ABSTRACT

SHEIK NAINAR, MOHAMED ASHRAF. Development and Empirical Assessment of a Model of Situation Awareness for Multitasking with Locomotion. (Under the direction of David B. Kaber and Simon M. Hsiang).

Human locomotion has long been considered an overly practiced motor behavior. However, recent research has revealed a demand of locomotion on attentional resources, especially when performed during multitasking. Situation Awareness (SA), a cognitive construct critical to decision making and performance in complex tasks, has been shown to be important while multitasking with cognitive and physical workloads. No research has been conducted on the role of SA during locomotion with perturbations (e.g., slips and trips) and concurrent cognitive task performance (e.g., walking and talking on cell phone).

The primary objective of this research was to develop a model of SA for multitasking with locomotion and conduct an empirical study to assess the validity of the proposed model for explaining proactive gait control in response to locomotion hazards. To support the empirical work, a virtual reality locomotion interface (VRLI) was developed to present walkers with realistic virtual locomotion environments (VLE) similar to everyday locomotion activities. An initial version of the VRLI consisted of a computer controlled treadmill, a head mounted display (HMD), and a graphical workstation running the VLEs and controlling the treadmill, based on participant movement using motion tracking sensors. The VRLI setup was validated through a pilot study that compared overground walking with treadmill walking in a VLE. Results showed similarities in walking characteristics between the conditions. Based on the pilot study, further enhancements were made to the setup. These included using a rear projection screen with a stereo projector and light-shutter goggles and a new treadmill with an embedded force plate

(under the treadmill belt) for collecting gait ground reaction forces (GRF) and center of pressure (COP) data.

Using the enhanced VRLI, an experiment was conducted to evaluate the utility of SA during locomotion and validate the proposed model of SA for proactive gait control for responding to locomotion hazards. In this experiment, the controlled variables included navigation aid type (NT), a priori knowledge (AK) and perturbation cueing (PC). NT consisted of two levels – map-based navigation (MBN) and instruction-based navigation (IBN) and was manipulated between-subjects. AK consisted of three levels, low, medium and high, and was also manipulated between-subjects. The AK manipulation involved controlling the initial exposure of the walker to the test VLE and hence controlled their mental model development on the task environment. The low AK group was trained with a low fidelity VLE while the medium AK and high AK groups were trained with a high-fidelity VLE, but only the latter group experienced a perturbation. The PC variable was manipulated within-subjects and it consisted of combinations of visual cueing and physical cueing of locomotion hazards forming four levels – visual only, physical only, visual plus physical and no cueing. Dependent variables measured included a battery of GRF and COP variables along with response accuracy to SA probes presented using a real-time probing technique. Twelve males and twelve females from the NCSU student population participated in the experiment and performed the navigation task following four different routes in the VLE.

Results revealed participant proactive preparation for locomotion hazards, as observed through significant changes in GRF and COP measures. Effects included the nature of cueing of the perturbation and prior exposure to a trial with a perturbation involving visual cueing. There was also complex interactions between NT, AK and PC that revealed greater participant proactive control during MBN with higher AK under visual plus physical cueing compared to

IBN with lower AK under visual only cueing. SA accuracy under MBN was higher for probes requiring subjects to project VLE future states, as compared to IBN.

Analysis of correlations between SA performance and gait response measures in five strides leading up to participants encountering perturbations revealed a negative relationship between SA and weight acceptance force (at heel strike) with each stride closer to the perturbation. The correlation was also significantly affected by the manipulated variables (NT, AK and PC) and their higher order interactions. The study revealed that higher SA performance was associated with greater proactive control (decreased weight acceptance – flat footed walking). The results provided preliminary empirical validation for the proposed model of SA for multitasking with locomotion. Further experimental studies need to be conducted for a more detailed investigation of the relationship of SA with specific proactive gait control (e.g., accommodating, avoiding) as well as predictive and reactive gait control mechanisms under multitasking situations.

DEVELOPMENT AND EMPIRICAL ASSESSMENT OF A MODEL OF SITUATION AWARENESS FOR MULTITASKING WITH LOCOMOTION

By

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A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the requirements for the Degree of
Doctor of Philosophy

INDUSTRIAL ENGINEERING

Raleigh, NC

2007

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DEDICATION

To my family for their unconditional love and support.

BIOGRAPHY

Mohamed Ashraf Sheik-Nainar was born in a small town called Nagore, in the state of Tamil Nadu in the southern part of India. He was raised in Madras (now called Chennai), where he completed his high school education in 1994. He later joined the University of Madras for a Bachelor of Engineering in Mechanical Engineering and graduated in 1998. Following graduation, he joined Caborundum Universal Ltd., an abrasive manufacturing company as a Graduate Engineer Trainee.

In fall 2000, he began his graduate study at North Carolina State University. He completed his Master of Science in Computer Engineering in 2002 and started the doctoral program in Industrial Engineering from fall 2003. He has been working with Dr. David Kaber in the Cognitive Ergonomics Laboratory from fall 2000 and was involved in a number of research projects focusing on telepresence in teleoperation, human computer interaction, situation awareness, and, physical and cognitive workload under multitasking.

He worked as an intern with SA Technologies, Marietta, GA from 2004-06 and was involved in projects funded by Army Research Institute including a field data collection exercise at Ft. Benning, Columbus, GA. Currently, he is working as a Usability Researcher at Synaptics Inc., Sunnyvale, CA evaluating and developing new interaction devices.

ACKNOWLEDGEMENTS

I wish to thank a number of people for their assistance and support in the course of this work. First I would like to thank my academic advisor and committee chair Dr. David Kaber for his continuous support, assistance and guidance through my graduate studies in NCSU. It was a great learning experience in working with him for the past six and a half years. I would like to thank Dr. Simon Hsiang and Dr. Gary Mirka for their advice and support during this work. I would also like to thank my committee member Dr. Jason Osborne for his time and comments. Thanks are due to Tao Zhang who helped me during the crucial moments in experiment data collection and in data preparation for analyses.

I also like to thank the Department of Industrial Engineering for supporting my research and Sigma Xi for the grant to compensate participants for their participation in the experiment.

I like to express my sincere gratitude to my parents for their encouragement, to my sister for her inspiration when I needed the most, to my brother for envisioning me to become a researcher and to my wife for her patience and unconditional love. Without you all, I would have never been where I am today!

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LIST OF ABBREVIATIONS

2D - Two-dimensional

3D - Three-dimensional

AK - A priori Knowledge

ANOVA - Analysis of Variance

AP - Anterior-Posterior

ART - Available Response Time

BOS - Base of Support

CNS - Central Nervous System

COF - Coefficient of Friction

COM - Center of Mass

COP - Center of Pressure

CT - Cognitive Task

DLS - Double-leg Support

DOF - Degree of Freedom

EMG - Electromyography

GDTA - Goal Directed Task Analysis

GRF - Ground Reaction Force

HIP - Human Information Processing

HMD - Head Mounted Display

HSD - Honestly Significant Difference

IBN - Instruction-based Navigation

LTM - Long Term Memory

MANOVA - Multivariate Analysis of Variance

MBN - Map-based Navigation

MS - Mid-stance force

MTT - Multiple Task Test

NC – No Constraint

NT - Navigation aid Type

OW - Overground Walking

PC - Perturbation Cueing

PO - Push-off force

POR - Push-off Rate

PP - Physical Cueing

RCOF - Required Coefficient of Friction

SA - Situation Awareness

SC - Spatial Constraint

SAGAT - Situation Awareness Global Assessment Technique

SART - Situation Awareness Rating Technique

SE - Standard Error

SLP - Slope

SLS - Single-leg Support

SME - Subject Matter Expert

SPAM - Situation Present Assessment Method

SSE - Sum of Squares of Errors

SSQ - Simulator Sickness Questionnaire

TC – Temporal Constraint

TO - Trial Order

TTC - Time-to-task Completion

TW - Treadmill Walking

TWVR - Treadmill Walking with Virtual Reality

VC - Visual Cueing

VE - Virtual Environment

VESS - Virtual Environment Software Sandbox

VLE - Virtual Locomotion Environment

VR - Virtual Reality

1. INTRODUCTION

Human locomotion movements are normally automatic in nature; that is, they can be considered subconscious in the cycle of human information processing (Trew & Everett, 1997). They only come under voluntary or conscious control under special circumstances, such as a new experience or perturbation. However, recent studies have presented results contrary to the belief that walking is an overly practiced automatic motor-control behavior (Woollacott & Shumway-Cook, 2002). For example, Kerr, Condon & McDonald (1985) showed attentional demands of posture control. Lajoie, Teasdale, Bard & Fleury (1993) showed that walking demands more attentional resources than sitting or standing and Ebersbach, Dimitrijevic & Poewe (1995) showed that performance of a concurrent task has an effect on the control of walking style. These works have generated interest in the study of cognitive aspects of posture, balance and locomotion (Woollacott & Shumway-Cook, 2002).

Situation awareness (SA) has been defined as a cognitive construct critical to decision making and performance in complex tasks and systems control (Endsley, 1995). The concept of SA is based on human perception of elements in an environment, operator relation of elements to task goals, and predictions of future task states (Endsley, 1988). SA has been found to be particularly important in multitasking situations in which humans must manage cognitive and physical workloads across tasks with often conflicting goals and competing demands (Perry, Sheik-Nainar, Segall, Ma & Kaber, 2006). However, in general, little research has investigated the role of SA in performance when operators must balance motor-control and cognitive tasks, for example, walking while talking on a cell phone.

Locomotion is a day-to-day activity and is generally considered as a secondary task in situations like walking and talking on a phone. Under multitasking conditions with physical and cognitive loads, recent studies have shown reductions in attentional resources leading to poor performance in either the primary or secondary task, or both (Bloem, Valkenburg, Slabbekoorn & Wilemsen, 2001; Brown, Shumway-Cook & Woollacott, 1999). Poor performance in locomotion, as a secondary task, could result in slight perturbations in gait (a slip or trip) to a total loss of stability (fall). As long as a gait perturbation results in recoverable instability, it is of less concern; however, situations in which combined cognitive and physical loads exceed attentional resources can lead to falls causing critical injuries or fatalities. Unfortunately, research has shown that the number of slip and fall related accidents occurring in occupational as well as residential settings is substantial (Lin, Chiou & Cohen, 1995). The incidence rates of slips and falls may be attributable, in part, to losses of SA in multitasking situations, as a result of reductions in attentional resources, leading to gait perturbations and unrecoverable states of instability. The focus of this dissertation was to study the potential role of cognitive functions, specifically SA, in contributing to control of locomotion while performing concurrent tasks.

The following literature review is organized into four sections. Section 2 provides a detailed review of competing SA theories and justification for selection of a specific theory for locomotion under multitasking scenarios. Section 3 provides a description of human locomotion from a physiological perspective and psychological factors, including components of SA. Section 4 provides a review of perturbations during locomotion, specifically slips and fall incidents, the etiology of slips, and risk factors and control mechanisms. Section 5 discusses available locomotion research tools, including virtual reality (VR) – based locomotion interfaces for studying factors in locomotion performance, including cognitive variables like SA.

2. SITUATION AWARENESS IN LOCOMOTION

Situation awareness has been established as a cognitive construct relevant to decision making and task performance in complex dynamic systems, such as air-traffic control, flying aircraft, operation of nuclear power plants, and military command and control (Durso & Garland, 1999). A dynamic system can be defined as one in which the state of elements in the environment is constantly changing as a function of time with complex interactions among elements. Many everyday activities, such as walking and talking, walking and reading signs, walking and carrying loads, etc., are dynamic in nature. As walking alone, under nominal conditions, can be considered an over-practiced motor-control task, it is unlikely that locomotors must maintain SA for successful performance. However, SA may be related to higher-order cognitive processes in locomotion, such as navigation, and the extent to which situation assessment occurs during locomotion may be critical to dealing with spatial and temporal perturbations. Beyond this, SA may be particularly relevant during locomotion as part of multitasking, including performing a cognitive task like reading, talking or sending a text message on a cell phone while pushing/pulling/carrying and maintaining balance and stability against perturbation hazards.

Typically, prediction and recovery from a perturbation to locomotion occurs within a very short period of time during which appropriate gait control has to be initiated in order to prevent a possible loss of balance. This gait control is a complex coordination of cognitive, sensory and musculoskeletal systems. In order to accurately coordinate these systems for control of balance and continued performance of simultaneous cognitive tasks, it is the contention of this research that a locomotor must have a complete up-to-date internal situational model of the surrounding environment and tasks. Thus, one has to perceive the changes in the physical environment, comprehend the meaning of these changes to locomotion behavior and cognitive and physical work loads (tasks), and project the implications of those changes with respect to successful task performance as well as maintaining balance and stability. Thus, the application of the construct of SA to complex locomotion circumstances may be considered valid and appropriate.

In this section, competing theories on the construct of SA are reviewed in detail. Justification for selection of a theory for application to the study of multitasking and locomotion under perturbation situations is also provided. In light of the selected theory, an explanation is provided on how SA is applicable to locomotion under multitasking.

Brenton and Rousseau (2001) surveyed and classified 26 different definitions of SA. They said the definitions can be evenly divided into two classes – SA as a "state" or as a "process." Theory on SA as a state of knowledge has been developed by Endsley (1988, 1995). According to her, SA is a mental "snapshot" of a dynamic situation, forming a basis for decision making at a particular instant of time. Competing with this theory, Smith and Hancock (1995) advocated a process-oriented, ecological theory of SA, in which they defined SA as adaptive, externally directed consciousness. Durso and Gronlund (1999) said that the state-oriented definition of SA can be associated with a situation-focused approach to achieving SA, which is determined by the elements in the environment in which the operator is to work. In this theory, operator SA can be assessed based on the states of an environment. They also said the process-oriented definition can be associated with an operator-focused approach to achieving SA, which is centered on the properties (action/behaviors) of the operator or agent. In this theory, operator SA is assessed in terms of overt behaviors. The following sub-sections review details of Smith and Hancock's process-oriented theory and Endsley's state-oriented theory.

2.1. Process-oriented theory

Smith and Hancock (1995) said SA, like adaptation to an environment, is a dynamic concept that exists at the interface between the agent (human) and the interacting environment. Building on this analogy, they said that SA is a process by which an agent channels its knowledge and behavior to attain goals as tempered by conditions and constraints imposed by the task environment. Hence, the study of SA requires assessment of the agent-environment relationship and depends heavily on experience in the environment and development of alternative action plans.

Since SA is considered an externally directed relationship between the agent and the task environment, goals of the behavior that SA directs must reside in the task environment rather than in the agent's mind. Until an external goal and criteria for achieving it are defined, actions are governed by introspection rather than SA. An agent must seek information and generate action to achieve an externally specified goal. Without the normative focus of an externally specified goal, SA denigrates into introspection (Smith & Hancock, 1995).

Smith and Hancock (1995) say competence in a task directs behavior but is independent of the situation, while performance constitutes actions in the world guided by competence. Performance is dependent upon the information available in the environment, whereas, competence is context independent. According to process-oriented theory, SA is the competence that directs an agent's understanding of the environment and generates behaviors to solve a problem in the task environment. Smith and Hancock (1995) proposed that SA is specified by an invariant at the core of an adapted agent's perception-action cycle. SA structures the information available from the environment for application of knowledge of an agent and actions to meet the constraints of an externally specified goal. However, other historical theories on high-level competence (e.g., mental model formulation) (Johnson-Laird, 1983) have supported context-dependence of long term memories and knowledge. That is, certain competencies may develop through training or experience in a particular context and it is possible that the ability to apply a mental model and internal situation model may depend upon the particular task environment.

Considering a locomotion task under multitasking, the goal is to perform the locomotion along with any secondary cognitive task without compromise to stability and balance. Behaviors are the type of gait control mechanisms utilized when facing novel situations, which are expected to be guided by competence (past experience). Thus, according to a process-oriented theory, SA would generate the momentary knowledge and the action required to attain the goals of avoiding perturbations to locomotion based on cues available from the environment.

2.2. State-oriented theory

The most widely accepted and applied theory of SA was developed by Endsley (1988, 1995). She defined SA as, "the perception of the elements in the environment within a volume of space and time, the comprehension of their meaning, and the projection of their status in the near future." Endsley said that SA is a state of knowledge and this distinguishes it from the process of achieving, acquiring and maintaining SA, which she termed situation assessment. She pointed out that SA is not inclusive of all knowledge a person may have on an environment, but only that portion relevant to the state of the current task at hand. This state-oriented theory of SA, also referred to as situation-focused theory, is concerned with the mapping of the relevant information in the environment onto one's internal mental representation of the environment/situation and is heavily dependent on human information processing (HIP) theory for explanation. Endsley said that in the context of HIP, SA is a separate mental construct from decision making and performance but they can influence each other.

According to Endsley, SA is developed on three hierarchical levels including perception, comprehension and projection. Level 1 SA is perception of attributes and dynamics of relevant information from the environment. In the context of locomotion, it is the perception of the texture of a walking surface (e.g., slippery, oily, muddy, etc.), other people and object movement in the locomotion path, one's own state of balance, etc. Level 2 SA is the comprehension of the perceived objects and states of the environment in light of goals (e.g., maintaining balance and walking safely). Level 3 SA is the projection of future states of elements in the environment, as a basis for planning or choosing appropriate courses of future action. This situation model of the locomotion environment must be maintained in addition to an internal model of any complex cognitive task being performed simultaneously. In a locomotion scenario, on the basis of locomotor comprehension of the perceived situation, if he or she projects/predicts that a person/object might disrupt the planned path of locomotion, then a decision is made to slow down, let the person/object pass, or step aside and change the path to continue locomotion. This decision is implemented by appropriate gait corrections (adjustments or accommodations).

In Endsley's model of SA, she identified a number of factors as being influential in the development and maintenance of SA. She grouped these as individual factors and task/system factors.

2.2.1. Individual factors

Individual factors that can affect SA include expertise and experience in the task and the environment, the ability to divide attention between tasks during multitasking, and the ability to perform actions on the environment. Experience plays an important role in the development of mental models, and according to Endsley (1995), the ability to achieve SA. Experience helps in picking-up critical environment cues for performance. Detailed mental models help users know what to look for in an environment in order to achieve task goals. In locomotion, this may mean early detection of cues leading to correct perception of perturbation hazards and better proactive control of gait. Another benefit of mental models with respect to developing SA is that detailed models can reduce working memory (WM) load and the potential for information processing bottlenecks. WM bottlenecks can occur in situations when the user/operator is a novice or the situation is novel. In which case, few long term memory (LTM) structures may be available for performance causing a high dependence on WM and increasing demand on attentional resources. WM capacity limitations can inhibit the development of SA by preventing operators from associating all elements in the environment with existing LTM structures. The ability to divide attention between tasks also affects SA, but this can be offset through practice and experience.

2.2.2. Task/system factors

Task/system factors affecting SA include system capability, interface design, stress and workload, and complexity and automation. The factors relevant to SA during locomotion under perturbation are stress, workload and complexity. Endsley (1995) said that stress factors include: physical stressors, such as noise, vibration, heat/cold, lighting, atmospheric conditions, drugs, boredom or fatigue and cyclical changes; and social psychological stressors, such as fear or anxiety, uncertainty, mental workload, time pressure, self-esteem and prestige. The important implication of any stressor is attentional tunneling which can lead to misperception/missing of critical events in the environment leading to bad SA. This is particularly important in multitasking and locomotion where one may be distracted from the locomotion by a cognitive task and not perceive critical cues about the walking environment. This could result in a potential slip/trip hazard. Bentley and Haslam (1998) investigated high accident rates in Royal British Postal employees and found that their practice of reading the next delivery address while walking distracted them from observing changes in the walking surface causing them to slip or trip.

High mental workload is a key stressor that can affect SA, if the combination of demands on attention due to task design and demands due to the need to maintain SA exceed operator capacity. Task complexity is dictated by the number of goals, tasks (multitasking) and decisions to be made with regards to the tasks. High task demand can increase mental workload resulting in decrements to SA. Sauer et al. (2002) found that increases in workload resulted in SA decrements during a simulated remote display of a ship's bridge environment, where a single operator performed navigation, engine control and cargo control. Cummings (2004) conducted an experiment to study human performance issues in supervisory control using a simulation of tactical Tomahawk missile control and found that subjects were distracted by a secondary (instant) message task. The secondary task drew attentional resources to the extent that there was an overall degradation of mission performance and, in particular, a loss of operator SA. It has been recently identified that physical workload in a primary locomotion task can compete for attentional resources and cause deficiencies in SA development and maintenance (Perry et al., 2006).

2.3. Summary

In this section, two different perspectives on SA theory have been reviewed with suggestions of application to locomotion. Both the state- and process-oriented theories of the mental construct seem to fit well to a locomotion scenario under multitasking and perturbation. However, the state-oriented theory developed by Endsley has several advantages for the present work. As reviewed, Endsley's (1995) theory has been successful in characterizing SA in other domains, such as driving (Ma & Kaber, 2005), small unit military operations (Strater, Endsley, Pleban & Matthews, 2000) and air traffic control (Endsley & Rodgers, 1994). This success can be largely attributed to the translation of Endsley's theory to operational definitions of SA for these domains using the SAGAT (Situation Awareness Global Assessment Technique) methodology. The SAGAT allows for direct, objective assessment of operator SA by making comparison of operator responses to knowledge questionnaires with the "ground truth" of a domain simulation. In this way, the accuracy of operator perceptual knowledge, comprehension of environment states relative to goals and predictions of future states can be accurately assessed and related to performance. With respect to the process-oriented theory of SA, objective measures exist such as performance observations, eye movement tracking (Hauland, 2002) and testable responses to environment events (Prichett & Hansman, 2000); however, these measures do not provide for direct insight into the construct of SA, like SAGAT, and the state of a user's internal situation model must be inferred.

SAGAT has been used in several studies (e.g., Kaber & Endsley, 2004; Endsley & Kaber, 1999) to evaluate operator SA in complex multitasking scenarios, and the measure has been correlated with performance outcomes. This type of analysis is critical to any research that seeks to explain dynamic workload management in combined physical and cognitive task performance in terms of SA and to establish SA as a factor in preventing errors in physical task behavior under cognitive distracter tasks. For these reasons, this research used Endsley's state-oriented theory of SA as a basis for modeling locomotion behavior in multitasking under perturbations.

3. HUMAN LOCOMOTION

Locomotion is the general term for the act of moving from one place to another. It is derived from two Latin words – *locus* meaning location and *motus* meaning to move. Human ambulation falls under the category of biped locomotion. The anatomical and physiological system which produces this locomotion is complex, sophisticated and versatile. The literature shows that human locomotion was first studied by the Weber brothers in 1836 (Berme, Oggero & Pagnacco, 1997). Since then, researchers from different domains, for example clinicians, neurologists, kinesiologists, sports therapists, etc., have studied the mechanisms behind human locomotion. This chapter provides an introduction to the terminology used in human locomotion research and sets the stage for further discussion on specific the topic of the dissertation in subsequent sections.

Human walking is produced by continuous loss and recovery of balance in the plane of progression. The body leans forward to the limit of its stability causing the center of mass (COM) to move outside base of support (BOS) (see Figure 3.1), which is recovered by the forward stepping foot and propelled over the stable foot. The cycle continues carrying the COM alternatively over the left and right legs to produce locomotion. The direction and point of application of support forces provided by the ground, also called the center of pressure (COP), are used to control the COM over the BOS.

People walk (or run) in distinctive styles and this is commonly referred to as gait. The most common type of gait investigated in research is walking on flat surface. Typically the gait cycle begins from the contact of one heel with ground at the heel and continues from heel to toe, where the contact is broken; therefore one foot always remains in contact with the ground. This produces two distinct phases of gait – single support (SS) and double support (DS), meaning one or both feet are in contact with the ground. Figure 3.2 shows the normal ground reaction force (GRF) of the right and left legs during normal walking. The overlapping part of the force curve signifies the double-support phase.

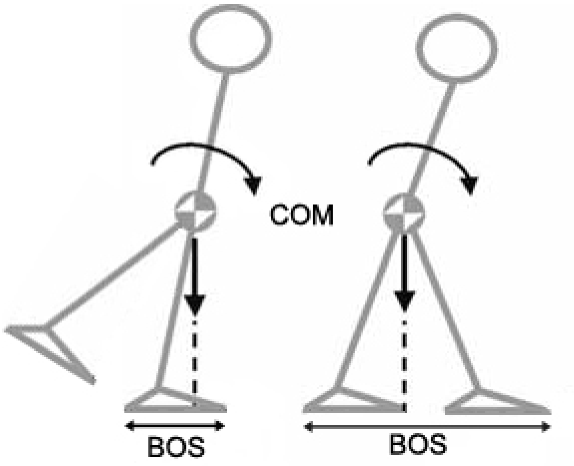


Figure 3.1 Loss and recovery of balance while walking.

3.1. Measures and description of gait

Human gait can be defined by a number of different types of variables – spatial, temporal, kinematic and kinetic. Common variables used to readily characterize gait in clinical settings are stride length, cadence and speed, which fall under the category of spatio-temporal variables. Stride length is the horizontal distance in the plane of progression from the heel down of one leg to the heel down of the same leg. One stride length essentially consists of two step lengths (right and left). Cadence is the number of steps taken within one minute duration and speed is the numerical combination of stride length and cadence expressed in meters/second. Other temporal variables typically used in gait analysis include stance time, swing time, single-support time and double-support time.

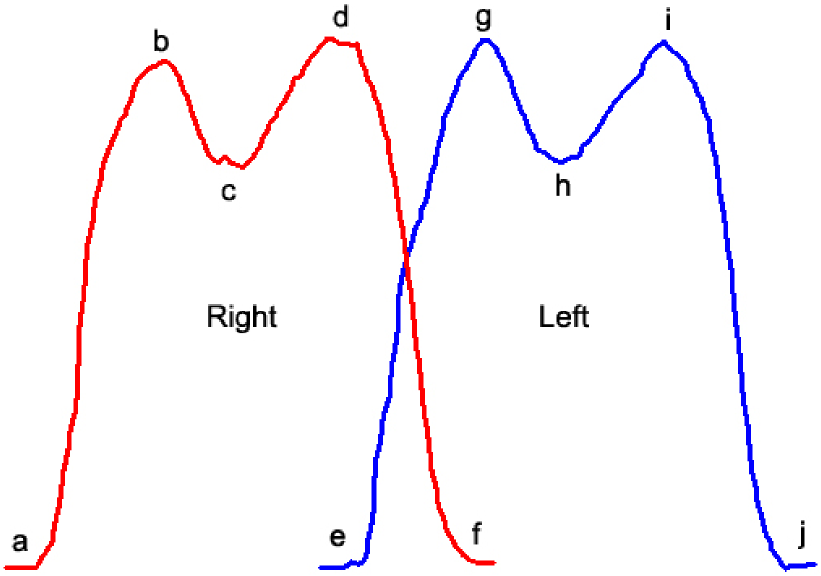


Figure 3.2 Normal ground reaction force (GRF) while walking.
(a, e) Initial (heel) contact, (b, g) Weight acceptance, (c, h) Mid-stance (d, i), Push-off (f, j) Toe-off.

Kinetic variables used in gait research consist of simple forces and higher order time derivatives of forces in various phases of the gait cycle. These are typically recorded using force plates fitted with a number of piezoelectric or strain-gauge sensors. Referring again to Figure 3.2, let's say the gait cycle begins with the right heel making initial contact with the ground (a). This is followed by transfer of body weight to that leg (b), which is termed weight acceptance (WA). The rate at which this transfer occurs is referred to as the weight acceptance rate (WAR). The foot then touches flat on the walking surface and the body weight is fully transferred to that leg. This phase is called the mid-stance (MS) and is marked by Region (c) in the figure. At this time, the other leg (left) swings and crosses the right leg and starts its heel down (e). Now, the weight is slowly transferred to the left leg and the right leg begins to enter the swing phase with a push-off (PO) (d) to generate the momentum to move the COM over the BOS and to break contact between the right foot and ground at toe-off (f). The rate at which the body weight is unloaded from the right leg during push-off is referred to as the push-off rate (POR).

Kinematics variables used in gait research consist of angular displacement, velocity and acceleration and are typically measured using a 3-dimensional motion tracking device or video analysis system. Variables commonly seen in the literature include ankle plantar-flexion and dorsi-flexion, knee flexion and extension, hip flexion and range of motion, pelvic tilt and rotation, etc. Surface Electromyography (EMG) can also be used to record various muscle activities during different phases of the gait cycle to infer forces produced by muscles and can be used to predict forces and moments at different joints using biomechanical models.

3.2. Sensory systems in locomotion

Three major physiological mechanisms exist in the human body that inform us of the status of whole body balance during locomotion and assist us in regaining balance and stable posture in the case of locomotion perturbations. These include the vestibular, proprioceptive and visual sensory systems.

The vestibular system provides two sets of information to the body, when the head is rotated. The semicircular canals provide information regarding the angular acceleration of the head (Berne & Levy, 1993) and the otolith organs provide information about the effective direction of gravity. Stimulation of the semicircular canal system provides information about the rate rather than direction of movement (Seeley, Stephens & Tate, 1992). This information is sent through the brain to lateral, medial and vestibulospinal and reticulospinal tracts resulting in activation of extensor and flexor muscles throughout the body to control posture. The otolith organs provide for absolute position of the head in space. Information from this organ is used to maintain the head at its neutral balanced position through changes in tone of the neck muscles (Seeley et al., 1992).

The proprioceptive system consists of muscles, tendons, joints and pressure receptors of skin, which sense the relative positions and movements of the limbs and other body parts. Pressure receptors in the feet provide the body with information about the distribution of body support and movement of the COP. Differences in pressure at different point on the soles of the feet during standing signal the position of the vertical projection of COM relative to body supports (Carpenter, 1984).

Finally, the visual system provides information on static features of near and far environments that must be negotiated in locomotion. Vision provides the only direct measure of self-motion, used in regulating velocity of locomotion and direction (Warren, 1995). Vision can provide information from a distance almost instantaneously, which helps in identifying and avoiding potential spatial and temporal perturbations to stability in locomotion (e.g., disturbances in path following or pacing). Information from the visual system can override veridical information from other sensory modalities including vestibular and proprioceptive, at times of conflict and can compensate for errors or deficits in the vestibular system (Young & Lee, 1966; Horack, Nashner, & Diener, 1990).

These three sensory systems work together in concert to provide feedback on the state of overall balance in order for the CNS to generate appropriate motor programs to produce locomotion. Blumle, Maurer, Schweigart and Mergner (2006) say there are two types of interactions between the sensory systems – direct and indirect. In direct interaction, each system has an internal representation and can generate postural responses either alone or in combination with the other systems. In indirect interaction, the information from one system doesn't generate a postural response but modulates the response due to other systems (changes in the gain of other systems). Peruch et al. (1999) said any deficits in the vestibular system severely affect the control of dynamic tasks such as locomotion. Deshpande and Patla (2006) observed an initial reliance on vestibular input under novel impoverished visual information conditions but habituation caused the visual system to dominate postural responses during goal-directed walking. The indirect interaction of sensory systems helps overcome sensory deficits in one system by shifting emphasis to the other systems.

3.3. Cognition in locomotion

If a person is asked how many joints they moved during locomotion, or their range of motion when they climbed a set of stairs, it is unlikely that (s)he will be able to answer these questions. This is because practiced motor tasks occur at a subconscious or reflex level (Trew & Everet, 1997). Most of our day-to-day motor activities, like walking, are so practiced that specific motor programs or schemas exists in our LTM stores for many actions (e.g., Pavol et al., 2004) and they can be automatically activated by direct perception of stimuli in the environment or, for example, postural stability requirements. These motor programs generate patterns of movements rather than control of individual joints and contraction of muscles (Trew & Everet, 1977). Tens of thousands of motor units in hundreds of muscles are activated and deactivated at correct times to produce motion patterns and the brain activity to coordinate complex motor control is tremendous (Trew & Everet, 1997). However, for the vast majority of the population, walking or climbing stairs do not represent mentally overloading tasks such that locomotion problems (slips and trips) are uncommon under nominal conditions. In fact, people often take on simultaneous cognitive activities (talking, thinking, task planning, etc.) while walking.

Contrary to these observations, recent studies have demonstrated that balance and posture control in locomotion can be attention demanding and less automatic than previously thought (Ebersbach et al., 1995; Hunter & Hoffman, 2001; Lajoie, et al., 1993; Woollacott & Shumway-Cook, 2002). Locomotion requires a high degree of balance control and attentional demands have been shown to increase with balance requirements of gait and postural tasks. Lajoie et al. (1993) evaluated attentional demands of static and dynamic equilibrium tasks using a dual-task methodology. Subjects performed a secondary stimulus-response task while sitting, standing and walking. They observed that walking required more attentional resources (higher verbal response time to auditory stimuli) compared to standing or sitting.

The loss of balance during the SS phase of locomotion appears to create higher attentional demands in young adults, as compared to the stable gait of experienced walkers during SS and DS phases (Lajoie, Teasdale, Bard & Fleury, 1996a; 1996b; Gage, Sleik, Polych, McKenzie & Brown, 2003). That is, a stance-phase affect on attention allocation does not emerge among older individuals showing equivalent demands for both SS and DS (Lajoie et al., 1996a; 1996b; Gage et al., 2003). This research has also established that the stance phase effect in young adults vanishes when they are subjected to a postural perturbation, implying that they approximate a locomotion control strategy similar to that of older adults. In older adults, such a situation results in systematic increases in attention to both phases of the gait cycle (Gage et al., 2003).

So one may ask, how is it that people are able to frequently locomote without incident? Rieser and Pick (2002) said that perception in locomotion is relative to the environment, as a frame of reference. People must keep track of information on dynamic changes in spatial orientation of self, as well as the positions of relevant objects and features of the environment for safe and productive locomotion. These information are acquired through visual, vestibular and somatosensory systems and are integrated in the brain to generate appropriate motor programs for the central nervous system (CNS) to act upon. Under nominal walking conditions, it may be easy to allocate adequate attentional resources to accurately perceive the state of the environment, achieve good SA, and to maintain postural stability across terrain through motor program use. However, maintenance of balance in locomotion can be further complicated by the need to deal with reaching targets (navigating), avoiding obstacles or dealing with unexpected perturbations, etc. Bardy and Laurent (1991) observed that attentional demands were greater during goal-directed walking (locomotion to a positional objective) than during normal walking. They studied participants walking toward a small and large target performing an auditory secondary task and found that the small target condition required higher attention causing increased reaction time in the auditory task. All this research suggests that locomotion becomes a conscious process under certain environmental and multitasking conditions. Therefore, it is important to describe and understand the potential role of SA in multitasking scenarios involving locomotion.

3.4. Summary

In this section, a brief review of the description and characterization of human gait using spatio-temporal, kinematic and kinetic variables was presented. Mostly importantly, this section has discussed the attentional requirement of gait, which is considered a highly practiced, automatic motor-control task under normal conditions and conscious or monitored task under novel perturbation conditions relying heavily on sensory systems for gait control. Perception and consequently, SA may be critical to locomotion under perturbations because of the need to accurately sense and project the implications of hazards on safety. Safety and performance in multitasking scenarios (including locomotion) may be even more dependent upon the sensory systems and good SA. This dissertation focused on the cognitive aspects involved during locomotion with perturbation hazards and multitasking with concurrent cognitive tasks causing divided attention, which is typical of day-to-day locomotive activities.

4. PERTURBATION AND LOCOMOTION

Perturbations can be defined as any changes to current posture, either in quiet standing or while walking, caused by changes to the COM-BOS relationship resulting in a stepping response (in the case of standing) or temporary disruption to the walking rhythm. If a perturbation is significant enough to cause difficulties in recovery, it may result in a fall. This chapter primarily focuses on perturbations to locomotion (walking) with some reference to the literature on standing posture and balance, in order to reflect upon the existing research knowledge.

