Examination of dual-task training protocols to alter performance on a concurrent auditory Stroop and obstacle crossing dual-task test

By

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Abstract

Examination of Dual-Task Training Protocols to Alter Performance on a Concurrent Auditory Stroop and Obstacle Crossing Dual-Task Test

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This thesis is an investigation of the feasibility of training protocols to alter dual-task performance in complex environments. The performance of a cognitive task during whole body movements is well established to cause performance decrements in either one of, or both tasks. Furthermore, these performance decrements are amplified as tasks become more challenging and in certain special populations, such as older adults. Research groups have developed training protocols to examine the possibility of reducing dual-task interference effects. However, it is currently unknown if training will transfer to improvements in more complex environments. The current thesis is composed of four experiments. The first experiment was designed to better understand the effects of structural interference on the concurrent performance of an obstacle avoidance task. Results from this experiment demonstrated larger dual-task interference effects on a concurrent obstacle crossing task in the presence of structural interference, indicating the selection of a cognitive task to pair with obstacle crossing has a major influence on performance outcomes. Experiments II & III examined different durations and compositions of training protocols in young adults designed to alter performance on a complex test of dual task performance (a concurrent obstacle crossing and auditory Stroop task). In Experiments II & III, dual-task training protocols composed of performing simultaneous walking and cognitive tasks were observed to increase minimum trail foot clearance in young adults, indicating a potentially more cautious obstacle crossing strategy following training. Conversely, in Experiment III, the training program based on computer-game based training did not alter obstacle crossing strategies to the same magnitude. Finally, the fourth experiment applied the most effective training protocol from the previous studies to a population of community dwelling older adults. Results from the experiment indicated older adult participants exposed to walking based dual-task training did not alter obstacle clearance values, but instead walked more slowly during the dual-task test following training, indicating an alteration to allow more time to implement an obstacle crossing strategy. Collectively, the results of this dissertation indicate that dual-task performance is largely modulated by the tasks included in the experimental protocol. Furthermore, the effects induced by a walking based dual-task training protocol to performance on a concurrent obstacle crossing and auditory Stroop test depend on the population tested.
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Chapter 1 Introduction & Thesis Objectives

1.1 General Introduction

Successful interaction with the environment requires an individual to attend to and make decisions based on relevant information (de Rugy et al. 2002; Hollands & Marple-Horvat 2001; Warren et al. 2001; Worden & Vallis 2016). The simultaneous performance of two tasks (dual-tasking) often leads to decrements in the performance of one or both tasks, as attention must be allocated between the two tasks (Kerr et al. 1985; Lajoie et al. 1993; Weerdesteyn et al. 2003). The effects of dual-task interference range from slowed response times in probe reaction time tests (Lajoie et al. 1993; Wellmon et al. 2013), to reductions in car driving performance (Consiglio et al. 2003; Levy et al. 2006), to increased falls risk in older adults (Makizako et al. 2010; Muhaidat et al. 2013; Shumway-Cook et al. 1997; Tinetti et al. 1995; Wong et al. 2008). Furthermore, populations such as older adults and special populations (e.g. Huntington’s disease, Parkinson’s disease, traumatic brain injury patients) have been observed to have larger performance decrements induced by dual-tasking as compared to young adults (Anguera et al. 2013; Chen et al. 1996; Delval et al. 2008; Dorman et al. 2015; Persa et al. 1995; Schaefer et al. 2015; Wellmon et al. 2013; Wild et al. 2013). Given the challenges that dual-tasking can pose for humans, a better understanding of the effects of dual-task interference, and the possibility of enhancing dual-task performance, is an important area of research.

How individuals are able to integrate and perform two tasks concurrently is one of the fundamental mysteries of cognitive processing, and theories explaining how this
occurs are still hotly debated (Navon & Miller 1987; Pashler 1994; Tombu & Jolicoeur 2003). Much of the peer reviewed research examining these fundamental questions has been conducted in the area of experimental psychology, with relatively simple postural tasks, such as seated in front of a computer and identifying tasks presented on a monitor (Levy et al. 2006; Pashler 1994; Ruthruff et al. 2001; Strobach et al. 2013). Within these paradigms, robust dual-task interference effects have been observed using many different cognitive tests, indicating that dual-task interference is generalizable across a wide range of situations (Levy et al. 2006; Pashler 1994; Ruthruff et al. 2001; Strobach et al. 2013). Although insight into the mechanisms and effects of certain concurrently performed tasks have been observed in these paradigms, much less is known about how the simultaneous performance of a secondary task affects more complicated human movements.

When examining the biomechanics literature, cognitive tasks have been paired with different postural tasks to examine how two very different tasks may interfere with each other, resulting in decreases in performance (Ebersbach et al. 1995; Lajoie et al. 2013; Schaefer et al. 2008; Yogev-Seligmann et al. 2010). In keeping with previous terminology within the biomechanics literature, the task which requires larger body movements (e.g. bodily segments moving through greater ranges of motion) will be termed the ‘postural task’, while the task that is performed concurrently (usually with little body movement for the response output, e.g. articulation of a verbal response) will be termed the ‘cognitive task’ (Brown et al. 1999; Schaefer et al. 2015; Siu et al. 2008). Dual-task situations where a posturally demanding task and a cognitive based task are simultaneously performed occurs frequently during everyday activities (e.g. remembering a shopping list while moving through the busy aisles of a grocery store), but have been
studied in less detail than simpler tasks. Interestingly, this area of research has only become prominent in the last 25 years, largely due to the influential works of key researchers who were interested in studying cognitive influences on motor control (e.g. Ebersbach et al. 1995; Kerr et al. 1985; Lajoie et al. 1993; Shumway-Cook et al. 1997).

Historically, research in this area was limited, perhaps due to the notion that some motor tasks (e.g. walking or standing) require relatively little attention to perform (i.e. they can proceed automatically) (Courtine et al. 2006; Hof 2008; Winter 1995). However, researchers now know that postural tasks do require some attention to be performed successfully (Ebersbach et al. 1995; Lajoie et al. 1993; Kerr et al. 1985; Shumway-Cook et al. 1997). Although past research has examined the effects of a cognitive task on human movement, it is important to note that no standardized approach has been implemented in the field, which makes interpretation of results across studies difficult. For example, cognitive tasks ranging from relatively simple (e.g. probe reaction time tests: Chen et al. 1996; Lajoie et al. 1993; Wellmon et al. 2013) to attentionally demanding (Stroop tests, working memory tasks: Kerr et al. 1985; Schaefer et al. 2008; Siu et al. 2008; Worden & Vallis 2014) have all been performed. Unfortunately, observed dual-task effects vary, in part due to the different cognitive tasks chosen in these paradigms (Ebersbach et al. 1995; Lajoie et al. 1993; Schaefer et al. 2008; Weerdesteyn et al. 2003; Worden & Vallis 2014). Generally, a task is composed of three unique processing stages (see Section 2.2), and dual-task studies have used tasks that result in interference at the perceptual (i.e. the stage of becoming aware of stimuli through sensory information) as well as the central response selection stages (i.e. the stage of selecting a response to the perceived stimuli) of performance (Chen et al. 1996; Potocanac et al.
2015; Kahneman & Chajczyck 1983). This further complicates comparisons made across studies due to the different probable locations of dual-task interference (Pashler & Baylis 1991; Strobach et al. 2013).

In spite of the identified limitations of a non-standardized approach to choosing cognitive tasks to pair with postural tasks, the results within the research field as a whole do highlight an overall performance reduction in task proficiency (in either the cognitive task, motor task or both tasks) when a cognitive and postural task are performed concurrently (Ebersbach et al. 1995; Lajoie et al. 1993; Kerr et al. 1985; Schaefer et al. 2008; Shumway-Cook et al. 1997). Due to dual-task interference causing decrements in the performance of motor tasks, the feasibility of training programs to alter dual-task outcomes has been investigated (Pellecchia 2005; Silsupadol et al. 2009; Trombetti et al. 2011; Worden & Vallis 2014). However, these training programs test improvements in relatively simple dual-task situations (Pellecchia 2005; Silsupadol et al. 2009; Trombetti et al. 2011), which arguably do not reflect more challenging everyday environments. Furthermore, the generalizability of dual-task training programs remains poorly understood (Basak et al. 2008; Bherer et al. 2005; Kramer et al. 1995) as to date, most training programs train individuals using tasks similar to what will be experimentally tested (Pellecchia 2005; Silsupadol et al. 2009; Worden & Vallis 2014).

Based on the identified gaps in the literature, the primary aim of this thesis was to better understand the feasibility of training programs to alter dual-task performance in complex environments. To address this question, an experiment (Experiment I) was first designed to examine the interference caused by a cognitive task on obstacle crossing, specifically the effect of interference induced at the perceptual and central response
selection stages, as compared to interference at purely central response selection stages. Following establishment of the effects of cognitive tasks on obstacle crossing, both young (Experiments II and III) and older adults (Experiment IV) were trained using dual-task training programs that varied in both duration and in the tasks performed and examined dual-task performance on a combined obstacle crossing and auditory Stroop experimental test. This allowed for an examination to determine if dual-task training could in fact influence changes in dual-task performance and collectively across these four experiments probe the generalizability of training effects to the performance of these dual-tasks. The work contained within this thesis is important, as it has major implications for expanding knowledge on how tasks are integrated and performed concurrently and the ability of cognitive and motor training to alter these observed effects. By asking these research questions, it allows for a systematic exploration of how tasks are integrated and performed following the application of training protocols, and how the natural ageing process alters this over time.

1.2 Thesis Overview

The following thesis is composed of four experiments that can be read independently as three manuscripts, or as part of the larger dissertation presented here. The experimental progression follows the order of research objectives outlined below (Section 1.3). The first experiment was conducted to better understand the effects that interference at the perceptual stage of dual-task performance, in addition to interference at the central response selection stage, would have on obstacle crossing behavior in
young adults. Experiments II and III were collected as separate experiments, but are presented together in Chapter IV as presentation of the results in this way is more impactful. The aim of Experiments II and III was to examine the effects of dual-task training programs (varied in both duration and task composition) on the test of dual-task performance (simultaneous obstacle crossing and auditory Stroop task). Specifically, we expected individuals to alter obstacle crossing performance following training to reflect a more cautious obstacle crossing strategy, while still performing the task within the constraints of the instructions provided (i.e. ‘Maintain your normal walking speed while safely stepping over the obstacle’). To reflect this, we expected an increase in obstacle clearance values with the trailing foot, given that this foot is the most likely to contact an obstacle (Mohagheghi et al. 2004; Patla et al. 1991; Rietdyk et al. 2005). This increase would increase the margin of error between the foot and obstacle, in the case that some perturbation was to spontaneously cause a lower foot crossing than anticipated. Conversely, if participants were to lower obstacle clearance values, this would reduce the effective safety margin, and increase the possibility of a trip (Mohagheghi et al. 2004; Patla et al. 1991; Rietdyk et al. 2005). For walking velocity, we expected individuals to increase velocity following training, as this would indicate an alteration by the individual’s system to better execute the task as outlined by instructions. An increased walking velocity would indicate that participants were better able to maintain their normal walking velocity, which likely reflects a reduction in task processing time to accurately move through the environment (Anguera et al. 2013).

The final experiment (Experiment IV) once again examined dual-task training, this time in an older adult population. This allowed for an examination of the effect of ageing
on training, specifically to determine if older adults would respond in a similar manner to the training paradigm as the young adults previously studied, thereby addressing the generalizability of the dual-task training approach. It is important to note that the proposed training alterations to obstacle crossing behavior were expected to be strategies employed by participants to improve the safety and quality of obstacle crossing. However, given our population of healthy young adults for Experiments II and III, and community dwelling older adults in Experiment IV, these individuals may, at baseline, already possess a strategy that allows them to effectively navigate the environment with a low rate of obstacle contacts.

In the following section, the goals and hypotheses for the four experiments of the thesis are presented (Section 1.3). Following the outline of the objectives of the four experiments, a literature review on topics relevant to the research is presented in Chapter 2. This chapter presents an overview of the literature (to date) and includes a brief justification for studying dual-task paradigms (Section 2.1), dual-task results from related literature in the field of psychology (Section 2.2), and evidence of dual-task interference in biomechanics literature (Section 2.3), the effect of advancing age on dual-task performance (Section 2.4), the use of obstacles in biomechanics literature and their applicability to dual-task paradigms (Section 2.5) and the possibility of using training programs to enhance dual-task performance (Section 2.6). Chapters 3-5 present Experiments I-IV in their manuscript format. Chapter 6 provides a general discussion of the findings from the separate experiments put into context with findings from other work in the field (Section 6). Finally, the thesis concludes with details regarding future directions for the work and a final few concluding statements (Section 6.3).
1.3 Summary of Objectives & Hypotheses

Based upon gaps within the peer reviewed literature, and the need to better understand training in complex dual-task situations, four experiments were designed and completed for this thesis. The objectives of each study, as well as the associated hypotheses are presented below.

1.3.1 Experiment I

The objective of Experiment I was to better understand the effects of concurrently performing two different cognitive tasks on obstacle crossing strategy. Specifically, two different Stroop tasks were used as the concurrent cognitive task: the visual Stroop task (which would produce interference at both the perceptual and central response selection stages of dual-task processing) and an auditory Stroop task (where interference would be limited to the central response selection stage). This study allowed us to better understand how the probable locations of interference (at the perceptual and or central response selection stages) influence obstacle crossing strategies. Due to the broad spectrum of tasks previously paired with obstacle navigation in the literature (and consequently the heterogeneous dual-task effects observed within these studies), knowledge gained from this experiment allows for a better understanding of previously reported dual-task effects. Based on the additional interference at the perceptual stage of dual-task processing, the following hypothesis was developed:

1) The concurrent performance of the visual Stroop task would induce larger dual-task costs in both the obstacle crossing task (larger changes to stepping parameters) and the visual Stroop task (slowed response times and decreased
accuracy) as compared to the auditory Stroop task (which was expected to cause similar effects but to a smaller magnitude).

1.3.2 Experiment II

The purpose of Experiment II was to examine if a concurrent unobstructed walking and cognitive task training program in healthy young adults would alter performance on the dynamic obstacle and auditory Stroop task measure of dual-task performance. To answer this question, participants were assigned to one of either: a control group (no training), a group trained for one week, or a group trained for four weeks. Furthermore, participants were re-tested five weeks after the completion of training to determine if training effects were retained following a period of no training.

1) Dual-task training was expected to alter obstacle crossing strategies (changes to walking velocity and increased foot clearance in relation to the obstacle) as well as reduce response time to the cognitive component of the dual-task test. Conversely, participants who were not trained were not anticipated to alter their dual-task performance from Visit 1 to Visit 2.

2) Furthermore, training duration was expected to have an effect, with four weeks of training producing larger alterations in walking velocity and obstacle clearance values during dual-tasking as compared to one week of training and no training.

3) Finally, following a period of no training (Visit 3), it was expected that all groups would maintain similar performance on both the auditory Stroop and
obstacle crossing task as had been observed immediately following the cessation of training (Visit 2).

1.3.3 Experiment III

The purpose of Experiment III was to compare the effectiveness of a concurrent unobstructed walking and cognitive task training program (similar to Experiment II) and a computer game based dual-task training protocol. By directly comparing these two training methods (as well as a no training control group), it was possible to examine the generalizability of training between a proximally related training protocol (an unobstructed walking protocol presents a similar postural load requirement as the dual-task test) and a more distally related training scenario (the computer game based training offers a different postural load) in healthy young adults.

1) Both training groups would alter obstacle crossing strategies, given both groups were training the integration and performance of a task requiring visual input (walking or computer based training) paired with the same cognitive tasks. Conversely, participants who were not trained were not expected to alter their dual-task performance from Visit 1 to Visit 2.

1.3.4 Experiment IV

Building on the observed training effects from Experiments II and III, the walking based dual-task training program (deemed most effective in young adults) was applied to
a community dwelling older adult population. This allowed for an examination of the effectiveness of training in a population with well-documented reductions in dual-task performance.

1) Dual-task training was anticipated to alter dual-task performance, as was observed in young adults in Experiments II & III (i.e. increases to minimum trail foot clearance).

2) Due to the increased postural threat imposed by obstacle crossing, older adults were expected to prioritize the motor task performance to ensure safe movement during obstacle crossing. As such, training was not expected to alter performance on the auditory Stroop task following practice due to the prioritization of attention on the motor task.

1.4 Statement of Ethics

All experiments contained within this thesis were performed within the ethical guidelines of the University of Guelph and were approved by the University of Guelph Research Ethics Board.
Chapter 2 Review of the Literature

2.1 What is Dual-Tasking and Why Study It?

In everyday situations, individuals are often required to perform several unique tasks simultaneously in a timely and effective manner. Each task typically requires some amount of attention (Kahneman 1973; Kahneman & Chajczyk 1983; Kerr et al. 1985; Lajoie et al. 1993) which will be defined in this thesis document as ‘…any situation in which the allocation of cortical processing is required to perform the situation successfully’ (Neumann 1996). A common example of this may be talking to a friend on the phone (Task 1) while walking to the corner store to grab a beverage (Task 2). Although this is an everyday occurrence, the underlying processes are complex and the mechanisms for how individuals are able to integrate and perform two tasks simultaneously remain poorly understood (Pashler 1994; Ruthruff et al. 2001; Strobach et al. 2013). Although the debate continues as to the specific causes of interference (Pashler 1994; Tombu & Jolicœur 2003), numerous research groups have repeatedly produced two key findings:

1) As tasks become more complex, researchers typically observe greater reductions in task performance in either one or both tasks (Kerr et al. 1985; Lajoie et al. 1993; Weerdesteyn et al. 2003)

2) In many situations, individuals can flexibly allocate attention from one task to the other (Kelly et al. 2010; Siu & Woollacott 2007; Yogev-Seligmann et al. 2010)

These characteristics are helpful in the fields of biomechanics and motor control, as manipulating certain parameters of interest in a dual-task paradigm can allow researchers
to better understand the attentional requirements of a given task(s) (Lajoie et al. 1993; Wellmon et al. 2013; Weerdesteyn et al. 2013). For example, by requiring participants to respond to a secondary cognitive task at different discrete times during a complex motor action, researchers can discern at what point in time more attention is required to perform the motor task (Brown et al. 1999; Wellmon et al. 2013). Furthermore, researchers can gain insight into how the central nervous system may organize the performance of tasks to safely and efficiently navigate through the environment (Bohm et al. 2012; Mersmann et al. 2013; Wellmon et al. 2013). For example, when examining the effect of a sudden perturbation to an individual’s stability that may induce a fall while dual-tasking, researchers have observed few changes to postural recovery responses, however large decrements in the performance of the cognitive task are observed, indicating that whole body stability may be prioritized in these situations (Bohm et al. 2012; Mersmann et al. 2013).

2.2 Dual-Task Interference in Simple Postural Tasks

Although the effects of dual-task interference have become increasingly studied in the areas of biomechanics and motor control in recent years (for reviews see: Al-Yahya et al. 2011; Woollacott & Shumway-Cook 2002; Yogev-Seligmann et al. 2008), research identifying the mechanisms behind the interference has lagged behind the fields of psychology and neuroscience (Pashler 1994; Strobach et al. 2013; Tombu & Jolicouer 2003). In these fields, dual-task interference effects were acknowledged much earlier, and have been studied extensively in numerous paradigms (e.g. Bowers et al. 1978; Holtzman & Gazzaniga 1982; Levy et al. 2006; Pashler 1994; Ruthruff et al. 2001; Stroback et al. (2004).
2013). Although these paradigms typically impose relatively simple postural requirements (e.g. seated on a chair in front of a computer monitor) that have not been manipulated to address potential changes to performance under differing postural loads; the area of cognitive psychology is a useful place to gain inspiration for study protocols and for theories on how and why dual-task interference occurs during whole body movements.

Dual-task interference has been most extensively studied in simple and choice reaction time tests (Bherer et al. 2005; Pashler 1994; Ruthruff et al. 2001; Strobach et al. 2013). To begin, it is prudent to provide a working definition of how a single task will be defined. For the purposes of this thesis, a single ‘task’ is some requirement imposed on the individual, which has a singular end goal, and can be quantified as correct or incorrect. For example, a choice reaction time task presents a participant with one of a number of possible stimuli, and requires the participant to choose a correct response based on the stimuli presented, and to then execute this response (Pashler & Baylis 1991; Strobach et al. 2013). A more complex single task example might be the task of walking along a path to a designated target. This task would be successfully executed if the subject were able to correctly identify the target in the environment and move their body to the location in a timely manner, without losing balance (falling). Each task comprises three components (Pashler & Baylis 1991; Strobach et al. 2013):

1) **Perception stage**: The stage during which information relevant to the task is perceived from the participant’s environment
2) **Central response selection stage**: Based upon the information collected from the environment, the participant identifies the correct stimuli, and chooses the appropriate response.

3) **Motor response stage**: Once the correct response has been selected, the participant must then implement this response.

Now that the components of a single task have been defined, examples of dual-task interference may be examined. One common way to manipulate dual-task interference is to present individuals with two unique tasks at different stimulus onset asynchronies (Pashler 1994; Ruthruff et al. 2001; Strobach et al. 2013). For example, Strobach et al. (2013) demonstrated dual-task interference effects when participants were required to perform an auditory tone identification task and a visual cue identification task concurrently. The researchers observed more errors and slower reaction times when the two tasks were performed closely together (at short onset asynchronies) as compared to when the tasks were presented independently (at longer onset asynchronies). Levy et al. (2006) demonstrated similar findings, this time using one choice reaction time task (identify how many auditory tones were presented) and one continuous task (in a simulator, “driving” a car along a path and braking when instructed). As before, the two tasks (identifying the tone and braking) were presented at separate stimulus onset asynchronies, and as the tasks were performed closer together, slower response times were again observed, indicating an increased cognitive interference between the tasks.

