head. Head position and rotation data from the rigid body were fed-back into the eye-tracker system and integrated with the eye rotation data to derive real-time POG during locomotion. Four scene planes, covering the entire walkway and the PPT, each containing one area of interest (first and second target, the stairs, and the door) were predefined, meshing both the eye-tracker and the motion analysis systems coordinates. This made possible, for the first time, to record POG in several geometric planes having a different spatial orientation (see Appendix for detailed diagrams). This setup entails combined head and eye rotation for gaze orientation in order to fixate specific environmental features during adaptive locomotion. Kinematics and eye-tracking data were synchronized at 120 Hz. In addition, a miniaturized video camera with the POG crosshairs superimposed was placed on the left side of the walkway covering the entire setup. The video recording (60 fps) was used as backup and not for data analysis purposes.

The task consisted of walking at a self-selected pace and pointing, with the anterior aspect of the foot at the center of the two targets en route without stopping, and continuing with the PPT as depicted in Figure 5.1.

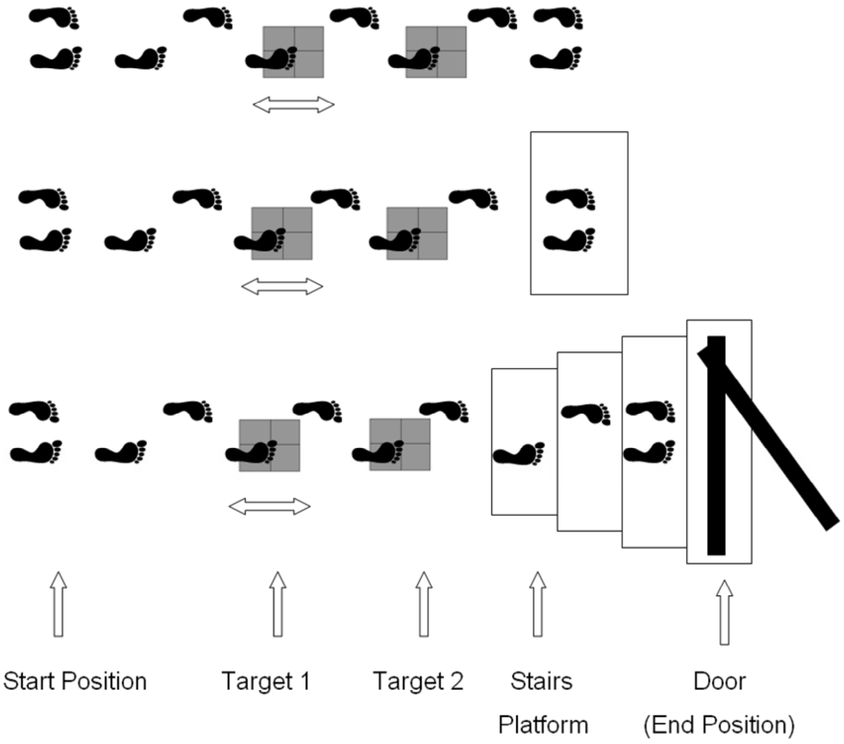


Figure 5.1 Experimental task diagram (dark footprints signify vision availability). From the top: control, platform, and stairs conditions respectively.

5.2.3 Procedure

The walkway layout was scaled to each participant's step length, measured during free walking before data collection. A total of seven steps were necessary to cover the distance from the start to the PPT. Two square targets (28 x 28 cm), flush to the ground, were placed along the walkway. The center of both targets (T1 & T2) was visibly marked by contrasting crosshairs for unequivocal target center location identification. Participants were given the choice to determine which foot was the most comfortable to point with. The pointing foot was determined during the practice trials. Once it was determined, the same foot was used throughout the data collection session (i.e., the pointing foot).

T2 neutral location was set at five steps from the starting location. This location required minimal step adjustments in order for the pointing foot to land on it. The distance between T2 and either of two PPT was set at 1½ steps. Both T2 location and the PPT location remained unchanged throughout the data acquisition session. The T1 location was set three steps away from the start. Its location was randomly changed from its neutral position to a position displaced forward or backward position by 10 cm. The T1 random relocation was done in order to ensure target position unpredictability and visually guided stepping modulation for both T1 and T2 targets during locomotion.

There were three PPT conditions. The complexity of the PPTs was manipulated by increasing the number of task components: walking continuation (W control condition), stepping on a raised platform (P), and climbing up a set of four stairs and opening a door with a door knob handle (S). The platform height and the stair riser height were 17 cm. The PPTs were presented as a block and the order of presentation was counterbalanced between participants.

Data collection began following several practice trials to ensure a comfortable and consistent walking pace. At the starting position, participants were asked to fixate their gaze away from the walkway to an object placed to their left 1m above the floor. They waited for a verbal command and were asked to proceed with the task immediately. Each participant completed a total of 27 trials: three for each target location for each of the three PPT conditions.

5.2.4 Data analysis

Gaze fixation data was reduced and analyzed using EYENAL software (Applied Science Laboratories, Bedford, MA). The program employs a moving window algorithm to compute gaze fixations duration. First, the gaze fixation location area was established based on the visual angle and set between 1.5^0 and 2.5^0. The gaze fixation duration computation was initiated when gaze was stabilized for 12 consecutive samples (100ms) inside this specified location area and was terminated when gaze fell outside this area for three consecutive samples. Subsequently, the gaze fixation location value was computed as the mean location for each sample located within a 3^0 visual angle. Each gaze location was automatically linked to the originally predefined scene planes and areas of interest within these scene planes.

Kinematics and gaze data were exported and reduced using a custom-written MATLAB program (The MathWorks, Inc. Natick, MA). The gait events and the timing of saccade-away relative to foot contact on targets were manually identified (Figure 5.2).

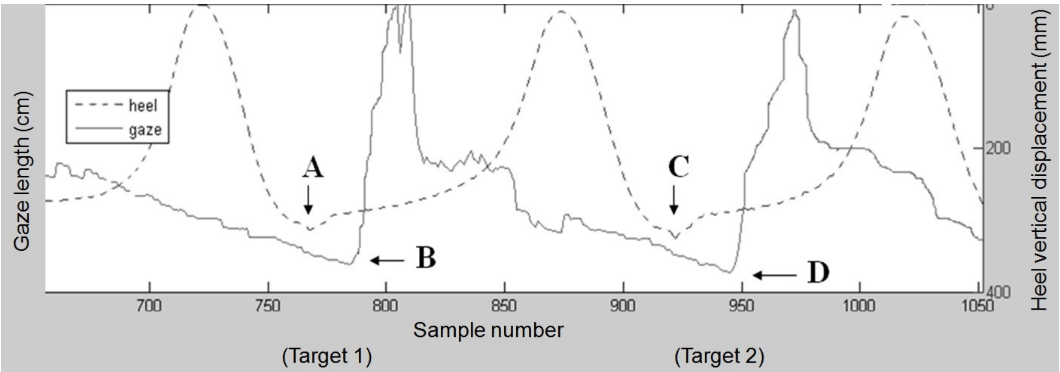


Figure 5.2 Single trial data for gaze length (distance from the left eye to the floor target location) and heel vertical displacement for the pointing foot. The key points for calculating the saccade-step latency values were: point A - Target 1 heel contact; point B - saccade away event at Target 1; point C - Target 2 heel contact; and point D - saccade away event at Target 2.

One step was defined as the event between two consecutive heel contacts with the opposite feet. Subsequent statistical analysis was carried out using STATISTICA for Windows (StatSoft, Inc., Tulsa, OK). A mixed ANOVA design with 2 age (YA vs. OA) x 2 target (T1 vs. T2) x 3 post-pointing tasks (W vs. P vs. S) with repeated measures on the last two factors was conducted on pointing-step parameters (step length and width, stance and swing duration), foot-pointing outcomes for both anterio-posterior (A-P) and medio-lateral (M-L) aspects (absolute constant error |CE| and variable error VE), and the saccade-step latency (absolute value for the temporal difference between gaze transfer away from the target and the foot contact with that target). The absolute constant error |CE| measure was used instead of constant error measure (CE) in order to avoid underestimating the average bias between group means (Schutz, 1977).

In addition, to establish the locomotor pointing pattern (overshooting vs.

undershooting and medial vs. lateral foot-pointing) and the saccade-step latency pattern (saccade away before foot-pointing vs. saccade away after foot-pointing), a hierarchical loglinear statistic using backward elimination was employed for the categorical data analysis (foot-pointing and saccade-step latency signed values). This approach would ensure the preservation of inter-subject variability throughout data reduction and analysis.

All variability data (standard deviation) was log transformed prior to data analysis. Confidence levels were set at $p < 0.05$; Bonferroni post hoc tests were employed where appropriate. Only statistically significant results will be reported in the next section.

5.3 Results

5.3.1 Gaze parameters

5.3.1.1 Saccade-step latency (absolute values)

The statistical analysis revealed a significant main effect of target $F(1, 16) = 6.60$, $p = .021$, $\eta^2 = .292$. A longer saccade-step latency was recorded for T2 (M = 0.214 s, SD = 0.100) as compared to T1 (M = 0.117 s, SD = 0.108). There was a significant main effect of task complexity as well $F(2, 32) = 13.40$, $p < .001$, $\eta^2 = .456$. The post hoc test indicated a shorter saccade-step latency for the S condition (M = 0.139 s, SD = 0.091) as compared to both the P condition (M = 0.214 s, SD = 0.100) and W condition (M = 0.232 s, SD = 0.102).

The target by task complexity interaction was also significant. Mauchly's test indicated that the assumption of sphericity has been violated χ^2 (2) = 7.32, p = .026. The degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (ε = .823), F (1.64, 26.34) = 8.15, p = .003, η^2 = .338. The post hoc test indicated that a shorter saccade-step latency was recorded for the T1S condition (M = 0.088 s, SD = 0.057) as compared to both T1W (M = 0.227 s, SD = 0.099) and T1P conditions (M = 0.212 s, SD = 0.106). The T1S condition (M = 0.088 s, SD = 0.057) also had a significantly shorter saccade-step latency compared to the T2S condition (M = 0.189 s, SD = 0.092) (Figure 5.3).

