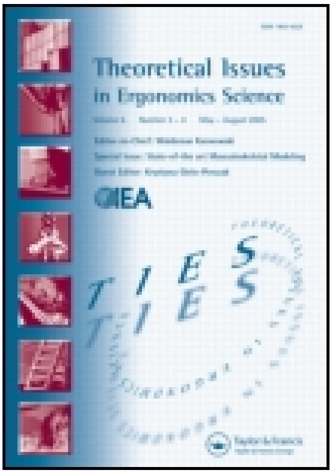
This article was downloaded by: [North Carolina State University]
On: 29 April 2015, At: 19:19
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Theoretical Issues in Ergonomics Science

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ttie20

Click for updates

Influence of cognitive and perceptual processing on multitask performance with locomotion

Mohamed Sheik-Nainar[a], David Kaber[b], Simon Hsiang[c], Carl Pankok Jr.[b] & Maryam Zahabi[b]

[a] Synaptics Inc, 1251 McKay Dr., San Jose, CA, USA

[b] Edward P. Fitts Department of Industrial and Systems Engineering, North Carolina State University, Raleigh, NC, USA

[c] Department of Industrial Engineering, Texas Tech University, Lubbock, TX, USA

Published online: 15 Jan 2015.

To cite this article: Mohamed Sheik-Nainar, David Kaber, Simon Hsiang, Carl Pankok Jr. & Maryam Zahabi (2015) Influence of cognitive and perceptual processing on multitask performance with locomotion, Theoretical Issues in Ergonomics Science, 16:3, 273-298, DOI: 10.1080/1463922X.2014.1001005

To link to this article: http://dx.doi.org/10.1080/1463922X.2014.1001005

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms &

Theoretical Issues in Ergonomics Science, 2015
Vol. 16, No. 3, 273–298, http://dx.doi.org/10.1080/1463922X.2014.1001005

Influence of cognitive and perceptual processing on multitask performance with locomotion

Mohamed Sheik-Nainar[a], David Kaber[b]*, Simon Hsiang[c], Carl Pankok Jr.[b] and Maryam Zahabi[b]

[a]*Synaptics Inc, 1251 McKay Dr., San Jose, CA, USA;* [b]*Edward P. Fitts Department of Industrial and Systems Engineering, North Carolina State University, Raleigh, NC, USA;* [c]*Department of Industrial Engineering, Texas Tech University, Lubbock, TX, USA*

(*Received 24 June 2014; accepted 17 December 2014*)

Prior research has shown contradictory results regarding the relationship between physical performance and cognitive load, and a lack of task environment models to compromise stability recovery. The objectives of this study were to assess influence of multitasking involving locomotion and concurrent cognitive demands as well as locomotor internal situation model formulation on proactive gait control for hazards. Twenty-four participants navigated a virtual walking environment including locomotion hazards (puddles, potholes). Three variables were manipulated, including a-priori knowledge (three levels of training fidelity), navigation aid type (instruction-based, map-based), and physical cueing (visual only, visual and physical). Significant differences in weight acceptance force and centre of pressure slope suggest that higher environment knowledge and lower cognitive load lead to greater proactive control. Participants adopted a three-stride advance preparation strategy to accommodate hazards. The experiment demonstrated accurate task environment knowledge and situation processing to dictate gait control for hazards when performing concurrent cognitive tasks.

Keywords: multitasking; cognitive performance; locomotion; slips and trips; proactive gait control

Introduction

Literature review

Many prior research studies have identified substantial numbers of slip and fall-related accidents in occupational and residential settings (Lin, Chiou, and Cohen 1995; Courtney et al. 2001; Nenonen 2013; Yeoh, Lockhart, and Xuefang 2013). Related to this, slipping has been shown to be the second largest source of unintentional mortality in the US. (Fingerhut, Cox, and Warner 1998). Slips and trips result from intrinsic or extrinsic factors. Extrinsic factors include the characteristics of walking surfaces, shoes, contaminants, elevations, steepness of an incline, insufficient lighting, poor housekeeping, etc. (Grönqvist 1999; Leclercq 1999). With respect to intrinsic factors, research has shown that experienced walker perceptions of surface slipperiness have significant positive correlations with objective coefficient of friction (COF) measurements (Cohen and Cohen 1994a, 1994b; Gao and Abeysekera 2002; Hsu and Li 2010). The majority of prior slip and fall research has focused on extrinsic factor investigation. Studying intrinsic factors during

---

*Corresponding author. Email: dbkaber@ncsu.edu

This article was originally published with errors. This version has been corrected. Please see Erratum (http://dx.doi.org/10.1080/1463922X.2015.1021192).

slip or trip hazard situations, such as accurate situation or mental model formation, is also considered to be critical to understanding how people prevent falls and achieve recoverable instability.

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 centre of mass (COM) to move outside its base of support (BOS), 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, called the centre of pressure (COP), are used to control the COM over the BOS. Patla et al. (1999) found that higher COP slope (COP SLP), compared to baseline walking, is indicative of control of foot landings in advance of encountering a locomotion hazard. Weight acceptance force (WAF) is the peak force loaded on a limb during its contact with the ground, generally with a heel strike. The magnitude of the WAF response provides an indication of the type of gait response, i.e. higher WAF during normal walking signifies a heel-to-toe walker, while lower WAF is indicative of a flat-footed walker. Any deviation from the nominal range of WAF for a participant may be due to voluntary control changes.

Trew and Everett (1997) found that human locomotion movements are normally automatic in nature; that is, they can be considered subconscious in the cycle of human information processing (Bailey 1989). Locomotion movements come under voluntary or conscious control under special circumstances, such as a new ground conditions or perturbations to gait. However, other studies have presented results contrary to the notion that walking is an overly practiced automatic motor-control behaviour (e.g. Woollacott and Shumway-Cook 2002; Kerr, Condon, and McDonald 1985; Ebersbach, Dimitrijevic, and Poewe 1995; Lajoie et al. 1993). These studies indicate that locomotion is partially dependent upon cognitive resources and that additional cognitive task loading may subtract from resources available for gait control.

Locomotion is generally considered as a secondary task in situations like walking and talking on a phone. Under such multitasking conditions with physical and cognitive loads, some studies have shown reductions in attentional resources leading to poor performance in either the primary or secondary task, or both (e.g. Brown, Shumway-Cook, and Woollacott 1999). Some research has also shown that subjects tend to allocate attentional (and, therefore, perceptual) resources to physical tasks first (e.g. standing or walking), and then to simultaneous cognitive tasks (e.g. Bloem et al. 2001; Bollens et al. 2014). Other studies have found that allocating greater attention to locomotion behaviour can have a negative effect on secondary task performance (Gage et al. 2003; Valerie, Janke, and Shumway-Cook 2010; Yogev-Seligmann et al. 2010). Similarly, some research suggests that a moderate level of physical exertion may increase concurrent cognitive task performance (Reilly and Smith 1986) while other findings suggest that any increase in physical exertion degrades concurrent cognitive task performance (Tomporowski 2003).

Poor performance in locomotion as a secondary task can also result in slight perturbations in gait (e.g. slip or trip) or a total loss of stability (e.g. fall). Yoshikawa (2003) found that as the complexity of a task increased (cognitive or physical), monitoring the state of the task increased and interruptions in performance of the concurrent task were greater. As long as a gait perturbation results in recoverable instability, it is of less concern; however, in situations in which combined cognitive and physical loads exceed attentional resources, falls causing critical injuries or fatalities may occur.

Related to the above findings, there are some contradictory results on the relationship between cognitive loading and physical task performance, in general. In a more recent study, Yogev-Seligmann et al. (2013) assessed the effect of cognitive loading on standing, cycling, and walking. Their results revealed that for young adults, performance on the two motor tasks that involved bilateral coordination (cycling and walking) deteriorated significantly in response to the dual task condition (motor and cognitive loading), while standing was not impacted. These findings indicate that locomotion is vulnerable to cognitive loading, in part, due to sensitivity of bilateral coordination of limb movements to effects of dual tasking. The differences in interference between standing and walking are also related to differences in processing stage demand. Walking requires information processing; standing only involves compensation for internal disturbances. In general, studies have shown that walking requires more attentional resources than sitting or standing (e.g. Lajoie et al. 1993). Bardy and Laurent (1991) also observed that attentional demands were greater during goal-directed walking (locomotion to a positional objective) than during normal walking. On the basis of recent reviews, it also appears that cognition, executive function, and dual-task performance are highly associated with falls or fall prevention (Amboni, Barone, and Hausdorff 2013; Hsu et al. 2012). However, Bohm et al. (2012) found that increasing cognitive demand did not have an increasing negative effect on predictive motor control during disturbed walking in young and old participants. Qu (2013) also found that only physical load, and not cognitive load or the interaction of the two, had significant effects on local dynamic stability. In another study, Li et al. (2012) assessed whether age-related cognitive prioritisation would emerge by experimentally manipulating cognitive task difficulty with concurrent physical task performance. Their results showed that in older adults, cognitive task performance did not suffer under dual-task conditions. Instead, dual tasking resulted in increased stride time, stride length, and hamstring activity. However, young adults showed negligible dual-task costs in the study domain.

Concerning recovering instability, and the potential for slips and falls, in locomotion, there are three major physiological mechanisms that inform us of whole body balance and assist in regaining balance and maintaining stable posture in the event of a perturbation. These include the vestibular, proprioceptive and visual sensory systems. Some studies have shown that slipping can be attributed, in part, to discrepancy between a locomotor's internal situation model and reality; that is, a failure to evaluate the differences between the state of the environment and one's internal model based on sensory inputs or prior knowledge (Tisserand 1985; Courtney et al. 2013). For example, if the surface has a lower COF with the walker's shoe than he or she expects (i.e. a poor mental model of the environment), the situation could lead to a slip, as the walker might not make necessary gait adjustments to adapt to the slippery surface. Therefore, vision and accurate perception are important for dealing with locomotion perturbations. However, Pyykkö, Jäntti, and Aalto (1990) found that corrective responses to slips solely based on vision are slower (120–200 ms), as compared to those of proprioceptive responses, which occur between 60 and 140 ms. In addition, studies have found that visually guided, proactive locomotion strategies depend on when and where in the step cycle a perturbation occurs (Patla et al. 1991; Ambati et al. 2013). Vision also regulates step length and width, walking velocity and orientation of limbs, etc., but cannot be relied upon as a sole means of recovery from perturbation on account of its latency (Patla 1991; Matthis and Fajen 2014).

