EXPLORING THE ATTENTIONAL DEMANDS OF WALKING AFTER TRAUMATIC BRAIN INJURY

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Abstract

Exploring the attentional demands of walking after traumatic brain injury

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Many individuals achieve independent ambulation after traumatic brain injury (TBI). The purpose of this thesis was to explore the attentional demands of walking for participants with TBI as compared to healthy peers. The healthy group did not demonstrate a dual-task effect when treadmill walking and concurrently performing reaction time tasks. However, significant increases in the mean or variability of simple reaction time (SRT) were demonstrated for TBI participants; suggesting that walking is more attentionally-demanding for those with TBI than their healthy peers. Contrary to hypotheses, walking did not uniformly delay RT in complex cognitive tasks and those that probed attention switching. Individual differences in locomotor dyscontrol and/or impaired cognitive processes may contribute to delays in attentional re-allocation and subsequent deterioration in performance under dual-task conditions. Further study is warranted to inform the development of appropriate rehabilitative assessments and interventions to maximize mobility outcomes and participation for those with TBI.

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Glossary of Terms

Attention	A universally accepted definition of attention has not yet appeared in the literature. Rather, attention refers to several different processes that are related aspects of how the organism becomes receptive to, and begin processing of, incoming stimuli. A further assumption of the attentional system is its limited capacity wherein only so much processing activity can occur at one time (Lezak 1995, p.39)
Attention switching	In this thesis, this term refers to the dynamic properties of attention and is used interchangeably with the term "attentional re-allocation". Specifically, we have used a measure of switch cost designed to measure the time required to reallocate attention between tasks

List of Abbreviations

CB&M	Community Balance & Mobility Scale
CIs	confidence intervals
COM	centre-of-mass
COP	centre-of-pressure
COVS	Clinical Outcome Variables Scale
CV	co-efficient of variation
FSR	force sensitive resistor
GCS	Glascow Coma Scale
NoSw	non-switch (referring to reaction time trials within the switch cost paradigm where the cognitive task remains the same)
NoSwOE	non-switch odd/even (referring to non-switch trials of the odd/even cognitive task)
NoSwSL	non-switch small/large (referring to non-switch trials of the small/large cognitive task)
OE	odd/even (referring to one of the cognitive tasks within the switch cost paradigm)
RM ANOVA	repeated-measures analysis of variance

RT	reaction time
SC	switch cost
SCOE	switch cost derived from the odd/even cognitive task
SCSL	switch cost derived from the small/large cognitive task
SD	standard deviation
SL	small/large (referring to one of the cognitive tasks within the switch cost paradigm)
SRT	simple reaction time
Sw	switch (referring to reaction time trials within the switch cost paradigm where the cognitive task switches)
SwOE	switch odd/even (referring to switch trials of the odd/even cognitive task)
SwSL	switch small/large (referring to switch trials of the small/large cognitive task)
TBI	traumatic brain injury

1.0 Introduction

Brain injury is reported to be the leading cause of death and disability for Canadians less than 45 years of age (Ontario Brain Injury Association, 2005). The brain injury survivor can therefore be faced with the challenges of significant, long-term physical and cognitive impairments. The Brain Injury Association of America has estimated that 5.3 million Americans are currently living with a disability due to brain injury (www.biausa.org). This underscores the need to develop effective rehabilitative interventions to maximize function, participation and quality of life.

It has been documented that many individuals achieve independent ambulation in the early stages of recovery from brain injury (Swaine & Sullivan, 1996; Katz, White, Alexander, & Klein, 2004). Conversely, symptoms of impaired balance and instability when walking have been cited as primary, long-term concerns even for community-dwelling, ambulatory individuals with TBI (Hillier, Sharpe, & Metzer, 1997; Dean, Colantonio, Ratcliff, & Chase, 2000a; Powell, Machamer, Temkin, & Dikmen, 2001; Basford et al., 2003) suggesting that evaluation of their balance and mobility issues requires further exploration. Upon review of the TBI literature between 1990 and 2004, Williams (Williams, Robertson, & Greenwood, 2004) reported that physical or mobility outcomes after TBI are most frequently characterized through more gross measures such as the FIM, and "high level mobility" issues remain poorly understood and commonly untreated. It is only within the last 5 years that laboratory research has emerged to validate that residual locomotor dyscontrol persists even in those who are independently ambulatory with walking velocities approaching or within normal values (Basford et al., 2003; McFadyen, Swaine, Dumas, & Durand, 2003; Chou, Kaufman, Walker-Rabatin, Brey, & Basford, 2004; Niechwiej-Szwedo et al., 2007) and clinical outcome measures have similarly emerged to appropriately assess mobility deficits at this end of the continuum (Howe, Inness, Venturini, Williams, & Verrier, 2006; Williams, Robertson, Greenwood, Goldie, & Morris, 2006). Further research is needed, however, to understand the nature of dyscontrol within this population, especially when a relationship between high level mobility skills and community integration after TBI has been demonstrated (Inness, Howe, Niechwiej-Szwedo, Jaglal, McIlroy & Verrier, 2004)

There has been a rapidly expanding area of research exploring the relationship between cognitive factors, such as attention, and the control of posture and gait. Using dual-task paradigms, it has been demonstrated that performing a concurrent cognitive task can result in altered postural or locomotor control; concurrent postural or locomotor tasks can result in altered cognitive performance, or; interference can occur in the performance of both the cognitive and postural / locomotor tasks (Woollacott & Shumway-Cook, 2002).

Dual-task studies have also demonstrated that the allocation of attention to postural control is dynamic not static. In healthy individuals, rapid switching of attention has been demonstrated between secondary tasks and postural control when balance has been perturbed (McIlroy et al., 1999; Norrie, Maki, Staines, & McIlroy, 2002) and, in the elderly, delays in attention switching have correlated to delays in the appropriate postural responses necessary for balance (Maki, Zecevic, Bateni, Kirshenbaum, & McIlroy, 2001). Collectively, these studies suggest that dynamic allocation of attention occurs within the course of recovery of stability and that the observed dual-task decrements in behaviour or performance may be related to delayed processes of attention switching. It is plausible that delays in attention switching could also be explanatory for decrements in performance when walking under dual-task conditions but this has not been specifically explored.

Problems with attention are one of the most consistent findings in individuals with brain injury (van Zomeren & Deelman, 1976; Gronwall, 1987; Brouwer, Ponds, Van Wolffelaar, & Van Zomeren, 1989; Park, Moscovitch, & Robertson, 1999; Stuss et al., 1989). Impairments in focusing, sustaining, dividing and/or shifting attention have all been widely observed (Sohlberg & Mateer, 1987; Lezak, 1995; Mathias & Wheaton, 2007; Niemann, Ruff, & Kramer, 1996).

Surprisingly, there are few studies exploring the relationship of attention and walking after brain injury. It has been shown that concussed athletes exhibit changes in mediolateral centre-of-mass (COM) displacement, suggestive of dynamic instability in the frontal plane, when walking under conditions of divided attention (Parker, Osternig, Lee, Donkelaar, & Chou, 2005; Parker, Osternig, Van Donkelaar, & Chou, 2006). In the only published study of those with moderate to severe TBI, it has been demonstrated that in comparison with healthy controls, the TBI group demonstrated significant dual-task changes in walking velocity in conditions where both the complexity of the cognitive (here Stroop interference test (Golden, 1978)) and locomotor task (obstacle avoidance) was manipulated (Vallee et al., 2006).

Given the paucity of studies to date, the purpose of this research was to further explore the attentional demands of walking in those with TBI who demonstrate high levels of functional mobility. Building on the above-mentioned research, we set out to specifically examine the influence of concurrently-performed cognitive tasks that were complex and that probed attention switching. The first experiment was conducted with a healthy group and provided normative data on a dual-task protocol for comparative use in the second experiment, which utilized the same protocol, but examined traumatically brain injured individuals.

The long-term objective of this work is to contribute to a greater understanding of the underlying issues of locomotor dyscontrol in the ambulatory individual with TBI and to inform the future development of appropriate rehabilitative assessments and interventions to maximize mobility outcomes and participation.

2.0 Background

2.1 The Epidemiology of Traumatic Brain Injury

Traumatic brain injury (TBI) results from an external force to the brain causing transient or permanent neurological dysfunction and is a relatively high-prevalence injury. Brain injury has been cited as the leading cause of death and disability for Canadians under the age of 45 years (Ontario Brain Injury Association 2005). The Canadian Institute for Health Information reports there are 16 811 hospitalizations as a result of traumatic head injury or 46 admissions every day (www.cihi.ca). Although there has been an encouraging decrease in reported incidence over the past 10 years, these figures under-report the true incidence of TBI in Canada. Many mild brain injuries, reportedly accounting for 60-80% of all brain injuries (Quinn & Sullivan, 2000), do not seek medical consult or result in hospitalization and therefore are not adequately captured.

The incidence of TBI is more common in males, representing 68% of reported cases (www.cihi.ca) with a high representation in those between 20 – 39 years of age (Khan, Baguley, & Cameron, 2003) . For this age group, motor vehicle accidents are the leading cause of brain injury with assaults and falls being the next most common (www.cihi.ca). Given the age of the population affected and the diversity and degree of secondary sequelae, the consequences of TBI can be long-term, complex and can severely and permanently alter a person's life. For example, the Brain Injury Association of America has estimated that 5.3 million Americans are currently living with a disability due to brain injury (www.biausa.org). As such, ongoing attention is required to act on factors that result in TBI and additionally to explore the underlying impairments contributing to limitations in activity and participation to inform and maximize rehabilitative interventions.

2.2 Locomotor Deficits After Traumatic Brain Injury

Many patients after TBI achieve the ability to ambulate in the early stages of recovery. Within a study of 116 patients with TBI, Katz and colleagues (Katz et al.,

2004) documented that independence in ambulation was achieved at a mean time of recovery of 5.7 $\pm$ 4.3 weeks. Similarly, Swaine & Sullivan (Swaine & Sullivan, 1996) reported that 50% of subjects with TBI were independently ambulatory for 25 m on both even and uneven ground within 6 weeks. Nonetheless, subjective complaints of balance and walking difficulties have been documented as one of the most persistent and common long-term concerns, 5 and 15 years (Hillier et al., 1997; Dean, Colantonio, Ratcliff, & Chase, 2000b) post-injury, indicating that evaluation of their balance and mobility issues needs further exploration.

It is only within the past five years that studies have emerged evaluating the locomotor capacity and "high-level" mobility issues of those with traumatic brain injury. A number of studies have identified a group of individuals with TBI who are high functioning, determined to be independently ambulatory, with high scores on clinical balance measures (McFadyen et al., 2003; Niechwiej-Szwedo et al., 2007) or with documented normal neurological and musculoskeletal clinical exams (Basford et al., 2003; Chou et al., 2004). Using laboratory measures, these studies have demonstrated that TBI subjects walked at significantly slower speeds (Basford et al., 2003; Chou et al., 2004; McFadyen et al., 2003; Niechwiej-Szwedo et al., 2007) and with decreased step lengths (Basford et al., 2003; Chou et al., 2004; McFadyen et al., 2003) compared to their healthy peers. McFadyen and colleagues reported that those with TBI demonstrated a more "cautious" gait with significantly slower crossing speeds for trail limb versus lead limb and a tendency for increased foot clearances when walking in a more complex environment requiring obstacle crossings (McFadyen et al., 2003). Additionally, significant increases in displacement and velocity of the centre-of mass (COM) in the mediolateral direction have been demonstrated in those with TBI when walking on level ground (Basford et al., 2003) and during obstacle crossing (Chou et al., 2004). Niechwiej-Szwedo and colleagues demonstrated significant increases in variability of step time and length when TBI subjects were performing fast or eyes closed walking conditions, as compared to healthy controls (Niechwiej-Szwedo et al., 2007). The above-mentioned studies suggest that dynamic instability and locomotor dyscontrol might be a persistent deficit in the high-functioning individual with TBI and may be more problematic in complex conditions or environments. The underlying issues, however, remain poorly understood but are worthy of study as a relationship between high level balance and mobility skills and community participation after TBI has been demonstrated (Inness, 2004).

2.3 Attention and Postural / Locomotor Control

Human walking has often been characterized as an "automatic" behaviour based on spinal neural networks referred to as central pattern generators (MacKay-Lyons, 2002). However, studies characterizing changes in regional cerebral blood flow using positive emission tomography (Ouchi, Okada, Yoshikawa, Nobezawa, & Futatsubashi, 1999) or single photon emission computed tomography (Fukuyama et al., 1997) and studies measuring cortical potentials (Quant, Adkin, Staines, Maki, & McIlroy, 2004) have demonstrated cortical involvement in the control of human standing and locomotor activities. Indeed, there is now convincing evidence that cognitive processes, specifically attention, contribute in some way to human postural and locomotor control; largely this evidence is based on studies using dual-task paradigms. The dual-task paradigm examines the automaticity or contribution of central mechanisms to a postural or locomotor task (primary task) by evaluating the performance of another concurrently-performed task (secondary task). The extent of the decrement in performance of the secondary task during simultaneous performance of the primary task, as compared to when performed alone, provides a measure of the attentional demands of the primary (postural) task (Abernethy, 1988). Other research, however, has studied the attentional demands of postural or locomotor control by examining the effects in both the primary and secondary tasks; the extent to which either task declined would indicate interference between the processes controlling the two tasks (Woollacott & Shumway-Cook, 2002). Indeed, studies with the healthy young and elderly, balance-impaired elderly and neurological populations have demonstrated that performing a concurrent cognitive task can result in altered postural or locomotor control (Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Brauer, Broome, Stone, Clewett, & Herzig, 2004; Dault, Frank, & Allard, 2001; Dault, Geurts, Mulder, & Duysens, 2001; Haridas, Gordon, & Misiaszek, 2005; Parker et al., 2005; Dubost et al., 2006; Parker, Osternig, VanDonkelaar, & Chou, 2006); concurrent postural tasks can result in altered performance of secondary cognitive tasks (Lajoie, Teasdale, Bard, & Fleury, 1993; Kerr, Condon, & McDonald, 1985; Kurosawa, 1994; Abernethy, Hanna, & Plooy, 2002; Sparrow, Bradshaw, Lamoureux, & Tirosh, 2002; Regnaux et al., 2005; Regnaux, Roberston, Smail, Daniel, & Bussel, 2006) or interference can occur in the performance of both the cognitive and postural tasks (Ebersbach, Dimitrijevic, & Poewe, 1995; Maylor & Wing, 1996; Shumway-Cook & Woollacott, 2000; Haggard, Cockburn, Cock, Fordham, & Wade, 2000; Li, Lindenberger, Freund, & Baltes, 2001; Maylor, Allison, & Wing, 2001; Jennings, Martin, & Furman, 2001; Teasdale & Simoneau, 2001; Redfern; Beauchet, Dubost, Herrmann, Kressig, 2005; Beauchet, Dubost, Aminian, Gonthier, & Kressig, 2005; Grabiner & Troy, 2005; Hyndman, Ashburn, Yardley, & Stack, 2006; Vallee et al., 2006). Collectively, these studies would support that postural and locomotor control are less automatic than previously thought and require some attention or cognitive resources. However, the interaction between cognition and postural or locomotor control is somewhat complex and dependent on a number of influential factors.

Influence of Age

Studies within the healthy young provide evidence that even highly-practiced, seemingly automatic tasks may require attention. Significant increases in secondary RT have been demonstrated in healthy young participants in standing as compared to sitting (Lajoie et al., 1993). Studies using dual-task paradigms during treadmill or overground walking have demonstrated decrements in performance of secondary cognitive tasks such as RT (Bardy & Laurent, 1991; Lajoie et al., 1993; Abernethy et al., 2002; Regnaux et al., 2006) or neuropsychological tests (Beauchet, Dubost, Herrmann, Kressig, 2005; Grabiner & Troy, 2005) and decrements in gait performance such as decreased stride length (Shkuratova, Morris, & Huxham, 2004; Parker et al., 2005;), walking velocity (Li et al., 2001; Beauchet, Dubost, Herrmann, Kressig, 2005; Parker et al., 2005) and increased double support stance time (Ebersbach et al., 1995). It is noteworthy, however, that the effects in the healthy young are often small; for example, studies have cited increases in double support stance time of 12 msec (Ebersbach et al., 1995) and decreases in stride velocity by 0.06 m/sec (Beauchet, O., Dubost, V., Herrmann, F.R., Kressig, R.W., 2005). Further, in some studies, no change in performance for the primary or secondary tasks has been noted for the healthy young (Yardley, Gardner, Leadbetter, & Lavie, 1999; Shumway-Cook & Woollacott, 2000; Haggard, Cockburn, Cock, Fordham, & Wade, 2000; Regnaux et al., 2005)

Increasing age may be an influential factor wherein the healthy elderly have demonstrated greater attentional demands for postural and locomotor control than the healthy young (Maylor & Wing, 1996; Marsh & Geel, 2000; Rankin, Woollacott, Shumway-Cook, & Brown, 2000; Li et al., 2001; Maki et al., 2001; Maylor et al., 2001; Sparrow et al., 2002; Melzer & Oddsson, 2004;). However, in some studies age differences only become apparent when the complexity of the postural (Shumway-Cook et al., 1997; Redfern et al., 2001; Shumway-Cook & Woollacott, 2000) or cognitive task (Huxhold, Li, Schmiedek, & Lindenberger, 2006) is increased.

Influence of the Individual's Balance and Locomotor Abilities

Numerous studies have demonstrated that the attentional requirements of posture and locomotion are greater in those populations (elderly or neurological) with balance or locomotor dyscontrol (Lundin-Olsson, Nyberg, & Gustafson, 1997; Shumway-Cook et al., 1997; Haggard, Cockburn, Cock, Fordham, & Wade, 2000; Shumway-Cook & Woollacott, 2000; Bowen et al., 2001; Brauer, Woollacott, & Shumway-Cook, 2001; Hausdorff, Balash, & Giladi, 2003; Sheridan, Solomont, Kowall, & Hausdorff, 2003; Hyndman et al., 2006; Yang, Chen, Lee, Cheng, & Wang, 2007). For example, Hyndman and colleagues demonstrated significant decreases in stride length and walking velocity under dual-task conditions, for those with stroke who were "fallers" versus "non-fallers" (Hyndman et al., 2006). In "frail elderly" populations, stride times increased by 100 msec and stride time variability increased by almost 7% when walking and performing simple arithmetic tasks (Beauchet et al., 2005). Several studies by Shumway-Cook (Shumway-Cook et al., 1997; Shumway-Cook & Woollacott, 2000) have also shown that, in contrast to their healthy counterparts, the balance-impaired elderly demonstrate increased COP displacement under dual-task conditions irrespective of the complexity of the secondary cognitive task (Shumway-Cook et al., 1997) and even on "simple" postural conditions such as standing on firm surfaces with eyes open (Shumway-Cook & Woollacott, 2000); in fact, a portion of this group who had been able to maintain stability in single-task conditions actually fell during the dual-task conditions (Shumway-Cook & Woollacott, 2000). This would be consistent with research that has suggested that the inability to perform a simple dual task such as "walk and talk" is highly predictive of fall risk (Lundin-Olsson et al., 1997).

Influence of Postural Challenge

LaJoie and colleagues (Lajoie et al., 1993; Lajoie, Teasdale, Bard, & Fleury, 1996) demonstrated, in the healthy young and elderly populations, a significant increase in secondary RT from sit to stand to walking conditions; suggesting that attentional demands will vary depending on the challenge of the postural task. Similarly, studies with the stroke population have demonstrated, significant increases in secondary RT when comparing stand to narrow stand (Brown, Sleik, & Winder, 2002) and stand to walk conditions (Regnaux et al., 2005). Additionally, studies have demonstrated increases in probe RTs as the somatosensory input and visual input has been decreased; plausibly increasing the challenge of the postural task (Shumway-Cook & Woollacott, 2000; Redfern et al., 2001; Teasdale & Simoneau, 2001).

Further, adapative locomotor tasks such as walking to large or small targets (Bardy & Laurent, 1991), with targeted foot placements (Sparrow et al., 2002), during alterations of gait speed (Abernethy et al., 2002; Kurosawa, 1994) or during obstacle avoidance (Chen et al., 1996; Weerdesteyn, Schillings, van Galen, & Duysens, 2003; Chou et al., 2004; Brown, McKenzie, & Doan, 2005; Vallee et al., 2006;) have been found to be more attentionally-demanding than unobstructed walking. Collectively, these findings suggest that cognitive-motor interference may be dependent on the complexity of the postural task.

Influence of the Type and Complexity of the Secondary Cognitive Task

A number of studies have investigated whether the type of sensory information processing influences the attentional demands of postural control. Specifically, it has been hypothesized that secondary tasks that involve visuospatial processing would cause greater interference to the performance of posture due to mutual requirements of visuospatial processing for both tasks. This hypothesis has been supported in some studies that have demonstrated that postural stability was influenced to a greater extent by secondary spatial versus non-spatial cognitive tasks (Kerr et al., 1985; Maylor & Wing, 1996)

There have been a number of studies, however, that have refuted this hypothesis (Shumway-Cook et al., 1997; Dault et al., 2001; Maylor et al., 2001; Redfern et al., 2001; Hunter & Hoffman, 2001; Huxhold et al., 2006) finding either no difference in effect of modality of the secondary task (Hunter & Hoffman, 2001; Huxhold et al., 2006) or greater effects with non-spatial tasks (Shumway-Cook et al., 1997; Maylor et al., 2001; Redfern et al., 2001).

The contradictory results related to the influence of type of secondary task, combined with studies that have demonstrated no dual-task interference with balance or walking when the secondary tasks performed were "simple" (Haggard, Cockburn, Cock, Fordham, & Wade, 2000), have led some to believe that the influential factor is more related to the complexity of the secondary task (Haridas et al., 2005; Melzer, Benjuya, & Kaplanski, 2001; Shumway-Cook et al., 1997). Huxhold and colleagues (Huxhold et al., 2006) found a significant increase in an elderly group's centre-of-pressure (COP) displacement when performing a concurrent, complex memory task versus a simple choice reaction time task, but found no differences between the verbal or visual memory task. Li and colleagues (Li et al., 2001) found that young healthy adults demonstrated dual-task costs when walking only when the challenge of the memory task was manipulated. Haridas (Haridas et al., 2005) also found that delays in anticipatory postural adjustment latencies during walking occurred only with concurrent choice reaction time not simple reaction time tasks. Again, it is worth mentioning that there have been a few studies that have found no change in effect with manipulation of the cognitive task (Regnaux et al., 2005; Regnaux et al., 2006).

Some studies have questioned the assumptions of the dual-task paradigm and the role of attention. Yardley and colleagues (Yardley et al., 1999) measured the COP sway path of healthy individuals and demonstrated that postural sway was impacted by articulation or visual conditions but not by attentional load. They suggested that the respiratory activity involved in speech could be a confounding factor. Maki and McIlroy

(Maki & McIlroy, 1996) demonstrated that healthy subjects tended to lean forward when standing and performing a secondary mental arithmetic task but that this effect was limited to subjects who reported higher than average anxiety scores and the degree of leaning was correlated to levels of physiological arousal. This flags arousal and balance-related anxiety as potential confounders when designing or interpreting dual-task study results.