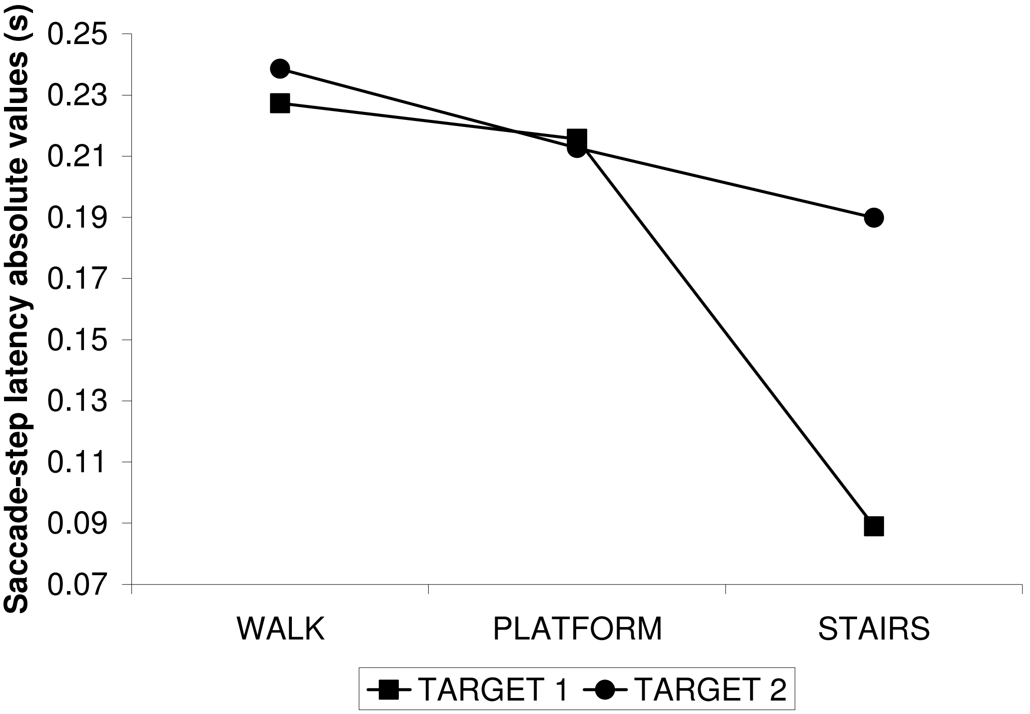


Figure 5.3 Saccade-step latency (absolute value for the temporal difference between gaze transfer away from the target and the foot contact with that target) as a function of target location and task complexity.

5.3.1.2 Saccade-step latency (signed values)

The four-way loglinear analysis, Age x Target x PPT Complexity x Saccade Timing, produced a final model that retained the Age x Saccade timing interaction and the Target x PPT complexity x Saccade Timing interaction as significant factors contributing to the model. The goodness-of-fit test for this model was Pearson χ^2 (10) = 6.27, p = .792, indicating that the expected values were not different for the observed data. Consequently, data was collapsed to retain only the significant interactions. The Age x Saccade interaction was significant, Pearson χ^2 (1) = 114.84, p < .001, indicating that the ratio of shifting the gaze before or after foot-pointing was different between the age groups. The odds ratio calculations show that YA were 11 times more likely than OA to shift their gaze after the pointing foot landed on the target (Figure 5.4).

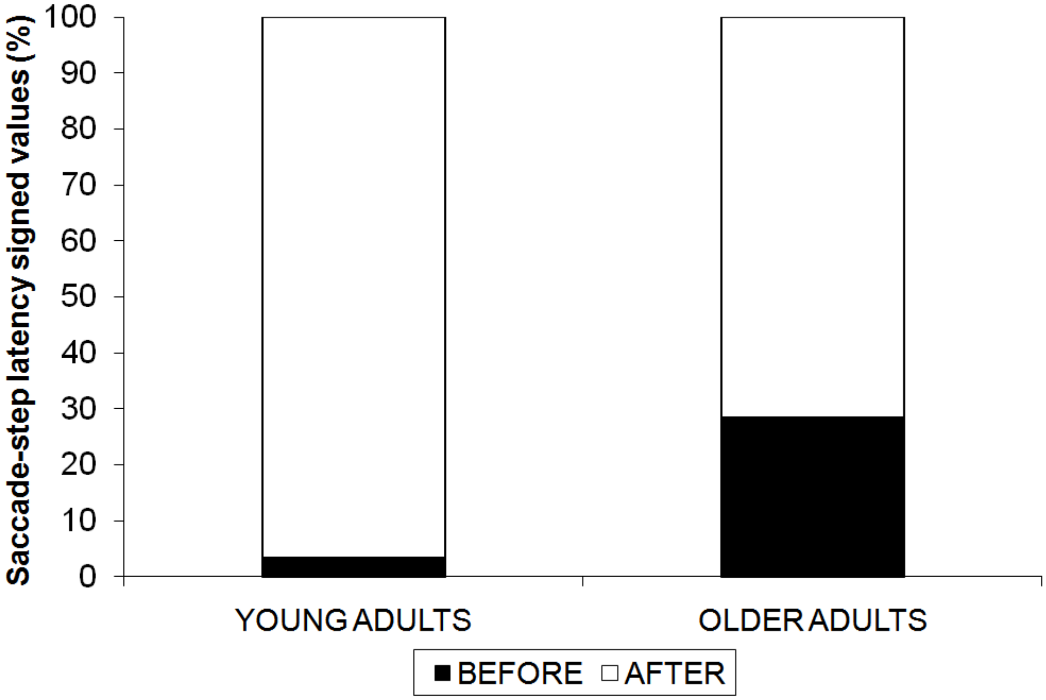


Figure 5.4 Saccade-step latency pattern (signed values for the temporal difference between gaze transfer away from the target and the foot contact with that target) as a function of age.

The Target x PPT complexity x Saccade Timing interaction was also significant, Pearson χ^2 (2) = 22.63, p < .001. The interaction showed that the ratio of gaze shifting relative to the pointing foot contact for T2 was different for the three PPT conditions. The odds ratios indicate that during the W condition, the after saccade is 2.06 times more likely to occur as compared to the P condition, and 4.52 times more likely to occur as compared to the S condition. The odds ratios also showed that during the P condition, the after saccade is 2.18 times more likely to occur as compared to the S condition (Figure 5.5).

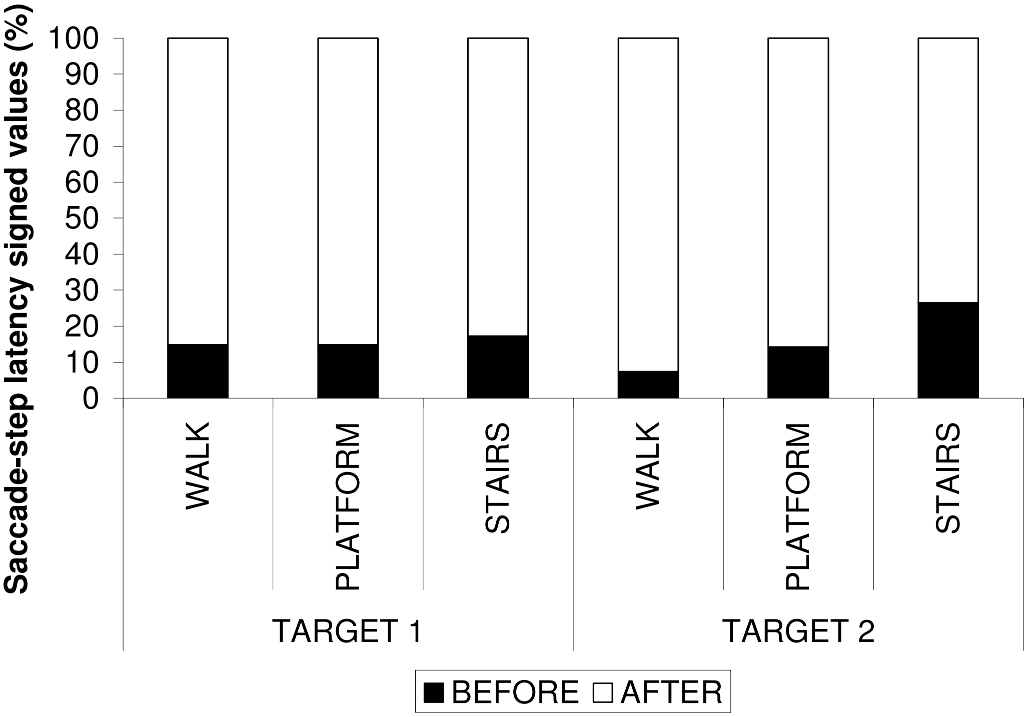


Figure 5.5 Saccade-step latency pattern (signed values for the temporal difference between gaze transfer away from the target and the foot contact with that target) as a function of target location and task complexity.

5.3.2 Last step parameters

5.3.2.1 Sagittal pointing error (signed values)

The four-way loglinear analysis Age x Target x PPT Complexity x Pointing Error by backward elimination produced a final model that retained the Age x Pointing, the Target x Pointing, and the PPT complexity x Pointing interactions as significant factors contributing to the model. The goodness-of-fit test for this model was Pearson χ^2 (14) < 0.001, p = 1, indicating that the expected values were not different for the observed data. Consequently, data was collapsed to retain only the three significant interactions.