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. Related to this, it has been postulated that gait control strategies can be proactive or reactive, 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 (Patla 2003). Proactive gait control is exhibited when the walker adjusts his or her gait in advance of a hazard to reduce the disturbance of locomotion while reactive gait control strategies occur after experiencing the tactile and proprioceptive forces indicative of the hazard and are characterised by foot elevation and landing strategies. Sensory responses to events before encountering the hazard are called proactive responses. Vision plays an important role in proactive control. Proactive control mechanisms are considered anticipatory or predictive in nature (Patla 2003).

Previous studies have also investigated the role of experience and accurate mental model formulation associated with perturbations during locomotion (Patla et al. 1991; Patla et al. 1999; Weerdesteyn et al. 2003). Patla et al. (1999) studied alternate foot placement (i.e. decision making) during avoidance of obstacles in the locomotion path. In addition, 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 (i.e. knowledge of the probability of a perturbation resulted from a good mental model of the environment and situation). Both studies found significant increases in success in obstacle avoidance when subjects had prior knowledge of hazards. Some other studies suggest that prior exposure to locomotion perturbations or knowledge of their occurrence helps to develop suitable internal or 'mental' models of locomotion situations and probable proactive/reactive strategies (e.g. Marigold and Patla 2002; Oliveira et al. 2012). For example, Pavol, Runtz, and Pai (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. Related to this, other prior research has gone as far as specifying the minimum time required for implementing most avoidance strategies. Matthis and Fajen (2014) offered that at least two step cycles are necessary for avoidance of a perturbation in locomotion.

Summary of research and objectives

Prior research has indicated that higher cognitive resources are required to maintain postural balance and stability during multitasking involving locomotion (e.g. Bloem et al. 2001; Brown, Shumway-Cook, and Woollacott 1999). However, there are some contradictory results on the relationship between cognitive loading and physical performance. In addition, studies have investigated the contribution of different sensory systems, as well as the integration of senses, for balance and posture (Vouriot et al. 2004). The visual system has been found to be effective for detecting locomotion perturbations in advance hazard exposure and for facilitating proactive gait control; however, proprioception, or faster than visual sensory responses, may be necessary to deal with certain perturbations. Gait control is a complex coordination of cognitive, sensory, and musculoskeletal systems. In order to accurately coordinate these systems for control of balance, a locomotor must have an accurate mental model of the surrounding environment and tasks. Such a model includes accurate knowledge of the slipperiness of a floor surface and/or the probability of encountering a locomotion perturbation in the path of progression. Thus, one has to perceive the changes in the physical environment, comprehend the meaning of these changes to locomotion behaviour and cognitive and physical workloads (tasks), project the implications of those changes with respect to successful task performance, as well as maintain balance and stability. Regarding proactive control strategies, Grönqvist et al. (2001) pointed out that lack of a 'good' mental model of the task and environment (e.g. slipperiness of the surface or the relative risk of tripping over an object in the walker's path) in locomotion could undermine the ability to predict the likelihood of a perturbation and generate necessary reactive steps for recovery. Knowledge of a situation and development of suitable mental models may help locomotors to avoid or recover from perturbations.

The literature paints a complex picture regarding the interaction between cognition, locomotion, and hazard accommodation strategies. However, a basic theoretical model including individual characteristics, mental model accuracy, and gait control strategy can be developed based on the findings to date. Regarding individual characteristics: innate abilities, experience, and knowledge all contribute to the development of an accurate mental model of the locomotion environment (through perception, comprehension, and projection), driving the appropriate gait control mechanism for the specific locomotion condition (e.g. a proactive control strategy). Therefore, gait strategy is considered to be dependent on the accuracy of the mental model, which in turn is dependent on individual characteristics.

Studies indicate that experience with a hazard and in an environment increases the ability to avoid an obstacle (Patla et al. 1991; Patla et al. 1999; Pavol, Runtz, and Pai 2004). In regard to the independent variables manipulated in the current experiment, a-priori knowledge of an environment may increase a walker's ability to avoid an obstacle. Regarding the effect of cognitive loading, Yogev-Seligmann et al. (2013) concluded that cognitive load resulted in deteriorated walking performance and two reviews concluded that dual-tasking was related to the occurrence of falls (Hsu et al. 2012; Amboni, Barone, and Hausdorff 2013). Generally, this would lead us to suspect that cognitive task performance, imposing a higher workload (such as the instruction-based navigation task as part of the current experiment), would lead to degraded locomotion performance and increased inability to avoid locomotion hazards vs. a task imposing lower cognitive load. Finally, the existing research indicates that vision and proprioception are better for corrective responses to hazards than vision alone (Pyykkö, Jäntti, and Aalto 1990; Matthis and Fajen, 2014). This indicates that greater proactive gait control should be expected when participants experience both visual and proprioceptive cues of hazards vs. visual only cueing.

With this mind, one objective of the present study was to assess the influence of multitasking involving cognitive performance during locomotion on the degree of proactive control for perturbations. If locomotion is sensitive to simultaneous cognitive task loading, then success in proactive control will be dictated by concurrent cognitive task demands. Our intent was to provide further evidence towards resolving the contradictory results in the literature regarding the potential sensitivity of gait control to cognitive resource demand. An additional objective was to assess the relation of locomotor internal situation model formulation, through perception, comprehension, and projection of environmental states, and the occurrence of proactive gait control in response to locomotion perturbations. We studied a multitasking situation posing spatial navigation requirements along with presentation of visual and physical perturbations to locomotion. Visual and physical cueing were manipulated with expectation of producing proactive gait control similar to real-world situations and to reinforce participant mental models of locomotion hazards. As described in more detail in the subsequent sections, operator mental model formulation was evaluated by measuring situation awareness, which is made up of measures of perception, comprehension, and perception. This method has been used in several prior empirical studies to evaluate operator mental models in complex multitasking scenarios (e.g. Endsley and Kaber 1999; Kaber and Endsley 2004; Zhang, Kaber, and Hsiang 2010). In this study, locomotor mental model formulation of the environment for the multitasking scenario was assessed using an established framework of cognition and correlated with success rate in proactive control for perturbations.

Method

Participants

Twenty-four volunteers (12 male and 12 female) were recruited from the NCSU undergraduate and graduate student populations for participation in the study. All participants had uncorrected or corrected 20/20 vision. (The use of glasses or contact lenses did not pose a conflict with the methods of visual stimuli presentation in the study.) 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). During the experiment, participants were instructed to walk at their 'normal' pace. Average observed speed was 3.38 ± 0.32 k/h (3.36 ± 0.39 for males and 3.40 ± 0.26 for females).

Experiment set-up

In this experiment, we used the virtual reality locomotion interface (VRLI) previously developed and validated for locomotion research by Sheik-Nainar and Kaber (2007). They demonstrated ankle and knee angles in locomotion with the VRLI to be comparable to the same angles in overground locomotion with identical perceptual stimuli presented to participants. The set-up included a Kistler-Gaitway instrumented treadmill. A single force plate was mounted beneath the belt of the treadmill. The plate contained eight piezoelectric transducers that recorded ground reaction forces (GRFs) at a sampling frequency of 500 Hz. A 3.05 × 3.05 metre rear projection screen was positioned approximately 1.5 meters in front of the treadmill belt for presentation of a virtual locomotion environment (VLE) to participants. An InFocus stereoscopic projector was used to present stereo images and to facilitate participant depth (binocular disparity) cues while walking on the treadmill. Participants wore 3-D light-shutter goggles for viewing the stereo images. The goggles did not obscure the lower visual field; Sheik-Nainar and Kaber (2007) found that obscuring peripheral vision with the use of a head-mounted display significantly changed gait characteristics as compared with overground walking. Participants also wore a 'beanie cap' with an Ascension Technologies Motionstar sensor mounted on top in order to capture participant head movements and to direct the viewpoint in the VR simulation. A large wood canopy structure surrounded the treadmill and projection screen. This structure included a participant suspension system. Participants donned a safety harness that was linked to the canopy structure via high-tensile metal cables. The cables were normally slack unless a participant fell while walking on the treadmill, in which case the cables became taut and suspended the body above the treadmill belt. Lightweight rope leashes were also attached to the ankles of participants via Velcro straps. The ropes released and recoiled from and into lawnmower engine recoil units as the participant walked on the treadmill. The release and recoil action of the recoil units could be locked in the early or late stages of a gait swing phase, providing the capability to induce trips and slips of participants during locomotion. Figure 1 shows a participant standing on the treadmill of the VRLI set-up (in front of the rear projection screen) wearing the motion tracking beanie cap, light-shutter goggles, safety harness, and ankle leashes.

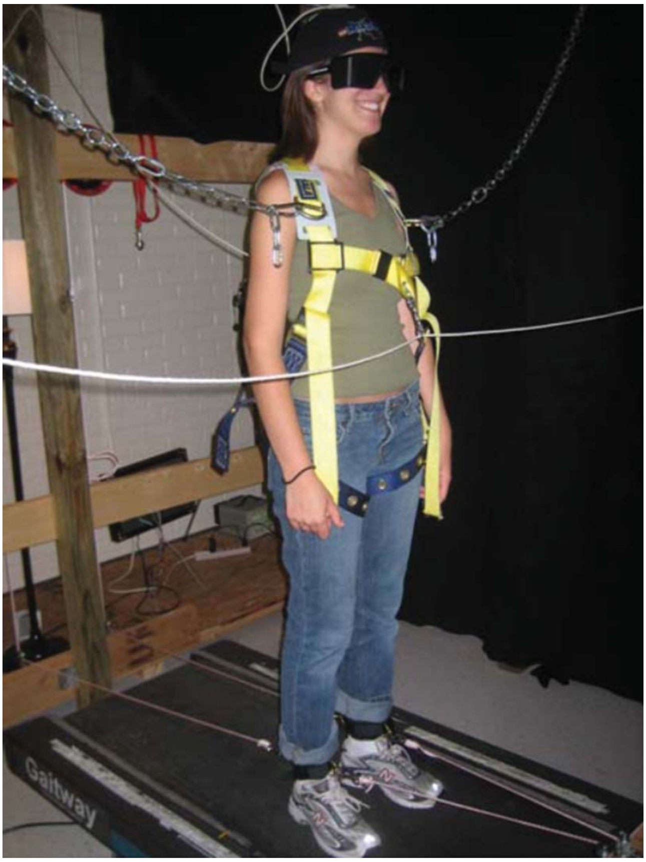


Figure 1. VRLI set-up.