In consideration of the dual-task literature as a whole, however, there would seem to be sufficient evidence to support that, in some way, attention to postural and locomotor control is required and that this may vary depending on the complexity of either the postural or secondary task performed and the balance or walking abilities of the individual.

2.4 Attention and Postural / Locomotor Control in Traumatic Brain Injury Populations

There are relatively few studies examining the interaction between attention and postural and locomotor control in TBI populations. Although Guerts (Geurts, Ribbers, Knoop, & van Limbeek, 1996) was able to demonstrate significant deficits in postural control in seemingly recovered individuals after TBI as compared to healthy controls, he was not able to demonstrate greater dual-task interference. Secondary task errors significantly increased across postural conditions (from sit to stand to weight shift) but there were no significant differences between those with TBI and the healthy controls; suggesting that postural control in the high-functioning individual post-TBI was not more attentionally-demanding than their healthy counterparts. However, it may have been that the secondary arithmetic task was too easy to elicit interference. Haggard (Haggard, Cockburn, Cock, Fordham, & Wade, 2000) also used a similar secondary cognitive task in their dual-task studies but discontinued it as it was insensitive to interference with concurrent gait in those with brain injury.

Brauer and colleagues (Brauer et al., 2004) used a range of simple and complex, non-spatial and visuo-spatial secondary tasks while subjects performed a more complex "step-stance" balance task. Those with TBI did demonstrate greater COP excursion and velocity during dual-task conditions than controls. In contrast to hypotheses, however, greater interference occurred during the secondary simple auditory tones discrimination task and during the control articulation task.

Despite the fact that many of those post-TBI become ambulatory, there are relatively few studies that have examined the attentional demands of walking of this group and only one published study with individuals after moderate to severe TBI. In two related studies, Parker (Parker et al., 2006; Parker et al., 2005) studied young athletes post-concussion and was able to demonstrate that those post mild-TBI demonstrated greater dual-task interference in walking than controls, exhibiting shorter stride lengths and slower ant/post COM velocity, and only the concussed group demonstrated changes in ML ROM when walking under dual-task conditions (this effect was still evident 28 days post-concussion). These results suggest that the ability to maintain stability in the frontal plane during walking is diminished in the concussed group under divided attention conditions.

Vallee and colleagues (Vallee et al., 2006) studied those with moderate/severe TBI but who demonstrated good locomotor recovery, with no significant differences in walking velocities as compared to controls. This study examined the attentional demands of more complex locomotor tasks involving obstacle avoidance. Whereas healthy controls demonstrated no difference in performance of the secondary Stroop test within unobstructed and obstructed walking conditions, those with TBI demonstrated significantly slower Stroop reading times while crossing the wide obstacles. Similarly, compared with unobstructed walking, only TBI subjects demonstrated slowed dual-task walking velocity and decreased stride length during combined performance of the Stroop test and wide obstacle crossing. Again, this study would support that locomotion is more attentionally-demanding in those with TBI but that group differences may become apparent only with more complex or challenging cognitive and locomotor tasks.

2.5 Dynamic Properties of Attention within Postural / Locomotor Control

Studies measuring somatosensory-evoked potentials have demonstrated that somatosensory stimuli that are irrelevant to a given task are often suppressed whereas task-relevant somatosensory information leads to selective facilitation and enhanced cortical activity of the primary somatosensory cortex (Ghatan, Hsieh, Petersson, Stone-Elander, & Ingvar, 1998; Staines, Brooke, & McIlroy, 2000; Staines, Graham, Black, & McIlroy, 2002). Similarly, in an fMRI study, it was demonstrated that task-relevant somatosensory stimulation led to enhanced activity within the contralateral primary somatosensory cortex but also a suppression of activity in the ipsilateral somatosensory cortex (Staines et al., 2000). The task-relevant enhancement and reciprocal inhibition of cortical activity would suggest that the allocation of attention is dynamic.

In a balance-related study, Quant and colleagues (Quant et al., 2004) measured perturbation-evoked cortical potentials of healthy young adults who were concurrently performing a continuous visuomotor tracking task. This study demonstrated reduced magnitudes of N1 responses (thought to reflect processing of afferent information) during the tracking task accompanied with larger COP displacement associated with the postural response. The authors proposed that the concurrent tracking task and associated attenuation of N1 responses reflected a diversion or reallocation of attention away from the processing of sensory information related to postural instability.

The dynamic properties of attention have also been demonstrated in a number of dual-task studies. It has been shown that rapid switching of attention occurs in young healthy individuals, to reallocate attentional resources between postural control during perturbations and a concurrent continuous, visuomotor tracking task (McIlroy et al., 1999; Norrie et al., 2002). Whereas initial automatic postural responses were demonstrated after applied perturbations, a pause in the tracking task followed 200-300 msec later, thought to reflect a switch in attention from the visuomotor task to the ongoing control of balance. Maki and colleagues (Maki et al., 2001) extended this work, using the same paradigm with the elderly. Whereas there were no significant differences in the frequency of tracking deviations between the healthy young and elderly, the onset of the switch of attention after a postural perturbation was significantly delayed in the elderly by about 67% or 123 msec. This delay was correlated to a delay in the generation of peak stabilizing COP responses in the later phases of the postural reactions; delays in switching of attention potentially influenced the overall timing of the behavioural response. Redfern (Redfern, Muller, Jennings, & Furman, 2002) also examined changes in RT at discrete times across the perturbation response and similarly demonstrated that the change in secondary probe RTs varied across the time course of perturbations, although this study suggested that the effect occurred earlier in the response to the perturbation than the above-mentioned studies. Collectively, the dual-task and evoked potential studies suggest that dynamic allocation of attention occurs within the course of recovery of stability and that dual-task decrements in performance may be related to the temporal aspects of re-allocating or switching of attention.

It is also plausible that the dynamic allocation of attention occurs within the course of walking. Studies have shown that attention varies within the single support versus double support stance phases in the gait cycle (Lajoie et al., 1993), during gait initiation versus steady-state walking (Sparrow et al., 2002), during alterations or imposed changes to walking velocity (Kurosawa, 1994), during the approach phase to a target (Bardy & Laurent, 1991; Sparrow et al., 2002) and during obstacle avoidance (Brown et al., 2005; Chen et al., 1996; Chou et al., 2004; Vallee et al., 2006; Weerdesteyn et al., 2003). As such, one might similarly question whether dual-task decrements in performance within the course of walking could be related to attention switching processes.

2.6 Rationale and Objectives

In sum, there is evidence to support that the control of human walking requires attention. However, the attentional resources required, and therefore the amount of dual-task decrement in performance, may vary depending on the complexity of the cognitive and/or locomotor task and the balance or walking abilities of the individual. Further, it has been identified that the re-allocation of attention is dynamic within dual-task conditions and delays in attention switching between tasks could be contributory to decrements in performance. Figure 1 represents a theoretical model of the above-stated relationship.

A number of studies have identified a group of individuals after TBI who are high-functioning and independently ambulatory but who have persistent complaints of incoordination or instability when walking. Locomotor deficits of this group have been characterized as that of a "slowed" or "cautious" gait where dynamic instability or locomotor dyscontrol often becomes apparent only in more complex conditions or environments. There is a paucity of studies examining the role of attention in relation to the locomotor deficits of the ambulatory individual with TBI but, in light of the above, it would seem a compelling area of study.

The objective of this work was, therefore, to explore the attentional demands of walking in the high-functioning individual post-TBI compared to their healthy peer group. This was accomplished through two experiments. Both experiments used the same dual-task protocol to study the influence of walking on the response times of concurrently-performed cognitive tasks that were complex in nature and that involved attention switching. The first experiment was conducted with a healthy group and provided normative data for comparative use in the second experiment, which replicated the dual-task protocol in individuals with TBI.

Walking within complex environments and while concurrently performing another task is common-place and underlies the performance of most activities of daily living. Any adverse impact in dual-task conditions could, therefore, have serious consequences to functional ability and participation. This work, therefore, begins to explore the underlying issues of attentional processes and locomotor dyscontrol in the ambulatory individual with TBI and has potential implications for the development of appropriate rehabilitative assessments and interventions to maximize mobility outcomes.

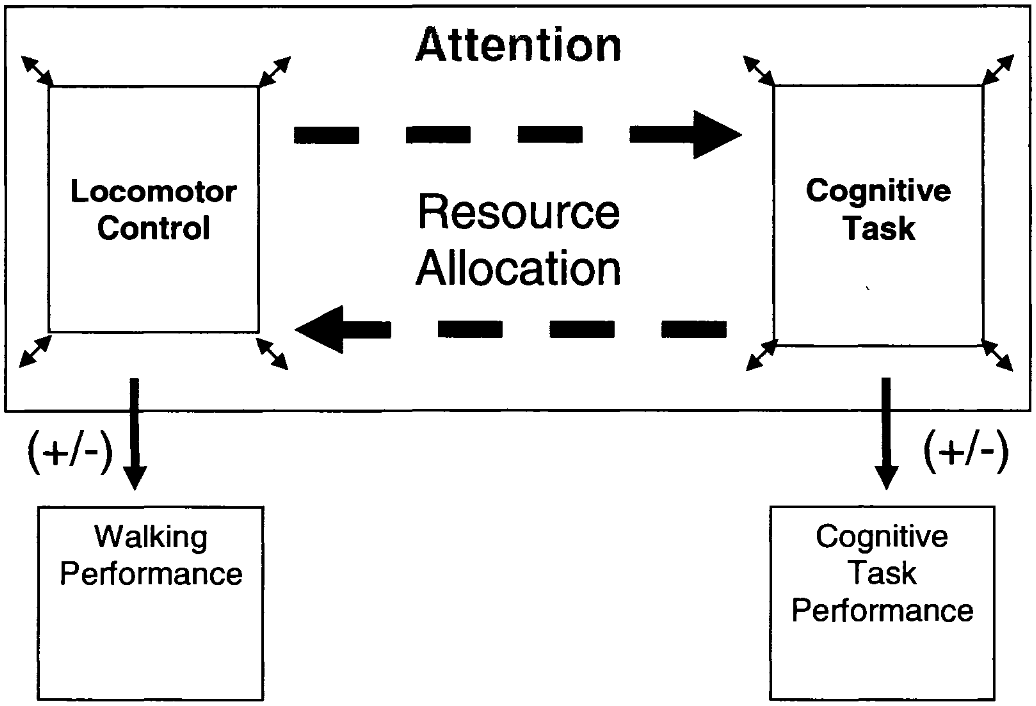

Figure 1. A theoretical model of attention, locomotor control and decrements in dual-task performance. It is proposed that rapid re-allocation or switching of attention occurs between walking and the concurrently-performed cognitive task. The re-allocation of attentional resources could be influenced by the attentional demands or requirements of the tasks (expanding arrows on boxes), specifically: 1) postural or locomotor dyscontrol of the individual; 2) the challenge of the locomotor task (not manipulated in this study), or; 3) the complexity of the cognitive task. The re-allocation of attentional resources could also be influenced by impaired cognitive processes regulating attention switching (dashed arrows). Delays in the re-allocation of attentional resources could translate into delayed behavioural responses with decrements in walking performance, cognitive task performance or both (+/-).

3.0 Experiment One: Attentional demands of walking in the healthy young: Probing complex cognitive tasks and attention switching

3.1 Introduction

There is convincing evidence that cognitive processes, specifically attention, are associated with human locomotor control (Woollacott & Shumway-Cook, 2002). Studies using dual-task paradigms in healthy young populations, during treadmill or unobstructed overground walking, have demonstrated decrements in performance of secondary RT (Abernethy et al., 2002; Bardy & Laurent, 1991; Lajoie et al., 1993; Regnaux et al., 2006) and neuropsychological tests (Beauchet, Dubost, Herrmann, Kressig, 2005; Ebersbach et al., 1995; Grabiner & Troy, 2005) and/or dual-task decrements in gait performance (Beauchet, Dubost, Herrmann, Kressig, 2005; Ebersbach et al., 1995; Grabiner & Troy, 2005). It is noteworthy, however, that the effects are often small and, in some studies, no change in performance for the primary or secondary tasks has been noted for the healthy young (Haggard, Cockburn, Cock, Fordham, & Wade, 2000; Regnaux et al., 2005; Shumway-Cook et al., 1997; Shumway-Cook & Woollacott, 2000; Yardley et al., 1999). These contradictory results would suggest that the interdependence between walking and cognition may vary due to a number of factors including, but not limited to, the challenge or complexity of the primary or secondary tasks (Haridas et al., 2005; Huxhold et al., 2006; Shumway-Cook et al., 1997).

A number of studies have also demonstrated that the allocation of attention within a dual-task paradigm is dynamic not static. In perturbation studies, it has been demonstrated that rapid switching of attention occurs, in young healthy individuals, to reallocate attention to postural control when concurrently performing a continuous, visuomotor tracking task (McIlroy et al., 1999; Norrie et al., 2002). Studies have also shown that the attentional demands can fluctuate throughout the course of walking (Abernethy et al., 2002; Bardy & Laurent, 1991; Kurosawa, 1994; Lajoie et al., 1993; Sparrow et al., 2002). It is plausible then that the dynamic re-allocation of attention also occurs within the course of walking and that dual-task decrements may be related to the time required for processes of attention switching between walking and the concurrently-performed cognitive task.

The focus of this study was, therefore, to investigate the attentional demands of walking in the healthy young, specifically probing the influence of walking on a concurrently-performed cognitive task that involves attention switching. The cognitive task used in this dual-task study was the switch cost paradigm which has been used in experiments to probe cognitive processes related to attention switching (Monsell, 2003). In these experiments, subjects are pre-trained on two RT tasks which use the same set of stimuli and responses but require attention to and classification of different elements or attributes of the stimulus. The subject then performs a series of trials wherein the task set changes across trials. A robust finding within these studies is that responses take longer to initiate on the "switch" than the "non-switch" trials, the difference of which is termed the "switch cost". The error rate is also often higher after a task set switch. Switch costs have been demonstrated in numerous studies of the healthy young (Monsell, Sumner, & Waters, 2003; Tornay & Milan, 2001; Wylie & Allport, 2000) and neurological populations (Aron, Monsell, Sahakian, & Robbins, 2004; Mecklinger, von Cramon, Springer, & Matthesvon Cramon, 1999; Rogers et al., 1998; Schmitter-Edgecombe & Langill, 2006). The switch cost is felt to be a measure of the additional time required for cognitive processes that are involved in attention switching between tasks (Monsell, 2003) and was used in this study to probe the re-allocation of attentional resources when walking.

A slowing of walking speed under dual-task conditions is a commonly-cited finding (Beauchet, Dubost, Herrmann, Kressig, 2005; Bowen et al., 2001; Dubost et al., 2006; Ebersbach et al., 1995; Haggard, Cockburn, Cock, Fordham, & Wade, 2000; Hyndman et al., 2006; Li et al., 2001; Parker et al., 2005; Parker et al., 2006; Yang et al., 2007). Allowing performance of the primary task to suffer, however, has been cited as a methodological flaw as it could potentially alter the attentional demands of this task (Abernethy, 1988) making comparisons of performance within or across groups difficult to interpret. Therefore, within this present study, walking was performed on a treadmill at a constant velocity to ensure consistency of performance in the primary task.

The objective of the first study was to investigate whether walking would influence the timing of concurrently-performed cognitive tasks that measure attention switching within a group of healthy young adults. Further, the paradigm enabled us to explore the influence of cognitive task complexity on dual-task interference by examining the performance on both a simple visual RT task and a more complex choice visual RT task embedded within the switch cost paradigm. The information obtained from the present study provided normative data for comparative use within the second study, which utilized the same protocol but examined traumatically brain-injured individuals.

Specific hypotheses are detailed below:

1) The influence of walking on a simple cognitive task

It was hypothesized that there would be no significant increase in the mean or variability of simple reaction time (SRT) when walking, as compared to sitting.

2) *The influence of walking on a complex cognitive task*

The switch trial of the odd/even task (SwOE) within the switch cost paradigm (detailed in methods) was used as the complex cognitive task. It was hypothesized that there would be a significant increase in the mean and variability of SwOE RT and SwOE error rates when walking, as compared to sitting.

3) The influence of walking on cognitive measures of attention switching

It was hypothesized that there would be a significant increase in switch costs (time and error) when walking, as compared to sitting. We propose that the increased switch costs under dual-task conditions reflect the additional time required to switch attention between walking and the cognitive task.

3.2 Methods

The study was a within subjects, repeated measures design, with reaction time measures compared across single and dual-task conditions (sitting and walking).

3.2.1 Participants

Ten healthy volunteers (5 males, 5 females) were recruited for this study from the undergraduate and graduate student and physical therapist population at the Toronto

Rehabilitation Institute who met the following inclusion criteria:

- were between the age of 18 – 50 years of age
- through self-report had no musculoskeletal or neurological injury that might affect their balance or walking abilities
- through self-report had no history of head trauma
- had no visual deficits that could not be corrected by glasses
- had the ability to provide informed consent

3.2.2 Protocol and Measures

This study protocol was approved by the Research Ethics Board of the Toronto Rehabilitation Institute, the Research Ethics Board of the Sunnybrook Health Sciences Centre and the Ethics Review Unit of the University of Toronto. Informed written consent was obtained from all participants prior to participation in this study.

All testing occurred in the Sunnybrook Health Sciences Centre for Stroke Recovery Motor Control Lab. Patients were tested under single-task and dual-task conditions. The performance of reaction time tasks in sitting was deemed to be the single-task condition; this methodology is consistent with that of other dual-task studies wherein baseline cognitive performance has been determined in a sitting condition (Dault et al., 2001; Dubost et al., 2006; Haggard, Cockburn, Cock, Fordham, & Wade, 2000b; Huxhold et al., 2006; Hyndman et al., 2006; Kerr et al., 1985; Lajoie et al., 1993; Maylor & Wing, 1996; Parker et al., 2006; Regnaux et al., 2005; Regnaux et al., 2006; Sparrow et al., 2002; Teasdale & Simoneau, 2001; Vallee et al., 2006). Dual-task conditions involved participants walking while concurrently performing the cognitive reaction time tasks (outlined in detail below).

Each subject was evaluated following a standard protocol which included a pre-test visual and cognitive screen; baseline measurement of participant characteristics; practice trials of the cognitive tasks and treadmill walking, and; the single and dual-task test paradigm. The test conditions were: 1) WALK with no cognitive task (single-task); 2) SIT with the SRT task (single-task); 3) WALK with the SRT task (dual-task); 4) SIT with the switch cost task (single-task), and; 5) WALK with the switch cost task (dual-task); 6) repeat SIT with SRT task at end of testing. The order of the postural condition (SIT versus WALK) while performing the switch cost task was counterbalanced.

Visual and Cognitive Screening

All participants had to pass basic visual and cognitive screens, designed for the purpose of this study, prior to proceeding with testing. To ensure the participant's visual acuity, they were asked to verbally respond and identify 5 digits randomly generated from the set (1,2,3,4,6,7,8,9) and projected on a screen. To ensure that the participants had the conceptual and cognitive ability to perform the switch cost task (outlined in detail below) they were asked to identify, through verbal response, if 5 digits randomly generated from the same set were small or large (1-4 vs 6-9) and, subsequently, whether the 5 numbers displayed were odd or even (1,3,7,9 vs 2,4,6,8). All subjects had to correctly identify 5/5 numbers in both the visual and cognitive screens to proceed with testing.

Participant Characteristics

Participant characteristics collected included age, sex, height, weight, leg length, handedness and years of education. Other measures characterizing the participant's balance and mobility performance included treadmill and overground gait velocity (m/sec) and perceived balance confidence (%) while performing the dual-task paradigm. This data was collected to determine potential influences of patient characteristics on dual-task results.

Overground gait velocity was measured using a pressure-sensitive mat (GAITRite®, CIR Systems Inc., Clifton, NJ, USA) which has been found to be a reliable and valid method of measuring gait parameters (Bilney, Morris, & Webster, 2003). The mat is a 4.6 meters in length and 0.9 meters in width with a spatial resolution of 1.27 centimeters and a temporal resolution of 100 Hz. Although numerous spatial and temporal characteristics of gait were captured, this thesis focused on overground gait velocity for comparison purposes with the participant's adopted treadmill velocity.

A modified version of the Activities-specific Balance Confidence Scale (Powell & Myers, 1995) was administered over 3 time points during testing. The participant was questioned verbally by the examiner, "How confident are you that you will not lose your balance and become unsteady when you....

1. Are sitting on this stool holding on to the batons?
2. Are walking on this treadmill holding on to the batons?
3. Are walking on this treadmill and doing the reaction time tasks at the same time?

The participants were asked to provide a rating on a scale from 0% (no confidence) to 100% (completely confident).

SIT and WALK Conditions

Participants wore comfortable clothes and walking shoes for the test. In the SIT condition, participants were seated on a stool placed on the treadmill track at its midpoint with feet stable and hands resting on their lap. Participants held a plastic, cylindrical baton in either hand, with thumbs resting and poised to press the force sensitive resistor (FSR) material mounted to it.

In the WALK condition, participants were asked to walk on a motorized treadmill at their preferred pace. Batons were held in either hand as per the SIT condition. Prior to testing, participants were allowed to practice walking on the treadmill while holding the batons. Treadmill velocity was increased to the participant's perceived preferred or "usual" walking velocity. This speed was maintained and then further increased as necessary once the participant became accustomed to it. Treadmill training continued until the participant demonstrated a consistent ability to walk at their preferred pace, maintaining a stable location while walking, without restriction of their arm swing while holding the batons and indicating self-perceived comfort. In the dual-task conditions, all participants commenced treadmill walking and indicated "readiness" prior to commencement of the cognitive tasks.

Insole footswitches were placed in the heel of the participants' footwear to measure temporal characteristics of gait during treadmill walking at a sampling rate of 500 Hz. Within this experiment, however, preferred velocity was determined and remained constant throughout testing to ensure consistent walking performance; therefore, this thesis did not focus on further gait analyses using the footswitch data.

Cognitive Tasks

The SRT and switch cost reaction time paradigms were generated using a custom software program, written in National Instruments LabView 7.1. Reaction times were defined as the time interval from the onset of the stimulus to the patient's response. Reaction time data were collected by a control computer (Intel Pentium PC) at a sampling rate of 300 Hz.

The visual stimuli of the cognitive tasks (circle or digits) were projected on a wall at eye level, 1.8 m (6 feet) from nose to centre of screen. The projection enlarged the stimulus to a height of approximately 20-30 cm (8 – 12 inches). For both SIT and WALK conditions, the participants were instructed to keep their eyes focused on the centre of the screen where the visual stimuli were displayed and the experimenter gave the verbal command "ready...starting now" as a warning signal that the testing was being initiated. During testing, window shades were drawn and the researcher administrating the test remained behind the subject to avoid visual distractions.