There are a number of ways in which perturbations can occur during normal locomotion. The literature identifies the following perturbation: slipping, tripping, stumbling, loss of balance, dizziness, tiredness, underlay tipped/rolled/slid, vehicles in motion, jumping or diving and loss grip (Courtney et al., 2001). Slips and trips are the most common perturbations to locomotion. Both can lead to falls, resulting in injuries and (in some cases) possibly fatalities.

4.1. Factors in slip and trips

Such perturbations may be caused due to extrinsic or environment factors, including the characteristics of walking surfaces, shoes, contaminants, elevations, steepness of an incline, insufficient lighting and poor housekeeping, and intrinsic or individual factors, including aging, vestibular diseases, peripheral-neuromuscular dysfunction, diabetes, osteoporosis, alcohol intake and use of anti-anxiety drugs (Grönqvist, 1999; Leclercq, 1999).

Some intrinsic factors are well known for elderly persons, but have not been explored in occupational settings (Hsiao & Simeonov, 2001). Lipscomb et al. (2006) studied injury reports filed during the construction of Denver International Airport between 1989 and 1994 and concluded that most cases of falls occurred due to complex interplay between environmental and individual factors. Tisserand (1985) argued that the reason behind slipping might be due to discrepancy between a locomotor's mental model and reality; that is, a failure to evaluate the differences between the state of the environment and the internal model based on sensory inputs. Endsley (1995) said that accurate mental model formulation in complex tasks is critically dependent upon situation assessment and development of an internal SA model. Marigold and Patla (2002) showed that previous experience with a slip perturbation and accurate knowledge of walking surface conditions (good mental models) resulted in gait adjustments for safe traverse over a slippery surface. Related to this, experienced walker perceptions of surface slipperiness have been tested in a number of studies (Cohen & Cohen, 1994a & b; Grönqvist, Hirvonen & Tuusa, 1993; Gao and Abeysekera, 2002) and found to have significant positive correlations with the objective coefficient of friction (COF) measurements. It is suspected that accurate perceptions of a perturbation hazard are based on accurate mental models of the same or similar hazard through prior experiences.

Studying intrinsic factors during slip or trip hazard situations, such as accurate situation and mental model formation, may be very important in understanding how people prevent falls and achieve recoverable instability. This research focuses on describing the potential role of higher-order cognitive constructs, specifically SA, in complex locomotion scenarios, involving during concurrent cognitive task performance, with perturbations hazards such as slips and trips.

4.2. Severity of perturbations to locomotion in occupational settings

Among trip and slip perturbations, trips are less complicated because they typically result in a forward fall and locomotor have the possibility to grab-on to other objects to recover from the perturbation or reduce the impact of the fall by controlling their landing, depending on the situation. Slips on the other hand, typically result in a backward fall with little possibility for the locomotor to do any damage control potentially resulting in severe injuries to back and head. In fact, slipping is a contributing factor in 55% of falls (Courtney et al., 2001) and is the second largest source of unintentional mortality in the U.S. (Fingerhut, Cox & Warner, 1998). Lin and Cohen (1997) reported slips as being responsible for 13.5% of all falling injuries. Bentley and Haslam (1998) reported that 42.5% of falls experienced by British mail carriers were the results of slips. According to Warner, Barnes and Fingerhut (2000), falls due to slipping are a major source of medically attended, non-fatal unintentional injuries. In 1997, in the U.S., 11.3 million non-fatal injuries due to falls were reported (age adjusted rate of 43.1 per 1000 persons). In 1998, the NSC (National Safety Council) reported that slips and falls accounted for 21% of emergency room visits. In fast-food outlets, Hayes-Lundy et al. (1991) reported that 11% of grease burns resulted from slips leading to falls. Niskanen (1985) reported that slips accounted for 25% of injuries in construction, while McNabb, Ratard, Horan and Farley (1994) reported slips led to 8% of falling injuries in petroleum drilling. Some time ago Shannon and Manning (1980) reported that slipping was the most frequently disabling event in automobile manufacturing, resulting in 27% of lost-time injuries. The estimated annual U.S. direct cost of fall-related occupational injuries alone was approximately $6 billion with no evidence of a reduction in losses due to slipping and falling over time (Courtney, Sorock, Manning, Collins & Holbein-Jenny, 2001).

4.3. Details of slip and trip perturbations

A slip can be defined as, "a sudden loss of grip, often in the presence of liquid or solid contaminants, resulting in sliding of the foot on a surface due to a lower coefficient of friction than that required for the momentary activity" (Grönqvist, 1999). Slips frequently happen during the landing phase of one's stride when the heel strikes the walking surface and slides forward. Sideway slips and falls can occur due to complex activities, such as turning or changing directions in stride, which often causes one to fall into the concavity of the bend. A trip can be defined as "a sudden interruption of the swing leg causing it to lag behind the velocity of the upper body". Eng et al. (1994) said trips can occur during the early or late stages of the swing phase.

Strandberg and Lanshammer (1981), using multi-image photography, demonstrated that ratios of horizontal (F_H) and vertical (F_V) components of forces (see Figure 4.1) exerted between the shoe and ground during normal walking can be used to determine where a slip is most likely to occur. In their study, a high value of F_H/F_V was recorded shortly after a heel contacted the ground during the landing, which produced a backward fall. A high F_H/F_V was also noticed during the take-off phase when a foot slipped backward resulting in a forward fall, similar to a trip.

The ratio of F_H/F_V is the minimum required coefficient of friction (RCOF) necessary to keep the foot from sliding at the time of contact resulting in a forward fall. The frictional force (F_μ) on a walking surface is directly proportional to the normal force (F_N) and so, for safe locomotion (unperturbed), the F_H/F_V should (at any point) be less than F_μ/F_N. That is, the RCOF should be less than the available COF.

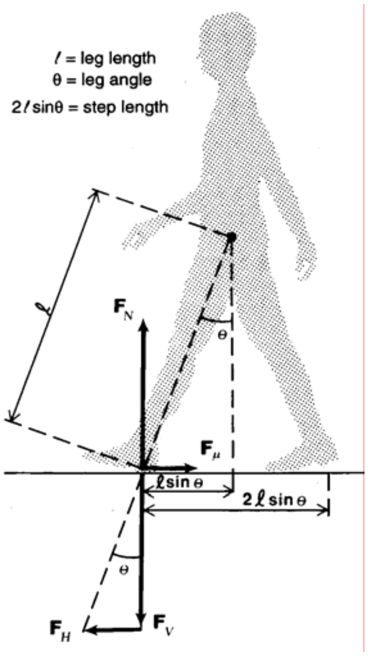


Figure 4.1 Force components during heel contact phase (Grönqvist, 1999).

Eng et al. (1994) demonstrated that if the tripping perturbation occurs during the early swing phase, the human reactive response is to use an elevation strategy, whereby the trailing leg is raised over the object in order to continue with the locomotion. In this situation, the perturbation hazard is not within the view volume as the body has moved past the object. When the perturbation occurs during the late swing phase, the resulting reaction consists of lowering strategy whereby the swinging leg is immediately landed to use as a support to move the stable leg over the hazard. In this situation the perturbation hazard is within in the view volume of the locomotor.

Historical studies have focused on developing an understanding of the effects of environmental factors on human responses to perturbations such as slipping on different slippery surfaces (e.g. Cham & Redfern, 2001) or tripping on obstacles of different heights at different phases of the gait cycle (e.g. Eng et al, 1994). In the next section, we will describe some of the risk factors in perturbations to locomotion.

4.4. Details on risk factors in perturbations to locomotion

The injuries caused by perturbations to locomotion, resulting in a fall, are not trivial incidents with simple prevention strategies. As mentioned earlier, they result from a complex mix of risk factors related to the locomotion environment and individual. The events occurring before and after the onset of a slip or trip are particularly determined by individual factors including perception, cognition, psychology, biomechanics, and motor control (Grönqvist et al., 2001). Many of the environmental and individual risk factors in falls are interrelated and can have cumulative effects. Environmental risk factors have been the historical focus of slips and falls research in order to understand the nature of perturbation hazards leading to falls. Notable research has been conducted on tribological factors causing slipping incidents and ways and means to measure and evaluate surface friction limits. Recently, more effort has been focused on understanding individual factors such as biomechanical, sensory motor and perceptual factors. All these classes of factors are discussed below.

4.4.1. Environmental factors

The most widely studied environmental factors in slip and fall research is the frictional requirements at the shoe-floor interface. Static friction is assumed to be important for preventing the initiation of slipping, while dynamic friction is considered to determine whether a foot slide might lead to a recoverable perturbation or a fall leading to injury. Even during walking over a dry, non-slippery surface, there is a small slip at the shoe-floor interface at the beginning of heel contact (Strandberg & Lanshammar, 1981; Perkins & Wilson, 1983). These slips, also called micro-slips have been found to be of less than 1 cm in length. Strandberg and Lanshammer (1981), after extensive testing using a slip-sticks and falls protocol, concluded that a slip will result in a fall if the slipping exceeds 0.1m in distance or 0.5 m/s in velocity. They observed that critical slip motion occurs at 50 ms after heel contact, when the vertical load is 60% of body weight, acting at the rear edge of the heel. Later, Leamon and Li (1990) proposed that micro-slips can range up to 3 cm, and they observed that 50% of the time, micro-slips go unnoticed. Any slip greater than 3 cm will be perceived as a slippery condition (Leamon & Li, 1990).

The common environmental factor studied in trip research is the height of the step over, either to a new surface or simply to clear an obstacle. Here the ability to raise the limb along with the upper body to provide enough toe clearance at the right stage of the swing phase is important to avoid being tripped. These findings are relevant to the present research because they speak to the sensitivity of the sensory and perceptual systems for triggering appropriate motor control responses in perturbed locomotion scenarios, specifically the proprioceptive system.

4.4.2. Biomechanical factors

Posture and balance are continuously challenged during locomotion because the BOS (base of support) moves at a different speed compared to the COM and also changes its size during SLS and DLS. The BOS is equal to the area of one foot during SLS, while, it is slightly bigger during the DLS. The COM is within the BOS only during the DLS, which is only 20% of a stride. The limb placement swing phase attempts to catch the COM during the remainder of the stride (Winter, 1991). Winter, Patla, Prince, Ishac, and Geilo-Perczak (1995) proposed that the body behaves like an inverted pendulum during locomotion perturbations and the COM is regulated through movement of the BOS by ankle plantar-flexor/dorsi-flexor moments in the sagittal plane and hip abductor/adductor moments in the frontal plane. Thus, compensatory stepping plays an important role in balance recovery from slips in addition to other protective responses involving upper and lower extremities.

During locomotion, joint moments are generated as part of biomechanical reactions to perturbation hazards in order to maintain or recover balance. Geilo-Perczak, Winter and Patla (1999) observed three types of postural strategies used by subjects during quiet standing, including ankle joints, hip joints and combined ankle & hip joint movements. A protective stepping strategy is used to cause large moments at the hip, knees and ankles. Tang, Woollacott and Chong (1998) suggested that proximal muscles, such as hip and trunk muscles, are used to make gait adjustments upon witnessing a known slippery condition in order to maintain balance. They also suggested that distal muscles, such as leg and thigh muscles, are used to recover balance after a perturbation has occurred. MacFadyen and Carnahan (1997) said that a knee-flexor strategy is used for stepping over known changing surface heights, while a hip pull-off strategy is used for stepping over unknown/anticipated obstacles. Responses to regain perturbed balance during locomotion involve regulation of more than 700 muscles in a multi-link system, including more than 200 degrees of freedom (Era et al., 1977). Related to the present research, use of the perceptual system is critical to the musculoskeletal responses that are required to maintain postural stability and to deal with locomotion perturbations through timely biomechanical responses.

4.4.3. Sensory motor factors

The sensory systems (proprioceptive, vestibular and visual) discussed earlier play an important role in maintaining balance and stability during standing, as well as walking, in order to prevent falling and injuries. The proprioceptive system consists of muscles, tendons and joints, which sense the relative positions and movements of the limbs and of body parts. This, along with vestibular system and vision maintain posture and balance. Even though these three systems provide distinctly different types of information, the high degree of integration in the CNS causes any degradation in sensory perception to have a significant affect on posture and balance control.

The visual system provides the only direct measure of self-motion, which is useful for regulating velocity of locomotion and direction (Warren, 1995). Vision also regulates step length and width, walking velocity and orientation of limbs, etc. (Patla, 1991, 1997; Warren, 1998), but cannot be relied upon as a sole means of recovery from perturbation on account of its latency. Corrective responses to slips solely based on vision are slower (120-200 ms) compared to that of proprioceptive responses, which occur between 60-140 ms (Pyykkö, Jäntti & Aalto, 1990; Eng, Winter & Patla 1994). Pyykkö et al. (1990) also argued that the vestibular system governs 65% of the body sway during sudden perturbation, while only

35% is accounted for by the visual and proprioceptive systems. Relevant to the present work, these studies suggest that vision and accurate perception (alone) may not be sufficient to deal with some locomotion perturbations. Perception of visual information of a potential perturbation to locomotion from the environment triggers comprehension of cues by matching with schemas available in LTM and projection of actions by alerting the CNS to prepare the biomechanical system to avoid or handle the perturbation.

4.4.4. *Perceptual and cognitive factors*

Brown, Shumway-Cook and Woollacott (1999) said that attentional and, consequently, perceptual resources are also required for postural recovery from unexpected perturbations. If resources are not available, this may lead to increased risk of loss of balance and falls, particularly in elders for whom cognitive capacities may be diminished. Although allocating more attention to locomotion behavior ("watching your step") may be useful for safer gait regulation in both SLS and DLS phases, Gage et al. (2003) said that it might have a negative effect on global navigation performance and could result in a decrement in (cognitive) secondary-task performance (like talking on a cell phone) in multitasking situations due to perceptual channel capacity limits (Kahneman, 1973). For example, it may reduce the probability of detection and negotiation of other potential environmental threats (at a distance), which might cause perturbations in balance (Gage et al., 2003).

Opposite to Gage et al., (2003) contention, regarding increased attention to locomotion behavior, Bentley and Haslam (1998) argued that the practice of postal employees reading the address for the next delivery point while walking a route was a cause of slips and falls among British Royal Mail employees. They said this is a real-world example that shows how distracting vision and cognition on secondary tasks can detract from stable gait resulting in slip/trip and fall incidents. It is possible that attention to the cognitive activity may have inhibited attention to the SLS and DLS phases of gait, increasing the potential for falls.

For investigation of the use of cognitive resources in multitasking involving maintaining balance (such as locomotion), Bloem et al. (2001) developed a balance test, the Multiple Task Test (MTT). This test consisted of more than two tasks, including: standing up, walking, turning around, avoiding obstacles, touching the floor, and answering a series of questions under visually impaired and slippery conditions, etc. The task combinations were intended to represent everyday situations compared to strict, laboratory dual-task scenarios. Results of experiments with the MTT showed that subjects tended to allocate attentional (and, therefore, perceptual) resources to the physical tasks, first (standing, walking), and then to simultaneous cognitive tasks. They found that as a result of postural control, there were hesitations (slowing in one or more components) or blocks (complete stops or inability to perform components) in the secondary (cognitive) tasks in order to address increased motor control task complexity. They also claimed that subjects exhibited prudent behavior to optimize postural control first at the expense of performance in cognitive tasks. This is inline with Yoshikawa's (2003) speculation on multitasking performance, specifically that as the complexity of a task increases (cognitive or physical), intermittent sampling or checking on the state of the task will increase the potential for interruption of performance in the concurrent task.

4.5. Control mechanisms

Any incident of perturbation to locomotion is composed of two distinct parts – events occurring before encountering the hazard and events occurring after experiencing the hazard. Sensory responses to events before encountering the hazard are called proactive or feed-forward controls and events after experiencing the hazard are called reactive or feedback controls. In this research, the primary focus was on proactive control mechanisms that are facilitated based on perception and cognition in order to prevent a fall from a slip or trip situation. As suggested earlier, vision plays an important role in proactive control and there is a wide body of literature documenting its importance in locomotion.

4.5.1. Reactive mechanisms

Strandberg (1983) suggested that if sliding velocity at the heel during locomotion exceeds 0.5 m/s, a slip is inevitable. Redfern et al. (2001) said that slip events are characterized by high linear impact heel velocities, slow foot angular velocities at heel contact, and fast sliding heel movements after heel contact. Strandberg (1983) also said that at the time of a slip, both peak shear and normal ground reaction forces are reduced resulting in incomplete transfer of weight to the supporting leg and the COM staying close to the ankle.

With respect to responding to slipping hazard conditions, Cham and Redfern (2001) said that an increased flexion moment at the knee is the dominant reactive control mechanism to slips between 25 and 45% into stance. This flexion along with extension at the hip produces corrective movements, such as increased knee flexion to rotate the shank forward, and restores the ankle angle to bring the foot close to body. Gielo-Perczak et al. (1999) said that joint stiffness is also a reactive control mechanism used to maintain balance and attempt recovery from slipping perturbations. Similarly, elevation and landing strategies, when implemented after encountering a trip perturbation, are considered as reactive responses to hazards that could have been avoided, if detected ahead time (in order to develop proactive strategy, as described below).

4.5.2. *Proactive mechanisms*

In order to avoid a potential slip, proactive control mechanisms are used to detect locomotion perturbations and implement appropriate corrective motor behaviors. It can be said that failures in proactive detection of slips lead to the use of reactive control mechanisms after the slip condition develops. Proactive control mechanism can be classified as anticipatory controls and predictive controls (Patla, 2003). Anticipatory control is based on identification of potential perturbations through sensory systems, primarily visual inputs, guided by past experience and knowledge (mental models) of locomotion conditions. Predictive control is based on estimation of the expected perturbation (e.g., slip potential) generated by ongoing movements of elements in the environment and concurrent movements of the body on the walking surface. Accommodation and avoidance are the two locomotion strategies by which proactive gait control under perturbation is implemented.

4.5.2.1 Accommodation in proactive control

Accommodation strategies involve modification of gait kinematics, such as stride length, frequency, direction and joint stiffness, sustained over several steps. This strategy is predominantly applied in slipping hazard situations. For example, when a person must walk over a visibly slippery surface, their immediate response is to accommodate the locomotion based on the perception of slipperiness. Grönqvist et al. (2001) suggested that accommodation of gait, as part of proactive control for perturbations, would involve a combined effect of force and postural changes to early stance. In such situations, Llewellyn and Nevola (1992) observed that subjects tend to take shorter steps and increase their knee flexion, while reducing the vertical acceleration and forward velocity of the body. These behaviors are all based on sensory perception and a locomotor's internal situation (mental) model of the environment.

When exposed to a known, visibly slippery surface, proactive control will generally be of the anticipatory type wherein subjects use mental models of the slipperiness of the surface based on previous experience or exposure. Swenson, Purswell, Schlegel and Stanevich (1992) said subject experience or knowledge of a workplace is a critical factor in anticipatory control. They said depending on locomotor a priori knowledge, appropriate gait accommodations can be effected almost immediately in order to traverse the entire length of a slippery surface without any initiation of slips (neglecting non-serious micro-slips). Marigold and Patla (2002) said that any prior knowledge about slipperiness helps proactive (anticipatory) control by decreasing foot angles and increasing foot contact areas with flat foot landings.

When exposed to an unknown visibly slippery surface, proactive control will generally be of a predictive nature, where subjects must estimate the slipperiness based on visual information and any available (generic) mental model developed from locomotion experience. This type of control may necessarily involve higher levels of cognitive demand and workload than anticipatory type control. Patla (2003) said that identification of many environmental characteristics, which are essential for safe locomotion, are not just visually observed but are visually inferred. For example, a delicate flower vase on the travel path is not just observed as an object, but is also inferred as being fragile. Knowledge based on past experience allows us to infer that the image of glass is brittle. Prior knowledge, even in the absence of previous exposure, can modify the gait response (Patla, 2003). Thus, an initial gait adjustment might be initiated, which may or may not match the actual slipperiness. Consequently, estimations of slipperiness can lead to erroneous behaviors that might create perturbations in the locomotion.

On stepping over a slippery surface, proprioceptive senses update the locomotor's mental model with the difference between the actual and the perceived slipperiness and subsequently, additional accommodation in gait behavior is initiated. This accommodation may, however, be considered reactive in nature, if slip conditions develop.

As another example of anticipatory type control and accommodation, Lee, Lishman and Thomson (1982) showed that during long jump approach, athletes made step length adjustments during the last several strides for proper foot landing on a take-off board. This is similar to the situation, where the subject initiates gait adjustments in order to securely place his/her dominant foot on a visibly slippery surface. This process is a function of his/her displacement in the environment perceived through optic flow (deRugy, Montagne, Buekers & Laurent, 2000) and the athlete mental model of the task environment, based on previous experience. Laurent, Paul and Cavallo (1988) suggest that gait accommodation in this situation is done not by calculating number of steps from the target but by the sense of how much farther or nearer to the target one is and how long it will take to reach the target at the current speed. Speed information is predominantly provided by peripheral vision, but in situations where no reliable visual information is available, or in emergency situations with short reaction times, target expansion rate using temporal information in optic flow (tau) is sufficient for the perception of time to reach a target (time-to-contact) (Laurent et al., 1988). The athlete or locomotor also relies on their situation or mental model for making predictions of the number of steps to the target. Thus, accommodation may be a precursor for further proactive control such as avoidance (described below), where the walker projects his foot landing in order to avoid a hazard.

4.5.2.2 Avoidance

Avoidance strategies involve avoiding the hazard situation altogether by: (1) selection of an alternate foot placement by modulating step length and width; (2) increasing ground clearance to avoid hitting an obstacle on the ground and increasing head clearance to avoid hitting an obstacle above the ground; (3) changing the direction of locomotion when the obstacle cannot be stepped over or under; and (4) stopping.

When exposed to a sudden risk factor such as an obstacle, puddle of oil, etc., the walker will need to make adjustments to gait in order to avoid the potential hazard. When the existence of such a hazard is known and the person has had exposure to the same incident, then the proactive control would be of an anticipatory type. In such situations, the nature of the hazard and the required avoidance strategy is known based on experience, except for the time and place of occurrence.

When the walker is aware of the existence of a potential hazard situation but not aware of the nature or occurrence of it, then the proactive control will be of a predictive type. In this situation, the person makes an estimation of the unforeseen hazard, based on the events occurring in the environment and available knowledge and experience of a similar situation. For example, if a mine worker is aware of a potential locomotion hazard in his work environment, say falling rocks, he might have had previous experience with such a hazard. In this case, the nature and occurrence of a rock falling on to a worker can only be predicted. If the worker is actually exposed to a falling rock, then this experience can be anticipated at future times.

In avoiding a slip/trip hazard, one must choose an alternate foot placement through various combinations of lengthening, shortening, widening or narrowing steps, changing direction or completely stopping. Stride modification helps clear the hazard and to continue in the same direction, while steering helps to avoid the hazardous landing area, if it cannot be passed by step length or width modification. Stopping helps in situations where either steering or step modification is not possible, or if the severity of the hazard could not be immediately perceived. The use of avoidance under anticipation or predictive control is dependent upon characteristics of a hazard.

The potential for success of the avoidance strategy is also critically dependent upon the time available for the avoidance response. Available response time (ART) is the time available to avoid an obstacle in the locomotion environment. It is the time period between the occurrence of an obstacle and a foot touching it, as if no avoidance reaction occurred. ART has been found to be one of the major determinants in avoidance success rate. As one would expect, lower ART results in an increased locomotion failure rate. Visually-guided, proactive locomotion strategies depend on when and where in the step cycle a perturbation occurs (Patla, Prentice, Robinson & Neufeld, 1991; Rietdyk & Patla, 1994; Patla, Prentice, Rietdyk, Allard & Martin, 1999). Prior knowledge of the probability of an obstacle occurring at a certain place in a locomotion scenario was found to increase avoidance success rate (Patla, 1997). This finding also supports the importance of the locomotor's mental model of a task in proactive, anticipatory control.

Studies have shown that the minimum time required for implementing most avoidance strategies is one step cycle. When visual cues are available, avoidance strategies must be implemented one step ahead and avoidance through steering needs to be planned in the previous step (Patla, Robinson, Samways & Armstrong, 1989; Patla et al., 1991). When environmental conditions demand gait adaptation over multiple steps, Rietdyk and Patla (1994) showed that strategies used for successive steps influence the current step. For example, planning avoidance through steering will affect performance in the current step. Patla et al. (1999) conducted an experiment to identify what people do when forced to seek an alternate foot placement spot in the direction of travel. Subjects were instructed not to step on a light spot in the travel path and the size, location and timing of presentation was manipulated. They observed that selection of alternate foot placement from available choices was not random but rather systematic. It was observed that dominant alternate foot placement always resulted in the smallest distance between the new foot placement position and the normal landing spot. They concluded that when there are choices for alternate foot placement subjects preferred to stay in the plane of progression, they preferred longer steps to shorter steps, and narrower steps to wider steps. This means the proactive control for predicted locomotion perturbations through avoidance strategies is largely dependent upon the gait behavior at the time of detection of the perturbation.

4.6. Summary

This section reviewed risk factors associated with locomotion perturbations, and various control mechanisms to avoid and recover from a potential perturbation hazard. As can be seen from the review, there has been little insight provided on cognitive functioning during the use of proactive control mechanisms and how they are selected and when they are implemented. Hence, more research is needed to study the details of cognitive constructs, such as SA, when people are exposed to a locomotion perturbation and how knowledge and experience with a situation (mental models) may affect the selection and execution of a gait control mechanism. No previous research has objectively described the internal mental/situation models of locomotor's in multitasking situations involving perturbed locomotion states in order to quantify the role of SA in the success of accommodation or avoidance strategies as part of anticipatory or predictive control.

5. LOCOMOTION RESEARCH TOOLS

Traditional locomotion research tools include linear or circular walking tracks with fall arrest mechanisms (e.g., suspended safety harnesses). They provide a natural walking environment similar to overground walking. However, they require large lab spaces and are also expensive to setup. Such tools also create constraints in setting-up video-based motion capture systems (cameras) to facilitate kinematic analyses and they limit the collection of EMG (Electromyography) data for kinetic analysis over a number of strides (Matsas, Taylor & McBurney, 2000; Stolze et al., 1997). With these limitations in mind, treadmills have been used in clinical studies for quite some time.

Treadmills provide convenient and controlled test-beds within small lab areas that can be used for empirical locomotion research. They also promote the ease with which kinematic data can be collected and kinetic analyses can be conducted over a number of steps. Beyond this, treadmills provide the capability to simulate incline and decline in locomotion tasks. There are experimental situations in which a walking track is the obvious choice for research. One such situation is biomechanical study of slips and falls in which subjects are exposed to slippery surfaces to simulate slips and record kinematic and kinetic data. In this case, a treadmill would be unsuitable, as slip conditions cannot be reproduced on a treadmill surface through the use of surface contaminants (liquids, etc.). However, treadmills may be a superior choice for conducting other types of experiments, for example, investigating multitasking scenarios involving locomotion to assess the effects of secondary cognitive task performance on gait behavior.

5.1. Treadmill versus overground walking

Treadmills have been used in prior locomotion research on account of economy and ease of data collection (Matsas et al., 2002; Stolze et al., 1997). However, the research community (as a whole) is not convinced of the use of gait data collected using treadmills for gaining insight into actual overground walking conditions. That is, results generated using treadmills may not be considered generalizable to actual gait behavior in real-world locomotion task.

Previous research has attempted to quantify the differences between treadmill walking (TW) and overground walking (OW) in terms of gait kinematics. Several studies have analyzed the kinematics of the lower limbs during OW and TW (Wall & Charteris., 1981; Pearce, et al., 1983; Strathy, Chao & Laughman, 1983; Murray, Spurr, Sepic, Gardner & Mollinger, 1985; Stolze et al., 1997; Alton, Badley, Caplan & Morrissey, 1998; White, Yack, Tucker & Lin, 1998; Matsas, Taylor & McBurney, 2000 and Warabi, Kato, Kiriyama, Yoshida & Kobayashi, 2005); however, results have been contradictory. Matsas et al. (2000) observed small insignificant differences in knee angle between TW and OW and concluded that there is no difference between the conditions. Contrary to this, Strathy et al. (1983) found significant differences in knee angle at heel strike and also found a trend towards increased stance time and decreased swing time during TW. Pearce et al. (1983) also found increased stance time during TW at lower speeds, as compared to higher speeds, as well as decreased stride length. However, Murray et al. (1985) found no significant differences in stride length, cadence, and stance and double-limb support times among OW and TW conditions.

Similarly, Alton et al. (1998) and White et al. (1998) found no significant differences in stride length. While White et al. also found no differences in cadence and stance time, Alton et al. observed a significant difference in both variables. Wall and Charteris (1980) observed longer stride lengths during TW, especially during the initial 10 minutes of TW. They attributed this difference to a lack of familiarization of participants with TW. On the contrary, Stolze et al. (1997) and Warabi et al. (2005) found increased cadence and decreased stride length along with decreased stance time during TW, as compared to OW.

Unfortunately, the results of many of these previous studies cannot be directly compared because of differences in experimental tasks and designs, time periods provided for familiarization with TW, landmarks used for joint angle measurement, procedures followed by participants in selecting speeds during OW and TW, and methods used for kinematic data filtering. For example, Matsas et al. (2000) said studies that found significant differences between TW and OW (Alton et al., 1998; Strathy et al., 1983) placed little emphasis on treadmill familiarization, while studies that reported insignificant differences (Murray et al., 1985; Wall & Charteris, 1981) provided 30 to 75 minutes of familiarization, ultimately fatiguing the participants. Related to these differences, Alton et al. (1998) pointed out that many of the previous studies comparing OW and TW failed to provide complete information on their methods making it difficult to compare or replicate results.

Of the previous studies comparing TW and OW, many have identified the lack of optic flow (i.e., the relative visual movement between a walker and the environment) during TW as a potential factor in observed differences in gait behavior among the conditions (Van Ingen Shenau, 1980; Pearce et al., 1983; Arsenault, Winter & Marteniuk, 1986; Stolze et al., 1998; Matsas et al., 2000). Optic flow provides a sense of self-motion (perception of movement in an environment) that, when coupled with vestibular inputs, has been found to affect postural control (Stoffregen, Draper, Kennedy & Compton, 2002). This coupling, however, is typically not available in TW. Consequently, there may be perceptual cue conflicts (i.e., a lack of the sense of self-motion combined with the sense of physical motion (kinesthetic cues)) resulting in participants adapting a more conservative approach to locomotion (e.g., shorter stride length), as compared to OW. As mentioned, familiarization with TW may help in adaptation of the perceptual system to artificial walking circumstances. On the basis of the prior work, it was hypothesized that the presence of optic flow during TW might make the experience more comparable to OW by reducing perceptual cue conflicts, and that this change would be evidenced by TW gait behavior more closely approximating OW behavior.

Prokop, Schubert and Berger (1997) specifically studied the effects of optic flow on locomotion using a treadmill and concluded that changes in optic flow resulted in changes in walking velocity. They argued that during locomotion, visually induced modulation might induce a modulation of stride length. This finding supports our hypothesis; however, Prokop et al. (1997) used very low-fidelity visual cues for optic flow in TW and they did not make direct comparison of TW with OW conditions. It is possible that virtual environment technology can generate optic flow during TW by providing realistic high-fidelity visuals, as compared to the abstract low-fidelity cues used in previous research, in order to create a visually compelling walking experience. No experiments have compared specific gait variables during OW with TW in the presence of realistic optic flow for creating the perception of self-motion.

5.2. Virtual environment technology

Loomis, Blascovich and Beall (1999) said that virtual environment (VE) technology is a promising tool for psychological research and provides good ecological validity without compromising experimental control by allowing for decoupling of variables that may naturally co-vary. VEs can perceptually surround an individual and provide continuous stream of stimuli, producing a sense of inclusion and interaction with an environment (Witmer & Singer, 1998). VEs provide a compelling sense of personal, social and environmental presence for users (Witmer & Singer, 1998), while providing investigators the capability to control the experimental environment and actions within it (Blascovich et al., 2002).

5.3. Locomotion interfaces

In order for VEs to be perceived as realistic, users should be able to interact with them and execute control over elements in the VE. For example, in order to navigate or move around in VEs, motion interfaces are used. Motion interfaces are generally categorized as active or passive (Durlach & Mavor, 1995). Active motion interfaces are often referred to as locomotion interfaces, which require user self propulsion (Hollerbach, 2002). An important feature of locomotion interfaces is the integration of proprioception with vision. Hollerbach (2002) said that physical energy requirement imposed, and sensorimotor integration achieved, by using locomotion interfaces might cause increased sensation of presence in VEs. Hollerbach (2002) identified classes of locomotion interfaces to include: pedaling devices, walk-in-place devices, programmable foot platforms, sliding surface devices, linear treadmills and omni-directional treadmills.

5.3.1. Pedaling devices

These interfaces use simple bicycles for locomotion in VEs, which are integrated with sensor technology to control the presentation of visuals to riders. Turning is facilitated by moving the handle bars of the physical bicycle. Friction brakes and electric motors can be used to simulate inertia, viscosity and slope. Georgia Tech's Bicycle on a motion platform (see Figure 5.1) (Brogan, Metoryer & Hodgins, 1998) integrates a road bicycle and a moving platform to simulate uphill and downhill driving. The Sarcos Uniport (http://www.sarcos.com) is another example of a pedaling device interface. The uniport integrates sensors in the seat of the pedaling device to sense user movement for facilitating turns in a VE. Of course, these devices cannot be used for locomotion research in VR.

Figure 5.1 Georgia Tech's bicycle on tilt platform (Brogan, Metoyer, & Hodgins, 1998).

5.3.2. Walk-in-place systems

These interfaces do not use any moving devices but, rather, require user stepping in place. Such systems often require different sets of muscles to be used for stepping; however, they represent a low cost locomotion interface alternative. For example, the gaiter system (Templeman, Denbrook & Sibert, 1999) employs magnetic trackers attached to the thighs (just above the knee) and force sensors in foot pads (see Figure 5.2). Knee height, rate and direction are used to cause forward movement of avatars in a VE and foot pad sensors help segment the steps of virtual humoid representations of users in VEs. Magnetic sensors placed at the waist and head control orientation and gaze direction.

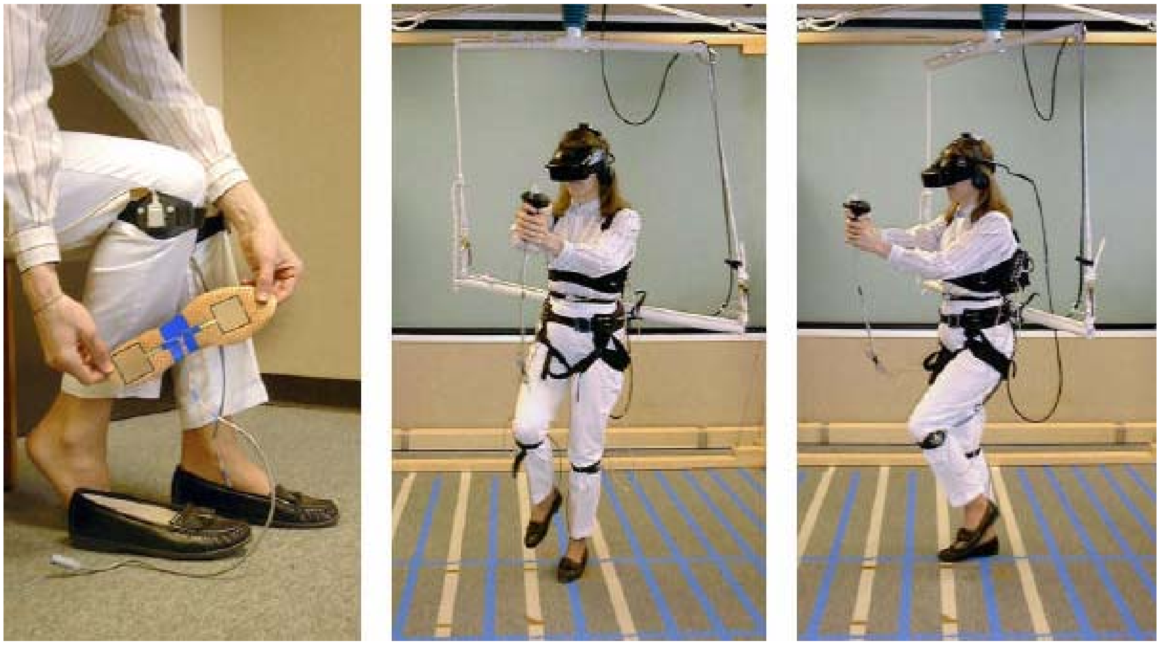


Figure 5.2 Walk-in-place system (Templeton, Denbrook, & Sibert, 1999).