As illustrated in these experiments, dual-task interference is consistently observed in young adults. The next logical question is to address why interference is occurring during dual-task performance. Entire programs of research in many labs are devoted to
answering this question, which has given rise to numerous theories. For example, supporters of the ‘Bottleneck Theory’ propose that a processor is required to perform both tasks, and the processor can only be accessed by one task at a time, resulting in a bottleneck at this stage of processing (Pashler 1994; Ruthruff et al. 2001). This subsequently results in the slowed performance of tasks, especially the second task to reach the bottleneck stage, in the case of staggered stimulus onset asynchronies (Pashler 1994; Ruthruff et al. 2001; Strobach et al. 2013). Conversely, advocates of the ‘Capacity Sharing Theory’ hypothesize that tasks can proceed in parallel, but processing capacity is limited by the amount of cognitive resources available. It is these limitations in cognitive processing that result in reduced task performance for either one or both tasks (Tombu & Jolicoeur 2003; Woollacott & Shumway-Cook 2002). Numerous other theories exist, such as the cross talk theory (Koch 2009; Navon & Miller 1987) and the action-selection theory (Neumann 1987; Pellecchia 2005). Data has yet to conclusively rule out competing theories, and the debate continues as to the true mechanism of dual-task interference; it is also possible that multiple mechanisms may be at work depending on the situation. Most theories agree that interference effects likely occur at the central response selection stage, especially in experimental paradigms where perceptual and motor stages use different cognitive processes (Kaheman & Chajczyck 1983; Strobach et al. 2013). The purpose of this document is not to wade into the discussion of which theory best explains the observed dual-task interference effects. Instead, this thesis will aim to use knowledge gained from these proposed theories to design the experimental protocols, which will be highlighted in the separate study chapters.
2.3 Dual-Tasking in Whole Body Movements

As highlighted previously, dual-task interference is commonly observed in simple and choice reaction time tests, but what about the performance of two concurrent tasks which are less similar in their nature (e.g. one cognitive task and one motor task)? When examining whole body movements such as standing or walking, much of the control can be modelled independent of supraspinal structures (e.g. central pattern generators, limited to motor and visual areas), and thus could theoretically proceed without access to frontal lobe structures (i.e. the neural substrates of central response selection) (Bauby & Kuo 2000; Cappozzo et al. 1976; Courtine et al. 2006; Warren et al. 1986). Within these models of human motion and postural control, the attentional requirements of walking could therefore be interpreted to be negligible. However, early work in patients with reductions to executive function mental processes (necessary for central planning and cognitive processing) demonstrated deficits in walking, indicating that the frontal and prefrontal lobes may have a role in locomotion (Clarkson-Smith & Hartley 1989; Cocchini et al. 2004). Furthermore, when cognitive tasks were completed with whole body movements (such as walking), researchers observed altered performance for the cognitive task (Kelly et al. 2010; Kerr et al. 1985), the motor task (Ebersbach et al. 1995; Marone et al. 2014), or both tasks (Beauchet et al. 2005; Pellecchia 2005; Schaefer et al. 2015). It is important to note that a wide range of dual-task effects have been reported, and this is heavily influenced by the type of secondary task chosen and instructional set provided to participants; these concepts will be discussed and expanded upon below (Section 1.2.3).
2.3.1 Dual-task interference in standing tasks

To begin, dual-task research has been conducted on less destabilizing postural tasks such as standing. Standing is widely regarded to require less attention than walking due to the relatively constant environment that surrounds the individual (Colledge et al. 1994; Hegeman et al. 2007). For quiet standing, the ground forces are constant, and complex neuromuscular firing patterns are not at work to propel the body’s center of mass forward (Hegeman et al. 2007; Winter 1995). Dual-task interference effects are typically observed during standing, especially in the cognitive task (Kerr et al. 1985; Lajoie et al. 1993; Pellecchia 2005). For example, moving from a seated to standing posture has been shown to affect performance on an unrelated cognitive task (Kerr et al. 1985; Lajoie et al. 1993). Lajoie et al. (1993) monitored performance on a simple probe reaction time test (say ‘top’ as quickly as you can when you hear the tone) during sitting as well as standing (with both a wide and narrow base of support). The authors noted that reaction times to the cognitive task were slower during both standing postures as compared to sitting; based on these observations, the researchers suggested that attentional requirements to maintain upright posture must be greater than sitting. Kerr et al. (1985) found similar effects with poorer performance on a working memory test during a difficult standing task as compared to sitting. In their study, young adult participants performed either a spatial or nonspatial working memory task during tandem Romberg stance. They observed that center of pressure sway range was not different between single and dual-task standing, while performance on the spatial memory task was reduced through poorer recall performance. The authors proposed that effects were only found for the spatial task (and not the nonspatial memory task) due to fact that both
the spatial memory task and postural task theoretically relied on similar visual pathways within the brain. The authors went on to suggest that visual pathways were the location of the interference in this dual-task task, however the experimental design could not conclusively prove these ideas.

Standing can be further challenged by using an unstable support surface to increase the attentional requirements of the task (Brown et al. 1999; Schaefer et al. 2008). For example, Schaefer et al. (2008) examined dual-task performance in young adults while performing the method of loci memory task (memorization of a list of words by forming an interactive mental map, and encoding the words within the map) and concurrently standing on a wobble board. Younger adults showed significant dual task costs on both the number of items retrieved for the method of loci task and on the postural sway on the wobble board as compared to single task performance. Brown et al. (1999) examined recovery strategies following a floor perturbation (designed to challenge the participant’s ability to maintain upright posture) while simultaneously performing a backward counting task. The researchers examined the performance of the counting task both pre- and post-perturbation, and found that counting was slower following the perturbations, indicating that returning the body to a stable position following a perturbation was more attentionally demanding than quiet standing before the perturbation. Interestingly, if the perturbation did cause a participant to step, participants stepped earlier (i.e. with their center of mass further from their base of support boundary) than under single task conditions. When the center of mass exceeds the base of support, a step must be taken or a fall will occur (Hof 2008; Winter 1995). Brown et al. (1999) hypothesized that participants stepped earlier as the interference of the cognitive task on
the postural task induced a strategy to step earlier than needed to ensure stability was maintained.

2.3.2 Walking dual-task paradigms

Given that interference effects are observed in both quiet standing and in more difficult standing postures (e.g. following postural perturbations), the next step is to examine what effect a more complex motor task has on dual-task interference. Walking tasks are commonly examined within dual-task paradigms, as researchers now know walking requires greater attention to navigate through the environment while maintaining dynamic stability (Beauchet et al. 2005, Kelly et al. 2010; Lajoie et al. 1993). With locomotion, the central nervous system must integrate complex muscle firing patterns, control the center of mass with respect to the base of support, the change in sensorimotor input with each stride as well as a moving visual environment (Cappozzo et al. 1976; Colledge et al. 1994; de Rugy et al. 2002; Hof 2008; Warren et al. 2001; Winter 1995). Therefore, it is generally assumed that a walking task requires additional input from cognitive areas to ensure that the goal directed locomotor task is successfully executed, which requires the on-line integration of information about the environment and how to safely move through it (Hollands & Marple-Horvat 2001; Warren et al. 1986; Warren et al. 2001). It is likely that this increased cognitive load further interferes with the performance of secondary cognitive tasks, again producing robust interference effects (Abbud et al. 2009; Beauchet et al. 2005; Grabiner & Troy 2005; Lajoie et al. 1993).

Dual-task costs have been observed in unobstructed walking tasks with relatively simple cognitive tasks such as backwards counting, which require little executive
function processes to perform (Kahneman & Chajczyk 1983). For example, Beauchet et
al. (2005) examined stride characteristics in the gait of young adults during backwards
counting. They reported small but significant decreases in stride velocity and increases in
stride time when dual-tasking. Also, significantly fewer numbers were recited during the
dual task than while sitting. It is interesting to note that the interference effect was higher
on the cognitive task than the walking task, perhaps indicating a prioritization to the
motor task. As the cognitive tasks employed become more complex, interference effects
are again observed (Ebersbach et al. 1995; Grabiner & Troy 2005). Ebersbach et al.
(1995) examined either a memory retention task (digit span) or a fine motor task (opening
and closing a coat button) while standing and walking. The researchers noted that when
the cognitive tasks were combined with walking, participants spent more time in double
support while walking (i.e. the phase of the gait cycle where the body’s mass is supported
by both feet within a relatively larger base of support as compared to being supported by
a single leg during the single support phase of gait). With more time spent in double
support, the participant has more time to implement minor step-to-step corrections to
control the movement of the upper body before the next step is taken. Furthermore,
performance on the digit span task (but not the buttoning task) was reduced when
walking as compared to standing. This is interesting, as it indicates walking may interfere
with memory retention tasks to a greater degree than fine motor tasks, providing further
evidence that interference is occurring centrally as the cognitive task complexity
increases.

Within the gait cycle, dual task costs change depending on when the cognitive
task is performed (Abbud et al. 2009; Gage et al. 2003; Lajoie et al. 1993). Lajoie et al.
(1993) provided the first evidence for this, demonstrating slower response times to a probe reaction time test when participants were in single support (the less stable period of a stride due to the smaller base of support) as opposed to double support during walking. Gage et al. (2003) furthered this work by examining the performance of a probe reaction time test in young adults while walking in a number of challenging conditions (e.g. elevated surfaces, walking along a narrow path), and found slower probe reaction times in single support as compared to double support. Interestingly, reaction times for the cognitive task also increased during the condition that posed the largest postural threat to participants (narrow walking on an elevated surface), which may be related to task performance anxiety (as determined by the recorded galvanic skin responses). Abbud et al. (2009) expanded on these findings by initiating the cognitive task at different phases of the gait cycle in healthy young adults. Subjects walked on a treadmill while doing mental arithmetic (subtractions by 7 or 1). They collected surface electromyography from eight muscles of the dominant leg while the subject walked above their normal pace on a treadmill. At phases of the gait cycle that are more attentionally demanding, they expected to see decreases in muscle activity in muscle groups active during that specific phase of gait (e.g. plantar flexors during toe off) indicating greater dual-task interference. As had been demonstrated previously for cognitive task performance, subjects took longer to respond and were less accurate when walking as opposed to standing. The researchers reported decreases in muscle activity of plantar flexors during single leg support phase when dual tasking. These results suggest that performing a cognitive task during gait does reduce muscle activation in specific muscles, and that which phase of the gait cycle the cognitive task begins at also affects muscle activation. A trend was
apparent that the most attentional interference occurred during the single leg support phase. The literature appears to be clear on this point: dual-task interference effects increase as stability decreases (i.e. moving from standing to walking: Brown et al. 1999; Ebersbach et al. 1995; Lajoie et al. 1993). As humans walk, we cycle through double and single support phases. While in single support, the functional base of support is much smaller, and individuals thus have to maintain their center of mass within a smaller area in contact with the ground (Hegeman et al. 2007; Hof 2008; Winter 1995). This smaller base of support makes an individual less stable, and perhaps more attention is needed to maintain balance through this phase of the gait cycle, producing the observed increases in attentional demand during single support (Abbud et al. 2009; Gage et al. 2003).

2.3.3 Choice of cognitive task in dual task paradigms influences results

At this point it is important to acknowledge that varying levels of dual-task interference have been reported in the biomechanics literature, and that interference can be strongly influenced by the types of tasks included within each experimental paradigm (Ebersbach et al. 1995; Lajoie et al. 1993; Worden & Vallis 2016). First, it is important to address that many studies have defied one of the major stipulations when attempting to isolate central interference effects; many of these studies have used cognitive tasks that interfere at the perceptual stage or motor stage. Such interference is termed structural interference (Kahneman 1973; Kahneman & Chajczyk 1983), which produces interference effects based (at least partly) on the fact that both tasks require access to the same perceptual pathways or motor response mechanisms to be completed. An example would be the use of a secondary visual cognitive test, requiring participants to look
somewhere other than the travel path while walking. This splits the perceptual
mechanism (eyes) between two different stimuli, and in turn structural interference
results. Although these studies can produce interesting insights into real world examples
of dual-task costs, these paradigms do not further facilitate the systematic exploration of
why interference occurs at the central response selection stage. For example, Chen et al.
(1996) examined the effects of a visual cue identification task on dynamic obstacle
avoidance. However, because the visual system was required to monitor the ground in
front of them (for the obstacle) as well as lights located at eye height at the end of the
walkway (for the visual cue task), results from their experimental paradigm are heavily
influenced by the visual system being required to perceive information from two separate
locations at the same time. Thus, it could be argued that claims in the discussion
regarding attentional requirements of both tasks at the central stages of processing can be
challenged due to this experimental limitation.

Conversely, a systematic approach to choosing which tasks to pair can allow
researchers to examine central response selection interference effects (Kahneman 1973;
Kahneman & Chajczyk 1983). In this situation, different perceptual pathways are needed
to perform the two tasks, such as navigating a crowded grocery store aisle while
remembering a list of needed items on a shopping list. Weerdesteyn et al. (2003)
improved on the shortfalls of the Chen et al. (1996) study when they designed their study
aimed at understanding dynamic obstacles and cognitive task interference effects. Instead
of using a visual cognitive task, they paired an auditory Stroop task (perceived by
auditory pathways) with an obstacle avoidance task (perceived by visual pathways). The
design of this experiment removed structural interference, and therefore any observations
of dual-task interference effects could be attributed to interference at the central response selection stage. Although numerous paradigms exist that have used either structural or purely central interference to induce interference (Chen et al. 1996; Perrochon et al. 2013; Weerdesteyn et al. 2003; Worden & Vallis 2016), these two sources of cognitive interference are rarely directly compared, making it difficult to understand the effect that interference at the central stage has on dual-task performance. Better understanding the effect of structural as compared to purely capacity interference will be the focus of the first experiment in this PhD Dissertation (Section 3).

Once it has been determined whether the tasks used cause structural or purely central interference, the next consideration is the type of mental process the cognitive task may employ. Varying tasks have been included from arithmetic, to working memory, visuospatial, and so on (Beurskens & Bock 2013; Kerr et al. 1985; Pellecchia 2005; Schaefer et al. 2008; Worden & Vallis 2016). Depending on the type of cognitive task chosen, the interference effects observed have been reported to differ (Brandler et al. 2011; Ebersbach et al. 1995; Kerr et al. 1985). For example, the previously given example of Kerr et al. (1985) only found interference effects in the spatial memory task when quiet standing (and not the non-spatial memory task). Furthermore, within each category of cognitive tasks, the difficulty of the presented cognitive stimuli plays a major role in outcomes observed. For example, Brandler et al. (2012) had participants say the alphabet, with the starting letter being either “a” or “b” (start of alphabet; easier task) or “m” or “n” (middle of alphabet; more difficult task) while walking. The authors reported significant differences on the performance of the cognitive task depending on whether participants began at the start or middle of the alphabet; beginning at the middle of the
alphabet was more challenging for participants as indicated by more letters recited and fewer errors. Another example is from the work done by Marone et al. (2014) who examined how cell phone texting while walking on a treadmill affected stability.

Contrary to other studies that have detected reductions in stability during dual-tasking with unconstrained arms (Hawkes et al. 2012; Hollman et al. 2007; Montero-Odasso et al. 2012; Taylor et al. 2013; Toebes et al. 2012), Marone et al. observed an increase in margin of stability (a measure of stability that examines the location of the body’s center of mass and velocity with respect to the base of support: Hof 2008), which was thought to be a proactive strategy to increase the participant’s safety due to the participant’s upper body being constrained while holding the phone.

Another important consideration is related to the constraints of the tasks themselves. Numerous researchers have reported that in situations where personal safety is at risk, participants will focus attention to the postural task, at the cost of the cognitive task’s performance (Bohm et al. 2012; Brown et al. 1999; Mersmann et al. 2013). For example, when examining results from platform perturbation studies that pose a major threat to personal safety, young adults tend to prioritize performance on the motor task, at the expense of major decrements to the cognitive task performance (Bohm et al. 2012; Brown et al. 1999; Mersmann et al. 2013). Mersmann et al. (2013) induced walking perturbations (using a floor with an element that when stepped upon caused a slip) while performing mental arithmetic. The researchers observed no changes to margin of stability following the addition of a cognitive task, while cognitive task accuracy was greatly reduced following an induced perturbation. Shumway-Cook et al. (1997) coined the “posture-first hypothesis” to explain this phenomenon, stating that, “a hierarchy exists in
the allocation of attentional resources, with posture being a first priority”. Although this effect is commonly observed (Bohm et al. 2012; Brown et al. 1999; Mersmann et al. 2013), there are certain situations where postural stability is reduced when a cognitive task is performed concurrently (Montero-Odasso et al. 2012; Shumway-Cook et al. 1997; Taylor et al. 2013). In the 1997 paper by Shumway-Cook et at., increased center of pressure displacement was noted (indicating poorer postural control) when young adult participants had to complete an auditory word processing task (but not a visual perceptual matching task) during quiet standing on both a firm and compliant surface. The observed results did not coincide with the posture-first hypothesis, leading the authors to eloquently state: “…the allocation of attention during the performance of concurrent tasks is complex, depending on many factors including the nature of both the cognitive and postural task, the goal of the subject, and instructions” (pp M238). Thus, as has been identified by numerous researchers, there is a wide range of outcomes that can be expected and observed, based on the environment presented to the individual (Bohm et al. 2012; Brown et al. 1999; Weerdesteyn et al. 2003; Worden & Vallis 2014).

Lastly, instructional set also plays a major role in the outcome of dual-task tests. Numerous studies have shown that the instructions given to participants can influence the allocation of attention, and subsequently the outcome of an experiment (Kelly et al. 2010; Kelly et al. 2013; Siu et al. 2007; Yogev-Seligmann et al. 2010). Yogev-Seligmann et al. (2010) examined the effects of prioritization on gait variability and gait speed in healthy young adults. Gait was the postural task and verbal fluency (given a letter, name as many words beginning with that letter in a one minute period as you can) was the cognitive task. When asked to prioritize gait, young adults significantly increased gait speed, while
no change to the verbal fluency task was noted. When asked to prioritize the cognitive
task, younger adults showed a decrease in gait speed (of smaller magnitude than the
increase), but again no change in verbal fluency performance was observed. The results
indicated that instructional set did have a significant effect on how young adults perform
dual-tasks, specifically on the postural task. Siu et al. (2007) performed a similar study to
examine the effects of prioritization, this time using a quiet standing task coupled with a
visual spatial memory task presented on a screen in front of participants. The researchers
observed that instructions prioritizing the cognitive task improved performance on that
task, but when participants were instructed to prioritize the standing task, no effects were
observed. These findings were contrary to the improvements noted in the experiment by
Yoge-Seligmann et al. (2010), and may indicate a ceiling effect whereby in a relatively
easy postural task (e.g. standing), performance cannot be improved further by altering
instructional sets.

2.4 The Effect of Ageing on Dual-Task Performance

So far, dual-task interference in simple and complex tasks has been examined, as
well as the effects that the choice of experimental paradigm can have on results.
However, perhaps the fastest growing area of research, and the variable that has the
largest effect on task performance is that of age. In the literature it is clearly apparent that
age plays a major role in dual-task capability (Anguera et al. 2013; Bherer et al. 2005;
Clouston et al. 2013; Kramer & Larish 1996; Verhaeghen et al. 2003; Weeredesteyn et al.
2005). For example, work by Anguera et al. (2013) examined ageing effects on dual-task
performance across the lifespan (from 20 year olds to 79 years old). For their experiment,
participants were required to attend to a visual cue while steering a race car around a track on a computer screen. The researchers observed a gradual decrease in dual-tasking performance proficiency past the age of thirty years old. Other researchers have also documented the dual-task performance reductions commonly seen in older adults during the performance of relatively simple postural tasks (Bherer et al. 2005; Kramer & Larish 1996; Verhaeghen et al. 2003). Unfortunately, poor dual-tasking ability has also been linked to an increased risk of falling in older adults (Faulkner et al. 2007; Lundin-Olsson et al. 1997; Makizako et al. 2010).

2.4.1 Older adult dual-tasking in biomechanical analyses of locomotion

Given the above highlighted changes to dual-task performance with increasing age, it is not surprising that a large volume of research has examined these effects (Anguera et al. 2013; Bherer et al. 2005; Kramer & Larish 1996; Verhaeghen et al. 2003), and an examination of dual-tasking during whole body movements becomes an important area of focus, given the potential implications for falls prevention and improved quality of life (Lundin-Olsson et al. 1997; Makizako et al. 2010). In the biomechanics literature, similar trends of poorer dual-tasking ability with increasing age are observed (Lindenberger et al. 2000; Weerdesteyn et al. 2003; Wellmon et al. 2013). For example, Lindenberger et al. (2000) tested the hypothesis that performing a challenging locomotor task (walking on a narrow pathway) while memorizing a list of words becomes increasingly difficult with advancing age. In their paradigm they included young (mean age 24 years), middle (45 years old) and older (older than 65 years) healthy adults. Subjects were trained in a mnemonic memory recall task and asked to walk along either
an oval or an aperiodic track (the track was built of short straight segments, with many turns of different angles). With increasing age they saw a decrease in memory accuracy while walking. Memorizing while walking resulted in decreases to gait speed in middle and older adults, with walking accuracy decreases (stepping outside of the tracks) only observed for the older adult group.

Similar decreases in performance with increasing age are observed under structural interference conditions (Berg & Murdock 2011; Bock et al. 2011). Berg & Murdock (2011) examined locomotor targeting (accurate placement of a foot onto a target on the ground during walking) under no, low and high structural interference in old and young adults. They found high structural interference had the greatest effect on older adults, in comparison dual-tasking under all conditions did not affect young adult performance. Bock et al. (2011) examined whether unpredictable visual distracters would alter gait pattern more in healthy older (mean age 68.2 years) as compared to healthy younger adults (mean age 25.6 years). The participants walked along a pathway with four monitors located on each side. An auditory cue instructed the participant to look left or right, then a letter was presented off axis for two seconds on a monitor and participants were required to identify whether it was a mirror image or correctly written. Again, they found the gait of young adults changed little after the verbal stimulus, while larger effects were observed in older adults, especially in the four to six strides after the cue; for example, variability in step duration was increased in older adults. This protocol is representative of a common, routinely experienced situation; often individuals will have to look to the side to analyze a piece of information (room number) while walking through the environment. Of concern is that fact that the older adults performed this task
with increased step variability, which is an indicator of increased falls risk (Montero-Odasso et al. 2012; Taylor et al. 2013; Toebes et al. 2012). These results highlight the importance of understanding dual-task costs in older population and for developing compensatory techniques for mitigating falls risk.

Under more challenging and posturally threatening conditions, old age again leads to larger dual-task interference effects. For example, Schaefer et al. (2015) asked young and older adults to perform a range of walking tasks of different difficulties while backwards counting. They observed that in certain situations (e.g. walking on an elevated surface), older adults sped up their walking velocity and had more mis-steps. This can be interpreted as a ‘riskier’ strategy, as during dual-task conditions these older adults had more mis-steps and were walking faster, which would result in less time to correct these movement errors. Conversely, young adults did not execute more mis-steps in challenging conditions, and also did not increase their velocity, indicating selection of a strategy that they can easily adapt to environmental constraints. These results may indicate that with increasing age, the ability to adopt a posture first strategy to prioritize safe movement may be compromised, potentially leading to more movement errors (Schaefer et al. 2015; Shumway-Cook et al. 2007; Yogev-Seligmann et al. 2010).

2.5 Dual-Tasking Using Locomotor Obstacle Paradigms

Obstacle paradigms have been studied extensively in the biomechanics literature (Brown et al. 2005; Heijnen et al. 2012; Patla et al. 1991; Rietdyk et al. 2015; Worden & Vallis 2015). They provide a useful model of how the central nervous system initiates a plan to step over an obstacle in the travel path (in addition to insight from on-line
corrections to an ongoing plan in the case of a suddenly appearing obstacle). It is generally accepted that obstacle crossing imposes greater attentional demands on an individual, as typical overground walking patterns must be adjusted based on visual information about the obstacle on approach, to safely and efficiently clear the obstacle (Patla et al. 1991; Rhea & Rietdyk 2007; Siu et al. 2008; Weerdesteyn et al. 2003).