The Age x Pointing error interaction was significant Pearson χ^2 (1) = 42.66, $p < .001$. The interaction indicates that the ratio undershooting/overshooting the target was different for YA and OA. The odds ratio calculations indicate that older adults were 2.5 times more likely to overshoot the target as compared to young adults (Figure 5.6). The Target x Pointing error interaction was significant Pearson χ^2 (1) = 6.68, $p = .010$. The interaction indicates that the undershooting/overshooting ratio was different between the two targets. The odds ratio calculations indicate that T2 is 1.5 times more likely to be undershot than T1. Finally, the PPT complexity x Pointing error interaction was significant Pearson χ^2 (2) = 7.19, $p = .027$. The interaction indicates that the ratio undershooting/overshooting the target was different for the three PPTs. The odds ratio calculations showed that during the W condition the target is 1.7 times more likely to be undershot than during the P condition, and 1.9 more times more likely than the S condition. The odds ratio also showed that during the P condition the target is 1.1 times more likely to be undershot than during the S condition (Figure 5.7).

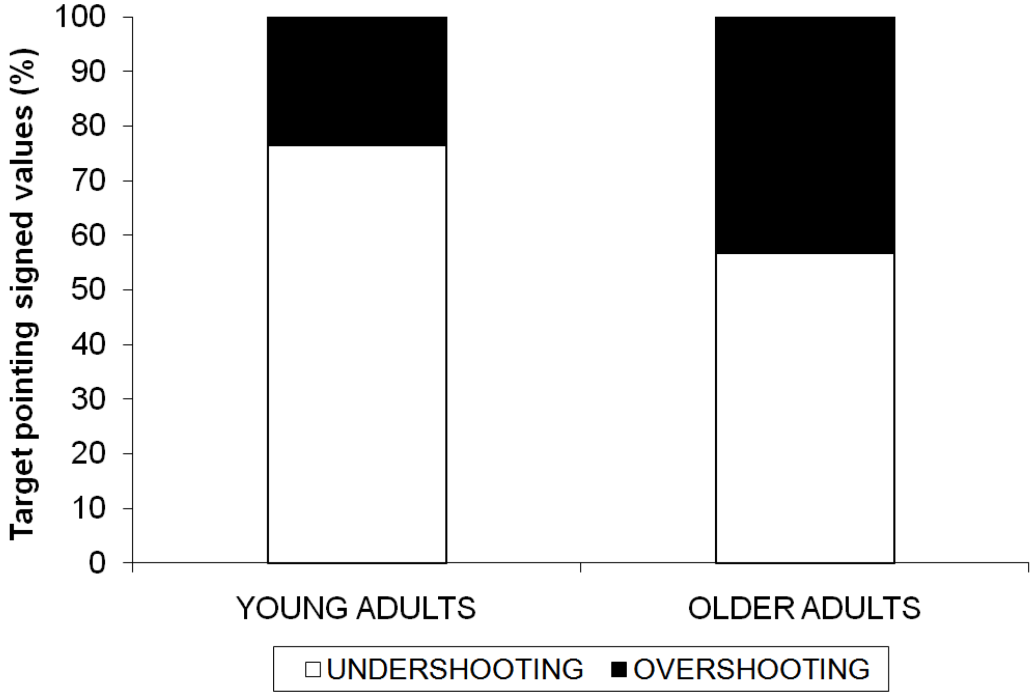


Figure 5.6 Anterior-posterior foot-pointing pattern as a function of age.

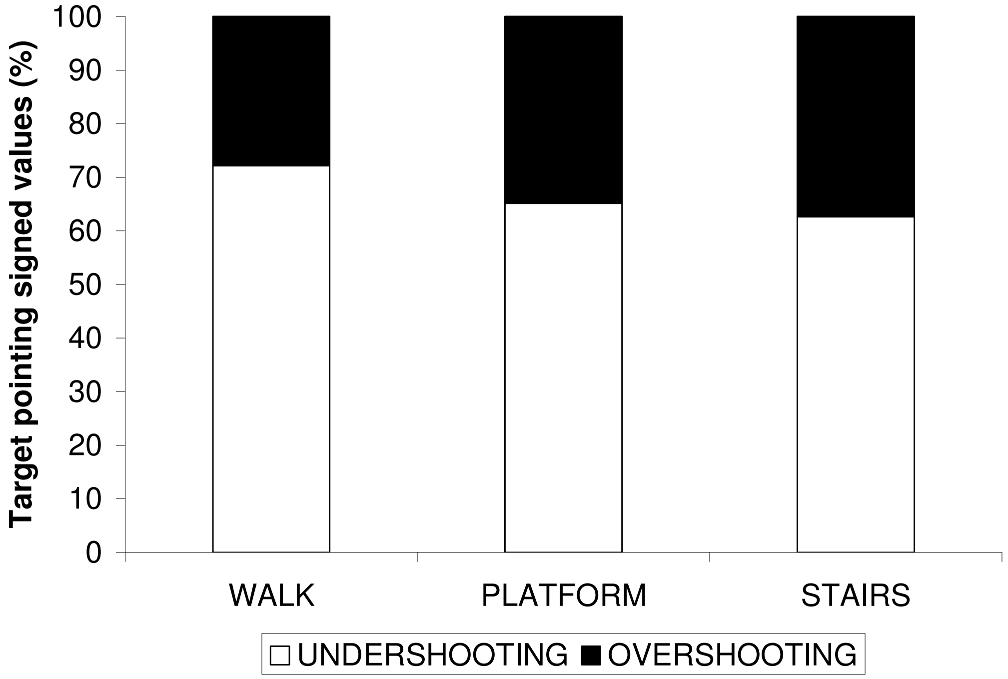


Figure 5.7 Anterior-posterior foot-pointing pattern as a function of task complexity.

5.3.2.2 Medio-Lateral pointing error (absolute values)

The analysis showed a significant main effect of target F (1, 16) = 4.96, p = .041, $\eta^2 = .237$. A significantly larger error was recorded for T1 (M = 11.83 mm, SD = 5.33) as compared to T2 (M = 9.57 mm, SD = 5.97). There was a significant main effect of task complexity. Mauchly's test indicated that the assumption of sphericity has been violated χ^2 (2) = 7.86, p = .020. The degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .808$), F (1.61, 25.86) = 3.89, p = .041, $\eta^2 = .196$. The post hoc test indicated a larger pointing error for the P condition (M = 12.41 mm, SD = 7.34) as compared to the S condition (M = 9.21 mm, SD = 4.18).

The target by task complexity interaction was also significant F (2, 32) = 5.14, p = .012, $\eta^2 = .243$. The post hoc test showed a significantly smaller error for the T2S condition (M = 7.09 mm, SD = 2.96) as compared to both T2W (M = 10.41 mm, SD = 6.07) and the T2P conditions (M = 11.20 mm, SD = 7.45). Moreover, a smaller error was recorded for the T2S condition (M = 7.09 mm, SD = 2.96) as compared to the T1S condition (M = 11.32 mm, SD = 4.21) (Figure 5.8).

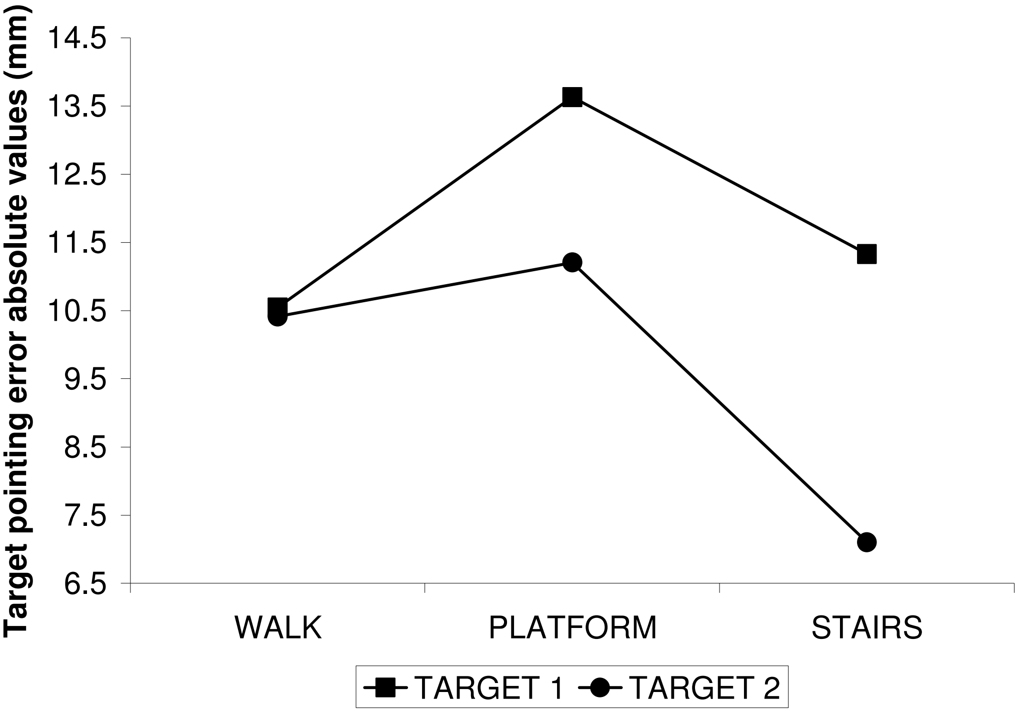


Figure 5.8 Medio-lateral foot-pointing error (absolute values) as a function of target location and PPT complexity.

5.3.2.3 Medio-Lateral pointing error (signed values)

The four-way loglinear analysis Age x Target x PPT Complexity x Pointing Error produced a final model via backward elimination retaining the Age x Pointing and the Target x Pointing interactions as significant factors. The goodness-of-fit test for this model was Pearson χ^2 (16) = 4.67, p = .997 (expected values not different than observed data). Data was collapsed to retain only the two significant interactions.