Independent variables

The independent variables manipulated in the present study were selected to assess the role of multitasking, including simultaneous cognitive task and locomotion performance, on gait control as well as the relation of locomotor situation or mental model formulation to proactive gait control for perturbations. The cognitive task posed to participants required navigation through the VLE. The simulated environment was a suburban town (modelled based on a real environment) with two-lane streets, sidewalks, crosswalks, necessary street signage, and stop lights. The streets and sidewalks were populated with pedestrians and vehicular traffic, respectively. The streets were lined with shopping centres, city buildings, churches, and residential developments in some sections. The number of items appearing in the VLE was selected in order to make the simulation appear realistic. Four scenarios with different start and end locations along with different routes were randomly assigned to participants for navigation in each trial. We presented participants with different types of navigation aids (NT) that varied in the cognitive load they pose for walkers. Second, we manipulated the level of participant a-priori knowledge (AK). Finally, in order to evaluate the impact of multitasking and locomotor situation models on proactive control, we presented various types of physical cues (PC) to locomotion hazards.

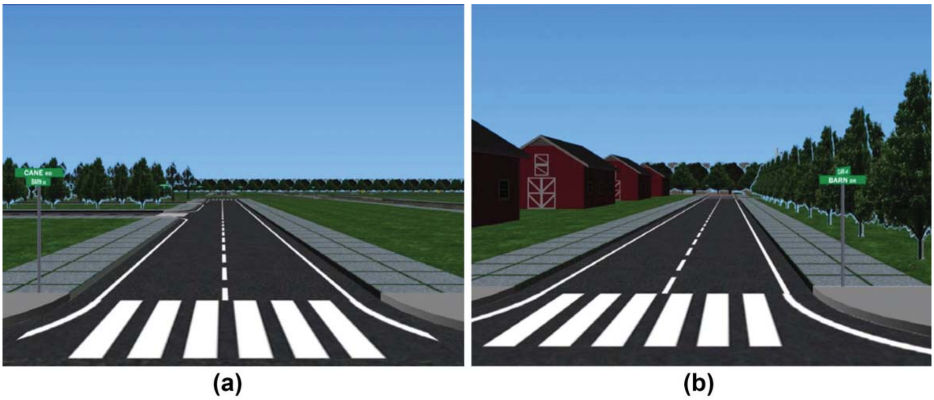


Figure 2. (a) Image of the low and (b) high fidelity VLEs.

Half of the participants followed instruction-based navigation (lists of directions) while the remaining subjects performed map-based navigation of the VLE. Participants in the map-based group could use only the map (which was presented for 10 seconds upon request and then disappeared) to navigate, while the instruction-based group had access to both the map and verbal instructions given to them at various points in the simulation. Furthermore, the instruction-based condition required participant location reporting at every intersection in the VLE; whereas, the map condition did not require reporting. For these reasons, it was expected that the instruction-based navigation would impose a greater cognitive load on participants than map-based navigation.

The levels of the AK variable included no participant exposure to the VLE (low AK) in advance of test trials, participant exposure to the VLE only (medium AK), and participant exposure to the VLE and a locomotion hazard (high AK). The ‘low a priori knowledge’ group was trained in a VR presenting a rural neighbourhood with no buildings, trees, pedestrians, etc. while the other two groups were trained in a VR that closely resembled the suburban town environment used in the experiment trials, as shown in Figure 2.

The PC variable had two levels: present and not present. That is, in the ‘not present’ trials, locomotion hazards were only presented by visual images in the VR scene without a corresponding physical cue, or locking of the ankle leashes to induce a slip or trip, when a participant encountered the hazard in the VLE. Trials including physical cues were intended to represent real-world multitasking situations involving locomotion with perturbation hazards (i.e. presence of both visual and proprioceptive forces associated with a locomotion hazard). These trials were expected to provide evidence of predictive and adaptive gait control. Alternatively, trials presenting only visual cues were expected to provide evidence of purely predictive gait control. Here it is important to note that the motion of the treadmill belt was synchronised with the motion of the participant in the VLE; when the belt moved, the first-person presentation of the VLE moved at exactly the same pace. This set-up, along with the head-motion tracking, gave participants a strong sensation that the VLE imagery was directly linked to their body and head movements.

Experiment design

The study followed a 2 × 3 × 2 mixed experiment design, based on the levels of the independent variables; NT, AK, and PC. Both NT and AK were between-subjects variables

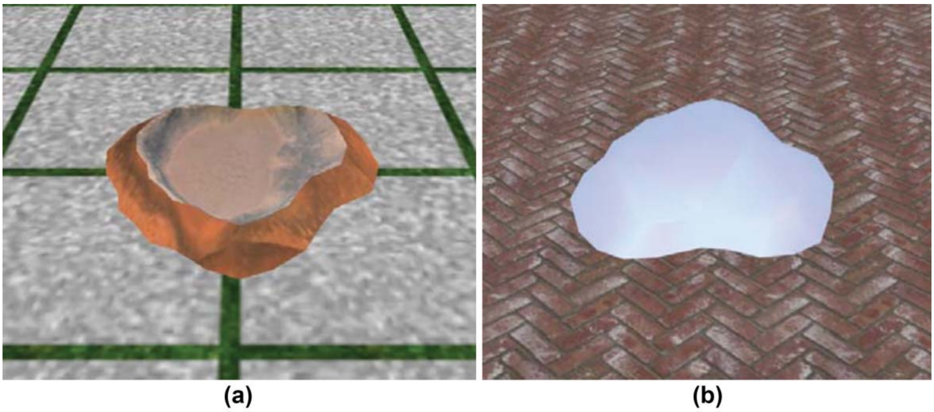


Figure 3. (a) Image of a pothole and (b) water puddle used in the test VLE.

while PC was manipulated as a within-subjects variable. The AK manipulation varied the degree of exposure and experience with the VLE and was expected to influence the development of participant mental models of the environment. Since the navigation task performance under the instruction-based and map-based navigation conditions was different, the levels of AK were considered to be nested within the NT settings. Two types of locomotion perturbations, slips and trips, were posed during the navigation task. For the trip 'hazard', the visual cue was an image of a pothole and the physical cue was locking of an ankle leash during the latter part of the swing phase of the right lower limb. For the slip hazard, the visual cue was a puddle of water and the physical cue was locking of an ankle leash during the early part of the swing phase of the right limb. Figure 3 presents close-up images of the pothole and water puddle in the VLE.

Dependent variables

The dependent variables recorded in the study included gait parameters and measures of participant situation awareness on the VLE. The gait parameters were selected to reveal proactive gait control in response to perception (visual or proprioceptive) of locomotion hazards and included: WAF and COP SLP (described in more detail in the introduction). The WAF is a GRF measuring the transfer of body weight to a leg/foot making contact with the ground. The COP SLP is a linear regression line fitted to the x-y position of the foot on the treadmill belt during test trials and it was calculated for each step.

In order to assess locomotor mental model formulation, participant situation awareness (i.e. perception, comprehension, and projection of system states) was measured using the Situation Awareness Global Assessment Technique (SAGAT; Endsley 1995). SAGAT has been used in previous research to assess mental model formulation, and outcomes of SAGAT have been correlated with performance in other multitasking scenarios (e.g. Kaber et al. 2012; Ma and Kaber 2007). In this way, the accuracy of operator recognition of states of the locomotion environment, relation of states to navigation objectives, and predictions of future conditions along a route, could be assessed and related to the gait control parameters indicating control strategies. The SAGAT methodology involves posing situation awareness queries to participants during task performance. Some studies have used a simulation freeze technique to deliver queries (Endsley and Kaber 1999);

however, in order to prevent performance disruptions in the present study, we verbally queried participants while they were walking and navigating the VLE. The queries were phrased in a manner to elicit close-ended or brief responses (e.g. yes/no) from participants. In turn, the participants verbally responded to queries. In this study, we posed nine different queries in each test trial. The trials were approximately five minutes in duration so queries occurred roughly every 30 s. The types of queries and the locations of presentation (in relation to the task VLE) were identified in advance, as part of the scripting for each scenario. Example queries included, ‘What was the last intersection you passed?’, ‘What was the last turn you made?’, ‘What will be your next turn?’, and ‘How long do you think it will take to reach your destination?’ An experimenter recorded all participant responses. The ground truth of the simulation was also recorded at the time of a query. The average query response accuracy (QRA) was determined for each participant in each trial by comparing responses with the simulation ground truth. A query response was either correct or incorrect. The QRA response ranged from 0% to 100%.

Procedure

Upon arrival at the laboratory, participants were randomly assigned to NT and AK conditions. They were given an overview of the experiment and the specific procedures to be followed. They were presented with an informed consent form and provided a signature. Anthropometric data were recorded, including gender, age, height, and weight. An experimenter then helped the participants don the body harness and they were permitted to walk on the treadmill for 10 minutes. After this initial warm-up, participants continued walking on the treadmill for another five minutes with the ankle leashes attached to the recoil units. Once participants became accustomed to wearing the ankle leashes, they were presented with the procedure related to the VLE. They were initially required to complete the simulator sickness questionnaire (SSQ; Kennedy et al. 1993) in order for us to capture baseline ratings of disorientation, nausea, and oculomotor-disturbances. Subsequently, they donned the beanie cap with the integrated head-motion tracking sensor and light-shutter goggles for 3D viewing of the simulation.

Following the VRLI familiarisation, participants were trained in the navigation task. The VLE to which they were exposed depended on the AK group assignment. Before performing the training trial, participants assigned to the map-based navigation group were provided with a map of the VLE (Figure 4 shows an example) and time to become acquainted with the defined walking route. Those assigned to the instruction-based navigation group were trained on self-reporting of location and receiving online navigation instructions. Participants belonging to the high AK group were cautioned on the possibility of virtual locomotion hazards appearing during the training trial and were exposed to one trip perturbation with physical cueing administered through locking of an ankle leash in the late swing phase, which lasted for approximately 200−300 milliseconds. After the training session, participants completed another SSQ in order to determine if any simulator sickness symptoms had developed. The survey was followed by a five-minute break.