Furthermore, the design of the obstacle also plays a major role in the types of strategies and difficulty of the obstacle crossing task (Patla et al. 1996; Rhea & Rietdyk 2007; Rietdyk & Rhea 2011). For example, a solid obstacle has been reported as being cleared successfully more often (characterized as fewer obstacle contacts occur) as compared to an obstacle of the same dimension but with less visible structure (only the top edge of the obstacle visible) (Rietdyk & Rhea 2011). Furthermore, more variable trailing toe clearances have been observed for obstacles with less visible structure (Heijnen et al. 2014; Rietdyk & Rhea 2011). An individual’s perception of the construction of the obstacle also plays a role in observed stepping strategies (Patla et al. 1996). Obstacles that are perceived to be more fragile are generally cleared more cautiously (cleared by a larger margin) than obstacles that appear robust and that would not be damaged if contacted (Patla et al. 1996). These findings further highlight that an accurate perception of the obstacle contributes to the clearance strategy chosen to allow for successful navigation (Patla et al. 1996; Rhea & Rietdyk 2007; Rietdyk & Rhea 2011). Furthermore, when information about the obstacle is not consistently available, or available for only a short amount of time such as with dynamic obstacles, walking is further challenged (Chen et al. 1996; Patla et al. 1991; Weerdesteyn et al. 2003; Worden & Vallis 2016).
When examining obstacle crossing, the end goal is to safely step over the obstacle without tripping. Thus, the outcome measures typically reported examine the spatial strategies used by individuals to cross the obstacle. This includes measures such as minimum lead and trailing foot clearances (the minimum vertical distance between the foot and the obstacle as the foot passes over the obstacle), take off distance and landing distance (Chou & Draganich 1998; Heijnen et al. 2012; Rietdyk & Rhea 2011; Worden & Vallis 2014). Interestingly, ~90% of all obstacle contacts occur with the trailing toe, likely due to the reduced visual feedback as this foot cannot be easily viewed when stepping over the obstacle as compared to the leading foot (Heijnen et al. 2012; Mohagheghi et al. 2004; Rietdyk & Rhea 2011). Thus, minimum trail foot clearance is an important measure used to analyze stepping strategies given the relationship to the likelihood of tripping (Heijnen et al. 2012; Rietdyk & Rhea 2011).

2.5.1 Obstacle crossing in the dual-task literature

Obstacle avoidance paradigms serve as a useful model for studying dual-task effects, as it is a complex task, with a discrete quantifiable outcome (i.e. do participants successfully clear the obstacle?). As alluded to above, it involves a greater degree of postural control and the efficient implementation of avoidance to safely navigate through the environment (Patla et al. 1991; Rietdyk & Rhea 2011; Siu et al. 2008; Weerdesteyn et al. 2003). Furthermore, the discrete nature of obstacle avoidance allows for synchronizing a discrete cognitive task with the obstacle crossing task for subsequent examination of results to determine when central interference effects are greatest. For example, Wellmon et al. (2013) presented young and older adults with a probe reaction time test during
different time points when approaching and stepping up onto a curb. The authors focused their analysis on the verbal response time, as no significant dual-task interference effects on walking performance were noted in the two age groups. The authors found that for all ages, the step onto the curb was the most attentionally demanding (produced the slowest probe response times for all groups), and that increases in response times were much greater in older as compared to younger adults. To further probe the allocation of attention during obstacle crossing, Siu et al. (2008) compared the effects of an auditory Stroop task on performance of sitting, walking and obstacle crossing. They found that as postural difficulty increased, response times increased, while there were no observed changes on obstacle crossing performance (measured with velocity, step length and center of mass motions) under dual-task conditions. The authors postulated that participants were prioritizing gait stability and the performance of the obstacle crossing task, at the expense of decrements in performance of the cognitive task (Shumway-Cook et al. 1997). Furthermore, Siu et al. presented the auditory Stroop task before, during and after the obstacle was crossed by participants, and again observed no significant differences in the performance of either task.

Some research groups have used virtual obstacles, which pose a lower level of postural threat to the individuals while still challenging the integration of information in dual-task situations (Chen et al. 1996; Potocanac et al. 2015). Chen et al. (1996) examined crossing a virtual obstacle (a light beam projected on the floor) in both young and older adults. The obstacle was projected along a walkway at either 350 ms or 450 ms before participants reached it. Concurrently, participants had to respond as quickly as possible to the appearance of a light cue located at the end of the walkway. The
researchers found that for both age groups, when both tasks were performed concurrently, a much higher rate of stepping on the obstacle was observed. Furthermore, older adults were significantly more likely to step on the obstacle and to mis-identify the light cue task. Finally, the researchers observed that the shorter duration light presentation (350 ms) was more challenging for both age groups.

Building on the work of Chen et al. (1996), Weerdesteyn et al. (2003) examined obstacle avoidance during treadmill walking in healthy young adults. They had participants walk on a treadmill while performing the auditory Stroop task, and at some point an object was dropped onto the treadmill belt, and participants subsequently had to cross the obstacle with their left leg. It was observed that during the concurrent performance of an auditory Stroop task, more obstacle contacts were noted, especially when the available response time for the appearance of the obstacle on the treadmill was reduced. Hegeman et al. (2012) conducted a similar study, this time with an older adult population. Again, they found a negative effect of auditory Stroop task on obstacle crossing in older adults, with more obstacle contacts and delayed muscle activation (e.g. biceps femoris muscle) during obstacle crossing trials.

2.6 Training to Improve Dual-Task Performance

In the literature, considerable research has been conducted on training dual-task performance with goals as diverse as the development of programs to improve dual-tasking in daily life (Li et al. 2010; Silsupadol et al. 2009; Trombetti et al. 2011) to programs designed to gain a better fundamental understanding of the cognitive mechanisms behind dual-task interference (Basak et al. 2008; Bherer et al. 2005; Ruthruff
et al. 2001; Strobach et al. 2013). Within this area, the focus has typically involved two unique and discrete tasks, such as simple or choice reaction time tasks (Ruthruff et al. 2001; Strobach et al. 2013). For example, Strobach et al. (2013) examined dual-task training improvements following eight training sessions in two choice reaction time tasks. In their training protocol the two tasks were performed concurrently, and subsequently reductions in response times for the tasks were observed. Anguera et al. (2013) trained older adults in a custom race car and visual cue identification computer program. They found that following extended practice, the dual-task costs observed when dual-tasking in trained older adults was reduced to the level of untrained young adults. Dual-task training with simple postural tasks has found improved performance on the trained tasks (Anguera et al. 2013; Ruthruff et al. 2001; Strobach et al. 2013), as well as transfer to untrained tasks (Basak et al. 2008; Bherer et al. 2005).

2.6.1 Training in biomechanics literature

Given that dual-task interference is arguably at its most costly during complex whole body tasks (Makizako et al. 2010; Mersmann et al. 2013), training programs have recently been employed to examine the capability of different programs to improve performance of more complex whole body movements (Li et al. 2010; Silsupadool et al. 2009; Trombetti et al. 2011). This area of research has important implications, as this line of questioning leads to an increased understanding of how complex tasks are completed in the presence of a second, attention demanding task. Furthermore, programs designed to better integrate information from two tasks may aid individuals known to struggle in
dual-task situations (Faulkner et al. 2007; Lundin-Olsson et al. 1997; Makizako et al. 2010).

One of the pioneering studies examined different training methods to improve postural control during a quiet standing and backwards counting cognitive task was conducted in 2005 by Pellecchia. The author examined different methods of training to improve performance on the dual-task test. Young adult participants were divided into three groups: a no training group, a single task training group (trained both tasks independently), and a dual-task training group (trained both the backwards counting and standing tasks together). The authors observed that before training, dual-tasking increased center of pressure sway range, which they described as reduced postural control in their paradigm. Following training, this increase in postural sway during dual-tasking was again observed in the no training and single task training groups. However in the dual-task training group sway range was not increased, indicating greater postural control following dual-task training. The work provided clues that for whole body actions, dual-task training must practice integration of tasks (Naumann et al. 2015; Neumann 1996), and that training tasks independently does not improve performance over the same time period.

Worden & Vallis (2014) expanded on the work of Pellecchia (2005) by implementing a similar study design (no training, single task training and dual-task training) but using more complex tasks. For this study, the cognitive task was the auditory Stroop task, and the postural task was dynamic obstacle crossing (using an obstacle that would change height as participants approached). The researchers again noted, similar to Pellecchia’s results, that the dual-task training group showed
improvements on performance of the obstacle crossing task, through less variable stepping strategies. Conversely, for participants who were not trained, or trained tasks independently, these effects were not observed.

Silsupadol et al. (2009) furthered the dual-task training work involving older adults, by examining how they perform simultaneous walking and mental arithmetic tasks. As in the previous two examples, the researchers examined the efficacy of training tasks independently as well as under dual-task conditions. Furthermore, participants were trained in either fixed priority instructions or variable priority instructions for the dual-task training. This is important, as studies have reported that the instructional set used during training can influence the outcome (Bherer et al. 2005; Kramer et al. 1995). Fixed priority instructions have a strict set of instructions provided to participants on how to allocate attention to the tasks during practice, while variable priority instruction allows for an individual to flexibly allocate information between both tasks (Bherer et al. 2005; Kramer et al. 1995). The authors observed that only the dual-task training groups improved dual-task performance in older adults (as quantified by increased walking velocity). Furthermore, the variable-priority training group demonstrated improvements earlier than the fixed priority training group, and these improvements were retained for longer following training. Similar results had been observed in simple cognitive tasks, indicating variable priority training may be advantageous in these types of paradigms (Basak et al. 2008; Bherer et al. 2005; Kramer et al. 1995).

Other researchers have had similar success in older adults using training programs that, by design, provide more variable instructional sets by design (Theill et al. 2013; Trombetti et al. 2011; Wollesen et al. 2015). Trombetti et al. (2011) demonstrated
positive effects on dual-task performance following a dual-task based training protocol in older adults. The dual task tested was to walk at their normal pace while counting backward by ones. The intervention involved six months of motor and cognitive tasks such as performing movements (e.g. fitness classes) while responding to rhythms within music. After six months of training, the training group showed increases in stride length, stride velocity, and decreases in stride length variability.

From the information summarized above based on peer reviewed research involving various dual-tasking paradigms, it becomes apparent that a large volume of work has already been performed across disciplines to better understand the interference effects observed when two tasks are performed concurrently. Furthermore, training programs have been designed and implemented which demonstrate training effects for both simple and more challenging postural tasks across a wide variety of outcome measures. However, it remains unclear how different cognitive tasks may influence postural tasks; this question will be addressed in the third chapter of this PhD dissertation. Furthermore, the ability of training programs to effect change on a challenging locomotor task while a simultaneous cognitive task is performed has been studied in less detail, and will be the focus of the Fourth Chapter. Finally, the feasibility of a training program to alter performance on a challenging walking task with an added cognitive load in community dwelling older adults will be addressed in Chapter Five of the thesis.
Chapter 3 Experiment I: Measuring the effects of a visual or auditory Stroop task on dual-task costs during obstacle crossing

(Submitted in Gait & Posture. GAIPOS-D-16-00168R1)

3.1 Abstract

Successful planning and execution of motor strategies while concurrently performing a cognitive task has been previously examined, but unfortunately the varied and numerous cognitive tasks studied has limited researchers’ fundamental understanding of how the central nervous system successfully integrates and executes these tasks simultaneously. To gain a better understanding of these mechanisms a set of cognitive tasks were used that required similar central executive function processes and response outputs but required different perceptual mechanisms to perform the motor task. Thirteen healthy young adults (20.6±1.6 years old) were instrumented with kinematic markers (60 Hz) and completed 5 practice, 10 single-task obstacle walking trials and two 40 trial experimental blocks. Each block contained 20 trials of seated (single-task) trials followed by 20 cognitive and obstacle (30% lower leg length) crossing trials (dual-task). Blocks were randomly presented and included either an auditory Stroop task (AST; central interference only) or a visual Stroop task (VST; combined central and structural interference). Higher accuracy rates and shorter response times were observed for the VST versus AST single-task trials (p<0.05). Conversely, for the obstacle stepping performance, larger dual task costs were observed for the VST as compared to the AST for clearance measures (the VST induced larger clearance values for both the leading and trailing feet), indicating VST tasks caused greater interference for obstacle crossing (p<0.05). These results supported the hypothesis that structural interference has a larger
effect on motor performance in a dual-task situation compared to cognitive tasks that pose interference at only the central processing stage.

3.2 Introduction

To successfully move within and adapt ongoing movement patterns, an individual must be able to quickly assess the surrounding environment, and determine what stimuli deserve attention. If a cognitive task is performed simultaneously while walking in these challenging environments, attention must be shared between the tasks to ensure the successful completion of both tasks (Kelly et al. 2010; Woollacott & Shumway-Cook 2002). Improper allocation of attention during these dual-tasking scenarios has been previously identified as a falls risk in older adults (Liu-Ambrose et al. 2008; Makizako et al. 2010); even young adults produce movement errors when trying to perform more than one task at a time (Kelly et al. 2010; Weerdesteyn et al. 2003).

When examining past findings from the psychology and biomechanics literature, numerous different cognitive tasks have been utilized in a dual-task situation (Bathurst et al. 1994; Bock & Beurskens 2011; Kelly et al. 2010; Levy et al. 2006; Strobach et al. 2013; Woollacott & Shumway-Cook 2002), which vary in their: 1) perceptual mechanisms (how individuals perceive stimuli relevant to the task), 2) central cognitive processes (matching the perceived stimulus with the correct response) and/or, 3) response output (producing a response to the perceived information) (Strobach et al. 2013). Although these varied experimental paradigms do provide insight into how different concurrent cognitive tasks effect human movement, it limits the ability to compare results across studies (Kelly et al. 2013; Woollacott & Shumway-Cook 2002). For example,
Bock & Beurskens (2011) found few changes in the gait of young adults when they were required to walk along an unobstructed pathway and identify visual cues as compared to single-task walking (Bock & Beurskens 2011). Conversely, Kelly et al. (2013) reported that performance of an auditory Stroop task during unobstructed gait resulted in slower walking velocity and reduced cognitive task performance when participants had to perform a difficult walking task (narrow walking) as compared to single-task walking (Kelly et al. 2013).

To better understand the mechanisms of how different cognitive tests affect the ongoing control of human movement, researchers can use a set of cognitive tasks requiring similar central processes and response outputs, but requiring different perceptual mechanisms to perform the task (Kahneman & Chajczyk 1983; Strobach et al. 2013). An example of this would be to examine the interference effects caused by either a visual Stroop task (VST) or an auditory Stroop task (AST) during the performance of a challenging locomotor task (e.g. stepping over an obstacle) (Kahneman & Chajczyk 1983; Morgan & Brandt 1989). Both Stroop tests require similar executive processes to be performed correctly (Kahneman & Chajczyk 1983; Morgan & Brandt 1989), and have been theorized to cause central interference at the central processing stages when simultaneously performed while walking (Kelly et al. 2010; Weerdesteyn et al. 2003).

Furthermore, both VST and AST require the same response output mechanism, as participants are required to verbally produce their answers. The major difference between the two Stroop tasks is the presence or absence of structural interference at the perceptual stage (Kahneman & Chajczyk 1983). Structural interference occurs when two concurrently performed tasks require the same perceptual structures in order for
successful stimuli identification, and subsequently task completion (Kahneman & Chajczyk 1983). An example of structural interference is completion of a visual stimuli identification test and a concurrent walking task through a cluttered environment; both tasks require vision to be performed successfully (Bock & Beurksens 2011; Chen et al. 1996). Although cognitive tasks with and without structural interference are common in everyday life, it remains unclear how the presence of structural interference influences an individual’s navigation through complex environments, and if this type of interference predisposes an individual to more movement errors and subsequently an increased risk of tripping or falling.

The purpose of this study was to examine dual-task interference effects using a cognitive task involving executive function (the Stroop task) that was varied in design to induce a combined central and structural interference (VST), or limited to central interference only (AST) while concurrently performing a challenging locomotor task (obstacle crossing; OBS). It was hypothesized that for dual-task conditions, the VST would yield larger performance decrements (e.g. slowed response times to the cognitive stimuli, reduced walking velocity and greater foot placement errors when crossing the obstacle) as compared to dual-tasks involving an AST. If the assumption that both the VST and AST create similar central interference is true (Kahneman & Chajczyk 1983; Morgan & Brandt 1989), the observed performance differences in VST and AST conditions could be attributed to the rapid switching of foveal vision between a visual Stroop test cue and a visual scan of the walking path. This finding would indicate that structural interference limited an individual’s ability to effectively perform the combined tasks as compared to when the tasks were performed independently (i.e. single-task
scenario). Investigation into the effects of structural interference on human movement, specifically obstacle crossing, will allow for better understanding of how dividing perceptual resources can influence the planning and execution of complex motor patterns.

3.3 Methods

3.3.1 Participants

Thirteen healthy young adults (20.6 ± 1.6 years; 6 Females) provided written informed consent and completed the study (approved by the Institutional Research Ethics Committee). All participants reported an absence of neuromuscular, auditory or visual (20/20 acuity or better) impairments that could inhibit their ability to perform any of the tested tasks.

3.3.2 Experimental Tests

The cognitive task component of the dual-task test was composed of performing either the VST (creating structural interference + central interference) or AST (only central interference). The VST consisted of five colour words written in either congruent colours (e.g. the word blue written in blue ink) or incongruent colours (e.g. the word blue written in red ink). The participants were instructed to “Respond by identifying the colour of the word, and not the word itself, as quickly and accurately as possible”. The AST consisted of the words “high” or “low” being produced by speakers in either a high or low pitch. The stimuli were either congruent (e.g. the word “high” spoken in a high pitch) or incongruent (e.g. the word “high” spoken in a low pitch). For the AST, participants
were instructed to “Respond by identifying the pitch of the voice, and not the word spoken, as quickly and accurately as possible”. Stimuli for both the VST and AST were one second in duration, and were produced using a custom Labview program (Version 10.0, National Instruments, Austin, TX, USA). The cognitive task was administered using a set of speakers (to produce the AST; Koss HD 50 speakers) and a computer monitor (to produce the VST; Dell E1910 LCD 19” monitor), which was positioned at eye height at the end of the walkway.

The OBS task component of the dual-task test was conducted along a 7 m long walkway, and required participants to step over a stationary obstacle that was normalized to 30% of the participant’s lower leg length (defined as the distance from the tibital plateau to the ground). The obstacle was a wooden dowel (1 cm in diameter, 95 cm wide) placed between two metal posts. Participants always stepped over the obstacle with their dominant foot first, as determined using the Waterloo Footedness Questionnaire (Elias et al. 1998). During dual-task trials, the OBS task also served as a trigger to produce the cognitive task at a consistent time for each trial (at the last step, specifically at heel contact, before obstacle crossing). To ensure this, a laser gate was placed two steps away from the obstacle; the delay between the laser being crossed and the cognitive stimuli being produced was 400 ms.

3.3.3 Experimental Paradigm

Participants were instrumented with five rigid bodies consisting of infrared emitting diodes mounted on the head, trunk, pelvis, and dorsum of both feet (barefoot). Anatomical landmarks (e.g. metatarsals, calcaneus for the foot) were digitized with
respect to these rigid bodies, and kinematic data were collected at 100 Hz (Optotrak 3020 system, Northern Digital Inc., Waterloo, Ontario). The participants were also fitted with a custom lapel microphone (4000 Hz) to record response times for both Stroop tasks. First, participants completed 5 practice OBS trials, to help researchers identify a standardized starting location, such that the participants always stepped over the obstacle leading with their dominant foot first (foot positioning). Participants then completed 10 (single-task) OBS stepping trials to ensure participants were comfortable stepping over the obstacle under no cognitive load (task familiarization). Participants then completed two experimental test blocks. Each block contained 20 trials of seated single-task cognitive trials (produced at a frequency of one cue every 30 seconds) followed by 20 cognitive and obstacle (30% lower leg length) crossing trials (dual-task). Blocks included either an auditory Stroop task (AST; central interference only) or a visual Stroop task (VST; combined central and structural interference); the order in which the AST and VST blocks were completed was randomized between participants (Figure 3.1). For the dual-task trials, participants received additional instruction to not prioritize one task over the other, and to attempt to complete both tasks simultaneously.
Figure 3.1. The block randomized experimental paradigm. Single-task obstacle crossing was always completed first, followed by the VST and AST experimental blocks (in a randomized order).
3.3.4 Data and Statistical Analyses

This section outlines the data and statistical analyses conducted on obtained cognitive and kinematic data. All statistical analyses used SPSS Version 22; IBM, Armonk, New York, USA) with significance level set to p < 0.05. For all repeated measure ANOVA tests performed, Stroop congruency was set as the between-subjects factor and Stroop type as the repeated measure.

Single-task performance was first quantified for both the AST and VST seated cognitive tasks for the dependent outcome measures of response accuracy (the percentage of stimuli correctly identified) and response time (the duration from when the cognitive task was presented until the participant identified the stimuli). A repeated measure ANOVA was then conducted for both mean response accuracy and mean response time to determine if there were differences in the difficulty between the single-task performance of the two cognitive tasks (AST and VST).

In order to analyze and quantify the interference effects induced by the dual-task paradigm Dual Task Cost (DTC; Equation 1) was calculated for both cognitive task accuracy and response time when the AST and VST tasks were simultaneously performed with the OBS crossing trials (using a repeated measure ANOVA). DTC provides a measure of the amount of change in task performance when a task is performed independently (single-task) or in combination with another task (dual-task). DTC can be either a positive value (increased value when performed as a dual-task) or negative (decreased value when performed in a dual-task situation) (Bock & Beurskens 2011; Kelly et al. 2010). Furthermore, the interpretation of DTC values are task dependent (e.g. a negative value for walking velocity means a slowed velocity during the
dual-task conditions, whereas a negative value for response time would indicate participants are completing the cognitive task faster).

\[(\text{Dual task} - \text{Single task})\]  \[\text{[Equation 1]}\]

Single task

The remainder of the statistical analysis focused on the kinematic measure DTC associated with the simultaneous performance of the cognitive and OBS task. Only trials where participants performed both tasks correctly (i.e. safely stepping over the obstacle and correctly responding to the cognitive stimuli) were included in statistical analyses for the kinematic variables. Seven kinematic measures were calculated and included: walking velocity (3 steps), minimum lead and trail foot clearance, takeoff and landing distances. Walking velocity was calculated as the first derivative of the pelvis center of mass for two steps before the obstacle (velOBS-2), one step before the obstacle (velOBS-1) and at obstacle crossing (velOBS-xing) (Worden & Vallis 2016). Minimum Lead foot Clearance (MLC) was calculated as the minimum vertical distance between the first metatarsal or heel (whichever was less) as the foot passed over the obstacle. Minimum Trail foot Clearance (MTC) was the distance from the top of the obstacle to the first metatarsal as it passed over the obstacle. The distance from the first metatarsal of the trailing foot to the obstacle in the direction of progression (Takeoff Distance; TOD), and heel of the leading foot after crossing the obstacle (Landing Distance; LD) in the direction of progression were also calculated.
These seven kinematic measures were calculated for all single-task OBS trials as well as the dual-task trials (OBS + cognitive tasks) for both AST and VST experimental trial blocks. Dual task costs were then calculated for these trials (Single-task=OBS crossing only; Dual-task=OBS crossing + cognitive task; Equation 1). Two repeated measure ANOVAs were then performed for walking velocity DTC and obstacle crossing spatial measures DTC, to test whether dual task costs varied across the Stroop tasks, or with Congruency of the Stroop tasks. For all outcome measures, outlying trials (trials greater than 2.5 standard deviations outside of the calculated participant’s mean for a given trial condition) were removed. This step was taken to more accurately reflect the true mean of a participant’s measures for the statistical analyses, as unaccounted for outliers would influence the normality of the data.

3.4 Results

All participants were able to perform both dual-task trial types (> 70 % accuracy). No participants contacted the obstacle during walking trials. Due to technical error, microphone data was incomplete for three participants, so response time data includes only 10 participants. No higher order interaction effects were observed in the statistical analyses, so only main effects will be presented below.