The Age x Pointing error interaction was significant Pearson χ^2 (1) = 45.71, p< .001. The interaction indicates that the ratio between medially and laterally target pointing was different for young and older adults. Based on the odds ratio calculations, the OA were 2.57 times more likely than YA to point medially at targets. The Target x Pointing error interaction was also significant Pearson χ^2 (1) = 33.92, $p < .001$, revealing that the ratio for medially and laterally target pointing was different for the two targets. The odds ratio calculations indicate that participants were 2.22 times more likely to point medially at the second target as compared to the first target.

5.3.2.4 Relationship between saccade-step latency and foot-pointing outcome patterns

There were small but significant correlations between the saccade-step latency pattern and the sagittal foot-pointing pattern for each target for the older adults group. The phi-coefficient for dichotomous variables was computed for each target. For the first target $r_{\phi} = -.197$, $\chi^2 (1) = 9.41$, $p = .002$ and for the second target $r_{\phi} = -.199$, $\chi^2 (1) = 9.63$, $p = .002$.

5.3.2.5 Step length

The ANOVA analysis revealed a significant main effect of target F (1, 16) = 7.90, p = .013, $\eta^2 = .331$. A longer step was taken prior to pointing at T2 (M = 772.90 mm, SD = 28.43) as compared to pointing at T1 (M = 734.82 mm, SD = 49.80). The age by task complexity interaction was significant as well F (2, 32) =

7.46, $p = .002$, $\eta^2 = .318$. The post hoc test indicated that during the W condition the older adults took a longer pointing step (M = 766.46 mm, SD = 53.19) than did the young adults (M = 738.93 mm, SD = 37.96).

5.3.2.6 Step length variability

There was a main effect of target F (1, 16) = 43.04, $p < .001$, $\eta^2 = .729$. Increased variability was recorded for pointing at T2 (M = 69.78 mm, SD = 13.57), compared to pointing at T1 (M = 47.60 mm, SD = 14.88). In addition, there was a main effect of age F (1, 16) = 8.67, $p = .010$, $\eta^2 = .351$. Increased variability was recorded for YA (M = 63.81 mm, SD = 16.28) as compared to OA (M = 53.57 mm, SD = 18.37).

5.3.2.7 Step width

The target by task complexity interaction was significant F (2, 32) = 3.69, $p = .036$, $\eta^2 = .188$. The post hoc test showed that the pointing step was narrower for the T2S condition (M = 123.82 mm, SD = 30.21) as compared to the T1S condition (M = 134.27 mm, SD = 34.96). The age by target by task complexity interaction was also significant, F (2, 32) = 10.20, $p < .001$, $\eta^2 = .389$. The post hoc test revealed a narrower pointing step for OA during the WT2 condition (M = 123.61 mm, SD = 27) as compared to the WT1 condition (M = 145.37 mm, SD = 43.04).

5.3.2.8 Stance duration variability (non-pointing foot)

The age by target interaction was significant F (1, 16) = 7.53, p = .014, η^2 = .320. The post hoc test indicates that for T1, the OA group had a significantly smaller stance duration variability (M = 0.028 s, SD = 0.008) as compared with YA (M = 0.036 s, SD = 0.014).

5.3.2.9 Swing duration

The analysis showed a significant main effect of target F (1, 16) = 4.97, p = .040, η^2 = .237. A longer swing duration was recorded for T2 (M = 0.674 s, SD = 0.050) as compared to T1 (M = 0.658 s, SD = 0.036).

5.4 Discussion

The main goal of this study was to investigate synchronized gaze and stepping behavior during a locomotor pointing task. The differences between young and older healthy adults as well as the associated changes due to increased task complexity were assessed using a novel technique for head-free gaze computations. The real-time POG (combined head and eye rotation) was derived for several predefined scene planes with different spatial orientations overlapping the entire task configuration.

Three task configurations required participants to navigate a preset environment (i.e., no changes were made after the trial initiation) and point with the forefoot at two targets en route. The task was successfully completed by all participants regardless of age or PPT complexity without visibly altering the gait, hesitating, or tripping. However, our results show age and task complexity-related changes in both gaze behaviour and foot-pointing patterns.

5.4.1 Gaze behavior (qualitative analysis)[8]

Gaze was directed toward relevant environment features and maintained fixation until about foot contact (i.e., gaze anchoring). The pattern of gaze fixations was consistent between trials and participants, and followed each key task landmark in order of occurrence similar to sequential aiming tasks (Neggers & Bekkering, 2002; Wilmut et al., 2006), object manipulation tasks (Johansson et al., 2001; Land & Hayhoe, 2001), and foot-pointing tasks (Chapman & Hollands, 2006, 2007; Hollands et al., 1995; Hollands & Marple-Horvat, 2001; Patla & Vickers, 2003) adding empirical support to the motor equivalence proposal by Georgopoulos and Grillner, (1989) regarding the visuomotor coordination in aiming and locomotion.

Specifically, for the current study setup, first the POG left the offset target fixation at the "GO" command and was shifted sequentially toward the first target (closest to the start location), the second target, then the platform top or the first or second step of the stairs, and finally the door knob. Between saccading away from

---

[8] Participants were instructed to disengage their gaze from the offset target and proceed with the task immediately after the "GO" command. However, this procedure was not set up for a typical reaction time protocol. As such, both the saccade reaction times and target fixation duration parameters were affected and therefore discarded from subsequent data analyses.

one location to the next, the POG was anchored to each location until just before or immediately after foot contact with that particular location of interest. No participant visually scanned the environment before or after initiating the trial. Moreover, during trials, gaze was not shifted between the key task features, indicating that each task sub-movement was planned sequentially in order of occurrence (Figure 5.9).

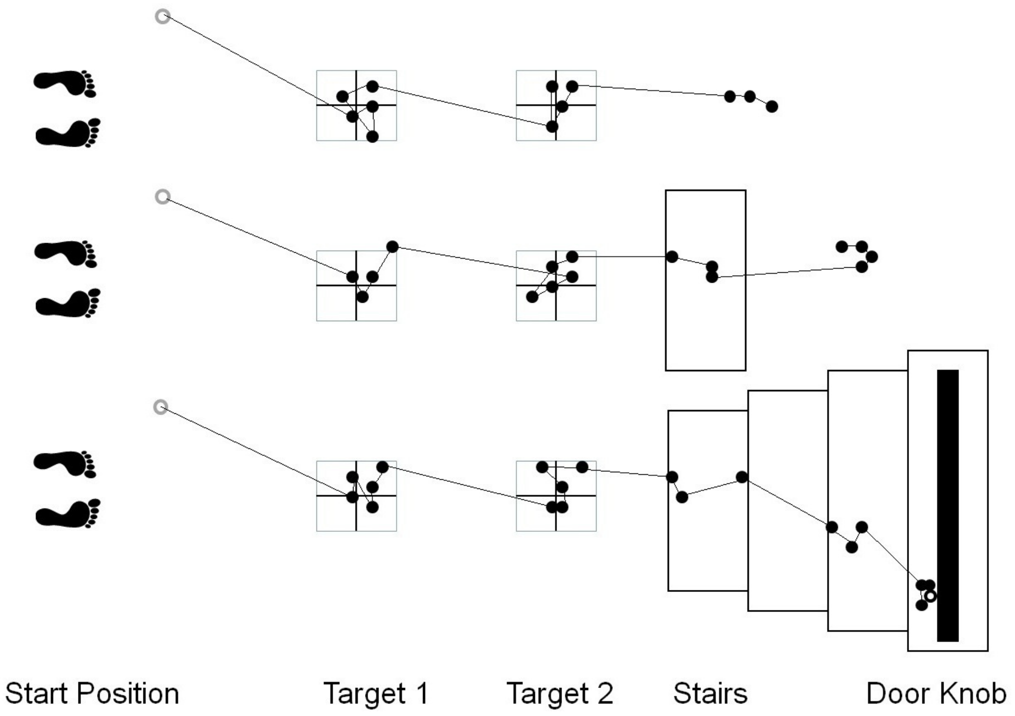


Figure 5.9 Typical single trial depiction of gaze fixation locations for each experimental condition. The empty circle depicts the gaze fixation location before trial initiation; the filled circles represent gaze fixation locations en route. The connecting line between circles shows the order of fixations during the task

The succession of proactive saccades away and fixations is consistent with feed-forward visual control for limb movement. The gaze arrived at the critical environmental features long before the foot-pointing. This proactive gaze behavior provided participants with sufficient time to collect relevant information for planning and implementing stepping adaptations without disrupting the overall walking gait pattern consistent with previous reports (Chapman & Hollands, 2006, 2007; Hollands et al., 1995; Hollands & Marple-Horvat, 2001; Patla & Vickers, 2003).

5.4.2 Saccade-step latency (quantitative analysis)

Healthy individuals perform sequential or manipulative motor tasks without interruptions between movement segments. This necessitates planning of future movements in the sequence while the current sub-movements unfolded. Such strategy benefits from advance visual information for planning and current visual information for guiding limb movement (correcting limb trajectory during movement as needed). Research shows that gaze disengages from the current location just before hand contact without affecting the movement outcome for the hand (Land and Hayhoe, 2001; Wilmut et al., 2001).

In contrast, during locomotor pointing tasks, while the sequential and proactive fixation-saccade pattern maintains a consistent overall walking pace, it has an impact on foot-pointing outcome which is both age- and task-related (Chapman and Hollands, 2006, 2007; Hollands et al., 1995). Of particular interest to this study was the time gap interval between the POG saccade away from a target and foot-pointing contact with that particular target (i.e., saccade-step latency). Recent evidence indicates that premature saccade away relative to foot contact is detrimental for the locomotor pointing performance outcome (Chapman and Hollands, 2006, 2007).

Our results show that the magnitude of the saccade-step latency (absolute values) changes as a function of the PPT complexity. Specifically, the temporal gap between the two events narrows as the PPT complexity increase (i.e., the two events tend to coincide temporally). In order to reveal the pattern showing the exact relationship between the saccade away and foot-pointing, a fine grained analysis was conducted to show whether the gaze shift occurred before or after the foot contact.