All participants were provided with instructions for the experiment test trials, specifically the possibility of locomotion hazards occurring in the VLE with or without an accompanying physical perturbation. They were advised to exercise caution in walking as they would in a real-life situation. Each participant completed two test trials under the identified conditions of visual cueing of perturbations and combined visual and physical cueing. Each test trial included one slip and one trip perturbation and the order of

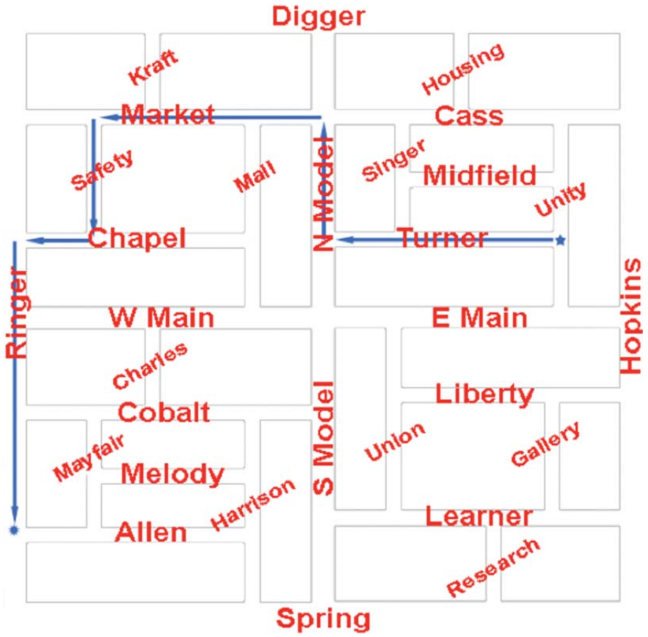


Figure 4. Example of VLE map and navigation route.

presentation was balanced across the test trials. Before performing a trial, participants were given the map of the test VLE with the predefined navigation route marked from start to finish. Figure 4 shows one of the four different routes (from Turner St. to Model St. to Market St., etc.) followed during the test trials. Each route took approximately five minutes to walk. Participants were provided with another five-minute break at the end of the second test trial. After completing the fourth trial, participants filled-out another SSQ and were debriefed on the objectives of the study. The entire experiment was conducted in one session and took approximately two hours to complete. Participants who successfully completed the experiment received $20 for their time.

Hypotheses

We organised the research hypotheses according to the different types of response measures recorded during the test trials (i.e. WAF, COP SLP, and QRA). The hypotheses are also related to the expectations identified in the experiment design section.

Marigold and Patla (2002) offered that any prior knowledge about a locomotion hazard, such as surface slipperiness, helps in terms of proactive control by decreasing foot angles and increasing foot contact areas with flat foot landings (i.e. accommodating for hazard negotiation). Therefore, a lower WAF equates to a higher degree of proactive gait control. On the basis of the literature, the following hypotheses were formulated:

Hypothesis (H) 1.1 – The WAF was expected to be greater for the lower AK group. Similarly, the higher AK group was expected to exhibit a higher degree of proactive gait control (lower WAF).

H1.2 – Due to the instruction-based navigation condition placing a greater demand on attentional resources and potentially reducing locomotor situation awareness, less proactive control or higher WAF was expected for the instruction group than the map-based navigation participants. Similarly, the map-based condition (reducing the cognitive demands of the navigation task) was expected to result in a higher degree of proactive gait control (lower WAF values).

H1.3 – The VC condition was also expected to be associated with lower proactive gait control or higher WAF than the VPC trials, which provided greater realism in terms of presentation of the locomotion hazard.

Other prior research (Patla et al. 1999) has shown that higher COP SLP is indicative of control for foot landings due to the presence of an impending hazard. Under these circumstances, the locomotion task becomes conscious and may demand greater attention than the simultaneous cognitive (navigation) task performance. A voluntary response of this nature is indicative of an avoidance strategy, which is a form of proactive gait control (Patla et al. 1999). On the basis of this literature, the following hypotheses were formulated:

H2.1 – The COP SLP was expected to be greater for the high AK group. The higher AK group was expected to allocate greater attention to locomotion when approaching a perturbation.

H2.2 – Due to lower cognitive demands of the map-based navigation condition, the map group was expected to exhibit larger SLPs than the instruction-based group. The map-based condition was expected to allow for greater attention to locomotion approaching a perturbation as compared to instruction-based condition.

H2.3 – Due to the realism of the VPC condition, participants were expected to exhibit greater SLP responses than in VC trials. The addition of physical cues was expected to result in greater attention allocation to locomotion hazards as compared to visual cueing alone.

Prior research on situation awareness in multitasking scenarios has shown positive correlations with performance, including task accuracy (Zhang, Kaber, and Hsiang 2010). This association is dependent upon human ability to perceive, comprehend, and project states of the task environment. On the basis of the literature, the following hypotheses were formulated:

H3.1 – Greater QRA was expected to be associated with greater AK of the VLE.

H3.2 – The QRA was expected to be greater for the map-based navigation group, experiencing lower cognitive demands in the navigation, than the instruction-based group. The map-based condition was expected to facilitate greater situation awareness for the navigation task than the instruction-based condition.

H3.3 – Due to the VPC condition drawing additional attention to locomotion hazards, the QRA for the VPC trials was expected to be lower than in the VC trials. The addition of the physical to visual cues was expected to result in less attentional resources for the cognitive (navigation) task and, consequently, a decrease in participant situation awareness.

Finally, it was hypothesised (H4) that greater AK of the VLE and situation awareness (QRA) during the navigation task would be associated with greater proactive gait control, as indicated by lower WAF and/or higher SLP.

Results

Data analyses

A preliminary data analysis did not reveal an effect of the type of perturbation (i.e. trip or slip) on the various response measures. Participants had no prior expectation of the type of perturbation to be presented in a trial until they experienced the first perturbation. In general, it was expected that subjects would exhibit greater proactive control in encountering a second perturbation, particularly under the VPC condition. Consequently the full data analysis only considered those WAF and SLP observations recorded on the second perturbation in the first test trial and subsequent perturbations in additional trials. This approach was taken to promote the sensitivity of the analysis and hypothesis testing for differences among the physical cueing conditions.

Towards the completion of participant training in the navigation task, walking force profiles were captured using the Kistler Gaitway treadmill. Participants walked under nominal conditions, i.e. no perturbations to locomotion, for a period of 20s. The distribution of forces during multiple gait cycles was determined and used as a basis for normalising all WAF and SLP observations recorded during experiment trials. The test observations were compared with the baseline distribution and expressed as z-scores. This approach yielded a normalised data-set useful for comparisons of conditions across participants.

Based on the experiment design, expected mean square rules were used for defining pseudo F-tests to estimate the main effects of NT and AK since the test trial conditions were not replicated. To examine any effects of NT, AK, and PC on participant situation awareness QRA, a total accuracy score was computed for each test trial and used in the analysis. With respect to the predicted relation of navigation task knowledge and situation awareness with the occurrence of proactive control of gait in responding to perturbations, Pearson's product moment correlation coefficients were calculated on the QRA and the WAF and SLP variables for each of five strides directly preceding participant negotiation of a locomotion hazard (pothole, puddle). The r-values from the correlation analyses were used as inputs to an Analysis of Variance (ANOVA) to identify any mediating effects of the independent variables. All *post hoc* comparisons were conducted using Duncan's Multiple Range (DMR) test with an alpha criterion of 0.05. 'Participant' was used as a blocking variable in all ANOVAs and accounted for additional response variability attributable to individual differences.

Weight acceptance force

An ANOVA on WAF revealed significant main effects of PC ($F(1,336) = 7.50$; $p < 0.05$) and trial order ($F(1,336) = 10.23$; $p < 0.05$), another predictor variable included in the ANOVA models. The analysis also revealed a significant three-way interaction between NT, AK, and PC ($F(2,336) = 6.37$; $p < 0.05$). The absence of physical cueing (mean $=$ 0.089; SE $=$ 0.14) produced higher WAF, as evidenced by higher z-scores, compared to trials that included physical cueing (mean $= -0.250$; SE $= 0.17$). The significant trial order effect revealed significantly greater WAF for the first hazard exposure than for subsequent exposures. As shown in the left panel of Figure 5, participants in the map-based navigation group exhibited a trend of decreasing WAF with greater AK and this trend was more pronounced when participants were exposed to physical cues compared with visual only cues. For the instruction-based group (see the right panel of Figure 5), DMR tests revealed significantly greater sensitivity of low and medium AK groups to the presence of physical cueing than the high AK group.

Centre of pressure slope

An ANOVA on COP SLP z-scores revealed a significant three-way interaction between NT, AK, and PC. Similar to the WAF results, the left panel of Figure 6 reveals an increasing trend

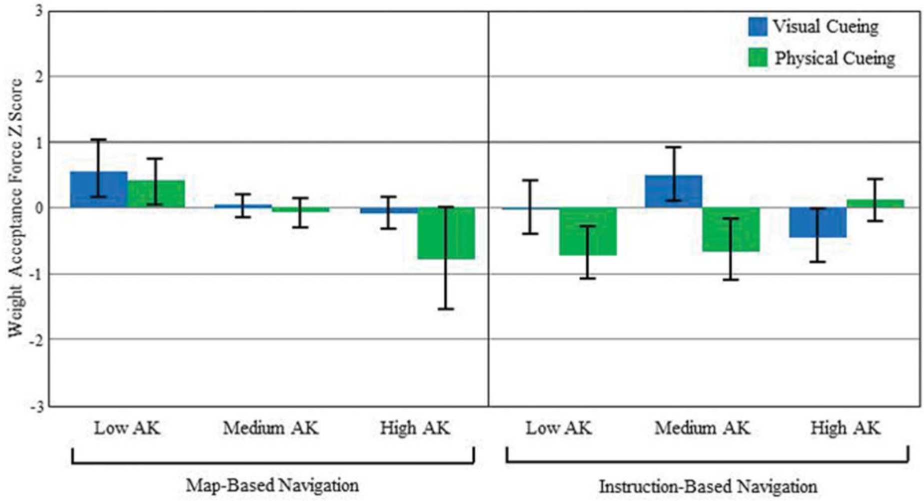


Figure 5. WAF *z*-scores plotted against AK levels for each navigation condition under each PC condition (lower values equate to greater proactive control).

in SLP as AK increased for the map-based navigation group, particularly in the absence of physical cueing. For the instruction-based group, there was a decrease in COP SLP with the exception of the medium AK group with no physical cues. This group exhibited the largest COP SLP response of all of the groups (see the right panel of Figure 6).