- *Simple Reaction Time*

The visual stimulus for the simple reaction time test was a bright green circle displayed on a black background. The stimulus duration was 500 msec with a random gap duration of 600 – 1650 msec and a post-stimulus delay of 750 msec (Kray & Lindenberger, 2000). Participants were instructed to press the force sensitive resistor (FSR) as fast as possible with their (right/left) hand when the green circle appeared. Participants performed 30 trials each with their right and left hand for a total of 60 RT trials in both the SIT and WALK conditions.

- *Switch Costs*

The switch cost paradigm used in this study utilized digits from a set (1,2,3,4,6,7,8,9) that were sampled randomly and visually displayed as the stimuli. The two cognitive tasks embedded in the switch cost paradigm were: 1) to classify the digits visually presented as either small/large (1-4 vs 6-9), and; 2) to classify the digits visually presented as odd/even (1,3,7,9 vs 2,4,6,8) (Monsell et al., 2003). Participants were instructed to press their left hand if the digit displayed was small or odd and the right hand if the digit displayed was large or even, for the respective tasks. An "alternating-runs" paradigm (Rogers & Monsell, 1995) was used wherein the task would alternate predictably every 2 trials (see figure 2). Participants were asked to prioritize speed and accuracy equally.

The digits were in "Application Font", in a white font colour on a black background. The numbers were presented with a stimulus duration of 1000 msec and constant gap duration of 2000 msec. A cue ("small/large" or "odd/even") was presented 100 msec prior to the stimulus to assist the individual in keeping track of the task. Each block consisted of 20 clusters with 2 small/large (SL) or odd/even (OE) trials per cluster. Five blocks were performed each for the sitting and walking condition to yield a total of 200 RTs wherein 100 were non-switch RTs (50 NoSwSL and 50 NoSwOE) and 100 were switch RTs (50 SwSL and 50 SwOE) for each postural condition.

Participants were provided with practice trials of the switch cost task prior to testing. This included practice of non-alternating trials of the SL and OE tasks to learn the stimulus-response mappings; 2 blocks of 20 trials for each of the SL and OE tasks. This was followed by practice of the SL and OE tasks in the alternating paradigm; 2 blocks of 20 clusters (1 cluster = 2 trials of SL or OE).

Cluster Number (1-20)	**Cluster 1**		**Cluster 2**		**Cluster 3**		**Cluster 4...**	
Trial Type	*	**NoSwitch**	**Switch**	**NoSwitch**	**Switch**	**NoSwitch**	**Switch**	**NoSwitch**
Task	SL	SL	OE	OE	SL	SL	OE	OE
Digit Displayed	1	4	9	6	7	2	8	7
Correct Response	L	L	L	R	R	L	R	L

Figure 2. Diagram of switch cost paradigm.
This paradigm uses an alternating runs design where the task switches predictably every 2 trials. The small/large (SL) task requires a left (L) hand response if the digit displayed is small (1-4) and a right (R) hand response if the digit displayed is large (6-9). The odd/even (OE) task requires a left hand response if the digit displayed is odd and a right hand response if the digit displayed is even.
*The first digit displayed in not considered a switch trial.

3.2.3 Data Analysis

SigmaStat 3.0® statistical software was used for data analysis. Statistical significance was set at $p \leq 0.05$. Descriptive statistics were used to identify mean and standard deviation of all outcome variables. Pearson Product Moment correlations were used to analyze the degree of association between dual-task changes observed in RT measures and patient characteristics.

Prior to statistical analyses, RT trials with errors (incorrect responses or missed responses) or RTs that were < 100 msec were excluded (Regnaux et al., 2005; Regnaux et al., 2006). Reaction times in trials following an error were not excluded from analysis; these RTs were determined to fall within the 95% confidence intervals of the mean RTs of their respective cognitive task and postural condition. Extreme RT scores or outliers were not removed from the sample. There were no significant differences between the left and right hand SRT responses within sitting or walking conditions for any of the 10 healthy participants; therefore, subsequent analyses were conducted on RT data which combined both hands. All RT data was tested for normality and rank transformation was performed when the data significantly departed from normality. Data analyses to test hypotheses of this study are outlined below.

The Influence of Walking on the Performance of Simple and Complex Cognitive Tasks

Both the mean reaction time in milliseconds (msec) and the variability in SRT using the coefficient of variation (CV = SD/mean SRT X 100) was examined.

Pilot data determined the switch trial of the odd/even (SwOE) task within the switch cost paradigm to be the most complex task as defined by mean duration of reaction time and error rate. Both the mean reaction time (msec) and the variability in SwOE reaction time (CV = SD/mean RT X 100) were examined.

To ensure stability of the SwOE RT across the course of testing, a 1 way repeated-measures analysis of variance (RM ANOVA) was performed, with factors of time (blocks 1-5). There was no significant difference in mean SwOE RT across time in the SIT condition ($F(4,9)= 1.07$, $p=0.385$) but there was a main effect of time in the WALK condition ($F(4,9)=3.80$, $p=0.011$). Therefore, to determine the influence of walking on RT in the simple and complex cognitive tasks, paired t-tests were used to determine differences in the mean SRT in SIT versus WALK conditions and a 2 way RM ANOVA was performed with factors of postural condition (sit vs walk) and time (blocks 1-5) to determine differences in the mean SwOE data in SIT versus WALK conditions.

There was no significant difference in the variability of SwOE RT (%CV) across time (blocks) in the SIT condition ($F(4,9)=0.860$, $p=0.497$) or the WALK condition ($F(4,9)=1.578$, $p=0.201$). Therefore, subsequent analyses were conducted on one CV score (based on the mean and SD of a total of 60 SRT and 50 SwOE RT trials obtained across all 5 blocks) for each postural condition per participant. Paired t-tests were used to determine differences in the variability of SRT and SwOE RT in SIT versus WALK conditions within the healthy group.

As there were no "incorrect" responses (only premature responses) within the SRT task, error rates for this task were not determined. Errors within the SwOE task were defined as all responses on the switch trials of the OE task that were incorrect or RTs that were > 3000 msec (that would indicate a missed response). There was no significant difference in the SwOE errors across time in SIT ($F(4,36)=0.136$, $p=0.965$) or WALK ($F(4,35)=1.246$, $p=0.310$), therefore one SwOE error rate was calculated (# errors / 50 SwOE trials X 100) for each postural condition per participant. An exception occurred for participant #10 where SwOE error rates for the SIT condition were calculated over 40 trials; errors were not counted in one block as they were a result of this participant incorrectly holding the FSR. Paired t-tests were used to determine the difference in error rates between SIT versus WALK conditions in the SwOE cognitive tasks.

Influence of Walking on Switch Costs

Switch costs (msec) were calculated as the difference between the mean SwRT and NoSwRT obtained across all 5 blocks. Analyses for switch costs were conducted on one switch cost score for each participant in sitting and walking conditions. Paired t-tests revealed a significant difference between the switch costs of the SL versus the switch costs of the OE cognitive tasks in sitting ($p=0.032$) and walking ($p=0.047$). Therefore, to determine the differences in switch costs in SIT versus WALK conditions, a 2 way RM ANOVA was used with factors of postural condition (SIT vs WALK) and complexity (SL vs OE).

Switch cost error rates (%) were calculated as the difference between the switch error rates (# errors on switch trials/ 100 total switch trials) and the non-switch error rates (# errors on non-switch trials / 100 total non-switch trials). Analyses for switch cost error rates were conducted one switch cost error rate for each participant in sitting and walking conditions. There was no significant difference in switch cost error rates for the SL or OE cognitive tasks in sitting (p=0.629) or walking (p=0.339), therefore, error data was combined. Paired t-tests were used to determine differences in switch cost error rates in SIT and WALK conditions.

3.3 Results

3.3.1 Participant Characteristics

Ten healthy volunteers (5 males and 5 females) were recruited for this experiment. Characteristics of the participants are listed in Table 1. All subjects were naïve to the objectives and hypotheses of the experiment and reported no neurological or musculoskeletal conditions that might affect their balance or walking abilities. All participants were able to perform the treadmill walking while maintaining a constant velocity and successfully perform the concurrent reaction time task without observable decrement to the walking task or loss of balance.

3.3.2 Influence of Walking on Performance of Simple and Complex Cognitive Tasks

Reaction time values for the SRT and reaction time values and error rates for the SwOE cognitive tasks within sitting and walking conditions are displayed in Table 2. There was no significant difference (p=0.183; Cohen's d= 0.33) between the mean SRT for SIT (290 $\pm$ 24 msec) versus WALK (300 $\pm$ 35 msec) conditions. The mean SwOE RTs in sitting and walking were 677 $\pm$ 171 and 676 $\pm$ 148 msec, respectively. A 2 way RM ANOVA performed on the SwOE RT data, with factors of postural condition (SIT vs WALK) and time (blocks 1-5), confirmed a main effect of time ($F(4,36)=3.214$, $p=0.024$) but no effect of postural condition ($F(1,9)=0.009$, $p=0.925$) and no interaction between postural condition and time ($F(4,36)=2.083$, $p=0.103$). Walking did not significantly influence the reaction times of either the simple or complex cognitive task (see figure 3).

Six of the 10 participants demonstrated a decrease in SwOE RT when walking as compared to sitting and there was a significant decrease for participants #5 and #9 (see Table 2). To determine if these individual responses had an impact on the group effect, analyses were re-run with the data of participants #5 and #9 omitted. The mean SwOE RTs in sitting and walking were 653 $\pm$ 156 and 672 $\pm$ 138 msec, respectively. A 2 way RM ANOVA confirmed a main effect of time ($F(4,28)=4.180$, $p=0.009$) but no effect of postural condition ($F(1,7)=1.012$, $p=0.348$) and no interaction between postural condition and time ($F(4,28)=2.320$ $p=0.082$). With the data of participants #5 and #9 omitted, there was no significant difference in SwOE RT when walking as compared to sitting in the healthy group.

There were no "missed" responses (ie. RTs greater than 3000 msec) for any of the participants in single or dual-task conditions, therefore, all error data represents incorrect responses. There was no significant difference ($p=0.975$; Cohen's d= 0.33) between the mean error rates of the SwOE task in sitting (12 $\pm$ 6%) versus walking conditions (10 $\pm$ 6%) for the healthy group; walking did not significantly influence the error rates of this complex cognitive task. The results of the SwOE RT and error rate data, viewed in aggregate, would also suggest that there was no change in speed-accuracy prioritization across the sit and walk conditions.

Table 1. Characteristics of healthy participants (n=10)

	Group Means (SD)	Totals	*Subject #* 1	2	3	4	5	6	7	8	9	10
Demographic Variables												
Age (yrs)	29 (7)	-	23	34	27	22	22	24	33	31	43	34
Gender (male/female)	-	5/5	M	M	F	M	F	F	F	F	M	M
Education (yrs)	18 (4)	-	15	22	16	14	14	16	22	16	22	22
Hand Dominance (right/left)	-	9/1	R	R	R	R	R	R	R	L	R	R
Height (cm)	173 (11)	-	183	188	157	183	174	165	155	178	175	174
Weight (kg)	75 (15)	-	80	95	65	86	68	50	61	73	89	95
Average Leg Length (cm)	91(8)	-	90	105	MD	95	94	86	77	96	90	86
Balance & Mobility Variables												
Overground Velocity (m/sec)	1.4 (0.2)	-	1.8	1.5	1.0	MD	MD	1.3	1.4	1.5	1.4	1.3
Treadmill velocity (m/sec):												
Preferred	1.0 (0.21)		1.1	1.1	0.9	1.5	1.0	0.9	0.7	0.9	1.1	1.0
% of overground velocity	70 (11)		64	74	88	MD	MD	72	49	65	76	74
Perceived balance confidence*:		-										
In sitting	100(0)		100	100	100	100	100	100	100	100	100	100
In walking single-task	100 (0)		100	100	100	100	100	100	100	100	100	100
In walking dual-task	95 (8.5)		100	80	100	100	100	100	90	100	80	100

MD = Missing data

*Balance confidence rating modified from the Activities-Specific Balance Confidence Scale (Powell & Myers, 1995)

Table 2. Performance on simple and complex cognitive tasks in sit versus walk in the healthy group.

	Participant	Sit (means ± SD)	Walk (means ± SD)	*Dual-task difference (msec)*
SRT	1	255 ± 24	285 ± 32	30**
	2	338 ± 45	343 ± 51	4
	3	303 ± 50	346 ± 81	43**
	4	277 ± 34	273 ± 35	- 4
	5	296 ± 46	352 ± 53	56**
	6	258 ± 23	255 ± 30	- 3
	7	301 ± 49	305 ± 48	4
	8	289 ± 38	271 ± 34	-18*
	9	280 ± 40	279 ± 37	- 1
	10	298 ± 50	296 ± 39	- 3
	Group Mean	290 ± 24	300 ± 35	10 ± 23
SwOE RT	1	569 ± 129	685 + 159	116**
	2	884 ± 235	844 ± 238	-40
	3	657 ± 151	635 ± 148	-22
	4	658 ± 247	684 ± 207	26
	5	959 ± 211	875 ± 187	-84*
	6	489 ± 85	476 + 85	-13
	7	884 ± 241	865 ± 217	-19
	8	496 ± 126	513 ± 146	16
	9	588 ± 128	517 ± 108	-71*
	10	587 ± 149	673 ± 268	86
	Group Mean	677 ± 171	676 ± 148	-1 ± 64
	Participant	**Sit (means ± SD)**	**Walk (means ± SD)**	**Dual-task difference (%errors)**
SwOE Error Rates (%)	1	4	8	4
	2	10	4	-6
	3	10	6	-4
	4	12	20	8
	5	8	2	-6
	6	18	14	-4
	7	24	18	-6
	8	10	14	4
	9	14	10	-4
	10	8	6	-2
	Group Mean	**12 ± 6**	**10 ± 6**	**-2 ± 5**

SRT and SwOE RT (msec) and SwOE error rates (%) are displayed.
Values are mean ± standard deviation. SwOE error rates were calculated as # errors/50 trials X 100 except for participant #10 where error rates in sitting were conducted with 40 SwOE trials. Dual-task difference was calculated as walk – sit RT or error rate, respectively.
*p <0.05; **p<0.001

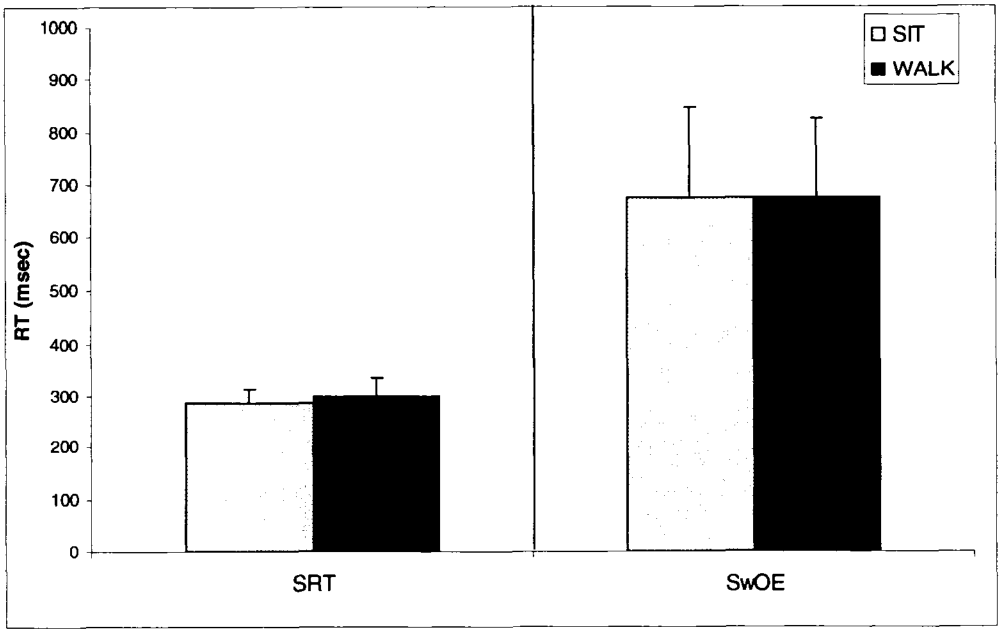

Figure 3. Comparison of mean RTs (msec) in sit versus walk for simple (SRT) and complex (SwOE) cognitive tasks in the healthy group (n=10).
Error bars indicate 1 standard deviation.

The variability of RT (%CV) for the SRT and SwOE cognitive tasks across SIT and WALK conditions is displayed in Figure 4. There was no significant difference (p=0.595; Cohen's d= 0.0) in SRT variability between sit (14 $\pm$ 3 %CV) and walk (14 $\pm$ 3 %CV) conditions. There was no significant difference (p=0.613; Cohen's d= 0.18) in SwOE RT variability in sit (25 $\pm$ 5 %CV) and walk conditions (26 $\pm$ 6 %CV) for the healthy group. Walking did not influence the variability of responses in either the simple or more complex cognitive tasks.

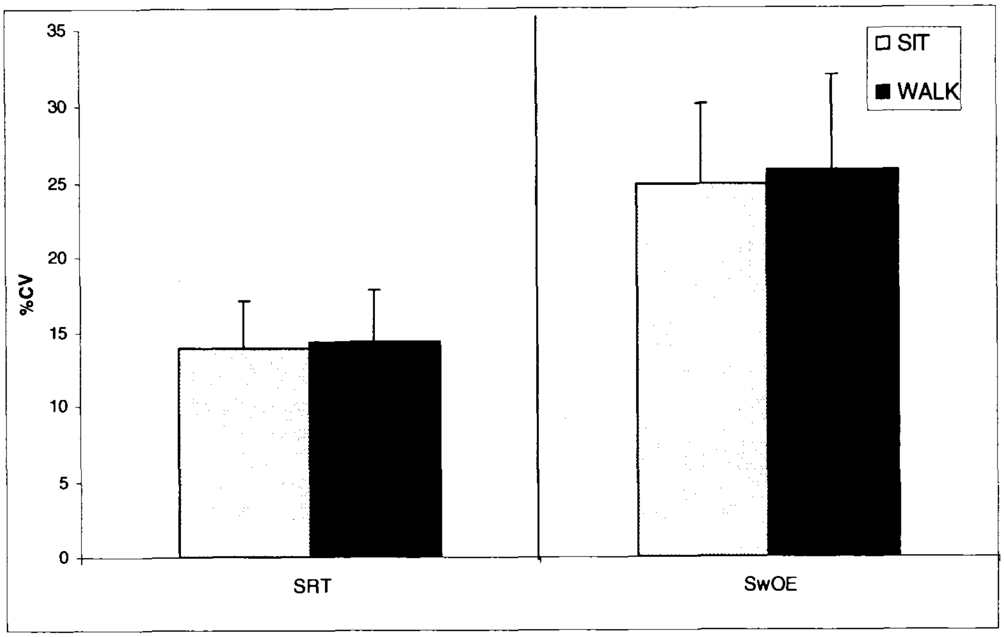

Figure 4. Comparison of mean variability of reaction time (%CV) in sit versus walk for simple (SRT) and complex (SwOE) cognitive tasks in the healthy group (n=10). Error bars indicate 1 standard deviation.

3.3.3 Influence of Walking on Switch Costs (time and error)

Switch costs in time and error of all healthy participants within sitting and walking conditions are displayed in Table 3. Significant switch costs (difference between mean SwRT and NoSwRT) of 68 $\pm$ 53 and 81 $\pm$ 57 msec were demonstrated in sitting ($p=0.003$; Cohen's d= 0.49) and walking ($p=0.001$; Cohen's d= 0.67), respectively. A 2 way RM ANOVA with factors of postural condition (SIT vs WALK) and complexity (SL vs OE) determined that there was no effect of postural condition ($F(1,9)=1.672$, $p=0.228$), a main effect of complexity ($F(1,9)=6.894$, $p=0.028$) but no interaction between postural condition and complexity ($F(1,9)=0.149=0.708$). Walking did not significantly influence switch costs in the healthy group (see figure 5).

Upon examination of the switch cost derivatives, displayed in Table 3, it was noted that some participants demonstrated a decrease in NoSwRT and SwRT, respectively when walking as compared to sitting; post-hoc t-tests revealed a significant decrease in NoSwRT for 2 participants (participant #6; Δ = -27 msec; $p< 0.05$ and participant #9; Δ = -72 msec; $p<0.001$) and a significant decrease in SwRT for 2 participants (participant #5; Δ= -88; $p<0.05$ and participant #9; Δ= -67 msec; $p< 0.05$).

To determine if these individual responses had an impact on the group effect, switch cost analyses of the healthy group were re-run with the data of participants #5, #6 and #9 omitted. The subsequent mean switch cost in sitting was 80 $\pm$ 57 msec and in walking was 99 $\pm$ 59 msec. A 2 way RM ANOVA on the revised group data with factors of postural condition (SIT vs WALK) and complexity (SL vsOE) determined that there was no effect of postural condition ($F(1,6)=1.869$; $p=0.221$), a main effect of complexity ($F(1,6)=7.691$; $p=0.03$) but no interaction between postural condition and complexity ($F(1,6)=0.103$; $p=0.760$). With the data of participants #5, #6 and #9 omitted, there was no significant difference in switch cost when walking as compared to sitting in the healthy group.

The mean switch cost error rate (difference in mean Sw and NoSw error rates) in sitting (3 $\pm$ 4 %) was not significant ($p=0.080$; Cohen's d = 0.82). The mean switch cost error rate in walking (1 $\pm$ 4%) was not significant ($p=0.388$; Cohen's d = 0.565). The difference between switch cost error rates in SIT versus WALK conditions (-2 $\pm$ 5%) was not significant ($p=0.393$; Cohen's d= 0.49). Walking did not significantly influence switch cost error rates (see figure 5).

3.3.4 Influential Factors Affecting Dual-Task Interference

Mean post-test SRT was 286 $\pm$ 28 msec compared to the initial mean SRT of 290 $\pm$ 24 msec. There was no significant difference between initial and post-test SRT ($p=0.681$; Cohen's d= 0.15) suggesting no effect of fatigue on visuomotor responses in the healthy group.

There were no significant correlations between dual-task differences in SRT, SwOE RT or switch cost and factors of baseline reaction times, age, balance confidence, treadmill velocity or treadmill velocity as a % of adjusted over ground velocity. Similarly, none of these factors appeared explanatory for variation at the individual level. For example, in contrast to the group response, participant #1 demonstrated a significant increase in SRT, SwOE RT and a switch cost greater than 2 standard deviations above the group mean when walking as compared to sitting. However, this participant was a 23 year old university student whose treadmill velocity was slightly above the group mean and who reported 100% balance confidence during dual-task conditions.

Table 3. Switch costs in sit versus walk conditions in the healthy group.