3.4.1 Cognitive Task Performance

For single-task performance, a main effect of Stroop Type was detected (F(1,18)=48.198, p<0.0001) for mean response accuracy, with participants being less
accurate at identifying the AST as compared to the VST (Table 3.1.A). No main effect of
Stroop congruency during single-task trials for response accuracy was detected for
participants identifying the congruent cue (94 ± 1.8 %) as compared to the incongruent
cue (89 ± 1.8 %). When examining mean response time during single-task trials, a main
effect of Stroop Type was observed ($F_{(1,18)}=18.245$, $p<0.0001$). Participants identified the
VST faster than the AST (Figure 3.2). No Congruency effect was observed for single task
response time for the Congruent cue (1.19 ± 0.07s) as compared to the Incongruent cue
(1.23 ± 0.07s). No DTC effects were observed for response accuracy or response time.
Table 3.1.A. Mean ± standard error response accuracy and response time for both the VST and AST under both single-task and dual-task. No DTC effects were observed, however a main effect of Stroop Type was observed for both outcome measures. Specifically, AST trials were statistically different from VST (accuracy\(^a\) and time\(^b\); \(p<0.05\)) and OBS+AST trials were statistically different from OBS+VST trials (accuracy\(^c\) and time\(^d\); \(p<0.05\); \(p<0.05\)). Note that OBS = obstacle crossing.

<table>
<thead>
<tr>
<th>Variable</th>
<th>AST</th>
<th>VST</th>
<th>OBS+AST</th>
<th>OBS+VST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response Accuracy</td>
<td>83.3 ± 2.54(^a)</td>
<td>100 ± 0(^a)</td>
<td>86.7 ± 1.71(^c)</td>
<td>99.0 ± 0.77(^c)</td>
</tr>
<tr>
<td>Response Time</td>
<td>1.36 ± 0.14(^b)</td>
<td>1.06 ± 0.08(^b)</td>
<td>1.46 ± 0.13(^d)</td>
<td>1.03 ± 0.10(^d)</td>
</tr>
</tbody>
</table>
Figure 3.2. Stroop task response time (mean ± standard error) for both the AST and VST during obstacle crossing (dual-task situation). AST responses were significantly slower than VST responses (p<0.05).
3.4.2 Walking Task Performance

Average gait kinematic outcome measures calculated are presented in Table 3.1.B. No main effects were observed for velOBS-2 or velOBS-1 DTC. However, a main effect of Stroop Type was detected for velOBS-xing DTC \( F(1,24)=9.277, p=0.006 \), indicating participants crossed the obstacle at a higher velocity for the VST condition as compared to the AST. A main effect of Stroop Type was detected for both MLC DTC \( F(1,24)=17.139, p<0.0001 \); Figure 3.3) and MTC DTC \( F(1,24)=46.103, p<0.0001 \); Figure 3.4). For both MLC and MTC, a larger dual-task cost was observed for VST as compared to AST, indicating that under structural and central interference (VST), participants cleared the obstacle by a greater vertical distance as compared to the change from single-task walking that was caused by central interference alone (AST). A main effect of Stroop Type was observed for both TOD DTC \( F(1,24)=5.501, p=0.028 \) and LD DTC \( F(1,24)=5.841, p=0.024 \). The TOD DTC and LD DTC values indicate that participants took off further away from the obstacle and landed closer when performing the AST as compared to the VST (see Table 3.1.B).
Table 3.1.B. Gait parameter data, mean ± standard error values for single-task obstacle crossing (SW) and dual-task walking for the VST and AST task. Mean ± standard error values for TOD and LD DTC are also presented in this table. Asterisks represent statistical significance (p<0.05).

<table>
<thead>
<tr>
<th>Variable</th>
<th>OBS</th>
<th>OBS+AST</th>
<th>OBS+VST</th>
</tr>
</thead>
<tbody>
<tr>
<td>velOBS-2 (m/s)</td>
<td>1.24 ± 0.05</td>
<td>1.23 ± 0.04</td>
<td>1.23 ± 0.04</td>
</tr>
<tr>
<td>velOBS-1 (m/s)</td>
<td>1.20 ± 0.05</td>
<td>1.21 ± 0.04</td>
<td>1.20 ± 0.04</td>
</tr>
<tr>
<td>velOBS-xing (m/s)</td>
<td>1.07 ± 0.05</td>
<td>1.08 ± 0.04</td>
<td>1.04 ± 0.04</td>
</tr>
<tr>
<td>MLC (m)</td>
<td>0.10 ± 0.01</td>
<td>0.11 ± 0.01</td>
<td>0.14 ± 0.02</td>
</tr>
<tr>
<td>MTC (m)</td>
<td>0.15 ± 0.02</td>
<td>0.14 ± 0.02</td>
<td>0.16 ± 0.02</td>
</tr>
<tr>
<td>TOD (m)</td>
<td>0.29 ± 0.02</td>
<td>0.28 ± 0.02</td>
<td>0.27 ± 0.02</td>
</tr>
<tr>
<td>LD (m)</td>
<td>0.18 ± 0.02</td>
<td>0.19 ± 0.02</td>
<td>0.21 ± 0.02</td>
</tr>
<tr>
<td>TOD DTC</td>
<td>-0.04 ± 0.04*</td>
<td>-0.10 ± 0.03*</td>
<td></td>
</tr>
<tr>
<td>LD DTC</td>
<td>0.05 ± 0.04**</td>
<td>0.15 ± 0.06**</td>
<td></td>
</tr>
</tbody>
</table>
**Figure 3.3.** MLC DTC (mean ± standard error) for both the AST and VST during obstacle crossing (dual-task situation). The VST had a larger MLC DTC as compared to the AST (p<0.05), indicating these participants cleared the obstacle by more when performing a concurrent visual Stroop task as compared to baseline obstacle crossing.
Figure 3.4. MTC DTC (mean ± standard error) for both the AST and VST during obstacle crossing (dual-task situation). The VST had a larger MTC DTC as compared to the AST (p<0.05), indicating these participants cleared the obstacle by more when performing a concurrent VST as compared to baseline obstacle crossing.
3.5 Discussion

The purpose of the current study was to gain increased understanding of the influence of structural and central cognitive interference during an obstacle crossing task. When examining cognitive task performance, higher accuracy rates and shorter response times were observed for the VST as compared to the AST. For the obstacle crossing performance, larger DTCs were observed for the VST as compared to the AST. These results supported the hypothesis that structural interference would cause larger effects on obstacle crossing performance as compared to solely central interference.

3.5.1 Cognitive Task Performance

In this study, participants were less accurate at identifying the AST compared to the VST. Although both tests rely on similar executive processes to match the correct response to the correct stimuli (Kahneman & Chajczyk 1983), participants were not able to execute this process with equal success. One potential explanation is that the perception of visual stimuli was easier than auditory stimuli for the participants. Participants reported being able to easily distinguish the different colours employed for the test, while identifying pitches appeared to be more challenging. Response times support this anecdotal finding, as participants were able to correctly identify stimuli more quickly for the VST as compared to the AST. Given that the response mechanism (verbal response) was the same across both conditions, the accelerated response times for the VST task compared to AST task was at the perceptual and or central response selection stages (Strobach et al. 2013). Again, this suggests that participants were more efficient at identifying visual stimuli, which is likely more frequently encountered in everyday life.
(as compared to information about noise pitch). Interestingly, when examining dual-task cost for both AST and VST, no significant differences in either response accuracy or response time were observed, indicating that when paired with a concurrent obstacle crossing task, performance of the Stroop tasks was not altered. Kelly et al. (2013) reported similar results in regards to response accuracy for the AST being similar between single (seated) and dual tasking (normal and narrow base walking), however, they did observe an increase in response time in the dual-task situation (Kelly et al. 2013). This may be the result of differences in instructions, as participants in their study were instructed to walk as quickly as possible, potentially shifting prioritization to the walking task, while the study required participants to maintain their normal walking speed, potentially creating a more equal division of attentional resources.

3.5.2 Obstacle Stepping Performance

When analyzing obstacle stepping performance, dual-task costs for MLC, MTC and velOBS-xing were greater for the VST as compared to the AST. These findings indicate that when participants performed a dual-task test involving structural interference (i.e. required to switch foveal gaze between the obstacle and VST) they cleared the obstacle by a higher margin and more slowly than participants performing a dual-task test involving strictly central interference. This finding is similar to previous work that demonstrated increased toe clearance over obstacle in single-task conditions when vision was occluded during obstacle stepping (Patla 1998; Timmis & Buckley 2012). Although this study did not directly occlude vision during testing, the need to locate and respond to the visual task required that the gaze be removed from the lower
limb and focused on the monitor at the end of the walkway (Miyake-daSilva & McIlroy 2012). Higher toe clearance and slower crossing may have been a safety precaution, in the absence of accurate and consistent visual information. Furthermore, larger DTCs were observed for both TOD and LD in the VST condition. The results indicate that in the OBS + VST condition, participants took off closer to the obstacle, and landed further away. Previous work has shown that improper TOD (taking off too close to the obstacle) can result in obstacle contacts (Chou & Draganich 1998; Patla & Greig 2006). Therefore, the strategy employed by participants in the VST condition may increase the likelihood of obstacle contacts. However, since participants in this condition also increased minimum foot clearance, this particular stepping strategy is likely not a major tripping risk.

3.6 Conclusion

This study improves understanding on the effects of structural interference on movement strategies through complex environments. When choosing tasks to measure dual-task performance, special attention must be given to the selection of the cognitive task, especially as the difficulty of navigating the environment is increased (e.g. obstacle crossing). Future work should implement a visual gaze tracking system to elucidate where foveal vision is directed when concurrently performing an obstacle crossing and VST or AST dual-task paradigm.
3.6.1 Conflict of Interest Statement

The authors declare no conflict of interest regarding this manuscript.
Chapter 4 Experiments II & III: Examining transfer of dual-task training effects to a complex dual-task environment

(Submitted in Journal of Motor Behavior, 35-16-068-RA)

4.1 Abstract

Training protocols designed to improve dual-task performance of an obstacle crossing and auditory Stroop task (OBS+Stroop) were tested. In Experiment II, following baseline collection of OBS+Stroop trials, proximally related walking training was performed, and, participants were then re-tested on the OBS+Stroop test. After training participants adopted a more cautious obstacle crossing strategy, indicating a potentially safer navigation strategy. Transfer effects from distally related training were then examined (Experiment III); a computer game training paradigm was examined using the same testing protocol as Experiment II. Computer based training demonstrated improved dual-task performance on some measures, but had a smaller effect than walking training. Results indicate that dual-task training needs to be similar to the targeted tasks to yield positive training outcomes.

4.2 Introduction

Dual-task interference arises when two separate tasks are completed simultaneously, resulting in reduced task performance in either one or both tasks (Ebersbach et al. 1995; Levy et al. 2006; Ruthruff et al. 2001). This interference has been described during both simple choice reaction tasks (Ruthruff et al. 2001; Strobach et al. 2013) as well as complex whole body tasks (Levy et al. 2006; Siu et al. 2008; Wellmon et al. 2013). Reduced task performance has been quantified as increased processing times
for task completion and increased error rates in comparison to when tasks are performed independent of each other (Lajoie et al. 1993; Ruthruff et al. 2001; Siu et al. 2008). Multiple theories have proposed different causal mechanisms to explain observed dual task interference effects (Pashler 1994; Tombu & Jolicoeur 2003). For example, proponents of the ‘Bottleneck Theory’ believe that a central processor is required to perform both tasks, and that this processor can only be accessed by one task at a time, resulting in a bottleneck of cognitive resources at this stage of processing (Pashler 1994). Another theory is the ‘Central Capacity Sharing Theory’ and advocates of this idea propose that tasks can proceed in parallel; central processing capacity therefore is limited by the amount of cognitive resources available. It is these limitations in cognitive processing that result in reduced task performance on either one or both tasks (Tombu & Jolicoeur 2003; Woollacott & Shumway-Cook 2002). Although the debate continues as to which theory most accurately describes dual-task interference findings, this work will focus on scientific approaches that have been used to reduce interference effects in dual-task situations during whole body movements.

Due to the potential for major negative consequences of dual-task interference, considerable research has been invested into acquiring a better understanding of the mechanism(s) for multiple task integration in the brain, and the idea that training may improve one’s dual-tasking ability (Schumacher et al. 2001; Strobach et al. 2013). Surprisingly, far less is known about dual-task interference when at least one of the tasks is a continuous motor task (Lajoie et al. 1993; Siu et al. 2008). Although less studied, this situation arises frequently in everyday life as individuals navigate complex and sensory rich environments while attending to many unique cognitive tasks (e.g. walking along a
crowded sidewalk and remembering a daily to-do list). Negative consequences of dual-task interference during walking may also result in serious events, including an increased risk of falling and experiencing an injury for an older adult (Makizako et al. 2010). Many unique paradigms involving at least one complex motor action have reported dual-task interference (for reviews, see Woollacott & Sumway-Cook 2002; Yogev et al. 2008), further strengthening the argument for central interference producing dual-task costs. In these complex tasks, the performance of more than one task at a time has been linked to slower walking velocity, reduced stability, and falls risk in the elderly (Al-Yahya et al. 2009; Beauchet et al. 2005; Ebersbach et al. 1995; Lajoie et al. 1993; Makizako et al. 2010).

Interestingly, few studies have examined training methods to improve the ability to perform a concurrent motor and cognitive task in young adults. Pellecchia (2005) examined practice of standing balance and a serial subtraction task in young adults following three training sessions that involved either practicing the tasks independently or together in a dual-task situation. Findings from this work demonstrated that if tasks were practiced simultaneously increases in performance on the postural task (e.g. decreased sway range and sway velocity) were obtained compared to when tasks were practiced independently or with no practice at all. Worden & Vallis (2014) expanded on this work by examining a more complex task, stepping over an obstacle that had the ability to move while completing an auditory Stroop task with the goal of investigating optimal practice strategies for performing two simultaneous tasks. After just one training session (which required subjects to practice either: both tasks concurrently, only the cognitive task, or no practice), a significant improvement (more consistent obstacle
crossing strategy) was noted in only the dual-task practice condition.

Although the works of both Pellecchia (2005) and Worden & Vallis (2014) have shown that dual-task practice can yield improvements in dual-task performance in healthy young adults, it is important to note that the trained tasks were identical to the tasks tested to quantify dual-task performance. Both studies proposed that the reduction in dual-task interference was explained by task-integration, whereby practice had improved the coordination of performing both tasks concurrently (Pellecchia 2005; Worden & Vallis 2014). It is important to acknowledge then that this training may be specific to the integration of unique tasks, and may not transfer to the performance of other tasks; when one task is altered, observed improvements due to task integration may be lost. In everyday situations individuals are confronted by changing environments and dynamic situations that require the selection of appropriate action-perception responses for many unique tasks. It would be impossible to train task integration for each unique situation; therefore to truly understand the mechanisms of multiple task integration, researchers must examine in detail the transference of training effects from trained tasks to different situations. Previous work on computer-based cognitive tasks has shown dual-task transfer effects (Basak et al. 2008; Bherer et al. 2005; Kramer et al. 1995). For example, Kramer et al. (1995) trained participants in two cognitive tests (a monitoring task and an alpha-numeric task), and then examined transference to two different tasks (a scheduling task and a working memory task). The researchers reported that when tasks were trained together, there were transfer effects to related tasks (i.e. tasks which required similar mental processes). Furthermore, research examining training with complex computer games have shown transfer effects to many measures of executive function. For
example, Basak et al. (2008) examined transfer effects in older adults playing a commercially available strategy-based computer game. After four to five weeks of playing the game, participants were then re-tested on a battery of executive function tests (e.g. Operation Span, N-Back task), and demonstrated improvements in four of the five executive function tests. The authors concluded that this was an indication of what they termed ‘proximal’ transfer of training effects; practicing one task results in improved performance on that specific task that then transfers to a second unpracticed task which requires similar executive function processes. Interestingly, when participants in this study were tested on a more ‘distally’ related set of visual-spatial attention tasks (i.e. the two tasks tested required different cognitive processes), the observed training effects disappeared. This observation suggests that a transfer of skills exists between proximally related tasks, but not to more distally related tasks. The transfer effects to proximally related tasks may be the result of practicing similar skill sets (executive skills such as maintaining information in working memory and switching between tasks), required to perform other related tasks (Basak et al. 2008; Kramer et al. 1995). However, when examining more distally related tasks that require different sets of mental processes (such as field of view tasks), the training effects do not produce improvements (Basak et al. 2008; Kramer et al. 1995). Far less is known about transfer effects in complex environments requiring whole body control and at this time it is unclear if improvements in dual-task performance can be transferred to more distally related tasks.

The aim for the current work was to execute two experimental protocols to determine if dual-task training can transfer to proximal and/or distally related tasks; if transfer did occur, it was important to determine if these improvements would be retained
following cessation of the training sessions. This study is the first, to our knowledge, to examine the transfer of training effects in complex dual-task environments (pairing of a cognitive and gait related task; obstacle crossing) in young adults. Specifically, the experiment was conducted to better understand the training effects on the control strategy for safely stepping over an obstacle while performing a concurrent cognitive task. In Experiment II, a training program using tasks similar to the tested task (i.e. walking while simultaneously performing cognitive tasks) was employed to determine if improvements could be achieved in the obstacle crossing strategy with training of proximally related tasks. Experiment III was designed to replicate the results of Experiment II, while also including a more distally related training task (i.e. playing a computer game while concurrently performing cognitive tasks). Research findings from this work are important, as some individuals struggle under dual-task situations (e.g. older adults, individuals with Parkinson’s Disease; Rochester et al. 2014; Schaefer et al. 2015) and may benefit from the development of training and fall prevention programs constructed based on the transfer of training effects to everyday dual-task situations.

4.3 General Methods

4.3.1 Measure of Dual-Task Performance: Concurrent Obstacle Crossing and Auditory Stroop Task

To examine dual-task performance, an experimental paradigm previously validated was chosen (Worden & Vallis 2014) during which participants perform two unique tasks concurrently that require different perception and action responses. This test of dual-task performance allowed for designing training paradigms that were related, in
varying levels, to the tested tasks. The dual-task test was a complex obstacle crossing and auditory Stroop task (OBS+Stroop) that requires constant monitoring of the participant’s environment, and rapid updating of stepping strategies when the obstacle moves (Worden & Vallis 2014). Previous work has shown that obstacle crossing requires a high level of attention, and as available response time decreases (i.e. reduced time to adapt to environmental constraints), attentional requirements increase (Chen et al. 1996; Weerdesteyn et al. 2003). A dynamic obstacle therefore creates a useful means for manipulating attentional needs of a task while also presenting a novel paradigm to explore how the body controls complex movements to allow for safe navigation. The auditory Stroop task component of the test requires a high level of attention to perform correctly, relying on the executive function process of inhibition (Kahneman & Chajczyk 1983; Morgan & Brandt 1989; Siu et al. 2008). This OBS+Stroop test was related to the tasks trained, but also unique which facilitated the examination of task training transfer effects between the training tasks and the OBS+Stroop test.

A dynamic obstacle was placed along a 7 m walkway (4 m from the start), and participants were instructed to “Maintain your normal walking speed while safely stepping over the obstacle”. The obstacle was a wooden dowel 1.0 cm in diameter and 94.0 cm in length, mounted between two motorized arms, which facilitated movement of the dowel (Figure 4.1.A). A laser gate, placed two leg lengths (one leg length was defined as the distance from the participant’s greater trochanter to the ground) before the obstacle, triggered movement of the obstacle (Figure 4.1.B). The obstacle had two possible heights, a ‘high’ height, which was 50 % of lower leg length (measured as the distance from the tibial plateau to the ground; range of 42 to 51 cm for the participants)
or a ‘low’ height, which was 18.0 cm below the ‘high’ height. The obstacle would either remain in a ‘low’ position for the entirety of the trial (stationary trial) or move in a circular arc toward the participant as they approached it, before coming to a rest at the ‘high’ height 180 degrees above the starting position (dynamic trial; 310 ms for the obstacle to move from the low to high position).
Figure 4.1. Panel A) depicts an image of a participant stepping over the obstacle used in this paradigm. The obstacle is shown in the low position, but for 50% of the trials would dynamically switch to a high position upon approach. Panel B) demonstrates the approach of participants towards the obstacle. The steps on approach two steps before the obstacle (OBS-2), one step before the obstacle (OBS-1), and at obstacle crossing (OBS-xing) are depicted. It took participants approximately one second from crossing the laser gate to reach the obstacle.
Concurrently, an auditory Stroop task was presented using a custom Labview program (Version 10.0, National Instruments, Austin, TX, USA) (human voices; 2 male and 2 female) speaking the words ‘high’ or ‘low’ in a high pitch or a low pitch. A congruent cue was composed of the word said matching the pitch (e.g. the word ‘low’ spoken in a low pitch), while an incongruent cue did not match (e.g. the word ‘high’ spoken in a low pitch). Participants were instructed to “Identify, out loud, the pitch of the word as quickly and accurately as possible while ignoring the actual word said”. A single auditory Stroop stimulus was evoked at approximately the same time each trial, as the trailing foot was in swing before heel contact immediately before obstacle crossing.

4.3.2 Training Sessions

Training sessions took place in a different location than the testing sessions. The training sessions were composed of two unique tasks (components) performed concurrently. The first component (consistent across all types of training) included three different cognitive tasks: i) backwards counting, ii) an auditory Stroop task (with voices different than what were presented during testing sessions) and iii) a modified N-back task (a list of letters was produced by speakers in the room, and the participant would be required to recite either the second or third last letter produced based on the cue at the end of the list of letters). The second component was manipulated for each experiment, and will be discussed in each experiment’s respective methodology sections. Note that the first and second components were performed concurrently during training trials in order to create dual-task training scenarios. Each of the three dual-task scenarios took approximately 7 minutes to complete, and each training session was approximately 25
minutes (including approximately 2 minutes of rest between each of the three auditory task types). After each response to the cognitive task by participants, the individual facilitating testing would provide feedback on the correctness of the response.

4.3.3 Testing Sessions

All participants were healthy young adults recruited from the University student population, and were screened for any neuromuscular disorders, visual or hearing impairments. The University Research Ethics Board granted approval for the study and all participants provided written consent. Each data collection session was performed in the same manner. Upon arrival to the laboratory for the baseline testing session (Visit 1), participants were given a brief overview of the tasks for the session. Following this, participants were then instrumented with non-collinear rigid triads of infrared lights placed on the head, trunk, pelvis and left and right feet. An optoelectric camera system (Optotrak 3020 NDI, Waterloo, Canada) collected kinematic data at 100 Hz. Anatomical landmarks were digitized in relation to each rigid body (e.g. left and right ear for the head segment), and a simplified body center of mass model was computed (Winter 2005). Participants also wore a custom built microphone, which collected participant responses to the auditory Stroop task, sampled at 4000 Hz. Participants then practiced 20 seated (10 congruent and 10 incongruent) auditory Stroop task trials to ensure that task instructions were understood.

Following the auditory Stroop practice trials, participants were introduced to the dynamic obstacle task. All walking trials were performed barefoot. To ensure each participant was comfortable stepping over the obstacle before experimental trials were
conducted, six practice walks over both the stationary and dynamic obstacles were allotted. These practice trials also allowed the researchers to determine a suitable gait initiation position, such that the participant approached the obstacle consistently, and always stepped over the obstacle with their dominant foot first (as defined by the Waterloo Footedness Questionnaire; Elias et al. 1998). For obstacle crossing trials, participants were instructed to “Maintain your normal walking speed while safely stepping over the obstacle”. Following practice walking trials, participants completed 40 dual-task trials (OBS+Stroop test). The 40 dual-task trials were balanced for obstacle movement and auditory Stroop congruency (i.e. 10 trials for each obstacle position and Stroop congruency combination). For these trials, participants were instructed to “Perform both tasks at the same time and with equal importance”.