Navigation task query response accuracy

An ANOVA on the QRA revealed a significant two-way interaction between NT and the level of locomotor cognitive processing (F(2,231) = 3.84; $p < 0.05$) for achieving

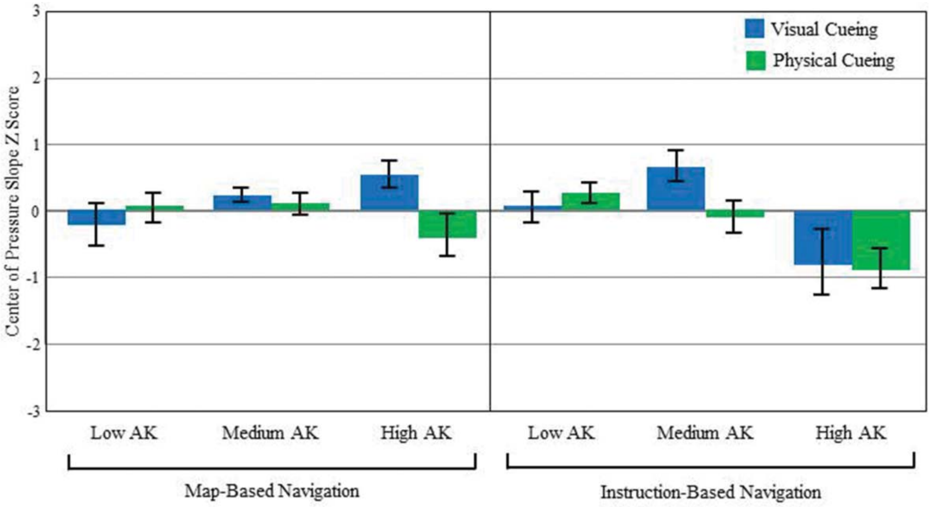


Figure 6. SLP *z*-scores plotted against AK for each PC condition under each navigation condition (higher values equate to greater proactive control).

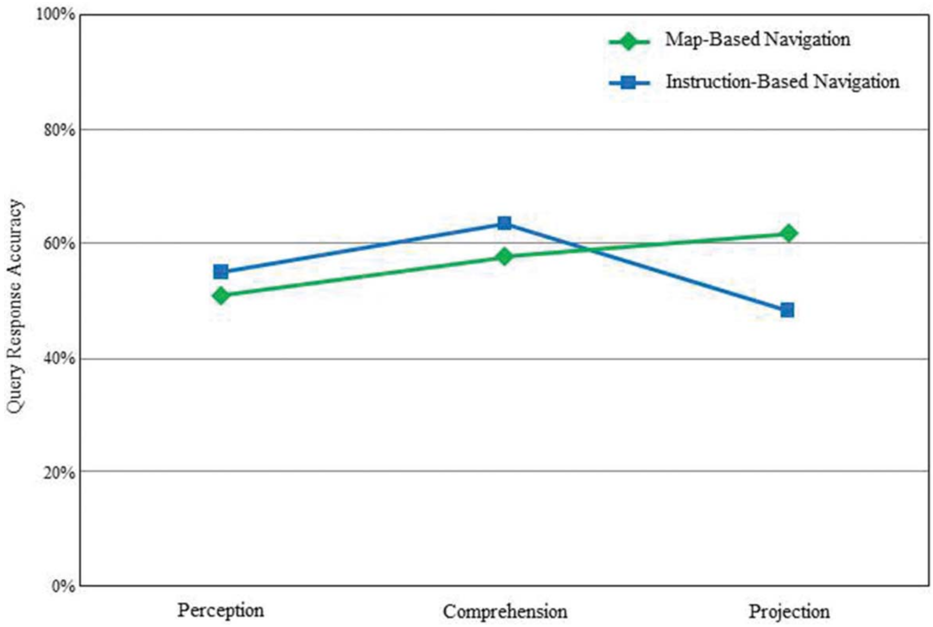


Figure 7. Cognitive processing level plotted against query response accuracy.

situation awareness (i.e. perception, comprehension, and projection). Further analysis of the two-way interaction using DMR tests indicated that there was a significant difference ($p < 0.05$) between the mean QRA in achieving comprehension of VLE states under instruction-based navigation (mean = 63.271; SE = 4.14) vs. projection of task environment states (mean = 48.234; SE = 4.30). Figure 7 provides a graphical representation of the two-way interaction between NT and the level of cognitive processing. It can be observed that the trend of QRA in perceiving and comprehending the VLE was higher under instruction-based navigation than map-based navigation. However, with respect to projection of VLE states, it can be observed that map-based navigation (mean = 61.854; SE = 3.73) resulted in higher QRA than instruction-based navigation (mean = 48.234; SE = 4.30). This suggests that instruction-based navigation may support operational and tactical behaviours in locomotion whereas map-based navigation may better support strategic behaviour. (We say more about the influence of the NTs on the gait and cognitive performance responses in Discussion section.)

Correlations

As previously mentioned, correlations of the QRA with WAF and SLP responses were examined using Pearson coefficients. The Pearson correlation coefficient values were used as inputs to an ANOVA to identify any mediating effects of the controlled manipulations (e.g. NT and AK) on the role of locomotor cognition in gait control. An ANOVA on the r-values between QRA and WAF revealed significant main effects due to NT, AK, and the number of the STRIDE preceding a perturbation. All two-way and three-way interactions included in the statistical model also proved to be significant, save AK*STRIDE, which was marginally significant ($p < 0.10$). Table 1 shows the ANOVA results for all terms assessed in the model.

Table 1. ANOVA results for IV effects on QRA and WAF correlations across five 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	$p < 0.05$

Further analysis of the two-way interaction between NT and PC showed that the presence of physical cues under instruction-based navigation produced significantly higher ($p < 0.05$) *r*-values (stronger relation of cognition with gait control; mean = 0.2; SE = 0.12) as compared to the physical cue trials under map-based navigation (mean = −0.44; SE = 0.08). Similar negative mean *r*-values were observed for the no-physical-cues condition under both map-based and instruction-based navigation. In general, the NT*PC interaction revealed a stronger correlation between cognition and gait control in the presence of physical cues as compared to the absence of cues. The significant effect of physical cueing was also evident in the AK*PC interaction, which showed that the mean correlation under physical cueing with low AK (mean = 0.03; SE = 0.15) was significantly higher ($p < 0.05$) as compared to all other conditions, which had negative correlations.

The two-way interaction involving NT and STRIDE was highly significant. Further analysis using DMR tests revealed that mean *r*-values at four strides before perturbation occurrence under instruction-based navigation were significantly higher (range of 0.05 ± 0.4) from those observed for at three strides (mean = −0.56; SE = 0.15) and one stride (mean = −0.54; SE = 0.11) before a perturbation under the map-based condition ($p < 0.05$). Figure 8 shows mean *r*-values for the strides leading up to perturbations across the map-based and instruction-based navigation conditions. In general, it can be observed from the plot that the task-knowledge mediation of the WAF response was higher under map-based navigation as compared to instruction-based navigation. Specifically, under map-based navigation, mean *r*-values at three strides and one stride before a perturbation were higher than the other strides for the map-based group. This data suggests that there might have been groups of participants following advance preparation strategies at one and three strides before reaching a hazard. This finding is related to Matthis and Fajen's (2014) observation of at least two gait cycles being necessary for hazard avoidance.

An ANOVA on the correlation between the degree of comprehension 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 in the absence of visual cueing (mean = −0.07; SE = 0.07) were significantly lower than the physical cue trials (mean = 0.15; SE = 0.08). *Post hoc* tests on STRIDE number revealed the linear association between comprehension of VLE

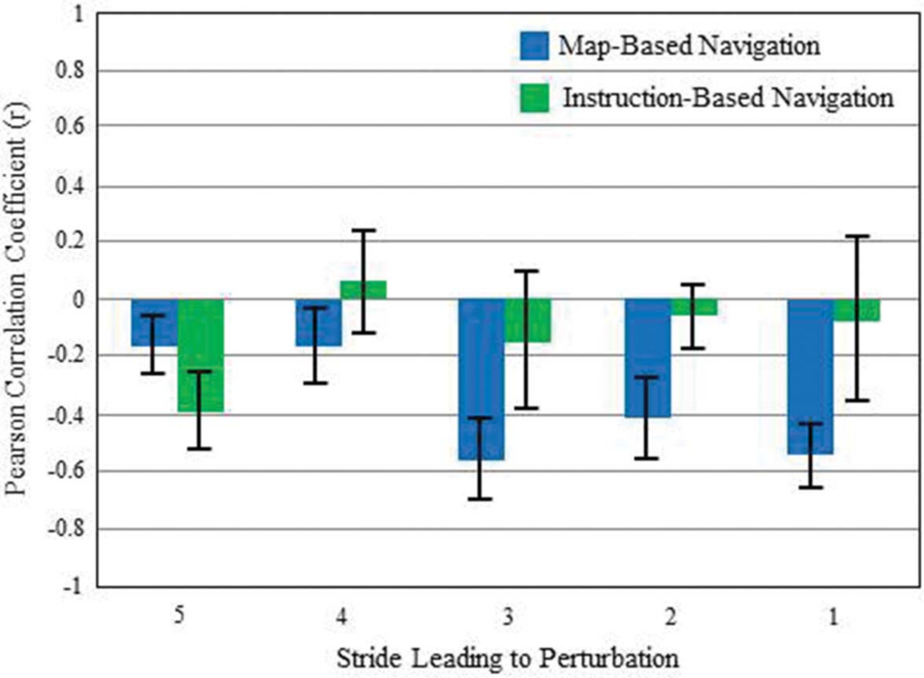


Figure 8. SAT correlation with WAF for strides leading up to perturbation across NT (lower values equate to greater awareness and control).

states and SLP to positive and significantly greater ($p < 0.05$) at one, two and three strides before a perturbation, as compared to four and five strides before the perturbation, which yielded negative associations of QRA and COP SLP. Figure 9 shows the mean *r*-values for the strides leading up to perturbation.