Participants	SIT NoSw (msec)	SIT Sw (msec)	SIT SC (msec)	WALK NoSw (msec)	WALK Sw (msec)	WALK SC (msec)	*Dual-task difference in SC (msec)*
1	502 ± 132	505 ± 125	2	495 ± 93	587 ± 164	93**	91
2	713 ± 237	842 ± 235	129**	671 ± 169	816 ± 248	144**	15
3	582 ± 131	634 ± 144	52*	607 ± 151	646 ± 171	39	-13
4	531 ± 148	637 ± 229	106**	536 ± 145	653 ± 244	116**	10
5	804 ± 260	887 ± 235	83*	742 ± 222	799 ± 186	57*	-26
6	446 ± 80	465 ± 102	18	419 ± 95	450 ± 91	31*	13
7	635 ± 176	804 ± 222	168**	609 ± 117	808 ± 249	199**	31
8	405 ± 87	456 ± 114	52**	428 ± 72	487 ± 129	59**	7
9	560 ± 155	583 ± 147	23	488 ± 121	517 ± 115	29	6
10	515 ± 139	562 ± 155	48*	560 ± 142	605 ± 227	45	-3
Group Mean	569 ± 121	637 ± 156	68 ± 53*	556 ± 104	636 ± 134	81 ± 57**	13 ± 31
Participants	NoSwErr (%)	SwErr (%)	**SCErr** (%)	NoSwErr (%)	SwErr (%)	**SCErr** (%)	***Dual-task difference in SCErr (%)***
1	0	3	3	1	4	3	0
2	3	5	2	5	7	2	0
3	6	9	3	8	4	-4	-7
4	2	9	7	3	15	12	5
5	2	5	3	7	1	-6	-9
6	13	11	-2	6	7	1	3
7	5	14	9	6	11	5	-4
8	7	6	-1	7	9	2	3
9	7	10	3	10	9	-1	-4
10	6	8	2	8	8	0	-2
Group Mean	5 ± 4	8 ± 3	3 ± 3	6 ± 3	8 ± 4	1 ± 5	-2 ± 5

Reaction time values (msec) and error rates (%) for switch costs (SC) and derivative switch (Sw) and non-switch (NoSw) trials in sit and walk conditions and dual-task differences for healthy participants (n=10). Dual-task difference was calculated as walk – sit switch cost (RT or error rate).

Values are mean ± 1 standard deviation. *$p < 0.05$; **$p < 0.001$

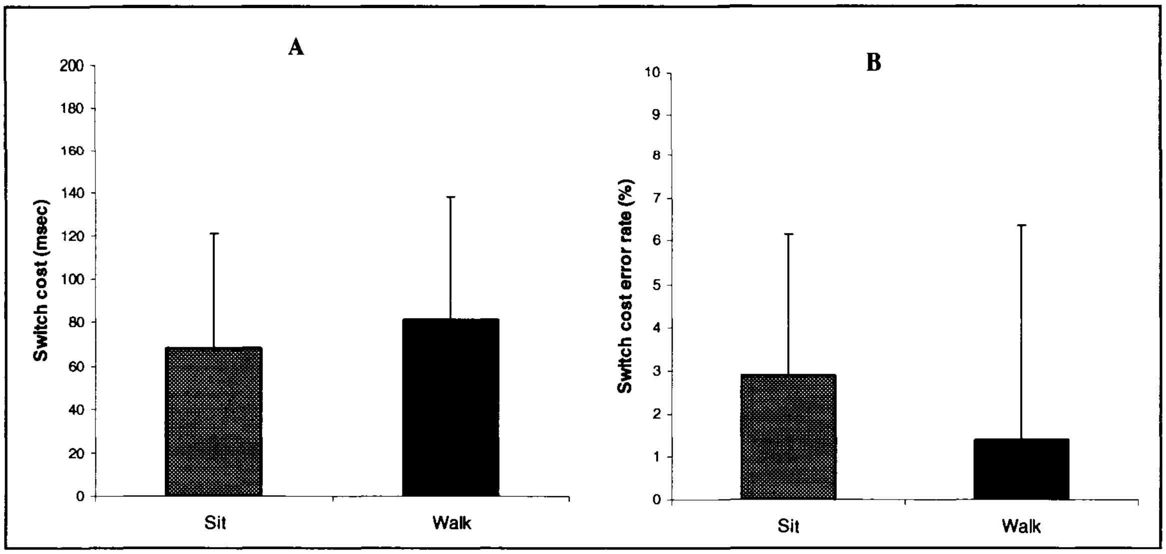

Figure 5. Comparison of switch costs (time and error) in sit versus walk conditions in the healthy group

Comparison of switch costs in time (A) and error (B) across sitting and walking conditions for the healthy group (n=10). Error bars indicate 1 SD.

Switch costs (time) = Mean SwRT – NoSwRT

Switch costs (error) = Mean Sw error rate – NoSw error rates

3.4 Discussion

In support of the hypothesis, there was no effect of walking on the mean or variability of SRTs within the healthy group; the healthy group did not modify their responses within the simple task when walking. In refute of the hypothesis, there was no effect of walking on the mean, variability or error rate of the more complex SwOE task. The baseline mean SwOE RT was 387 msec greater than the baseline mean SRT, confirming the SwOE to be more complex however, walking did not influence the responses of this more complex task in the healthy participants.

Switch costs were demonstrated in sitting and walking conditions independently, where the healthy young adults required a significantly longer time to initiate responses on "switch" versus "non-switch" trials. This finding is consistent with other studies (S. Monsell, 2003). However, in refute of the hypothesis, walking did not significantly increase switch costs in the healthy group.

This is the first study to use the switch cost paradigm or specifically probe the temporal aspects of attention within a dual-task walking paradigm so there are no other studies to which these results can be directly compared. Based on existing literature, there are several possible interpretations of the lack of effect in the healthy young. It was noted that there was a tendency for some healthy participants to demonstrate faster RTs when walking and there was a significant decrease in NoSw RT when walking as compared to sitting for participants #6 and #9 and a significant decrease in SwRT and SwOE RT when walking as compared to sitting for participants #5 and #9. It is possible that for some participants there was an overall heightened response when walking and performing the switch cost paradigm that influenced the switch cost and SwOE RT (as a sub-task of the paradigm) under dual-task conditions. "Enhanced" effects during dual-task paradigms have been observed in other studies. While standing and performing concurrent cognitive tasks, healthy young adults have demonstrated decreases in COP sway (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Brown, Sleik, Polych, & Gage, 2002; Dault et al., 2001; Dault, Geurts et al., 2001; Huxhold et al., 2006; Vuillerme, Nougier, & Teasdale, 2000; Weeks, Forget, Mouchnino, Gravel, & Bourbonnais, 2003) and decreases in COP variability (Riley, Baker, & Schmit, 2003; Riley, Baker, Schmit, & Weaver, 2005). Grabiner & Troy also found healthy young adults decreased their step width variability while treadmill walking and concurrently performing the Stroop test (Grabiner & Troy, 2005). A study by Brown and colleagues found that COP sway decreased and, of potential relevance to this study, that cognitive performance also improved under dual-task conditions when postural threat increased (Brown, Sleik, Polych et al., 2002). The enhanced effects were associated with an increase in arousal as measured by galvanic skin conductance, demonstrated also in other dual-task studies (Maki & Whitelaw, 1993; Maki & McIlroy, 1996). Of the three participants in our study who demonstrated significantly improved performance on the cognitive tasks during walking, only participant #9 reported a decrease in the dual-task balance confidence rating, which may be indicative of perceived balance-related anxiety.

This study did not directly measure arousal, however, it is possible that the complexity of the cognitive task combined with the more challenging walking task (as compared to sitting) could have caused some participants to "sharpen" their responses; an energizing effect of arousal could have resulted in improved performance for some participants. Thus, it is plausible that arousal within some healthy participants caused faster RTs within the switch cost paradigm when walking. However, is noteworthy that there was still no significant change in SwOE RT or switch costs when the data of the three participants, who demonstrated significant decreases in RT when walking, was removed from analyses. Therefore, whereas influences of balance-related anxiety and arousal when walking may be worthy of consideration and should be measured more directly in future research, these factors may not be completely explanatory of the negative findings in this study.

Alternatively, treadmill walking may have been not sufficiently attentionally-demanding for the healthy young population to demonstrate an effect of the cognitive task, irrespective of its complexity. This would be consistent with the findings of Kurosawa (Kurosawa, 1994) and Regnaux (Regnaux et al., 2005) who combined SRTs using auditory and electrical stimulus, respectively, with sitting and walking on a treadmill and found no difference in RT between postural conditions in a healthy group of participants. Regnaux and colleagues (Regnaux et al., 2006) also compared the effects of a simple RT and choice RT task, using a bite response to varying intensities of an electrical stimulus and found no difference between the secondary simple and choice RTs of a healthy group when treadmill walking. Arguably, the choice RT task used in the former study was less complex than the probe switch task used in this research (which involves a choice RT within the course of switching tasks). However, it is possible that, once initiated, treadmill walking became a more automatic "steady-state" walking task and, as these previous studies suggest, required little attentional demand. As such, attentional resources could be more fully devoted to the cognitive task irrespective of its complexity and processes involved in the re-allocation of attention or attention switching may not have been required.

Given that other studies have demonstrated that secondary responses, and hence attentional demands, can vary within the course of the gait cycle (Gage, Sleik, Polych, McKenzie, & Brown, 2003; Lajoie et al., 1993) during walking, an alternative interpretation may be that temporal dynamics of attention were still at play while treadmill walking. However, the efficiency and rapidity of attention switching combined with the low attentional demands of treadmill walking within the healthy young group, may have limited the extent of the dual-task interference as measured by the switch costs.

4.0 Experiment 2: Attentional Demands of Walking after TBI – Probing Complex Cognitive Tasks and Attention Switching

4.1 Introduction

It has been documented that individuals after TBI achieve independent ambulation in the early stages of recovery from brain injury (Katz et al., 2004; Swaine & Sullivan, 1996). Conversely, symptoms of impaired balance and instability when walking have been cited as primary, long-term concerns even for community-dwelling, ambulatory individuals with TBI (Basford et al., 2003; Chou et al., 2004; Dean, Colantonio, Ratcliff, & Chase, 2000a; Hillier et al., 1997; Powell et al., 2001) suggesting that evaluation of their balance and mobility issues requires further exploration.

Successful walking within the course of daily activity requires attention to multiple stimuli and tasks. Deficits in attention after TBI have been well-documented (Ponsford & Kinsella, 1995; Sohlberg & Mateer, 1987; Stuss et al., 1989; van Zomeren & Deelman, 1976). However, there are surprisingly few studies that have explored the relationship of attention and locomotor dyscontrol after TBI. It has been shown that when walking under dual-task conditions, concussed athletes exhibit shorter stride lengths, slower anterior/posterior COM velocity, and increased mediolateral COM displacement relative to healthy controls, suggestive of dynamic instability (Parker et al., 2005; Parker et al., 2006). In the one published study of those with moderate to severe TBI, it was demonstrated that decrements in both cognitive performance (Stroop reading times) and walking performance (stride lengths and walking velocity) occur, in comparison to healthy controls, when the complexity of the cognitive task and locomotor task (wide obstacle avoidance) are manipulated (Vallee et al., 2006).

Given the paucity of studies to date, the objective of the research was to explore further the attentional demands of walking in people with TBI who demonstrate high levels of functional mobility. Replicating the study in Experiment One and using the normative data obtained from it, we specifically set out to investigate whether cognitive tasks that probed the timing of attention switching would be affected by walking in those with TBI, as compared to healthy peers. Further, the paradigm enabled us to explore the influence of cognitive task complexity on dual-task interference by examining performance on a simple visual RT task and a more complex choice visual RT task within the switch cost paradigm. The following were the hypotheses of the second study:

1) The influence of walking on a simple cognitive task

It was hypothesized that walking (as compared to sitting) would result in a significant increase in mean and variability of SRT within the TBI participants, as compared to healthy peers.

2) The influence of walking on a complex cognitive task

It was hypothesized that walking (as compared to sitting) would result in a significant increase in mean and variability of SwOE RT and significant increase in SwOE error rates within the TBI participants, as compared to healthy peers.

3) The influence of walking on cognitive measures of attention switching

It was hypothesized that walking (as compared to sitting) would result in significant increases in switch costs of time and error in the TBI participants, as compared to healthy peers. We proposed that increased switch costs when walking would implicate delays in the re-allocation or switching of attention between walking and the cognitive task as a source of decrement in dual-task performance after TBI.

4.2 Methods

A non-consecutive case series design was used. Individual participant performance was compared to healthy group data obtained from Study One.

4.2.1 Participants

All TBI participants were enrolled in a larger study examining recovery of cognitive and motor functions; thus, the patients in this study met the inclusion and exclusion criteria for the larger study, as well as further specific criteria for the present study.

The inclusion criteria for the larger study were:

- diagnosis of TBI in acute care
- post-traumatic amnesia 1 hour or more and/or Glasgow Comas Score of 12 or less either at hospital Emergency department or the scene of accident

- positive CT or MRI findings (based on clinical records)
- able to follow simple commands in English based upon the Speech Language Pathology intake assessment
- competency to provide informed consent for study or availability of legal decision maker.

Further inclusion criteria for the present study were:

- individuals between the age of 18 – 50 years of age
- ability to ambulate on a treadmill with no upper extremity support required

Exclusion criteria for the larger study were:

- history of psychotic disorder
- diseases primarily or frequently affecting the central nervous system
- not emerged from post-traumatic amnesia by 6 weeks post-injury, as measured by the Galveston Orientation Amnesia Test
- TBI secondary to other brain injury (e.g., a fall due to stroke)

Further exclusion criteria for the current study were:

- any musculoskeletal injury that might affect their balance or walking abilities
- any visual deficits not corrected by glasses

4.2.2 Protocol and Measures

The study protocol was approved by the Research Ethics Board of the Toronto Rehabilitation Institute, the Research Ethics Board of the Sunnybrook Health Sciences Centre and the Ethics Review Unit of the University of Toronto. Informed written consent was obtained from all participants prior to participation in this study. The protocol used in this study was a replication of Experiment One (see 3.2.2) except for the following.

In addition to the participant characteristics collected in Experiment One, data related to diagnosis, time of injury, relevant medical history and current medications were collected. As per Experiment 3.0, measures characterizing the participant's balance and mobility performance included treadmill and overground gait velocity (m/sec) and perceived balance confidence (%) while performing the dual-task paradigm. Additional data was also obtained from the measures performed as part of the larger study which is tracking cognitive and motor performance over time. Specifically, this included: 1) balance and mobility performance, as measured by the Clinical Outcomes Variables Scale (Seaby & Torrance, 1989) and the Community Balance & Mobility Scale (Howe et al., 2006), and; 2) cognitive performance as measured by the Trail Making Test Part B (Trails B) (Reitan & Wolfson, 1985). A description of these measures is outlined below:

Clinical Outcome Variables Scale (COVS)

The COVS is a measure of functional independence and the mobility items specifically include walking independence, endurance, velocity and use of walking aids (Seaby & Torrance, 1989). It is a 10-item, 7-point scale with a total score of 91 and has been found to be a reliable measure for use within the neurological patient population.

The Community Balance & Mobility Scale (CB&M)

The CB&M measures performance of more challenging balance and mobility tasks that require speed, precision, accuracy and sequencing of movement components (Howe et al., 2006; Inness et al., 2004). Examples of some items include tandem walking, rapid step-ups, rapid lateral cross-overs, transitioning from forward to backward walking and walking while looking at laterally-placed targets. It is a 13-item, 6-point scale with a total score of 96 and has been found to be a reliable and valid measure for use with the ambulatory TBI population.

Trail Making Test Part B (Trails B)

The Trails B measures complex visual scanning, flexibility in attention shifting and psychomotor speed (Reitan & Wolfson, 1985; Lezak 1995, p.381). Specifically, individuals must connect circles randomly distributed on a page as quickly as possible by alternating sequentially between those that are labeled by number and those that are labeled by a letter. The score is reported as the time required to complete the task. All scores were interpreted by a neuropsychologist and raw scores were transformed into T-scores based on age-, sex- and education-adjusted normative data (Spreen & Strauss, 1998).

Due to issues related to feasibility of scheduling and participant burden, the above-mentioned tests were administered at separate time points than the current study for 4/5 participants. However, total scores on clinical measures for the last two time points of testing were stable for both the COVS and the CB&M and, therefore, the last test score was used. The exception would be for participant #11 who demonstrated total CB&M scores of 68/96, 74/96 and 66/96 when tested 3, 6 and 12 months post-injury; this participant was tested at 15 months post-injury for the present study. An average of CB&M scores was, therefore, used as representative of this participant's balance abilities. Similarly, Trails B T-scores were stable for the last two time points of testing and, therefore, the last test score was used except for participant #11 and #12. Participant #11 demonstrated Trails B T-scores of 38, 46 and 34 when tested at 3, 6 and 12 months post-injury and participated in this study at 15 months post-injury. Participant #12 demonstrated Trails B T-scores of 29 and 33 at 3 and 6 month months post-injury and was tested for this study at 9 months post-injury. An average of the Trails B T-scores was used for these two participants to represent their cognitive performance.

4.2.3 Data Analysis

To compare difference in performance between participants with TBI and healthy peers, 95% confidence intervals (CIs) about the average performance of the healthy group were determined (from Experiment One data) for SRT, SwOE RT , SwOE error rates and switch costs (time and error). Significant differences were inferred when RT or error rate values of the TBI participants deviated outside the bands determined for the healthy group.

Trials with errors (incorrect or missed responses) or with RTs that were < 100 msec were excluded from the analysis. Extreme RT scores or outliers were not removed from the sample. There were no significant differences between the left and right hand SRT responses within sitting or walking conditions for any of the 5 participants with TBI; therefore, subsequent analyses were conducted on RT data which combined both hands.

As per Experiment One, SRT and SwOE RTs were used to test hypotheses related to the influence of walking on concurrently-performed simple and complex cognitive tasks in those with TBI. To ensure stability of the SwOE RT data across the course of testing, a 1 way ANOVA was performed with the factor of time (blocks 1-5), in sit and walk conditions, for each of the 5 participants. There was no effect of time within the sitting condition ($p=0.966$, $p=0.979$, $p=0.999$, $p=0.580$, $p=0.986$) for participants #11, 12, 13, 14 and 15, respectively. There was no effect of time within the walking condition ($p=0.242$, $p=0.073$, $p=0.410$, $p=0.334$) for participants #11, 12, 14, and 15, respectively. There was a main effect of time ($F(4,40)=3.626$; $p=0.013$) within the walking condition for participant #13. Therefore, subsequent analyses of SwOE RT were performed on data that was combined across blocks for sit and walk conditions, respectively. T-tests were used to determine significant differences in SRT and SwOE RT for sit versus walk conditions for individual TBI participants, with the exception of participant #13 where a 2 way ANOVA with factors of postural condition (SIT vs WALK) and time (blocks 1-5) was conducted for SwOE RT data. Comparisons between TBI participants and the healthy group were conducted using: 1) one mean SRT and SwOE RT value for each postural condition per TBI participant; 2) one %CV score (based on the mean and SD of a total of 60 SRT and 50 SwOE RT trials obtained across all 5 blocks) for each postural condition per TBI participant, and; 3) one SwOE error rate (# errors / 50 SwOE trials X 100) for each postural condition per TBI participant. An exception occurred for participant #12 where SwOE RT and SwOE error rate values for the WALK condition were calculated over 40 trials; one block of data was removed due to the participant inappropriately holding the FSR.

Comparisons between values for TBI participants and the healthy group were also conducted using one switch cost score (the difference between the mean RT of the Sw and NoSw trials combined across blocks) for each postural condition per TBI participant. As a significant difference was demonstrated between switch cost values derived from the small/large versus odd/even sub-tasks in Experiment One, ($p=0.032$ and $p=0.047$ for sitting and walking, respectively), comparisons between TBI participants and the healthy group were conducted on switch costs with both combined and separate SL and OE switch costs for sit versus walk conditions.

4.3 Results

4.3.1 Participant Characteristics

Five community-dwelling participants diagnosed with a first-time TBI (3 males and 2 females) were recruited. All subjects were naïve to the objectives and hypotheses of the experiment. Characteristics of the individuals with TBI and comparisons with that of the healthy group are outlined in Table 4. Four of the 5 participants had documented severe brain injuries as per their GCS (range 3-7) whereas participant #14's GCS was not known. Neuro-imaging results confirmed evidence of TBI for all subjects. None of the TBI participants were taking medication. The participants ranged from 5 to 23 months post-injury. Participant COVS scores were at or approaching the ceiling and all participants received 7/7 on COVS walking item scores which indicated they were able to walk independently over environmental barriers with no aide required, with a minimum velocity of 0.9 m/sec (see Table 4 for actual overground velocities) and endurance of 500 metres. The TBI participants were similar to the healthy group with respect to age ($p=0.298$), over ground walking velocity ($p=0.46$) and treadmill velocity ($p=0.712$). There was a significant difference between the healthy group and TBI participants' years of education ($p=0.027$). The years of education tended to be lower for the TBI participants (mean=14 ± 2; range 12-16 years) than that of the healthy group (mean 18 ± 2; range 14-22years) but all had completed secondary education. All TBI participants were able to perform the treadmill walking while maintaining a constant velocity and successfully perform the concurrent reaction time task without observable decrement to the walking task, loss of balance or need for upper extremity support.

Table 4. Characteristics of participants with TBI and healthy group comparisons

	Healthy Group (n=10)	TBI Group (n=5)	*Participants with TBI*				
Participant	**1- 10**	**11-15**	**11**	**12**	**13**	**14**	**15**
Demographic Variables							
Age (years)	29 (7)	36 (12)	38	49	28	21	46
Gender (male:female)	5:5	3:2	male	male	female	male	female
Education (years)	18 (4)	14 (2)	12	12	14	14	16
Hand Dominance (right:left)	9:1	3:2	left	left	right	right	right
Height (cm)	173 (11)	168 (16)	173	152	163	193	161
Weight (kg)	76 (15)	74 (21)	91	68	46	100	66
Average Leg Length (cm)	91 (8)	87(3)	85	87	83	92	84
Brain Injury Variables							
Time since Injury (months)	-	15 (7)	15	9	5	23	20
GCS at injury (score)	-		3	7	7	unknown	6
Cognitive Variable							
Trails B (T-score)	-	-	39	31	57	78	47
Balance & Mobility Variables							
Overground walking velocity (m/sec)	1.4 (0.2)	1.5 (0.2)	1.2	1.5	1.3	1.6	1.8
Treadmill velocity (m/sec):							
Preferred	1.0 (0.2)	1.0 (0.2)	0.8	0.9	0.8	1.2	1.3
% of over ground velocity	70 (11)	65 (7)	63	59	58	76	69
COVS score (x/91)	-	90 (1)	89	91	90	91	90
CB&M score (x/96)	-	80 (10)	69	75	84	91	83
* Balance confidence (%):							
In sitting	100 (0)	100 (0)	100	100	100	100	100
In walking single-task	100 (0)	96 (9)	100	100	80	100	100
In walking dual-task	95 (8.5)	88 (13)	70	80	90	100	100

Values represent the mean (SD) or n.
GCS = Glascow Coma Score. CB&M = Community Balance & Mobility Scale. COVS = Clinical Outcomes Variable Score
Trails B = Trail Making Test Part B
Balance confidence ratings adapted from the Activities-specific Balance Confidence Scale (Powell & Myers, 1995)

4.3.2 Influence of Walking on Simple and Complex Cognitive Tasks

Table 5 summarizes the reaction time values for the SRT task and reaction time values and error rates for the SwOE cognitive task, within sit versus walk conditions, for each TBI participant. A comparison of TBI participant SRT and SwOE RT values to those of the healthy group is displayed in Figure 6. Baseline SRTs for participants #11 and 15 (323 and 366 msec, respectively) were significantly greater than those of the 95% CIs (275 – 305 msec) of the healthy group. Walking significantly delayed the onset of the SRT responses as compared to sitting in 4/5 individuals with TBI. Dual-task differences for these subjects ranged from 35 – 57 msec ($p < 0.001$ for all) and were greater than the 95% CIs (-3 to 26 msec) determined within the healthy group.