We found that young adults were more likely to fixate on targets until after foot contact, unlike older adults, which is consistent with previous reports (Chapman & Hollands, 2006, 2007; Hollands et al., 1995). It is possible that, despite the preset task, target fixation throughout the swing phase until pointing-foot contact provides visual information necessary for the foot guidance. This is consistent with on-line limb control finely tuning the foot trajectory before target pointing. The increase in PPT complexity caused a significant increase in the number of occurrences for saccades away prior to foot contact, regardless of the age group. The current PPT protocol imposed a gait change, presenting a real possibility of tripping going beyond the mere theoretical consequences of missing targets flush with the-floor surface. This may also account for the differences in saccade-latency duration (absolute values) when compared with previous reports made by Chapman and Hollands (2006, 2007). Arguably, the saccade-step latency duration increase is a direct reflection of the change in PPT complexity, impinging on visuomotor transformations needed for the gait change, which overlaps the execution of the foot-pointing task. This corroborates the hypothesis set forth by Chapman and Hollands (2006, 2007).That is, complex adaptive locomotor tasks compel individuals to adopt a gaze strategy (i.e., premature gaze shift) favoring advance step planning in detriment of the current ongoing foot-pointing task execution.

5.4.3 Stepping control and foot-pointing outcome

The experimental protocol required step adaptations beyond the typical naturally occurring stepping during free walking. Participants were able to maintain pointing accuracy and precision in the direction of progression (AP absolute values) consistent with previous results for healthy young and older individuals (Chapman and Hollands, 2006, 2010). Contrary to our hypothesis, participants reduced their absolute M-L pointing error as PPT complexity increase. This contradicts the results of Chapman and Hollands (2006, 2007), which showed that healthy and at-risk-for-falling older individuals demonstrated a decreased accuracy and precision about the target centre in the M-L direction. The explanation for the seemingly contradictory findings could come from task design differences between studies. In contrast with previous reports, the current study had participants point with the forefoot at a visibly marked target center; both landmarks were clearly identifiable to participants thus eliminating possible spatial ambiguity during foot-pointing. In addition, the nature of the task (i.e., collinear task design and the increased space structure due to the PPT) could contribute to a better side-to-side positioning of participants before foot-pointing translated in increased pointing accuracy outcomes. This is corroborated by the fact that although the POG (central vision) was kept on targets, both PPT structures (the platform and the stairs) were within the participants' peripheral visual field during the approach, providing the necessary visual cues for target alignment.

Older adults overshot the target twice as much as young adults. Similar to the saccade-step latency parameter, a complementary analysis on foot-pointing outcomes was conducted to account for the pattern of directional error (signed values). The signed values for the A-P error indicate significant pointing-pattern differences for both the age group and the PPT complexity factors. In addition, the increase in task complexity was accompanied by an increased likelihood of target overshooting as the task progressed from walking continuation (control), to platform stepping, and stair climbing. We interpret target overshooting as indicative of detrimental stepping control. An optimal foot-pointing strategy would maintain a visible target location throughout the movement for possible on-line foot trajectory corrections based on the actual foot-target spatial discrepancies before foot contact. There is evidence that healthy individuals typically undershoot visibly marked targets, preserving the possibility of accurately guiding the pointing foot towards the target (Laurent & Thomson, 1988; Popescu et al., 2010).

The directional pattern of foot-pointing for the ML aspect (signed values) shows that older adults point more medially to targets (i.e., stepping narrow). This also corroborates previous findings despite the underlying computational differences used to derive the signed foot-pointing pattern (Chapman and Hollands, 2006; 2007). An argument was made that the control of the ML aspect of stepping is more problematic in older adults and might be linked to the increased risk of falling in the older adults (Chapman and Hollands, 2006, 2010). Our protocol kept the M-L aspect of target positioning unchanged throughout the data collection. As such, we reserve our judgment until further research, incorporating specific dynamic balance measurements during adaptive locomotion, is available to verify this aspect of locomotor pointing relative to stepping control and dynamic balance correlates derived from free-walking protocols.

Significant step modulations were recorded for the second target prior to foot-pointing before proceeding with the PPT. Regardless of age group or PPT complexity, participants had longer pointing step length and swing duration. Footfall location preplanning during the target approach notwithstanding, we infer that some sort of on-line stepping control likely took place before foot-pointing, consistent with previous reports (Chapman and Hollands, 2007; Popescu et al., 2010).

5.4.4 Relationship between saccade-step latency and foot-pointing performance

Our analysis for saccade-step latency and foot-pointing patterns (signed values) showed similarities for the older adults group. Particularly, the older participants had a tendency to shift gaze away from the targets before foot contact and also had the tendency to overshoot the targets. In light of these two trends, we subsequently found a modest correlation between the two parameters. This suggests that the detrimental foot-pointing outcome may be partly explained by this premature POG transfer away from the ongoing foot-pointing task. Such a relationship between gaze and foot-pointing was previously reported by Chapman and Hollands (2006; 2007), supporting the hypothesis that the older adults require more time to process environmental information to execute precision stepping. In coping with this, the only alternative would be to plan future stepping during the execution of current steps while maintaining forward progression unaltered (i.e., without visibly slowing down or briefly halting). For older individuals prone to falling, the correlation between the premature gaze shift away from the ongoing foot-pointing task and its outcome is much larger. Consequently, a larger proportion of foot-pointing error may be explained by a premature gaze shift (Chapman & Hollands, 2006; 2007). Although our results indicate comparable absolute foot-pointing values irrespective of age group, the change in gaze strategy and the resulting foot-pointing outcome may constitute an intermediate phase, signaling future and more dramatic changes in visual sampling requirements for adaptive locomotor control in the older adults.

5.4.5 Conclusion

The novel head-free gaze computation allowed matching the experimental task with daily encountered adaptive locomotor tasks. Invariably the POG arrives at key environmental locations ahead of the foot during locomotor pointing tasks following each key task feature in a sequential order. The POG remains anchored almost until the foot contacted the target. The occurrence of premature POG disengagement from targets increases with age and task complexity, negatively reflecting on the foot-pointing outcome. These findings show subtle changes in visual sampling and stepping control in healthy older adults, and we interpret them as being a precursor of more dramatic changes in visuomotor control with aging. We propose that future research should attempt the investigation of causal relationships between the spatio-temporal gaze and stepping control during foot-pointing tasks. Such findings may be utilized in applied settings for rehabilitation protocols and retirement house interior design.

5.5 References

Chapman, G. J., & Hollands, M. A. (2006). Evidence for a link between changes to gaze behavior and risk of falling in older adults during adaptive locomotion. *Gait & Posture,* 24, 288-294.

Chapman, G. J., & Hollands, M. A. (2007). Evidence that older adult fallers prioritize planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait & Posture,* 26, 59-67.

Chapman, G. J., & Hollands, M. A. (2010). Age-related differences in visual sampling requirements during adaptive locomotion. *Experimental Brain Research,* 201, 467-478.

Elliott, D., Hansen, S., Grierson, L. E. M., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010).Goal-directed aiming: Two components but multiple processes. *Psychological Bulletin,* 136 (6), 1023-1044.

Folsten, M. F., & Folsten, S. E., & McHugh, P. R. (1975). "Mini-Mental State" A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research,* 12, 189-198.

Georgopoulos, A. P., & Grillner, S. (1989). Visuomotor coordination in reaching and locomotion. *Science,* 245, 1209-1210.

Ginsburg, A. P. (1984). A new contrast sensitivity vision test chart. *American Journal of Optometry and Physiological Optics,* 61, 403-407.

Goodale, M. A., Pelisson, D., & Prablanc, C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature,* 320, 748-750.

Helsen, W. F., Elliott, D., Starkes, J. L., & Ricker, K. L. (1998). Temporal and spatial coupling of point of gaze and hand movements in aiming. *Journal of Motor Behavior,* 30 (3), 249-259.

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., & Marple-Horvat, D. E. (2001). Coordination of eye and leg movements during visually guided stepping. *Journal of Motor Behavior,* 33 (2), 205-216.

Johansson, R. S., Westling, G., Backstrom, A., & Flanagan, J. R. (2001). Eye-hand coordination in object manipulation. *The Journal of Neuroscience,* 21 (17), 6917-6932.

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

Land, M. F. (2009). Vision, eye movements, and natural behavior. *Visual Neuroscience,* 26, 51- 62.

Laurent, M., & Thomson, J. A. (1988). The role of visual information in control of a constrained locomotor task. *Journal of Motor Behavior,* 1, 17-37.

Lee, D. N. (1978). The functions of vision. In H. L. Pick jr. and E. Saltzman (Eds.). *Modes of perceiving and processing information* (pp. 159-170). Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers.

Neggers, S. F. W., & Bekkering, H. (2002). Coordinated control of eye and hand movements in dynamic reaching. *Human Movement Science,* 21, 349-376.

Patla, A. E. (1997). Understanding the roles of vision in the control of human locomotion. Gait & Posture 5, 54-69.

Patla, A. E. (2004). Gaze behaviors during adaptive human locomotion: Insights into how vision is used to regulate locomotion. In Vaina, L. M., S. A. Beardsley, and S. K. Rushton (Eds.) *Optic Flow and Beyond* (pp. 383-399). Netherlands: Kluwer Academic Publishers.

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, 3361-3365.

Patla, A. E., & Vickers, J. N. (2003). How far do we look when required to step on specific locations in the travel path during locomotion? *Experimental Brain Research,* 148, 133-138.

Podsiadlo, D., & Richardson, S. (1991). The Timed "Up & Go": A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society,* 39, 142-148.

Popescu, A., Runnalls, K., & Maraj, B. K. V. (2010). Intermittent visual information affects motor strategies during locomotor pointing. *International Journal of Sport Psychology,* 41, 313-326.