Discussion

Based on the results of the statistical analyses, there was a complex interaction of participant AK and PC on gait responses in multitasking involving locomotion. Furthermore, QRA or situation awareness in the navigation task appeared to play a mediating role in the degree of proactive preparation for locomotion perturbations in strides leading up to participants encountering a virtual hazard.

Weight acceptance force

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’. On this basis, H1.1 posited that WAF would decrease as AK increased, i.e. WAF would decrease as knowledge of the hazard increased. There was no significant main effect of AK or any two-way interaction involving AK on the WAF response; however, the significant three-way interaction between AK, NT, and PC revealed significant differences in the WAF response among low AK and no physical cueing and high AK and

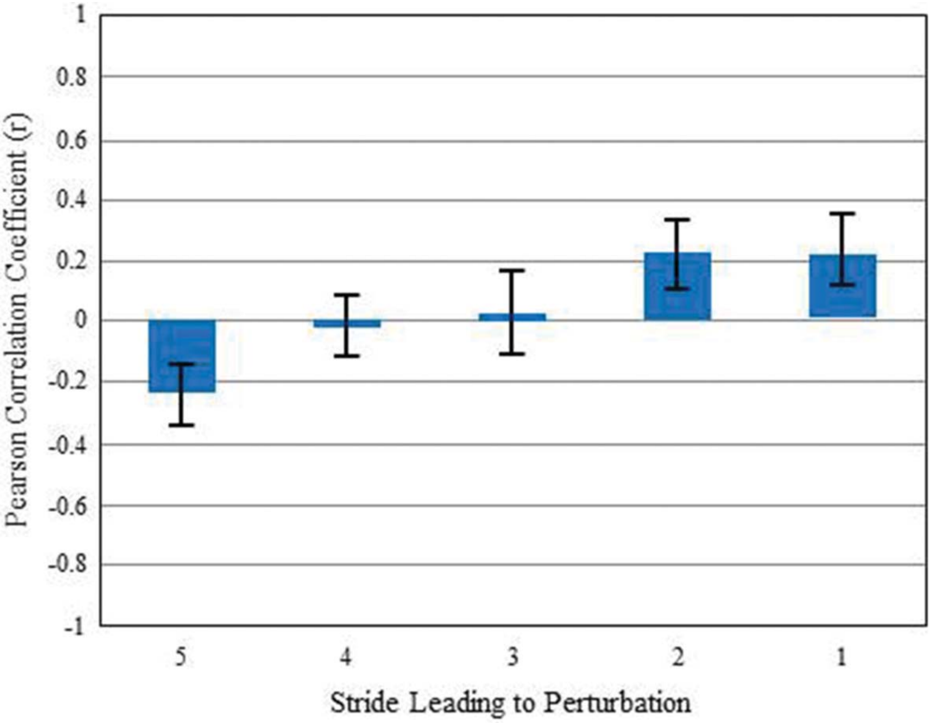


Figure 9. Correlation between degree of comprehension and SLP in strides leading up to perturbation (higher values equate to greater awareness and control).

physical cueing conditions during map-based navigation. These conditions can be considered extremes of one another in the range of conditions examined in the experiment. No prior knowledge on the task environment, combined with lower perceived risk of hazards under no physical cueing produced the highest mean WAF response compared to map-based navigation with high prior knowledge of the task environment and physical cueing. Plots on map-based navigation performance revealed the response to decrease steadily from the low AK to high AK conditions for both no-physical-cueing and physical cueing conditions. All of these findings were in support of our hypothesis and suggest that the higher-fidelity training trials facilitated formulation of more accurate mental models of the environment, allowing walkers to exercise proactive gait strategies when approaching a locomotion perturbation.

Further support for the notion that prior experience effects proactive gait control was found with the significant trial order main effect. It was observed that WAF responses during the second trial involving visual cueing were significantly lower than those in the second trial, indicating that previous experience with, or knowledge of, the visual characteristics of the locomotion hazard increased proactive gait control when similar hazards were encountered at a later time. It is interesting to note that the mean WAF *z*-scores for the second trials were lower than the mean of the baseline WAF distribution, indicating that in the five strides leading up to a perturbation, participants exhibited a WAF response lower than in normal walking. On the other hand, when they were not aware of the nature or features of a locomotion hazard (i.e. in their first exposure), participants exhibited WAF responses which were higher than in normal walking, as evidenced by positive

WAF *z*-scores. This result also supports the role of prior experience in forming an accurate mental model of the environment and hazards, as evidenced by walker proactive gait strategy.

Hypothesis 1.2 stated that WAF would be greater for instruction-based navigation than for map-based navigation, suggesting that the use of map-based navigation would be associated with a more proactive gait strategy due to the lower loads imposed by the map-based navigation task. There was no significant main effect of NT or any two-way interactions containing the NT variable. In general, the significant three-way interaction revealed that WAF decreased as AK increased under map-based navigation, supporting H1.2 for high AK but refuting the hypothesis for medium and low AK. However, the WAF response during instruction-based navigation was mixed. It is 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) previously concluded that participants exhibited a higher precedence of attention allocation to physical tasks (i.e. walking), as compared to cognitive tasks. In the present experiment, the use of the treadmill did not permit participants to slow down or stop walking in order to further concentrate on the cognitive task, and they could not completely ignore the location reporting task, as their responses were required to receive additional 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 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 and Doane 2003). Hypothesis 1.2 was supported under some conditions of the present study (e.g. map-based navigation at high AK) but was refuted by the results on the majority of conditions. It appeared that the combination of high AK and the lower cognitive resource requirements of the map-based navigation task facilitated accurate mental model formulation, leading to proactive gait control.

Hypothesis 1.3 posited that WAF would be lower under physical cueing as compared to the absence of physical perturbation cues. The PC main effect on the WAF response indicated that participants walked less cautiously under the absence of physical cueing condition with significantly higher WAF *z*-scores, as compared to trials with physical cueing, supporting H1.3. The presence of physical cueing along with visual presentation of the locomotion hazard may have increased the perceived severity of the hazard, possibly causing participants to be more cautious in the strides leading up to subsequent perturbations and forming more accurate mental models. Information regarding the severity of a perturbation is dependent on accurate identification of the hazard, which might also depend on perception of surrounding environmental cues. This situation emphasises the need for accurate knowledge and understanding of a locomotion environment (i.e. H1.1), particularly when performing concurrent cognitive tasks.

Centre of pressure slope

H2.1 stated that SLP would increase with increasing AK. The higher AK group was expected to allocate greater attention to locomotion when approaching a perturbation as a result of more accurate mental models of the environment and hazard conditions. There was no significant effect of AK or a significant two-way interaction containing AK on SLP. Through the three-way interaction, it was revealed that higher SLP *z*-scores occurred with medium and high AK under map-based navigation, supporting the hypothesis. However, results on the instruction-based navigation condition refuted the hypothesis, suggesting that there was a higher level of cognitive workload under the instruction-based condition, possibly preventing participants from devoting attentional resources to locomotion when approaching a perturbation.

Hypothesis 2.2 posited that SLP would be higher under map-based than under instruction-based navigation. As with AK, there was no significant effect of NT or a significant two-way interaction containing NT on SLP. In general, results of the three-way interaction were mixed; under high and medium AK, the hypothesis was supported, but not under low AK. It is likely that under the high and medium conditions, participants became familiar enough with the task and VLE that they could devote greater attention to locomotion under map-based navigation; however, as suggested above, any effect of the higher levels of AK might have been moderated by cognitive workload associated with the instruction-based navigation location reporting task.

Hypothesis 2.3 stated that SLP would be greater when trials included physical perturbation cues, as compared to trials that did not include physical cueing. Physical cues of perturbations were expected to lead to more accurate mental models of hazards than visual only cueing and to cause greater attention to locomotion than visual only cueing. There was no significant main effect of NT or a significant two-way interaction containing NT on SLP. The significant three-way interaction revealed that across all levels of NT and AK, SLP in the absence of physical cueing was greater than in the presence of physical cueing. This finding was counter to our expectation. Results revealed the lack of physical cues to reduce otherwise high attention allocation to locomotion under map-based navigation. It is possible that, as a result of participants being unaware of the actual severity of perturbations when no physical cues were presented, they overestimated severity and made excessive gait control adjustments. On the other hand, when physical cues were presented, participants knew the degree of perturbation severity and adjusted their gait accordingly.

Navigation task query response accuracy

Hypothesis 3.1 posited that higher AK would be associated with higher QRA. Similarly, H3.3 posited that QRA would be higher in the absence of visual cues than in the presence of visual cues. There was no significant effect of either the AK variable or the PC variable on QRA, refuting both hypotheses. Since the three training sessions did not provide preparation for the navigation task (i.e. the sessions focused on familiarisation with the VLE and perturbations), it is possible that all participants were at the same level of awareness when it came to navigating through the simulated environment. Similarly, it is possible that the visual image of a locomotion hazard alone was enough to affect QRA; that is, the physical perturbation did not affect knowledge and understanding of the navigation task.

Hypothesis 3.2, which stated that QRA would be higher under map-based than under instruction-based navigation, was supported for queries measuring the ability to project future states of the VLE, but not for queries measuring perception or comprehension, as evidenced by the significant two-way interaction between NT and level of processing. (The main effect of NT on QRA was not significant.) It is possible that the location-reporting task as part of instruction-based navigation task focused participant attention on perceiving and comprehending cues from the environment, significantly impairing their ability to project future events.

Navigation task query score and proactive gait control

Hypothesis 4 posited that higher navigation task knowledge, as indicated by higher QRA, would positively impact proactive gait control. A significant two-way interaction between NT and the STRIDE before a locomotion hazard indicated an association between task knowledge and WAF (across strides) for map-based navigation, but not for instruction-based navigation. Under map-based navigation, higher negative associations for strides 1-3 suggested that participants adopted a 1-3 stride advance strategy for proactive preparation for locomotion hazards. This observation was in line with previous research (e.g. Patla et al. 1999; Matthis and Fajen 2014). For the instruction-based group, there was no clear three-stride or one-stride strategy indicated by the lack of an increasing or decreasing trend of the mean r-values presented in Figure 8. The variability in the correlation between QRA and WAF during those strides was high, indicating that some participants may have exhibited proactive preparation for hazards.