5.3.3. Programmable foot platform

This type of locomotion interface is derived from stair-stepper exercise machines. Two foot platforms are integrated in such interfaces and they are individually programmable for positioning in three-dimensional (3D) space. For example, the Sarcos Biport (http://www.sarcos.com) employs hydraulically actuated 3-degree-of-freemdom (DOF) serial-link arms on which a user stands. When the user lifts a foot, the attached arm follows with zero force to avoid dragging the foot and when the user steps to contact a virtual surface, the real stepper arm provides a rigid surface. The Gaitmaster developed by Iwata and Yoshida (1999) (see Figure 5.3) uses two 3-DOF parallel drive platforms with passive, spring-loaded yaw joints to allow turning. The platform accommodates forward, backward and sideways motion.

Figure 5.3 Gait Master (Iwata & Yoshida, 1999).

5.3.4. Sliding surface systems

In this kind of interface, a user stands and walks (or skates) in place on a supporting platform. User either slide their feet across the platform or use roller skates to cause avatar motion. Huang (2003) developed a new kind of VR locomotion interface called the omni-directional stroll-based platform (see Figure 5.4), which facilitates user motion in a VE by requiring them to slide over a surface. His arrangement consists of a series of pressure sensitive ball bearings arranged in concentric circles on a concave platform. A total of 975 sensors are arranged in 19 concentric circles. An important feature of this technology is that it does not require any motor or any other tracking device (except a head-motion tracker for controlling avatar gaze direction), because the pressure sensitive ball bearings are the motion trackers used to deduce a walker's position and speed. The locomotion interface is connected to a computer, which reads the sensor state (1 bit for each sensor). A gait sensing algorithm records the states of the sensors to calculate the velocity and direction of the walker. The algorithm also filters the noise from sensors. The algorithm works similar to the one used in the Torus treadmill (Iwata, 1999) with a dead center region where the walker is assumed to be still. Any movement outside this center region is recorded as motion.

Huang's system requires a sophisticated workstation cluster because of the high computational requirements associated with the sensor data integration and gait sensing algorithm. He also mentioned that a simulator, based on this setup, has been developed for training and certification of overhead crane operators in Taiwan.

As another example of a sliding surface system, Iwata and Fuji (1996) developed a Virtual Perambulator where a subject wears a head mounted display (HMD) and walks on an omni-directional sliding device with a waist hoop. The device has break pads at the toe, which generates force while moving forward and provides haptic feedback. The walker is free to move in any direction within the hoop.

Figure 5.4 Omni directional stroll-based platform (Huang, 2003).

5.3.5. Linear treadmills

These interfaces are inspired by exercise treadmills. The Sarcos Treadport (Hollerbach, Xu, Christensen & Jacobson, 2000) is a large 4 × 8 foot treadmill. The user walks on the treadmill while attached to a 6-axis mechanical tether (at their waist), which serves to center the walker on the treadmill as well as provide force feedback for incline and decline walking.

The ATR Atlas (Noma & Miyasato, 1998) is a regular exercise treadmill mounted on a platform that can provide pitch, roll and yaw motions (see Figure 5.5). Motion control of an avatar in a VE is provided by optical tracking of markers attached to a user's foot and a magnetic tracker is used for capturing user head orientation and directing the gaze of the avatar. The ATR Ground Surface Simulator (Noma, Sugihara & Miyasato, 2000) is similar to an ordinary treadmill but can simulate locomotion on uneven or step-like terrain in use with a VR setup.

5.3.6. Planar treadmills

The omni-directional Treadmill (Darken, Cockayne & Carmein, 1997), designed by Virtual Space Devices, Inc., provides a two-dimensional (2D) surface to facilitate turning in locomotion. Two orthogonal (treadmill) belts are arranged to create the 2D surface. A mechanical position tracker on an overhead boom attached to a harness worn by the user is used to control the treadmill response to user locomotion behavior.

The Torus Treadmill (Iwata, 1999) (see Figure 5.6) is 2D treadmill design, which employs 12 small treadmills connected, side-by-side, to form the shape of a torus. Motion control is achieved by foot tracking to keep the walker centered in the treadmill. The maximum speed the device can support is about 1.2 m/s.

A more recent development is the Omni-directional Treadmill System (Wang, Bauernfeind & Sugar, 2003) at Arizona State University. In this system, the walking surface is moved using powered offset casters, developed by Stanford University. Two, three or four casters are mounted on a circular board to slide a large piece of cloth material beneath a user's feet. This is used instead of a regular belt. The researchers were able to modulate the resistance felt by the user using the powered caster and by applying brakes. This system is currently under development.

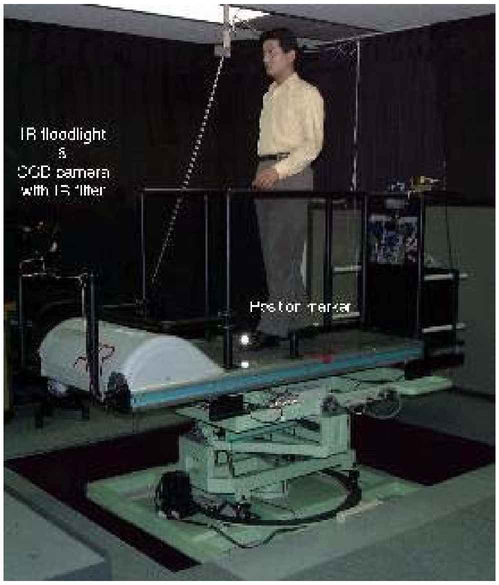


Figure 5.5 The ATR Atlas (Noma & Miyasota, 1998).

Figure 5.6 The Torus treadmill (Iwata, 1999).

5.4. Summary

Prior research reviewed in this section has sought to develop optimized locomotion interfaces for making immersive environments more realistic. Gait kinematics during linear and planar treadmill use has more of a resemblance to overground walking compared to other types of locomotion interfaces. Linear treadmills restrict movement to one direction (forward and backward) while planar treadmills offer movement in a two dimensional plane. Unfortunately, at the present time, planar treadmills are very expensive and may restrict the speed of locomotion due to hardware limitations. Linear treadmill type locomotion interfaces, even though specialized, do not suffer from similar disadvantages and offer a chance to be economically employed in locomotion research. In this research, a linear treadmill locomotion interface as part of a VR system setup was used as a tool for further study of the role of perceptual and cognitive factors in gait control behavior during perturbations in locomotion.

6. PROBLEM STATEMENT

Hsiao and Simeonov (2001) said that the extrinsic factors in locomotion perturbations (slips, trips and falls) have been studied in-depth for adults in occupational settings, but few studies exist on intrinsic factors during perturbations. These intrinsic (human) factors, which include perceptual and cognitive factors, are being studied for older adults with pathology (e.g., Parker et al., 2004; Beauchet, Dubost, Aminian, Gonthier & Kressig, 2005). Studies have looked into attentional resources and resource competition during multitasking and standing (Bloem et al., 2001; Lajoie et al., 1993; Shumway-Cook et al., 1997) and involving locomotion (Brown et al., 1999; Gage et al., 2003) and its effect on regaining balance and stability against perturbation (Weerdesteyn, Schillings, van Galen & Duysens, 2003). These studies concluded that higher cognitive resources are required to maintain balance and stability while multitasking, which is typical of everyday activities.

Studies have also been conducted on the contribution of different sensory systems (vision, vestibular and somatosensory), and the integration of senses, on balance and posture (Simoneau, Ulbrecht, Derr & Cavanagh, 1994; Vouriot et al., 2004). In general these studies are conducted by having subjects stand on a platform, which can be displaced or moved to perturb balance. Vouriot et al. (2004) conducted a study in which subjects were exposed to different trials with sensorial conflicts among vision, vestibular and somatosensory systems while standing on a movable platform. They concluded that higher dependence on the visual system causes delays in reactive recovery from perturbations. Similar observation has been made on older adults (Cohen, Heaton, Congdon & Jenkins, 1996). However, the visual system is also the only sensory system capable of detecting locomotion perturbations well in advance in order to facilitate proactive control of gait to maintain balance and posture (Patla, 1997; Warren, 1995).

Only few studies have looked into the human factors of perturbations during locomotion (Patla et al. 1991; Patla et al. 1999; Weerdesteyn et al., 2003). Patla et al. (1999) studied alternate foot placement (decision making) during avoidance of obstacles in the locomotion path. Patla et al. (1991) studied avoidance success rate when subjects were aware or unaware of the probability of a perturbation occurring at a certain place in the locomotion path. They found significant increases in success in obstacle avoidance when subjects had prior knowledge. This suggests that prior exposure to locomotion perturbations or knowledge of their occurrence helps to develop suitable mental models of locomotion situations and probable proactive/reactive strategies. Pavol et al. (2004) found that repeated exposure to slips caused young and old subjects to adapt their proactive and reactive strategies to effectively avoid and recover from slips. They found that gait changes were due to reactive strategies during the first 2-3 slips and, thereafter, changes were driven by proactive strategies. Progressive changes in slip avoidance strategies indicate that subjects created an internal model of the situation and that specific motor programs were associated with this model for application to the situation. Pavol et al. (2004) found that gait behavior can be perfected over subsequent exposures. It is important to note that in this study, subject initial adaptations were more of a reactive nature. This suggests that development of proactive strategies is fueled by knowledge of the extent of possible reactive adaptation.

In general, both of these studies (Patla, 1991; Pavol et al., 2004) indicate that knowledge of a situation, and the development of suitable mental models, helps locomotors to avoid or recover from perturbations. The development of an internal model of complex task performance is considered to be based on situation assessment and maintenance of an internal situation model for any given moment in the task (Endsley, 1995). However, no study has been conducted to quantify locomotor SA in multitasking scenarios before or after the onset of perturbations to the locomotion. Furthermore, no research has sought to objectively describe locomotor mental models and to relate either of these cognitive constructs to success in accommodation or avoidance strategies (proactive control) in critical locomotion situations (while performing concurrent cognitive tasks).

Grönqvist et al. (2001) pointed out that lack of good SA in locomotion could undermine the ability to predict the likelihood of a perturbation and generate necessary reactive steps for recovery. This makes sense because the time available to avoid a perturbation or prevent a slip or trip from becoming a fall in everyday life is very short and good SA may be critical to proactive control for perturbations. There is a need to quantify SA in complex locomotion situations and to correlate an objective measure of SA with success rates in proactive control for locomotion perturbations.

The objective of this research was to develop a SA-based model of human locomotion and use the model to explain the development of proactive gait control mechanisms to counter perturbation hazards during walking as part of multitasking performance (including concurrent cognitive tasks). To achieve this objective, an experiment was conducted in which SA was measured using real-time probes during locomotion while performing a concurrent navigation task to a target destination. The utility of SA for effective gait control for perturbations hazards (slips & trips) to locomotion was evaluated. The research manipulated the initial mental model of the subjects through different levels of introductory training on the task environment and examined how the training influenced the development of SA during the task. The research also examined any mediating effect of a priori knowledge of task environment on the use of proactive gait control to deal with perturbation hazards. To support the experimental work, a VR-based locomotion interface (VRLI) was developed to present realistic and unique virtual walking environments to walkers similar to everyday locomotion activities. The VRLI setup (described in detail in Section 8) was validated with a pilot experiment comparing gait behavior during TW (treadmill walking) with VR (TWVR) and OW (overground walking) using a head-mounted display (HMD). The results of the pilot experiment are presented in Section 9.

7. A MODEL OF SA IN GAIT CONTROL

As part of this research, a model of SA for human locomotion was proposed with a focus on situations involving locomotion and hazards while performing concurrent cognitive tasks. It was postulated that gait control strategies could be proactive, reactive or predictive based on a locomotor's perception of the current state of a walking environment and potential hazards to locomotion, as well as previous experiences in the specific, or a similar, environment (see Figure 7.1). A proactive strategy would be employed if one develops a complete understanding of the nature and severity of the perceived perturbation. Consequently, the walker would accommodate their gait or avoid the obstacle, resulting in no affect of the impending perturbation to locomotion. Patla (2003) termed this type of control as anticipatory strategy. This form of control could be considered representative of a state of "perfect" SA on the locomotion conditions, where there is a very high probability of successful avoidance or navigation of the perturbation to locomotion. However, as Endsley (1995) has pointed out, performance and SA do not always go hand-in-hand as many other factors may affect and/or mediate performance or people can have bad SA and simply can get lucky in a task.

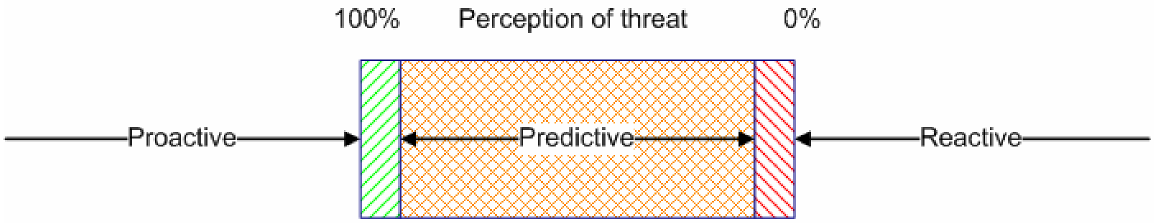


Figure 7.1 Gait control mechanism based on perceived locomotion hazard.

A predictive strategy, as defined by Patla (2003), would be employed in a situation when the human is exposed to a novel locomotion condition for which they are aware their perception may not match reality. That is, they have never dealt with such a hazard before but they can recognize the possibility of a potential perturbation. Such a strategy will also be utilized when the human has "bad" SA on the environment leading to inaccurate perception of the threat. In such situations, only partial accommodation or avoidance control can be initiated and the walker must rely on feedback (proprioceptive and vestibular inputs) on the nature and severity of the perturbation for further reactive adjustments. It can be said that a predictive strategy to gait control is a combination of proactive and reactive control mechanisms.

In case of poor SA on the locomotion environment, such as total incapacity to perceive, comprehend and project the future states of the locomotion situation or a failure to perceive important environmental cues, the human would have no perceptual knowledge about the impending locomotion hazard. Consequently, the walker would detect the perturbation only after exposure, which is a classic example of the application of a completely reactive gait control mechanism. Under this circumstance, recovery of postural stability is dependent on the reaction time available to respond to the perturbation and the tonal condition of the musculoskeletal system.

Figure 7.2 presents a novel model of SA-based gait control for addressing perturbations during locomotion, while performing concurrent cognitive tasks. As previously stated, during locomotion under nominal conditions, it is likely that a walker does not need to develop a detailed internal model of the locomotion environment for successful performance and gait control may occur in a semi-automatic manner. However, one's perception of the environment and mental model (based on any previous experience) may become critical under high workload due to multitasking and the occurrence of locomotion hazards. The new model presented here uses Endsley's (1995) state-oriented theory of SA as a basis for defining relations among specific aspects of SA and types of gait control mechanisms used in critical locomotion conditions.

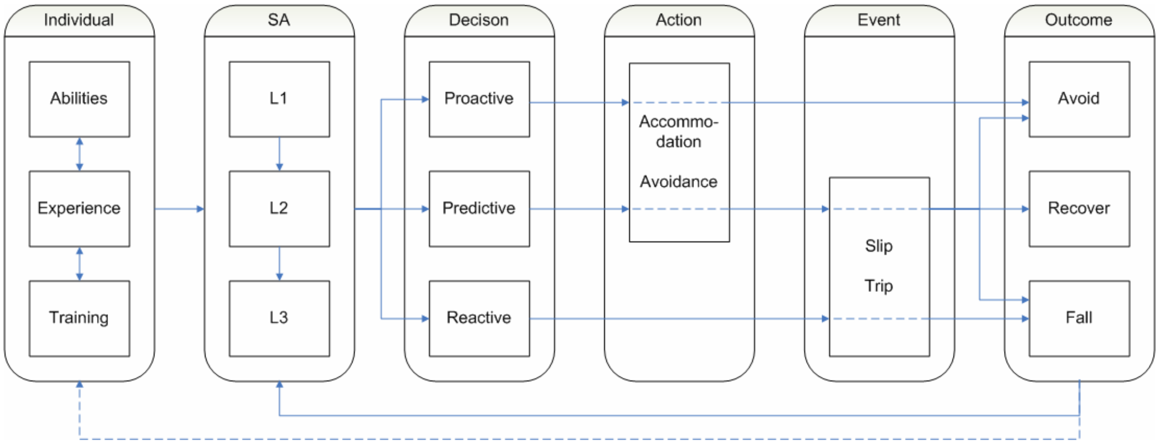


Figure 7.2 SA model for human locomotion under multitasking.

According to the model, innate abilities, experience and knowledge all contribute to the development of appropriate SA (perception (L1), comprehension (L2) and projection (L3)) on the locomotion environment, which drives the decision making process of choosing an appropriate gait control mechanism for the specific locomotion condition. As discussed previously, good SA was expected to facilitate/support proactive gait control in response to potential perturbations, resulting in avoiding any negative outcomes. That is, if the walker could perceive the perturbation and had developed an accurate internal model of the environment, gait control was expected to be proactive in nature resulting in successful avoidance of the hazard. It was also expected that a predictive mechanism would be employed when a walker's SA was not complete, resulting in partial initiation of proactive control and further compensation for the hazard via reactive control. That is, if a walker had previously experienced a locomotion hazard but couldn't clearly perceive the current environment, or (s)he had no experience with the locomotion condition but could see it, for example, a slippery surface, well in advance, they were expected to exhibit predictive control. The effectiveness of the predictive control (combination of proactive and reactive control) depends on the quality of the SA model, in order to avoid or recover from the locomotion hazard. An inaccurate SA model was expected to result in total misperception of the locomotion situation resulting in reactive control after a perturbation event had occurred, potentially leading to a fall. That is, poor SA during multitasking situations involving locomotion with hazards was expected to lead to potential falls. In this study, only specific aspects of the model of SA were assessed including the role of task training in perception, comprehension and projection on a locomotion environment. The study also focused on the role of SA in proactive gait preparation when encountering locomotion hazards.

There are many potential underlying factors of errors in SA that might contribute to locomotion problems in multitasking. Some are similar to the extrinsic and intrinsic factors in slips and falls identified by Gauchard et al. (2001). As previously reviewed, Endsley (1995) said that factors limiting SA include the capacity of cognitive resources and the competence/knowledge to recognize critical environment variables. Attentional resources might be limited during multitasking and lead to failures in a walker's perception of the locomotion environment. Level 1 SA can be inaccurate or incomplete depending on available cognitive resources and could be affected by divided attention and attention tunneling. Furthermore, critical cues in the environment, for example, the shimmer of water on a metal surface under indirect lighting might not be salient to all walkers. This could lead to a walker misperceiving or missing critical cues in the environment and failure to exercise any gait control in order to prepare for or avoid a potential locomotion hazard.

Errors in Level 2 SA might be due to other factors, including a lack of experience or knowledge, resulting in an inaccurate mental model and/or bad control strategy selection for the situation. Level 3 SA might be compromised also by an incorrect situation/mental model and limitations in memory and attention, as well as lack of automaticity of task performance leading to a slip or trip in action. In the context of locomotion under potentially hazardous conditions, these errors could lead to inability to understand or correlate various environmental cues, and as a result, inability to project the nature of the impending perturbation and initiate (or correct) gait control responses.

As a complete example, consider a nurse (or lab technician) walking with a tray of medical test tubes in a laboratory setting. (S)he should understand the nature of the material (s)he is carrying and how critical it is to a larger process of patient care. (S)he should also be aware of her gait, friction at the shoe-floor interface, and other elements in the environment, such as colleagues, objects in her path, etc. This information forms the basis for Level 1 SA in the locomotion/transit task. It should be noted here that if the nurse is talking to colleagues while she is walking, it may be more mentally challenging for him/her to gather key data from the environment in order to achieve Level 1 SA. To achieve Level 2 SA, the nurse must perceive his/her balance state and slipperiness of the floor (based on perception of slipperiness at the shoe-floor interface), movement of colleagues around him/her, and the emergence of any obstacle on the planned path in order to understand the implication of the current state of the task environment on the task plan. Again, any concurrent task performance may place an increased load on WM (working memory) potentially undermining the resources that could be used for Level 2 SA development process. With respect to Level 3 SA, the nurse, based on his/her perception of balance and slipperiness of the shoe-floor interface, and presence and movement of objects/colleagues, must be able to project that (s)he might slip or collide with an object and, consequently, (s)he must make the decision to select an appropriate proactive or predictive strategy to accommodate or avoid a potential perturbation hazard.

Figure 7.3 presents a novel decision ladder model of the role of SA in a slip/fall situation when the slip hazard is visible. In a multitasking situation, as described above, it should be noted that attentional demands (mental workload) mediate the ability of the locomotor to perceive the environment, which in turn affects the achievement of accurate SA and selection and utilization of the correct mental model for projecting future task states and recognition-primed decision making (see Klein, 1998).

From Figure 7.3, it can be seen that reactive control is possible only if there is an error in subject perception of the environment. Errors in Level 2 and 3 SA result in the use of a predictive control strategy, which is a combination of proactive and reactive control. As previously stated, the proportion of proactive control during the use of a predictive strategy depends on the relative accuracy of the SA model developed and maintained by the subject.

In order to further describe and quantify the role of SA in locomotion during gait control under multitasking situations as well as validate the proposed SA-based locomotion model, an experiment was conducted to investigate the underlying factors in the achievement of

Level 1, 2 and 3 SA under perturbed locomotion conditions. The experiment design, explained in detail in the Methodology section, allowed for functional constraints on task performance and cueing of locomotion perturbations along with systematic manipulation of subject exposure to the navigation task environment. The role of each of these independent factors in locomotor SA and gait control is conceptually reflected in the decision ladder model in Figure 7.3.

Figure 7.3 Model of SA in a slip/fall situation.

Current walking tracks or treadmills widely used in locomotion research, have limited usefulness because the visual scene available/presented to subjects is static. Furthermore, the uniqueness of perturbations in such setups (e.g., belt braking and speeding responses) is highly limited after first exposure since subjects develop experience and expectation with the behavior of the treadmill. It was expected that a VR-based locomotion interface could alleviate these problems by providing compelling visuals of realistic simulations to subjects while using a linear treadmill and such visuals might mediate subject expectations of perturbations. The next section describes the development of a virtual reality locomotion interface (VRLI) setup and a pilot experiment conducted to validate the setup.

8. VIRTUAL REALITY LOCOMOTION INTERFACE

The virtual reality locomotion interface (VRLI) developed for this study was inspired by the linear treadmill-based locomotion interfaces reviewed earlier. An advanced linear rehabilitation treadmill was used in the current setup to provide flexibility in the types of locomotion conditions that can be delivered (forward, backward, inclined walking), facilitate integration of the treadmill with PC technology, and to allow for comparison of experiment results with those of other studies conducted using linear treadmills.

8.1. Setup

The setup consisted of a Biodex treadmill, Ascension Motionstar system, Silicon Graphics Inc. (SGI) Zx10 workstation and a VirtualResearch VR8 HMD. The workstation was equipped with Dual Pentium III Zeon processors and a 3D labs Wildcat 4110 dual-digital head graphics card with 256 MB of video memory. Figure 8.1 shows the schematic of the VRLI setup with a human in the loop. An explanation of how the overall system works is provided in the next sub section.

8.2. Virtual environment simulation

Two virtual locomotion environment (VLE) simulations were developed for an experiment to validate the use of the VRLI for locomotion research relative to using a walking platform and overground test trials. The VLEs included a simulation of: (1) an Ergonomics Laboratory in the Department of Industrial Engineering at NCSU; and (2) a hallway on the 3rd floor of the Riddick Labs building at NCSU. Graphical models for the simulations were created using Multigen Paradigm's Creator in openflight file format. These models were then imported into the Virtual Environment Software Sandbox (VESS), developed by the Institute for Simulation and Training at University of Central Florida. The VESS is a scenegraph application that includes a rendering engine and it allows for coding of user interactions with VE objects using many input devices, including the motionstar and treadmill.

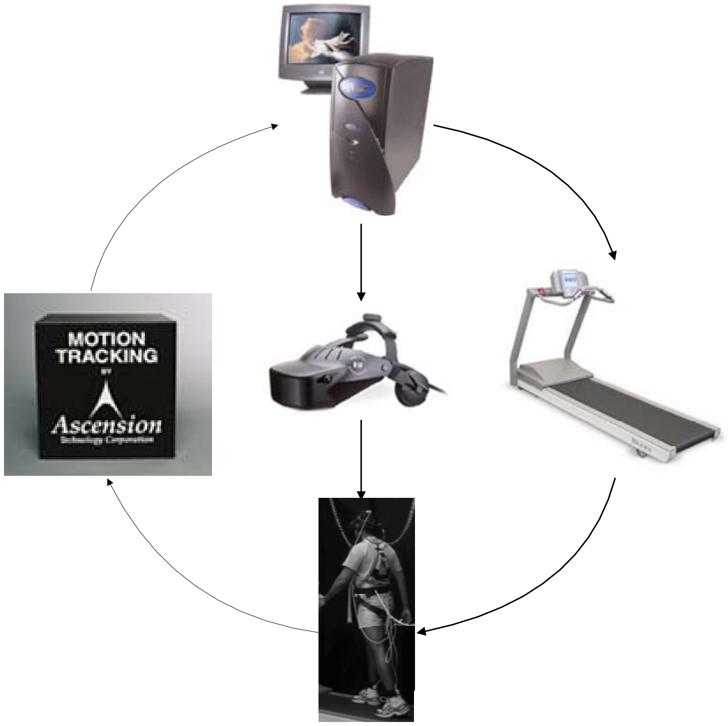


Figure 8.1 Schematic diagram of the VRLI setup.

In the VRLI setup, as a subject started to walk on the treadmill, the Motionstar sent position information on the hip and ankles of subjects to the VLE simulation running on the SGI workstation. This occurred through an Ethernet network. The simulation then used the subject position and velocity data to calculate the required speed of the treadmill and this information was sent to the treadmill using a serial port. The simulation also used the subject position data to update the avatar viewpoint translation and to present updated visuals to subjects through the HMD. Thus, the subject could vary their locomotion behavior on the treadmill and the speed of the treadmill belt adjusted adaptively. Figures 8.2 and 8.3 show images from the two VLEs developed for the validation experiment.

Figure 8.2 Simulation of the Ergonomics Laboratory.

Figure 8.3 Simulation of a hallway in Riddick Labs building.

9. VALIDATION OF THE VRLI

The use of the treadmill and its importance in locomotion research has been discussed in Section 5. This section further addresses the current evidence both for and against the use of TW data as a basis for making inferences on OW gait control. The goal of this preliminary investigation was to assess the effects of optic flow generated using VR technology on gait kinematics during TW and to determine whether the resulting locomotion behavior was comparable to OW. Visual cues during TW were provided through high-fidelity 3D graphical simulations of real environments in which OW trials were also conducted. Based on Prokop's research, it was hypothesized that the presence of visual cues (and, therefore, optic flow) during TW with VR (TWVR) would cause gait kinematics to differ substantially from a simple TW condition and to be comparable to gait kinematics observed in OW. In this way, the study was also to validate the VR locomotion interface setup as a reliable and affordable tool for complex locomotion research (e.g., studying cognitive factors in slip and fall scenarios).

9.1. Methodology

9.1.1. Participants

Nineteen (19) participants from the NCSU student population (5 females and 14 males) were recruited on a voluntary basis for the experiment. Gender was not used as selection criteria in recruiting participants for the study. Participants were selected at random resulting in unbalanced male-female ratio. The participants ranged in age from 21 to 36 years with a mean of 24.6 ± 3.7. Participants had 20/20 vision (with or without correction) and had some experience in training with a treadmill (however, this was not formally recorded through a survey).

9.1.2. Experiment design

An experiment was designed in which the participants walked under three locomotion conditions (LC), including OW, TW and TWVR, as well as three walking constraint (WC) conditions including no-constraint (NC), a temporal constraint (TC) and a spatial constraint (SC). The WC conditions were used as a check of the locomotion condition manipulation on gait behavior across different spatial and temporal circumstances. During the NC (control) condition, participants walked with their preferred (baseline) step length and cadence. Under the TC (or pacing) condition, participants walked with their baseline step length but were required to use a 25% higher cadence. Under the SC (or path following) condition, participants walked with a 25% longer step length at their baseline cadence.

Each participant was exposed to all combinations of LC and WC using a 3×3 completely within-subjects, repeated measure experiment design with four repetitions under each LC×WC combination. The participant served as a blocking factor with the LC manipulated as a whole-plot factor and the WC manipulated as a split-plot factor.

9.1.3. Task and setup

During the OW condition, participants walked on a wooden platform (20” wide by 25’ long) positioned along one wall of the Ergonomics Lab and covered with a rubber mat having a surface texture similar to the treadmill belt (see Figure 9.1). During TW, participants walked on the treadmill, which was placed inside a wooden canopy structure used to suspend a safety harness system (see Figure 9.2). Finally, in the TWVR condition, participants walked on the treadmill wearing the HMD and were immersed in a VLE (also see Figure 9.2).

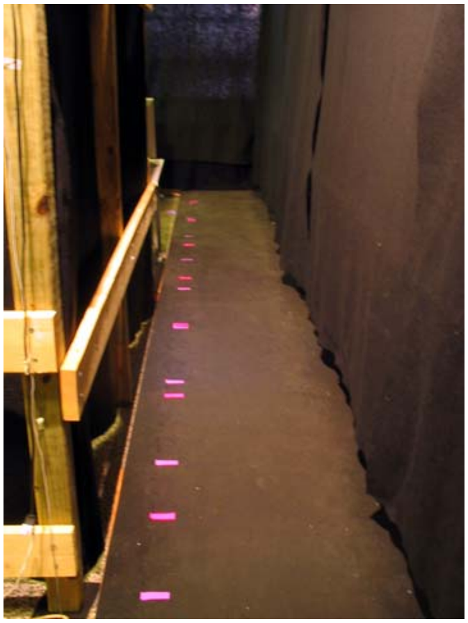


Figure 9.1 Overground walking platform.

Figure 9.2 Canopy structure with safety harness suspension system and treadmill.

Large black felt curtains were hung throughout the lab and within the canopy structure to clear the view volume of participants (during OW and TW) of potential visual distracter stimuli. In order to avoid injuries in the event of tripping under the TWVR condition, participants were required to wear a full-body harness hooked to a spring-mounted suspension system built into the canopy. The suspension system had a maximum capacity of 240 pounds. To avoid a possible bias in participant gait behavior under the TWVR condition due to use of the full-body harness, participants were also required to wear the harness under the OW & TW conditions. In order to re-create the effect of HMD usage during the TWVR trials under the other LCs (OW and TW), participants were required to wear a hard-hat with weights attached, providing a load distribution similar to the HMD. Light-shutter goggles were also worn by participants during the TW and OW conditions to restrict their peripheral vision and to make the environment viewing angle comparable to that caused by wearing the HMD during the TWVR condition.

Six spherical light-reflective markers were attached to the lower extremity of the participants to facilitate post-trial kinematic analysis of locomotion behaviors. The Peak motion measurement system with 2 high-speed cameras operating at 60 Hz was used to record complete test trials. Five markers were placed on the left side of the body and one on the right side. Left side markers were placed at (1) the head of the greater trochanter, (2) the lateral condyle of the tibia, (3) the lateral mallelous, (4) the head of the fifth metatarsal, and (5) the mid of the calcenous. On the right side, a marker was placed on the mid of the calcenous. These marker positions were later digitized using the Peak Motus software in order to calculate various gait kinematic and spatiotemporal variables.

9.1.4. Variables

Independent variables manipulated in this study comprised the LC (locomotion condition) with 3 levels (OW, TW and TWVR), and the WC (walking constraint) with 3 levels (NC, SC, TC). Dependent measures included the basic spatiotemporal variables of stride length, cadence and speed, which were generally examined in prior studies. We also measured temporal variables, including stance and swing phase (expressed as a percentage of stride time), single-limb and double-limb support phase (also expressed as a percentage of stride time), and gait kinematic variables such as knee and ankle angles at heel strike. These variables were determined from the digitization of the video recordings of trials using the Peak Motus system. (More details on the extraction of these variables from the videos are presented later.)

Beyond these kinematic response measures, we wanted to observe the relationship between participant perceptions of presence in the VLE during TWVR and gait behavior. We used a 19-question Presence Questionnaire (PQ) developed by Witmer and Singer (1994), which quantitatively represents subjective perceptions of the degree of immersion in a VE, including the degree of control over the VR (control factor), the fidelity of sensory stimuli (sensory factor), the degree of distraction from VE stimuli due to the interface (distraction factor), and the level of perceived realism (realism factor). The PQ was administered at the end of all trials under a specific WC. Thus, each participant completed three PQs during the course of the experiment. We speculated that as the sense of presence increases, user behavior in the VR might more closely approximate behavior in reality, including gait.

9.1.5. Procedures

Participants were first provided with an introduction to the experiment and the equipment. This was followed by completion of an informed consent and collection of anthropometric data such as sex, age, weight, height, length of the lower extremities and shoe size. Subsequently, participants stretched their leg muscles and prepared for the first LC of the experiment. Table 9.1 provides a summary of the procedures followed under each LC.

Table 9.1 Brief descriptions of procedures followed under each Locomotion Condition

Overground walking	
Training	Walk in a 35 meter long hallway (2 repetitions).
Baseline measurements	Step length and cadence were determined using number of steps and time taken to walk the hallway as if on a leisurely stroll.
Data collection	Walk on a wooden platform with step length and cadence controlled using floor markers (125% of baseline step length) and a metronome (125% of baseline cadence) according to the walking constraint condition (normal, spatial and temporal).
Treadmill walking	
Training	Walk on the treadmill for 10 minutes.
Baseline measurements	Step length and cadence determined using the time taken to walk 50-70 steps at a belt speed representative of a leisurely stroll.
Data collection	Walk on the treadmill with step length and cadence controlled using appropriate belt speed and the metronome, according to the walking constraint condition (normal, spatial and temporal).
Treadmill walking with VR	
Training	Walk using the VR locomotion setup for 15 minutes.
Baseline measurements	Step length and cadence determined using the time taken to walk 50-70 steps at a belt speed representative of a leisurely stroll.
Data collection	Walk on the VR locomotion setup with step length and cadence controlled using appropriate treadmill speed and the metronome, according to the walking constraint condition (normal, spatial and temporal).
Questionnaire	Complete simulator sickness and presence questionnaires at the end of four trials under each walking constraint condition.

The sequence of LCs was partially randomized to account for potential trial order effects. Three sequences were used in the experiment including: (1) OW-TW-TWVR; (2) TW-TWVR-OW; and (3) TW-OW-TWVR. These sequences allowed us to capitalize on participant experience with the treadmill, gained during the TW condition, in preparing them for TWVR trials. Within each LC, the sequence of WC conditions was randomized for each participant. At the end of the experiment, participants were debriefed on the objectives of the study. The total duration of the experiment ranged between 2.5 to 3.5 hours per participant.