The baseline SwOE RTs for 4/5 participants were within or at the upper margins of the 95% CIs (571-783 msec) of the healthy group whereas participant 11's baseline SwOE RT was significantly greater at 1036 msec. Participant #15 demonstrated a significant increase in SwOE RT of 105 msec ($p < 0.05$) when walking that was greater than the 95% CIs (-40 – 39 msec) of the healthy group. Participant #13 demonstrated an increase in SwOE RT of 34 msec when walking that was approaching significance, as compared to the healthy group CIs. The other TBI participants did not demonstrate a significant change in response time when walking and performing this complex cognitive task (see figure 6).

Baseline SwOE error rates were significantly greater than healthy group CIs (8 – 15%) for participant #11 and #14 at 20% and 18%, respectively. The change in SwOE error rates when walking rose marginally above the 95% CIs (-5 – 2%) for participant #12 and 13, with an increase in error rates, by 3% and 4% respectively (see figure 7). It is noteworthy that these individuals demonstrated error rates at baseline that were significantly less than those of their healthy peers and remained within or below values of the healthy group when walking. The SwOE error rates of the other TBI participants did not significantly change when walking

Table 5. Performance on simple and complex cognitive tasks and dual-task differences for those with TBI compared to the healthy group

	Participant #	Sit means ± SD	Walk means ± SD	*Dual-Task Difference*
SRT	11	323 ± 34	370 ± 68	47 **†
	12	301 ± 35	358 ± 51	57 **†
	13	296 ± 36	304 ± 53	8
	14	303 ± 36	338 ± 64	35 **†
	15	366 ± 57	413 ± 66	47 **†
	Healthy Group	290 ± 24	300 ± 35	10 ±23
	95% CI	275 - 305	279 - 322	-3 - 26
SwOE RT	11	1036 ± 285	1046 ± 384	10
	12	750 ± 153	754 ± 154	4
	13	789 ± 136	823 ± 141	34
	14	637 ± 141	633 ± 163	-4
	15	788 ± 260	893 ± 218	105*†
	Healthy Group	677 ± 171	676 ± 148	-1 ± 64
	95% CI	571 - 783	585 - 768	-40 - 39
SwOE Error Rates (%)	11	20	20	0
	12	0	3	3†
	13	6	10	4†
	14	18	16	-2
	15	10	8	-2
	Healthy Group	12 ± 6	10 ± 6	-2 ± 5
	95% CI	8-15	6-14	-5 - 2

Mean SRT (msec) and mean SwOE RT and error rates(%) in sit and walk conditions and dual-task differences for TBI participants and healthy group (n=10). Values are means ± standard deviations.
Error rates were calculated as (#SwOE errors/ #SwOE trials) X 100 with a total of 50 SwOE trials for each sit and walk condition.
Dual-task difference was calculated as mean walk – sit RT or error rate, respectively.
*p <0.05; **p<0.001; † values outside of the 95% confidence interval for the healthy group

A B

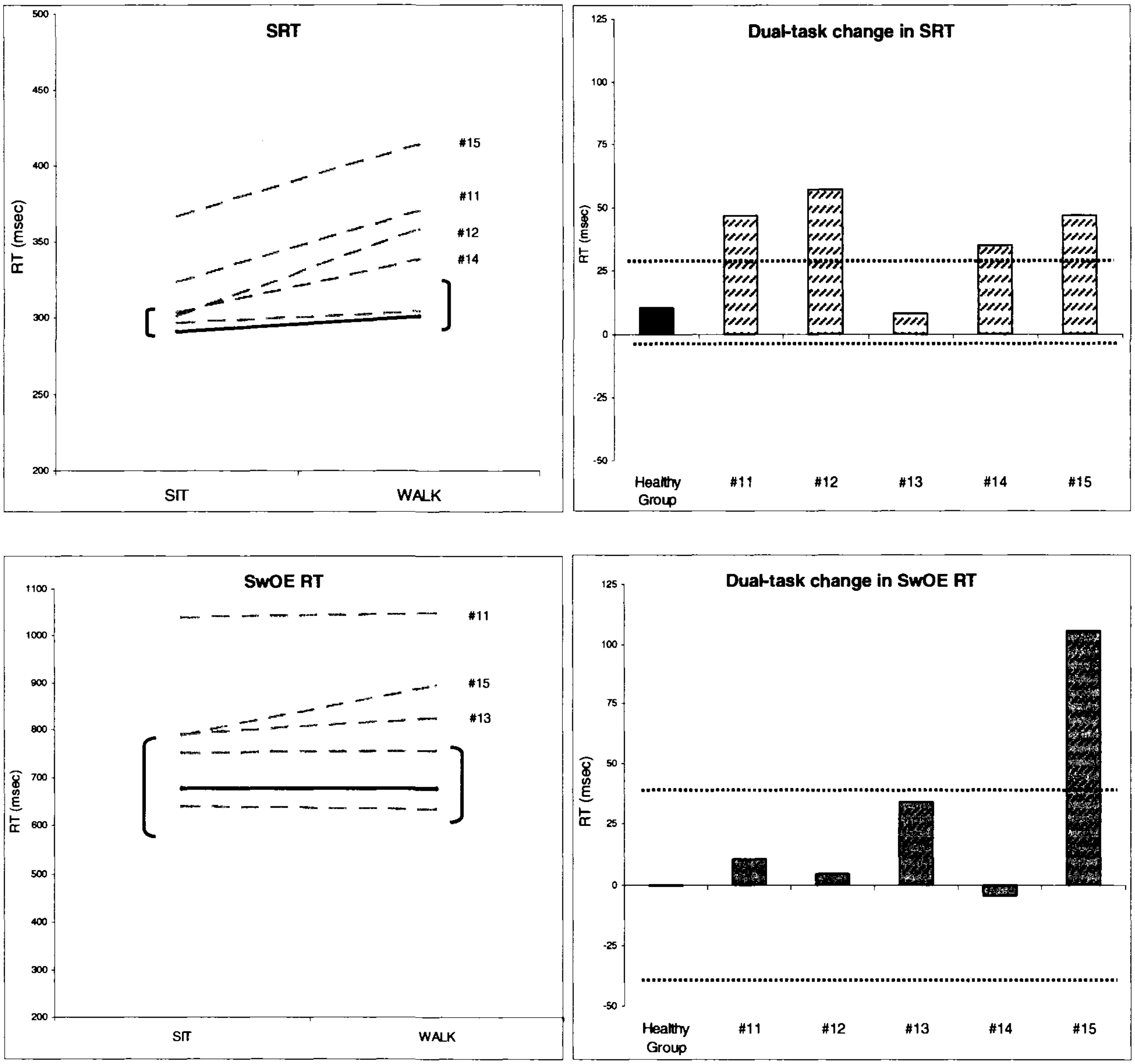

Figure 6. Comparison of mean reaction times in sit versus walk for simple and complex cognitive tasks in TBI participants as compared to the healthy group.
Comparison of mean RTs (msec) of SRT and SwOE cognitive tasks performed in sitting versus walking (A) and dual-task differences (B) for the healthy group (n=10) and individuals with TBI.
Solid lines in A represent healthy group mean RTs. Dashed lines in A represent TBI participant RTs. Black parentheses in A and dotted lines in B indicate 95% CIs of healthy group.

A B

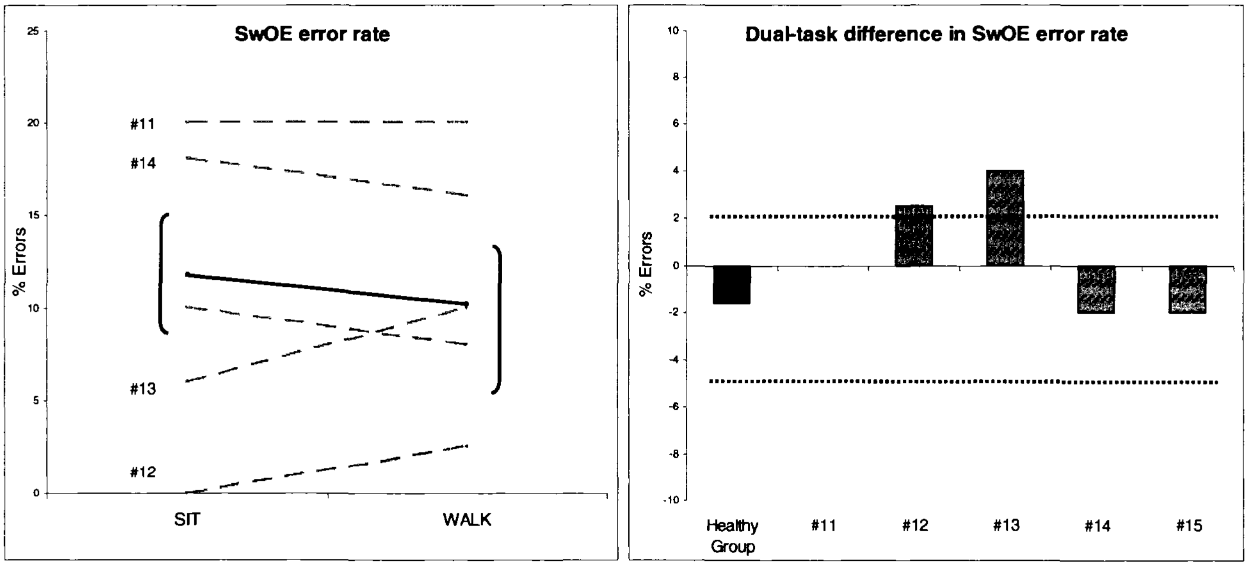

Figure 7. Comparison of SwOE error rates in sit versus walk conditions (A) and dual-task differences (B) for the TBI participants and the healthy group.
Solid lines in A represent healthy group mean error rates. Dashed lines in A represent mean error rates of TBI participants. Black parentheses in A and dotted lines in B indicate 95% CIs of the healthy group.

Changes in variability of RT (%CV) within the SRT and SwOE cognitive tasks when walking are displayed in Figure 8. Baseline SRT values for the TBI participants were all within or slightly below the 95% CIs of the healthy group. Walking increased the variability (%CV) of the SRT responses as compared to sitting in 3/5 individuals with TBI. Participants #11, 13 & 15 demonstrated dual-task increases in SRT variability of 8, 5 and 7 %CV, respectively compared to the healthy group 95% CI of -1 to 2 %CV.

In the SwOE task, baseline RT variability values for the TBI participants were within or slightly lower than the healthy CIs except for participant #15. The change in RT variability for the SwOE task varied across participants, with #11 demonstrating a significant increase (9 %CV) while #15 demonstrated a significant decrease in RT variability (-9%CV) when walking as compared to their healthy peers (95% CIs: -2 to 4 %CV). The variability of SwOE RT did not change significantly when walking for the other TBI participants.

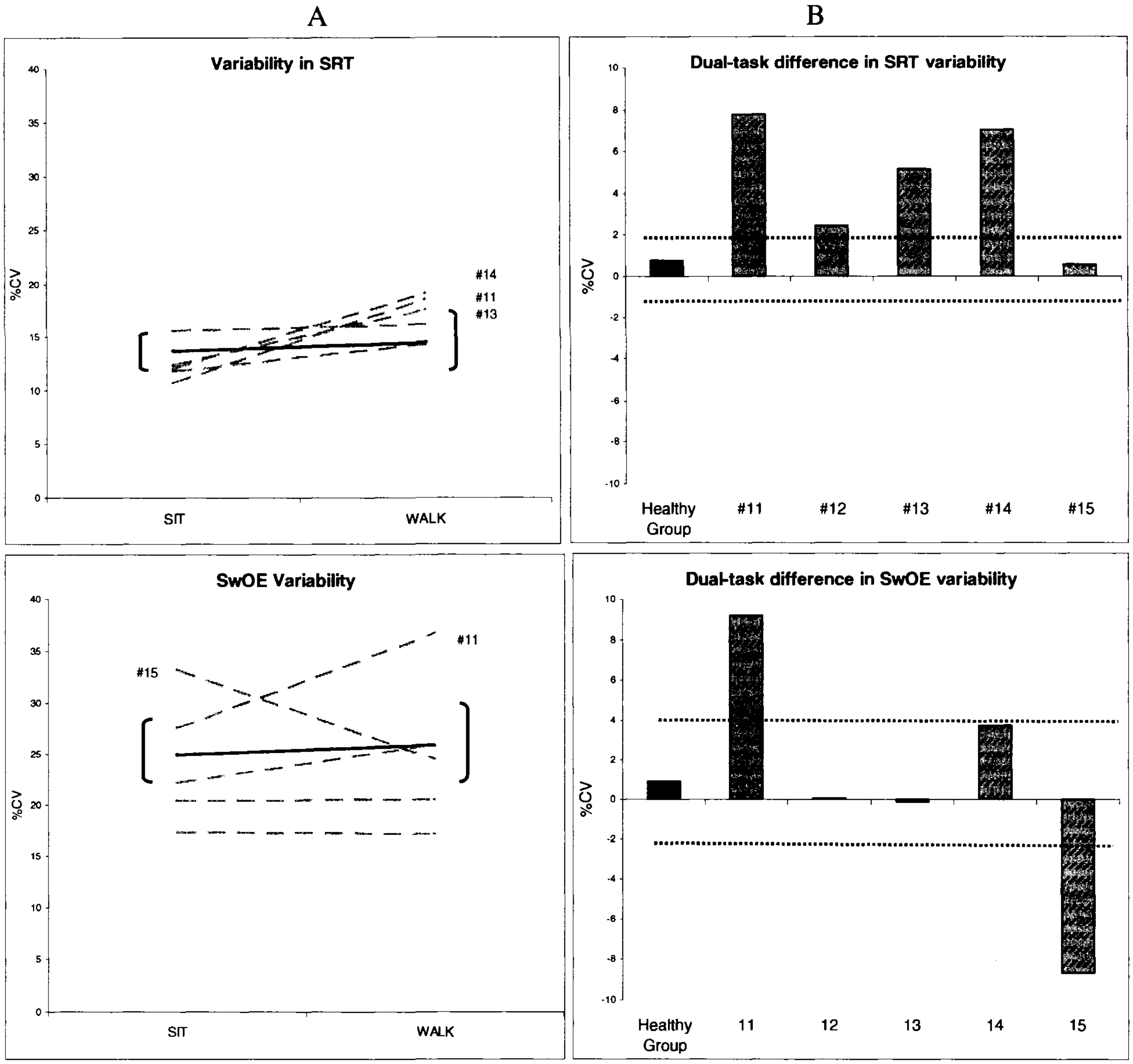

Figure 8. Comparison of mean variability of reaction time in sit versus walk for simple and complex cognitive tasks in TBI participants and healthy group.

Comparison of variability in RTs (%CV) of SRT and SwOE cognitive tasks performed in sitting and walking (A) and dual-task differences (B) for the participants with TBI and the healthy group (n=10). Solid lines in A represent mean RTs for healthy group. Dashed lines in A represent mean RTs for TBI participants. Black parentheses in A and dotted lines in B indicate 95% CIs of healthy group.

4.3.3 Influence of Walking on Switch Cost

Switch cost values and their NoSw RT and SwRT derivatives, for all TBI participants and the healthy group, across sub-tasks and postural conditions, are displayed in Table 6. All participants with TBI demonstrated significant switch costs in SIT and WALK conditions (significant differences between mean SwRT and NoSw RTs) except for participant #12 in the sitting condition. Participants #13 and #15 tended to have baseline switch costs that were at the margins or slightly greater than the 95% CIs of the healthy group. Participant #11 demonstrated significantly greater baseline switch costs than the healthy group, but only within the more complex OE task.

Comparisons of switch cost values, across SIT to WALK conditions for the TBI participants versus the healthy group, are displayed in Figure 9. When examining the switch costs overall and separately for the SL and OE tasks, participants #11, #12 and #13 demonstrated dual-task increases in switch costs that were greater than their healthy counterparts. Participant #11 demonstrated a significant increase in switch cost of 70, 89 and 54 msec for the combined, SL and OE data, respectively. Participants #12 and #13 also demonstrated significant increases in switch costs of 39 and 50 msec, respectively but derived from the SL task only. In contrast, participant #15 demonstrated a significant decrease in SL switch costs (-42 msec) but increase in OE switch costs (34 msec but not significant) when walking versus sitting, as compared to healthy peers.

As it would seem that there were varying dual-task differences in switch costs on the SL versus the OE task, these switch costs and their NoSw RT and SwRT derivatives were further analyzed (see figure 10) for participants #11, 12, 13 and 15. It is apparent that SwOE RTs were greater than SwSL RTs for all participants when walking, as expected. Participants #11 and #12 demonstrated a decrease in NoSw RT, to a greater extent within the "easier" SL task, when walking. This was also apparent, but less so, in the NoSw RTs in the SL task for participant #13 but who also had a smaller SL switch cost in sitting. Hence, there was a greater relative increase in SL switch cost (SwRT – NoSw RT) when walking for these participants. In contrast, participant #15 demonstrated a progressive increase in RT when walking across cognitive tasks. However, the switch cost increased proportionately less within the SL task and proportionally more within the OE task when walking as compared to sitting.

Table 6. Mean switch costs (msec) in sitting and walking and the dual-task difference for TBI participants as compared to the healthy group.

Participants	Sit			Walk			*Dual-Task Difference*
	NoSw	**Sw**	**SC**	**NoSw**	**Sw**	**SC**	**SC**
#11	763 (188)	903 (270)	**140**†**	699 (189)	909 (135)	**210**†**	**70†**
#12	696 (116)	733 (141)	37	668 (118)	728 (146)	**60***	22
#13	663 (141)	770 (139)	**107**†**	669 (130)	804 (153)	**135**†**	28
#14	568 (125)	637 (146)	**69****	566 (135)	626 (145)	**60***	-9
#15	644 (157)	755 (224)	**111**†**	705 (211)	817 (233)	**112****	0
Healthy Group	569 (121)	637 ± 156	68 (53)	556 ±104	637 ± 135	81 (57)	13 (31)
95% CI			35 - 101			46 - 116	-6 - 33
	NoSwSL	**SwSL**	**SCSL**	**NoSwSL**	**SwSL**	**SCSL**	**SCSL**
#11	711 (169)	780 (188)	69	629 (130)	786 (225)	**157**†**	**89†**
#12	670 (95)	706 (118)	36	624 (108)	700 (138)	**76***	**39†**
#13	660 (148)	752 (143)	**93**†**	647 (143)	790 (161)	**143**†**	**50†**
#14	564 (114)	635 (154)	**71***	557 (139)	619 (126)	**62***	-10
#15	625 (171)	722 (177)	**97*†**	681 (201)	736 (223)	55	**-42†**
Healthy Group	541 (114)	598 (146)	57 (52)	533 (100)	596 (127)	63 (55)	6 (46)
95% CI			24 – 88			28 – 97	-22 – 34
	NoSwOE	**SwOE**	**SCOE**	**NoSwOE**	**SwOE**	**SCOE**	**SCOE**
#11	814 (194)	1036 (285)	**222**†**	771 (214)	1046 (384)	**275**†**	**54†**
#12	723 (129)	750 (153)	27	714 (111)	754 (154)	40	13
#13	666 (134)	789 (136)	**123****	691 (113)	823 (141)	**132****	9
#14	572 (137)	637 (141)	**65***	575 (133)	633 (163)	58	-7
#15	662 (141)	788 (260)	**126***	730 (221)	893 (218)	**163**†**	37
Healthy Group	590 (117)	677 (171)	87 (70)	571 (91)	677 (148)	106 (71)	18
95% CI			43 - 130			61 - 150	-9 - 46

All values are RT (SD) in msec within Switch trials (Sw) and NoSwitch trials (NoSw) for combined, small/large (SL) or odd/even (OE) tasks.
Switch cost (SC) = Sw-NoSw RT. Dual-task difference was calculated as walkSC - sitSC.
SCSL = Switch cost derived from the small/large task. SCOE = Switch cost derived from the odd/even task.
** $p < 0.001$, * $p < 0.05$ calculated for individual TBI participants; † values outside of 95% confidence intervals (95% CI) of healthy group

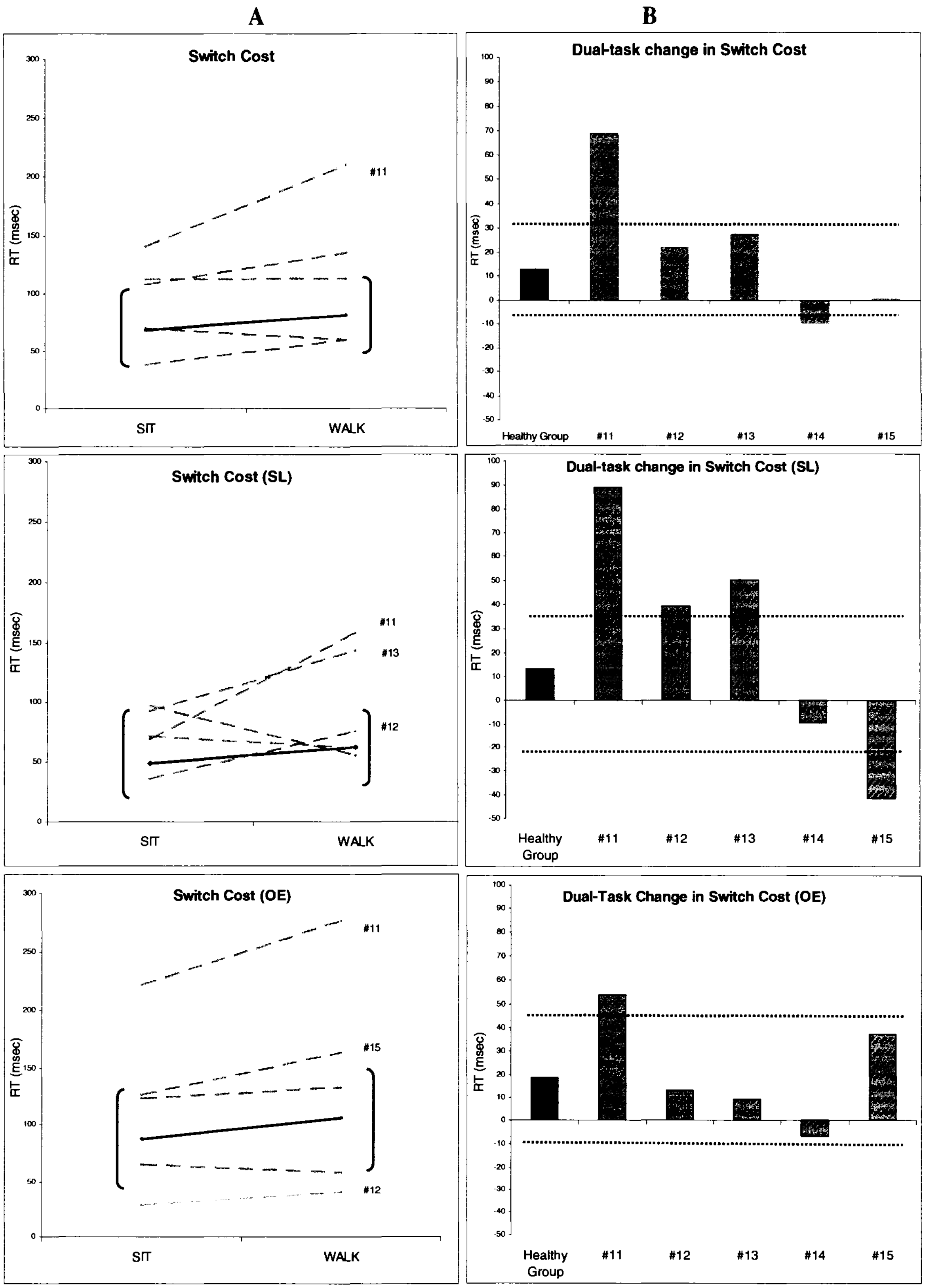

Figure 9. Comparison of switch costs (time and error) in sit versus walk conditions for the TBI participants and the healthy group.