Schutz, R. (1977). Absolute, constant, and variable error: Problems and solutions. In Mood, D. (Ed.) *The measurement of change in physical education: Proceedings of the Colorado Measurement Symposium* (pp. 82-100). Boulder, CO.

Thomson, J. A. (1980). How do we use visual information to control locomotion? *Trends in Neuroscience,* 3, 247-250.

VCTS application manual (1988). VISTECH Consultants, Inc., Dayton, OH. Retrieved on April 2nd, 2009 from http://www.agingeye.net/cataract/Vistech2.pdf

Wilmut, K., Wann, J. P., & Brown, J. H. (2006). How active gaze informs the hand in sequential pointing movements. *Experimental brain Research,* 175, 654-666.

6. General Discussion

6.1 Overview and research contributions

This work was concerned with the role played by vision during adaptive locomotion. Healthy participants walked towards and stepped on targets embedded at the end of an unconstrained approach. Specifically, the tasks were designed to measure the foot-pointing error about the center of a target as participants were engaged in adaptive locomotor tasks varying in difficulty or complexity under intermittent or full vision. This particular form of adaptive locomotor behaviour, requiring precise foot placement about predetermined locations, has become known as locomotor pointing. Such tasks fall under the category of accommodation strategies behaviour as opposed to that of avoidance strategies (e.g. clearing an obstacle in the travel path) according to the taxonomy proposed by Aftab Patla (1991).

The four experiments presented here employed all three paradigms typically employed for investigating the role of vision during goal-directed movement: intermittent vision, voluntary, self-sampled intermittent vision, and gaze behavior (the saccade timing and the fixation location). In addition, in order to systematically account for the influencing constraints on achieving the locomotor task goal, this work followed the ecological task analysis model for the experimental series designing (Burton & Davis, 1996; Davis & Burton, 1991; Newell, 1986). As such, the individual (age group), the task constraints (difficulty and complexity), and the environment (intermittent visual sampling) were manipulated in order to observe their effect on locomotion control. Consequently, this approach allowed for past research findings replication as well as extending the knowledge on locomotor pointing by filling some of the literature gaps. The novelties reported in this work are outlined next.

The results show for the first time that locomotor pointing tasks may be independently classified based on task difficulty (Study two) or complexity (Studies three and four). To my knowledge there is no other published research to provide evidence that the feed-forward locomotor control strategy is well preserved in healthy older adults during both full vision and intermittent vision conditions (Study three). In addition, a new technique was developed for deriving head-free gaze during locomotion using real-time integration of head and eye rotation throughout the task (Study four). This allowed for POG recording in several geometric planes having different spatial orientations. Finally, we report both locomotor pointing and saccade-step latency patterns (Studies two, three, & four). This way the inter-subject variability data was preserved and data cancellation during the process of averaging signed data sets was avoided.

Similar tasks were employed for all four studies. Participants had to walk in a straight line at a self-selected pace and accurately point with the fore-foot at the marked center of one target embedded at the end of the walkway (Studies one, two, & three) or two targets placed en route (Study four). The aim of the first study was to investigate the effect of intermittent visual information on locomotor control strategies and foot-pointing outcome. The second study looked at how locomotor pointing is affected by changing the task difficulty under intermittent visual sampling conditions. The externally controlled intermittent visual conditions were employed to probe the visuomotor control strategies. At the same time we tried to replicate daily encountered situations whereby brief shifts in attention would direct gaze away from the ongoing adaptive locomotor task. The third study in the sequence employed the self-sampling vision in order to answer precisely when and for how long vision would be necessary to complete locomotor pointing tasks of increased complexity as well as making direct comparisons between healthy young and older individuals. Finally, study four examined the differences in gaze behaviour between young and older adults and the associated changes in stepping control while performing locomotor tasks varying in complexity levels.

The overall discussion section will cut through the four experiments. The findings are grouped based on the topics of interest to this work. The next five different headings will cover findings regarding the locomotor control strategies (feed-forward and on-line), how visual information was sampled during the task (intermittent visual sampling and gaze behaviour), the foot-pointing outcome (average values and pointing pattern), and, finally, the visuomotor changes occurring during biological aging.

6. 2 Locomotor control strategies during adaptive locomotion

6.2.1 Participants adopted a feed-forward stepping control strategy during target approach

While approaching targets embedded at the end of an unconstrained walkway, all participants regardless of age group and experimental manipulation adopted a proactive locomotor control mechanism. This strategy (i.e., step planning) allowed for timely footfall adjustments optimally positioning participants for target pointing. In doing so, participants dispersed their footfall adjustments over several consecutive steps without disrupting the forward gait progression.

Typically, the footfall variability (the standard deviation of footfall location relative to the target center for each step across trials) would increase in the direction of locomotion progression and would dramatically decrease at target proximity while navigating stable environments. Similar locomotor control strategies were reported for field events (Lee, Lishman, & Thomson, 1982; Maraj, 2002; Renshaw & Davids, 2006) with only one published report for lab-confined adaptive walking tasks (Laurent & Thomson, 1988). We were able to replicate and extend these findings (Studies one & two) and report, for the first time, that such locomotor strategy is well preserved in healthy older individuals (Study three).

6.2.2 Participants also employed on-line stepping corrections during the pointing step to accommodate the highly constraining task demands

The timely stepping modulations initiated two or three steps prior to target pointing were typically augmented by guiding the foot during the last pointing step. This “fine tuning” control mechanism for precision stepping is necessary for highly constraining limb positioning tasks like the ones employed for this set of experiments. For the case where the task allowed for an unconstrained target approach (Studies one, two, & three) as well as for the target immediately preceding the post pointing task (Study four) results indicate step modulations taking place during the pointing step.

The studies reported here used kinematics measures to infer on-line control strategies. The results were augmented by supporting evidence from visual sampling and gaze behavior strategies. The findings from the self-sampled vision protocol (Study 3) reveal the fact that, although the overall sampling strategy varies, vision was consistently made available during the last step prior to target pointing. Moreover, gaze was fixated (anchored) on the targets until about the foot contact with that target took place (Study 4). Taken together, these results indicate that perceptual and locomotor control systems work in a flexible and coordinated manner to allow for the implementation of on-line stepping control as well.

The on-line stepping control strategy had been reported for highly constraining foot targeting tasks when vision was available during the step

(Reynolds & Day, 2005a**;** Chapman & Hollands, 2006). A more direct line of evidence comes from protocols employing sudden task changes during one step (Reynolds & Day, 2005b; Perry & Patla, 2001).

One inherent design limitation for locomotor pointing tasks with an unconstrained target approach regardless of visual manipulations is step footfall pre-planning. That is, step modulations may be planned at any location during the target approach and only executed during the pointing step. This may well be the case for adaptive locomotor tasks performed in stable environments (Studies one, two, three, & four). However, the findings derived from visual sampling based on need (Study three), the gaze pattern location, and saccade-step relationship, clearly show that visual information is sampled during the last step before foot-pointing. In addition, it has been reported that healthy individuals are capable of performing and implementing rapid visuomotor transformations for stepping modulation (Reynolds & Day, 2005b; Perry & Patla, 2001). Taken together, these results indicate the existence of robust and flexible perceptual and locomotor systems in healthy individuals.

6. 3 Visual information during adaptive locomotion

6.3.1 Discrete visual sampling is adequate during adaptive locomotion

Brief duration visual samples during target approach were sufficient for completing the task. The studies reported here employed intermittent visual sampling conditions to probe the visuomotor control strategies and mimic real-life encounters requiring brief instances of attention shifts from the ongoing locomotor task.

Vision was used proactively to plan stepping location (i.e., feed-forward control). As indicated by the rather similar magnitude of accumulated footfall variability during the three visual conditions, there was no preferred location for a visual sample during the gait cycle (Studies one & two). Moreover, when participants had full control over the visual sampling intervals, there was no clear pattern between the visual sample initiation and a specific gait event (Study three).

These findings are consistent with the fact that visual resources are shared during locomotion (Chapman & Hollands, 2006, Laurent & Thomson, 1988; Patla, 1997). Brief gaze shifts concurrently occur during walking as individuals occasionally scan the environment for orientation purposes or maintain eye contact while conversing.

The flexibility of the perceptual and locomotor systems was reflected in the fact that participants adopted a different control strategy for the intermittent vision conditions as compared with full vision conditions. They maximized the available visual sampling opportunities by slowing down the target approach (Study one) as well as lengthening the last adaptive step (Study one & three). Furthermore, during the self-sampling paradigm (Study three), half of the participants changed their sampling strategy during the approach.

When participants had control over the visual sampling location and duration, the total visual sample amounted to less than half of the trial duration, irrespective of the task complexity or the participant's age (Study three). This finding clearly indicates that continuous visual information is not necessary during adaptive locomotion for healthy individuals. Although different visual sampling strategies were recorded, the vast majority of them consisted of one or two samples with vision made available almost all the time during the pointing step.

6.3.2 Gaze behaviour characteristics for foot-pointing share similarities with goal-directed aiming tasks supporting the notion of motor equivalence for target-directed movements

Gaze was deployed towards key task landmarks before foot-pointing providing the possibility of using this information in a predictive way to make proactive stepping adjustments (i.e., feed-forward control). Gaze remained anchored until about limb contact with that particular landmark. This also provided participants with the necessary information to implement stepping adaptation (i.e., on-line control) while maintaining the overall locomotor pattern largely unchanged. The premature saccade-away from the target during the ongoing foot-pointing task was related to detrimental pointing-task outcome (Study four). Premature gaze disengagement with the target denies the necessary visual information for guiding the foot to the pointing location. Older individuals had a significant likelihood of prematurely saccading-away which was related to target overshooting. Similar results were recently reported by Chapman and Hollands (2006, 2007) especially for older individuals presenting an increased risk for falling.