9.1.6. Video data analysis

Gait data, including both the spatiotemoral and kinematic variables, were extracted from the test trial video recordings using the Peak Motus system. None of the participants reported any gait related pathology and hence we assumed gait symmetry. The fourth (and final) trial under each LC×WC condition was used for digitization purposes. This trial was used to ensure stable behavior from participants. The length of the digitized video consisted of one stride length (5-6 frames before a left heel strike to 5-6 frames after the next left heel strike). The digitized stride generally occurred after 10-15 steps following the beginning of a trial under the TW and TWVR conditions and from the 3rd step during OW. A fourth order zero-lag Butterworth filter was used to condition the data with a variable cut-off frequency calculated using the Jackson knee method (Jackson, 1979). This filtering algorithm was available as part of the Peak Motus system (Peak Performance Technologies, Peak Motus, Version 5, user manual).

Stride length, cadence and speed were determined using the horizontal (x) displacement of left and right heel markers. Heel down was determined using horizontal (x) velocity, and toe-off was determined using vertical (y) displacement of a heel marker. Swing and stance times and single and double support times were normalized using total stride time. Ankle angle was calculated based on the angle between the toe, heel and knee markers in the sagittal plane at a heel strike and was transformed to produce positive angles for dorsi-flexion and negative angles for plantar-flexion. Similarly, knee flexion angle was calculated as the angle between the hip, knee and heel marker in the sagittal plane at a heel strike.

9.1.7. Statistical analyses

An analysis of variance (ANOVA) was applied to a statistical model including the main effects of LC, WC and Subject along with the LC × Subject interaction term. All other insignificant second and higher order interactions were pooled with the error term. An alpha criterion of 0.05 was used for establishing the statistical significance of all test results. Power analyses using SAS Assist revealed that majority of tests on the dependent measures had high statistical power ($\beta<0.1$), save cadence, ankle angle and knee angle, which were below 0.8 ($\beta>0.2$). Duncan's multiple range test was used to investigate any significant differences among the means for the settings of LC and WC. Beyond this, Pearson Product-moment correlation coefficients were calculated on the overall PQ score and the four sub-factors, including the control factor, the sensory factor, the distraction factor and the realism factor, with all gait response measures observed during the TWVR condition in order to identify any significant relationships between the sense of presence in the VE and the locomotion behavior. Table 9.2 presents additional details on the aspects of a VE that contribute to each of the PQ sub-factors. Individual scores for the 19 items on the PQ collected during the TWVR trials were used to compute the overall presence score and scores for the sub factors (Witmer & Signer, 1998).

Table 9.2 Factors hypothesized to contribute to a sense of presence (Witmer & Singer, 1998).

Control Factors	Degree of control, immediacy of control, anticipation of events, mode of control, physical environment modifiability.
Sensory Factors	Sensory modality, environment richness, multimodal presentation, consistency of multimodal information, degree of movement perception, active search.
Distraction Factors	Isolation, selective attention, interface awareness.
Realism Factors	Scene realism, information consistent with objective world, meaningfulness of experience, separation anxiety, disorientation.

9.2. Results

All participants recruited for the experiment completed the locomotion test trials without any physical difficulty and the data on all participants, save one, were used in the analyses. One participant produced extreme (outlying) performance responses during the TW trials because of his adaptation to the treadmill as a work-out apparatus. The participant informed the experimenter (after the study) that he regularly used the treadmill for exercise. Each participant performed 4 trials under each of the nine combinations of LC ×WC, totaling 36 trials. Since only one trial was digitized under each LC × WC combination, 9 data points were available for every gait variable from each participant yielding a total of 162 (18 participants × 9 observations) data points across all subjects. The SAS GLM (general linear models) procedure was used in all ANOVAs to account for any missing observations in the data sets.

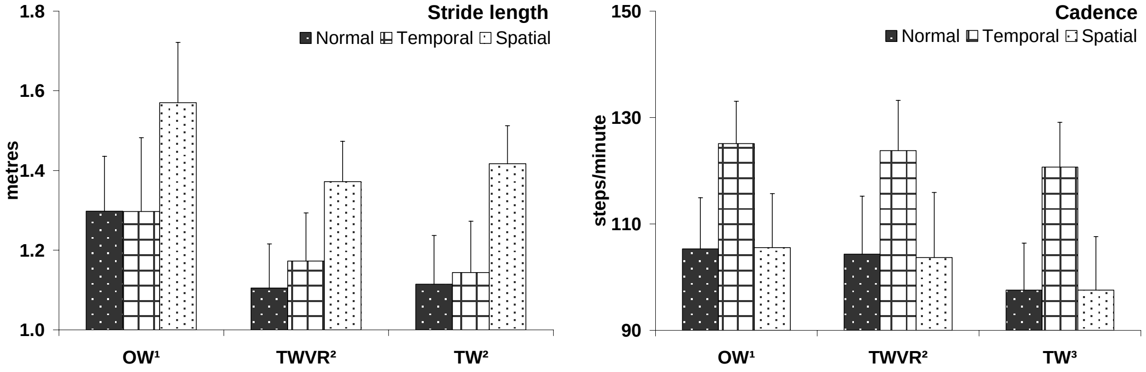
9.2.1. Gait variables

ANOVA results revealed significant effects of LC and WC on stride length, cadence, speed, swing and stance phase, single and double-limb support phase and ankle angle. Knee angle was affected only by the LC. All response measures were significantly affected by the Subject main effect. No significant effect of the LC × WC interaction was found on the dependent measures. The means and standard deviations for all dependent variables for each LC across all the levels of WC are presented in Table 3 along with the F-test and *p* values for the LC main effect. Figures 9.4, 9.5 and 9.6 shows the mean values of stride length (plate (a)), cadence (plate (b)), stance phase (plate (a)), double-limb support phase (plate (b)), and ankle and knee angles (plate (a) and (b)) respectively for each LC and WC combination. Error-bars have been included to represent one standard deviation on each mean response measure.

Table 9.3 Means, standard deviations and ANOVA results for LC main effect.

Superscripts (1,2) for the mean values indicate results of post-hoc grouping using Duncan's multiple range test.

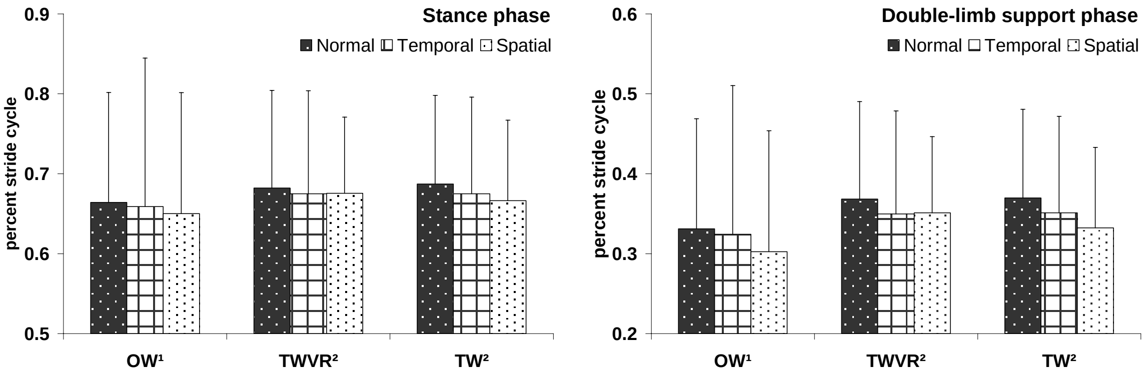
Response measure	OW		TWVR		TW			LC	
	Mean	SD	Mean	SD	Mean	SD	F	DOF	*p*
Stride length (m)	1.38^{1}	0.20	1.22^{2}	0.16	1.22^{2}	0.18	187.89	2,100	0.0001
Cadence (steps/min)	112.26^{1}	13.12	110.10^{2}	14.07	105.45^{3}	14.21	24.65	2,101	0.0001
Speed (m/s)	1.29^{1}	0.20	1.11^{2}	0.18	1.07^{3}	0.17	208.65	2,100	0.0001
Swing phase (% stride time)	0.34^{1}	0.02	0.32^{2}	0.01	0.32^{2}	0.02	28.42	2,101	0.0001
Stance phase (% stride time)	0.66^{1}	0.02	0.68^{2}	0.01	0.68^{2}	0.02	28.36	2,101	0.0001
Single stance phase (% stride time)	0.68^{1}	0.03	0.64^{2}	0.02	0.65^{2}	0.03	37.78	2,101	0.0001
Double stance phase (% stride time)	0.32^{1}	0.03	0.36^{2}	0.02	0.35^{2}	0.02	37.86	2,101	0.0001
Ankle angle at Heel strike (deg)	6.53^{1}	4.68	2.28^{2}	3.55	1.77^{2}	3.27	53.39	2,91	0.0001
Knee angle at Heel strike (deg)	4.62^{1}	5.12	4.63^{1}	4.62	2.59^{2}	4.53	5.34	2,93	0.0064



(a) (b)

Figure 9.3 Mean values of (a) stride length, (b) cadence for OW, TWVR & TW walking.

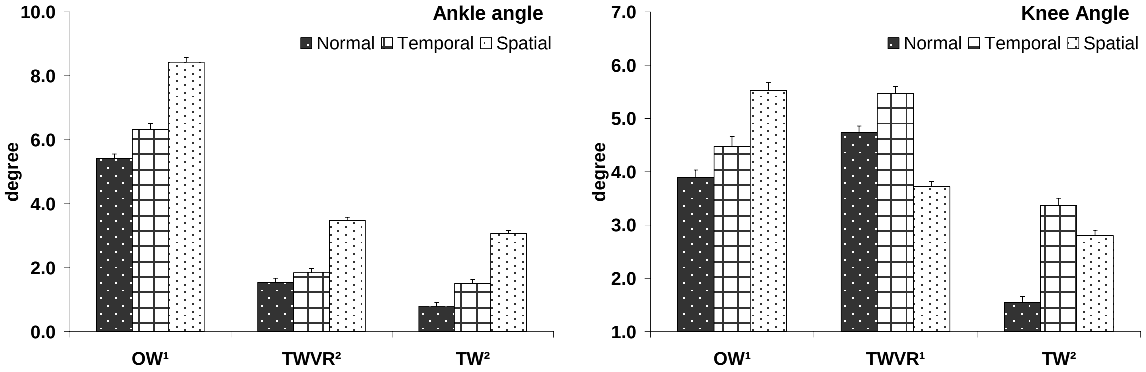
Superscript (1,2,3) indicate results of post-hoc grouping using Duncan's test.. Error bars present ±1 standard deviation.



(a) (b)

Figure 9.4 Mean values of (a) stance phase, (b) double-limb support phase for OW, TWVR & TW walking.

Superscript (1,2,3) indicate results of post-hoc grouping using Duncan's test.. Error bars present ±1 standard deviation.



(e) (f)

Figure 9.5 Mean values of (a) ankle angle, (b) knee angle for OW, TWVR & TW walking.

Superscript (1,2,3) indicate results of post-hoc grouping using Duncan's test.. Error bars present ±1 standard deviation.

Post-hoc analyses to investigate the specific effect of the LC on gait revealed that in OW, participants had a significantly longer stride length, as compared to TW and TWVR, which were similar. Cadence under OW was significantly different from TWVR, which in turn was significantly different from TW. Higher cadence and greater stride length under OW resulted in the highest walking speed followed by the TWVR condition and then TW. Analysis of ankle angle at heel strike revealed higher dorsi-flexion for OW, which was significantly different from TW and TWVR. However, knee flexion angle at heel strike was comparable between OW and TWVR, which were significantly different from TW.

Participants exhibited a significantly longer swing phase and shorter stance phase during OW than during the TW and TWVR conditions. Similarly, participants spent less time in double-limb support and more in single-limb support during OW than during TW or TWVR.

Table 9.4 presents the means and standard deviations for all dependent variables for each WC across all settings of LC along with the F-test and *p* values for the WC main effect. Not surprisingly, post-hoc analyses on the effect of the WC on gait variables revealed stride length during SC to be longer than NC and TC. Cadence during TC was higher than NC and SC conditions. Speed during the SC and TC conditions was not different and was significantly higher than for the NC setting. These results verify the nature of the WC manipulations. The swing phase during the SC and TC conditions was longer than for the NC, which resulted in longer stance time for the NC condition. The SC condition resulted in the longest single-limb support and shortest double-limb support times followed by the TC and NC conditions. Ankle angled during the SC and NC conditions were significantly different but not during the TC condition. No significance of the WC variable was found for knee angle during heel strike.

9.2.2. Presence and gait behavior

ANOVAs on PQ scores and control, sensory, distraction and realism sub-factors showed no significant effect of WC during the TWVR trials. Correlation analyses on the PQ scores, and its sub-factors, with the gait variables revealed a significant positive correlation between the sensory sub-factor of the PQ and locomotion speed (r=0.32, p<0.05); that is, an increased sense of presence in the VLE was associated with increased walking speed under the TWVR condition.

Table 9.4 Means, standard deviations and ANOVA results for WC main effect.

Superscripts (1,2) for the mean values indicate results of post-hoc grouping using Duncan's multiple range test.

Response measure	NC		TC		SC		WC		
	Mean	SD	Mean	SD	Mean	SD	F	DOF	*P*
Stride length (m)	1.17^2	0.15	1.21^2	0.14	1.45^1	0.17	470.41	2,100	0.0001
Cadence (steps/min)	102.37^2	10.22	123.17^1	10.73	102.32^2	9.15	293.94	2,101	0.0001
Speed (m/s)	1.00^2	0.16	1.24^1	0.18	1.23^1	0.17	295.81	2,100	0.0001
Swing phase (% stride time)	0.32^2	0.02	0.33^1	0.02	0.34^1	0.02	11.52	2,101	0.0001
Stance phase (% stride time)	0.68^1	0.02	0.67^2	0.02	0.66^2	0.02	11.28	2,101	0.0001
Single stance phase (% stride time)	0.64^3	0.03	0.66^2	0.03	0.67^1	0.04	19.26	2,101	0.0001
Double stance phase (% stride time)	0.36^1	0.03	0.34^2	0.03	0.33^3	0.04	18.59	2,101	0.0001
Ankle angle at Heel strike (deg)	2.47^2	4.24	3.09^2	3.88	4.53^1	4.67	13.42	2,91	0.0001
Knee angle at Heel strike (deg)	3.40	4.69	4.37	5.24	3.96	4.53	0.83	2,93	0.4394

9.3. Discussion

9.3.1. Overground versus treadmill walking

Our results indicated that OW produces stride lengths and cadences greater than under TW. This finding reinforces the contention that there are basic differences among these conditions, including optic flow, which may lead to differences in gait. These results are in partial agreement with those of previous studies that observed decreased stride length along with increased cadence under TW. Pearce et al. (1983) and Stolze et al. (1997) found increased cadence and decreased stride length during TW versus OW. Warabi et al. (2005) also found increased cadence during TW. Although Murray et al. (1985), White et al. (1998) and Matsas et al. (2000) did not find significant differences in OW and TW in terms of stride length and cadence, they all observed trends of decreasing stride length and increasing cadence.

This partial agreement is due to methodological differences between our study and previous studies. All the previous investigations that were reviewed required participants to choose a preferred walking speed during OW and the same speed was required during TW through experimenter manipulation of belt speed settings (Pearce et al., 1983; Strathy et al., 1983; Murray et al., 1985; Stolze et al., 1997; Alton et al., 1998; Matsas et al., 2000). When the same speed is used during TW as in OW, participants must maintain their speed by a combination of stride length and cadence (i.e., increased cadence and decreased stride length or vice-versa). However, in our study, participants selected a preferred walking speed during each LC, based on their perceptions of a "leisurely evening stroll". Prokop et al. (1997) observed that changes in optic flow patterns had an influence on gait parameters. This was the primary motivation for this study and, as such, the reason behind allowing participants to select a preferred walking speed under each locomotion condition. The objective was to specifically observe how the perception of walking speed changed across the three locomotion conditions and how it impacted gait behaviors. This approach facilitated a sensitive assessment of differences among the LCs. Since the participants self-selected the speed during TW, we inferred that the decrease in stride length and decrease in cadence compared to the OW condition was primarily due to the optic flow manipulation (specifically, the lack of optic flow).

It is important to note here that allowing subjects to select a preferred walking speed under each locomotion condition leads to a limitation in making comparisons in terms of stride length and cadence. Both stride length and cadence are positively correlated with speed and their rate of change may be different across different speeds. A regression analysis on the speed response measure for three LCs using stride length ($\beta 1$) and cadence ($\beta 2$) as predictors revealed parameter estimates for OW ($\beta 1$=0.892; $\beta 2$=0.011) and TWVR ($\beta 1$=0.893; $\beta 2$=0.010) to be almost equivalent, but the estimates for TW ($\beta 1$=0.840; $\beta 2$=0.009) were slightly different. Stride length (p<0.0001) and cadence (p<0.0001) did prove significant in predicting speed across LCs. A correlation analysis on the spatiotemporal variables revealed cadence and stride length to have a significant, negative linear association (r=-0.2, p<0.01).

In addition to optic flow, other factors have been identified as being potentially influential in differences in gait among OW and TW. Murray et al. (1985) said that decreased stride length in TW may be due to participant's anxiety associated with finite length of the treadmill belt. Alton et al. (1997) and Murray et al. (1985) suggested that treadmill users may have a sense of urgency to get their swinging leg on to the belt to maintain balance while the other leg is carried back and that this could cause increased cadence during TW. Stolze et al. (1997) said that the timing of stance and limb swing phases in TW may be handled differently by internal locomotor pattern generators than in OW when there are differences in the inflow of proprioceptive information. Related to this, Alton et al. (1997) and White et al. (1998) mentioned that the majority of participants in their study felt the speed of TW (the same as OW) in the absence of optic flow did not represent their OW speed and they perceived the speed of TW to be higher. This supports the contention that perception of self-motion during TW may be significantly degraded by a lack of optic flow otherwise available during OW. For this reason, the participants in the present study might have self-selected comparatively slower speeds during TW than TWVR and OW, which led to the longer stance phases (and double-limb support phases) and shorter swing phases (and single-limb support phases) for TW as compared to OW.

The present results revealed ankle dorsi-flexion angle at heel strike during OW to be significantly higher than TW and TWVR. This suggests that participants used a sharp heel landing during OW, as compared to flat-foot landing during TW and TWVR. None of the prior studies found any significant differences in ankle angle between OW and TW. Knee flexion angle at heel strike was found to be significantly different between OW and TW, with higher values for the former, but the OW and TWVR conditions were almost identical. Strathy et al. (1983) found significant differences in knee angle at heel strike between OW and TW, but did not provide any numerical values. Alton et al. (1997) did not find any significant differences. The lower ankle and knee angles observed in our study for TW could be attributed to lower speed and cadence, as compared to speed in OW trials, and potential participant anxiety and cautiousness during the TW conditions.

9.3.2. Introducing optic flow in treadmill walking

With the introduction of optic flow using VR in TW, the present results showed that stride length remained shorter than in OW. Cadence and speed were also significantly lower compared to OW, however the TWVR condition was also significantly different than TW in terms of the measures. The VLE we used was a scaled model of the actual OW environment and the speed of virtual movement in the VE was based on the actual walking speed of participants on the treadmill. Thus, we believe that the optic flow provided during TWVR trials influenced participant's perception of walking speed. As a result of shorter stride length on the treadmill (attributable to a sense of urgency or motor control programs), it is possible that participants increased their cadence to match the information from their visual and proprioceptive systems to perceived walking speed.

More interestingly, there was no significant difference between knee flexion angle in the OW and TWVR conditions. The knee angles observed for the TWVR condition demonstrate higher flexion than under the TW condition and gait behavior more closely approximating OW. This finding was not entirely expected. Since stride lengths were similar, it is possible that higher knee flexion occurred during TWVR as compared to TW as a result of hip flexion or pelvic rotation; however, these variables were not observed in the experiment. Participants could have relied more on the rotational moment generated at the knee joint (rather than the ankle) to maintain their balance, especially when there was lack of feedback on their physical position on the treadmill. It is important to note here that the knee angle measure was unidimensional and a multidimensional measure might have revealed more information about this change in gait behavior due to the use of the treadmill and optic flow. It should also be noted that these results should be interpreted with cautions since our power calculations revealed higher β-values for the gait kinematics variables.

A significant positive correlation between speed under the TWVR condition and the sensory sub-factor of the PQ indicated that an increased sense of participant presence in the VLE led to a more accurate perception of walking speed, relative to the OW condition. This was in line with the hypothesis that optic flow would enhance the sense of self-motion during TW and lead to changes in gait approximating OW.

It is important to note that since the 4th trial under each walking condition was analyzed, the applicability of the present results may be limited to situations in which there is a "break-in" period for subjects using treadmill. There could also be a gender bias in the response measures due to the unbalanced male-female participant ratio. The study utilized only one form of VR technology, which has it own quality, realism and feedback characteristics. Even though ambient lighting conditions used during the OW and TW conditions were simulated in the VLE for the TWVR condition, there might have been some differences that impacted gait behavior. The small number of markers used may have also been a limitation with respect to the amount of data collected on gait kinematics and gait characterization in the study. Future studies in this area need to apply additional controls for potential effects of these factors.

9.4. Conclusions

The presence of optic flow during TW through VR did impact gait behavior resulting in significantly higher cadence and higher speed, as compared to TW, and knee flexion angles for TWVR approximating OW gait behavior. The significant correlation of VE presence ratings with changes in gait speed during TWVR condition also supported the potential importance of optic flow using VR for motivating more realistic walking behavior with a locomotion interface. Gait behavior during TWVR did not completely approximate OW behavior, but TWVR was significantly different from TW for many response measures.

The differences between the OW and TWVR conditions may also be due to controllable factors including discomfort and disorientation in HMD use. Since the HMD worn during TWVR completely covered participants' peripheral vision, they did not have any visual contact with the ground or treadmill belt. Visually obscuring the ground influences the sense of stability, sense of trip-slip risk, and influences spatiotemporal and kinematic responses. This might have caused participants to display more cautious behavior during TWVR; thereby, partly masking the effect of optic flow on gait behavior.

This research revealed the impact of optic flow on locomotion behavior under VR and made direct comparison with OW. The work provides a basis for developing VRLI setups for enhancing locomotion research using treadmills. It can also be observed that a VRLI setup, as simple as the one used in this experiment, shows potential for application in locomotion research, specifically for evaluating gait behavior under normal walking conditions without perturbations for relatively short distances. A similar step was used in the primary experiment of this dissertation, but the treadmill included a force plate for additional data collection and subjects viewed the VLEs through a large rear projection screen (integrated with the canopy structure) and light-shutter goggles. The apparatus is described in detail in the next section.

10. EXPERIMENTAL METHODOLOGY

10.1. Objective

The objective of this experiment was to study the role of SA in human locomotion under multitasking scenarios, specifically its importance in dealing with perturbations to locomotion. The study was expected to provide empirical evidence to support the new model of SA in locomotion under multitasking situations and validate linkages between the levels of SA and types of gait control exhibited in response to perturbation hazards. The experiment was also expected to provide a quantitative description of SA during locomotion and the impact of potential discrepancies between a locomotor's internal situation model and reality and on the success rate of gait accommodation or avoidance strategies.

10.2. Experiment setup

The VRLI used in this experiment was a modified version of the setup used in the pilot experiment described in Section 9. Changes were made to the visual presentation of the graphical simulation and the type of treadmill. From the pilot study, we observed that using a HMD might have compromised the vestibular cues during walking on the treadmill and caused participants to walk with their heads at awkward angles, inconsistent with real-world walking postures. The participants also complained that the HMD was heavy and the heat produced by the electronics caused comfort issues and distraction of their attention from the VLE. Hence, we developed a 3D rear projection system using a stereo projector, an 8'×8' rear projection screen, and 3D light-shutter goggles. A single chip DLP (Digital Light Projection)-based Infocus DepthQ projector, capable of projecting images at 120 Hz (60Hz for each eye) was used. The screen was a laminated woven textile based rear projection screen from Draper and mounted on an aluminum frame. Stereo graphics input to the projector was generated by an Nvidia Quadro FX1400 graphics card with 128MB memory installed in a Dell Dimension 8400 machine with 3.2 GHz Hyper-threaded Pentium IV processor and running the Fedora 4 Linux operating system. A Stereographics infrared emitter connected to the graphics card using a 3-pin mini-DIN (Deutsches Institut für Normung) connector controlled the image display to the viewer through CrystalEyes light-shutter goggles. Through the glasses, a slightly different viewpoint of the VLE was presented to each eye at the rate of 60 Hz creating 3D effects. With this setup, vestibular cues remain uncompromised since participants can see their orientation in relation to the screen and can also see their physical location on the treadmill. This also allowed us to remove handrails from the treadmill apparatus to promote more natural walking. However, the safety harness system used in the pilot study remained intact. The use of stereographics goggles also prevented awkward subject head postures and discomfort.

The Biodex treadmill was replaced by a Kistler-Gaitway instrumented treadmill. This treadmill includes one force plates embedded beneath the belt that spanned the belt area. The force plate contains eight piezoelectric transducers that record ground reaction forces at a sampling frequency of 500 Hz. A Measurement Computing DAC16 16-channel data acquisition card installed on an ISA (Industry Standard Architecture) bus on the SGI Zx10 (used in the pilot study) machine acquired the output signals from the piezoelectric transducers through a Kistler charge amplifier attached to the treadmill. These output signals were processed by Kistler Gaitway software (KGS) for translation into force and position information, which were later exported as ASCII files for further processing and data analyses. Figure 10.1 shows the updated system. One important shortcoming of the

Kistler-Gaitway treadmill was the lack of computer control capability, like the Biodex treadmill used in the pilot study. This disadvantage was offset by the capability to acquire a variety of gait GRF data quickly, compared to the time consuming video digitization process used in the pilot experiment, with the Biodex device.

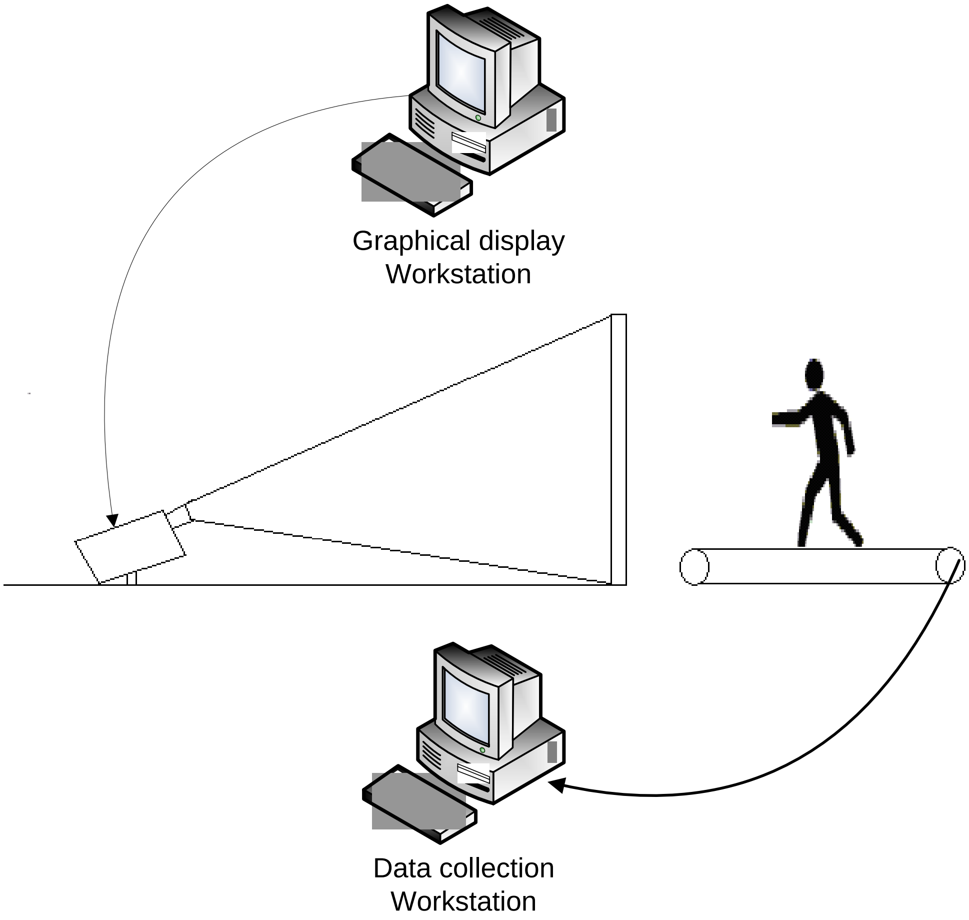


Figure 10.1 Updated VRLI setup.

Participants still wore the safety harness (used in the previous VRLI study) suspended from the canopy structure around the treadmill. They also wore ankle leashes connected to lawnmower engine starter recoils. The leashes provided the capability to simulate trips and slips by locking the recoils when the participant was in the early or late stages of swing phase. The VLE was displayed on the rear projection screen placed at approximately 5 feet from the center of the treadmill bed. Participants wore the 3D light-shutter goggles, which were controlled by the infrared emitter mounted on top of the projection screen facing towards the treadmill. Finally, participants wore a beanie hat with an Ascension Technologies Motionstar sensor mounted on top to capture participant head movement data and use them to drive the direction of the viewpoint in the VR simulation. Figure 10.2 shows a participant in the updated VRLI setup wearing the safety harness, ankle leashes, light-shutter goggles and the beanie hat, standing on the treadmill in front of the rear projection screen.

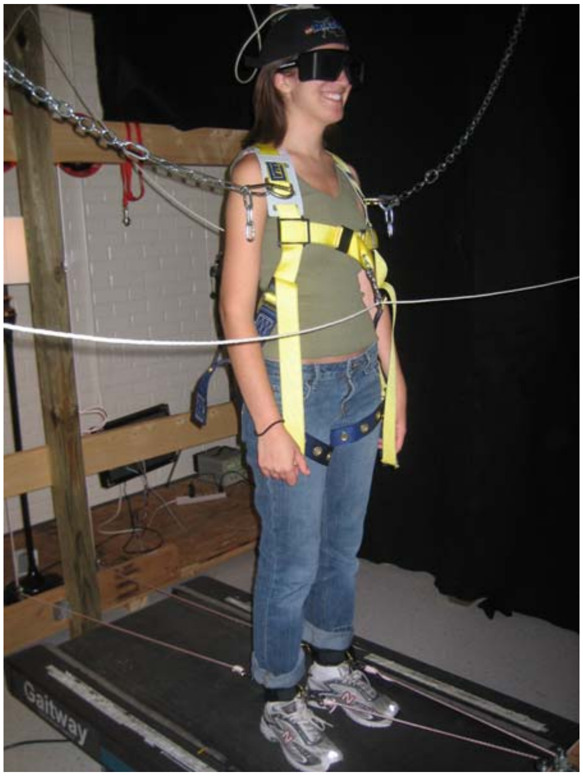


Figure 10.2 A participant in the updated VRLI setup.

10.3. Independent variables

Four independent variables were manipulated in this experiment including the navigation aid type (NT) provided in the locomotion task, the level of a priori knowledge (AK) of the task environment, visual cueing (VC) and/or physical cueing (PP) was provided on hazards. The type of navigation aiding was manipulated as a between-subjects variable. Half the participants performed instruction-based navigation (IBN) while the remaining subjects performed map-based navigation (MBN) of the VLE. Both groups were given the map of the task environment at the beginning of a trial with the start and end points marked on it and the walking route. They also had access to the map during the VR-based locomotion experience. Four scenarios with different start and end locations along with different routes were assigned randomly to participants in each trial for navigation. Three levels of a priori knowledge – no exposure to the VLE, exposure to the VLE and exposure to the VLE and a locomotion hazard was manipulated as a between-subjects variable. The setting of the variable corresponded to low, medium and high a priori knowledge of the task environment. It is important to note that the navigation task performance under IBN and MBN were different and hence the levels of AK were nested within NT.

The low knowledge group was trained on a low-fidelity VLE. The other two groups were trained on a VLE similar to the test VLE except the high knowledge group was also exposed to an artificial locomotion hazard, including visual and physical cueing (recoil stop). This factor was expected to manipulate the development of a subject's mental model of the task environment by varying the degree of exposure and experience with VLEs. The manipulation was expected to reveal the impact of levels of detail of a mental model on a subject's ability to develop and maintain accurate SA and, consequently, effect gait control mechanisms to hazards during locomotion while performing concurrent cognitive tasks. The two other independent variables, physical and visual cueing of the perturbation hazards were manipulated as within-subjects variables. Two kinds of perturbation hazards - slip and trip, were posed during the navigation task. A graphical object of a puddle of water was associated with a slip hazard and a graphical object of a pot-hole was associated with trip hazard. Each participant received four trials randomly assigned to each of the four perturbation cueing conditions – no cue, visual cue, physical cue, visual and physical cue.

10.4. Dependent variables

The dependent variables recorded in the experiment include percent correct responses to SA queries posed during the experiment trials, gait variables including weight acceptance (WA), mid-stance force (MS), push-off force (PO), weight acceptance rate (WAR), push-off rate (POR), slope (SLP) and sum of squares (SSE) of a linear line fitted to COP data. Refer to Section 3 for an explanation of the gait variables. SA queries were posed verbally during trials and participants responded verbally. Query responses and response time were recorded by the experimenter. The GRF and COP data time series recorded by the Kistler Gaitway software were exported as ASCII files and processed using a custom Matlab program to compile and generate gait variables of interest.

10.4.1. Situation awareness measurement

Measures of SA can be classified as subjective and objective measures. The most popular subjective measure is the Situation Awareness Rating Technique (SART) (Taylor, 1990). SART provides a 10-dimensional bipolar scale on three major factors – supply of attention, demand for attention, and understanding. Subjects rate each dimension using visual analog scales of measured length. Although, this method provides information on subject's confidence on SA, it is not an objective measure and is prone to memory decay since it is administered once at the end of a trial or the experiment.

SAGAT is the most commonly used direct, objective measure of SA (Endsley, 1995b). It has been shown to have a high degree of validity for measuring SA (Endsley, 2000). In this method, SA is captured by posing a series of questions to subjects at random points in time (SA freezes) during simulation trials. During the SA freezes, simulation displays are blanked and questions on subject perceptions, comprehension and projection are administered either electronically or using paper and pencil. After answering the SA queries, the simulation is resumed and the subject continues his/her task.

Even though some studies have empirically demonstrated a non-impact of SA freezes on task performance (e.g., Endsley, 1995b; Endsley & Kaber, 1999), many researcher remain skeptical of the effects of interruption of freezes on the continuity of performance and task outcomes (e.g., Hauland, 2000; Sarter & Woods, 1991). In an immersive simulation, like the VLE, it is possible that the level of involvement and immersion of subject senses in stimuli on the synthetic environment could be affected by SAGAT freezes. For the current experiment, freezing the simulation to ask questions before or after a perturbation might create a non-realistic feeling for subjects, since the scenarios were closely scripted to provide a natural multitasking experience involving locomotion. This scripting was intended to promote reliable assessment of the impact of subject internal situation models on the nature of gait control mechanisms developed to address perturbation hazards.

Consequently, due to the nature of the experiment design, an SA measure, which does not require task interruptions or influence the process of subject situation assessment is needed. Durso et al. (1998) utilized the Situation Present Assessment Method (SPAM) to assess the SA of air traffic controllers by posing queries at periodic intervals while controllers performed their task and displays remained in view. They found that there was a correlation between controller reaction time to the queries on Level 1 SA with a SME's (subject matter expert) subjective rating of controller performance. Jones and Endsley (2002) also used a real-time SA probe measure in experiments with air defense system operators under different task conditions (peace and war time) and found that a weak but significant correlation existed between probe response latency and probe accuracy. They also found a weak correlation of the accuracy of responses to probes with the percent correct subject responses to SAGAT queries administered in additional experiment test trials and subject ratings of perceived task workload.