Comparison of combined and component small/large (SL) and odd/even (OE) switch costs in sit and walk conditions (A) and dual-task differences (B) within TBI participants and the healthy group (n=10). Solid and dashed lines in A represent the healthy group and TBI participant switch cost values, respectively. Black parentheses (A) and dotted lines (B) indicate 95% CIs of healthy group.

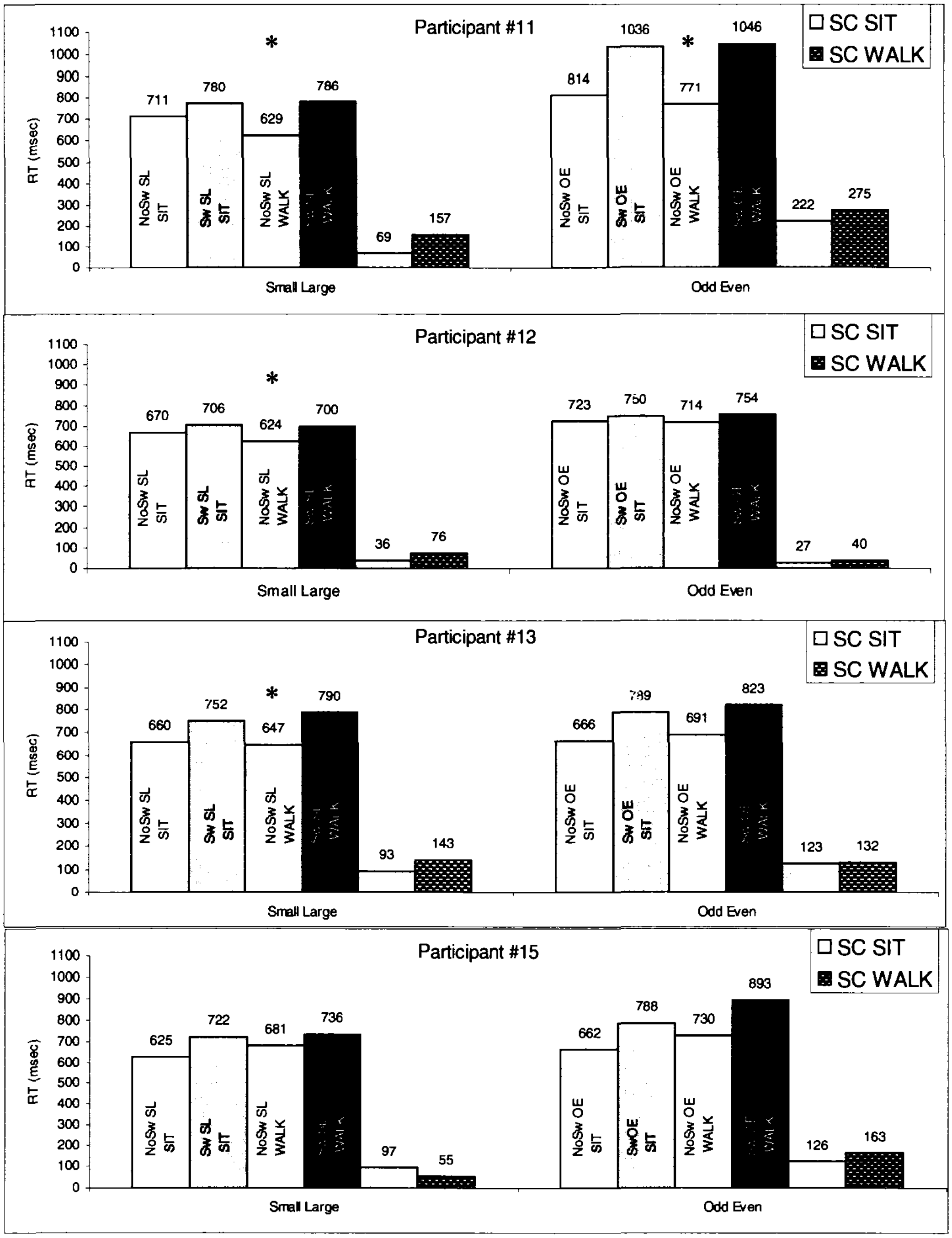

Figure 10. Switch costs and derivatives for TBI participants in sit versus walk conditions.
Switch costs in sit (SC SIT) and walk (SC WALK) and non-switch (NoSw) and switch (Sw)derivatives for small/large (SL) and odd/even (OE) tasks for participants #11, 12, 13 & 15.
Numbers reflect RT values in msec.
*Participant # 11and # 12 demonstrated a decrease in NoSw RT when walking to a greater extent within the SL task. Participant #13 demonstrated a small decrease in NoSw RT when walking and a lower initial SC SIT in the small/large task. This would explain the larger relative increase in switch costs for the SL versus the OE task when walking for these participants. Participant #15 demonstrated a progressive increase in RT when walking across cognitive tasks. However, the switch cost increased proportionately less within the SL task and proportionately more within the OE task when walking as compared to sitting.

Table 7. Switch cost error rates for TBI participants in sit versus walk conditions.

Participants	SIT NoSwErr (%errors)	SIT SwErr (%errors)	SIT SCErr (%errors)	WALK NoSwErr (%errors)	WALK SwErr (%errors)	WALK SCErr (%errors)	*Dual-Task Difference SCErr*
11	0	14	14	1	10	9	-5
12	0	1	1	3	1	-2	-3
13	0	5	5	0	7	7	2
14	10	13	3	7	10	3	0
15	1	6	5	3	7	4	-1
Healthy Group	*5 ± 4*	*8 ± 3*	*3 ± 3*	*6 ± 3*	*8 ± 4*	*2 ± 5*	-2 ± 5
95 % CIs	*3 - 7*	*6 – 10*	*1 – 5*	*4 - 8*	*5 - 10*	*-2 - 4*	*-4 - 1*
Participants	**NoSwErr (SL)** (%errors)	**SwErr (SL)** (%errors)	**SCErr (SL)** (%errors)	**NoSwErr (SL)** (%errors)	**SwErr (SL)** (%errors)	**SCErr (SL)** (%errors)	***Dual-Task Difference SCErr (SL)***
11	0	4	4	0	0	0	-4
12	0	2	2	0	0	0	-2
13	0	4	4	0	4	4	0
14	8	8	0	6	4	-2	-2
15	0	2	2	0	6	6	4
Healthy Group	*3 ± 3*	*5 ± 3*	*2 ± 4*	*5 ± 3*	*5 ± 4*	*0 ± 5*	-2 ± 7
95 % CIs	*1 - 5*	*3 - 6*	*-1 - 4*	*0 - 8*	*2 - 7*	*-4 - 3*	*-4 - 3*
Participants	**NoSwErr (OE)** (%errors)	**SwErr (OE)** (%errors)	**SCErr (OE)** (%errors)	**NoSwErr (OE)** (%errors)	**SwErr (OE)** (%errors)	**SCErr (OE)** (%errors)	***Dual-Task Difference SCErr (OE)***
11	0	20	20	2	20	18	-2
12	0	0	0	5	3	-3	-3
13	0	6	6	0	10	10	4
14	12	18	6	8	16	8	2
15	2	10	8	6	8	2	-6
Healthy Group	*7 ± 6*	*12 ± 6*	*5 ± 6*	*7 ± 4*	*10 ± 6*	*3 ± 8*	-2 ± 9
95 % CIs	*4 - 11*	*8 - 15*	*1 - 8*	*5 - 10*	*6 - 14*	*-2 - 8*	*-7 - 4*

Switch cost error rates (% errors) and dual-task differences for sitting versus walking for the TBI participants and healthy group (n=10).
Switch cost error rate (SCErr); Non-switch error rate (NoSwErr); Switch error rate (SwErr)
Dual-task difference was calculated as walkSCErr - sitSCErr

Switch cost error rates and their NoSw and Sw error rate derivatives, for the TBI participants and the healthy group, across sub-tasks and postural conditions are displayed in Table 7. Participant #11 demonstrated a significantly greater baseline SC error rate than the healthy group for both the combined and OE trials but not for the SC error rates derived from the SL trials. All other TBI participants demonstrated baseline SC error rates within or slightly below the 95% confidence bands.

The differences in SC error rates in sit and walk conditions, for the TBI participants versus the healthy group, are displayed in Figure 11. The effect of walking on switch cost error rates was varied across TBI participants. Participant # 13 tended to demonstrate an increase in SC error rates when walking as compared to sitting specific to the OE task of the paradigm. Participant #15 demonstrated a significant increase in errors when walking and switching within the SL task (4%) but a decrease in errors when walking and switching within the OE task (-6%), the opposite to the responses in switch cost (time) when walking noted above. It is noteworthy, however, that the dual-task differences in switch cost error rates for the TBI participants were at the margins or only slightly beyond the 95% confidence bands of the healthy group.

4.3.4 Influential Factors Affecting Dual-Task Differences in Responses

Given the variable responses across participants, results were summarized for each participant based on whether they demonstrated a significant difference in mean or variability of RT when walking as compared to their healthy counterparts for each cognitive measure (see Table 8). Participant #11 demonstrated the most robust effects of walking on response times of the cognitive tasks, demonstrating significantly greater mean and variability of SRT, variability of SwOE RT and switch costs under dual-task conditions than healthy peers. Participant #15 demonstrated a significant increase in SRT and SwOE RT as compared to the healthy and was approaching a significant increase for the OE switch cost. Participants #12 and 13 demonstrated varied results, with significant increases in mean or variability of SRT, respectively and significantly greater increases in switch costs specific to the SL task. Participant #14 did not demonstrate an influence of walking beyond an increase in SRT.

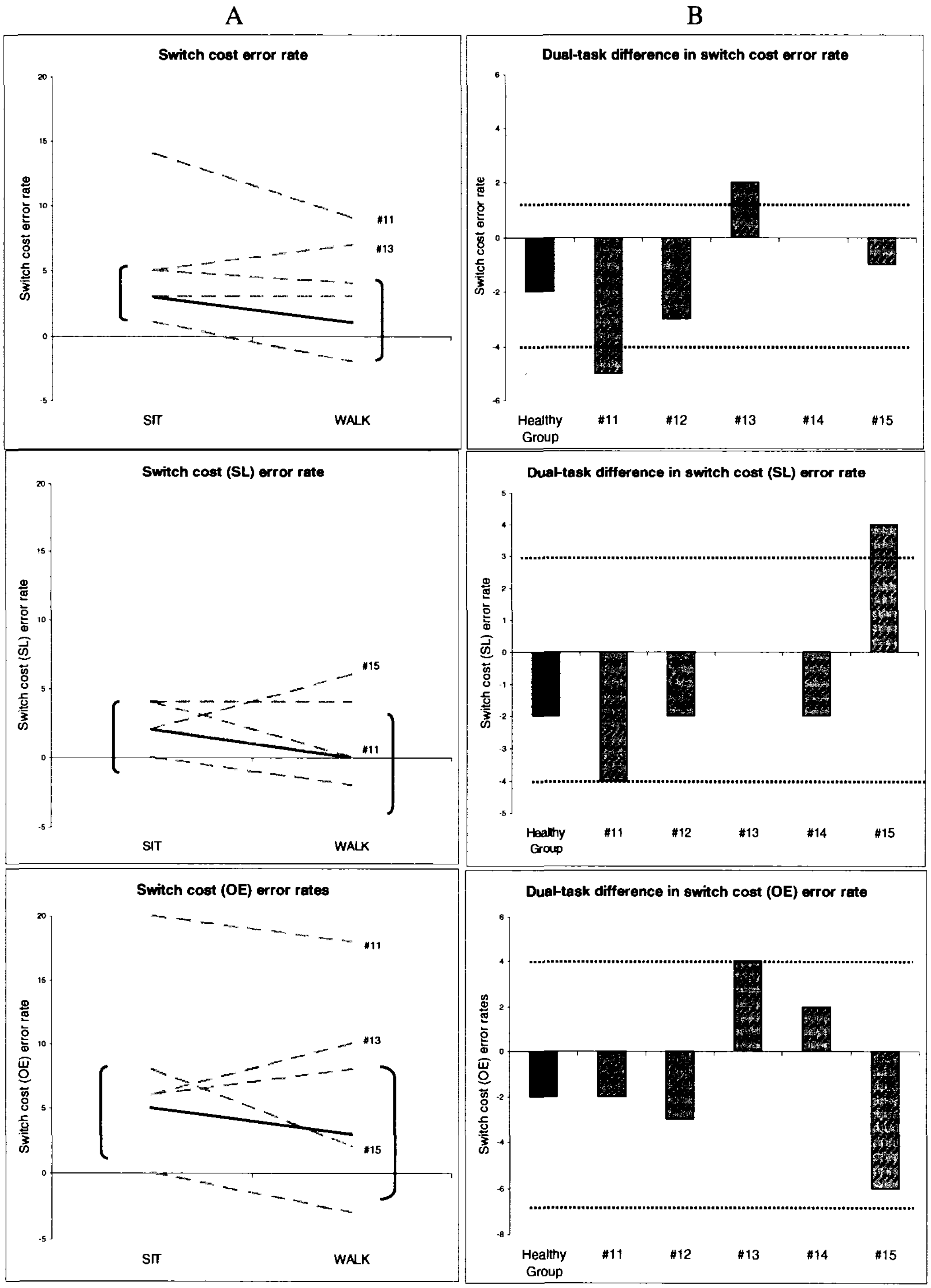

Figure 11. Comparison of switch cost error rates in sit versus walk conditions in TBI participant and healthy controls.

Combined and component small/large (SL) and odd/even (OE) switch cost (SC) error rates in SIT and WALK conditions (A) and dual-task differences (B) for TBI participants and the healthy group (n=10). SC error rates = Sw error rates – NoSw error rates.

Dual-task difference in SC = walk SC error rate – sit SC error rate.

Solid lines and dashed lines in A represent the SC error rates for healthy group and for TBI participants, respectively. Black parentheses in A and dotted lines in B indicate 95% CIs of healthy group.

Table 8. Summary of dual-task changes in reaction time.

	Healthy Group		#11	#12	#13	#14	#15
Cognitive Task	*Mean Δ (SD)*	*95%CI*	*Mean Δ*	*Mean Δ*	*Mean Δ*	*Mean Δ*	*Mean Δ*
SRT (msec)	10 (23)	-3 - 26	**47**	**57**		**35**	**47**
SRT (%CV)	1 (3)	-1 - 2	**8**		**5**	**7**	
SwOE RT (msec)	-1 (64)	-40 - 39					**105**
SwOE (%CV)	3 (8)	-2 - 4	**9**				**-9**
SC (msec)	13 (31)	-6 - 33	**70**				
SC (SL) (msec)	6 (46)	-22 - 34	**89**	**39**	**50**		**-42**
SC (OE) (msec)	18 (45)	-9 - 46	**54**				

Dual-task differences are listed for those values that were significantly different for the TBI participants (#11–#15) than the 95% CIs of the healthy group. Dual-task differences that were greater than the healthy group mean values are in light grey font.

Further evaluation occurred to determine if the variation in responses could be explained by individual differences in participant characteristics or other influential factors. Participants #12 and #14 demonstrated significantly greater post-test SRTs as compared to initial SRTs of 34 msec ($p < 0.001$) and 36 msec ($p < 0.001$), respectively. For these participants, then, visuomotor fatigue may have occurred over the course of testing (Stuss et al., 1989). However, these participants did not demonstrate a consistent dual-task increase in reaction time across the cognitive tasks; therefore, it would not appear that fatigue was influential. There was no significant difference between initial and post-test SRTs for participants #11 or #13 and participant #15 demonstrated a significant, albeit small, decrease in post-test SRT versus initial SRT of 14 msec ($p=0.004$).

Upon examination of the data, there was no obvious relationship between the individual TBI participants' ages or times since injury and corresponding dual-task changes in their individual mean or variability of SRT, SwOE RT or switch cost. There was also no obvious relationship between the individuals' baseline performances and dual-task effects in SRT or SwOE RT. For example, participants # 12, 13 and 15 had similar baseline SwOE RTs of 750, 789 and 788 msec however demonstrated varied dual-task increases in SwOE RT when walking of 4, 34 and 105 msec, respectively. There was also no clear relationship between baseline performance and dual-task changes in switch costs when the SL and OE component tasks were examined separately (see figure 12). Participant #11 demonstrated the greatest dual-task increase in SL and OE switch cost but tended to have the greatest baseline switch costs only within the OE task (baseline SL switch costs were noted to be within healthy group confidence intervals). Conversely, participants #13 and #15 tended to have greater baseline SL and OE switch costs than the other participants (noted to be at the upper bands of healthy group confidence intervals) but did not consistently demonstrate an increase in SL or OE switch cost when walking.

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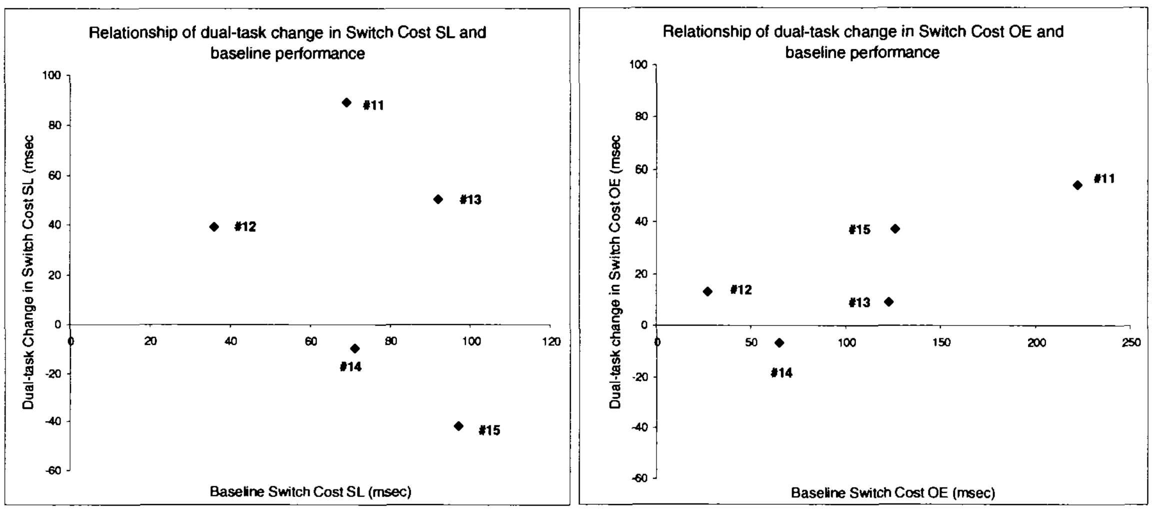

Figure 12. Comparison of TBI participants' baseline performances and dual-task changes in switch costs. The relationship of individual TBI participants' (#11 - #15) dual-task changes and baseline performances of switch cost (msec) within the small/large (SL) tasks (A) and the odd/even (OE) tasks (B).

We further examined the data to determine if there were any relationships between dual-task changes in switch cost and baseline cognitive and balance performance as measured by Trails B T-scores and CB&M scores (see figure 13). A Trails B T-score of less than 40 has been identified as below average or borderline impaired (Spreen & Strauss, 1998; Lezak 1995, p.159) and therefore this threshold was used to identify possible impairments in attention and cognition. To identify impairments in balance, 95% CIs were calculated around the average CB&M scores from unpublished data of age-referenced healthy adults (n=17; mean CB&M score=86.3$\pm$6.83). Impairments were inferred when CB&M scores of the TBI participants deviated below these lower confidence bands.

Participant #11, who demonstrated the greatest increase in switch cost when walking, demonstrated CB&M scores below healthy group values and also below average scores on the Trails B test. In contrast, participant #14, who did not demonstrate a dual-task increase in switch cost, demonstrated high performance on both the balance and cognitive measures. Participants #12 and #13 both demonstrated comparable increases in switch costs while walking; however, participant #12 demonstrated low balance scores and borderline impaired cognitive scores whereas participant #13 tended to have balance scores at the lower bands of the healthy CIs but average cognitive performance as per Trails B T-scores (Spreen & Strauss, 1998; Lezak 1995, p.159). Participant #15 demonstrated no dual-task change in switch cost (although increases in switch cost specific to the OE task were noted) and, similar to participant #13, demonstrated balance performance that was at the lower confidence bands of the healthy group but demonstrated average performance on the Trails B test (Spreen & Strauss, 1998; Lezak, 1995).