As the results show, both the on-line and feed-forward control strategies were used by participants in combination based on the need to address the task challenges. Previous reports using mathematical modeling showed that gait adaptations are based on need (deRugy, Montagne, Buekers, & Laurent, 2000). These findings were replicated during adaptive locomotion in a virtual environment (deRugy, Taga, Montagne, Buekers, Laurent, 2002). That is, individuals would initiate stepping modulations if the perceived target distance exceeded a certain expected error threshold. These findings were found to hold during field events like long jumping (Montagne, Cornus, Glize, Quaine, & Laurent, 2000) and longer cricket bowling approaches consisting of two visually regulated phases during one trial (Renshaw & Davids, 2006).

6. 4 Foot-pointing outcome

The foot-pointing outcome measures were used to gauge the effectiveness of implementing various locomotor strategies to overcome the imposed constraints impinging on the adaptive locomotor task.

Regardless of the task setup, participants typically undershot the target. The first study (Study one) was designed to replicate and extend the few existing lab reports regarding the role of visual control for distant embedded foot-pointing constraints. Young and healthy participants maintained the foot-pointing outcome parameters despite intermittent visual sampling during target approach consistent with the pioneering report of Laurent & Thomson (1988).

The experiments were designed specifically to observe foot-pointing correction made in the direction of locomotion progression (A-P direction). Corrections were necessary due to the accumulation of naturally occurring small inconsistencies (Studies one & two) as well as the random target location change during trials (Studies three & four).

6.4.1 Task difficulty and complexity effects are reflected in the foot-pointing outcome

Studies two, three, and four were designed to assess the impact of the task nature on locomotor pointing outcome. Specifically, the second study in the sequence (Study two) modified the target size to increase task difficulty whereas studies three and four (Studies three & four) manipulated the post pointing task complexity while maintaining the size of the target constant. Additionally, for these three studies, both the anterior-posterior (A-P) and the medio-lateral (M-L) pointing aspects were considered.

Task difficulty affected the foot-pointing outcome: the mean absolute constant error (A-P) increased for the small target (Study two). This is consistent with previous reports (Bradshaw & Sparrow, 2000; Drury & Woolley, 1995) considering adaptive locomotion from a speed-accuracy trade-off standpoint consistent with Fitts' law (Fitts, 1954, reprinted 1992). The last swing duration as well as the last step length were similar across conditions, decreasing the pointing task accuracy.

In line with the first study and previous reports (Laurent & Thomson, 1988) there was no vision manipulation effect on the AP foot-pointing aspect (Studies two, three, & four). However, the lack of vision during the pointing step increased the mean absolute constant error (M-L) regardless of task difficulty. This discrepancy between the pointing accuracy and consistency, and the experimental conditions implies independent stepping-control mechanisms (Gabell & Nayak, 1984; Brach, Perera, Studenski et al., 2008). It was proposed that the stepping-pattern control mechanism (including the step length) was linked with the planning and execution of adaptive steps. The first study results support this due to the increase in task difficulty which would impose higher constraints to such cognitive processes. Conversely, the balance control mechanism (step width) was associated with sensory deficits represented by the intermittent visual manipulations. The post-pointing task complexity (PPT) was reflected in the ML pointing aspect exclusively (Studies three & four). Specifically, the presence of the post-pointing structure at the end of the walkway increased the pointing outcome accuracy and consistency. We interpret this as being the effect of the collinear task design allowing participants to make use of visual cues from the structures' edges, contributing to a better side-to-side positioning prior to target pointing.

6.4.2 Absolute constant error versus signed foot-pointing pattern

The mean absolute constant error pointing values were reported in order to avoid the possibility of underestimating the average pointing bias between groups of signed data sets (Schutz, 1977). In addition, a finer grain analysis was carried out with regard to the foot-pointing pattern. In order to establish the signed foot-pointing error patterns as well as to preserve the naturally occurring inter-trial and inter-subject variability, statistical analyses were carried out on the signed pointing data values as well.

The increased task difficulty (smaller target size) generated a significant target overshooting pattern in the A-P direction for the young participants (Study two). This foot-pointing outcome pattern was similar to the findings for the older participants (results expounded in the next section). In addition, the increase in PPT complexity effect was related to the foot-pointing pattern in the A-P direction as well (Study four). Specifically, participants were more likely to overshoot the target as the PPT complexity increased from simply continuing to walk (the control condition) to platform stepping and to stair climbing respectively.

These results may be interpreted as signs of a detrimental stepping-control strategy. As shown in the previous section, the possibility of making corrections during the last swing prior to foot-pointing significantly reduces the error outcome. The nature of the pointing task throughout this work argues for visual feedback cues during the last swing (Steenhuis & Goodale, 1988). As such, the expected foot-pointing behaviour was to increase the safety margin and undershoot the target while preserving the opportunity to make visually guided swing corrections. Target overshooting would block the sight of the target's center depriving participants of the required cues for on-line foot guidance. In addition, a consistent overshooting foot-pointing pattern was recorded for older adults as well (Studies three & four). These findings are detailed in the next section.

6. 5 Aging and adaptive locomotion

6.5.1 Older adults preserve the typical locomotor control strategies while showing detrimental foot-pointing patterns

The locomotor control strategies (feed-forward and on-line), as well as the visual sampling characteristics and gaze pattern, are highly similar regardless of the age groups (Studies three & four). However, despite these well preserved behaviours, results show that older adults have a detrimental foot-pointing pattern outcome when compared with their young counterparts. They have a significant tendency to overshoot and point more medially (i.e., stepping narrow) at targets. This foot-pointing pattern was found under both self-sampled intermittent vision (Study three) and full vision conditions (Study four). As pointed out before, overshooting the pointing location automatically denies the chance of visually-guided foot trajectory which is an important control strategy for fine-tuning footfall location on target for highly constraining locomotor pointing tasks. The negative connotation attached to a medially pointing pattern stems from its impact on dynamic balance associated with an increased risk of falling in the older adults (Chapman & Hollands, 2010). It is prudent to postpone such functional significance attribution due to experimental design limitations.

6. 6 Conclusion

This work clearly demonstrates the existence of specific locomotor strategies related to adaptive locomotion for accommodative tasks (i.e., locomotor pointing). Specifically, healthy individuals use a combination of feed-forward (future step planning) and on-line (current step guidance) control in order to make accurate foot contact with a target. These locomotor control strategies are predominantly regulated by means of visual information. Visual sampling patterns (duration and location) as well as gaze fixation location patterns, are very similar from one age group to the next, and are highly consistent with the environmental setup. Significant differences between age groups were recorded for saccade-step latency and the resulting foot-pointing outcome patterns. Older adults disengage prematurely from the targets and show an increased likelihood of overshooting the targets. Overall, healthy individuals preserve robust and flexible perceptual and locomotor control mechanisms. The findings regarding ageing differences between gaze and foot-pointing may be interpreted as a sign indicating future and naturally-occurring detrimental changes in visuomotor control for adaptive locomotion.

6.7 Limitations

The results of these four studies are consistent and the participants who engaged in performing the respective locomotor tasks changed from study to study. The findings are also consistent with previous reports. Despite this, there are limitations due to design and sampling procedures that argue for caution in generalizing the results.

Each study used a relatively small sample size of volunteers. The experimental tasks were designed to mimic the daily adaptive locomotor tasks encounters for stable environments. As such, participants were familiar with the tasks and this familiarity could have influenced or masked some of the outcomes. In addition, the tasks design only imposed adaptive constraints in the direction of locomotor progression. Although significant effects on the lateral foot-pointing components were found, more testing is needed before a definitive conclusion may be drawn. Finally, there are limitations concerning the adopted screening tests comparing the health status of the age groups. Arguably, additional tests are necessary to reveal a more accurate participants' status, including clinical evaluations testing executive functioning and the attentional status.

6.8 Future directions

The findings reported in this work can be used to extend the knowledge base on the control of adaptive locomotion by incorporating variables including but not limited to ambient lighting condition, walking surface characteristics, and attentional capacity effects during a dual-tasks paradigm testing. Also, steps need to be taken in order to close an evident gap in the literature regarding the on-line stepping control phase and the time frame necessary to plan and implement step changes. To establish a causal relationship, the target location has to suddenly change during approach or the last swing (Reynolds & Day, 2005; Chapman & Hollands, 2010).

A different line of future research direction extending our findings pertains to intervention strategies. Adaptive locomotor tasks can be specifically designed to retain similar levels of difficulty and/or complexity with common daily locomotor tasks. They may be used as screening tools for identifying at-risk individuals. Conversely, the known gait adaptation limitations may be used for interior design purposes to prevent or minimize the environment complexity. Finally, besides screening protocols and interior design benefits, another application of results can lead to designing training protocols for specific intervention groups (Young & Hollands, 2010).

6. 9 References

Brach, J. S., Studenski, S., Perera, S., VanSwearingern, J. M., Newman, A. B. (2008). Stance time and step width variability have unique contributing impairments in older persons. *Gait & Posture,* 27, 431-439.

Bradshaw, E. J., & Sparrow, W. A. (2000). The Speed-Accuracy trade-off in human gait control when running toward targets. Journal of Applied Biomechanics 16, 331-341.

Burton, A. W. & Davis, W. E. (1996). Ecological task analysis utilizing intrinsic measures in research and practice. *Human Movement Science,* 15, 285-314.

Chapman, G. J., & Hollands, M. A. (2006). Age-related differences in stepping performance during step cycle-related removal of vision. *Experimental Brain Research,* 174, 613-621.

Chapman, G. J., & Hollands, M. A. (2006). Evidence for a link between changes to gaze behavior and risk of falling in older adults during adaptive locomotion. *Gait & Posture,* 24, 288-294.

Chapman, G. J., & Hollands, M. A. (2007). Evidence that older adult fallers prioritize planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait & Posture,* 26, 59-67.

Chapman, G. J., & Hollands, M. A. (2010). Age-related differences in visual sampling requirements during adaptive locomotion. *Experimental Brain Research,* 201, 467-478.