Jones and Endsley (2002) identified several caveats associated with the use of real-time SA probe measures. Because of the weak correlation with SAGAT queries, they said that probes may measure some facets of SA, but that they may also be indicative of workload. They stressed the need for further study and validation of probe measures of SA. Jones and Endsley (2002) also identified some potential pit-falls of real-time probes, which include potential for cueing subjects to attend to specific information in the task environment that they may not be focused on as part of concurrent task performance.

A real-time probe measure of SA was used in this study in order to address the potential problem of task performance interruptions with a SAGAT measure, as discussed above.

However, to avoid the potential pit-falls of probes identified by Jones and Endsley (2002), an extensive goal directed task analysis (GDTA) on the locomotion navigation task and the task environment (test VLE) was conducted to identify specific SA requirements of locomotors. The GDTA was used to develop probes that targeted specific aspects of SA and subject memories of the environment that should be readily available during test trials. In this experiment, the accuracy of responses to real-time probes was used as a measure of SA, while the response time to a probe was used as an objective measure of workload. Probes were phrased in a manner to cause subject responses to be as short as possible. Example questions included: "How many turns have you made so far?"; "How many blocks are you from your destination?"; "What will be your next turn?"; "What were the last intersecting streets?"; "Is there a change in the walking surface?"; "Do you need to change your walking speed?" Jones and Endsley (2002) recommended that at least one probe be presented every 2-minutes. In this study, 9 probes (3 at each level of SA) were presented during each trial of approximately 5 minutes in duration. The type of probes and the location of presentation (in relation to the task environment) were identified in advance, as part of the scripting for each scenario.

10.5. Task

Participants were to walk in a suburban VLE (see Figure 10.3) and navigate from a start location to a destination. Before the beginning of a trial they were provided with a plan-view map of the VLE with their start and end locations marked as well as the route they were to walk. They were given up to 5 minutes to study the route before starting the trial. As mentioned earlier, the pool of participants was divided into two groups – map-based and instruction-based navigation aiding. The map-based group relied only on the map to navigate in the VLE and the instruction-based group was provided with navigation assistance through verbal instructions during trials, including specific turn commands. On approaching an intersection, an audio cue was played to prompt the participants to report their current location including current street name and the next/previous intersecting street names. An example location reporting would be – "I am on Barn Drive approaching the intersection with Silo Street." Following this reporting, navigation instructions were presented verbally through computer speakers. An example navigation instruction would be – "Continue on Barn Drive past Silo Street". Cues for location reporting and navigation instructions were played automatically by the simulation, based on participant position in the VLE.

Both participant groups had unlimited access to the VLE map during the simulation, which was presented in the top right corner of the display. Every time the map was displayed it would disappear within 10 seconds. In order to make a turn in the VLE, both groups needed to provide a verbal turn request ('right', 'left', or 'straight') upon reaching an intersection. A 3-way arrow was presented in the middle of the screen when approaching an intersection, as a cue to deliver the turn request (see Figure 10.3). Based on the predefined route, the participant's viewpoint in the VLE would be smoothly steered to make the turn. An error was recorded if the subject requested an incorrect turn; however, the simulation always kept them on the right track. For the instruction-based group, the location reporting, navigation instructions and turn request happened in a sequence. First the audio cue was played to prompt for a location report, followed by the specific navigation instructions and then presentation of the 3-way arrow to prompt for the turn request.

Figure 10.3 Image of the high fidelity suburb VLE.

While walking in the VLE, participants were posed with questions (SA probes), which targeted their awareness of various objects within the environment. These probes were presented verbally through the computer speakers and participants provided verbal responses, which were recorded by the experimenter. Similar to navigation instructions, SA probes were also played by the simulation automatically based on a participant's position in the VLE.

During navigation in the VLE, participants also encountered virtual locomotion hazards, such as pot-holes and puddles of water (see Figure 10.4). Physical cueing of these virtual perturbation hazards was administered by pulling the ankle leashes on the participant. A slipping perturbation was associated with puddles of water, by a forward pull of the right leg before heel down, and a tripping perturbation was associated with pot-holes, by a rearward pull on the right leg after toe-off. Figure 10.5 shows the ankle leash setup.

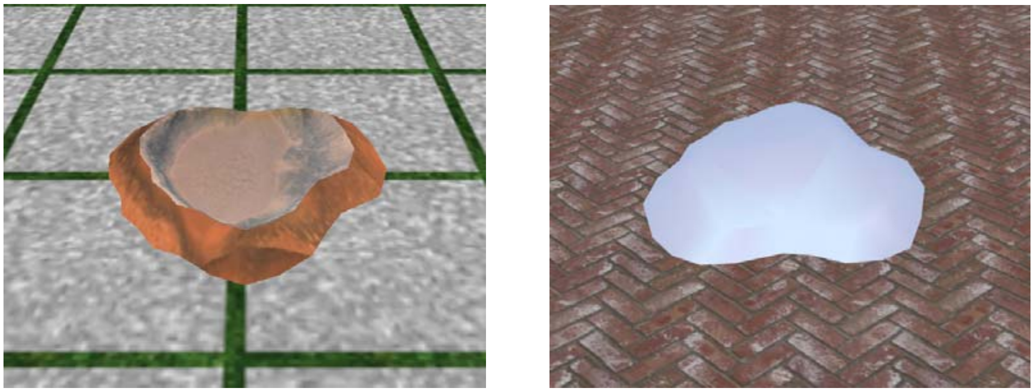


Figure 10.4 Graphical images of pot-hole and puddle of water used in the VLE.

Figure 10.5 Picture of the ankle leash setup.

10.6. Experiment design

A 2x3x2x2 mixed design was used in this experiment. Two levels of NT (navigation aid type) (map-based and instruction-based) and three levels of AK (a priori knowledge) (low, medium and high) were manipulated as between-subjects variable and two levels of VC (visual cueing) and PP (physical cueing) (presence or absence) of locomotion hazards were manipulated as within-subjects variable. Table 10.1 shows the overall data collection table for the experiment. The combination of the visual and physical cueing of perturbations resulted in four different types of trials. Trials with both visual and physical cueing were intended to represent real-world multitasking situations involving locomotion with perturbation hazards. Trials without either of these conditions provided a baseline for assessment of the effects of multitasking on locomotion. On the other hand, trials with only physical perturbations were expected to provide insight into purely reactive gait control responses and trials with only visual cueing were expected to provide evidence on purely predictive control. It was also expected that the cueing manipulation would help control for subject expectations and counter advance preparation for physical perturbations in the other trials.

Table 10.1 Data collection table based on the experiment design.

		Navigation Type																							
		Map-based												Instruction-based											
		Apriori knowledge of locomotion condition																							
		No exposure to VLE				Exposure to VLE				Exposure to VLE & Perturbation				No exposure to VLE				Exposure to VLE				Exposure to VLE & Perturbation			
Subject		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Visual cue	Physical cue																								
	No Physical cue																								
No visual cue	Physical cue																								
	No Physical cue																								

10.7. Subjects

Twenty four volunteers (12 male and 12 female) from the NCSU undergraduate and graduate student populations participated in the study. All subjects had uncorrected or corrected 20/20 vision (whether they wore glasses or not did not pose a conflict with the projection screen use). The average age of the sample of participants was 22.5±3.0 years (22.2±2.9 for male and 22.8±3.2 for female subjects). They walked at an average speed of 2.1±0.2 mph (2.09±0.24 for male and 2.11±0.16 for female).

10.8. Procedures

The experiment was conducted in one session of approximately 2 hours in duration. All instructions to participants were pre-recorded and played through computer speakers. When subjects came into the lab, they were given an overview of the experiment and procedures to be followed. They were then presented with an informed consent form (see Appendix A) and were given time to thoroughly understand the potential risk and benefits of the experiment. Participants who successfully completed the experiment received $20 for their time. Following this, anthropometric data such as gender, age, height and weight were recorded. Subjects were then provided with a warm-up period to stretch their lower leg muscles. The experimenter then helped the participants don the full-body harness and they walked on the treadmill for 10 minutes. Every time a participant walked on the treadmill, the safety harness was attached to the suspension system in the canopy structure. After the initial warm-up period, participants continued walking on the treadmill for another 5 minutes with the ankle leashes attached to the recoil system.

Following this, participants were introduced to the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) and completed the first SSQ to provide a baseline rating of symptoms. Subjects were then introduced to the enhanced VRLI (integrating Kistler treadmill and rear projection system), and practiced walking in an outdoor VLE. They wore the beanie hat with an integrated head motion tracking sensor and light-shutter goggles for 3D viewing of the simulation. After the initial introduction to the VRLI, they completed another SSQ to monitor for any simulator sickness. After this, subjects were trained on the navigation task. The VLE to which they were exposed depended on their a priori group assignment. The "low a priori knowledge" group walked in a low-fidelity VLE (Figure 10.6);

while the other two groups walked in a high-fidelity VLE (Figure 10.7) of a rural neighborhood.

Figure 10.6 Image of the low fidelity VLE.

Figure 10.7 Image of the high fidelity rural VLE.

Before performing the training trial, subjects were provided with a map of the VLE (Figure 10.8) and time to become acquainted with the defined walking route. They were trained on self-reporting of location and receiving on-line navigation instructions, if they were assigned to the IBN group. All participants received instructions on how to make turn requests in order to negotiate corners in the VLEs and how to use (verbally request) the electronic map through the VLE.

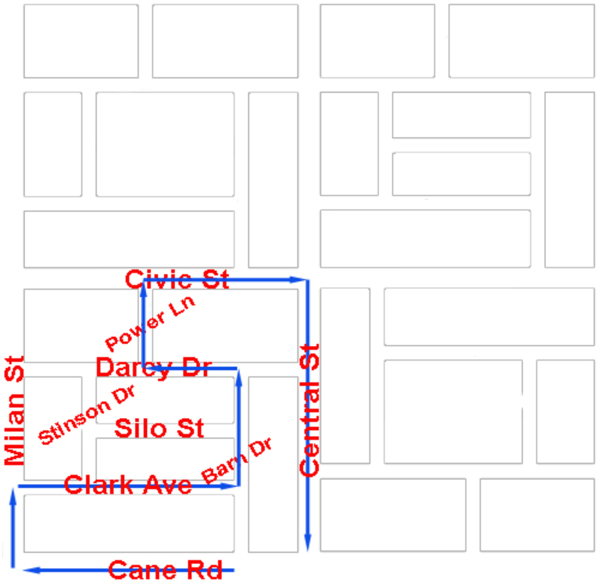
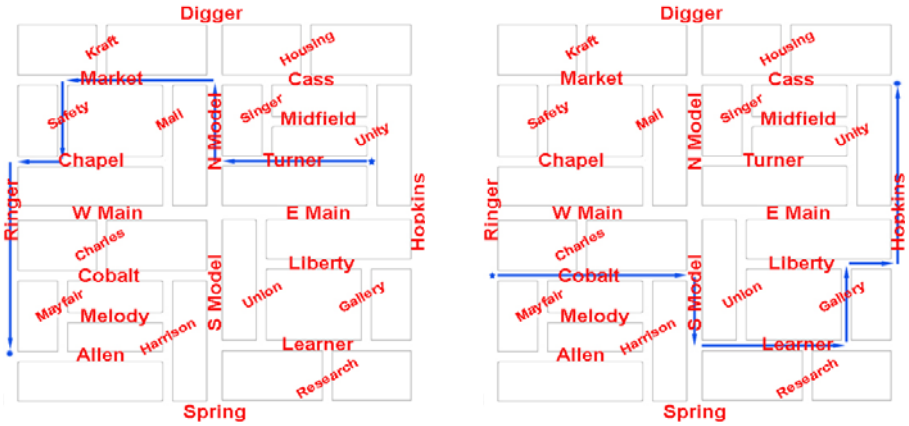


Figure 10.8 Map of the training VLE.

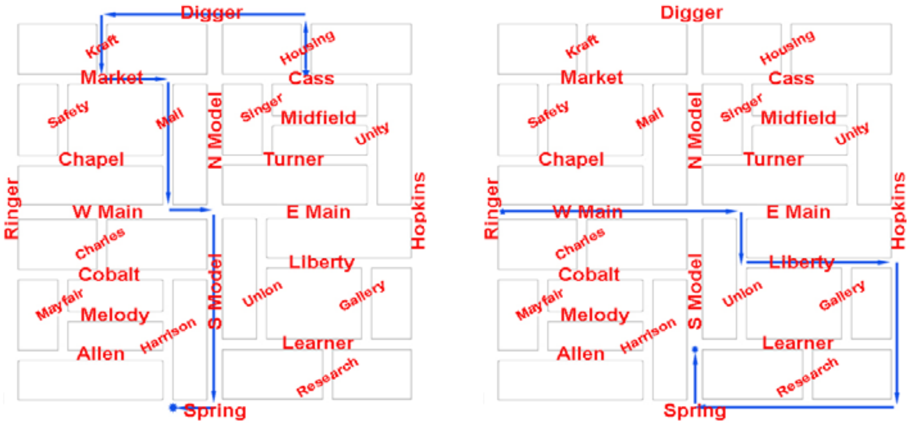
Finally, subjects were introduced to the SA probes to be administered during the navigation task. Participants belonging to the "high a prior knowledge group" were cautioned on the possibility of virtual locomotion hazards appearing during the simulation trial and were exposed to one trip perturbation with physical cueing administered through yanking of the ankle leashes, which lasted for approximately 200-300 milliseconds. During the training trial, participants were provided with assistance to make them knowledgeable and comfortable in the navigation task. Additional training was provided if the participants had difficulty performing the task. It was observed that some participants assigned to the instruction-based navigation required more training in order to become accustomed to the proper sequence of location reporting (on cue) along with listening to navigation instructions and requesting turns in the VLE. After this training, they completed another SSQ to determine if any simulator sickness symptoms had developed. Following this, they received a 5-minute break.

Following the break, all participants were given instructions about the experiment trials, specifically the possibility of appearance of virtual perturbations with or without a physical perturbation during navigation. They were advised to exercise caution in walking as they would in real life situations. Each participant completed four trials of approximately 5-minutes in duration. Before performing a trial, they were given the map of the test VLE with the predefined route marked clearly from the start to end location. Figures 10.9 and 10.10 shows the map marked with the four different routes followed during the test trials. Figures 10.11 and 10.12 show the sequence of events for scenario 1 during IBN and MBN respectively. Appendix B shows the form used for recording the participants SA probe responses. Participants were offered a 5-minute break at the end of the 2nd trial. After completing the 4th trial, participants completed another SSQ and were debriefed on the objectives of the study. Table 10.2 provides an overview of the procedures followed during the experiment and Appendix C shows the details of the instructions provided to the participants.



(a) (b)

Figure 10.9 (a)-(b) Map of the VLE with routes for scenarios 1 and 2.



(a) (b)

Figure 10.10 (a)-(b) Map of the VLE with routes for scenarios 3 and 4.

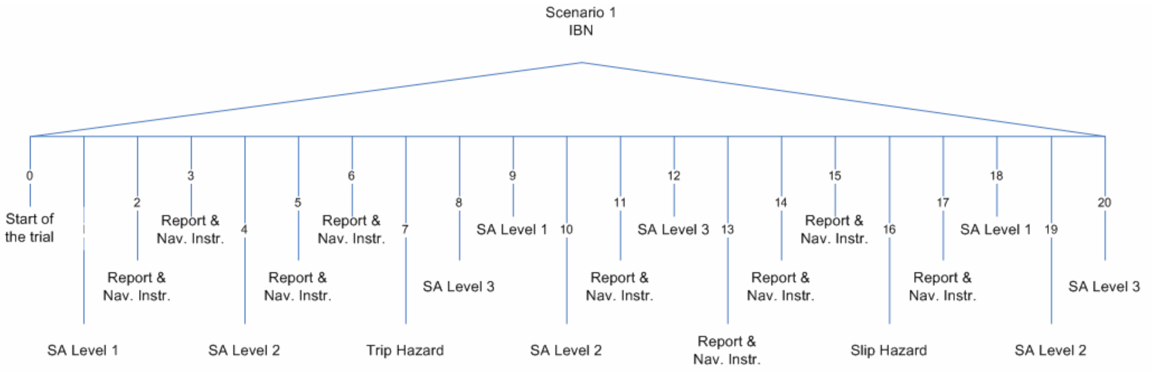


Figure 10.11 Sequence of events during a trial under IBN.

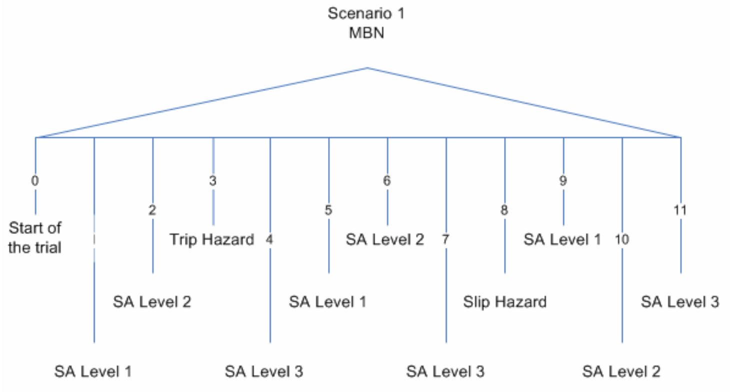


Figure 10.12 Sequence of events during a trial under MBN.

Table 10.2 Summary of overall procedure for the experiment, including the steps and associated times.

Step	Procedure	Time in min
1	Introduction to the experiment and overview of the procedures.	5
2	Completion of Informed consent form.	5
3	Collection of Anthropometric data.	2
4	Stretching of lower leg muscles.	5
5	Warm up on the treadmill.	10
6	Warm up on the treadmill with ankle leash.	5
7	Introduction to Simulator Sickness Questionnaire (SSQ) & completion of baseline SSQ.	5
8	Introduction to VR Locomotion setup and walking in outdoor VLE.	5-7
9	Completion of SSQ	2
10	Introduction and completion of training trial	10-15
11	Completion of SSQ	2
12	Break	5
13	Introduction to experiment trial	5
14	Completion of Trials 1 & 2	10-15
15	Break (optional)	5
16	Completion of Trials 3 & 4	10-15
17	Completion of SSQ and debriefing on the study	5

10.9. Hypotheses

10.9.1. A priori knowledge

It was hypothesized that prior knowledge and experience with the locomotion hazards would be a significant factor in participants exhibiting proactive gait control when exposed to such hazards (trips and slips). It was expected that participants with exposure to the training VLE comparable to the test VLE and a perturbation during training, would be more prepared to respond proactively when presented with hazards during test trials due to the development of a mental model of the environment and the nature of the hazards. It was expected that they would be able to exhibit proactive gait control compared to those with exposure to the low-fidelity VLE or no hazard exposure. It was also expected that proactive control could be identified by significant deviations in gait GRF variables, such as WA, MS, PO, WAR and POR in participant steps before encountering a virtual locomotion hazard from the mean value of GRF variables observed during training (baseline). Finally, it was expected that participants trained on the perturbations would reallocate attention to locomotion at appropriate times based on their experience, resulting in increased COP movement as indicated by higher sum of squares errors (SSE) for observations deviating from a linear trend fitted to the COP data for a test trial. It was also expected that those participants will devote adequate attentional resources to SA building resulting in correct responses to SA probes.

Subjects not exposed to the high-fidelity VLE were expected to have trouble dividing attention between locomotion and cognitive task performance due to the unfamiliar environment demanding higher visual attention to develop an accurate internal situation model. Consequently, this information processing for achieving SA was expected to cause participants to produce reactive responses to perturbations, as evidenced by no significant changes in gait GRF variables relative to training (baseline values) in participant steps preceding a perturbation and no significant changes in COP movement. Subjects were also expected to respond less accurately to SA probes.

Subjects exposed to the VLE used during testing but not to locomotion hazards were expected to have some form of situation model prior to testing, which might have aided them in predicting perturbations to locomotion to a limited extent. It was expected that performance by these participants would fall midway between the other two training (a priori knowledge) groups and that they might use predictive gait control strategies while multitasking with reasonable SA performance.

10.9.2. Navigation aid type

It was expected that participants in the instruction-based navigation group would have higher mental workload due to location reporting at every intersection and this might result in failure to notice potential locomotion hazards. It was expected that the cognitive task performance (verbal communications) would decrease attentional resources resulting in predictive responses to perturbations, decreased response accuracy to SA probes, and lower COP movement, when compared to the participants in the map-based navigation group. On the other hand, map-based navigation did not require any location reporting and this reduced the use of cognitive resources for the task performance leaving enough resources to divide between SA development and locomotion task performance.

10.9.3. Visual and physical cueing

Visual cueing of potential perturbation hazards in the VLE (i.e., graphical objects of potholes and puddles of water) was expected to increase proactive gait control. This would be reflected by significant changes to gait GRF variables for participant steps before reaching the virtual locomotion hazard relative to GRF variable mean values observed during training under no hazards. Visual and physical cueing of perturbations was expected to produce proactive/reactive gait control similar to real-world situations and to reinforce participant mental models on the locomotion hazards in the VLE. Only physical cueing of perturbations was expected to result in purely reactive gait responses causing diversion of attentional resources from cognitive task processing (navigation) to locomotion and to impact the accuracy of response to SA probes.

10.9.4. Interactions

Significant interactions were expected between AK, NT, and visual and physical cueing of perturbation hazards. It was expected that high AK with MBN and visual cueing would result in accurate SA probe responses with the lowest response times as well as proactive gait control, as indicated by significantly different values in gait GRF variables (including WA, MS, PO, WAR, POR and COP movement) relative to baseline values. If MBN was replaced by IBN and physical cueing of perturbation hazards was added to the above conditions, then the navigation task becomes more demanding and it was expected that dividing attention between the primary and secondary task (verbal communications) would result in reduced accuracy in SA probe responses and reduced proactive control, as indicated by smaller differences in gait GRF values and lower COP movements from the baseline values.

Participants with low AK performing the IBN and experiencing physical perturbations were expected to produce poor SA response accuracy and no significant increase in COP movements. These expectations were attributed to the potential for limited proactive control and more of reactive control. Subjects may have failed to perceive locomotion hazards during such trials and they may not have previous experience with a perturbation during training. This was expected to result in higher attentional demand due to postural control and poor performance on all response measures in terms of significant deviations from baseline response.

It should be noted that there could be a possible learning effect during the experimental trials for subjects who were not exposed to the VLE and/or locomotion perturbations during training (low and medium a priori knowledge group). These subjects may perform better during the latter trials compared to the first (unique) trials. However, the experiment design blocked on the subject and, consequently, any learning effects for subjects was distributed across the visual and physical cueing conditions using randomization.

11. DATA ANALYSES

Based on the design of the experiment, there were two between-subjects variables (NT and AK) and two within-subject variables (VC and PP of perturbations). The dependent variables recorded in the study included GRF variables, specifically WA, MS, PO, WAR and POR, and COP variables, specifically SLP and SSE, as well as participant response to SA probes.

GRF and COP data were extracted from the KGS (Kistler-Gaitway software) by exporting the recorded time-series as ASCII files. These files were later processed by a custom Matlab program to extract the forces, including WA, MS, PO, WAR and POR. For COP, a linear function was fitted to the x-y position data of each foot step and the corresponding slope and SSE were calculated. After extracting the variables of interest from the KGS, the series of walking steps relevant for the investigation were identified; that is, steps leading up to participants encountering a perturbation. The video recordings of trials were used to pin point the specific steps within the collected data for analyses. To facilitate synchronization between the video and gait data, a large LED counter was placed within the view volume of the camera used to record trials and it was triggered at the same time the KGS started acquiring data from the treadmill.

Subjects' verbal responses to the SA probes were recorded by the experimenter during the experiment. These were compared with the "ground truth" in the VR simulation. The percent correct responses to probes was calculated using an excel spreadsheet.

With respect to the specific hypotheses of the study, the response dataset was reduced to support only those analyses directly relevant to hypothesis testing, based on the following criterion:

Since only trials with visual cueing produced proactive control in participants, the data from those trials and trials involving visual plus physical cueing of perturbations were used in the analysis. Consequently, the two within-subjects variables, VC and PP, were collapsed into one new within-subjects variable called perturbation cueing (PC) with two levels – visual cueing (VC) and visual plus physical cueing (VPC). This dataset was used for the analyses of GRF and COP variables. Related to this, subject responses to perturbations during trials involving only physical cueing could not be captured because of the nature of the force plate setup under the treadmill belt and the algorithm used by the KGS to capture GRF and COP measures. KGS can recognize foot strikes only if one foot is within the one half of the force plate and the other foot on the other half of the plate. Anytime, this spatial constriction is violated, KGS couldn't recognize the foot strikes causing missing data points.

Each trial consisted of one slip and one trip perturbation and the order was balanced across the 4 walking scenarios. Even though the visual representation of a puddle or pot-hole suggested a slip or a trip hazard, the physical cueing simply involved yanking of one of the ankle leashes at different points during the right limb swing phase. Preliminary data analysis also did not reveal any main effect due to the perturbation type. Hence, it was decided that the final data analyses should not differentiate between the types of perturbation (i.e., slip or trip).

Participants had no prior expectation of the type of perturbation (VC or VPC) until they experienced the first perturbation within a trial. It was expected that subjects would exhibit greater proactive control in encountering a second perturbation. Therefore, only the GRF and COP data recorded for the second perturbations in trials was used to promote the sensitivity of analyses and hypotheses testing.

The entire dataset without any of the above criteria was used for SA analyses including the two between-subjects variables and the new within-subjects variable recoded to represent the two within-subjects variables explained in the Methodology section. The new within-subjects variable for this dataset consisted of four levels – visual only, physical only, visual plus physical and no cueing.

A Multivariate Analysis of Variance (MANOVA) was conducted on the GRF and COP variables due to the strong possibility of inter-correlation. Analyses of variance (ANOVA) were then conducted on any significant main effects and interaction effects revealed by MANOVA results. The statistical model used for the ANOVA on GRF, COP and SA response variables was as follows:

$$\begin{aligned} Y_{i,j,k,l,m,n} = {} & \mu + NT_i + AK(NT)_{j(i)} + PC_k + SUB(AK \cdot NT)_{l(j(i))} + TO_m \\ & + NT \cdot PC_{i,k} + AK \cdot PC_{j,k} + NT \cdot AK \cdot PC_{i,j,k} + \varepsilon_{(ijklm)} \end{aligned}$$

Where,

μ = Mean.

$Y_{i,j,k,l,m,n}$ = Response variable (GRF, COP and SA variables)

NT_i = Navigation type.

$AK(NT)_{j(i)}$ = A priori knowledge nested within navigation task.

PC_k = Perturbation cueing.
$SUB(AK \cdot NT)_{l(j(i))}$ = Subject nested within navigation task and a priori knowledge.
TO_m = Trial order of visual and visual + physical cueing
$\varepsilon_{(ijklm)}$ = Error.
i = 1, 2 (map-based or instruction-based navigation)
j = 1, 2, 3 (low, medium and high a priori knowledge)
k = 1, 2 (visual and visual + physical cueing) for GRF & COP analyses
= 1, 2, 3, 4 (visual, physical, visual + physical and no cueing) for SA analyses
l = 1…24
m = 1, 2

Towards the completion of participant training in the navigation task, force profile data was collected for a period of 20 seconds. GRF and COP data during that period was extracted to create a normal distribution for baseline walking conditions (i.e., no perturbations). All GRF and COP data during experiment trials were compared with the baseline distribution and expressed as z-scores. This approach yielded a normalized dataset suitable for comparison across participants. Related to this, the planned trial involving no cueing (no visual or physical perturbation) was not used as control because subjects could have been exposed to the condition at any point in the random sequence of trials. Thus, there might have been some bias in using data on this condition for generating baseline distribution of gait variables. Expected mean square (EMS) rules were used for defining pseudo F-tests to estimate the main effects of NT and AK since test trial conditions were not replicated. To study the main effects of NT, AK and PC on SA, a score for the total accuracy in responding to probes across all levels of SA was used in the analysis. Post-hoc comparisons were conducted using Duncan's Multiple Range test with an alpha criterion of 0.05. Simple effects analyses were conducted to further explain any significant interaction effects.

With respect to the predicted influence of SA on the onset of proactive control in gait responding to perturbations, Pearson's product moment correlation coefficients were calculated on the total SA score and the GRF and COP variables for each of the five strides directly preceding participant negotiation of the perturbation. These r-values were used as inputs to an ANOVA using the following statistical model.

$$\begin{aligned} Y_{i,j,k,l,m} = {} & \mu + NT_i + AK(NT)_{j(i)} + PC_k + SN_l + NT \cdot PC_{i,k} + NT \cdot SN_{i,l} + AK \cdot PC_{j,k} \\ & + AK \cdot SN_{j,l} + PC \cdot SN_{k,l} + NT \cdot AK \cdot PC_{i,j,k} + \varepsilon_{(ijkl)} \end{aligned}$$

Where,

μ = Mean.

$Y_{i,j,k,l,m}$ = Response variable (r-value between SA score & GRF and COP variables)

NT_i = Navigation type.

$AK(NT)_{j(i)}$ = A priori knowledge nested within navigation type.

PC_k = Perturbation cueing.

SN_l = Number of strides preceding perturbation (Stride 5 was the earliest stride included in the analyses and Stride 1 was the stride right before the participant experienced locomotion hazard)

$\varepsilon_{(ijkl)}$ = Error.

i = 1, 2 (map-based or instruction-based navigation)

j = 1, 2, 3 (low, medium and high a priori knowledge)
k = 1, 2 (visual and visual + physical cueing)
l = 1…5

This model allowed for assessment of the various main effects and interaction on the strength of SA in influencing proactive gait control. All analyses were conducted using SAS statistical software version 9.1 running on Windows XP operating system.

12. RESULTS

As mentioned in the previous section, the results presented here are from three types of analyses: (1) the IV effects on GRF and COP variables; (2) the IV effects on SA accuracy; and, (3) the correlation of SA with the occurrence of proactive gait control as revealed through the GRF and COP variables.

12.1. Ground reaction forces

Five GRF forces variables that describe gait were measured using the KGS including, WA (weight acceptance), MS (mid-stance), PO (push-off), WAR (weight acceptance rate) and POR (push-off rate). As previously stated, these variables were transformed into z-scores assuming a normal distribution and using statistical parameters for each participant's baseline walking performance (mean and standard deviation). The transformed GRF variables were used in all data analyses. Results of a MANOVA on the dependent GRF measures along with ANOVA results are shown in Table 12.1. Appendix D shows the ANOVA output for participant WA response. The MANOVA revealed all IVs, save NT and AK, as well as two-way and three-way interactions to be significant in affect on the family of gait response variables.

12.1.1. Weight acceptance force

It was expected that as the level of AK increased, there would be a progressive decrease in mean WA response due to subject proactive preparation for perturbations. It was also expected that the MBN would result in a lower WA response compared to the IBN condition. An ANOVA on WA showed significant main effects due to PC (perturbation cueing) (F(1,336)=7.50; $p<0.05$), TO (trial order) (F(1,336)=10.23; $p<0.05$) and individual differences (F(17,336)=6.14; $p<0.0001$) (Here it should be noted that the numerator degrees of freedom in the F-test for subject main effect amounted to 17 because of missing subjects). The analysis also revealed a significant three-way interaction between NT, AK and PC (F(2,336)=6.37; $p<0.05$) (see Figures 12.1 and 12.2). The ANOVA results revealed that VC (visual cueing only) (mean=0.089; SE=0.14) resulted in higher WA (as evidenced by higher z-scores) compared to VPC (visual plus physical cueing) (mean=-0.250; SE=0.17). The ANOVA also revealed that WA during the second trial with visual cueing (i.e., a VC or VPC trial following previous exposure to the VPC or VC) to be significantly lower (mean=-0.257; SE=0.17) than in the first exposure to visual cueing (mean=0.124; SE=0.01).

Further analysis of the three-way interaction effect also revealed an overall trend of higher WA during VC (relative to baseline) than during VPC of locomotion hazards. More specifically, significantly higher ($p<0.05$) WA z-scores were observed during the MBN (map-based navigation) with low AK and VC (mean=0.521; SE=0.50) compared to VPC under the same NT and the high AK condition (mean=-0.765; SE=0.75). When MBN is used and AK is high, WA appears to be far lower than for low AK, particularly during VPC. Similarly, WA z-scores during IBN (instruction-based navigation) under medium AK and VC were significantly higher ($p<0.05$) (mean=0.493; SE=0.41) compared to VPC (mean=-0.621; SE=0.45) under same NT and AK condition. The difference in the cueing condition appeared to be more important under IBN when subjects have some knowledge of the VLE.

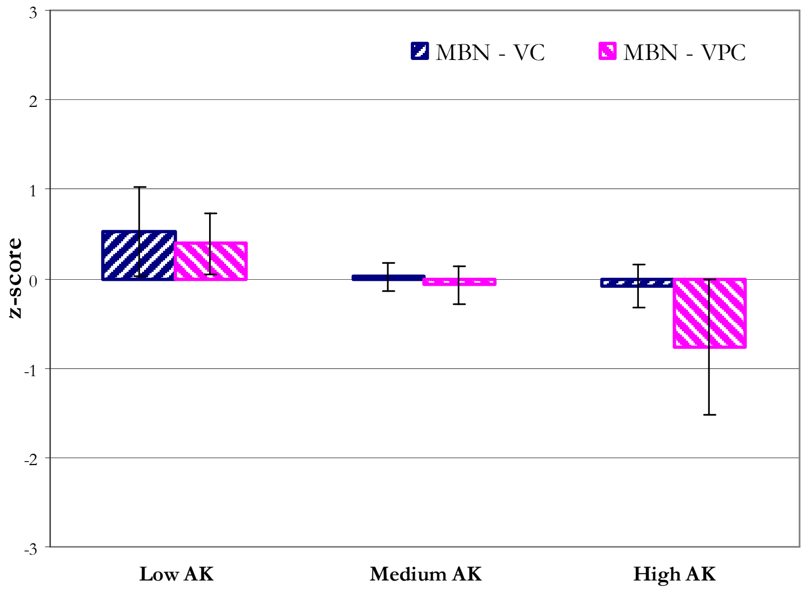


Figure 12.1 WA z-scores plotted against AK levels for MBN under each PC condition.

(Error bars represent ± standard error. Lower z-scores indicate more cautious gait behavior relative to baseline gait performance)

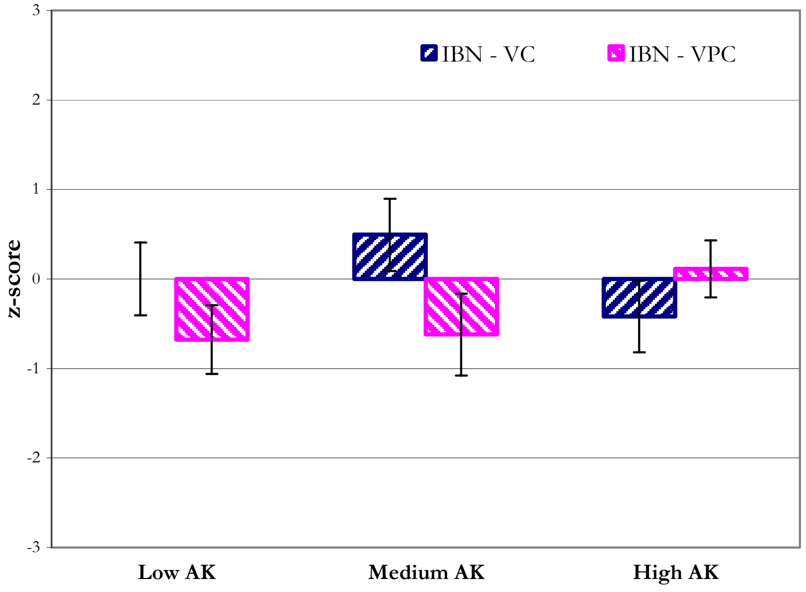


Figure 12.2 WA z-scores plotted against AK levels for IBN under each PC condition.