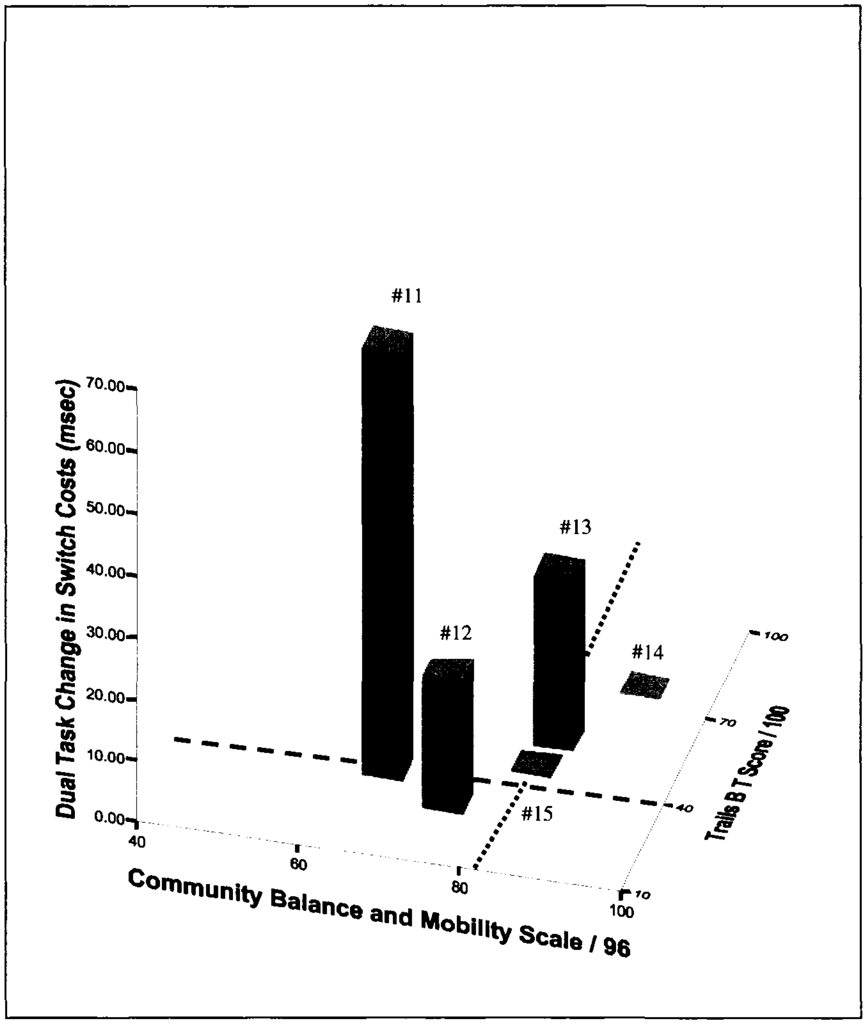

Figure 13. Relationship between dual-task changes in switch cost and balance and cognitive performance.
Dual-task changes in switch cost are displayed with the Community Balance and Mobility Scale and the Trail Making B T-scores for each TBI participant. The dashed line indicates a T-score of 40, where less than 40 indicates below average or borderline impairment. The dotted line represents the lower 95% confidence bands for age-referenced healthy group CB&M values from a previous study. Individual TBI participant values are indicated by their number (#11-15).

4.4 Discussion

The purpose of Experiment Two was to examine within individuals post-TBI, the effect of walking on concurrently-performed simple and complex cognitive tasks and those that involved attention switching. In support of the hypothesis, walking delayed the onset of the mean SRT responses in 4/5 participants and increased the variability of the SRT responses in 3/5 participants with TBI as compared to their healthy peers. It is noteworthy that the effect size of these TBI participants was comparable to a few healthy subjects (see Experiment One, Table 2). However, proportionally, the TBI participants had a more robust dual-task effect on SRT; all individuals with TBI demonstrated either a significantly greater mean or variability of SRT when walking as compared to the healthy control group. This would suggest, then, that walking is more attentionally-demanding for those with TBI than their healthy counterparts, even for those who are demonstrating a high level of functional mobility with overground walking velocities that are within age-referenced normal values (Oberg, Karsznia, & Oberg, 1993).

In refute of the hypothesis, walking did not uniformly result in delays or increases in the mean or variability of responses of the SwOE task as compared to the healthy group. The mean differences between SwOE RT and SRT at baseline, across TBI participants, ranged from 334 to 713 msec, confirming that the SwOE task used in this study was more complex. Participant #15 and #11 demonstrated a significant increase in mean SwOE RT and variability of SwOE RT, respectively. Participant #13 demonstrated an increase in mean SwOE RT that was approaching significance. The other participants did not demonstrate a change in SwOE RT when walking.

In refute of the hypothesis, walking did not uniformly result in increased switch costs for all TBI participants as compared to the healthy group. Significant switch costs (differences between mean SwRT and NoSw RT) were demonstrated in sitting and walking conditions independently for 4/5 and 5/5 TBI participants, respectively. In refute of the hypothesis, walking did not uniformly result in increased switch costs for all TBI participants as compared to the healthy group. Participant #11 demonstrated a significant dual-task increase in switch cost and participants #12 and #13 demonstrated increases in switch cost that were approaching the upper confidence bands of the healthy group. It is noteworthy that participant #11 and #12's increased switch costs were a result of shorter

NoSwRTs, not longer SwRTs, when walking versus sitting. Whereas response selection may have become faster when walking, the relative time required to switch attention between tasks was still proportionately greater in walking than sitting; therefore, it is felt that these switch cost values are valid.

Applying the results to our theoretical model

Although walking did not uniformly result in delays in RTs when performing the more complex cognitive tasks, our theoretical model may still be explanatory for some individual differences in response. According to our model, the re-allocation of attention could be influenced by the attentional demands or requirements of the tasks; specific to this study, attentional demands could be influenced by the complexity of the cognitive task or the individual participant's postural or locomotor dyscontrol. Participant #14 did not demonstrate significant delays in SwOE RT or in switch cost when walking. It may be noteworthy that this individual was a community ambulator, demonstrated overground walking velocities of 1.8 m/sec, was within normal limits for balance and mobility scores on the CB&M and was 100% confident of his balance during dual-task walking. As per the results of the healthy group in Experiment One, treadmill walking may have become a more "automatic" walking task for this individual and not significantly attentionally-demanding. As such, attention switching may not have been required or attention switching was still occurring but the speed of switching paired with the low attentional requirements of walking limited the extent of interference with the concurrently-performed cognitive task, irrespective of its complexity. Given that all participants were community ambulators and had overground walking velocities that were within age-related norms (Oberg et al., 1993), this may be partially explanatory for the lack of robust effect of dual-task walking overall. A dual-task study by Vallee (Vallee et al., 2006) also evaluated a group of high-functioning individuals with moderate to severe TBI who had relatively normal walking speeds (mean = 1.4 m/sec) and found that increasing the complexity of the cognitive task had varied effects but the most robust group differences occurred when both the cognitive and locomotor task was manipulated for complexity. Future dual-task studies, with this high-functioning population, may need to consider incorporating more challenging locomotor tasks that would be typical of the complex, community environment.

In contrast, participant #11 was noted to have the lowest overground and treadmill walking velocities and balance and mobility scores on clinical measures of all the TBI participants. Participant #11 also demonstrated the most robust effect with significant increases in SRT, SwOE RT variability and switch costs when walking, as compared to the healthy group. The results of others studies would suggest that with deterioriation in systems controlling balance and locomotion, greater allocation of attention to postural or locomotor control may be necessary (Bowen et al., 2001; Brauer et al., 2001; Haggard, Cockburn, Cock, Fordham, & Wade, 2000a; Hausdorff et al., 2003; Hyndman et al., 2006; Lundin-Olsson et al., 1997; Sheridan et al., 2003; Shumway-Cook et al., 1997; Shumway-Cook & Woollacott, 2000; Yang et al., 2007). Studies have also suggested that when there is competition between tasks there is an inherent bias to prioritize the task of maintaining stability (Brown, Sleik, & Winder, 2002; Li et al., 2001; Norrie et al., 2002) sometimes referred to as the "posture-first" principle. Wickens (Wickens, 1989) describes a similar concept of "degree of optimality" where "we attend to those things … that will produce the greatest benefit and ignore those things … [that] will lead to the smallest cost". Given the fixed walking speed on the treadmill and therefore the inability to lower the attentional demands of walking, prioritization of attentional resources to the cognitive task would come at a greater "cost" to performance (ie. loss of balance on the treadmill) than prioritization of the locomotor task. For participant #11, a dual-task decrement in cognitive performance may then reflect delayed attention switching from the locomotor task to the cognitive task due to the increased attentional requirements of walking combined with the reciprocal deleterious "cost" to walking performance if it were not prioritized. Participant #12 and #13 demonstrated dual-task increases in switch cost and also tended to have lower treadmill velocities, balance abilities and balance confidence when dual-task walking. Participant #15 demonstrated dual-task increases in switch cost specific to the OE task and was also noted to have balance abilities, as per the CB&M, that were at the lower threshold of healthy values. For these participants then, the re-allocation of attention may similarly have been delayed by the attentional requirements of walking due to postural or locomotor dyscontrol.

The conceptual model also proposed that the re-allocation of attention in dual-task conditions could be influenced by impaired cognitive processes regulating attention switching. Indicators of cognitive impairment in the present study can be discerned from the participant baseline switch costs in sitting as well as performance on the Trails B test. Participant #11 demonstrated the greatest increase in switch cost when walking and was noted to have significantly greater baseline OE switch costs as compared to the healthy group of Study One. This participant was also scored as below average performance on the Trails B test; the constructs of which includes, but are not limited to, flexibility in attention switching and psychomotor speed (Reitan, 1985; Lezak, 1995). Therefore, it is possible that impaired cognitive processes involved in attention switching could have been the source of the interference and the observed increase in switch costs during dual-task conditions, when both the cognitive and locomotor task required attention. Deficits in the ability to switch attention after brain injury have been demonstrated in the neuropsychological literature (Sohlberg & Mateer, 1987). A significant relationship between performance on the Trails B test and performance when walking in complex conditions (over obstacles) has also recently been demonstrated in a group of individuals with moderate to severe TBI (Cantin et al., 2007). It may then be that, for some individuals after TBI, impaired abilities to inhibit attention from one task and redirect attention to the other task could result in delayed performance under dual-task conditions involving walking. However, participants #12 and #13 demonstrated comparable dual-task increases in switch cost when walking but varied in their initial switch cost values in sitting. Further, these participants had varied Trails B T-scores; participant #12 was noted to be below average while participant #13 was within average values for Trails B T-scores. This would suggest that impaired cognitive processes related to attention switching could contribute but may not be the sole source of dual-task interference.

Why the more robust effect within the simple versus complex task?

The more robust effect with the simple cognitive task as compared to the complex task requires some reflection. It is possible that changes in prioritization of attention between the simple and complex task conditions could occur (Brauer et al., 2004; Li et al., 2001); that is, attention may have been prioritized to walking during the concurrent simple task but not when performing the more complex cognitive task. A shift in attentional priority could result in relatively better cognitive performance at the expense of the walking performance. In this study, however, this possibility was controlled for by use of the treadmill at a fixed velocity and, thereby, controlling for a constant level of walking performance.

A dual-task study by Brauer evaluated a group of individuals with acquired brain injury while standing and performing a range of simple and complex cognitive tasks (Brauer et al., 2004). Similarly, the greatest interference occurred with the simple cognitive task and the control articulation task. Articulation as a confounder would not be explanatory in the present study, which required manual responses. However, Brauer argued that distractibility or lack of "concentrated focus" could be partially explanatory for their findings. Distractibility is a common finding post-TBI (Whyte, Fleming, Polansky, Cavallucci, & Coslett, 1998; Whyte, Schuster, Polansky, Adams, & Coslett, 2000) and greater distraction when performing a simple versus complex cognitive task may have occurred in this study; however, it is not completely clear why there would be greater distraction when performing the SRT task in walking versus sitting.

It was noted that participants #11 and #12 tended to have faster NoSw RTs when walking; this was also apparent, but less so, in participant #13. As the SwOE RTs reflect the time taken for both processes of response selection for the OE task and task switching, there may been a resultant dampening of the SwOE RTs due to faster response selection while walking. The "heightened" or "enhanced" cognitive performance while walking was also noted in some healthy subjects within Experiment One (see section 3.0 Discussion) and has been observed in performance of the primary or secondary tasks in other dual-task studies with the healthy young (Andersson et al., 2002; Dault et al., 2001; Dault, Geurts et al., 2001; Grabiner & Troy, 2005; Huxhold et al., 2006; Riley et al., 2003; Riley et al., 2005; Weeks et al., 2003). In Brauer's study referenced above, there was also a trend for the participants with brain injury to demonstrate a reduction (rather than an increase) in COP amplitude, particularly in the mediolateral direction, when standing under dual-task conditions (Brauer et al., 2004). This "enhanced" effect has been linked, in other studies, to postural threat and levels of arousal. For example, Brown and colleagues (Brown, Sleik, Polych et al., 2002) found in healthy controls that cognitive performance improved under dual-task conditions when postural threat increased. There was also an associated increase in arousal as measured by galvanic skin conductance consistent with other dual-task studies (Maki & Whitelaw, 1993; Maki & McIlroy, 1996). It may be noteworthy that participants #11, #12 and #13 who demonstrated this enhanced effect tended to have lower treadmill velocities, balance confidence and balance and mobility abilities than the other TBI participants. It is possible that the increased complexity of the switch cost paradigm (versus the SRT task), combined with the competing attentional demands of walking and an inability to adjust the attentional requirements of walking by slowing walking speed, caused these individuals to "sharpen" their responses to optimize performance. For participant #11 who had the lowest balance and mobility abilities, increased variability of RT in the more complex SwOE task was still noted, suggesting that for this individual the need to sacrifice cognitive task performance to modulate locomotor control could not be completely mediated by levels of arousal. For participants #12 and 13, however, beneficial effects of arousal may have dampened the dual-task effect on the SwOE RT. The influence of balance-related anxiety, focused attention or arousal on the allocation of attentional resources cannot be clearly determined in this study but are all worthy of consideration in future studies.

Another possibility worth consideration is one proposed by McFadyen and colleagues (McFadyen et al., 2003). In this study, characterizing locomotor capacity of high-functioning individuals post-TBI, the main findings were that participants walked slower with a tendency for greater foot clearances over obstacles than their healthy peers. The authors suggested that this "cautious" gait could be a carryover from early stages of functional recovery even when locomotor capacity has been more fully restored. With relevance to this study, one may similarly propose that there is a "cautious" approach to the re-allocation of attentional resources away from locomotion based on early stages of recovery; hence the dual-task interference in the simple task. In times of challenge, however, participants can actually perform (walk and maintain stability with less attentional resources) if they have to; hence the more variable response in dual-task interference with the more complex cognitive task.

Our conceptual model has been revised based on the insights our study have provided about the relationship between attention and walking after moderate to severe TBI (see figure 14). Walking was shown to be more attentionally-demanding in those with TBI as compared to healthy peers; noteworthy given their high level of functional mobility. Individual differences in postural or locomotor dyscontrol and/or altered cognitive processes regulating attention may influence the allocation of attention during the course of walking and result in subsequent deterioration in performance under dual-task conditions.

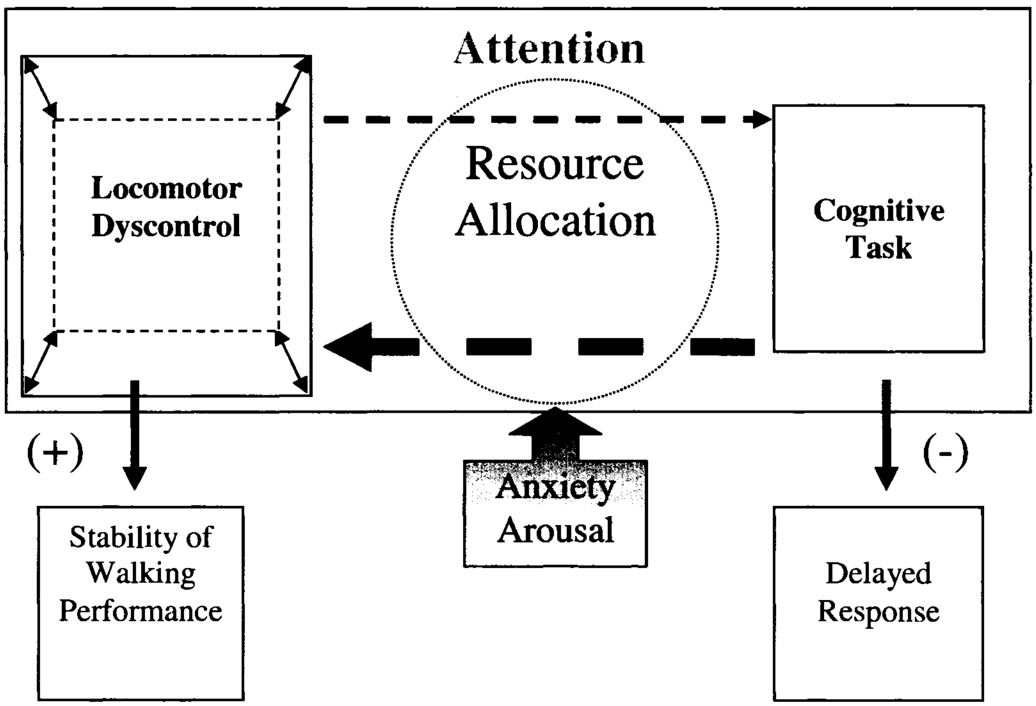

Figure 14. Application of findings to the theoretical model of attention, locomotor control and dual-task decrements in performance.
The results of this study suggest that the re-allocation of attentional resources between walking and the concurrently-performed cognitive task may be influenced by the postural or locomotor dyscontrol of the individual (expanded box). To maintain walking performance, attention may be allocated to locomotor control (thick arrows) negatively impacting on the cognitive task (narrow arrow) and resulting in delayed responses. The re-allocation of attention could additionally be influenced by impaired attention switching processes (dashed arrows). Anxiety or arousal levels of the individual (dotted circle) may also be influential but was not measured in the present study.

5.0 Conclusions

The purpose of the present work was to explore the attentional demands of walking in the high-functioning individual post-TBI compared to their healthy peer group. The healthy group in Experiment One demonstrated no dual-task decrements when walking and concurrently performing the reaction time tasks. However, the results of Experiment Two provide some insight into the residual deficits of the higher functioning, ambulatory individual with moderate to severe TBI. Although functional levels of walking were approaching or within normal limits for all the TBI participants, we found significant increases in the means and variability of SRTs when walking for most of the TBI participants and individual differences in performance of RT tasks that varied in complexity and that probed attention switching during concurrent treadmill walking. Our results suggest that walking is more attentionally-demanding for those with TBI than their healthy counterparts. This is particularly noteworthy given the high level of functional mobility within these individuals. Further, the results suggest that individual differences of locomotor dyscontrol and/or cognitive processes regulating allocation of attention may contribute to delayed attention switching when walking and subsequent deterioration in performance under dual-task conditions. As such, these are areas that warrant further study prior to the development of appropriate rehabilitative assessments and interventions to maximize mobility outcomes and participation for those with TBI.

5.1 Significance/Contributions

Walking within dual-task conditions is the norm not the rarity as we go about our activities of daily living. Whereas there have been numerous dual-task studies examining the attentional demands of walking in healthy and elderly populations, there is a paucity of studies examining those with TBI. At this time there is only one published dual-task study examining the attentional demands of walking within those with moderate to severe brain injury (Vallee et al., 2006) which focused on the more complex walking condition of obstacle crossings. Our study adds to this important area of research and suggests that unobstructed walking is also more attentionally demanding in the high-functioning individual post-TBI than their healthy peers.

It is also interesting that the more robust effect of walking on cognitive task response times was demonstrated by the TBI participant with the lowest treadmill velocity, balance and mobility scores on clinical measures and dual-task balance confidence scores. This finding is consistent with the results of studies in other populations that have demonstrated that the attentional requirements of posture and locomotion are greater in those with balance or locomotor dyscontrol (Woollacott & Shumway-Cook, 2002). What is noteworthy is that this participant was independently ambulatory in the community environment and walking at overground speeds that were within normal limits (Oberg et al., 1993). This would underscore the need to not only use appropriate measures to identify "high-level" balance and mobility deficits (Howe et al., 2006; Williams et al., 2006) but also that these more subtle aspects of balance or locomotor dyscontrol may require increased attentional demands and lead to decrements in performance under dual-task conditions.

The results of this study would also reinforce the need to develop and utilize dual-task assessments within clinical practice to explore the influence of cognitive processes, such as attention, on locomotor control after TBI. In current clinical practice, balance and mobility assessment and training are often focused on "motor output" and performed in single task conditions. Dual-task assessment and training may occur within natural environments but is not approached in a systematic or deliberate manner nor with any real understanding of the underlying causes of dual-task decrements in performance for the individual. Our results would suggest that, indeed, there may be individual differences of dual-task performance that may be dependant on the individual's postural or locomotor dyscontrol and/or the ability to rapidly switch attention between walking and the cognitive tasks. These factors and possibly others may need to be considered in future research to inform the development of more sophisticated assessment tools and strategies for the rehabilitation of walking in the high-functioning individual with TBI.

5.2 Limitations of the Study

There are a number of factors that may limit the conclusions of this work that require elucidation. Experiment Two recruited a sample of convenience of individuals with TBI from a larger ongoing study. The five community-dwelling individuals recruited would not be representative of all ambulatory individuals with TBI and likely higher-functioning than those typically seen for rehabilitation to address balance or gait retraining. As the future goal of this work would be to inform rehabilitation and in light of the more robust effects demonstrated within the individual with greater locomotor dyscontrol, it may be important for future studies to focus on a sub-group of individuals after TBI who are ambulatory but with self-reported concerns of balance and walking or with documented balance deficits identified through outcome measures.

It is possible that fatigue or practice could affect results of the studies, however, a number of factors suggest that these were not influential. Firstly, the order of the sit and walk conditions was counterbalanced so that any possible negative or positive influence of time on participant responses would not differentially influence one postural condition over the other. Visuomotor fatigue was measured in this study by comparing pre and post SRTs, as used in a study by Stuss and colleagues exploring attention in TBI (Stuss et al., 1989). In Experiment One, the healthy control group did not demonstrate a significant difference in pre and post SRT suggesting that fatigue was not confounding. In Experiment Two, TBI participants #12 and #14 demonstrated significantly greater post-test versus pre-test SRTs possibly indicating visuo-motor fatigue; however, neither of these participants demonstrated consistent dual-task increases in reaction time across cognitive tasks. Further, as noted in the methods section of the studies, analyses of mean SwOE RT across blocks demonstrated a main effect of time in the walk condition for the healthy control group but there was no interaction of time and postural condition. Similarly in Experiment Two, only participant #13 demonstrated an effect of time (difference in SwOE RT across blocks) when walking but no interaction of time and postural condition. Therefore, time did not differentially influence the difference in SwOE RT between sit and walk conditions. In light of the above, it was not thought that fatigue or practice greatly influenced the results of the experiments.