Davis, W. E. & Burton, A. W. (1991). Ecological task analysis: Movement behavior theory into practice. *Adapted Physical Activity Quarterly,* 8, 154-177.

deRugy, A., Montagne, G., Buekers, M. J., & Laurent, M. (2000). The control of human locomotor pointing under restricted informational conditions. *Neuroscience Letters,* 281, 87-90.

de Rugy, A., Taga, G., Montagne, G., Buekers, M. J., & Laurent, M. (2002). Perception-action coupling model for human locomotor pointing. *Biological Cybernetics* 87, 141-150.

Drury, C. G. & Woolley, S. M. (1995). Visually-controlled leg movements embedded in a walking task. *Ergonomics,* 38, 4, 714-722.

Fitts, P. M. (1992). The information capacity of the human motor system in controlling the amplitude of movement (Reprint). *Journal of Experimental Psychology: Human Perception and Performance: General* 121 (3), 262-269.

Gabell, A. & Nayak, U. S. L. (1984). The effect of age on gait variability. *Journal of Gerontology,* 39 (6), 662-666.

Laurent, M., & Thomson, J. A. (1988). The role of visual information in control of a constrained locomotor task. *Journal of Motor Behavior* 20 (1), 17-37.

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

Maraj, B. K. V. (2002). Control and co-ordination in the triple jump. In K. Davids, Savelsbergh, G., & Bennett, S. J. (Eds.) *Interceptive actions in sport: Information and movement* (pp. 334-342). New York: Routlege.

Montagne, G., Cornus, S., Glize, D., Quaine, F., & Laurent, M. (2000). A perception-action coupling type of control in long jumping. *Journal of Motor Behavior* 32 (1), 37-43.

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade and H. T. A. Whiting (Eds.). *Motor development in children: Aspects of coordination and control* (pp.341-360). Dordrecht, the Netherlands: Martinus Nijhof Publishers.

Patla, A. (1991). Visual control of human locomotion. In A. E. Patla (Ed). *Adaptability of human gait* (pp. 55-97). Amsterdam: Elsevier.

Patla, A. (1997). Understanding the roles of vision in the control of human locomotion. *Gait & Posture 5*, 54-69.

Perry, S. D. & Patla, A. E. (2001). On-line adjustments to body center of mass and limb elevation to suddenly changing obstacle height. In J. Duysens, Smits-Engelsman, B. M., & Kingma, H. (Eds.), *Control of posture and gait* (pp. 485-487). Maastricht, Netherlands.

Renshaw, I., & Davids, K. (2006). A comparison of locomotor pointing strategies in cricket bowling and long jumping. *International Journal of Sport Psychology* 37, 1-20.

Reynolds, R. F., & Day, B. L. (2005a).Visual guidance of the human foot during a step. *Journal of Physiology,* 569 (2), 677-684.

Reynolds, R.F. & Day, L. B. (2005b). Rapid visuo-motor processes drive the leg regardless of balance constraints. *Current Biology,* 15 (2), R48-R49.

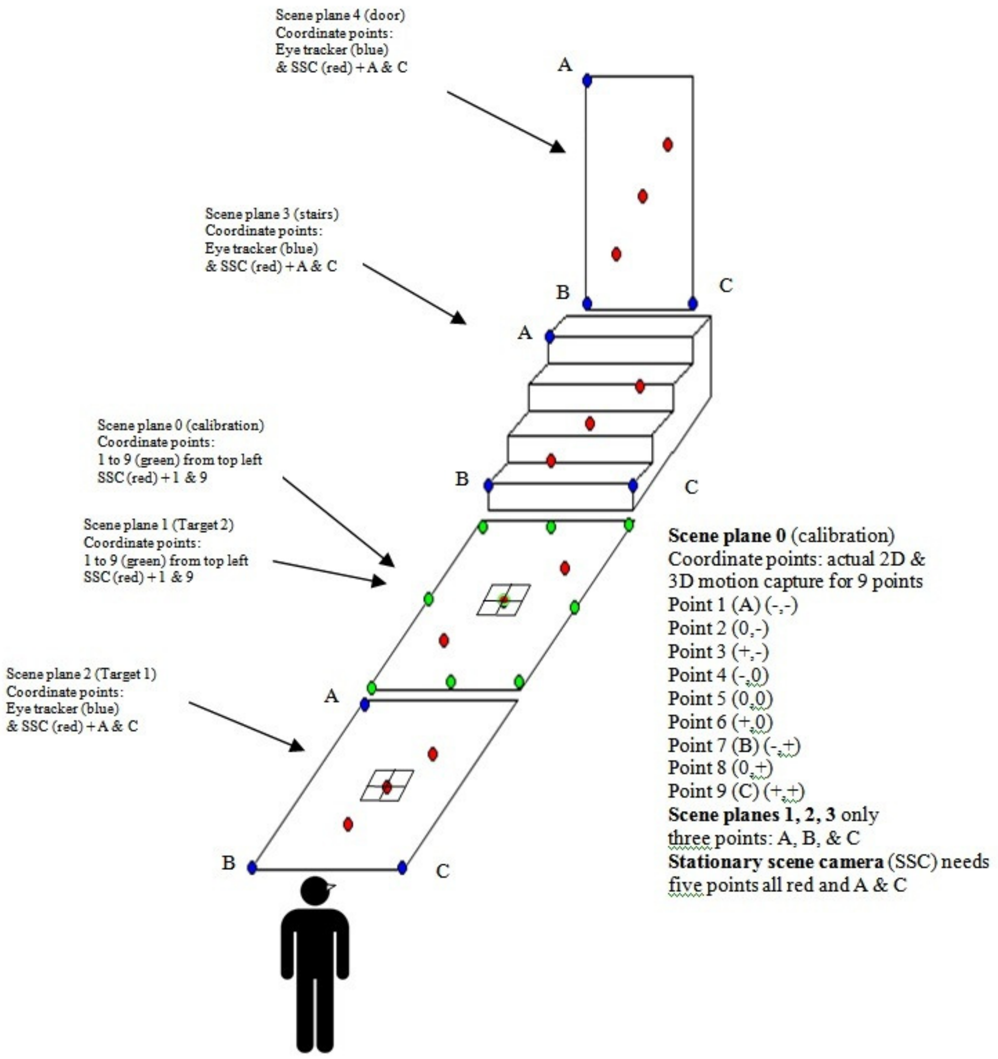
Schutz, R. (1977). Absolute, constant, and variable error: Problems and solutions. In Mood, D. (Ed.) *The measurement of change in physical education: Proceedings of the Colorado Measurement Symposium* (pp. 82-100). Boulder, CO.

Steenhuis, R. E., & Goodale, M. A. (1988). The effect of time and distance on accuracy of target-directed locomotion: Does an accurate short-term memory for spatial location exist? *Journal of Motor Behavior,* 20 (4), 399-415.

Young, W. R. & Hollands, M. A. (2010). Can telling older adults were to look reduce falls ? Evidence for a causal link between inappropriate visual sampling and suboptimal stepping performance. *Experimental Brain Research,* 204, 103-113.

7. **Appendix**

Eye-tracking integration



Experimental task diagram showing the superimposed eye tracker scene planes and the corresponding 2D (eye tracker) and 3D (motion capture system) coordinates.

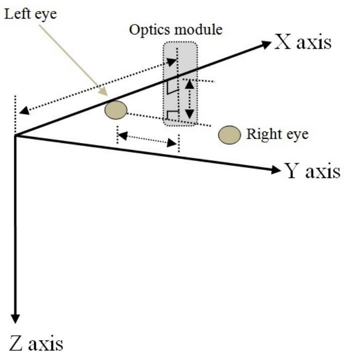
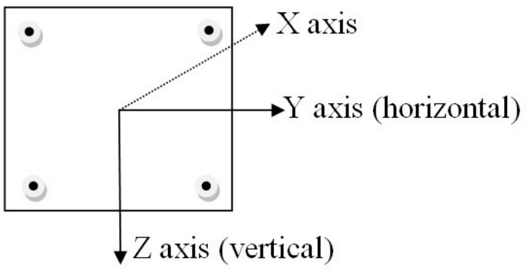
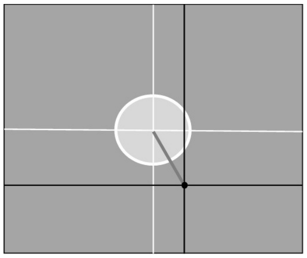


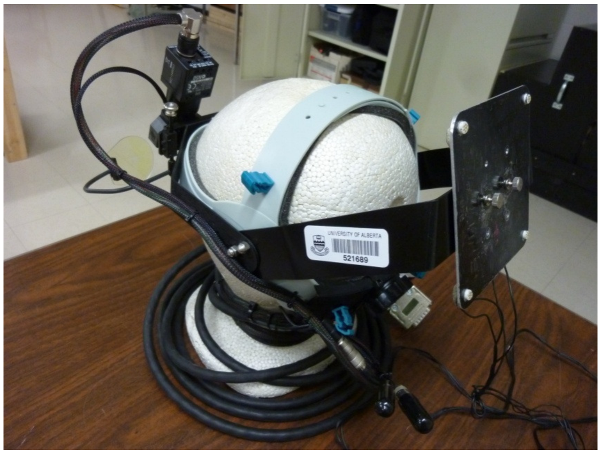
Diagram for the sensor-to-eye (optics module) orientation (adapted from Applied Science Laboratories, Bedford, MA)



Spatial orientation diagram for the rigid body. The RB depicted as attached to the eye-tracker headband. The four LED markers are located at the corners of the rigid body.



The eye tracker uses a bright pupil method and measures the vector between the center of the pupil (light crosshairs) and the corneal reflection center (dark crosshairs). The vector magnitude and orientation changes with each subject and task setup requiring eye calibration before data collection.



The HS-H6 monocular head-mounted mobile eye tracker (Applied Science Laboratories, Bedford, MA). The rigid body is attached behind the head and the optics module is located in front of the left eye.