(Error bars represent ± standard error. Lower z-scores indicate more cautious gait behavior relative to baseline gait performance)

Table 12.1 MANOVA and ANOVA results for GRF and COP variables.

		ANOVA results						
		Dependent variables						
Independent variables	**MANOVA (Wilks' Lambda)**	**WA**	**MS**	**PO**	**WAR**	**POR**	**SLP**	**SSE**
Navigation type (NT)	F(7,11)=0.34 $p=0.9212$							
A priori knowledge (AK)	F(14,22)=0.86 $p=0.6049$							
Perturbation cueing (PC)	F(7,330)=2.63 $p<0.05$	F(1,336)=7.50 $p<0.05$	F(1,336)=0.07 $p=0.7862$	F(1,336)=4.29 $p<0.05$	F(1,336)=2.60 $p=0.1079$	F(1,336)=0.22 $p<0.6420$	F(1,336)=0.29 $p=0.5893$	F(1,336)=0.19 $p=0.6623$
Subject (SUB)	F(119,2162)=7.7 $p<0.0001$	F(17,336)=6.14 $p<0.0001$	F(17,336)=15.57 $p<0.0001$	F(17,336)=18.08 $p<0.0001$	F(17,336)=6.47 $p<0.0001$	F(17,336)=8.03 $p<0.0001$	F(17,336)=4.04 $p<0.0001$	F(17,336)=3.90 $p<0.0001$
Trial order (TO)	F(7,330)=5.58 $p<0.0001$	F(1,336)=10.23 $p<0.05$	F(1,336)=11.81 $p<0.001$	F(1,336)=8.04 $p<0.05$	F(1,336)=0.51 $p=0.4776$	F(1,336)=1.03 $p=0.3116$	F(1,336)=0.17 $p=0.6793$	F(1,336)=4.57 $p<0.05$
NT * PC	F(7,330)=2.92 $p<0.05$	F(1,336)=0.03 $p=0.8674$	F(1,336)=1.11 $p=0.2938$	F(1,336)=5.94 $p<0.05$	F(1,336)=0.46 $p=0.4998$	F(1,336)=12.09 $p<0.001$	F(1,336)=1.51 $p=0.2193$	F(1,336)=2.27 $p=0.1329$
AK * PC	F(14,660)=4.39 $p<0.0001$	F(2,336)=0.21 $p=0.8135$	F(2,336)=16.02 $p<0.0001$	F(2,336)=4.86 $p<0.05$	F(2,336)=0.68 $p=0.5070$	F(2,336)=4.13 $p<0.05$	F(2,336)=1.20 $p=0.3020$	F(2,336)=1.69 $p=0.1868$
NT * AK * PC	F(14,660)=4.97 $p<0.0001$	F(2,336)=6.37 $p<0.05$	F(2,336)=6.23 $p<0.05$	F(2,336)=19.61 $p<0.0001$	F(2,336)=0.04 $p=0.9652$	F(2,336)=1.99 $p=0.1382$	F(2,336)=3.67 $p<0.05$	F(2,336)=0.08 $p=0.9261$

12.1.2. Mid-stance force

For the MS response, similar to WA, it was expected lower values would occur for subjects with higher AK and those that experienced the MBN condition. An ANOVA on MS z-scores showed main effects due to TO (F(1,336)=11.81; $p<0.001$) and individual differences (F(17,336)=15.57; $p<0.0001$). The analysis also revealed a significant two-way interaction between AK and PC (F(2,336)=16.02; $p<0.0001$) and a significant three-way interaction between NT, AK and PC (F(2,336)=6.23; $p<0.05$).

The ANOVA results on the TO effect showed that the second exposure to a perturbation trial produced significantly lower MS z-scores (mean=-0.698; SE=0.17) than the first trial (mean=-0.286; SE=0.14). This suggested that subjects may have been more cautious in their gait behavior once they were familiar with the nature of the perturbation through a previous trial with visual cueing (with or without physical cueing). Further analysis of the two-way interaction between AK and PC showed that VPC under high AK produced the lowest MS response (mean=-1.566; SE=0.37) while VPC under medium AK produced the highest (more than baseline) MS response (mean=0.992; SE=0.21). VC condition produced a consistent response under all AK levels. Further analysis of the three-way interaction between NT, AK and PC showed a similar relation as the two-way interaction under IBN condition. Under MBN condition, higher than baseline MS response were observed under medium AK for both VC (mean=0.524; SE=0.24) and VPC (mean=0.704; SE=0.18) conditions. VPC condition under MBN produced greater proactive behavior with significantly lower MS response under high AK (mean=-1.673; SE=0.75; p<0.05).

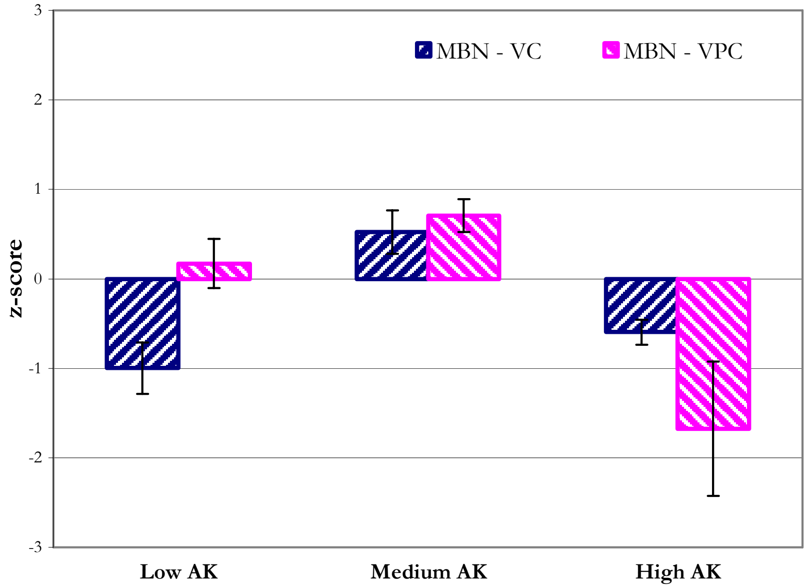


Figure 12.3 MS z-scores plotted against AK levels for each PC condition under MBN.

(Error bars represent ± standard error. Lower z-scores indicate more cautious gait behavior relative to baseline gait performance)

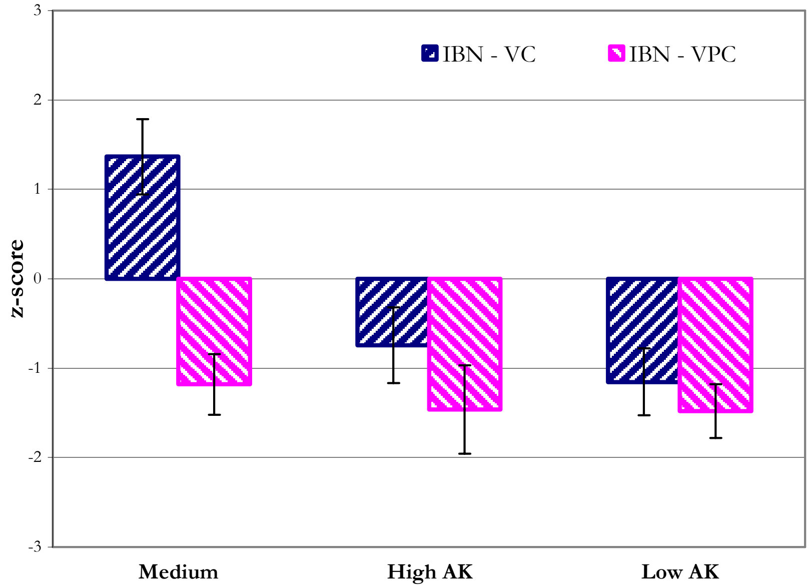


Figure 12.4 MS z-scores plotted against AK levels for each PC condition under IBN.

(Error bars represent ± standard error. Lower z-scores indicate more cautious gait behavior relative to baseline gait performance)

12.1.3. Push-off force

It was expected that higher PO might be evident under higher AK and the MBN condition due to subject expectation of the need for proactive gait control. An ANOVA on the PO z-scores showed significant main effects due to PC (F(1,336)=4.29; $p<0.05$), TO (F(1,336)=8.0; $p<0.05$) and individual differences (F(17,336)=18.08; $p<0.0001$). There were also significant two-way interactions between NT and PC (F(1,336)=5.94; $p<0.05$) as well as AK and PC (F(2,336)=4.86; $p<0.05$) and a significant 3-way interaction between NT, AK and PC (F(2,336)=19.61; $p<0.0001$).

The ANOVA results on the PC effect revealed VC to produce higher z-scores ($p<0.05$) (mean=0.152; SE=0.15) compared to VPC (mean=-0.100; SE=0.20). This suggested that subjects may have been more cautious when they experienced the physical perturbation. Similarly, ANOVA results on TO main effect showed that participants used significantly higher ($p<0.05$) PO during the second trial (mean=0.071; SE=0.17) compared to the first trial (mean=-0.014; SE=0.17). Further analysis of the two-way interaction between AK and PC revealed the highest z-score for VC under high AK (mean=0.829; SE=0.21) and the significantly lowest score ($p<0.05$) for VPC under low AK (mean=-0.678; SE=0.41). Figure 12.5 indicates a linear trend between the PO z-scores and AK levels for both VC and VPC conditions. One would expect to see a lower PO response in relation to lower WA and MS responses during walking. However, since the speed of the treadmill belt remained constant during the entire trial, any changes to the gait, such as shorter, flatter steps, resulted in increased steps per minute. As a result of this, higher values of PO would have been possible along with lower WA and MS response as the participants prepared proactively to encounter a locomotion hazard. In line with this argument, higher mean PO z-scores were observed with higher levels of AK.

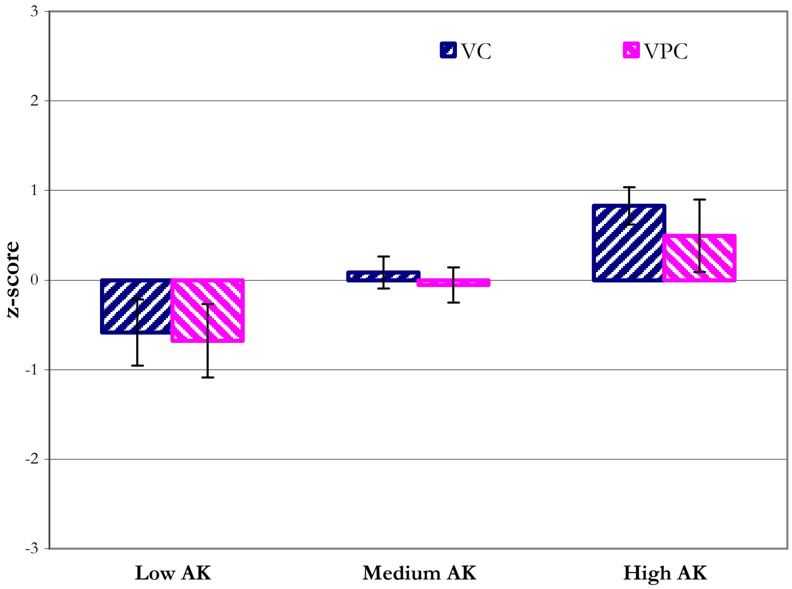


Figure 12.5 PO z-scores plotted against AK for VC and VPC conditions.
(Error bars represent ± standard error. Higher z-scores indicate more cautious gait behavior relative to baseline gait performance)

Further analysis of the two-way interaction between NT and PC showed significantly higher ($p<0.05$) PO z-scores during MBN compared to IBN for both VC and VPC condition. Table 12.2 shows the means z-scores and standard error for each NT and PC combination and Figure 12.6 provides a graphical presentation of the relationship. This result is consistent with WA and MS, where participants showed more caution (proactive preparation) under MBN compared to IBN condition. Further analysis of the three-way interaction between NT, AK and PC showed IBN under high AK and VPC to produce the highest PO z-score (mean=1.469; SE=0.25), while IBN under low AK and VC produced the lowest (mean=-1.359; SE=0.63) (see Figures 12.7 and 12.8).

Table 12.2 Post-hoc grouping of NT and PC interaction.

Grouping	Mean	Std. Err.	NT	PC
A	0.546	0.17	MBN	VC
A	0.234	0.25	MBN	VPC
B	-0.325	0.26	IBN	VC
B	-0.434	0.30	IBN	VPC

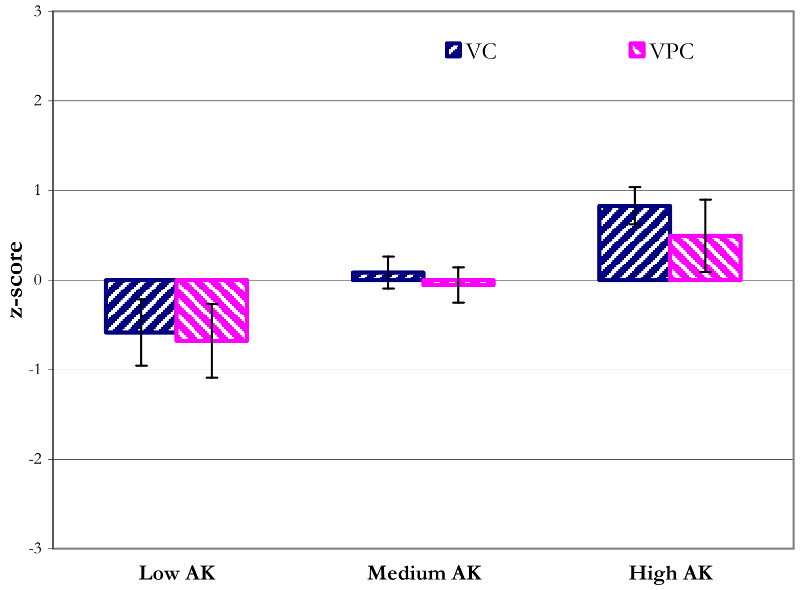


Figure 12.6 PO z-scores plotted against NT for VC and VPC conditions.

(Error bars represent ± standard error. Higher z-scores indicate more cautious gait behavior relative to baseline gait performance)

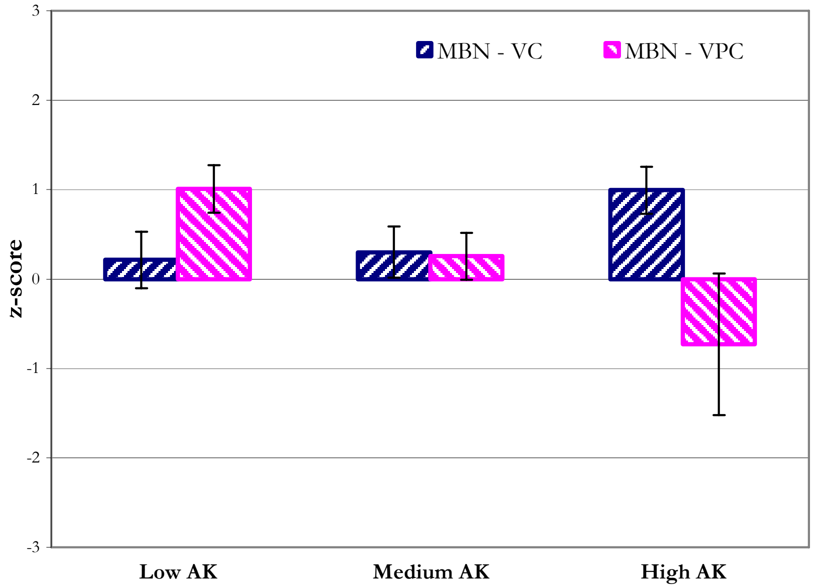


Figure 12.7 PO z-scores plotted against AK for VC and VPC conditions under MBN.

(Error bars represent ± standard error. Higher z-scores indicate more cautious gait behavior relative to baseline gait performance)

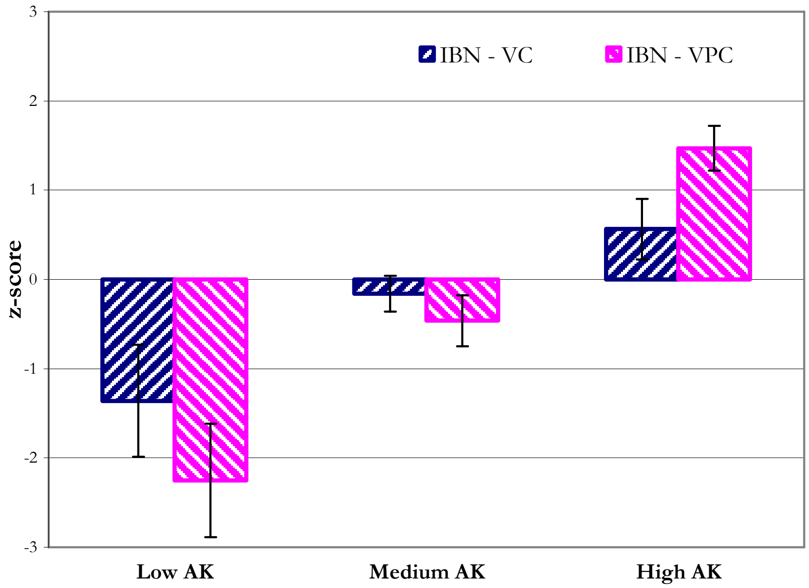


Figure 12.8 PO z-scores plotted against AK for VC and VPC conditions under IBN.
(Error bars represent ± standard error. Higher z-scores indicate more cautious gait behavior relative to baseline gait performance)

12.1.4. Weight acceptance rate

With proactive control, it was expected that WAR would be higher due to lower observed WA, especially for higher AK and the MBN condition. An ANOVA on WAR z-scores revealed main effects due to PC (F(1,336)=5.61; $p<0.05$) and individual differences (F(17,336)=6.47; $p<0.0001$). The ANOVA results showed that the mean z-score for VPC (mean=0.611; SE=0.18) was significantly higher ($p<0.05$) than VC (mean=0.093; SE=0.13). No significant interaction effect was observed.

12.1.5. Push-off rate

Similar to the expectation for WAR, POR was also expected to be higher under higher AK and the MBN condition. An ANOVA on POR z-scores showed a significant main effect due to individual differences (F(17,336)=8.03; $p<0.0001$) and also significant two-way interactions between NT and PC (F(1,336)=12.09; $p<0.001$) as well as AK and PC (F(2,336)=4.13; $p<0.05$).

Further analysis of the AK and PC interaction showed that z-scores were significantly different ($p<0.05$) between medium (mean=0.084; SE=0.22) and high (mean=0.829; SE=0.22) AK for the VC condition. Figure 12.9 shows the POR z-scores plotted against AK levels for the VC and the VPC condition. In general, the plot indicates a positive linear trend in POR with increasing level of AK. Low AK with VPC produced the lowest z-score (mean=-0.678; SE=0.17; $p<0.05$). Further analysis of the NT and PC interaction showed that POR z-scores under IBN with VC (mean=-0.266; SE=0.22) were significantly lower ($p<0.05$) than IBN with VPC (mean=0.625; SE=0.15). Figure 12.10 shows the z-scores of POR for VC and VPC plotted against NT conditions.

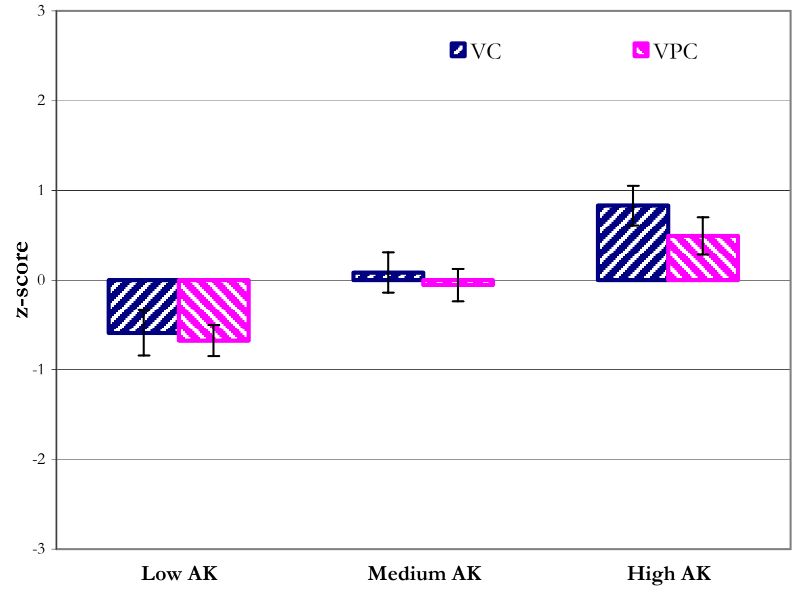


Figure 12.9 POR z-scores plotted against AK for VC and VPC conditions.

(Error bars represent ± standard error. Higher z-scores indicate more cautious gait behavior relative to baseline gait performance)

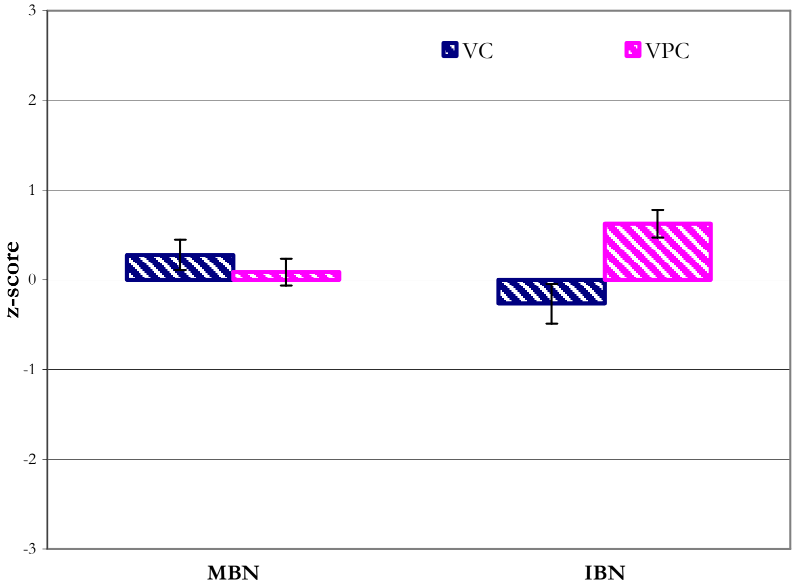


Figure 12.10 POR z-scores plotted against NK for VC and VPC conditions.

(Error bars represent ± standard error. Higher z-scores indicate more cautious gait behavior relative to baseline gait performance)

12.2. Center of pressure

Similar to the GRF variables, z-scores were calculated for the COP variables based on a baseline distribution for the locomotion of each participant recorded during the training period. Variables analyzed included the SLP (slope) and SSE (sum of squares of errors) of a linear trend fitted to the COP data. It is important to note that there was approximately 6.3% variation in the number of data points collected among test trials, which were used in the regression analyses to determine COP SSE. Table 12.1 presents MANOVA and ANOVA results on the COP dependent measures. Again, the MANOVA results did not reveal significant main effects of NT or AK on the COP variables.

12.2.1. Slope

It was expected that higher AK and MBN would result in a higher COP SLP on account of voluntary changes to gait due to proactive preparation for hazards. An ANOVA on SLP z-scores showed no significant main effect except that of individual differences (F(17,336)=4.04; p<0.0001). However, there was a significant three-way interaction between NT, AK and PC. Further analysis of the three-way interaction using Duncan's test showed that SLP during MBN under the high AK with the VC (mean=0.493; SE=0.20) was higher (p<0.05) than the VPC (mean=-0.365; SE=0.34) condition. Similarly, SLP during IBN under medium AK (mean=0.622; SE=0.23) was significantly different from high AK (mean=-0.756; SE=0.45) for VC of locomotion hazards. Figures 12.11 and 12.12 show the SLP z-scores plotted against AK for each NT and PC condition. From the plots, it can be observed that the SLP under medium AK was generally higher than in the high AK condition, except for MBN under the VC condition. Results indicated higher AK to produce higher SLP indicative of higher proactive preparation.

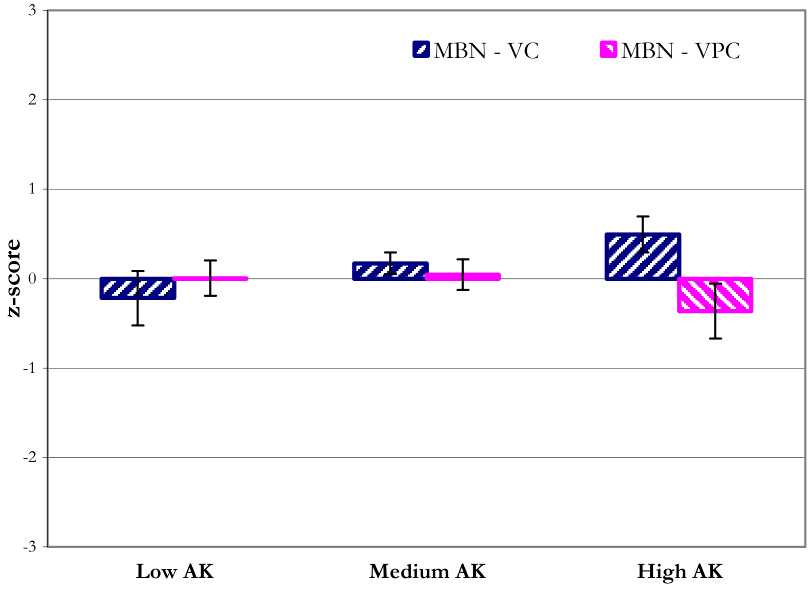


Figure 12.11 SLP z-scores plotted against AK for each PC condition under MBN.
(Error bars represent ± standard error. Higher z-scores indicate more cautious gait behavior relative to baseline gait performance)

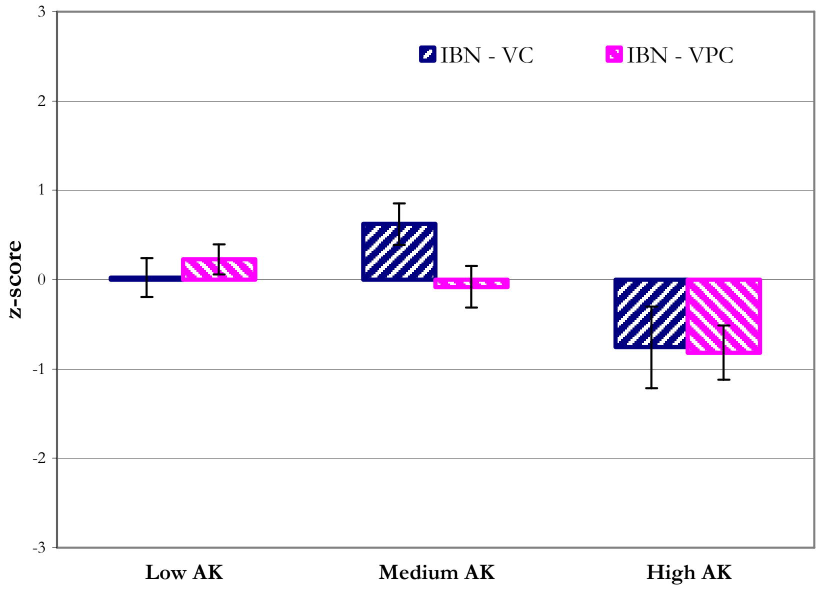


Figure 12.12 SLP z-scores plotted against AK for each PC condition under IBN.
(Error bars represent ± standard error. Higher z-scores indicate more cautious gait behavior relative to baseline gait performance)

12.2.2. Sum of squares of errors

It was expected that higher COP SSE may be due to voluntary changes in gait by participants for control and, hence, it was expected that higher SSE would occur under higher AK and the MBN condition. An ANOVA on the SSE z-scores showed main effects due to TO (F(1,336)=4.57; *p*<0.05) and individual differences (F(17,336)=3.90; *p*<0.0001). No effect due to two-way or three-way interactions was observed. ANOVA results on TO showed that SSE z-scores were significantly lower (*p*<0.05) for the first trial (mean=0.406; SE=0.10) compared to the second trial (mean=0.711; SE=0.13). The results suggest that proactive gait control produced COP variability higher than that observed during baseline (normal) walking.

12.3. Situation awareness

Overall SA scores and SA scores for each level were calculated for the various scenarios. For analysis of overall SA scores, the general statistical model was used without the TO term. For the analysis of SA scores by level, the TO term was replaced by a variable representing the levels of SA and its two-way interactions with all other IVs were modeled. As mentioned earlier, unlike the GRF and COP analyses, all four PC conditions were used in this analysis including, visual only, physical only, visual plus physical and no cueing conditions.

12.3.1. Overall SA score

It was expected that higher AK would result in higher SA scores. It was also expected that the IBN would promote better participant awareness of the environment because of location reporting in order to receive navigation instructions and hence higher SA scores. An ANOVA on overall SA scores failed to reveal any significant main effects due to NT, AK or PC or any interaction effects. Though not significant, mean values of the overall SA score when plotted against AK for all PCs indicated a trend of higher scores for medium AK compared to low or high AK (Figure 12.13). This trend was inline with the pattern of results on the gait variables.

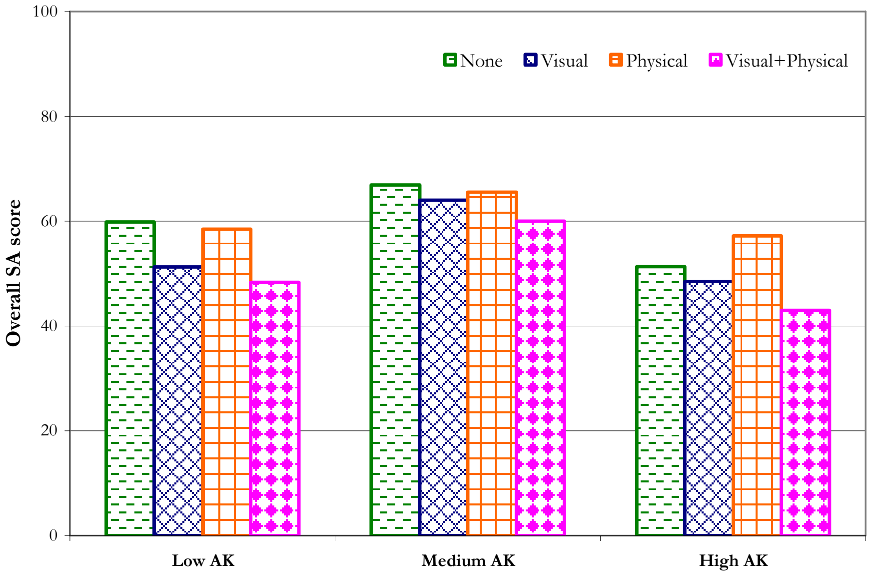


Figure 12.13 Overall SA score plotted against AK for all PC conditions.

12.3.2. SA score by level

An ANOVA on SA scores by level revealed a significant main effect due to individual differences (F(18,231)=1.86; *p*<0.05) and a significant two-way interaction between NT and levels (F(2,231)=3.84; *p*<0.05). Further analysis of the two-way interaction showed that there was a significant difference (*p*<0.05) between mean SA score under IBN among level 2 (mean=63.271; SE=4.14) and level 3 SA (mean=48.234; SE=4.30). This suggests that subject projection of states of the navigation environment may not have been comparable to their capability to comprehend the current state of the VLE when instructions were provided for navigation. Figure 12.14 provides a graphical representation of the two-way interaction between NT and SA levels. It can be observed that the scores under IBN show a higher trend compared to MBN for level 1 and 2 SA. For level 3 SA, it can be observed that MBN (mean=61.854; SE=3.73) resulted in higher scores compared to IBN (mean=48.234; SE=4.30). This suggests that IBN may support operational and tactical behaviors in locomotion; whereas, MBN may better support strategic behavior.

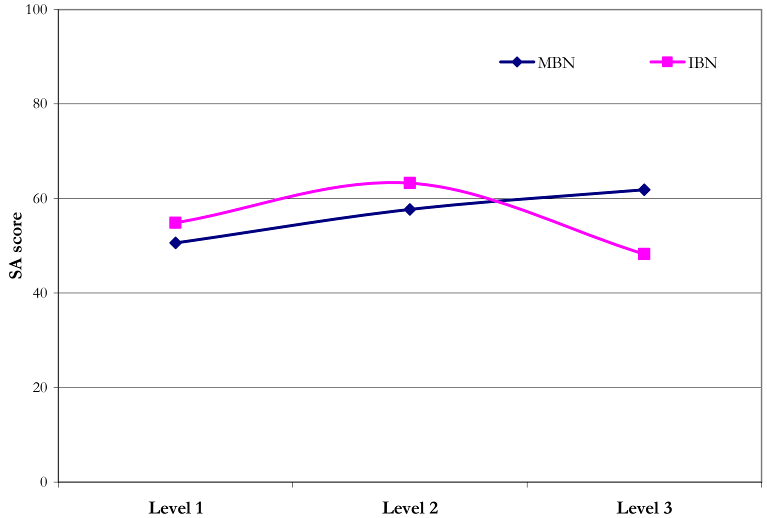


Figure 12.14 SA score by level plotted against NT.

12.4. SA effect on proactive gait control

It was expected that correlations between SA scores and the GRF and COP variables for the 5 strides leading up to a perturbation would provide evidences supporting the effect of SA on proactive gait control. Before calculating these correlations, overall correlations between total SA (SAT) scores and mean GRF and COP variables were calculated to investigate any significant linear association. Results revealed a marginally significant correlation between SAT and WA under the VC condition ($r=0.36$; $p=0.10$). Similarly, overall correlation coefficients were calculated for SA Level 1 (SAL1), SA Level 2 (SAL2) and SA Level 3 (SAL3) with the gait variables. Significant correlations were observed between SAL2 and WA under the VC condition ($r=0.43$; $p<0.05$), and SAL2 with SLP under the VPC condition ($r=0.43$; $p=0.05$).

Further analyses were conducted to assess the potential influence of the NT and AK manipulations on the strength of the significant linear associations between SA scores and gait variables, as described above, for the strides leading up to perturbations. ANOVAs were conducted with the calculated correlations between SA scores and gait variables (for each pre-perturbation stride) as response measures and the controlled experimental manipulations and interactions as predictors. The model used for this analysis was presented in the Data Analysis section. It is important to note that in these analyses, the PC condition has only two levels – visual only and visual plus physical cueing.

12.4.1. SAT association with WA

An ANOVA on the correlation between SAT and WA revealed significant main effects due to NT, AK and STRIDE number preceding the perturbation. All the two-way and three-way interactions proved to be significant, save AK*STRIDE, which was marginally significant ($p<0.10$). Table 12.3 shows the ANOVA results for all terms assessed in the statistical model.

Table 12.3 ANOVA results of IV effects on SAT and WA correlations across 5 strides preceding a hazard.