4.3.3.1 Data Analyses

The two outcome measures for the auditory Stroop task were response accuracy and response time. For the Stroop task, a researcher manually recorded response accuracy (correct/incorrect) following each trial. To determine response time, microphone data from the auditory Stroop task were bandpass filtered (700-1400 Hz cutoff) using a dual-pass second order Butterworth filter (Visual 3D, C-motion, Germantown, MD, USA; Version 4). The data were then rectified, and low-pass filtered (10 Hz cutoff) using a dual-pass second order Butterworth filter. The onset time for the participant’s response was then defined as the point in which the microphone output deviated from baseline (silence) by greater than 2 standard deviations. The time at which the speaker presented the cue was previously known, and response time was defined as the temporal difference
between the speaker producing the stimuli and the participant’s response.

All kinematic analyses were conducted using Visual3D (C-motion, Germantown, MD, USA; Version 4). Kinematic data were first interpolated using a 5-point cubic spline, then low-pass filtered using a dual-pass second order Butterworth filter (10 Hz cutoff). Left and right heel contacts were defined as the maximal distance from the pelvis center of mass to the left and right heel, respectively (Zeni et al. 2008). Walking velocity was calculated at three separate heel contacts: i) 2 steps before the obstacle (velOBS-2), ii) 1 step before the obstacle (velOBS-1) and iii) at obstacle crossing (velOBS-xing). Velocity was the first derivative of the displacement for the simplified COM model (head, trunk and pelvis; Winter 2005).

Takeoff distance (TOD) was defined as the horizontal distance of the first metatarsal to the obstacle at heel contact of the non-leading foot immediately before stepping over the obstacle. Similarly, landing distance (LD) was calculated as the horizontal distance of the obstacle to the heel of the leading foot at heel contact immediately after crossing the obstacle. Minimum lead foot clearance (MLC) was the minimum vertical distance between the leading first metatarsal or heel (whichever was less) and the top of the obstacle at the instant when the foot was directly over top of the obstacle. Similarly, minimum trail foot clearance (MTC) was defined as the minimal vertical distance between the trailing first metatarsal and the top of the obstacle. For spatial measures of obstacle crossing (TOD, LD, MLC and MTC) the coefficient of variation (CV) was calculated. CV was calculated as the standard deviation divided by the mean (averaged over 10 trials) for each experimental condition.
4.3.3.2 Statistical Analyses

All statistical analyses were performed in SPSS Version 22 (IBM, Armonck, New York, USA). All analyses conducted were repeated measure ANOVAs with Visit (three different testing sessions) as the repeated measure. Accuracy analyses for the auditory Stroop task was conducted using a univariate repeated measure ANOVA (Congruency x Obstacle Position x Group). For all of the following data analyses, statistical tests were only performed on those trials where participants were able to correctly perform both tests (e.g. correctly identifying the auditory cue and safely stepping over the obstacle for the cognitive-motor task). A univariate repeated measures ANOVA (Congruency x Obstacle Position x Group) was performed on response time for the auditory Stroop task. For kinematic outcome measures, two separate repeated measure MANOVAs (Congruency x Obstacle Position x Group) were conducted as follows: i) velocity measures, and ii) spatial kinematic measures (clearances, takeoff and landing distances). For any multivariate interactions, univariate ANOVAs were conducted to further probe these effects, and paired samples T-tests compared means between Visits where appropriate (with Bonferroni corrections). A Greenhouse-Geisser correction was used for variables that were significant for sphericity. Significance level was chosen as p<0.05. For all outcome measures, outlying trials (trials greater than 2.5 standard deviations outside of the calculated participant’s mean for a given trial condition) were removed. This step was taken to more accurately reflect the true mean of a participant’s measures for the statistical analyses, as unaccounted for outliers would influence the normality of the data.
4.4 Experiment II: Examining training effects from a concurrent locomotor and cognitive task training program on both immediate and retained performance changes

4.4.1 Objective

The purpose of Experiment II was to examine if a dual-task training program focused on proximal tasks involving similar cognitive and locomotor components could transfer to an improvement on the OBS+Stroop test of dual-task performance. This experiment served the secondary function of examining the retention of training effects following a period of no training. Participants attended an initial testing session (Visit 1) to determine baseline performance levels on the OBS+Stroop test. Following baseline testing, participants were randomly assigned to one of three training groups: no training (CONTROL), one-week of training (ONE) and four weeks of training (FOUR). Participants were tested on the OBS+Stroop task one week after training completed (Visit 2) to quantify immediate training effects. Finally, five weeks after Visit 2, participants returned to the lab for one final data collection of the OBS+Stroop task (Visit 3) to measure retention effects. It was hypothesized that training would improve dual-task performance quantified as greater accuracy on cognitive tests, and a more cautious obstacle crossing strategy (i.e. increased foot clearance values and TOD). Furthermore, it was expected that a longer duration of training (FOUR) would produce positive changes in more kinematic and cognitive outcome measures than a limited training period (ONE), due to increased time available for consolidation of the task performance. Finally, it was anticipated that both training groups would maintain similar training effects on Visit 3 following a period of no training as were observed at Visit 2.
4.4.2 Participants

Thirty-three healthy young adults participated in the experiment (19.8 ± 1.21 years; 21 females and 12 males). Five total subjects (two from CONTROL, one from the ONE, and two from FOUR) dropped out of the study due to time constraints (see Fig. 2 for sample sizes at each testing session).

4.4.3 Training Sessions

Training sessions were scheduled as depicted in Figure 4.2. Recall that these training sessions required participant to complete both training components simultaneously, effectively producing a dual-task scenario. The first training component was composed of the previously described three cognitive tasks. The second training component was the same task for both the ONE and FOUR groups. This task involved walking in a room while weaving between obstacles placed on the floor in a figure-of-eight pattern. While feedback was provided to participants regarding their cognitive task performance, no kinematic data was recorded for these practice sessions and no feedback was provided on the performance of the walking task.
Figure 4.2. Demonstrates the timeline for testing and training for the three different experimental groups. All groups performed Visit 1 (V1) at week 0, followed by training before Visit 2 (V2). Visit 3 (V3) was the same for all three groups, occurring five weeks after Visit 2 following a period of no training. Each training block encompassed 2 sessions a week for approximately 25 minutes. The training session was composed of walking in a room while weaving through obstacles. For the cognitive component of training, participants performed three separate tasks: backwards counting, a modified N-back test, and an auditory Stroop task. Below each Visit the number of participants included in the analysis for this study is listed (note that in all groups one participant dropped out after Visit 2).
4.4.4 Testing Sessions

Testing sessions were scheduled as demonstrated in Figure 4.2. The CONTROL group received no contact between week 0 and week 2 (when the re-testing session on Visit 2 occurred). The ONE group received one week of training (training involved two total training sessions; total of approximately 50 min of training), followed a week later by Visit 2. The FOUR group received four weeks of training (eight total training sessions; total of approximately 200 min of training), followed a week later by Visit 2. For all three groups, Visit 3 was performed 5 weeks after Visit 2 to test for retention effects from the practice sessions. During the 5-week period between Visits 2 and 3, no contact was made with the participants.

4.4.5 Results

All participants were able to successfully complete the dynamic obstacle and auditory Stroop test (> 75 % accuracy). Due to microphone error during data collection, response time data was not available for this experiment. Due to camera volume error, data was incomplete for MTC for one participant (from the FOUR week training group), thus this data could not be included in subsequent analyses.

4.4.5.1 Auditory Stroop Task

No interactions or main effects were detected for auditory Stroop task accuracy in the OBS+ Stroop trials. Response accuracy for the three groups is presented in Table 4.1.
Table 4.1. Experiment II Accuracy Rates (%) for correctly identifying the auditory Stroop task pitch while concurrently performing the obstacle crossing task across the three different training groups. Note that no improvements were noted in this component of the dual-task test; no interaction or main effects were observed for training Group or Visit.

<table>
<thead>
<tr>
<th>Group</th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>92.5 ± 3.8 %</td>
<td>93.3 ± 3.5 %</td>
<td>91.3 ± 4.0 %</td>
</tr>
<tr>
<td>One Week Training</td>
<td>88.4 ± 3.5 %</td>
<td>89.9 ± 3.2 %</td>
<td>88.0 ± 3.6 %</td>
</tr>
<tr>
<td>Four Week Training</td>
<td>92.4 ± 2.8 %</td>
<td>92.5 ± 2.9 %</td>
<td>95.1 ± 2.6 %</td>
</tr>
</tbody>
</table>
4.4.5.2 Velocity Measures

Velocity means ± standard error for velOBS-2, velOBS-1, and velOBS-xing are presented in Table 4.2. An interaction of Visit*Group was observed for OBS-xing velocity \(F_{(3.204, 147.406)} = 3.019, p=0.029\). For the CONTROL group, velocity at OBS-xing for Visit 3 was greater than Visits 1 and 2. For the ONE group, participants increased velocity on Visit 2 as compared to Visit 1, but Visit 3 was not different from the other visits. Finally, in the FOUR group velocity at Visit 2 was significantly greater than at Visit 1 and Visit 3. Thus, both trained groups demonstrated increased obstacle crossing velocity immediately following training (Visit 2), while CONTROL demonstrated this increase at Visit 3 only. A main effect of Visit was detected for velOBS-2 \(F_{(2, 184)} = 50.94, p<0.001\) and velOBS-1 \(F_{(2, 184)} = 47.96, p<0.001\), where for both parameters, velocity on Visits 2 and 3 was greater than on Visit 1 across all groups.
Table 4.2. Experiment II kinematic data results; mean ± standard error values for velocity, MLC, LD, MLC CV and LD CV. All data presented are for those trials where participants successfully performed both the cognitive and locomotor tasks. Different letters within each group denote differences between Visits (p < 0.05). Note than an interaction of Visit*Group was observed for OBS-xing velocity, see Results section for details regarding statistical findings involving interaction effects between Group*Visit.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group</th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>velOBS-2 (m/s)</td>
<td>Control</td>
<td>1.12 ± 0.06(^a)</td>
<td>1.18 ± 0.053(^b)</td>
<td>1.21 ± 0.06(^b)</td>
</tr>
<tr>
<td></td>
<td>One</td>
<td>1.21 ± 0.04(^a)</td>
<td>1.26 ± 0.044(^b)</td>
<td>1.29 ± 0.05(^b)</td>
</tr>
<tr>
<td></td>
<td>Four</td>
<td>1.23 ± 0.04(^a)</td>
<td>1.29 ± 0.044(^b)</td>
<td>1.30 ± 0.05(^b)</td>
</tr>
<tr>
<td>velOBS-1 (m/s)</td>
<td>Control</td>
<td>1.12 ± 0.06(^a)</td>
<td>1.17 ± 0.058(^b)</td>
<td>1.20 ± 0.07(^b)</td>
</tr>
<tr>
<td></td>
<td>One</td>
<td>1.18 ± 0.04(^a)</td>
<td>1.24 ± 0.045(^b)</td>
<td>1.27 ± 0.05(^b)</td>
</tr>
<tr>
<td></td>
<td>Four</td>
<td>1.20 ± 0.04(^a)</td>
<td>1.26 ± 0.044(^b)</td>
<td>1.25 ± 0.04(^b)</td>
</tr>
<tr>
<td>velOBS-xing (m/s)</td>
<td>Control</td>
<td>0.99 ± 0.04(^a)</td>
<td>1.02 ± 0.047(^a)</td>
<td>1.07 ± 0.05(^b)</td>
</tr>
<tr>
<td></td>
<td>One</td>
<td>1.11 ± 0.05(^a)</td>
<td>1.15 ± 0.046(^b)</td>
<td>1.14 ± 0.06(^a,b)</td>
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<tr>
<td></td>
<td>Four</td>
<td>1.09 ± 0.04(^a)</td>
<td>1.14 ± 0.052(^b)</td>
<td>1.10 ± 0.06(^a)</td>
</tr>
<tr>
<td>MLC (m)</td>
<td>Control</td>
<td>0.11 ± 0.02(^a)</td>
<td>0.10 ± 0.015(^a)</td>
<td>0.09 ± 0.01(^a)</td>
</tr>
<tr>
<td></td>
<td>One</td>
<td>0.10 ± 0.01(^a)</td>
<td>0.10 ± 0.014(^a)</td>
<td>0.11 ± 0.01(^a)</td>
</tr>
<tr>
<td></td>
<td>Four</td>
<td>0.10 ± 0.01(^a)</td>
<td>0.10 ± 0.013(^a)</td>
<td>0.10 ± 0.01(^a)</td>
</tr>
<tr>
<td>LD (m)</td>
<td>Control</td>
<td>0.19 ± 0.02(^a)</td>
<td>0.17 ± 0.013(^b)</td>
<td>0.17 ± 0.01(^b)</td>
</tr>
<tr>
<td></td>
<td>One</td>
<td>0.23 ± 0.01(^a)</td>
<td>0.22 ± 0.019(^b)</td>
<td>0.21 ± 0.02(^b)</td>
</tr>
<tr>
<td></td>
<td>Four</td>
<td>0.22 ± 0.02(^a)</td>
<td>0.21 ± 0.014(^b)</td>
<td>0.20 ± 0.02(^b)</td>
</tr>
<tr>
<td>MLC CV (%)</td>
<td>Control</td>
<td>20.10 ± 3.50(^a)</td>
<td>18.90 ± 2.70(^a)</td>
<td>20.70 ± 3.80(^a)</td>
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<tr>
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<td>One</td>
<td>27.50 ± 7.10(^a)</td>
<td>19.60 ± 3.20(^b)</td>
<td>22.30 ± 3.90(^a,b)</td>
</tr>
<tr>
<td></td>
<td>Four</td>
<td>32.10 ± 4.90(^a)</td>
<td>24.70 ± 6.00(^a,b)</td>
<td>16.10 ± 2.70(^b)</td>
</tr>
<tr>
<td>LD CV (%)</td>
<td>Control</td>
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<td>27.70 ± 2.30(^a)</td>
<td>15.6 ± 2.4(^a)</td>
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<tr>
<td></td>
<td>One</td>
<td>14.60 ± 1.70(^a)</td>
<td>40.00 ± 4.70(^a)</td>
<td>12.9 ± 1.9(^a)</td>
</tr>
<tr>
<td></td>
<td>Four</td>
<td>18.20 ± 3.70(^a)</td>
<td>19.50 ± 3.60(^a)</td>
<td>13.1 ± 1.9(^a)</td>
</tr>
</tbody>
</table>
4.4.5.3 Distance Measures

There was an interaction of Visit*Group, for both TOD ($F_{(4, 178)}=6.045, p<0.001$) (see Figure 4.3) and MTC ($F_{(3.707,164.96)}=4.507, p=0.02$) (see Figure 4.4). Paired samples t-tests were then performed to further probe this interaction, with significance shown in Figures 4.3 & 4.4, respectively. The t-tests revealed that all three groups increased TOD following Visit 1, while only the trained groups increased MTC. A main effect of Visit was detected for LD ($F_{(2, 178)}=11.119, p=0.001$) (see Table 4.2). For LD, on Visits 2 and 3, the participants landed closer to the obstacle than on Visit 1. No main effects or interactions were detected for MLC (Table 4.2).
Figure 4.3. Mean + standard error for take-off distance (TOD) to the obstacle (in meters) is shown for the three experimental groups during the three testing sessions. For the CONTROL group, Visit 2 had a longer take-off distance than Visit 1. For the ONE week training group, take-off distance got progressively longer for each visit. For the FOUR week training group, take off distance was longer for Visits 2 & 3 as compared to Visit 1. An asterisk represents statistical significance (p < 0.05).
Figure 4.4. Mean + standard error for minimum trail foot clearance (MTC) is demonstrated for the three experimental training groups during the three testing sessions. Participants in the CONTROL group decreased MTC on Visit 3 as compared to the first two Visits. For both the ONE week and FOUR week training groups, participants cleared the obstacle by more on Visits 2 & 3 as compared to Visit 1. An asterisk represents statistical significance (p < 0.05).
When examining coefficient of variation for distance measures, a Visit*Group*Obstacle interaction for MTC was detected ($F_{(3.346,140.533)}=4.714, p=0.003$) as illustrated in Figure 4.5. A Visit*Group interaction for TOD ($F_{(2.379, 99.929)}= 3.445, p=0.028$) was detected as depicted in Figure 4.6 with both trained groups reducing TOD CV. A Visit * Group interaction for MLC CV was observed ($F_{(3.390, 142.371)}=5.481, p=0.012$) (see Table 2). For the Control Group, there was no change in MLC CV across the three testing sessions. For the ONE week training group, the coefficient of variation was reduced on Visit 2 as compared to Visit 1, but was not different from Visit 3. For the FOUR week training group, MLC CV was reduced on Visit 3 as compared to Visit 1, while Visit 2 was not different from either.
Figure 4.5. Panel A) demonstrates minimum trail foot clearance (MTC) coefficient of variation (mean + standard error) while stepping over the dynamic obstacle for the three experimental groups during the three testing sessions. The CONTROL group increased MTC CV during Visit 3 as compared to Visit B. Both training groups reduced the MTC CV on Visits 2 & 3 as compared to Visit 1. An asterisk represents statistical significance (p < 0.05). Panel B) shows minimum trail foot clearance coefficient of variation (mean + standard error) while stepping over the stationary obstacle for the three experimental groups during the three testing sessions. Only the FOUR week training group demonstrated a change, with MTC CV being reduced on Visit 3 as compared to Visit 1. An asterisk represents statistical significance (p < 0.05).
Figure 4.6. Mean + standard error for take-off distance (TOD) coefficient of variation for the three experimental groups on the three testing sessions. The ONE week training group reduced TOD CV on Visit 3 as compared to Visits 1 & 2. Similarly, the FOUR week training group reduced TOD CV on each subsequent testing session. An asterisk represents statistical significance (p < 0.05).
4.4.6 Summary of Findings from Experiment II

When examining the cognitive task performance (response accuracy) for this experiment, no improvements were detected within any of the groups. These results indicate that regardless of training, participants did not improve their ability to accurately identify the pitch of the Stroop cue. This finding for response accuracy may be due to attention being shifted to prioritize improvements in the obstacle stepping aspect of the task, and this can be further explored by examining performance on the obstacle crossing task.

In this experiment, only the trained groups increased the MTC distance. Hitting an obstacle with the trailing foot has been reported to cause over 90% of all trips in an experimental setting (Heijnen et al. 2012; Rietdyk & Rhea 2011). Therefore, these results indicate the trained individuals adopted a more cautious strategy for clearing the obstacle; increasing MTC would decrease the likelihood of contacting the obstacle. Although these are the first clearance adaptation results following the completion of a training protocol to be reported, differences in obstacle crossing strategies between different populations have been previously described (Rietdyk et al. 2005; Rietdyk & Rhea 2011). For example, Rietdyk et al. (2005) examined platform stepping strategies utilized by healthy young adults in comparison to strategies used by young roofers (workers who replace shingles on roofs and frequently have to navigate through complex and hazardous environments i.e. stepping over obstacles on roofs while performing secondary motor and cognitive tasks). Roofers had larger minimum foot clearance values than the healthy young adults, which indicates these individuals prioritized larger clearance values to ensure a trip would not occur. The findings reported by Rietdyk et al. (2005) may also be true for the
WALKING groups, which demonstrated a safer obstacle crossing strategy following training. It is possible that training a concurrent walking and cognitive task allowed participants to practice the allocation and processing of sensory information for simultaneous walking and cognitive tasks. Furthermore, as a reduction in the coefficient of variation was observed for the WALKING groups for MTC (Figures 4.5 & 4.6), these individuals adopted a more consistent strategy that also reduces the likelihood of obstacle contacts or trips. Conversely, when examining strategies employed by the no training CONTROL group, mean MTC was reduced on Visit 3 (compared to other Visits), while not altering the coefficient of variation. This indicates that without training, participants on average crossed the obstacle by a smaller margin with the trailing foot. The closer placement of the foot in relation to the obstacle on Visit 3 arguably reduces the margin of safety when obstacle crossing, as the smaller clearance distance leaves less room to account for the variability inherent within stepping trajectories, increasing the likelihood of a trip (Heijnen et al. 2012; Rietdyk & Rhea 2011). Interestingly, only the FOUR group reduced MTC CV for the stationary obstacle (at Visit 3). This finding may indicate that participants were already quite consistent when choosing a stepping strategy for a non-moving obstacle (i.e. the easier obstacle condition), and that further refinement of the strategy was not obtained with this training protocol or necessary for safe navigation.

In addition to examining MTC, past research has proposed that a proportion of obstacle contacts are caused by improper foot placement (TOD) before the obstacle, with a smaller TOD increasing the likelihood of an obstacle contact (Chou & Draganich 1998; Heijnen et al. 2012; Patla & Greig 2006). All groups increased TOD following Visit 1,
indicating that participants adopted a more cautious obstacle crossing strategy by allowing more distance between the trailing foot and the obstacle during the crossing step. Furthermore, WALKING training reduced the coefficient of variation for TOD; indicating that participants adopted a more consistent foot placement strategy, which again, would reduce the likelihood of a foot placement error causing an obstacle contact (Chou & Draganich 1998; Patla & Greig 2006).

For the other distance measures of LD and MLC, fewer and less consistent changes across testing Visits were observed. This was likely due to the leading foot being more easily controlled during obstacle crossing (a result of the participant being able to view the leading foot step over the obstacle and land on the other side) (Chou & Draganich 1998). This increased visual information manifests as being safer, as few obstacle contacts are attributed to MLC and LD errors (Chou & Draganich 1998; Heijnen et al. 2012; Patla & Greig 2006). Although no change to mean MLC values were observed, it is interesting that training induced participants to reduce the variability in this foot as it crossed the obstacle, while no training caused no change in variability. Also, although participants landed closer to the obstacle following Visit 1, LD is not typically identified as a major contributor to obstacle contacts, and the small reduction in LD observed here likely does not indicate participants were at a greater risk of obstacle contacts on Visit 2 or Visit 3.

In general, an increase in walking velocity to complete the OBS+Stroop task on Visit 2 as compared to Visit 1 was observed. Given that all groups increased velOBS-2 and velOBS-1 (the two steps vital for the formulation of a plan to safely cross the obstacle), it is likely that on second exposure all individuals were more efficient at
integrating information about the environment and obstacle position in choosing a stepping strategy (i.e. they could integrate the same information needed to safely clear the obstacle in a shorter amount of time; Chen et al. 1996; Weerdesteyn et al. 2003). The increased velocity at OBS-xing may represent an improved ability to integrate and process sensory information needed to successfully clear the obstacle (Chen et al. 1996; Weerdesteyn et al. 2003).