The correlation between SLP and QRA focusing on participant comprehension of the VLE revealed mediating effects of PC and STRIDE. As shown by the main effect of PC, the strength of association of VLE comprehension and SLP was lower when there was no physical cueing compared to trials that included physical cueing, indicating participants exhibited greater proactive gait control when they had higher comprehension of states of the environment, which was facilitated by presentation of physical perturbation cues. Related to this, the association of VLE comprehension and SLP revealed a linear increase across the five strides leading-up to a perturbation, shown by the marginally significant effect of stride and presented in Figure 9. The last two strides before a perturbation revealed a significantly higher association between VLE comprehension and SLP, indicative of greater proactive control for locomotion hazards.

Conclusions

The primary objective of this research was to assess the influence of multitasking involving cognitive performance (a navigation task) during locomotion on the degree of proactive control for perturbations. A second objective was to assess the relation of locomotor internal situation model formulation and the occurrence of proactive control. The independent variable manipulations were designed to address these objectives. Specifically, the NT involved manipulating the degree of cognitive assistance or locomotor workload in the navigation task and the AK condition manipulated participant familiarity with the VLE. Based on the results, gait behaviour was affected by the combination of NT and AK as well as the type of PC. In general, more accurate mental model formulation, which was facilitated by higher fidelity training (a priori knowledge), and repeated exposure to hazards (trial order) led walkers to develop proactive gait strategies. Including physical perturbation cues in training and testing increased the realism of the task scenario and presented forces at appendages allowing walkers to make more accurate predictions of hazard severity. This situation was particularly true for lower cognitive loads (i.e. map-based navigation) as the higher cognitive loads, associated with the instruction-based navigation task, interfered with mental model formulation. Overall, the significant results of the independent variable manipulations provide a link among (1) the ability to form accurate mental models of an environment and its hazards, (2) cognitive loading, and (3) adoption of proactive gait strategies.

Measurement of situation awareness QRA through the real-time probing technique was used to assess three levels of participant cognitive processing, including perception, comprehension, and projection of VLE states. The correlation analyses on task knowledge and gait responses assessed linkages between the levels of cognitive processing and the occurrence of proactive gait control. The linear association of QRA and WAF provided evidence supporting higher navigation task knowledge/understanding (in general) leading to higher proactive control. Other links were found between participant comprehension of the locomotion environment and proactive gait control. In general, the experiment demonstrated that accurate task knowledge and situation processing are required for gait control for locomotion hazards when performing concurrent cognitive tasks. Furthermore, the data analysis revealed that participants might have followed a three-stride advance preparation strategy for accommodating hazards and a one-stride advance preparation strategy for avoiding hazards. Participants appeared to develop greater proactive control when their comprehension of environmental cues increased, particularly in the last two strides prior to encountering a perturbation. Overall, these results shed light on the relationship between cognitive states and gait control strategies and can be used to assess how workers, who walk on a variety of different surfaces and encounter a wide variety of locomotion hazards, accommodate for hazards when under concurrent cognitive loads.

One limitation of the present research was the lack of participant control of their walking speed. In order to record the various gait response measure, participants needed to roughly maintain a position near the centre of the treadmill belt during the locomotion trials. If participants foot strikes did not land at or near the center of the treadmill belt, there would be a loss of data and potential compromise in statistical analysis of proactive gait responses. Since participants were required to maintain a defined pace in the test trials, this also prevented assessment of navigation and locomotion performance in terms of time-to-task completion. Beyond this limitation, it is possible that the verbal nature of the situation awareness queries interfered with the navigation task performance, particularly for participants under the instruction-based navigation condition.

Related to these limitations, future work should focus on predictive and reactive gait control strategies in response to locomotion hazards under multitasking scenarios. Kinematic and electromyography data should be collected, which may provide additional evidence of specific strategies that are adopted for hazards accommodation and avoidance. Finally, eye-tracking data could be collected, in order to identify exactly what information a locomotor perceives during navigation task performance. Such a response measure might provide objective evidence of participant situation awareness in a locomotion scenario with high cognitive load.

Funding

Two authors' work on this research was supported in part by a grant from the U.S. National Institute for Occupational Safety and Health [grant number NIOSH: No.2 T42 OH008673-13]. The opinions expressed in this report are those of the authors and do not necessarily reflect the views of NIOSH.

About the authors

Mohamed Sheik-Nainar is a senior usability researcher at Synaptics, Inc. He received his PhD in Industrial and Systems Engineering in 2007 from North Carolina State University. He received his MS from the same institution in 2002. His current research interests include multifingered touchpad design.

David Kaber is a professor of Industrial Engineering at North Carolina State University. He received his PhD in Industrial Engineering from Texas Tech University in 1996. He was an assistant professor at Mississippi State University from 1996–2000. His current research interests include human multitasking performance involving locomotion and cognitive tasks.

Simon Hsiang is the E. L. Derr Professor of Industrial Engineering at Texas Tech University. He received his PhD in Industrial Engineering from Texas Tech University in 1992 and his MS in 1989. He was an associate professor at North Carolina State University from 2005–2011.

Carl Pankok, Jr is a doctoral student in the Edward P. Fitts Department of Industrial and Systems Engineering at North Carolina State University. He received his MS in Industrial and Systems Engineering in 2013 from North Carolina State University and his BS in Industrial and Systems Engineering in 2009 from Rutgers University.

Maryam Zahabi is a doctoral student in the Edward P. Fitts Department of Industrial and Systems Engineering at North Carolina State University. She received her MS in Industrial and Systems Engineering in 2013 and her BS in Industrial and Systems Engineering in 2011 from Sharif University of Technology.

References

Ambati, V.N., N.G. Murray, F. Saucedo, D.W. Powell, and R.J. Reed-Jones. 2013. “Constraining Eye Movement When Redirecting Walking Trajectories Alters Turning Control in Healthy Young Adults.” *Experimental Brain Research* 226 (4): 549–556. doi: 10.1007/s00221-013-3466-8.

Amboni, M., P. Barone, and J.M. Hausdorff. 2013. “Cognitive Contributions to Gait and Falls: Evidence and Implications.” *Movement Disorders* 28 (11): 1520–1533. doi: 10.1002/mds.25674.

Bailey, R.W. (1989). *Human Performance Engineering: A Guide for System Designers* (2nd ed., Chap. 1). Englewood Cliffs, NJ: Prentice Hall.

Bardy, B.G., and M. Laurent. 1991. “Visual Cues and Attention Demand in Locomotor Positioning.” *Perceptual and Motor Skills* 72 (3): 915–926. doi: 10.2466/pms.1991.72.3.915.

Bloem, B.R., V.V. Valkenburg, M. Slabbekoorn, and M.D. Wilemsen. 2001. “The Multiple Task Test: Development and Normal Strategies.” *Gait and Posture* 14: 191–202. doi: 10.1016/S0966-6362(01)00141-2.

Bohm, S., F. Mersmann, S. Bierbaum, R. Dietrich, and A. Arampatzis. 2012. “Cognitive Demand and Predictive Adaptational Responses in Dynamic Stability Control.” *Journal of Biomechanics* 45 (14): 2330–2336. doi: 10.1016/j.jbiomech.2012.07.009.

Bollens, B., F. Crevecoeur, C. Detrembleur, T. Warlop, and T.M. Lejeune. 2014. “Variability of Human Gait: Effect of Backward Walking and Dual-tasking on the Presence of Long-range Autocorrelations.” *Annals of Biomedical Engineering* 42 (4): 742–750. doi: 10.1007/s10439-013-0961-9.

Brou, R.J., and S.M. Doane. 2003. “Individual Differences in Object Localization in Virtual Environments.” *Spatial Cognition and Computation* 3 (4): 291–314. doi: 10.1207/s15427633scc0304_3.

Brown, L., A. Shumway-Cook, and M. Woollacott. 1999. “Attentional Demands and Postural Recovery: The Effects of Aging.” *Journal of Gerontology* 54A: M165–M171. doi: 10.1093/gerona/54.4.M165.

Cohen, H.H., and D.M. Cohen. 1994a. “Perceptions of Walking Surface Slipperiness Under Realistic Conditions Utilizing A Slipperiness Rating Scale.” *Journal of Safety Research* 25: 27–31. doi: 10.1016/0022-4375(94)90005-1.

Cohen, H.H., and D.M. Cohen. 1994b. “Psychophysical Assessment of the Perceived Slipperiness of Floor Tile Surfaces in Laboratory Setting.” *Journal of Safety Research* 25: 19–26. doi: 10.1016/0022-4375(94)90004-3.

Courtney, T.K., G.S. Sorock, D.P. Manning, J.M. Collins, and M.A. Holbein-Jenny. 2001. “Occupational Slip, Trip, and Fall-Related Injuries: Can the Contribution of Slipperiness be Isolated?.” *Ergonomics* 44 (13): 1118–1137. doi: 10.1080/00140130110085538.

Courtney, T.K., S.K. Verma, W.R. Chang, Y.H. Huang, D.A. Lombardi, M.J. Brennan, and M.J. Perry. 2013. “Perception of Slipperiness and Prospective Risk of Slipping at Work.” *Occupational and Environmental Medicine* 70 (1): 35−40. doi: 10.1136/oemed-2012-100831.

Ebersbach, G., M.R. Dimitrijevic, and W. Poewe. 1995. “Influence of Concurrent Tasks on Gait: A Dual-Task Approach.” *Perceptual and Motor Skills* 81 (1): 107−113. doi: 10.2466/pms.1995.81.1.107.

Endsley, M.R. 1995. “Measurement of Situation Awareness in Dynamic Systems.” *Human Factors* 37 (1): 65−84. doi: 10.1518/001872095779049499.

Endsley, M.R., and D.B. Kaber. 1999. “Level of Automation Effects on Performance, Situation Awareness and Workload in a Dynamic Control Task.” *Ergonomics* 42: 462−492. doi: 10.1080/001401399185595.

Fingerhut, L.A., C.S. Cox, and M. Warner. 1998. *International Comparative Analysis of Injury Mortality: Findings from the ICE on Injury Statistics, Advanced Data from Vital and Health Statistics*. Hyattsville, MD: National Center for Health Statistics.

Gage, W.H., R.J. Sleik, M.A. Polych, N.C. McKenzie, and L.A. Brown. 2003. “The Allocation of Attention During Locomotion Is Altered by Anxiety.” *Experimental Brain Research* 150: 385−394. doi: 10.1007/s00221-003-1468-7.