IV	**F-value**	**p-value**
NT	F(1,20)=12.46	$p<0.05$
AK(NT)	F(4,20)= 4.04	$p<0.05$
PC	F(1,20)= 0.25	$p>0.05$
STRIDE	F(4,20)= 2.86	$p=0.05$
NT*PC	F(1,20)= 8.87	$p<0.05$
AK*PC	F(2,20)= 4.00	$p<0.05$
NT*STRIDE	F(4,20)= 4.25	$p<0.05$
AK*STRIDE	F(8,20)= 2.07	$p<0.10$
NT*AK*PC	F(2,20)= 3.90	$p<0.05$
NT*AK*STRIDE	F(6,20)= 2.71	$p<0.05$

The ANOVA results on the NT main effect showed that the mean r-value (correlation between SAT and WA) was lower for MBN (mean=-0.36; SE=0.06) compared to IBN (mean=-0.13; SE=0.08). This suggests that higher SAT scores are associated with lower WA responses, which is a sign of proactive preparation for a hazard. However, the strength of this association appears to be greater under MBN compared to IBN. Further Analysis of the AK main effect using Duncan's post-hoc test showed that the Low AK condition under IBN produced a significantly positive mean r-value (mean=0.26; SE=0.18) compared to high AK under MBN, which produced a significantly negative mean r-value (mean=-0.47; SE=0.10) across the strides leading up to a perturbation. Figure 12.15 shows the distribution of mean r-values across different levels of AK under both NT conditions. It can be seen from the plot, there is a progressive increase in the strength of the association between SAT and WA with the increase in the level of a prior knowledge of the task environment. This increase is evident in both MBN and IBN conditions but at different magnitudes as described by the NT main effect.

Post-hoc analysis of the STRIDE main effect on the linear association of SAT and WA showed a significantly lower ($p<0.05$) r-value for Stride 4 (mean=-0.07; SE=0.11) compared to Strides 3 (mean=-0.39; SE=0.14) and 1 (mean=-0.33; SE=0.15). Figure 12.16 shows the SAT-WA correlation across the 5 strides leading up to perturbation (Note: Stride #1 is the stride directly preceding subject negotiation of the locomotion hazard – pot hole or water puddle). It is interesting to note that there was a higher SAT-WA correlation at one stride before the perturbation (r=0.33) and three strides before the perturbation (r=0.39). This data suggests that groups of participants might have used two different strategies – i.e., one stride advance preparation and/or three strides advance preparation.

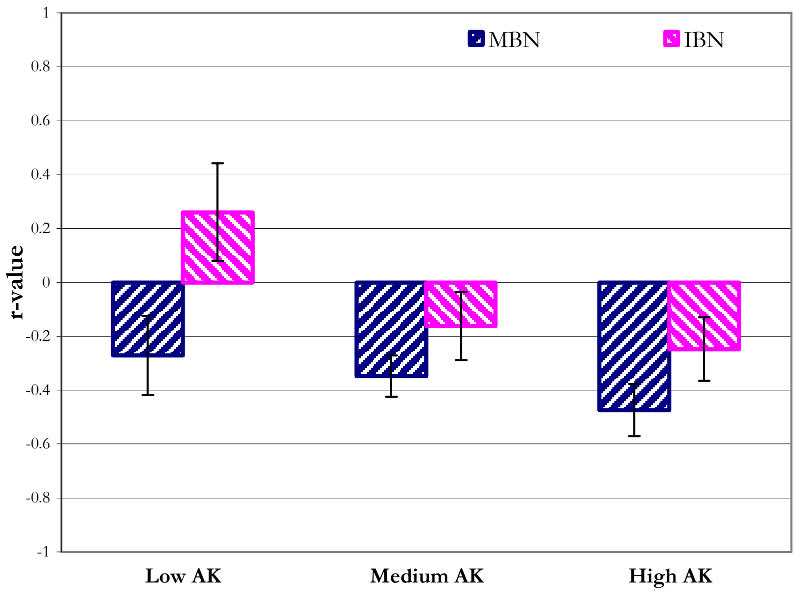


Figure 12.15 SAT correlation with WA for levels of AK under each NT condition.
(Error bars represent ± standard error. Lower r-values indicate higher SA was associated with lower WA indicative of proactive performance)

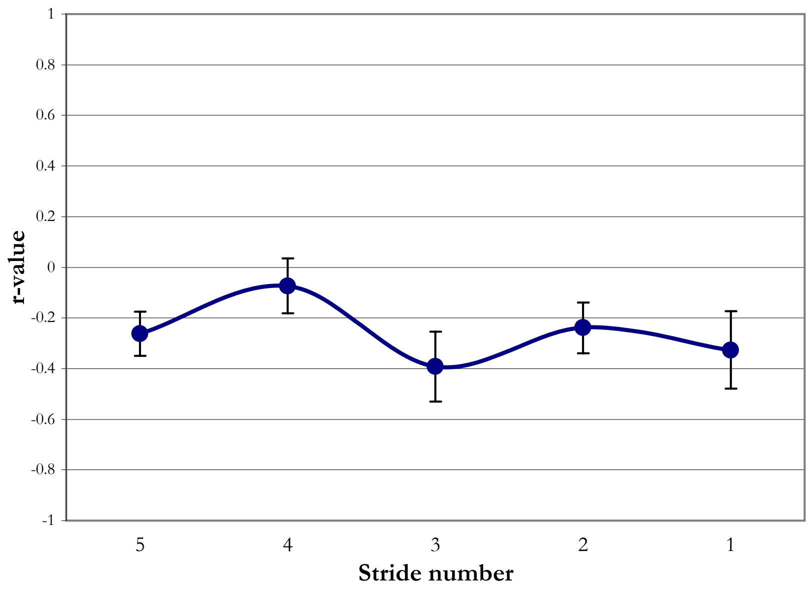


Figure 12.16 SAT correlation with WA for strides leading up to perturbation.
(Error bars represent ± standard error. Lower r-values indicate higher SA was associated with lower WA indicative of proactive performance)

Further analysis of the two-way interaction between NT and PC showed that the VPC condition under IBN produced significantly higher (p<0.05) r-values (mean=0.02; SE=0.12) compared to VPC under MBN (mean=-0.44; SE=0.08). Similar negative mean r-values were observed for the VC condition under both MBN and IBN. Further analysis of the two-way interaction between AK and PC showed that the mean correlation under VPC and low AK was significantly different (mean=0.03; SE=0.15) compared to all other conditions (p<0.05), which had negative correlations.

The two-way interaction involving NT and STRIDE was highly significant. Further analysis showed that mean r-values for Stride 4 before the perturbation under IBN was significantly different (0.05±0.4) from those observed for Stride 3 (mean=-0.56; SE=0.15) and Stride 1 (mean=-0.54; SE=0.11) under MBN condition (p<0.05). Figure 12.17 shows mean r-values for the strides leading up to perturbations across the MBN and IBN conditions. It can be seen from the plot that the SA mediation of the WA response is higher under MBN compared to IBN. Specifically, under MBN, mean r-values for Strides 3 and 1 (directly before the perturbation) are higher than the other strides under MBN. This data further supports the notion that there might be groups of participants following advance preparation strategies one and three strides before reaching a hazard.

There was only a marginally significant (p<0.10) interaction between AK and STRIDE. Further analysis with Duncan's test revealed significantly different mean r-values for Stride 4 (mean=0.11; SE=0.29) and Stride 3 (mean=-0.79; SE=0.03) before encountering a perturbation under low AK. There was also a significant difference between the mean r-values for Stride 3 (mean=-0.19; SE=0.22) and Stride 1 (mean=-0.64; SE=0.03) before a perturbation under medium AK. Figure 12.18 shows the mean r-values for each stride under each AK levels.

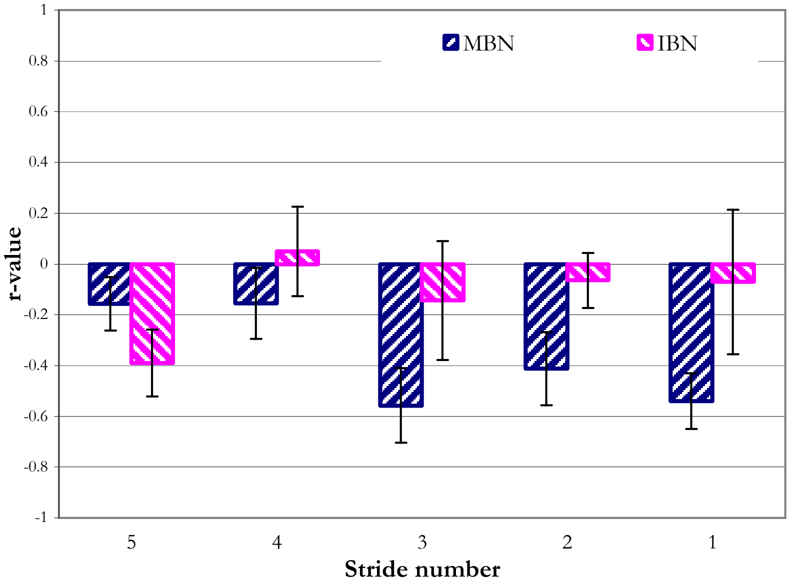


Figure 12.17 SAT correlation with WA for strides leading up to perturbation across NT.
(Error bars represent ± standard error. Lower r-values indicate higher SA was associated with lower WA indicative of proactive performance)

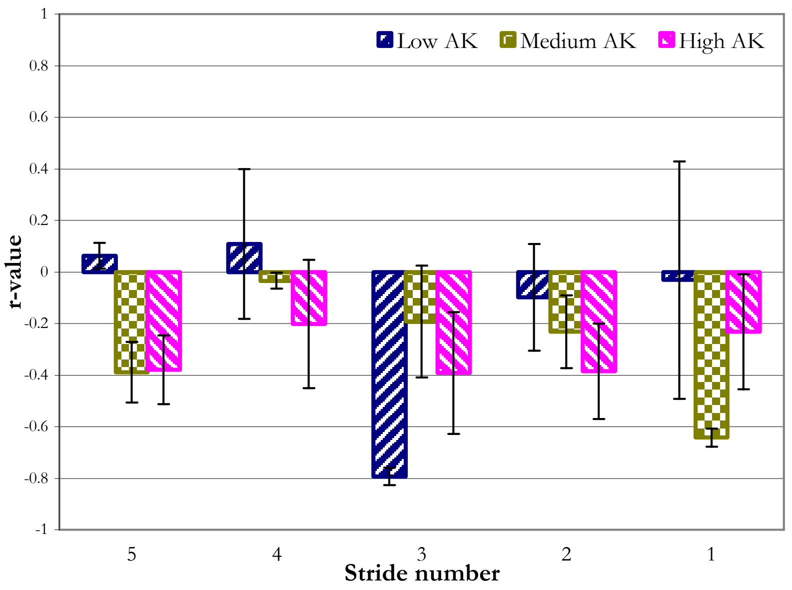


Figure 12.18 SAT correlation with WA for strides leading up to perturbation for all AK conditions.
(Error bars represent ± standard error. Lower r-values indicate higher SA was associated with lower WA indicative of proactive performance)

From the plot, it can be observed that there is a sharp increase in the strength of the linear relationship between SAT and WA for three strides before the perturbation for low AK, while there is a gradual progression in the strength of this relation from four strides before the perturbation under medium AK. For high AK condition, it appears that the strength of association between SAT and WA was generally higher across strides, especially in Strides 5, 3 and 2 before a perturbation. Even though, the mean r-value for one stride before the perturbation under low AK was small, the error bar shows a very high variability from a strongly positive correlation to strongly negative correlation between SAT and WA, and this could be due to differences in the participants' responses.

Further analysis of the significant three-way interaction due to NT, AK and PC showed a significant difference (*p*<0.05) in r-values between MBN (mean=-0.16; SE=0.16) and IBN (mean=0.35; SE=0.22) for the VPC condition under low AK. Similarly, significant differences

($p<0.05$) were observed between MBN (mean=-0.70; SE=0.06) and IBN (mean=0.09; SE=0.14) for the VPC condition under high AK. Overall, the trend observed under MBN was similar to that observed for the AK and PC interaction. Analysis of the three-way interaction between NT, AK and STRIDE number resulted in comparison of mean r-values among 30 different combinations. Overall, the results for the MBN reflect similar trends as observed in the AK and STRIDE interaction.

12.4.2. SAL2 association with WA and SLP

An ANOVA on the correlations between SAL2 and WA calculated for the five strides leading up to perturbations showed a significant main effects of AK (F(4,24)=4.65; $p<0.05$) and PC (F(1,24)=5.50; $p<0.05$) and a three-way interaction between NT, AK and PC (F(2,24)=6.92; $p<0.05$). The ANOVA on the PC main effect revealed mean r-values under the VPC condition (mean=-0.01; SE=0.09) to be significantly different from the VC condition (mean=-0.23; SE=0.07). Post-hoc tests on the AK main effect showed that mean r-values under medium AK and MBN were significantly different (mean=0.32; SE=0.13; $p<0.05$) from those observed under other conditions. Mean r-values for the other conditions showed a negative association between SAL2 and WA. Further analysis of the significant three-way interaction effect revealed a significant difference ($p<0.05$) between r-values for medium AK (mean=0.68; SE=0.08) and high AK (mean=-0.48; SE=0.08) under MBN for the VPC condition. Similarly, there was a significant difference ($p<0.05$) between medium AK (mean=-0.30; SE=0.14) and high AK (mean=0.25; SE=0.17) under IBN for the VPC condition. Figures 12.19 and 12.20 show the mean r-values for all AK and PC levels for MBN and IBN. In general, the trend of association between SAL2 and WA was similar to SAT and WA, save the participant performance under medium AK and VPC during MBN. It could be argued that it might be due to good SA and aggressive behavior or bad SA and cautious behavior.

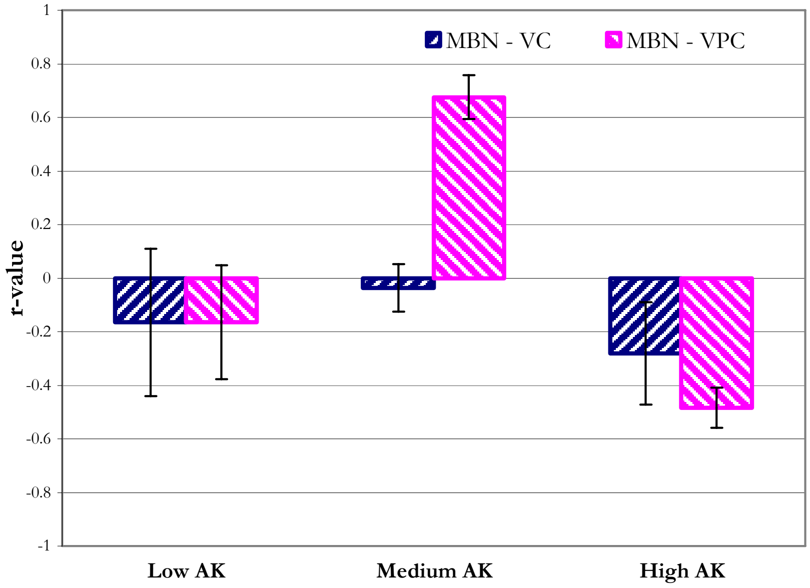


Figure 12.19 Correlation between SAL2 and WA in the strides leading to perturbation for the MBN.
(Error bars represent ± standard error. Lower r-values indicate higher SA was associated with lower WA indicative of proactive performance)

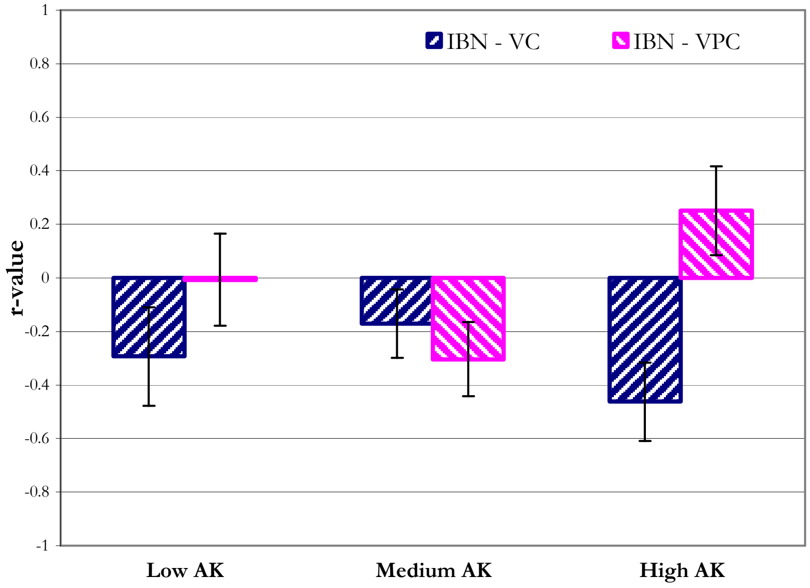


Figure 12.20 Correlation between SAL2 and WA in the strides leading to perturbation for the IBN.
(Error bars represent ± standard error. Higher r-values indicate higher SA was associated with higher SLP indicative of proactive performance)

An ANOVA on the correlation between SAL2 and SLP showed a significant main effect due to PC (F(1,24)=4.36; $p<0.05$) and a marginally significant main effect due to STRIDE number (F(4,24)=2.57; $p<0.10$). The ANOVA indicated that mean r-values under VC (mean=-0.07; SE=0.07) were significantly lower than for VPC (mean=0.15; SE=0.08). Post-hoc tests on STRIDE number showed the linear association between SAL2 and SLP to be significantly different ($p<0.05$) and positive during one, two and three strides before a perturbation, as compared to four and five strides before the perturbation, which were negative. Figure 12.21 shows the mean r-values for the strides leading up to perturbation.

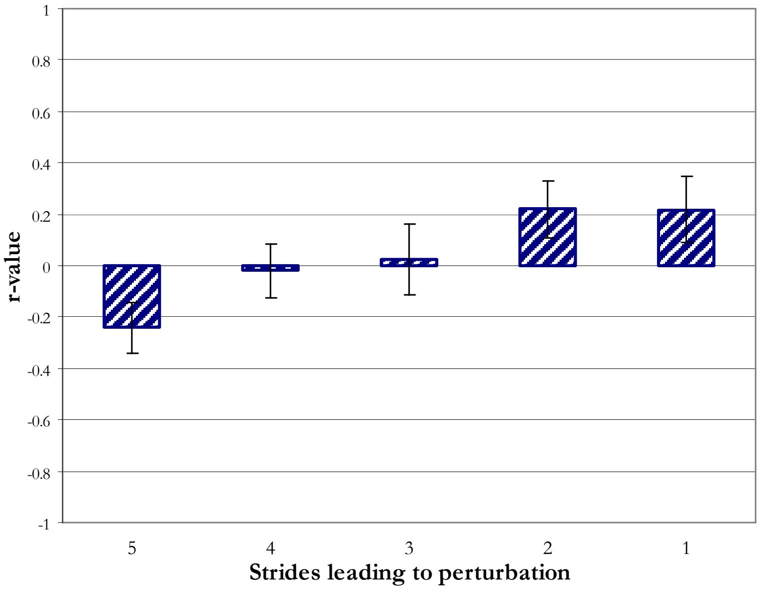


Figure 12.21 Correlation between SAL2 and SLP in the strides leading up to perturbation.

(Error bars represent ± standard error. Higher r-values indicate higher SA was associated with higher SLP indicative of proactive performance)

13. DISCUSSION

Based on the results presented in the previous section, there was a complex interaction of a priori knowledge and perturbation cueing on gait responses in multitasking involving locomotion. This interaction was also affected by the level of cognitive workload, in task performance, as evidenced by significant differences in responses to map-based and instruction-based navigation. In addition to the effects due to a priori knowledge of the VLE (virtual locomotion environment) and the level of workload, situation awareness also appeared to play a mediating role in the degree of proactive preparation for locomotion perturbations in the strides leading up to participants encountering a virtual hazard. These findings are discussed in light of the hypotheses described earlier in the dissertation.

13.1. Ground reaction forces

13.1.1. Weight acceptance force

WA is the peak force loaded on a limb during its contact with the ground, generally with a heel strike. The magnitude of the WA response provides an indication of the type of gait response, i.e., higher WA during normal walking signifies a heel-to-toe walker, while lower WA is indicative of flat-footed walker. Any deviation from the nominal range of WA for a participant may be due to voluntary or involuntary changes. In this experiment, the WA response was significantly affected by TO, PC and the interaction of NT, AK and PC. In general, it was expected that participants exhibiting proactive gait control would either accommodate for hazards with shorter, flatter steps (increased impedance) or avoid hazards by stepping over them with a long step preceded by a few shorter steps for preparation of a "leap".

From the TO main effect, it was observed that WA responses during the second trial involving visual cueing were significantly lower than those observed in the first trial. The results indicated that previous experience with, or knowledge of, the visual characteristics of the locomotion hazard helped in proactive gait control when similar hazards were encountered at a later time. It is interesting to note that the mean WA z-scores for the second trials were lower than the mean of the baseline WA distribution, indicating that in the five strides leading up to a perturbation, participants exhibited a WA response lower than in normal walking. On the other hand, when they were not aware of the nature or the features of a locomotion hazard, i.e., through an initial test trial, participants exhibited WA responses, which were higher than in normal walking, as evidenced by positive WA z-scores.

The PC main effect on the WA response revealed that participants walked less cautiously under the VC condition with significantly higher WA z-scores compared to VPC trials. As mentioned in the data analysis section, the dataset used for the analyses of GRF and COP responses consisted of observations on the second perturbation in each test trial. Before beginning each trial, participants were cautioned about the possibility of encountering locomotion hazards and instructed to respond as they would in a real-life situation. From the results, it is clear that after experiencing the first perturbation in the VC condition, participants might have developed a better understanding of the nature or the severity of the hazard (pot-hole or water puddle), making them less cautious when they encountered additional locomotion hazards within the same trial. That is, since the first experience with a locomotion hazard under the VC condition didn't produce any severe effect (an actual slip or trip), they might have expected a similar outcome for subsequent hazards and hence showed less caution.

On the other hand, the presence of physical cueing along with visual presentation (the VPC condition) of the locomotion hazard increased the perceived severity of the hazard (a forward yank of the right ankle leash for the water puddle and a rearward yank of the same leg for the pot-hole), possibly causing participants to be more cautious in the strides leading up to subsequent perturbations. Information regarding the severity of the perturbation is dependent on proper identification of the hazard, which might also depend on identifying associated environmental cues. This is the basis for the need for accurate SA of the locomotion task environment, particularly when performing concurrent cognitive tasks.

The three-way interaction effect of NT, AK and PC on the WA response indicated that, in general, the VPC condition produced lower WA z-scores compared to VC across the other conditions. The analysis also revealed significant differences in the WA response among low AK and VC and high AK and VPC during MBN. These can be considered as extreme conditions. No prior knowledge on the task environment, combined with lower perceived risk of hazards under to VC produced the highest mean WA response compared to MBN with high prior knowledge of the task environment and VPC. Plots on MBN performance revealed the response to decrease steadily from the low AK to high AK conditions for both VC and VPC conditions. This finding was inline with the expectation for higher a priori knowledge of task environments to contribute to the perceived severity of locomotion hazards and to produce proactive gait control when participants encountered perturbations.

As evidenced by the main effect of PC, the mean z-scores of the WA response under MBN for all AKs for the VPC condition indicated more cautious gait behavior compared to the VC condition. The WA response during IBN was mixed. That is, there was a linearly increasing

WA response with increasing AK for the VPC condition. This was directly in contrast to the trend observed for the MBN condition under VPC. It is possible that with higher AK, participants devoted more attention to the demanding location reporting task during IBN versus concentrating on gait control to the extent observed under MBN. It is also be possible that the cognitive workload posed by the location reporting task might have pushed attentional capacity limits for some participants leading to mixed outcomes and reducing the sensitivity of analyses on the manipulation. Bloem et al. (2001), in their experiment using the MTT (multiple task test), observed hesitation in the walking task when participants performed simultaneous cognitive tasks. They concluded that participants showed a higher precedence of attention allocation to physical tasks (walking) compared to cognitive tasks. In the present experiment, participants could not slow down or stop walking to perform the cognitive task, and they could not completely ignore the location reporting task, as their responses were necessary for them to receive navigation instructions. This set of circumstances could have led to intense cognitive resource competition. It is also possible that some participants developed a superior strategy for managing the allocation of resources between the locomotion and navigation tasks. It should also be noted that the sense of heading direction and navigation is a skill that is highly susceptible to individual differences (Brou & Doane, 2003)

13.1.2. Mid-stance force

MS is the force observed on the foot when it is flat on the ground and the limb is perpendicular to the ground surface. It is the lowest force observed after the first peak force (WA) is reached in a step. At the time of MS, the COM is within the BOS. This phase of gait is between the heel-down and toe-off phases and hence the label MS. The only main effect observed for the MS response was due to TO. Participants produced lower MS responses during trials following prior exposure to a trial with visual cueing of a perturbation. Similar to the WA response, advance knowledge of the severity of the hazard increased the cautiousness and proactive control exhibited by the participants, just steps just prior to encountering the perturbation.

A significant two-way interaction between AK and PC showed that the overall MS response across all test conditions was lower than the baseline MS response, except for medium AK under VPC. It was also observed that with VC and VPC, MS responses were higher with medium AK compared to low or high AK. This suggests that participants, having some knowledge about the test VLE, devoted less attention to their locomotion performance as compared to the navigation task. Hence, it could be that subjects attempted to strike a balance between spending resources for the purpose of avoiding hazards during locomotion as well as observing and perceiving environmental cues to develop SA.

The results on the three-way interaction between NT, AK and PC also reflected the above findings on the medium AK condition. MS z-scores were generally higher (relative to baseline forces), as compared to the other two AK levels (low & high). The plots on MS response for high AK under both VC and VPC were very similar for MBN and IBN. However, it is important to note there was a large standard deviation in MS for the high AK and VPC condition under MBN. This indicates that high knowledge of the task environment may have caused some participants to be overly confident and aggressive in gait and others to be extremely conservative. Participants appeared to be more aggressive in gait control under IBN than MBN for medium AK and the VPC condition. Recall that the WA response indicated proactive control and better performance in test trials, where participants had medium AK. This contradiction suggests the MS response may not be as sensitive a measure of voluntary changes in gait behavior, compared to WA, in locomotion circumstance like those examined in this study.

13.1.3. Push-off force

PO is the peak force generated by a limb (during the toe-off phase) to propel the body forward. After this, the limb starts its swing phase while the other stable (grounded) limb completes its heel-down (WA) phase and progresses into the MS phase. Similar to the WA results, PO was also significantly affected by the PC and TO. The mean PC response under the VC condition was significantly higher compared to the VPC condition. Here, higher values of PO suggest that subjects were trying to control the landing of their foot in order to proactively prepare for encountering a perturbation. During normal walking, reducing the heel strike angle to produce a flat landing will result in reduced WA and PO with a corresponding reduction in walking speed. However, in the present experimental setup, the speed of walking was constant throughout a trial. Flat foot landings through smaller step lengths resulted in reduced WA forces, but, this also increased the number of steps per minute due to the need for participants to maintain their walking speed. In turn, this resulted in higher PO responses. Hence, participants showing higher PO responses were either preparing to accommodate for hazards with smaller steps or to avoid hazards with a longer step. This is also reflected by the TO main effect, with higher PO responses during the second trials signifying better preparation compared to the first exposure to a trial with visual cueing.

The significant interaction between AK and PC showed that PO responses during VC with high AK were significantly higher than during VPC and low AK. An interaction plot revealed a linearly increasing trend in the PO response with an increase in the AK level. The lower AK condition produced lower than baseline PO responses, meaning that there was no preparation or any voluntary changes to the gait for impending locomotion hazards test trials. The PO responses for participants with medium AK were slightly higher than the mean of the baseline PO distribution and, in comparison with the results from WA and MS, might have been enough to produce the required proactive gait control to deal with locomotion hazards.

The two-way interaction between NT and PC showed that the PO responses were significantly different and higher for MBN compared to IBN for both the VC and VPC conditions. This goes back to the higher expected cognitive workload under the IBN condition, which may have influenced the amount of mental resources available for locomotion control leading to proactive preparation for any sort of hazard.

The three-way interaction effect between NT, AK and PC showed that PO responses under MBN for all AK and PC conditions (save VPC under high AK) were higher than the mean baseline PO, indicating proactive gait control. It was also observed that the high AK condition under IBN produced greater proactive control while the low and medium AK did not. A lack of exposure to the target task environment (low AK) may have resulted in participants needing to devote attention to perceiving environmental cues in order to perform the navigation task. In turn, this may have significantly impacted their preparedness for locomotion hazards.

13.1.4. Weight acceptance rate

WAR is the speed at which the peak force (WA) is attained when the limb contacts the walking surface. Higher rates signify faster transfer of body weight, which can occur during shorter strides. WAR responses were significantly affected by the PC manipulation. The analysis showed significantly higher WAR under the VPC condition compared to the VC condition. This result suggests that participants exhibited greater proactive preparation during the VPC condition compared to the VC condition. As mentioned earlier, the dataset used for these analyses consisted of gait responses to the second perturbation occurring in each trial. Therefore, prior exposure to the VPC within the same trial may have increased a participant's awareness of the severity of the hazard causing them to reduce their stride length, either to accommodate or to prepare to step over the perturbation in order to avoid it.

13.1.5. Push-off rate

Similar to WAR, POR is the rate of achieving the peak propulsive force (PO) just before the toe breaks contact with the walking surface. A higher rate indicates faster forward propulsion and since the speed of walking remained constant, subjects had to change their step lengths causing higher/lower cadence. As mentioned for PO, a higher POR may indicate greater proactive control for locomotion hazards. Analysis showed significant two-way interactions between NT and PC and AK and PC. Across all NT by PC combinations, MBN appeared to produce higher than baseline POR, indicating greater preparedness for hazards. On the other hand, the VC condition produced significantly lower POR compared to the VPC condition under IBN. This suggests that the VC condition did not produce any proactive control under IBN causing more aggressive gait behavior, while the VPC during IBN produced the highest PO response. Higher mean POR during IBN and VPC suggests the perceived severity of the locomotion hazard caused participants to allocate more attention to gait control, as argued by Bloem et al. (2001).

The interaction between AK and PC produced a linearly increasing POR trend across the levels of AK for both PC conditions. This relation was similar to that observed for the PO response variable with low AK producing the lowest POR and high AK producing the highest POR. Medium AK produced higher than mean baseline PORs and this might have been just enough to control the landing of the heel and the WA for hazard negotiation. Higher POR for participants with high AK suggested that they were either overly cautious for the locomotion hazard or extremely casual with longer strides, as the latter situation can also give rise to a higher POR. In any case, medium AK seems to have produced a consistent response in gait control.

13.2. Center of pressure

The two COP variables analyzed in this study included the slope and sum of squares of the errors for a linear trend fitted to the x-y position of the foot on the treadmill belt during test trials. Higher COP slopes, compared to baseline walking, can be indicative of controlling the foot landing, while higher SSE can be due to higher uncertainty in foot landings. These were the general expectations for these responses and the results appeared to be inline with expectation. Only the three-way interaction of NT, AK and PC was significant in influence on the SLP. Higher z-scores occurred with medium and high AK except under IBN for both VC and VPC conditions. Lower SLP z-scores, under the high AK and IBN conditions, were attributed to higher cognitive workload and lower attention to the locomotion task. However, it was surprising to see lower COP SLP for the high AK group under MBN for the VPC condition.

The variability in the response for this combination of conditions indicates that a number of participants may have been casual in their response to the perturbation even though they were highly aware of the potential implications and were experiencing lower cognitive loading.

SSE of the COP was only affected by the TO, which showed higher errors (greater uncertainty in gait preparations for perturbations) during the second trial compared to the first. From the results on the two COP variables, it can be inferred that the sensitivity of these variables to proactive gait control, under the current setup, may have been limited when compared to the GRF variables.

13.3. SA performance

Though the statistical analysis of SA data did not reveal any significant main effects or interaction effects due to NT, AK and PC, there were some important trends inline with prior expectation. The absence of the NT main effect indicated that when considering the overall SA score, there was no difference between MBN and IBN. Both methods appeared to be equally acceptable for navigating the city environment along different routes. The conditions examined in this experiment were akin to a foot soldier navigating an enemy city with either a handheld GPS unit or following instructions from a remote commander in an urban search and rescue situation. The results suggest advanced portable map-based technology many not offer a significant advantage over radio support for navigation from a SA perspective.

The lack of a main effect due to AK was counter to hypothesis, as higher AK was expected to positively affect SA performance. Similarly, regarding the absence of a PC effect, physical cueing was expected to increase the perceived risk associated with hazards and consume more mental resources for gait control; thereby, affecting SA performance.

Further dissection of the SA data by level revealed a significant two-way interaction between NT and SA level. Level 2 and Level 3 SA performance appeared to differ under IBN. It is possible that the location reporting task as part of IBN focused participant attention on perceiving and comprehending cues from the environment and significantly affected their ability to project future events.

The time-to-task completion between the two types of navigation could not be compared in the experiment since the walking speed was held constant during IBN and MBN trials. Otherwise, it can be postulated that IBN, requiring separate modalities for interaction/navigation and locomotion, might result in faster completion of the task. MBN, on the other hand, might pose some interference with the visual modality used for locomotion due to map-reading/navigation and lead to longer task completion times. This relation may be very important in certain application such as soldier navigation in enemy terrain or in urban search and rescue operations where there is a need to navigate as fast as possible to a target while simultaneously making important projections on enemy movement or potential victim sites. Thus, such situations demand the ability to switch back and forth between IBN and MBN in order to provide faster command instructions as well as autonomy for decision making regarding future targets.

13.4. SA and proactive gait control

It was expected that higher knowledge about the target task environment would support development of accurate SA on the environment and advance preparation for any locomotion hazard. It was expected that higher SA would positively affect proactive gait control. From the results of the correlation analysis on SAT and WA, there was a stronger negative association of these response variables for MBN than IBN. That is, increases in awareness on the task environment appeared to lead to reduced WA responses, particularly during MBN. Even though, SA scores during the IBN were higher than the MBN, the lower workload in the latter condition may have allowed for better translation of awareness into action, causing increased association between SAT and WA.

The linear association between SAT and WA indicated that higher AK led to higher mediation of gait variables and participants exhibited proactive control for dealing with perturbations. It can also be noticed that increases in SA, irrespective of the level of AK, appeared to contribute to proactive gait control. This points to the need for accurate SA during locomotion with concurrent cognitive task performance.

Linear association between SAT and WA for the five strides leading up to a perturbation, showed that there was a negative relationship across all five strides. However, the interesting aspect of the results was the high association of those variables at three strides and one stride before a participant encountered a perturbation. The strength of the correlation for the 3rd stride before a perturbation ranged from 0.0-0.8 and 0.0-0.65 for one stride before a perturbation. It is likely that participants followed a 3-stride advance or 1-stride advance strategy for proactive preparation for locomotion hazards. It could have been that the 3-stride strategy was followed by those participants who increased their gait impedance (accommodation), while the 1-stride strategy might have been followed by those who tried to step over the hazard. These observations are in line with Patla et al. (1999) previous findings that one to two steps (one stride) may be sufficient to avoid an obstacle either by stepping over or stepping to the side. However, Montagne et al. (2000) said that in the study of visual control of goal-directed locomotion in long jump, the mechanism for accurate foot positioning on the board is not dependent on a specific step (or stride) number but a function of the amount of required adjustment. From this viewpoint, the 3-stride strategy may have been implemented when the participants decided to accommodate the hazard (instead of avoiding it) and hence they made early or progressive adjustments to gait behavior.