Collectively, these results demonstrate that training in a proximally related walking and cognitive task situation can produce improvements in performance (i.e. more cautious and potentially safer stepping strategies) of the OBS+Stroop task. Given these results, the next logical step was to alter the training scenario slightly, to determine if a more distal set of training tasks would still elicit improvements in the OBS+Stroop test.
4.5 Experiment III: Comparing training effects on a complex obstacle crossing and auditory Stroop task from a proximal (locomotor and cognitive task) or distal (computer-game and cognitive task) training program

4.5.1 Objective

Experiment III was designed to further probe the relationship between the proximity of the tasks trained and the observed immediate training effects on the dual-task test. Specifically, the purpose of Experiment III was to examine the transference of training between a proximal training protocol (the same training tasks as Experiment II, now termed the WALKING group) and a more distal training scenario (the cognitive tasks remained the same, while the walking task component was replaced with a computer-based race car game, termed the COMP group). The COMP task was considered to be more distally related to the OBS+Stroop test due to the reduced postural load (the whole body movement complexity required to perform the COMP training scenario was reduced as compared to the WALKING group) (Lajoie et al. 1993). A computer-based game was chosen as the experiment sought to examine whether training on tasks with reduced postural loads would transfer to complex whole body movements of dual-task performance. Results from this second study may have important implications for future research studies involving older adults and/or individuals with mobility challenges who may not be able to complete physically taxing walking and cognitive task training programs.

As in Experiment II, participants first completed a testing session to determine baseline performance levels on the OBS+Stroop test. Following Visit 1, participants were
randomly assigned to one of three training groups: no training (CONTROL), three weeks of locomotor and cognitive task training (WALKING) or three weeks of computer game and cognitive task training (COMP). Participants were trained for three weeks as both the one and four weeks of training in Experiment II demonstrated similar training effects. As a result, a moderate amount of training was chosen when expanding the investigation to other training modalities in this experiment. Four weeks after Visit 1, participants returned to the lab for their second testing session on the OBS+Stroop task (Visit 2) to quantify immediate training effects (see Figure 4.7 for Experiment III testing timeline). It was hypothesized that the WALKING group would produce similar results as demonstrated in Experiment II, with participants adopting a more cautious obstacle crossing strategy while navigating the OBS+Stroop environment following training. Similarly, it was expected that the COMP group would show similar alterations to the stepping strategy, although it remained unknown if the more distally related task would produce the same magnitude of results as the WALKING group. As in Experiment II, no significant changes to the cognitive task performance were expected to be observed following training.
Figure 4.7. Demonstrates the timeline for testing and training for the three different experimental groups. All groups performed Visit 1 (V1) at week 0, followed by training before Visit 2 (V2). Each training block encompassed 2 sessions a week for approximately 25 minutes. The WALKING training session was composed of walking in a room while weaving through obstacles. For the cognitive component of training, participants performed three separate tasks: backwards counting, a modified N-back test, and an auditory Stroop task. The COMP training session was composed of the same cognitive tasks, but the walking component was replaced with a race car video game. Below each Visit the number of participants included in the analysis for this study is listed.
4.5.2 Participants

Thirty-two healthy young adults (different individuals from Experiment II) participated in the experiment (19.8 ± 0.80 years; 17 females and 15 males). Three total subjects (two from the CONTROL group and one from the COMP group) dropped out of the study due to time constraints (see Figure 4.7 for sample sizes at each Visit).

4.5.3 Training Sessions

Training sessions were scheduled as depicted in Figure 4.7. The WALKING training was composed of the same two components as was implemented for the ONE and FOUR groups in Experiment II. For the COMP training group, the first component was the same three cognitive tasks as the WALKING group. The second component was a commercially available racing car computer game (Formula Racer, TurboNuke, USA). The game required participants to use a set of computer key strokes to ‘steer’ a car along a defined roadway with many turns (arrow keys steered the car, and depressing the space bar provided a speed boost) while also avoiding other race cars and roadside obstacles. This game was chosen as it required a relatively simple set of instructions for the participants. Furthermore, it was a game that required a high degree of visual attention to steer the car and avoid roadside obstacles. This was similar to the WALKING group in the sense that it required participants to avoid obstacles positioned in their walking path. Performance on race times were recorded and presented to each participant at each training session to ensure that they were focusing on the task and motivated to try their best, although these training results were not analyzed further.
4.5.4 Testing Sessions

A minor adjustment was implemented from Experiment II to the OBS+Stroop task. The obstacle in Experiment III was placed 1.5 leg lengths in front of the obstacle (as compared to 2 leg lengths in Experiment II). This allowed for a greater challenge the attentional demands of the obstacle avoidance task, as available response time was reduced by approximately 250 ms as compared to Experiment II. Additionally both the WALKING and COMP groups received three weeks of training (training involved six total training sessions; total of approximately 150 min of training), followed a week later by Visit 2. This training duration was different from Experiment II because pilot work for Experiment III demonstrated that three weeks of training produced similar effects as four weeks of training with walking + cognitive task training. Note that the CONTROL group received no contact between week 0 and week 4 when the re-testing session on Visit 2 occurred.

4.5.5 Results

All participants were able to successfully complete the dynamic obstacle and auditory Stroop test (> 75 % accuracy). Due to camera volume error, data was incomplete for MTC for two participants (one from CONTROL group and one from COMP group), thus, this data could not be included in subsequent analyses.
4.5.5.1 Auditory Stroop Task

When examining Stroop task accuracy during the OBS+Stroop trials, a trend for a Group * Visit interaction was detected ($F_{(2,104)}=2.892$, $p=0.06$), although it was not statistically significant. For auditory Stroop accuracy during the OBS+Stroop task, no group significantly improved performance (see Table 4.3). For auditory Stroop response time, there was an interaction of Group * Visit ($F_{(2,100)}=8.821$, $p<0.001$) (see Table 4.3). For the CONTROL group, response time was reduced on Visit 2 as compared to Visit 1. Conversely, the COMP group increased response times on Visit 2 as compared to Visit 1. Finally, the WALKING group demonstrated no change in response times from Visit 1 to Visit 2.
Table 4.3. Experiment III accuracy rates (%) and Response Times (s) for the auditory Stroop task of the three different Groups. Accuracy rates denote the groups mean average for correctly identifying the auditory Stroop task pitch while concurrently performing the obstacle crossing task. Response times were only calculated for trials where participants successfully performed both tasks. Different letters within each group denote differences between Visits A and B (p < 0.05).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group</th>
<th>Visit 1</th>
<th>Visit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response Accuracy</td>
<td>Control</td>
<td>85.30 ± 4.50 %&lt;sup&gt;a&lt;/sup&gt;</td>
<td>92.50 ± 3.30 %&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Computer Training</td>
<td>86.70 ± 4.70 %&lt;sup&gt;a&lt;/sup&gt;</td>
<td>87.30 ± 5.30 %&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Walking Training</td>
<td>88.90 ± 3.03 %&lt;sup&gt;a&lt;/sup&gt;</td>
<td>89.80 ± 3.50 %&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Response Time (s)</td>
<td>Control</td>
<td>0.78 ± 0.08&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.72 ± 0.08&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Computer Training</td>
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<td>0.94 ± 0.10&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Walking Training</td>
<td>0.84 ± 0.07&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.88 ± 0.09&lt;sup&gt;a&lt;/sup&gt;</td>
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</tbody>
</table>
4.5.5.2 Velocity Measures

Gait velocity mean ± standard error values are presented in Table 4.4. An interaction of Group * Visit was detected for OBS-2 velocity \((F_{(2,104)}=3.708, p=0.028)\). The COMP group increased velocity from Visit 1 to Visit 2. Conversely, both the CONTROL group and WALKING group showed no change from Visit 1 to Visit 2. An interaction of Group * Visit was observed for OBS-1 velocity \((F_{(2,104)}=3.282, p=0.041)\). Again, only the COMP group increased velocity from Visit 1 to Visit 2. Both the CONTROL group and the WALKING group showed no change in velocity at OBS-1. A main effect of Visit was found for velOBS-xing \((F_{(1,104)}=7.457, p=0.007)\) with participants from all groups crossing the obstacle more quickly on Visit 2 as compared to Visit 1.
Table 4.4. Experiment III kinematic data results; mean ± standard error values for velocity, MLC, LD, MLC CV and LD CV. All data presented are for those trials where participants successfully performed both the cognitive and locomotor tasks. Different letters within each group denote differences between Visits (p < 0.05). Note than an interaction of Visit*Group was observed for OBS-xing velocity; see Results section for details regarding statistical findings involving interaction effects between Group*Visit.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group</th>
<th>Visit 1</th>
<th>Visit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>velOBS-2 (m/s)</td>
<td>Control</td>
<td>1.24 ± 0.06a</td>
<td>1.26 ± 0.05a</td>
</tr>
<tr>
<td></td>
<td>Comp</td>
<td>1.27 ± 0.05a</td>
<td>1.34 ± 0.04b</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>1.20 ± 0.03a</td>
<td>1.22 ± 0.03a</td>
</tr>
<tr>
<td>velOBS-1 (m/s)</td>
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<td>1.23 ± 0.05a</td>
<td>1.24 ± 0.05a</td>
</tr>
<tr>
<td></td>
<td>Comp</td>
<td>1.24 ± 0.05a</td>
<td>1.30 ± 0.04b</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>1.19 ± 0.03a</td>
<td>1.20 ± 0.04a</td>
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<tr>
<td>velOBS-xing (m/s)</td>
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<td>1.13 ± 0.06b</td>
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<tr>
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<td>Comp</td>
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<td>1.16 ± 0.04b</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
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<td>1.11 ± 0.04b</td>
</tr>
<tr>
<td>MLC (m)</td>
<td>Control</td>
<td>0.11 ± 0.02a</td>
<td>0.12 ± 0.02a</td>
</tr>
<tr>
<td></td>
<td>Comp</td>
<td>0.12 ± 0.01a</td>
<td>0.12 ± 0.02a</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>0.10 ± 0.01a</td>
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<td>LD (m)</td>
<td>Control</td>
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<td>0.22 ± 0.02b</td>
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<tr>
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<td>Comp</td>
<td>0.26 ± 0.02a</td>
<td>0.26 ± 0.03a</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>0.25 ± 0.02a</td>
<td>0.22 ± 0.02b</td>
</tr>
<tr>
<td>MLC CV (%)</td>
<td>Control</td>
<td>22.8 ± 5.50a</td>
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<td>Comp</td>
<td>17.6 ± 2.80a</td>
<td>17.6 ± 2.00a</td>
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<tr>
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<td>Walking</td>
<td>22.9 ± 5.40a</td>
<td>19.5 ± 2.80a</td>
</tr>
<tr>
<td>MTC CV (%)</td>
<td>Control</td>
<td>22.3± 3.70a</td>
<td>26.2 ± 3.80a</td>
</tr>
<tr>
<td></td>
<td>Comp</td>
<td>17.9 ± 2.20a</td>
<td>16.6 ± 1.40a</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>23.3± 3.70a</td>
<td>22.2 ± 3.20a</td>
</tr>
<tr>
<td>TOD CV (%)</td>
<td>Control</td>
<td>10.6 ±1.29a</td>
<td>11.0 ± 2.03a</td>
</tr>
<tr>
<td></td>
<td>Comp</td>
<td>11.0 ± 1.38a</td>
<td>9.9 ± 1.40a</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>12.9 ± 1.18a</td>
<td>12.4 ± 1.25a</td>
</tr>
<tr>
<td>LD CV (%)</td>
<td>Control</td>
<td>16.6 ±2.74a</td>
<td>14.7 ± 1.88a</td>
</tr>
<tr>
<td></td>
<td>Comp</td>
<td>14.2 ± 1.93a</td>
<td>13.0 ± 1.87a</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>14.2 ± 1.84a</td>
<td>15.1 ± 2.40a</td>
</tr>
</tbody>
</table>
4.5.5.3 Distance Measures

Similarly to Experiment II, training induced increases in TOD. An interaction of Group * Visit was detected for TOD ($F(2,98)=4.63, p=0.012$) (see Figure 4.8). The CONTROL group showed no change in TOD, while both training groups increased TOD (similar to Experiment II). An interaction of Group * Visit was detected for LD ($F(2,98)=6.771, p=0.002$) as well (Table 4.4). The CONTROL group landed further away from the obstacle on Visit 2 as compared to Visit 1. Conversely, the WALKING group landed closer to the obstacle on Visit 2 as compared to Visit 1. Finally for LD, the COMP group demonstrated no change in LD from Visit 1 to Visit 2. An interaction of Group * Visit was observed for MTC ($F(2,98)=3.587, p=0.031$) as illustrated in Figure 4.9. As in Experiment II, no effects or interactions were observed for MLC (see Table 4.4). When examining coefficient of variation for distance measures, no main effects or interactions were observed (see Table 4.4).
Figure 4.8. Mean + standard error for take-off distance (TOD) to the obstacle (in meters) is shown for the three experimental groups during the two testing sessions. For the CONTROL group, there was no change in TOD across Visits. For both the COMP and WALKING training groups, TOD got longer on Visit 2 as compared to Visit 1. An asterisk represents statistical significance (p < 0.05).
Figure 4.9. Mean ± standard error for minimum trail foot clearance (MTC) is demonstrated for the three experimental training groups during the two testing sessions. Participants in the CONTROL and COMP demonstrated no change in MTC across Visits. Conversely, the WALKING group increased MTC following training. An asterisk represents statistical significance (p < 0.05).
4.5.6 Summary of Findings from Experiment III

The purpose of Experiment III was to examine training protocols that varied in their composition to probe the transfer of training effects. It was hypothesized that a training scenario with a higher degree of similarity (WALKING) to the dual-task tests would produce greater improvements in performance as compared to a more distal task (COMP). As was observed in Experiment II, WALKING training resulted in participants adopting a more cautious obstacle crossing strategy, as evidenced by increased TOD and MTC values. The COMP training group demonstrated similar trends to the WALKING group (increased TOD and trending towards increasing MTC), although these changes were not of the same magnitude. As was found in Experiment II, the CONTROL group did not modify their obstacle crossing strategy to become more cautious, which is in contrast to the trained groups. When examining the cognitive task performance, again no changes in Stroop accuracy were noted, although the CONTROL group performed the task more quickly on Visit 2.

Again, as in Experiment II, training did not alter accuracy performance on the cognitive task on Visit 2 as compared to Visit 1. However, when examining the time needed by participants to correctly identify the Stroop cue (response time), the CONTROL group was able to reduce the amount of time needed to perform the cognitive task. Conversely, the WALKING group demonstrated no change in the time needed to perform the tasks, and the COMP group increased the time needed to respond to the auditory Stroop task, indicating no improvements in cognitive response time for either of the trained groups. These results may indicate differences between training on how information is integrated and prioritized. Past work has demonstrated that attention can
be flexibly allocated during dual-task completion, depending on the constraints of the tasks (Kelly et al. 2010; Kelly et al. 2013; Siu & Woollacott 2007). It is therefore possible that the different training types imposed different constraints, suggesting that participants adapted changes to their movement patterns specific to the training imposed. As noted above, the CONTROL group did not demonstrate significant improvements for the obstacle crossing task, thus it is possible attention was shifted to the completion of the auditory Stroop task and the identification of the auditory cues more quickly. Conversely, both trained groups demonstrated changes in walking parameters, which may reflect an increased allocation of attention to the obstacle crossing task, with no change or reduced focus on the cognitive task. Ultimately, this strategy may be advantageous for the complex task studied in this experiment, as an improvement in performance of the obstacle crossing task will reduce the risk of tripping and falling, whereas improvements to the auditory Stroop task will not improve safety of the individual.

The velOBS-2 and velOBS-1 results are different from Experiment II, as only the COMP group increased velocity on these steps at Visit 2, while in Experiment II both the CONTROL and WALKING groups were also able to increase velocity. One possible explanation may be that the altered laser gate placement from Experiment II to Experiment III (reduced reaction time of ~250 ms) may have created a more challenging scenario for the body, such that the time needed to integrate information about obstacle location could not be sped up on Visit 2 for the CONTROL and WALKING groups (Chen et al. 1996; Weerdesteyn et al. 2003). Conversely, given the task requirements for COMP training (to steer a car along a race course while rapidly adapting to the changing environment), it is possible this group was more efficient at quickly integrating
information about the environment (Casutt et al. 2014; Gopher et al. 1994; Green & Bavelier 2003) and implementing a strategy to move through it. For velOBS-xing, the above results are consistent with Experiment II for the WALKING group, which increased velocity at the OBS-xing step. Interestingly, the CONTROL group increased velocity at the velOBS-xing step, while this was not observed in Experiment II. It is not surprising that all three groups crossed the obstacle at an increased velocity on Visit 2, given that the approach steps are important for the integration and planning of a crossing strategy, while the crossing step executes the plan. Therefore, although the COMP group integrated and formed a plan more quickly on approach (increased velocity at velOBS-2 and velOBS-1), once all groups had formulated a plan, it was executed quicker than on Visit 1.

The present work provided evidence to indicate that both WALKING and COMP training protocols increased TOD, while CONTROL was only able to increase this distance in Experiment II. Similarly, as in Experiment II, the WALKING group increased MTC, while there was no change for the CONTROL or COMP group. The increased MTC for the WALKING group was interpreted as a more cautious obstacle crossing strategy (Chou & Draganich 1998; Heijnen et al. 2012; Patla & Greig 2006), while the more distally related method of training (performing a computer game while performing cognitive tasks simultaneously) was unable to have the same effect of inducing a cautious obstacle crossing strategy in participants. This effect may be due to the postural load (seated in front of a computer), which was quite different from the OBS+Stroop task (Lajoie et al. 1993). Therefore, the types of sensory information being integrated were different, and the gains from this type of training may be reduced (Basak et al. 2008;
Kramer et al. 1995). Interestingly, for Experiment III no alterations in the coefficient of variation were observed as compared to Experiment II for any of the spatial stepping measures (TOD, MLC, MTC and LD). It is likely that given the reduced time available to respond to the movement of the obstacle (due to the shortened available response time), participants were unable to employ a consistent stepping strategy on Visit 2 (Chen et al. 1996; Weerdesteyn et al. 2003). It is possible that with training the participants would have eventually reduced the coefficient of variation for these spatial measures.

These results again demonstrate (similarly to Experiment II) that the proximally related WALKING group produced improvements in performance of the postural task (i.e. more cautious and potentially safer stepping strategies) of the OBS+Stroop task, while a more distal training program (COMP) and no training (CONTROL) did not produce the same improvements.

4.6 General Discussion

These two experiments sought to gain a better understanding of dual-task training effects, and the possibility of proximal and/or distal transference to a complex dual-task test. In Experiment II, it was demonstrated that individuals trained in a proximally related concurrent walking and cognitive task improved performance on the OBS+Stroop task (following training, a more cautious and refined obstacle crossing strategy was observed). For Experiment III, the WALKING group again adopted a more cautious obstacle crossing strategy, while the CONTROL group demonstrated very modest or no changes in parameters. Interestingly, the COMP group showed the same general trends as WALKING, although not to the same magnitude of change. Overall, the results from
Experiment III, demonstrate that a paradigm with a similar postural load (WALKING) produced more advantageous training effects (i.e. a more consistent and cautious obstacle crossing strategy) than the more distal, computer based training program.

4.6.1 Possible Mechanisms for the Findings

The training of concurrent walking and cognitive tasks improved performance on the OBS+Stroop test, however the mechanism for such changes remains unclear. The obstacle crossing task was designed to allow for performance improvements in both tasks (e.g. tasks required different perception mechanisms and action responses, sufficient time was given for training) (Schumacher et al. 2001; Strobach et al. 2013). Therefore, improvements in both tasks were possible, and given the instructions to participants to not prioritize one task over the other, the observed results are an indication as to how the different training methods affected task integration for the OBS+Stroop test. Previous work has proposed that improved dual-task performance occurs at the perception and response selection stages of task performance, while few changes are seen in the motor response mechanism that actualizes the first two steps (Strobach et al. 2013). In this context, through practice, participants become quicker at perceiving and identifying relevant information from the environment (i.e. monitoring the position of the obstacle and hearing the Stroop cue), and matching the perceived stimuli to the appropriate response. It is possible that the training was simply improving the perception and response selection for specific tasks, and this contributed to the improved dual-task performance. However, although the trained tasks were similar to the OBS+Stroop test, it is unlikely that improvements in perception and response selection fully explain the
results. Recall that participants completed the training and testing sessions in different laboratory environments, thus, participants could not simply reproduce the same responses to stimuli that had been previously trained. Similar findings have been reported when training different types of cognitive tasks, where alterations to the perceived stimuli during follow-up testing do not remove performance improvements (Bherer et al. 2005; Kramer et al. 1995).

It is important to note that in the context of transfer of training, other researchers have found different results for single task training. Naumann et al. (2015) trained participants using two different devices (either the Nintendo Wii Fit Balance Board or the MFT Challenge Disc) three times a week for four weeks. Both devices require participants to modify avatars on a screen by shifting their body’s center of pressure on the device. Even though the devices accomplish this in quite different manners, both are designed to improve postural control. The participants were then tested on both devices following training, with the hypothesis that training on one device should transfer to improved performance on the other device. However, the researchers observed that participants only improved on the device on which they were trained, which is opposite to the results from the training program, which did demonstrate transfer effects for the WALKING training condition. These conflicting results may be traced back to the paradigm employed by Naumann et al. (2015), which provided participants with a strict set of instructions as to how to perform balance tasks on each device. This instructional set has been described previously as ‘fixed priority’ (Kramer et al. 1995). Conversely, the program did demonstrate transfer effects across tasks, potentially due to the nature of the instructions to participants during the training sessions. Participants in the experiments
were not instructed to prioritize one task over the other, which in turn allowed for more flexible allocation of attention to separate tasks, termed ‘variable priority’ training (Kramer et al. 1995). Past work by Silsupadol et al. (2009) compared fixed and variable priority training during dual-tasking in older adults. They discovered that only dual-task training with variable priority instructions retained training effects and saw significant improvements in performance on the postural task (Silsupadol et al. 2009).

One limitation of the study is the potential for ceiling performance effects with some of the tests. It is possible that some participants already possessed a high level of efficiency in the tasks (e.g. an obstacle crossing strategy which was already relatively safe and consistent, a range of 86.7 to 92.5% accuracy rate for the auditory Stroop task), and thus any training may have had little effect on improving performance. However, the experimental protocol attempted to account for this with the testing of challenging and unique tasks (Worden & Vallis 2014), which participants would not previously have had a high level of experience. Given that none of the measures were at the physiological or mechanical limits of the body system (i.e. no movement or cognitive performance measures were at the extremes of what the human body is capable of), improvements were possible for participants within any of the groups. Finally, the inability to ensure homogeneity between the baseline performances of all groups on Visit 1 is a potential limitation. Across the wide range of tested variables, there were baseline differences on performance between some of the tasks. However, due to the wide range of outcome measures calculated for Experiments II & III, it was not possible to have matching means for all conditions for all groups. This is likely not a major limitation, as for each participant, the statistical analysis measured changes to initial performance induced by
training. For both Experiments, on Visit 1 there was always some baseline perception of the tasks for each participant, and they executed their performance based on this initial perception and response selection. Participants then experienced either a training program or no training, and the analysis examined how training affected their initial performance on subsequent testing sessions. Furthermore, the research questions and within-subjects statistical design looked for changes within groups, and were never conducted to examine differences across groups.

4.7 Conclusion

In conclusion, training with a proximally related walking task induced a more cautious and consistent obstacle crossing strategy when navigating the complex OBS+Stroop environment. Training with a more distally related computer game, or no training at all was not able to reliably produce the same training effects during obstacle crossing in a complex dual-task environment. Future work should examine a WALKING training protocol in special populations known to struggle with dual-task integration as a possible intervention.