Gao, C., and J. Abeysekera. 2002. “The Assessment of the Integration of Slip Resistance, Thermal Insulation and Wearability of Footwear on Icy Surfaces.” *Safety Science* 40: 613−624. doi: 10.1016/S0925-7535(01)00062-5.

Grönqvist, R. 1999. “Slips and Falls.” In *Biomechanics in Ergonomics*, edited by S. Kumar, 351−375. London: Taylor & Francis.

Grönqvist, R., J. Abeysekera, G. Garg, S.M. Hsiang, T.B. Leamon, D.J. Newman, K. Gielo-Perczak, T.E. Lockhart, and Y.C. Pai. 2001. “Human-Centered Approaches in Slipperiness Measurement.” *Ergonomics* 44 (13): 1167−1199. doi: 10.1080/00140130110085556.

Hsu, Y., and K. Li. 2010. “A Field Assessment of Floor Slipperiness in a Fish Market in Taiwan.” *Safety Science* 48 (5): 556−561. doi: 10.1016/j.ssci.2010.01.001.

Hsu, C.L., L.S. Nagamatsu, J.C. Davis, and T. Liu-Ambrose. 2012. “Examining the Relationship Between Specific Cognitive Processes and Falls Risk in Older Adults: A Systematic Review.” *Osteoporosis International* 23 (10): 2409−2424. doi: 10.1007/s00198-012-1992-z.

Kaber, D.B., and M.R. Endsley. 2004. “The Effects of Level of Automation and Adaptive Automation on Human Performance, Situation Awareness and Workload in a Dynamic Control Task.” *Theoretical Issues in Ergonomics Science* 5 (2): 113−153. doi: 10.1080/1463922021000054335.

Kaber, D.B., Y. Zhang, S. Jin, P. Mosaly, and M. Garner. 2012. “Effects of Hazard Exposure on Driver Situation Awareness and Performance and the Interaction with Roadway Complexity and Driver Age.” *Transportation Research Part F: Traffic Psychology and Behaviour* 15: 600−611. doi: 10.1016/j.trf.2012.06.002.

Kennedy, R.S., N.E. Lane, K.S. Berbaum, and M.G. Lilienthal. 1993. “Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness.” *International Journal of Aviation Psychology* 3: 203−220. doi: 10.1207/s15327108ijap0303_3.

Kerr, B., S.M. Condon, and L.A. McDonald. 1985. “Cognitive Spatial Processing and the Regulation of Posture.” *Journal of Experimental Psychology: Human Perception and Performance* 11: 617−622. doi: 10.1037//0096-1523.11.5.617.

Lajoie, Y., N. Teasdale, C. Bard, and M. Fleury. 1993. “Attentional Demands for Static and Dynamic Equilibrium.” *Experimental Brain Research* 97: 139−144.

Leclercq, S. 1999. “The Prevention of Slipping Accidents: A Review and Discussion of Work Related to the Methodology of Measuring Slip Resistance.” *Safety Science* 31: 95−125. doi: 10.1016/S0925-7535(98)00064-2.

Li, K.Z., G.A. Abbud, S.A. Fraser, and R.G. DeMont. 2012. “Successful Adaptation of Gait in Healthy Older Adults During Dual-Task Treadmill Walking.” *Aging, Neuropsychology, and Cognition* 19 (1-2): 150−167. doi: 10.1080/13825585.2011.628375.

Lin, L.J., F.T. Chiou, and H.H. Cohen. 1995. “Slip and Fall Accident Prevention: A Review of Research, Practice and Regulations.” *Journal of Safety Research* 26 (4): 203−212. doi: 10.1016/0022-4375(95)00017-K.

Ma, R., and D.B. Kaber. 2007. “Situation Awareness and Driving Performance in a Simulated Navigation Task.” *Ergonomics* 50 (8): 1351−1364. doi: 10.1080/00140130701318913.

Marigold, D.S., and A.E. Patla. 2002. “Strategies for Dynamic Stability During Locomotion on a Slippery Surface: Effects of Prior Experience and Knowledge.” *Journal of Neurophysiology* 88: 339–353. doi: 10.1152/jn.00691.2001.

Matthis, J.S., and B.R. Fajen. 2014. “Visual Control of Precise Foot Placement When Walking Over Complex Terrain.” *Journal of Experimental Psychology – Human Perception and Performance* 40 (1): 106–115. doi: 10.1167/13.9.121.

Nenonen, N. 2013. “Analysing Factors Related to Slipping, Stumbling, and Falling Accidents at Work: Application of Data Mining Methods to Finnish Occupational Accidents and Diseases Statistics Database.” *Applied Ergonomics* 44 (2): 215–224. doi: 10.1016/j.apergo.2012.07.001.

Oliveira, C., A. Souza, D. Farina, and U.G. Kersting. 2012. “Biomechanical Strategies to Accommodate Expected Slips in Different Directions During Walking.” *Gait and Posture* 36 (2): 301–306. doi: 10.1016/j.gaitpost.2012.03.016.

Patla, A.E. 1991. “Visual Control of Human Locomotion.” In *Adaptability of Human Gait: Implications for the Control of Locomotion*, edited by A.E. Patla, 55–97. Amsterdam: Elsevier.

Patla, A.E. 2003. “Strategies for Dynamic Stability During Adaptive Human Locomotion.” *IEEE Engineering in Medicine and Biology Magazine* 22 (2): 48–52. doi: 10.1109/MEMB.2003.1195695.

Patla, A.E., S.D. Prentice, S. Rietdyk, F. Allard, and C. Martin. 1999. “What Guides the Selection of Alternate Foot Placement During Locomotion in Humans?” *Experimental Brain Research* 128: 441–450. doi: 10.1007/s002210050867.

Patla, A.E., S. Prentice, C. Robinson, and J. Neufeld. 1991. “Visual Control of Locomotion: Strategies for Changing Direction and for Going Over Obstacles.” *Journal of Experimental Psychology – Human Perception and Performance* 17 (3): 603–634. doi: 10.1037/0096-1523.17.3.603.

Pavol, M.J., E.F. Runtz, and Y.C. Pai. 2004. “Young and Older Adults Exhibit Proactive and Reactive Adaptations to Repeated Slip Exposure.” *Journal of Gerontology* 59A (5): 494–502. doi: 10.1093/gerona/59.5.M494.

Pyykkö, I., P. Jäntti, and H. Aalto. 1990. “Postural Control in Elderly Subjects.” *Age and Ageing* 19: 215–221. doi: 10.1093/ageing/19.3.215.

Qu, X. 2013. “Effects of Cognitive and Physical Loads on Local Dynamic Stability During Gait.” *Applied ergonomics* 44 (3): 455–458. doi: 10.1016/j.apergo.2012.10.018.

Reilly, T., and D. Smith. 1986 “Effect of Work Intensity on Performance in A Psychomotor Task During Exercise.” *Ergonomics* 29 (4); 601–606. doi: 10.1080/00140138608968294.

Sheik-Nainar, M.A., and D.B. Kaber. 2007. “The Utility of A Virtual Reality Locomotion Interface for Studying Gait Behavior.” *Human Factors* 49: 696–709. doi: 10.1518/001872007×215773.

Tisserand, M. 1985. “Progression in the Prevention of Falls Caused by Slipping.” *Ergonomics* 28: 1027–1042. doi: 10.1080/00140138508963225.

Tomporowski, P.D. 2003 “Effects of Acute Bouts of Exercise on Cognition.” *Acta Psychologica* 112: 297–324. doi: 10.1016/S0001-6918(02)00134-8.

Trew, M., and T. Everett. 1997. *Human Movement*. New York: Churchill Livingstone.

Valerie, K.E., A.A. Janke, and A. Shumway-Cook. 2010. “Effects of Instructed Focus and Task Difficulty on Concurrent Walking and Cognitive Task Performance in Healthy Young Adults.” *Experimental Brain Research* 207 (1–2): 65–73. doi: 10.1007/s00221-010-2429-6.

Vouriot, A., G.C. Gauchard, N. Chau, L. Benamghar, M.L. Lepori, J.M. Mur, and P.P. Perrin. 2004. “Sensorial Organization Favouring Higher Visual Contribution Is a Risk Factor of Falls in an Occupational Setting.” *Neuroscience* 48 (3): 239–247. doi: 10.1016/j.neures.2003.11.001.

Weerdesteyn, V., A.M. Schillings, G.P. van Galen, and J. Duysens. 2003. “Distraction Affects the Performance of Obstacle Avoidance During Walking.” *Journal of Motor Behavior* 35 (1): 53–63. doi: 10.1080/00222890309602121.

Woollacott, M., and A. Shumway-Cook. 2002. “Attention and the Control of Posture and Gait: A Review of an Emerging Area of Research.” *Gait and Posture* 16: 1–14. doi: 10.1016/S0966-6362(01)00156-4.

Yeoh, H.T., T.E. Lockhart, and W. Xuefang. 2013. “Nonfatal Occupational Falls on the Same Level.” *Ergonomics* 56 (2): 153–165. doi: 10.1080/00140139.2012.746739.

Yogev-Seligmann, G., N. Giladi, L. Gruendlinger, and J.M. Hausdorff. 2013. “The Contribution of Postural Control and Bilateral Coordination to the Impact of Dual Tasking on Gait.” *Experimental Brain Research* 226 (1): 81–93. doi: 10.1007/s00221-013-3412-9.

Yogev-Seligmann, G., Y. Rotem-Galili, A. Mirelman, R. Dickstein, N. Giladi, and J.M. Haurdorff. 2010. “How Does Explicit Prioritization Alter Walking During Dual-task Performance? Effects of Age and Sex on Gait Speed and Variability.” *Physical Therapy* 90 (2): 177−186. doi: 10.2522/ptj.20090043.

Yoshikawa, H. 2003. “Modeling Humans in HCI.” In *The Human-computer Interaction Handbook*, edited by J. Jacko, and A. Sears, 119−146. Mahwah, NJ: Erlbaum.

Zhang, T., D.B. Kaber, and S.M. Hsiang. 2010. “Characterization of Mental Models in A Virtual Reality-Based Multitasking Scenario Using Measures of Situation Awareness.” *Theoretical Issues in Ergonomics Science* 11 (1-2): 99−118. doi: 10.1080/14639220903010027.