A two-way interaction between NT and STRIDE indicated associations of SAT and WA across stride numbers for MBN, but this was not seen in IBN. For IBN, there was no clear 3-stride and 1-stride strategy indicated by mean r-values. The variability in the correlation of SAT and WA during those strides was very high indicating that some participants may have exhibited proactive preparation for hazards. An AK by STRIDE interaction revealed that participants with low AK prepared during the 3rd stride and at one stride before a perturbation. For the medium AK group, proactive control appeared at one stride before a perturbation and for the high AK group proactive control appeared during the 2nd and 1st stride before a perturbation. This indicates that differences in the level of a priori knowledge (AK) not only affected the magnitude of proactive control but also dictated the type of strategy followed for proactive preparation for locomotion hazards. That is, greater proactive control during higher AK does not necessarily imply earlier preparation to locomotion hazards. From the above results, it can be inferred that people may prepare for perturbations many steps in advance and not necessarily just one or two steps (one stride) before the perturbation is encountered as argued Patla et al. (1999). Their preparation appears to be driven by knowledge of and exposure to a locomotion hazard.

Analysis of the linear association between SAL2 and WA revealed an increase in Level 2 SA for participants under the VC condition to produce greater proactive control than under VPC. It is interesting to note that in the analysis of the GRF data it was observed that WA responses were significantly lower under VPC than VC. Even though the overall WA mean under the VPC condition indicated proactive control, it might be possible that participants were spending more mental resources on gait control and less on cognitive task performance. In the end, the participants achieved better gait control performance but had bad SAL2. An AK main effect on the correlation of SAL2 and WA revealed participants under medium AK to be more aggressive than other AK levels. The interaction effect due to NT, AK and PC showed the association between SAL2 and WA to produce proactive control across all AK levels except medium AK under MBN and VPC and high AK under IBN and VPC. These results indicate that participants might have had bad SA but were very cautious in their gait control.

The correlation between SAL2 and SLP showed PC and STRIDE number main effects. The strength of the SAL2-SLP association was lower under VC than VPC. This indicates participants became more relaxed when they had higher comprehension of task environment cues. The relationship between SAL2 and SLP for the 5-strides leading up to a perturbation showed that there was a linear increase in the association of those variables as the participants approached the hazard. The last two strides before a perturbation revealed a significantly higher association between SAL2 and SLP, indicative of greater proactive control for locomotion hazards.

13.5. Validation of SA model

The IV manipulations in the experiment were designed to evaluate the role of the elements in the "Individual" block of the new model on SA (see Figure 13.1). Specifically, NT involved manipulating the training in the navigation task and the AK condition manipulated the experience in the task environment. Measurement of participant SA through the real-time probing technique was used to assess the Level 1, 2 and 3 responses (perception, comprehension and projection) of subjects, as represented in the "SA" block of the model. The correlation analyses on SA and the gait responses assessed the link between the "SA" block and the "Decision" block of the model with a focus on proactive gait control strategies.

From the results of the gait variable analyses, it was evident that gait responses were affected by the combination of NT and AK along with the type of perturbation cueing. The SA analysis showed significant differences in Level 2 and Level 3 scores for IBN condition and trends of higher Level 1 and Level 2 scores for IBN compared to MBN condition. This validated the link between the "Individual" and "SA" blocks, specifically in terms of a connection between task training and experience and locomotion environment comprehension and projection. Correlation between SA scores and a gait response variable (WA) provided evidence supporting higher SA (in general) leading to higher proactive control, i.e., reduced WA response. Other links were found between subject comprehension of the locomotion environment (Level 2) and proactive gait control, including reduced WA response and increased COP SLP response based on the correlation analyses. This validates the most important link between the "SA" and "Decision" blocks of the model and provided evidence that SA may be required for gait control for locomotion hazards when performing concurrent cognitive tasks.

Figure 13.1 show the proposed SA model and highlight the links that were assessed and validated by the experiment. Due to the nature of the experimental setup, as explained in the next section, it was not possible to assess the linkage between SA and predictive or reactive gait control in order to provide a more complete validation of the SA model. This is the direction for future research.

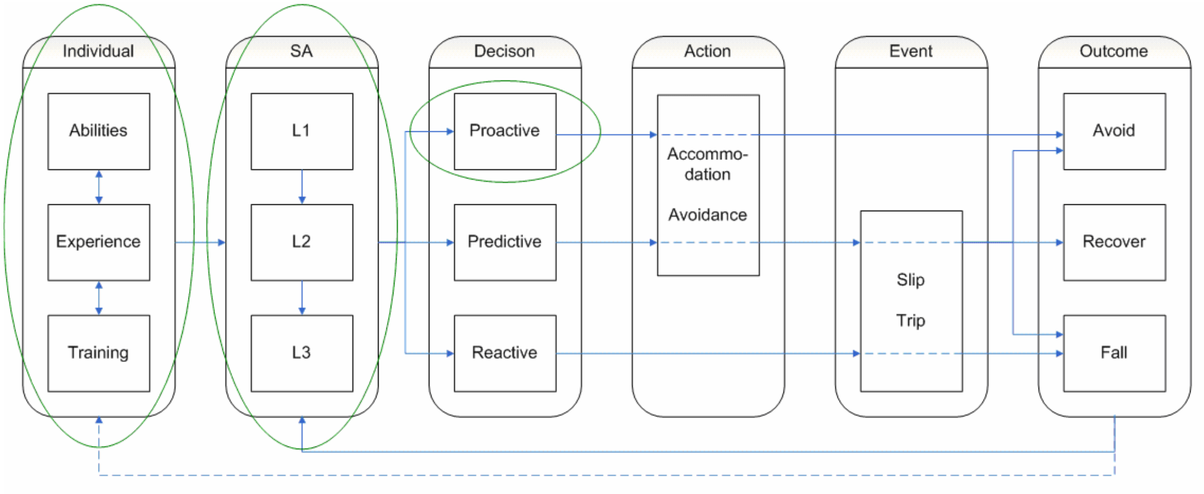


Figure 13.1 Portion of the SA model in locomotion assessed by the experiment.

14. CONCLUSIONS

The primary objective of this research was to develop a model of SA for multitasking with locomotion and conduct an empirical study to assess the validity of the proposed model for explaining proactive gait control in response to locomotion hazards. To support the empirical work, it was also an objective of the research to develop a VRLI (virtual reality locomotion interface) that could be used to simulate realistic VLEs (virtual locomotion environments) to study cognitive factors in locomotion, such as SA and multitasking performance.

The results from the pilot experiment provided evidence supporting the utility of the VRLI setup developed for the experiment and showed that treadmill walking with VR provides some approximation to overground walking. Based on observations during the pilot experiment on pros and cons of the VRLI, further enhancements were made to the setup, especially the technology used for presentation of visual information. These included the use of a rear-projection screen with a stereo projector and light-shutter goggles. A new treadmill system was also integrated to allow for recording of participant GRF (ground reaction forces) and COP (center of pressure) data during locomotion. The updated VRLI was used in the primary experiment to study the role of SA in locomotion and its impact on gait control for locomotion perturbations while performing a concurrent cognitive task. Results from this experiment were grouped in terms of: (1) gait responses; (2) SA performance; and (3) SA and gait response correlation. Thus, the conclusions have been organized in a similar manner.

14.1. Gait responses

GRF variables showed greater sensitivity to the IVs (independent variables) of the experiment including NT (navigation aid type), AK (a priori knowledge) and PC (perturbation cueing), than the COP variables. Nonetheless, both types of responses revealed significant results in line with hypotheses. Results showed that as participants prepared for a locomotion hazard, they reduced their WA (weight acceptance force) and MS (mid-stance force) responses with a possible increase in the PO (push-off force) response. WAR (weight acceptance rate) and POR (push-off rate) were higher and significantly different from baseline gait behavior recorded just prior to test trials and following extensive training. This indicated deviations from normal walking in steps leading up to a participant encountering a locomotion hazard. Higher SLP (slope) of the COP indicated that participants voluntarily changed their gait during foot landings before a perturbation. Higher SSE (sum of squares of errors) of the fitted line to the COP during test trials, as compared to baseline walking, indicated cautious locomotion behavior in steps leading up to a perturbation.

Statistical results on the PC condition indicated greater proactive control by subjects when provided with VPC (visual and physical cueing) compared to VC (visual only cueing) of locomotion hazards. The TO (trial order) manipulation also revealed that knowledge of the visual characteristics of locomotion hazards through an initial trial significantly improved participant's proactive preparation for perturbations in a second trial. The interaction of the NT, AK and PC suggested greater proactive control for MBN compared to IBN across all settings of the other variables. The difference in performance was attributed to higher cognitive workload posed by location reporting as part of IBN. This may have resulted in difficulty for participants allocating resources between the competing physical and cognitive tasks potentially degrading physical performance. Higher AK was associated with increased gait control and proactive preparation for hazards, specifically for MBN. This relationship was somewhat mixed for IBN, which might have been due to cognitive task workload going beyond the limits of some participants.

14.2. SA performance

Results of the analyses on overall SA scores showed no effects of the IVs manipulated in the experiment. This may have been due to the potential lack of sensitivity of the probe measures to differentiate between the IV manipulations because of a low number of probes posed within a trial. A similar observation was made by Kaber et al. (2006) on the sensitivity of a real-time probe measure of SA during soldier VR-based training for urban combat. Analysis of the levels of SA in this experiment revealed a significant NT and SA level interaction. It was evident that participants' Level 3 SA was significantly higher under MBN compared to IBN. There was also a trend for higher Level 1 and Level 2 SA for IBN compared to MBN. This is an important relationship as it indicates that IBN may be more suited for tasks requiring operational and tactical decision making but MBN may be more suited for strategic decision making tasks. This has practical application for situations such as soldier navigation in enemy terrain, urban search and rescue operations, etc.

14.3. SA and gait response correlation

Analyses revealed a mediating effect of SA on the onset of proactive gait control when participants encountered locomotion hazards. Correlations between SAT and WA for each stride were significantly affected by NT, AK and STRIDE number as well by higher order interactions. MBN participants exhibited greater proactive control with increased SA compared to IBN participants. Higher AK resulted in a stronger negative association of SA and proactive control during both MBN and IBN tasks. There was also an increased association of SAT-WA with stride number, as participants approached a perturbation. The results suggested that participants might have followed a three-stride advance preparation strategy for accommodating hazards and a one-stride advance preparation strategy for avoiding hazards. Interaction effects showed that the 3-stride and 1-stride preparation strategies were primarily used by MBN participants. Participants with medium AK appeared to use the 1-stride advance preparation strategy and those with low AK might have used 1-stride or 3-stride advance preparation. However, the high AK group consistently used 3-stride and 2-stride accommodation for perturbations.

Analysis of the Level 2 SA response (SAL2) revealed a correlation with WA and COP SLP. Participants appeared to develop greater proactive control when their comprehension of environmental cues increased, especially under VC. The linear association SAL2 and SLP increased in strength from 5-strides to 1-stride before a perturbation. Notably, the results showed increasing SLP with increases in SAL2 performance during the last two strides leading up to the perturbation. It appeared that participants who had greater comprehension of the hazard exhibited proactive control in the last two strides prior to the encountering a perturbation.

It is evident from this experiment that there was a significant improvement in proactive control with increases in participant SA. This is inline with the hypothesized model of SA in locomotion. The AK manipulation was based on the experience and training of participants in the VLE and it appeared to drive the process of SA development during test trials. Although, it has been shown that increases in SA led to proactive control, the experiment (as designed) could not provide further details to establish the relationship between the quality of SA and the type of gait control (i.e., proactive, predictive or reactive). The features of the experiment setup did not provide the capability to record the outcome of a perturbation (i.e., reactive control response). This is detailed in the next section. Overall, the experiment provided an empirical basis demonstrating the utility of SA in proactive gait control and providing preliminary validation of the model of SA in locomotion and multitasking.

14.4. Caveats

The most important caveat of this experiment was the inability of participants to control their walking speed while on the treadmill. The treadmill used in the initial version of the VRLI had features for computer control of belt speed based on subject locomotion behavior; however, it did not have an embedded force plate beneath the belt for recording GRFs and COP. Using the Biodex treadmill would have necessitated the use of video cameras for gait variable data collection. This was not possible due to the use of the rear projection screen as a visual display because the available motion analysis system was not based on Infrared sensors but used visible, high-intensity lights. All though the Kistler Gaitway treadmill allowed for force data collection, the treadmill did not have PC control capability and, therefore, the belt speed could not be adjusted adaptively based on participant locomotion behavior.

In order for the KGS to record gait responses for each foot strike, only one foot can be located on one-half of the walking bed at any time. This means participants had to be positioned exactly on the center of the bed (at all times) for the software to record gait responses. If participants sped-up to step over a locomotion hazard or slowed down too much to accommodate for the hazard, their body position would move from the center portion of the belt resulting in the KGS missing gait data. This spatial constraint restricted the ability of the experiment to investigate any reactive gait responses, since foot strikes were lost after encountering a perturbation. Thus, the impact of the spatial constraint required to record the gait response, and the lack of adaptive treadmill speed control, reduced the sensitivity of the study and the completeness of the results (relating to the quality of SA to the specific gait response). This issue could be addressed through collection of kinematic data using an advanced Infrared-based video camera system for a more complete assessment of the proposed model of SA in locomotion and multitasking.

Potential lack of sensitivity of the SA probe measure may have masked the effect of the IV manipulations on the SA accuracy. It is possible that the probes might have interfered with the navigation task for participants under IBN since they had to listen to probes and respond verbally in addition to the location reporting. The probes may have further contributed to the high cognitive load during IBN.

Limited differences in gait response between medium and high levels of AK may have been due to lack of substantial differences in training between subject groups. The high AK group was exposed to only one locomotion hazard versus no exposure for the medium AK group. The effect of AK on the various gait and SA response measures may have been more pronounced if high AK subjects were repeatedly exposed to simulated perturbations during training.

14.5. Future research directions

The results from this experiment provide preliminary evidence of the model of SA in multitasking involving locomotion and justification for conducting more controlled empirical studies to further understand the nuances of SA during locomotion with perturbations. There is a need for further research to observe evidences of predictive and reactive control in order to fully assess the model of SA for gait control in dealing with perturbations while performing concurrent cognitive tasks.

Future experiments like the present investigation should collect kinematic data as well as EMG data, in addition to GRF and COP data. Biomechanical models may be developed using these three measures. Biomechanical models should be correlated with models of SA in locomotion, or SA should be evaluated as an underlying factor in biomechanical responses in multitasking scenarios.

Eye tracking can be used to collect information on objects perceived by subjects during tasks and can be used as an objective indicator of the development of Level 1 SA. It may be possible to construct cognitive models based on eye tracking data and SA performance data. Any biomechanical model of locomotion could be driven by the cognitive model in order to further validate the role of SA in gait response prediction by humans when encountering perturbations. The future of this line of research should be to bring biomechanical and cognitive modeling together and provide a means to simulate human performance in any situation such, as walking on the moon, functioning under high mach speed, etc.

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APPENDICES

APPENDIX A – INFORMED CONSENT FORM

Principal Investigator: Mohamed Sheik-Nainar Faculty Sponsor: Dr. David B. Kaber

We are asking you to participate in a research study. The purpose of this study is to investigate human gait behavior and situation awareness while walking and performing a simultaneous cognitive task.

INFORMATION

If you agree to participate in this study, you will be asked to walk on a treadmill wearing a full body harness in front of a large 8'x8' rear projection screen and view the virtual environment using a stereo goggles. You will be asked to wear a motion sensor for tracking your viewpoint in the VR and ankle straps (similar to a surfboard leash) that are connected to recoil system. Experiment trials will be recorded using a video camera, which will be used in synchronization of data collected using different computer systems. The experiment will be conducted in one session. You will be asked to commit a maximum of 3 hours for the entire experiment.

RISKS

Potential risks include: (1) general fatigue due to walking for a long period of time; (2) simulator sickness as a result of extended exposure to computer-generated visual stimuli during locomotion; and (3) loss of balance due to induced perturbations while walking on the treadmill (jerking of recoil system). Adequate rest periods will be provided in between trials for you to recuperate and relax. Simulator sickness questionnaires will be administered frequently to monitor your perception of health state and, if there is a substantial change from your baseline ratings collected at the beginning of the experiment, additional rest periods will be provided. If you're feeling of sickness does not subside, you will not be allowed to continue the experiment and a ride will be provided to your home. You will also be advised not to drive a motor vehicle for 24 hours. To avoid injury due to loss of balance during induced perturbations, you will wear a full body harness hooked to a canopy frame over the treadmill and also hold the handrails at all times while walking on the treadmill. An experimenter will closely monitor your movements and if he/she senses something is wrong, you will be safely removed from the treadmill.

BENEFITS

You will receive compensation of $25 upon successful completion of the experiment. You may also derive some indirect benefits including an understanding of human factors research methods and insight into factors in human locomotion, such as gait kinematics and optic flow. You will be exposed to cutting edge technologies such as virtual reality.

CONFIDENTIALITY

The information in the study records will be kept strictly confidential. Information such as name, address and social security number are collected only for tax reporting purpose and will be destroyed after reporting. Data collected on your performance will be stored securely in a locked filing cabinet in the Cognitive Ergonomics lab in the Edward P. Fitts Department of Industrial and Systems

Engineering and will be made available only to persons conducting the study. Video data will also be stored a computer dedicated to this experiment and will be deleted after the completion of data analysis. No reference will be made in oral or written reports, which could link you to the study.

CONTACT

If you have questions at any time about the study or the procedures, you may contact the researcher, Dr. David B. Kaber, at Department of Industrial Engineering, Box 7906, NCSU, or 919-515-3086. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Dr. Matthew Zingraff, Chair of the NCSU IRB for the Use of Human Subjects in Research Committee, Box 7514, NCSU Campus (919/513-1834) or Mr. Matthew Ronning, Assistant Vice Chancellor, Research Administration, Box 7514, NCSU Campus (919/513-2148)

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed at your request.

CONSENT

“I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may withdraw at any time.”

Subject's signature________________________________ Date _________________

Investigator's signature ____________________________ Date _________________

APPENDIX B – NAVIGATION AND SA RECORDING FORM

Scenario 1			
Event	**Probes**	**Ground Truth**	**Sub. Response**
S1(1)	What was the tallest building you passed?	Hilton	
N1	Continue past Singer lane	Straight	
N2	Make a right turn at the stop sign	Right	
S1(2)	What was the last intersecting street you crossed?	N Model &	
N3	Make a left turn at the Cass Avenue intersection	Left	
N4	Continue past Mall street	Straight	
Reset Timer - Record GRF - Produce Trip			
S1(3)	What will be your next turn?	Left turn	
S2(1)	What building was at the last intersection	Stores/Bank	
S2(2)	What was your starting street name?	Turner	
N5	Make a left turn into Safety lane	Left	
S2(3)	What type of neighborhood do you think you are in?	Shopping	
N6	Make a right turn at Chapel road	Right	
N7	Turn left at Ringer Blvd	Left	
N8	Continue past W Main street	Straight	
Reset Timer - Record GRF - Produce Slip			
N9	Continue past Cobalt street	Straight	
S3(1)	How many trucks were parked in the fire station?	2	
S3(2)	Has the walking surface changed?	Yes	
S3(3)	How fast were you walking?		

Scenario 2			
Event	**Probes**	**Ground Truth**	**Sub. Response**
N1	Continue on cobalt street past Mayfair street	Straight	
S1(1)	In which street did you saw a fire truck?	Mayfair	
S1(2)	What type of neighborhood do you think you are traveling?	Industrial	
N2	Continue past Harrison Avenue	Straight	
N3	Turn right into S Model street	Right	
N4	Turn left and cross the S Model street to enter Learner Avenue	Left	
N5	Continue past Union road	Straight	
Reset Timer - Record GRF - Produce Trip			
S1(3)	How many more turns to your destination?	5 turns	
S2(1)	What is the speed limit here?	25 mph	
S2(2)	What was the last encountered landmark?	Water tank	
N6	Turn left in front of the library	Left	
S3(2)	What were the last intersecting roads?	Learner & Gallery	
N7	Make a right turn into Liberty road	Right	
N8	Make a left turn into Hopkins road	Left	
N9	Continues past E Main Street	Straight	
Reset Timer - Record GRF - Produce Slip			
S3(1)	What was the time on the clock tower?	3:05	
S2(3)	What will be your next turn?	No turn	
S3(3)	How long do you think you have walked from starting location?	4-5 minutes	

Scenario 3			
Event	**Probes**	**Ground Truth**	**Subject**
N1	Turn left into Digger Pkwy	Left	
S1(1)	What type of building is to your left?	House	
N2	Continue past N Model St	Straight	
S1(2)	What was the last street you traveled?	Housing Drive	
S1(3)	What will be your next turn?	Left turn	
N3	Turn left into Kraft St	Left	
N4	Turn left into Market St	Left	
N5	Turn right into Market Street	Right	
Reset Timer - Record GRF - Produce Slip			
S2(1)	What is the name of the building to your right?	K-mart	
S2(2)	How many turns have you made so far?	4	
S2(3)	Which direction is your destination?	South	
N6	Turn left into W Main St	Left	
N7	Turn right into S Model St	Right	
S3(1)	Do you see any change in walking surface?	Yes	
N8	Continue past Cobalt street	Straight	
Reset Timer - Record GRF - Produce Trip			
S3(2)	Did you make a turn in the last intersection?	No	
S3(3)	Do you think you need to make a change in your step length?	Yes	
N9	Make a right turn into Spring Road	Right	

Scenario 4			
Event	**Probes**	**Ground Truth**	**Subject**
N1	Continue in W Main street past Charles street	Straight	
S1(1)	What was the gas price?	2.07	
S1(2)	How many blocks have you walked?	1	
N2	Continue in W Main street past Model street	Straight	
N3	Make a right turn into Union street	Right	
N4	Make a left turn into Liberty Road	Left	
Reset Timer - Record GRF - Produce Slip			
S1(3)	How many more turns to your destination?	2	
S2(1)	What was the name of the Community Hall?	Wells	
S2(2)	What was the last turn you made?	Left	
N5	Make a right turn into Hopkins road	Right	
S2(3)	How long will it take to reach the destination?	2-3min	
N6	Continue past Learner Avenue	Straight	
S3(1)	What is the name of the current street?	Hopkins	
N7	Make a right turn into Spring road	Right	
Reset Timer - Record GRF - Produce Trip			
S3(3)	Do you need to make adjustment to speed or step length?	Yes	
N8	Continue past Research drive	Straight	
S3(2)	How many police cars were there in the accident scene?	2	
N9	Turn right into S Model street	Right	

APPENDIX C – SUBJECT INSTRUCTIONS

Introduction

[Put 'Experiment in Progress' sign up on the door. Show subjects the location of the restrooms and the personal storage space on lab shelf. Ask subjects to turn their cell phone off.]

Welcome and thank you for volunteering to participate in this experiment.
The goal of this experiment is to study the role of Situation Awareness (SA) in human locomotion under multitasking and specifically its importance in dealing with perturbations to locomotion.

Overview of the Experiment:

This experiment will be conducted in one session. The procedures we will follow in this experiment include:

For the experimenter information,

Group 1	*Navigation*	*Exposure to Low fidelity VLE*
Group 2	*Navigation*	*Exposure to VLE*
Group 3	*Navigation*	*Exposure to VLE and perturbation*
Group 4	*Map*	*Exposure to Low-fidelity VLE*
Group 5	*Map*	*Exposure to VLE*
Group 6	*Map*	*Exposure to VLE and perturbation*

Training session

1. Completion of Informed Consent form *(3 min)*.
2. Anthropometric data collection - age, height and weight. *(1 min)*
3. Stretching muscles of the lower extremities. *(5 min)*
4. Warm-up in treadmill. *(5 min)*
5. Practice walking with recoil system *(10 min)*
6. Introduction to Simulation Sickness Questionnaire (SSQ). *(5 min)*

7. Introduction to VRLI & Training in outdoor VLE. *(10 min)*
8. Training in suburban VLE (low fidelity ***(groups 1, 4)*** or high fidelity ***(groups 2, 3, 5, 6)***) with voice commands for making turns. *(10 min)*
9. SSQ and break. *(5 min)*
10. Introduction to use of *(5 min)*
    a. navigation instructions ***(groups 1-3)***
    b. map ***(groups 4-6).***
11. Introduction to SA probes. *(5 min)*
12. Training in navigation in suburban VLE (low fidelity ***(groups 1, 4)*** or high fidelity ***(groups 2, 3, 5, 6))*** with practice SA probes ***with (groups 3, 6)***/ ***without (groups 1, 2, 4, 5)*** physical perturbation. *(10 min)*
13. SSQ and break. *(5 min)*
14. Preparation for experiment trials *(2 min)*
15. Administration of Trial 1. *(15 min)*
16. Administration of Trial 2. *(15 min)*
17. Completion of SSQ. *(5 min)*
18. 5-min break. *(5 min)*
19. Administration of Trial 3. *(15 min)*
20. Administration of Trial 4. *(15 min)*
21. Completion of SSQ. *(5 min)*
22. Debrief on the study. *(2 min)*

Total time will be less than 120 minutes.

1. Informed Consent Form

Before we begin, I ask you to read and sign this informed consent form. This form summarizes information about the experiment including risks and benefits. It also summarizes the University liability to the experiment.

[Present subject with two copies of the consent form and ask them to sign both and return one]

2. Anthropometric Data Collection

As mentioned earlier, anthropometric data such as age, height and weight will be collected.

[Record age and measure height and weight.]

3. Stretching muscles of lower extremities

In order to warm up your muscles, please follow me in a series of easy stretches.

- Calf stretch.

[Lunge with the back leg straight and the back foot flat on the ground. Lean forward until a stretch is felt in the calf muscle of the back leg. Hold for 5 seconds. Repeat with the other leg].

- Hamstring Stretch.

[Stand with feet together and slowly bend-over and touch the toes. Hold this position for 5 seconds. Come up and repeat once.]

- Quad Stretch.

[Place the left hand on a wall and using right hand, grab the right ankle and raise that leg behind the back till a stretch is felt in quads. Hold for 5 seconds, repeat with the other leg.]

4. Warm-up on Treadmill

You can take up to 5 minutes to practice walking on the treadmill. Please try to walk as fast as you can while feeling safe and comfortable. I will increase the speed of the treadmill until you reach your preferred speed. To avoid injury due to loss of balance, you will wear the full body harness and it will be attached to the canopy frame around the treadmill.

[Start the treadmill and the signal conditioner. Open Gaitway software. Enter "kistler" as username and leave password field blank. Create a new subject and input the anthropometric data. Help subjects wear the safety harness and attach it to the treadmill canopy. Switch on the camcorder and the LED clock. Switch the LED clock to timer mode. Record the weight of the subject as measured by the force plate. Record the treadmill speed. This will be the preferred walking speed to be used in the experiment. Toward the end of their warm-up period, record their GRF for 20 seconds. After recording verify that there are more than 6 consecutive steps.]

5. Treadmill walking with ankle leashes

Now you will practice walking on the treadmill wearing these ankle leashes. The two D-rings in the ankle strap will be attached to the recoil system in the front and back of the treadmill respectively. Please take some time to practice walking. I will slowly increase the treadmill speed up to your preferred walking speed recorded previously. You can take up to 5 minutes to practice walking.

[Help subjects wear the ankle leashes. Attach the recoil ropes to the D-rings. Position the subject on the treadmill and start the treadmill. Slowly increase the speed as the subjects gets comfortable walking with the recoil ropes. Reset timer and record GRF for 20 seconds]

6. Simulator Sickness Questionnaire (SSQ)

It is possible that you may experience simulator sickness when using the immersive virtual reality display later. Therefore, procedures will be employed to assure your safety and well-being. Please inform us at any point if you begin to experience motion sickness-like symptoms.

In order to determine the possible presence of simulator sickness symptoms, the Simulator Sickness Questionnaire (SSQ) will be administered to you before and after the treadmill with VR training session and at the end of test trials. If your pre-exposure scores on the SSQ indicate that you are not currently in good health, you will not be permitted to continue your participation. If the post-exposure scores indicate that you may be suffering from simulator-sickness, the questionnaire will be administered at 20-minute intervals for up to 1 hour. If scores do not return to pre-test levels within 1 hour after an experiment, you will be advised not to drive a motor vehicle for 24 hours, and a ride will be provided to you. It will also be recommended that you seek medical counsel for "motion sickness-like" symptoms. This first sim-sickness form will be used as a baseline to compare your post-trial scores. Please fill out this form carefully.

[Present the subject with baseline SSQ form and let them fill out.]

7. Training in outdoor VLE

Now you will be trained on the virtual reality locomotion. Your task is to walk on the treadmill immersed in a virtual representation of an outdoor walking environment. You will be required to walk on a treadmill wearing a 3D goggles while viewing the virtual environment on this big rear projection screen. You will continue to wear the full body harness and ankle leashes. I will

closely monitor your movement on the treadmill and if I sense that something is wrong, you will be safely removed from the treadmill. You will also wear a beanie hat with a motion tracking sensor attached to it in order to make the viewpoint in the VE track your head movements.
The treadmill will be set to your preferred walking speed. Once you start walking, you can instruct me to adjust the speed in the simulation in order to match with your perception of the walking speed on the treadmill.

[Help subjects wear the harness, goggles and hat. Start the outdoor simulation. Start the treadmill at 1.5 mph and slowly increase/decrease the speed based on subject's preferred speed. Toward the end of training, reset timer and record GRF for 20 seconds and verify whether the recording has at least 6 consecutive steps]

8. SSQ and Break

Please fill out this second sim-sickness form carefully. This will be used to assess your sickness level in comparison with your pre-trial scores.

[Present the subject with sim-sickness form and ask them to complete it. Calculate the SS score. Provide subject with additional break if the score is above the pre-test score otherwise continue with training after 3 min.]

9. Training on navigation method

Next, you will be introduced to a new walking environment. It is a virtual representation of a suburban environment. You task will be to navigate from a start location to a destination within the environment.

a. Navigation - verbal instructions *(groups – 1, 2, 3)*

You will connect to a friend on a cell phone (played through computer speakers) who will give you instructions to navigate from a start to the destination location. You will hear an audio cue to simulate a phone call and following the cue you should immediately report your location as follows: current street name and upcoming/recently passed intersecting street. He will then provide you with specific navigation instructions. Before beginning of the walking trial, you will be given a chance to briefly look at the map of the suburb with start and end locations along with the walking route clearly marked.

b. Navigation – map *(groups – 4, 5, 6)*

You will be provided with the map of the suburban environment with the start and end locations along with the walking route clearly marked. You will need to remember the route for navigation in the virtual environment.

[Provide the subject with the map.]

In order to navigate to the destination you will have to turn in the VLE. This can be achieved by calling out "left turn" or "right turn" and the experimenter will hit an appropriate key that will smoothly move your viewpoint in VLE. When you don't want to make a turn, you can simply say "continue straight". Making the correct turn is very important for timely completion of the task and any deviation from the prescribed route will be considered as an error and will be recorded. You will see a 3-way arrow in the middle of the screen whenever there is a possibility of changing direction and you should immediately say left, right or straight.

While walking in the VLE, you will have access to the map and will be displayed in the top-right corner of the screen. You can use the map as many times you want by calling out "map". Once displayed on the screen, the map will disappear in 10 seconds.

10. Training on SA query response

While walking in the virtual environment, you will be occasionally posed with questions about the state of your understanding of the environment. These questions will be presented verbally through the speaker and you will need to provide a verbal response as soon as possible after your hear the question. For example, you may be asked – What was the last intersection you passed? What was the last turn you made?

11. Training on physical perturbation *(groups 4 & 6)*

While you are walking in the virtual environment, you will encounter virtual locomotion hazards such as pot-holes and water puddles. These may occur with or without physical disturbances. Please use caution when you encounter such hazards and respond as you would in a real-life situation.

12. Training in Suburban VLE

Groups 1, 2, 3:

Now you will be performing a training trial in the suburban VLE while navigating to a nearby gas station from outside an office building. You will need to provide details of current location such as current street name and nearest intersecting streets (passed or approaching) as soon as you hear an audio cue and then you will receive specific navigation instructions. You will also have to give turn instruction whenever you approach an intersecting street and the 3-way arrow appears in the center of the screen. Occasionally, you will also be asked questions on the state of the environment. You will also have access to the virtual map anytime during the task performance.

Groups 4, 5, 6:

Now you will be performing a training trial in the suburban VLE while navigating to a nearby gas station from outside an office building. You will also have to give turn instruction whenever you approach an intersecting street and the 3-way arrow appears in the center of the screen. Occasionally, you will also be asked questions on the state of the environment. You will also have access to the virtual map anytime during the task performance.

Groups 3 & 6:

In addition, you will also experience a physical disturbance that may or may not occur in conjunction with a virtual hazard such as pot-hole or water puddle while walking in the virtual environment.

[Reset timer, record GRF for 30 seconds towards the end of the trial.]

13. SSQ and Break

Please fill out this sim-sickness form carefully. This will be used to assess your sickness level in comparison with your pre-trial scores. And then you can take a 5 minutes break.

[Present the subject with sim-sickness form and ask them to complete it. Calculate the SS score. Provide subject with additional break if the score is above the pre-test score otherwise continue with experiment after 5 min.]

14. Preparation for experiment trials

Now we will begin the experiment trials. Similar to the training trials, you will have to walk on the treadmill immersed in a suburban VLE. You will wear the safety harness and ankle leashes. [You will use a map of the VLE to plan your navigation route from start to destination]. [You will communicate with the navigator about your location and follow his instructions to reach the destination]. You will also be asked questions on your location as well as on the states of the environment, which you will answer verbally. You will also encounter virtual walking hazards that may occur in conjunction with physical disturbances. Please exhibit caution as you would in a real-life situation. Do you have any questions?

[Start the simulation, start the treadmill, prepare the gaitway to record GRF.]

15. Administration of Trial 1

16. Administration of Trial 2

17. 5-min break

18. Administration of Trial 3

19. Administration of Trial 4

20. Completion of SSQ and debrief on the study

The purpose of this study is to investigate the effects of situation awareness during locomotion while multitasking in an environment with perturbations.

APPENDIX D – SAMPLE ANOVA OUTPUT

```
                                             Sum of
Source                      DF          Squares     Mean Square    F Value    Pr > F

Model                       29       436.168285       15.040286       4.43    <.0001

Error                      336      1141.596891        3.397610

Corrected Total            365      1577.765176


                 R-Square     Coeff Var      Root MSE       wa Mean

                 0.276447     -2491.261      1.843261     -0.073989


Source                      DF        Type I SS     Mean Square    F Value    Pr > F

nt                           1        2.5631898       2.5631898       0.75    0.3857
ak(nt)                       4       22.8522532       5.7130633       1.68    0.1538
pc                           1       12.0053556      12.0053556       3.53    0.0610
sub(nt*ak)                  17      326.9945622      19.2349742       5.66    <.0001
tcord                        1       25.8886446      25.8886446       7.62    0.0061
nt*pc                        1        0.1768763       0.1768763       0.05    0.8197
ak*pc                        2        2.4156412       1.2078206       0.36    0.7011
nt*ak*pc                     2       43.2717624      21.6358812       6.37    0.0019


Source                      DF      Type III SS     Mean Square    F Value    Pr > F

nt                           1        3.3894655       3.3894655       1.00    0.3186
ak(nt)                       2       15.6201745       7.8100872       2.30    0.1020
pc                           1       25.4764713      25.4764713       7.50    0.0065
sub(nt*ak)                  17      354.6153961      20.8597292       6.14    <.0001
tcord                        1       34.7700886      34.7700886      10.23    0.0015
nt*pc                        1        0.0949270       0.0949270       0.03    0.8674
ak*pc                        2        1.4034056       0.7017028       0.21    0.8135
nt*ak*pc                     2       43.2717624      21.6358812       6.37    0.0019


     Tests of Hypotheses Using the Type III MS for sub(nt*ak) as an Error Term

Source                      DF      Type III SS     Mean Square    F Value    Pr > F

nt                           1       3.38946547      3.38946547       0.16    0.6919
ak(nt)                       2      15.62017446      7.81008723       0.37    0.6932
```