4.7.1 Acknowledgements

The authors would like to acknowledge funding for this work provided by NSERC (LAV) and the Ontario Graduate Scholarship program (TAW). We would like to thank the participants from the University of Guelph student community, all of the laboratory research assistants, and Dr. Allan Adkin and Dr. Naseem Al-Aidroos for their input and advice on experimental design and analyses.
Chapter 5 Experiment IV: Dual-task training effects on a concurrent auditory Stroop and obstacle avoidance task in community dwelling older adults

(In Preparation for Gait & Posture)

5.1 Abstract

Performing a concurrent cognitive task while simultaneously completing a postural task has previously been shown to induce movement errors in older adults. Training programs to alter dual-task performance have demonstrated promising results in relatively simple dual-task tests, however limited work has explored more complex dual-task situations in older adults. The purpose of this study was to examine the ability of a dual-task training protocol to affect a change in the performance of a concurrent motor (obstacle avoidance) and cognitive (auditory Stroop test) dual-task test. Six community-dwelling older adults (72.5 ± 3.21 years) completed two dual-task test sessions (baseline and follow up), separated by three weeks of dual-task training. Dual-task training was conducted twice a week for 30 minutes, and involved continuous unobstructed walking while performing different simultaneous cognitive tasks (e.g. backwards counting). Following training, the older adults improved accuracy but responded more slowly to the auditory Stroop task. For obstacle crossing, participants reduced their walking velocity during approach to the obstacle and while crossing, however no changes to obstacle foot clearances were observed for either the leading or trailing foot. In general, results from this study indicate that dual-task training altered performance of both the cognitive and locomotor tasks. Furthermore, the reduced walking velocity may be a cautious
adaptation, allowing participants more time to implement a successful obstacle stepping strategy.

5.2 Introduction

The simultaneous performance of two tasks is common in everyday environments, and often leads to decrements in the outcome of one or both tasks (Ebersbach et al. 1995; Lajoie et al. 1993; Shumway-Cook et al. 1997). Executing a dual-task can challenge the central nervous system’s ability to correctly attend to and integrate information, resulting in errors that can be relatively minor (e.g. incorrectly identifying a visual cue) to major in consequence (e.g. distracted driving, tripping) (Consiglio et al. 2003; Makizako et al. 2010; Shumway-Cook et al. 1997; Strobach et al. 2013). Furthermore for a variety of reasons, including reduced sensorimotor and cognitive capabilities (Anguera et al. 2013; Hegeman et al. 2012; Menant et al. 2010; Nagamatsu et al. 2011; Pijnappels et al. 2008; Speers et al. 2002), older adults are known to demonstrate greater reductions in dual-task performance as compared to young adults (Bock et al. 2011; Hegeman et al. 2012; Lindenberger et al. 2000; Schaefer et al. 2015). Thus the ability of training programs to effect change in the dual-tasking performance of older adults, especially in dynamic and challenging tasks that reflect real-world activities, is an important area of study.

Previous work has demonstrated improvements to dual-task performance following training in older adults during the performance of relatively simple choice reaction time tasks (Anguera et al. 2013; Basak et al. 2008; Bherer et al. 2005). In the biomechanics literature, researchers have designed dual-task training protocols to
improve dual-tasking performance during whole body movements (Silsupadol et al. 2009; Theill et al. 2013; Trombetti et al. 2011). For example, Silsupadol et al. (2009) designed a training program to improve performance on a concurrent walking and mental arithmetic task in older adults. The researchers observed that dual-task training led to performance improvements, such as increased walking velocity. Although the previous work on dual-task training has demonstrated promising results, the application to everyday life can be questioned. Ecological environments are complex, comprising many dynamic factors that require constant attention and the updating of on-going locomotor strategies for successful navigation (Hollands & Marple-Horvat 2001; Warren et al. 1986; Wellmon et al. 2013). To better understand dual-task effects in complex environments, researchers have used dynamic obstacles (which require constant monitoring and rapid updating of walking patterns) during the concurrent performance of cognitive tasks (Chen et al. 1996; Hegeman et al. 2012; Weerdesteyn et al. 2003, Weerdesteyn et al. 2005; Worden & Vallis 2014). Such paradigms have been shown to be more difficult than unobstructed walking, and pose a useful model for challenging attentional control in older adults (Caetano et al. 2016; Hegeman et al. 2012; Weerdesteyn et al. 2005).

To determine optimal training modalities in complex environments, Worden & Vallis (submitted; Journal of Motor Behavior MS #35-16-068-RA) tested performance of a concurrent dynamic obstacle and auditory Stroop task before and after dual-task training in young adults. Following training, study participants were observed to adopt a more ‘cautious’ obstacle crossing strategy (as indicated by larger minimum trail foot clearance values), however changes to the cognitive test performance were not consistently observed. It was proposed that the training protocol may have influenced the
allocation of attention, such that participants attended more to the obstacle crossing task, increasing minimum trail foot clearance to reduce the postural threat of the task (Heijnen et al. 2012; Patla et al. 1991; Rietdyk et al. 2005). If this interpretation of the data is correct, this may be a reasonable and useful training strategy for older adults to adopt in order to reduce the risk of tripping given the high number of reported tripping incidences for older adults trips in everyday and laboratory environments (Lord et al. 1993; Hegeman et al. 2012; Weerdesteyn et al. 2005).

The purpose of the current work was to determine if a training protocol similar to that previously used with young adults could affect similar change in healthy community dwelling older adults (≥65 years). It was hypothesized that similar to young adults, older adults would prioritize obstacle crossing performance, adopting a more cautious strategy that would reduce the risk of tripping (Mohagheghi et al. 2004; Patla et al. 1991; Rietdyk et al. 2005). Conversely, due to the increased attention required for the obstacle crossing task, improvements within the auditory Stroop task performance were not expected (Siu et al. 2008; Worden & Vallis 2014). This work is important as it furthers the understanding of dual-task integration, and the allocation of attention within complex environments.

5.3 Methods

Twenty community dwelling older adults (≥ 65 years) were recruited through flyers, word of mouth and announcements at local events. Through a telephone/email interview process interested individuals were screened for study inclusion. The inclusion criteria included: living independently in the community, being able to walk the
equivalent of one city block unassisted and the ability to step over small objects. The exclusion criteria included: uncorrected hearing or visual impairments, any neurologic, musculoskeletal cardiovascular impairment, or medications that would affect the safe performance of either training or testing sessions. Of the twenty older adults evaluated for potential enrollment, 4 people did not meet the inclusion criteria. Of the sixteen eligible to participate, six declined, and four dropped out (due to time commitment issues). Therefore, six older adults participated in the experiment (72.5 ± 3.21 years; 4 Females).

5.3.1 Testing Sessions

Dual-task performance was tested using a concurrent obstacle crossing and auditory Stroop task (OBS+AST), as previously described (Worden & Vallis, submitted Journal of Motor Behavior). Briefly, the auditory Stroop task (AST) cue was produced the step before the participant stepped over the obstacle using a custom Labview program (Version 10.0, National Instruments, Austin, USA). For the AST, lab speakers mounted next to the walkway produced the words ‘high’ or ‘low’ in a high or a low pitch. Participants were instructed to: ‘Identify the pitch of the word said as quickly and accurately as possible’. Half of the trials produced were congruent (pitch of the word matched the word said) and the other half were incongruent. Response accuracy for the AST was recorded manually, and a custom analog microphone (4000 Hz) recorded the onset of the participant’s response.

Concurrently, participants walked along a 7 m walkway and stepped over a dynamic obstacle located midway on the walkway with their dominant foot first (Elias et al. 1998). A laser gate was placed 2 leg lengths (as defined as the distance from the
greater trochanter to the ground for each participant) ahead of the obstacle; interruption of the laser beam triggered motion of the obstacle in dynamic trials as well as the speakers to produce the AST. For ‘dynamic trials’, the obstacle would move from a low (16 cm lower than the high position) to high position (50 % of lower leg length; 20.4 ± 1.04 cm) on approach. Participants were instructed to ‘Maintain your normal walking speed while safely stepping over the obstacle’. For dual-task trials, the same instructions for each task as above were repeated with the added stipulation: ‘Perform both tasks at the same time with equal importance, try not to prioritize one task over the other’.

Kinematic data were collected (100 Hz) using an optoelectric camera system (Optotrak 3020 NDI, Waterloo, Canada). Non-collinear rigid triads of infrared emitting diodes were affixed to the head, trunk, pelvis and left and right feet, and anatomical points were digitized relative to the rigid bodies (Winter 2005). A total of 40 randomized dual-task trials were completed on both Visit 1 and Visit 2.

5.3.2 Training Sessions

Participants trained for 30 minutes each session, twice a week for three weeks (total of 3 hours of time trained). A three week training protocol was chosen as previous work (Worden & Vallis, submitted Journal of Motor Behavior) had demonstrated positive training effects using a similar training protocol over the same duration in young adults. Training sessions took place in a different location than testing sessions, and were completed one-on-one with a researcher. Training involved continuous walking while navigating obstacles placed on the floor (e.g. turning around chairs) and concurrently performing different cognitive tasks. This training protocol had previously been validated.
to show improvements in dual-task obstacle crossing performance in young adults (Worden & Vallis, submitted *Journal of Motor Behavior*). The three cognitive tasks performed concurrently were: i) backwards counting, ii) auditory Stroop task (with different voices than the testing sessions) and iii) an N-back test. During testing, participants received real-time feedback on their cognitive task performance from the researcher.

5.3.3 Data Analyses

All data analyses were performed using Visual3D analysis software (C-Motion, Germantown, USA). Auditory response time data collected from the microphone were bandpass filtered (700-1400 Hz $f_{\text{cutoff}}$) using a dual-pass second order Butterworth filter. Microphone data was then rectified, and low pass filtered (10 Hz $f_{\text{cutoff}}$). The participant’s response was then defined as the point at which the microphone voltage deviated from ‘silence’ by greater than two standard deviations. The time at which the speaker produced the AST was previously known, thus Response Time was defined as the difference in time between the speaker producing the AST and the participant’s response. Kinematic data were interpolated and low-pass filtered using a dual-pass Butterworth filter (10 Hz $f_{\text{cutoff}}$). Participant velocity (velocity of the upper body center of mass head trunk and pelvis segments; Winter 2005) was calculated at heel contact two steps before (velOBS-2), one step before (velOBS-1) and at obstacle crossing (velOBS-xing). The minimum vertical distance between the foot and obstacle was calculated for both the leading (MLC) and trailing foot (MTC). Takeoff distance (TOD; horizontal distance from the first
metatarsal to the obstacle) and landing distance (LD; horizontal distance from the heel to the obstacle) were also calculated.

5.3.4 Statistical Analyses

All statistical analyses were performed in SPSS Version 23 (IBM, Armonck, USA) with significance level set as $p<0.05$. Accuracy analyses for the auditory Stroop task were conducted using a univariate repeated measure ANOVA (Congruency x Obstacle Position). For all of the following data analyses, statistical tests were only performed on those trials where participants were able to correctly perform both tasks in the test (e.g. correctly identifying the AST and no contact with the obstacle). A univariate repeated measures ANOVA (Congruency x Obstacle Position) was performed on Stroop task response time (dependent variable). For kinematic outcome measures, two separate repeated measure MANOVAs (Congruency x Obstacle Position with Visit as the repeated measure) were conducted on the following dependent variables: i) the three step velocity measures, and ii) spatial kinematic measures (clearances, takeoff and landing distances). For any multivariate interactions, univariate ANOVAs were conducted to further probe these effects. For all outcome measures, outlying trials (trials greater than 2.5 standard deviations outside of the calculated participant’s mean for a given trial condition) were removed. This step was taken to more accurately reflect the true mean of a participant’s measures for the statistical analyses, as unaccounted for outliers would influence the normality of the data.
5.4 Results

All participants were able to successfully complete the dynamic obstacle and auditory Stroop test (> 60 % accuracy). Due to camera volume error, data was incomplete for MTC for one participant and TOD for one participant, thus this data could not be included in subsequent analyses. No interactions were detected, so only main effects will be presented here; all data are reported as means ± standard error (SEM). The obstacle was contacted once (during Visit 1) by one female participant.

5.4.1 Auditory Stroop Task

A main effect of Visit was detected for Response Accuracy ($F_{(1,20)}=5.993$, p=0.024), with participants being more accurate on Visit 2 as compared to Visit 1 (Figure 5.1.A). Furthermore, a main effect of Congruency on Response Accuracy was observed ($F_{(1,20)}=9.757$, p=0.005), with participants being more accurate at identifying the congruent as compared to incongruent cues (Figure 5.1.A). When examining Response Time, participants were slower identifying the auditory Stroop task on Visit 2 as compared to Visit 1 ($F_{(1,20)}=38.605$, p<0.0001; Figure 5.1.B). Similar to Response Accuracy, a main effect of Congruency was observed for Response Time ($F_{(1,20)}=6.595$, p=0.018), with participants slower at identifying an incongruent cue as compared to a congruent cue (Figure 5.1.B).
Figure 5.1. Panel A) illustrates Stroop task Response Accuracy. Participants became more accurate on Visit 2 as compared to Visit 1. Furthermore, participants were more accurate at identifying the Congruent Stroop cue as compared to the Incongruent Stroop cue. Panel B) displays Response Time data for the auditory Stroop task. Participants responded more slowly to the cue on Visit 2 as compared to Visit 1. Also, Participants responded more slowly to the Incongruent cue as compared to the Congruent Stroop cue (* indicates p<0.05).
5.4.2 Velocity Measures

Velocity means ± standard error for velOBS-2, velOBS-1, and vel OBS-xing are presented in Figure 5.2. A main effect of Visit was detected for velOBS-2 ($F_{(1,20)} = 5.883, p=0.025$), velOBS-1 ($F_{(1,20)} = 9.682, p=0.005$), and velOBS-xing ($F_{(1,20)} = 25.249, p<0.0001$), with participants reducing velocity at all three steps from Visit 1 to Visit 2.
Figure 5.2. Walking velocity at two steps before the obstacle (velOBS-2), one step before the obstacle (velOBS-1) and at obstacle crossing (velOBS-xing) for Visit 1 and Visit 2. At all three steps, participants walked significantly slower on Visit 2 as compared to Visit 1 (* indicates p<0.05)).
5.4.3 Distance Measures

A main effect of Visit was observed for LD ($F_{(1,14)} = 5.249$, $p=0.038$), with participants placing their lead foot closer to the edge of obstacle on Visit 2 as compared to Visit 1 (Table 5.1). No main effects were observed for either MLC, MTC or TOD (see Table 5.1).
Table 5.1. Kinematic spatial measure results; mean ± standard error values for minimum lead foot clearance (MLC), for minimum trail foot clearance (MTC), take off distance (TOD) and landing distance (LD). All data presented are from trials where participants successfully crossed the obstacle and accurately identified the auditory Stroop task. A main effect of Visit was observed for just LD; participants placing their lead foot closer to the edge of obstacle on Visit 2 as compared to Visit 1.

<table>
<thead>
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<th>Visit 2</th>
<th>p-value</th>
</tr>
</thead>
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<tr>
<td>MLC (m)</td>
<td>0.154 ± 0.013</td>
<td>0.148 ± 0.020</td>
<td>p=0.057</td>
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<tr>
<td>MTC (m)</td>
<td>0.200 ± 0.025</td>
<td>0.201 ± 0.030</td>
<td>p=0.299</td>
</tr>
<tr>
<td>TOD (m)</td>
<td>0.301 ± 0.033</td>
<td>0.322 ± 0.024</td>
<td>p=0.282</td>
</tr>
<tr>
<td>LD (m)</td>
<td>0.215 ± 0.039</td>
<td>0.199 ± 0.035</td>
<td>*p=0.038</td>
</tr>
</tbody>
</table>
5.5 Discussion

The aim of this work was to determine if a training protocol developed with young adults would evoke similar improvements when performing a dual task (OBS + AST) in older adults with the goal of encouraging these older individuals to adopt safe movement strategies. Contrary to the previously stated hypothesis, the same adaptation post-training (i.e. increased foot clearance values) that was previously observed in younger adults was not detected in older adults (Worden & Vallis, submitted Journal of Motor Behavior). Instead, the older adult participants walked at a slower velocity and altered their performance on the AST.

Worden & Vallis (submitted Journal of Motor Behavior) used a similar dual-task training program that resulted in increased MTC and TOD in young adults. The observed adjustments to obstacle stepping behavior in this earlier work was interpreted as an advantageous strategy, as it is generally accepted in the literature that ~90% of obstacle trips are caused by the trailing foot not elevating sufficiently and contacting the obstacle (Heijnen et al. 2012; Mohagheghi et al. 2004; Patla et al. 1991; Rietdyk et al. 2005). It is interesting to note that in the current paradigm, the same training program did not have this effect in older adult participants. Instead, older adults maintained similar obstacle clearance values following completion of the training protocol. Given the high minimum trail foot clearance values observed for older adults (~33% greater than young adults), it is possible that this population inherently recognized the increased risk of tripping with the trailing foot, and choose to implement a default strategy to clear the obstacle by a larger margin. In choosing this default strategy, the older adults were able to set a very large margin of error for the trailing foot in relation to the obstacle, which could in turn
minimize the risk of an obstacle contact (Heijnen et al. 2012; Mohagheghi et al. 2004; Patla et al. 1991; Rietdyk et al. 2005). It is also possible that the observed obstacle clearance values on Visit 1 represented an upper threshold of what was possible for older adults to perform, given the reduced strength and slower perturbation responses typically observed in older adults (Schillings et al. 2005; Pijnappels et al. 2008). Thus, it may not have been possible for the older adult participants to safely increase clearance values further. It is also possible that lifting the foot higher over the obstacle may be potentially more destabilizing as more time must be spent in single support (Pan et al. 2016; Worden & Vallis 2016), which would impose a significant challenge to balance control for many older adults (Pan et al. 2016). In single support, the base of support is reduced for a longer period of time while the swing leg is in the air which may compromise an older adult’s ability to respond quickly and effectively if a correction to foot placement must be made rapidly (Schillings et al. 2005; Pan et al. 2016; Pijnappels et al. 2008).

Although no significant changes were noted in clearance values (e.g. MTC), older adults walked with a slower velocity on Visit 2, which may in turn be a safer strategy than what was observed on Visit 1. Past work has demonstrated that obstacle contact rates are increased as the available response time to alter obstacle stepping strategies decreases (Chen et al. 1996; Hegeman et al. 2012; Weerdesteyn 2005). Therefore, by slowing walking velocity, participants increased the time taken to reach the obstacle’s position, which subsequently allowed more time for a successful crossing strategy to be chosen. Other dual-task training studies in older adults typically report increases to walking velocity during dual-tasking as a performance improvement (Azadian et al. 2016; Lim et al. 2016; Plummer et al. 2012; Silsupadol et al. 2009). However, in this
paradigm, an increase in walking velocity may be considered a riskier strategy, as less
time would be available to react to the changing obstacle location and implement any
changes to their ongoing stepping strategy accordingly (Chen et al. 1996; Hegeman et al.
2012; Weerdesteyn 2005). Furthermore, previous work has demonstrated that in tasks
which are more posturally threatening (e.g. dynamic obstacle crossing), participants
prioritize performance of the postural task, ensuring that postural stability is maintained
(Bohm et al. 2012; Brown et al. 1999; Mersmann et al. 2013; Shumway-Cook et al.
1997). This highlights that training adaptations are likely dependent on the constraints of
the dual-task test, and must be considered in context with the tasks being examined.

Contrary to dual-task training in young adults (Worden & Vallis, submitted
*Journal of Motor Behavior*), older adults demonstrated significant changes in both
Response Accuracy and Response Time following training. The improved accuracy may
be the result of a ‘trade-off’, as response time was significantly greater on Visit 2 as
compared to Visit 1. This means that although participants became more accurate, they
were also slower to respond to the cue, perhaps allowing for more time to match the
correct response to the stimuli (Forster et al. 2003; Schouten & Bekker 1967; Wickelgren
et al. 1977). It is also possible that participants were prioritizing the obstacle avoidance
task, at the expense of a slower response to the Stroop test. Ultimately, delaying a verbal
identification of the cue may be an advantageous strategy for an older adult, as it would
allow participants to first prioritize attention to implementing an obstacle crossing
strategy, and then switching focus to the AST (Brown et al. 1999). Given that older adults
are known to struggle with task integration (Anguera et al. 2013; Nagamatsu et al. 2011),
implementing such a strategy may also be a safer strategy in a laboratory setting, but may
not be possible in some real world environments. (Lord et al. 1993; Makizako et al. 2010).

Although this study provides interesting insight into possible training adaptations to the performance of the OBS + AST task, there are limitations which must be acknowledged. Firstly, without a control group that was not trained, it is not possible to rule out the training effects were simply due to being exposed to the dual-task test a second time. However, past work with older adults has demonstrated that in simpler tasks, dual-task training is needed to alter performance, and repeat exposure effects do not typically alter performance on the dual-task test (Li et al. 2010; Silsupadol et al. 2009). Furthermore, although the sample size was in line with previous studies (N=6) (Silsupadol et al. 2009; Worden & Vallis 2014), the results may not be representative of a larger population. Finally, a limitation with all dual-task studies is being unable to confirm that participants interpret instructions as the researchers intend. Although participants were instructed to give both tasks equal attention, participants may have intrinsically prioritized one task over the other, which has been demonstrated to alter observed results (Kelly et al. 2010; Kelly et al. 2013; Siu et al. 2007; Yogev-Seligmann et al. 2010).

In conclusion, dual-task training had different effects on the older adult participants as compared to the previous work with young adults. The results highlight that training effects may be different across the lifespan, depending on the capabilities of individuals being observed and the tasks tested. Future work should examine longer duration training programs, to determine if participants will continue adapting over time.
5.5.1 Acknowledgements

The authors would like to acknowledge funding for this work provided by NSERC (LAV) and the Ontario Graduate Scholarship program (TAW). We would like to thank the older adult participants from the City of Guelph community, all of the laboratory research assistants, and Dr. Allan Adkin and Dr. Naseem Al-Aidroos for their input and advice on experimental design and analyses.
Chapter 6 General Discussion

6.1 General Findings

The primary goal of this thesis was to gain increased understanding regarding the efficacy of dual-task training programs to alter performance during the concurrent execution of a cognitive task and an obstacle crossing task. Better understanding the effectiveness of such programs will make important contributions to many training programs already employed to improve dual-tasking ability in older adults (Azadian et al. 2016; Plummer-D’Amato et al. 2012; Wollesen et al. 2015). In order to answer this question, a testing paradigm was first designed using a cognitive task paired with a postural task. Previous work in our lab (Worden & Vallis 2014), as well as other research groups had used an obstacle crossing task as the postural task, which allowed for a discrete locomotor event to be analyzed (Chen et al. 1996; Hegeman et al. 2012; Weerdesteyn et al. 2003). For the cognitive task, different research groups have used numerous different tasks, which vary in the presence (Bock et al. 2011 Chen et al. 1996; Perrochon et al. 2013; Siu & Woollacott 2007) or absence of structural interference (Ebersbach et al. 1995; Weerdesteyn et al. 2003; Worden & Vallis 2016)). Thus, Experiment I sought to better understand the effect that structural interference in addition to central interference (visual Stroop task) would have on obstacle crossing performance as compared to interference at only the central response-selection stage (auditory Stroop task). Results from Experiment I indicated that the visual Stroop task had a larger effect on obstacle crossing strategies, with participants elevating their feet significantly higher over the obstacle as compared to the auditory Stroop task. As well, the auditory Stroop
task was a more challenging cognitive task for participants, as indicated by slower and less accurate cognitive responses during both seated and obstacle crossing conditions.

Thus, Experiment I established that performance of a concurrent auditory Stroop task and obstacle-crossing task could be performed without major alterations to obstacle crossing strategies, as compared to the large effects observed with structural interference (Kahneman & Chajczyck 1983; Worden & Vallis 2016). This was important, as the subsequent experiments sought to test the ability of participants to alter stepping strategies that were relatively similar to single-task walking, which would better reflect walking strategies observed in everyday environments. In Experiment II, the strategies utilized to clear an obstacle while concurrently performing an auditory Stroop task in young adults were characterized. Specifically, the alterations to obstacle crossing strategies following the performance of a dual-task training protocol (training involved simultaneous unobstructed walking and cognitive tasks). Training was either one or four weeks in duration, and in general, trained individuals were observed to increased minimum trail foot clearance values and reduced clearance variability, indicating a more cautious obstacle crossing strategy (Mohagheghi et al. 2004; Patla et al. 1991). Furthermore, following five weeks of no training, the effects observed on Visit 2 were largely retained, indicating young adults may preserve obstacle crossing alterations following the cessation of training.

To examine the generalizability of dual-task training, Experiment III was designed to determine if a less similar training protocol (seated practice using a computer based race car game) could affect similar alterations in dual-task performance as a walking based training protocol (Bherer et al. 2005; Kamer et al. 1995). The race car
computer game based training protocol did not affect change in stepping strategies to the same extent observed following the walking based training protocol. This finding suggests that dual-task training effects are not transferable to a wide range of tasks, and must be somewhat related to the situations in which dual-task performance will be tested (Basak et al. 2008; Pellecchia et al. 2005). Finally, the walking based training program was applied to an older adult population in Experiment IV with the goal of examining the training protocol in a population known to show larger dual-task performance decrements (Anguera et al. 2013; Bherer et al. 2005; Lindenberger et al. 2000; Schaefer et al. 2015) Dual-task training was observed to alter the obstacle crossing performance of older adults, with reduced walking velocity (as compared to the increase in trail foot clearance observed in young adults). Furthermore, and in contrast to the hypothesis, older adults showed alterations to the cognitive task performance, with an increase in accuracy responding to the auditory Stoop task, although with slower response times.

6.1.1 Care must be taken when choosing a cognitive task to pair with a postural task

As identified in Section 2.3 of the Literature Review, a wide range of cognitive tasks have been employed to understand the attentional requirements of the postural tasks, resulting in dual-task interference (Ebersbach et al. 1995; Lajoie et al. 1993; Lindenberger et al. 2000; Worden & Vallis 2014). Within the literature, a spectrum of dual-task effects have been observed, ranging from little effect (Ebersbach et al. 1995; Marone et al. 2014), to only affecting one of the tasks (Bohm et al. 2012; Siu et al. 2008)) to major effects on both tasks (Weerdesteyn et al. 2003; Hegeman et al. 2012). One of the main reasons for the wide range of observed effects is likely due to the presence or
absence of structural interference (Kahneman & Chajczyck 1983). In addition to interfering at the central response selection stages, these tasks also interfere at the perceptual stages, which likely confound the control strategies used by participants and subsequently altered measured study outcomes (Kahneman & Chajczyck 1983). Although some research groups have acknowledged the (likely) confounding effects of structural interference, the first experiment (Section 3) was the first, to our knowledge, that directly compared two tasks that involved similar central response selection and response stage processes, but were varied at the perceptual stage (to induce or remove structural interference: Kahneman & Chajczyck 1983; MacLeod 1991).

When examining the effect the two Stroop tasks had on obstacle crossing strategy, differences in dual task costs were observed when comparing the auditory and visual Stroop tasks. Not surprisingly, when the visual system was required to attend to stimuli in two different locations (the computer monitor and obstacle), the participants demonstrated significant alterations to their walking strategies as compared to single task obstacle crossing (Bock et al. 2011; Chen et al. 1996; Perrochon et al. 2013). This was observed as larger obstacle clearance values, indicating a more cautious strategy to perform the task (Mohagheghi et al. 2004; Patla et al. 1991). Conversely, the auditory Stroop task did not greatly alter stepping strategies from single-task walking. The results highlight that the presence of structural interference does in fact have a significant effect on obstacle crossing strategy in young adults, where participants likely increase the margin of safety between the foot and the obstacle to compensate for less reliable and sporadic visual information (Patla 1998; Timmis & Buckley 2012). The results bring into question many of the peer-reviewed research articles examining dual-task interference
Many of these studies employed a cognitive task which induces structural interference (typically with the visual system having to attend to different locations to complete each task). These studies have been designed to better understand the central interference effects caused by completing a dual-task, but the interference also arises at the perceptual stage, which likely has an effect on results (Kahneman & Chajczyck 1983; Siu et al. 2008). Therefore, results from these studies should be interpreted with caution, as the observed dual-task interference effects are not purely due to interference at central processing stages (Kahneman & Chajczyck 1983; Siu et al. 2008).

6.1.2 Proximal training alters dual-task performance in complex environments

A primary aim of the work in this Dissertation was to better understand the feasibility and effectiveness of dual-task training to effect change in a challenging dual-task test. As highlighted previously, dual-tasking imposes a challenging situation on the central processing areas, as it requires the integration of information from multiple sources, and the output of two different responses (locomotor and verbalization of a cognitive response: Chen et al. 1996; Hegeman et al. 2012; Weerdesteyn et al. 2003). Ineffectiveness to perform tasks simultaneously is linked to many adverse events (Makizako et al. 2010; Muhaidat et al. 2013; Weerdesteyn et al. 2003), and therefore a better understanding of the integration, and possible improvements through training is necessary (Li et al. 2010; Silsupadol et al. 2009).
6.1.2.1 Dual-task training causes changes to spatial measures of obstacle crossing in young adults

Obstacle crossing is inherently a difficult task, requiring the perception of characteristics of an obstacle (Patla et al. 1996; Rietdyk & Rhea 2011; Worden et al. 2016), and using feedforward and online planning strategies to safely and efficiently adapt typical walking movement patterns to safely step over an obstacle (Patla et al. 1991; Patla & Prentice 1995). To add to the challenge, obstacles that rapidly appear in the travel path or change height upon approach reduce the time available to alter stepping strategies, further complicating the implementation of a successful strategy (Patla et al. 1991; Weerdesteyn et al. 2005). Finally, the addition of a concurrent cognitive task further challenges walking and obstacle crossing performance, as attention must now be allocated between two challenging tasks (Chen et al. 1996; Weerdesteyn et al. 2003). Given all of the factors that affect obstacle crossing, it is not surprising that a range of different results have been presented related to the design of the obstacle and populations tested (Chen et al. 1996; Perrochon et al. 2013; Siu et al. 2008; Weerdesteyn et al. 2003; Worden & Vallis 2014).

In healthy young adults, the walking and cognitive task training program produced similar alterations to spatial stepping strategies regardless of the duration of training (see Table 6.1 for a summary table of results from Experiments II & III). In the above chapter (Section 4), the results highlighted changes to both walking velocity and obstacle crossing strategies in young adults. Perhaps the most interesting findings were the alterations observed to minimum trail foot clearance values, which were increased from Visit 1 (baseline) in all durations of dual-task walking training. This indicated a
more cautious strategy, as the foot was lifted higher over the top of the obstacle, thereby increasing the safety margin for the foot in relation to the obstacle, effectively reducing the likelihood of contacting the obstacle (Heijnen et al. 2012; Mohagheghi et al. 2004; Patla et al. 1991; Patla & Prentice 1995; Rietdyk et al. 2005). Whenever an individual encounters an obstacle, an adaptive movement pattern must be implemented to avoid or step over the obstacle (Patla et al. 1991; Warren et al. 2001). Within the observed strategies, there is a balance that must be struck between choosing an ‘economical’ strategy with respect to energy consumption (deviating as little as possible from the original movement strategy) and a ‘cautious’ strategy (selecting a strategy which reduces the risk of injury) (Patla et al. 1991; Warren et al. 2001).
Table 6.1 Summary of walking dual-task training results for the OBS+Stroop dual-task test. Data are presented for young adults from the: ONE week training group (YA One, Experiment II), FOUR week training group (YA Four, Experiment II), THREE week training group (YA Three, Experiment III), as well as the three week training group in older adults (OA Three, Experiment IV). Visit 1 represents the baseline performance of participants on the OBS+Stroop task, whereas Visit 2 represents the performance on the OBS+Stroop task following training. All data presented are mean ± standard error values, where different letters within each training group denote differences between Visits (p < 0.05). Data presented are collapsed across Congruency and Obstacle Position (dynamic vs stationary).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group</th>
<th>Visit 1</th>
<th>Visit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>velOBS-2 (m/s)</td>
<td>YA One</td>
<td>$1.21 \pm 0.04^a$</td>
<td>$1.26 \pm 0.044^b$</td>
</tr>
<tr>
<td></td>
<td>YA Four</td>
<td>$1.23 \pm 0.04^a$</td>
<td>$1.29 \pm 0.044^b$</td>
</tr>
<tr>
<td></td>
<td>YA Three</td>
<td>$1.20 \pm 0.03^a$</td>
<td>$1.22 \pm 0.03^e$</td>
</tr>
<tr>
<td></td>
<td>OA Three</td>
<td>$1.21 \pm 0.08^a$</td>
<td>$1.17 \pm 0.06^c$</td>
</tr>
<tr>
<td>velOBS-1 (m/s)</td>
<td>YA One</td>
<td>$1.18 \pm 0.04^a$</td>
<td>$1.24 \pm 0.045^b$</td>
</tr>
<tr>
<td></td>
<td>YA Four</td>
<td>$1.20 \pm 0.04^a$</td>
<td>$1.26 \pm 0.044^b$</td>
</tr>
<tr>
<td></td>
<td>YA Three</td>
<td>$1.19 \pm 0.03^a$</td>
<td>$1.20 \pm 0.04^d$</td>
</tr>
<tr>
<td></td>
<td>OA Three</td>
<td>$1.17 \pm 0.08^a$</td>
<td>$1.09 \pm 0.06^c$</td>
</tr>
<tr>
<td>velOBS-xing (m/s)</td>
<td>YA One</td>
<td>$1.11 \pm 0.05^a$</td>
<td>$1.15 \pm 0.046^b$</td>
</tr>
<tr>
<td></td>
<td>YA Four</td>
<td>$1.09 \pm 0.04^a$</td>
<td>$1.14 \pm 0.052^b$</td>
</tr>
<tr>
<td></td>
<td>YA Three</td>
<td>$1.10 \pm 0.03^a$</td>
<td>$1.11 \pm 0.04^d$</td>
</tr>
<tr>
<td></td>
<td>OA Three</td>
<td>$0.97 \pm 0.13^a$</td>
<td>$0.86 \pm 0.10^b$</td>
</tr>
<tr>
<td>MLC (m)</td>
<td>YA One</td>
<td>$0.10 \pm 0.01^a$</td>
<td>$0.10 \pm 0.01^a$</td>
</tr>
<tr>
<td></td>
<td>YA Four</td>
<td>$0.10 \pm 0.01^a$</td>
<td>$0.10 \pm 0.01^a$</td>
</tr>
<tr>
<td></td>
<td>YA Three</td>
<td>$0.10 \pm 0.01^a$</td>
<td>$0.09 \pm 0.01^a$</td>
</tr>
<tr>
<td></td>
<td>OA Three</td>
<td>$0.15 \pm 0.01^a$</td>
<td>$0.15 \pm 0.02^a$</td>
</tr>
<tr>
<td>MTC (m)</td>
<td>YA One</td>
<td>$0.14 \pm 0.02^a$</td>
<td>$0.15 \pm 0.02^a$</td>
</tr>
<tr>
<td></td>
<td>YA Four</td>
<td>$0.12 \pm 0.02^a$</td>
<td>$0.14 \pm 0.02^b$</td>
</tr>
<tr>
<td></td>
<td>YA Three</td>
<td>$0.12 \pm 0.02^a$</td>
<td>$0.15 \pm 0.02^a$</td>
</tr>
<tr>
<td></td>
<td>OA Three</td>
<td>$0.20 \pm 0.03^a$</td>
<td>$0.20 \pm 0.03^b$</td>
</tr>
<tr>
<td>TOD (m)</td>
<td>YA One</td>
<td>$0.26 \pm 0.02^a$</td>
<td>$0.29 \pm 0.02^a$</td>
</tr>
<tr>
<td></td>
<td>YA Four</td>
<td>$0.28 \pm 0.02^a$</td>
<td>$0.32 \pm 0.01^a$</td>
</tr>
<tr>
<td></td>
<td>YA Three</td>
<td>$0.24 \pm 0.03^a$</td>
<td>$0.29 \pm 0.03^a$</td>
</tr>
<tr>
<td></td>
<td>OA Three</td>
<td>$0.30 \pm 0.033^a$</td>
<td>$0.32 \pm 0.024^a$</td>
</tr>
<tr>
<td>LD (m)</td>
<td>YA One</td>
<td>$0.23 \pm 0.01^a$</td>
<td>$0.22 \pm 0.019^a$</td>
</tr>
<tr>
<td></td>
<td>YA Four</td>
<td>$0.22 \pm 0.02^a$</td>
<td>$0.21 \pm 0.014^b$</td>
</tr>
<tr>
<td></td>
<td>YA Three</td>
<td>$0.25 \pm 0.02^a$</td>
<td>$0.22 \pm 0.02^b$</td>
</tr>
<tr>
<td></td>
<td>OA Three</td>
<td>$0.22 \pm 0.039^a$</td>
<td>$0.20 \pm 0.035^b$</td>
</tr>
<tr>
<td>Response Accuracy (%)</td>
<td>YA One</td>
<td>$88.4 \pm 3.5^a$</td>
<td>$89.9 \pm 3.2^a$</td>
</tr>
<tr>
<td></td>
<td>YA Four</td>
<td>$92.4 \pm 2.8^a$</td>
<td>$92.5 \pm 2.9^a$</td>
</tr>
<tr>
<td></td>
<td>YA Three</td>
<td>$88.9 \pm 3.0^a$</td>
<td>$89.8 \pm 3.5^a$</td>
</tr>
<tr>
<td></td>
<td>OA Three</td>
<td>$82.9 \pm 10.0^a$</td>
<td>$88.3 \pm 7.8^b$</td>
</tr>
<tr>
<td>Response Time (s)</td>
<td>YA One</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>YA Four</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>YA Three</td>
<td>$0.84 \pm 0.07^a$</td>
<td>$0.88 \pm 0.09^a$</td>
</tr>
<tr>
<td></td>
<td>OA Three</td>
<td>$1.25 \pm 0.07^a$</td>
<td>$1.62 \pm 0.15^b$</td>
</tr>
</tbody>
</table>
In Experiments II & III, young adult participants trained with a walking based training protocol adopted a less energy efficient obstacle crossing strategy (the body had to raise the trailing foot higher: Patla et al. 1991; Patla & Prentice 1995). Conversely, the elevated foot increased the safety margin, reducing the likelihood of the trailing foot contacting the obstacle (Patla et al. 1991; Patla & Prentice 1995). It is important to note that participants were never instructed as to what strategy to adopt during training (i.e. either an economical or cautious strategy). Thus it appears that training altered the participant’s perceptions of the obstacle, causing participants to adopt a more cautious strategy (Patla et al. 1991; Rietdyk et al. 2005; Rietdyk & Rhea 2011). Furthermore, all young adult groups increased walking velocity at obstacle crossing following Visit 1, indicating that they were likely integrating information about the location of the obstacle, and implementing a stepping strategy more rapidly, while still successfully clearing the obstacle (Weerdesteyn et al. 2003; Weerdesteyn et al. 2005). However, a faster velocity is a greater challenge to movement control (England & Granata 2007), as the body’s center of mass is now travelling with larger inertia, which would be difficult to control in the event of a trip (Hof 2008; Orendurff et al. 2004; Pijnappels et al. 2008). Therefore, it is important to note that only walking trained individuals accounted for this greater postural threat, by adopting stepping strategies to reduce the risk of tripping (Heijnen et al. 2012; Rietdyk & Rhea 2011).

Conversely, when examining the strategies implemented by the more distally related computer based training group (Experiment III), the same cautious stepping strategies were not observed (i.e. minimum trail foot clearance was not increased following training). Instead, the alterations to obstacle crossing strategy following
training in this group manifest as changes to walking velocity. Although all groups increased velocity while crossing the obstacle, only the computer based training individuals increased velocity on approach to the obstacle. This strategy would effectively reduce the amount of time available to adapt to the position of the obstacle and implement a stepping strategy to clear it (Chen et al. 1996; Weerdesteyn et al. 2003; Weerdesteyn et al. 2005). Although this would appear to be a more challenging strategy due to the imposed time constraints to choosing an obstacle crossing strategy, it is important to note that more obstacle contacts were not observed in this group. Thus, they were able to effectively perform under the reduced time constraints (Chen et al. 1996; Weerdesteyn et al. 2005).

6.1.2.2 Dual-task training reduces walking velocity in older adults

Older adults are reported to have increased interference under dual-task constraints (Anguera et al. 2013; Bock et al. 2011; Bherer et al. 2005; Lindenberger et al. 2000), and to perform obstacle crossing less successfully as compared to younger adults (Hegeman et al. 2012; Persad et al. 1995; Weerdesteyn et al. 2005). Furthermore, older adults have reduced sensorimotor and cognitive capabilities, which also challenge their ability to navigate complex and dynamic environments (Anguera et al. 2013; Hall et al. 2011; Hegeman et al. 2007; Menant et al. 2010; Persad et al. 1995; Pijnappels et al. 2008; Speers et al. 2002). In the older adult participants, the same type of walking based training was applied as used in Experiment II (one and four weeks in duration) and Experiment III (three weeks in duration). Furthermore, the same test of dual-task performance was utilized to quantify training alterations in young and older adults.
However, the training effects were much different than were observed for younger adults (see Table 6.1 for a summary of results from Experiment IV). The obstacle crossing strategy induced by training was a decrease in walking velocity at all three calculated steps, while no alterations to foot clearance were observed.

As previously stated, dynamic obstacles are more challenging than stationary obstacles, due to the reduced time available to implement an efficient crossing strategy (Chen et al. 1996, Weerdesteyn et al. 2005). One way to combat the challenges imposed by a dynamic obstacle is to reduce walking velocity, which provides more time for the participant to collect accurate information about the obstacle, and in turn choose a successful strategy to navigate over the obstacle (Chen et al. 1996; Patla et al. 1991; Weerdesteyn et al. 2005). This may represent a difference in strategy implemented to execute the challenging obstacle crossing task as compared to what was observed in young adults following training. To begin, older adults may lack the neuromuscular strength to further increase clearance values (Pijnappels et al. 2008; Schillings et al. 2005). Furthermore, the baseline obstacle crossing values in Experiment IV were similar to or larger than previously reported values (Barbieri et al. 2014; Lu et al. 2006), and thus there may be a limit with how much clearance values can physiologically increase in this population. Also, although it was not possible to calculate double support time in Experiment IV, a slower walking velocity would allow older adults to spend more time in double support (Brown et al. 2006; Maki 1997), which is an arguably safer strategy, as more time during a gait stride is spent with a larger base of support (Hof 2008; Winter 1995).
6.2 Future Directions

In the present dissertation, an overview of the research on the effects of a concurrent cognitive task on motor tasks was reported, as well as results from a number of studies that examined the effectiveness of training programs to alter dual-task performance (Section 2). Furthermore, Experiments I-IV in the thesis added to the literature by furthering the understanding of dual-task interference and training effects. However, there remain many unanswered questions and different avenues to explore within this area of research. Firstly, the Third Experiment examined the effectiveness of two training protocols, which were varied in their similarity to the obstacle crossing and auditory Stroop task test of dual-task performance (Lajoie et al. 1993; Winter 1995). Results from this study, as well as from other studies examining generalizability of training (Basak et al. 2008; Bherer et al. 2005; Naumann et al. 2015), indicate that training needs to be related to the tests of performance, or improvements will not be observed.

Although our computer game based training program in Experiment III did not yield alterations to obstacle crossing behavior to the same level as walking based training, it is important to note that other training programs which utilize computer based training to improve cognitive function may be able to alter dual-task performance (Hall et al. 2011; Li et al. 2010; Persad et al. 1995). For example, Li et al. (2010) demonstrated that computer game based training was able to alter performance on postural tasks in older adult participants. Briefly, participants trained for a total of five hours while performing numerous dual-task tests on a computer. Following training, participants completed normal standing and single leg standing, and reductions in the displacement and velocity
of the center of mass following training were observed, indicative of greater postural control. Furthermore, numerous other studies have found associations between decreased cognitive functioning and increased falls risk (Hall et al. 2011; Liu-Ambrose et al. 2008; Nagamats et al. 2011; Persad et al. 1995). Although it is debated whether the relationship between cognitive function and falls risk is causative or predictive (Clouston et al. 2013; Hall et al. 2011; Liu-Ambrose et al. 2008; Nagamats et al. 2011; Persad et al. 1995), it is an interesting research avenue to continue in the future.

Another interesting future direction for this work is to examine the attentional demands of adapting to an externally applied perturbation over time (Gribble & Scott 2002; Noble & Prentice 2006; Worden et al. 2016). Although the interference effects of dual-task performance are relatively well-accepted during two goal-directed tasks (Ebersbach et al. 1995; Lajoie et al. 1993; Schaefer et al. 2015), little work has examined how the effect of a simultaneous cognitive task may affect motor adaptation to situations where perturbations are applied to the body that require updating of movement patterns (Donkar et al. 2002; Gribble & Scott 2002; Noble & Prentice 2005; Reid & Prentice 2001; Worden et al. 2016). For example, numerous studies have reported adaptations to movement patterns following an externally applied perturbation to an individual while executing a repetitive motion task (Donkar et al. 2002; Gribble & Scott 2002; Noble & Prentice 2005; Reid & Prentice 2001; Worden et al. 2016). Noble & Prentice (2006) observed alterations to walking patterns following the asymmetrical application of a mass to the non-dominant leg during treadmill walking. The altered inertial properties of the lower leg had to be accounted for with adaptations to typical walking patterns to ensure adequate ground clearance of the foot and control of the body’s center of mass during
walking. Noble & Prentice (2006) observed that the recalibration of movement patterns took place over approximately 50 strides, and this timing was consistent across participants (Worden et al. 2016). However, it remains unknown if such adaptations to external applied perturbations are attentionally demanding, or can proceed with little supraspinal input (Lajoie et al. 1993). Thus, examining the stereotypical recalibration timing (e.g. ~50 strides for walking when a mass is applied) in the presence or absence of a simultaneous cognitive task could provide some insight into the attentional requirements of recalibration.

6.3 Conclusion

In conclusion, the present dissertation provides further information towards understanding the effects of a concurrently performed cognitive task on obstacle crossing strategies, and the feasibility of training programs to alter this dual-task paradigm. The findings suggest that structural interference (in addition to central interference) induces significant changes to obstacle crossing strategies through increased foot clearances. Furthermore, proximally related dual-task training induced alterations to performance on a concurrent obstacle crossing and auditory Stroop task, although effects were different for young (increased minimum trail foot clearance) as compared to older adults (reduced walking velocity and increased Stroop task accuracy). The contributions of this thesis work to the scientific literature advocate for continued research investigating the complex nature of cognitive control in complex adaptive gait.
Chapter 7 References


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