Anxiety and arousal can be confounding in dual-task experiments. A proxy measure for anxiety used in this study was the balance confidence scale asking participants "how confident are you that you will not lose your balance and become unsteady when you…" sit and walk in single and dual-task conditions. Studies have demonstrated that anxiety can increase the attentional demands of gait (Gage et al., 2003) and could, therefore, influence the allocation of attentional resources to locomotion and be explanatory for differences when comparing the healthy young to balance-impaired populations. Participant # 11, who demonstrated a significantly greater switch cost and participants #12 and #13 who demonstrated significant increases in SL switch costs, when walking as compared to the healthy group were noted to have dual-task balance confidence scores of 70, 80 and 90% as compared to the other TBI participants who reported 100% confidence. However, the perceived confidence scores also aligned with the participants' lower baseline scores on balance and mobility measures and treadmill velocities. Further, it was noted in the previous discussions, that these same TBI participants tended to have faster NoSw RTs when walking, questioning whether anxiety or arousal could have contributed to an enhanced rather than a detrimental effect on response time. This would be consistent with a finding by Brown et al (Brown, Sleik, Polych et al., 2002) who demonstrated in the healthy young that cognitive performance improved in dual-task conditions of postural threat and that there was an associated increase in arousal as measured by skin conductance. Without the use of more direct measures of physiological arousal, it is difficult in this study to disentangle the relative contribution of anxiety or arousal to the present findings but it is worthy of future study.

One of the deliberate features of the paradigm used in this study was the use of treadmill walking at a fixed velocity to ensure consistent performance of the primary task and, therefore, limit the ability of the participants to alter the attentional demands of walking. It is possible, however, that some participants may have prioritized the cognitive task with adverse effects on aspects of walking performance not reported in this study. For example, Grabiner and Troy demonstrated that, while treadmill walking at a fixed velocity, healthy participants demonstrated altered step width variability when in dual-task conditions (Grabiner & Troy, 2005). Future analyses of the participants' temporal aspects of gait, collected in this study using heel-switch apparatus, would be warranted. It was additionally noted that velocities on the treadmill were consistently lower than participants' over ground velocities. This could reflect a voluntary adaptation to alter the attentional demands of gait. However, it is noteworthy that the decreased treadmill as compared to over ground velocities was demonstrated in both the healthy controls and TBI participants and similar findings have been presented in other studies (Jung, 2004; March, 2006; Kautz, 2007). Finally, although the adjusted walking velocities on the treadmill were noted throughout the course of testing, it was a deliberate decision to proceed with what participants perceived as their "preferred pace". Other studies using treadmill paradigms have found that walking with imposed velocities other than one's self-selected speed can be attentionally-demanding (Abernethy et al., 2002; Kurosawa, 1994) and, therefore, if adopted in this study could also be considered confounding. A final point related to the treadmill paradigm would be that the reaction times of the concurrently-performed cognitive tasks, and hence the attentional demands of walking, would be specific to the participant's ability to walk on the motorized treadmill and, therefore, not generalizable to overground walking or walking in natural environments. One might propose that these environments would be more challenging requiring greater attention to locomotor control and that there would consequently be a greater effect than demonstrated in this study, but this requires further study to determine. An issue that will need to be considered, as these dual-task paradigms evolve into useful rehabilitation tools, is the benefit of using the treadmill and the relative advantage of being able to control walking parameters versus the potential limitations to ecological validity. The feasibility of its use for low versus high functioning individuals will also need to be considered.

The switch cost in this study was used as a measure of the time required to re-allocate attention between tasks. A significant difference in switch cost when walking was, therefore, proposed to implicate delays in the temporal aspects of attention switching when walking as a source of dual-task decrement in performance. However, it is noted that SwRTs were consistently greater than the other RT tasks for all participants and the SwOE RT was used as a "complex" cognitive task in this study. It is possible, then, that an increased switch cost when walking similarly reflects the influence of walking on the performance of a more complex cognitive task, not related to a specific construct of attention switching. However, the differential influence of walking on the RTs within some subjects may suggest otherwise. It was noted that the NoSw RTs of some participants actually decreased when walking while their SwRTs were comparable or increased. It is not completely explanatory why, if the Sw task was just more complex than the NoSw task, there was not a uniform response in directionality of the two when walking.

In addition to the time required to switch attention between tasks, another proposed source of switch costs is that of "transient task-set inertia" (Monsell, 2003). Specifically, studies have demonstrated prolonged processing on switch trials because of interference from the prior task set, that could include persistent inhibition of the task that is now required or persistent activation of the previous task (Allport, Styles & Hsieh, 1994; Meiran, Chorev & Sapir, 2000; Yeung & Monsell, 2003). It is possible, then, that treadmill walking did not demonstrate a great source of "cross-task interference" and, therefore, there was little change in switch cost when walking. The relative contribution of the time required for processes of attention switching versus transient task-set inertia to the switch costs demonstrated in this study are not known. Irrespectively, an alternative method to probe attention switching in future studies would be worthy of exploration.

Finally, in this study a significant difference in performance for the TBI participants was inferred when the RTs or error rate values deviated outside of the 95% confidence bands determined for the healthy group. Whether these differences in RT are functionally significant is not clear. There are no comparable dual-task studies using the switch cost paradigm that would guide us in interpreting meaningful change. However, one study cited significant differences in dual-task mean SRTs when walking between a healthy elderly group and a fall-prone elderly group of 300.3 ± 45.5 versus $331.8 + 28.1$ msec (Huo & Maruyama, 2006). Although not conclusive, this may suggest that a 30 msec difference in dual-task SRT between groups is functionally relevant. Accordingly, the dual-task SRT values demonstrated in this study, ranging from 35-57 msec for the TBI participants comparead to a healthy group mean of 10 msec, may have some functional significance. This conclusion is tentative but is an important area requiring future study. In this high-functioning population, slowed responses under dual-task conditions may or may not contribute to major events such as falls but could effect performance of various community living skills and the ability to "keep up with peers" that may have a profound impact on participation.

5.3 Future Directions

The results of our studies would provide some direction for future areas of research. The lack of effect of walking on switch costs in the healthy young and in some participants with TBI could suggest that processes involving attention switching were not at play during treadmill walking. An alternative interpretation would be that, for some, the rapidity of attention switching combined with the low attentional demands of walking limited the extent of the interference and the switch cost probes were not sensitive enough to capture potential differences. As such, alternative approaches to explore attention switching while walking should be considered. Future studies may benefit from using RT probes when it is hypothesized that varying demands (and hence attention switching) to walking may be occurring; for example, in double support versus single support phases (Lajoie et al., 1993). One might also consider using a secondary continuous tracking task and analyzing real-time variability in performance (rather than a mean score of variability) in sitting versus walking. Changes in variability of secondary task performance across time may correspond to attention switching activity between walking and the cognitive task. It is also noteworthy that in previous studies exploring the temporal dynamics of attention (Maki et al., 2001; McIlroy et al., 1999; Norrie et al., 2002), the re-allocation of attention was demonstrated when there was a disruption to postural control from a perturbation. It has also been previously noted that significant differences between those with TBI and a healthy group become most apparent when both the cognitive and locomotor task is manipulated for complexity (Vallee et al., 2006). Future studies in dual-task walking paradigms may benefit from probing attention switching during disruptions to dynamic stability or locomotor control; potentially explored through use of a secondary continuous tracking task while treadmill walking and introducing challenges to control through gait initiation, braking, change of speed, change in incline etc. Further, there may be the need to extend these studies by exploring more complex walking conditions within natural environments that would be typical of challenges faced in the community.

The present study did not have definitive conclusions about the relative contribution of postural and locomotor dyscontrol versus impaired cognitive processes to delays in attention allocation and subsequent decrement in dual-task performance. This requires further study, however, as it could be an important consideration for treatment. If primarily an issue of cognition, treatment may focus on training of processes involved in attention switching that may not need to be practiced within the context of walking. If postural or locomotor dyscontrol is the primary reason for delayed re-allocation of attention then focusing on retraining and subsequently decreasing the attentional demands of walking may be most crucial. Alternatively, as a pilot study by Silsupadilol and colleagues (Silsupadol, Siu, Shumway-Cook, & Woollacott, 2006) has recently suggested, both factors may be contributory and the development of dual-task training approaches that enable both the practice of balance and mobility tasks and the development of cognitive processing skills related to allocating attention between tasks may be most effective.

Walking while concurrently performing another task is common-place and underlies the performance of most of our activities of daily living. Therefore, continued study exploring the relationship of attention and walking and concerted efforts to use this research to inform the development of appropriate rehabilitative assessments and interventions in clinical settings is essential to maximize the mobility outcomes and participation of the individual after TBI.

6.0 References

Abernethy B (1988) Dual-task methodology and motor skills research: some applications and methodological constraints. *Journal of Human Movement Studies, 14:* 101-32

Abernethy, B., Hanna, A., & Plooy, A. (2002). The attentional demands of preferred and non-preferred gait patterns. *Gait & Posture, 15*(3), 256-265.

Allport, D. A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. *Attention and performance 15: Conscious and nonconscious information processing*. Cambridge, MA, US: The MIT Press p. 421-452

Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2002). Effect of cognitive load on postural control. *Brain Research Bulletin, 58*(1), 135-139.

Aron, A. R., Monsell, S., Sahakian, B. J., & Robbins, T. W. (2004). A componential analysis of task-switching deficits associated with lesions of left and right frontal cortex. *Brain, 127*(Pt 7), 1561-1573.

Bardy, B. G., & Laurent, M. (1991). Visual cues and attention demand in locomotor positioning. *Perceptual & Motor Skills, 72*(3 Pt 1), 915-926.

Basford, J. R., Chou, L. S., Kaufman, K. R., Brey, R. H., Walker, A., Malec, J. F., et al. (2003). An assessment of gait and balance deficits after traumatic brain injury. *Archives of Physical Medicine & Rehabilitation, 84*(3), 343-349.

Beauchet, O., Dubost, V., Herrmann, F.R., Kressig, R.W. (2005). Stride-to-stride variability while backwards counting among healthy young adults. *Journal of NeuroEngineering and Rehabilitation, 2*(26)

Beauchet, O., Dubost, V., Aminian, K., Gonthier, R., & Kressig, R. W. (2005). Dual-task-related gait changes in the elderly: Does the type of cognitive task matter? *Journal of motor behavior, 37*(4), 259-264.

Bilney, B., Morris, M., & Webster, K. (2003). Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait. *Gait & Posture, 17*(1), 68-74.

Bowen, A., Wenman, R., Mickelborough, J., Foster, J., Hill, E., & Tallis, R. (2001). Dual-task effects of talking while walking on velocity and balance following a stroke. *Age & Ageing, 30*(4), 319-323.

Brauer, S. G., Broome, A., Stone, C., Clewett, S., & Herzig, P. (2004). Simplest tasks have greatest dual task interference with balance in brain injured adults. *Human Movement Science, 23*(3-4), 489-502.

Brauer, S. G., Woollacott, M., & Shumway-Cook, A. (2001). The interacting effects of cognitive demand and recovery of postural stability in balance-impaired elderly persons. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 56*(8), M489-96.

Brouwer, W. H., Ponds, R. W., Van Wolffelaar, P. C., & Van Zomeren, A. H. (1989). Divided attention 5 to 10 years after severe closed head injury. *Cortex, 25*(2), 219-230.

Brown, L. A., McKenzie, N. C., & Doan, J. B. (2005). Age-dependent differences in the attentional demands of obstacle negotiation. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 60*(7), 924-927.

Brown, L. A., Sleik, R. J., Polych, M. A., & Gage, W. H. (2002). Is the prioritization of postural control altered in conditions of postural threat in younger and older adults?. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 57*(12), M785-92.

Brown, L. A., Sleik, R. J., & Winder, T. R. (2002). Attentional demands for static postural control after stroke. *Archives of Physical Medicine and Rehabilitation, 83*(12), 1732-1735.

Cantin, J. F., McFadyen, B. J., Doyon, J., Swaine, B., Dumas, D., & Vallee, M. (2007). Can measures of cognitive function predict locomotor behaviour in complex environments following a traumatic brain injury? *Brain Injury, 21*(3), 327-334.

Chen, H. C., Schultz, A. B., Ashton-Miller, J. A., Giordani, B., Alexander, N. B., & Guire, K. E. (1996). Stepping over obstacles: Dividing attention impairs performance of old more than young adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 51*(3), M116-22.

Chou, L. S., Kaufman, K. R., Walker-Rabatin, A. E., Brey, R. H., & Basford, J. R. (2004). Dynamic instability during obstacle crossing following traumatic brain injury. *Gait & Posture, 20*(3), 245-254.

Dault, M. C., Frank, J. S., & Allard, F. (2001). Influence of a visuo-spatial, verbal and central executive working memory task on postural control. *Gait & Posture, 14*(2), 110-116.

Dault, M. C., Geurts, A. C., Mulder, T. W., & Duysens, J. (2001). Postural control and cognitive task performance in healthy participants while balancing on different support-surface configurations. *Gait & Posture, 14*(3), 248-255.

Dean, S., Colantonio, A., Ratcliff, G., & Chase, S. (2000a). Client perspectives on problems many years after traumatic brain injury. *Psychological Reports, 86*(2), 653-658.

Dean, S., Colantonio, A., Ratcliff, G., & Chase, S. (2000b). Clients' perspectives on problems many years after traumatic brain injury. *Psychological Reports, 86*(2), 653-658.

Dubost, V., Kressig, R. W., Gonthier, R., Herrmann, F. R., Aminian, K., Najafi, B., et al. (2006). Relationships between dual-task related changes in stride velocity and stride time variability in healthy older adults. *Human Movement Science, 25*(3), 372-382.

Ebersbach, G., Dimitrijevic, M. R., & Poewe, W. (1995). Influence of concurrent tasks on gait: A dual-task approach. *Perceptual & Motor Skills, 81*(1), 107-113.

Fukuyama, H., Ouchi, Y., Matsuzaki, S., Nagahama, Y., Yamauchi, H., Ogawa, M., et al. (1997). Brain functional activity during gait in normal subjects: A SPECT study. *Neuroscience Letters, 228*(3), 183-186.

Gage, W. H., Sleik, R. J., Polych, M. A., McKenzie, N. C., & Brown, L. A. (2003). The allocation of attention during locomotion is altered by anxiety. *Experimental brain research.Experimentelle Hirnforschung.Experimentation cerebrale, 150*(3), 385-394.

Geurts, A. C., Ribbers, G. M., Knoop, J. A., & van Limbeek, J. (1996). Identification of static and dynamic postural instability following traumatic brain injury. *Archives of Physical Medicine & Rehabilitation, 77*(7), 639-644.

Ghatan, P. H., Hsieh, J. C., Petersson, K. M., Stone-Elander, S., & Ingvar, M. (1998). Coexistence of attention-based facilitation and inhibition in the human cortex. *NeuroImage, 7*(1), 23-29.

Golden CJ. Stroop Colour and Word Test. Chicago IL: Stoelting, 1978

Grabiner, M. D., & Troy, K. L. (2005). Attention demanding tasks during treadmill walking reduce step width variability in young adults. *Journal of NeuroEngineering and Rehabilitation, 2*(25)

Gronwall D. (1987). Advances in Assessment and Information Processing After Head Injury. In: Levin HS, Grafman J, Eisenberg M, editors. *Neurobehavioural Recovery from Head Injury. New* York: Oxford University Press , 355-71

Haggard, P., Cockburn, J., Cock, J., Fordham, C., & Wade, D. (2000a). Interference between gait and cognitive tasks in a rehabilitating neurological population. *Journal of Neurology, Neurosurgery & Psychiatry, 69*(4), 479-486.

Haggard, P., Cockburn, J., Cock, J., Fordham, C., & Wade, D. (2000b). Interference between gait and cognitive tasks in a rehabilitating neurological population. *Journal of Neurology, Neurosurgery & Psychiatry, 69*(4), 479-486.

Haridas, C., Gordon, I. T., & Misiaszek, J. E. (2005). Walking delays anticipatory postural adjustments but not reaction times in a choice reaction task. *Experimental Brain Research, 163*(4), 440-444.

Hausdorff, J. M., Balash, J., & Giladi, N. (2003). Effects of cognitive challenge on gait variability in patients with parkinson's disease. *Journal of Geriatric Psychiatry and Neurology, 16*(1), 53-58.

Hillier, S. L., Sharpe, M. H., & Metzer, J. (1997). Outcomes 5 years post-traumatic brain injury (with further reference to neurophysical impairment and disability). *Brain Injury, 11*(9), 661-675.

Howe, J. A., Inness, E. L., Venturini, A., Williams, J. I., & Verrier, M. C. (2006). The community balance and mobility scale--a balance measure for individuals with traumatic brain injury. *Clinical Rehabilitation, 20*(10), 885-895.

Hunter, M. C., & Hoffman, M. A. (2001). Postural control: Visual and cognitive manipulations. *Gait & Posture, 13*(1), 41-48.

Huo M & Maruyama H (2006) The Effectiveness of a simple Approach to the Assessment of the Risk of Falls in the Elderly – Probe Reaction Time and the Dispersion of the Time for A Single Step During Marking Time. *The Journal of Physical Therapy Science*, 18: 181-85

Huxhold, O., Li, S. C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: Aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin, 69*(3), 294-305.

Hyndman, D., Ashburn, A., Yardley, L., & Stack, E. (2006). Interference between balance, gait and cognitive task performance among people with stroke living in the community. *Disability & Rehabilitation, 28*(13-14), 849-856.

Inness EL, Howe JA, Niechwiej-Szwedo E, Jaglal S, McIlroy WE, Verrier MC. (2004) [Abstract] Measuring balance and mobility after traumatic brain injury: further validation of the Community Balance & Mobility Scale (CB&M). *Archives of Physical Medicine*; 85: E11

Jung T., Gilgannon M., Munjal R., Granata K., Abel, M. (2004). [Abstract]. Treadmill-based gait analysis for children with cerebral palsy: Biomechanical comparison of treadmill and overground walking. *Proceedings of the Gait and Clinical Movement Analysis Society.*

Kautz SA, Balasubramanan CK, Bowden MG, (2007). [Abstract] Comparison of treadmill and overground walking at self-selected speed in persons with post-stroke hemiparesis. *Proceedings of the International Society for Posture and Gait Research*

Katz, D. I., White, D. K., Alexander, M. P., & Klein, R. B. (2004). Recovery of ambulation after traumatic brain injury. *Archives of Physical Medicine & Rehabilitation, 85*(6), 865-869.

Kerr, B., Condon, S. M., & McDonald, L. A. (1985). Cognitive spatial processing and the regulation of posture. *Journal of Experimental Psychology: Human Perception & Performance, 11*(5), 617-622.

Khan, F., Baguley, I. J., & Cameron, I. D. (2003). 4: Rehabilitation after traumatic brain injury. *The Medical journal of Australia, 178*(6), 290-295.

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology & Aging, 15*(1), 126-147.

Kurosawa, K. (1994). Effects of various walking speeds on probe reaction time during readmill walking. *Perceptual and Motor Skills, 78*(3), 768.

Lajoie, L., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research., 97*, 139-144.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1996). Upright standing and gait: Are there changes in attentional requirements related to normal aging? *Experimental Aging Research, 22*(2), 185-198.

Lezak MD. Neuropsychological Assessment (New York: Oxford University Press), 1995

Li, K. Z., Lindenberger, U., Freund, A. M., & Baltes, P. B. (2001). Walking while memorizing: Age-related differences in compensatory behavior. *Psychological Science, 12*(3), 230-237.

Lundin-Olsson, L., Nyberg, L., & Gustafson, Y. (1997). "Stops walking when talking" as a predictor of falls in elderly people. *Lancet, 349*(9052), 617.

MacKay-Lyons, M. (2002). Central pattern generation of locomotion: A review of the evidence. *Physical Therapy, 82*(1), 69-83.

Maki, B. E., & McIlroy, W. E. (1996). Influence of arousal and attention on the control of postural sway. *Journal of Vestibular Research, 6*(1), 53-59.

Maki, B. E., & Whitelaw, R. S. (1993). Influence of expectation and arousal on center-of-pressure responses to transient postural perturbations. *Journal of Vestibular Research, 3*(1), 25-39.

Maki, B. E., Zecevic, A., Bateni, H., Kirshenbaum, N., & McIlroy, W. E. (2001). Cognitive demands of executing postural reactions: Does aging impede attention switching? *Neuroreport, 12*(16), 3583-3587.

Marsh, A. P., & Geel, S. E. (2000). The effect of age on the attentional demands of postural control. *Gait & Posture, 12*(2), 105-113.

Marsh AP, Katula JA, Pacchia CF, Johnson, LC, Koury KL, Rejeski WJ. (2006). Effect of Treadmill and Overground Walking on Function and Attitudes in Older Adults. *Medicine and Science in Sports and Exercise, 38* (6), 1157-64

Mathias, J. L., & Wheaton, P. (2007). Changes in attention and information-processing speed following severe traumatic brain injury: A meta-analytic review. *Neuropsychology, 21*(2), 212-223.

Maylor, E. A., Allison, S., & Wing, A. M. (2001). Effects of spatial and nonspatial cognitive activity on postural stability. *British Journal of Psychology, 92*(Pt 2), 319-338.

Maylor, E. A., & Wing, A. M. (1996). Age differences in postural stability are increased by additional cognitive demands. *Journals of Gerontology Series B-Psychological Sciences & Social Sciences, 51*(3), P143-54.

McFadyen, B. J., Swaine, B., Dumas, D., & Durand, A. (2003). Residual effects of a traumatic brain injury on locomotor capacity: A first study of spatiotemporal patterns during unobstructed and obstructed walking. *Journal of Head Trauma Rehabilitation, 18*(6), 512-525.

McIlroy, W. E., Norrie, R. G., Brooke, J. D., Bishop, D. C., Nelson, A. J., & Maki, B. E. (1999). Temporal properties of attention sharing consequent to disturbed balance. *Neuroreport, 10*(14), 2895-2899.

Mecklinger, A., von Cramon, D. Y., Springer, A., & Matthesvon Cramon, G. (1999). Executive control functions in task switching: Evidence from brain injured patients. *Journal of Clinical and Experimental Neuropsychology, 21*(5), 606-619. Tayor & Frans.

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology, 41*(3), 211-253.

Melzer, I., Benjuya, N., & Kaplanski, J. (2001). Age-related changes of postural control: Effect of cognitive tasks. *Gerontology, 47*(4), 189-194.

Melzer, I., & Oddsson, L. I. (2004). The effect of a cognitive task on voluntary step execution in healthy elderly and young individuals. *Journal of the American Geriatrics Society, 52*(8), 1255-1262.

Monsell, S., Sumner, P., & Waters, H. (2003). Task-set reconfiguration with predictable and unpredictable task switches. *Memory & Cognition, 31*(3), 327-342.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*(3), 134-140.

Niechwiej-Szwedo, E., Inness, E. L., Howe, J. A., Jaglal, S., McIlroy, W. E., & Verrier, M. C. (2007). Changes in gait variability during different challenges to mobility in patients with traumatic brain injury. *Gait & Posture, 25*(1), 70-77.

Niemann, H., Ruff, R. M., & Kramer, J. H. (1996). An attempt towards differentiating attentional deficits in traumatic brain injury. *Neuropsychology Review, 6*(1), 11-46.

Norrie, R. G., Maki, B. E., Staines, W. R., & McIlroy, W. E. (2002). The time course of attention shifts following perturbation of upright stance. *Experimental Brain Research, 146*(3), 315-321.

Oberg, T., Karsznia, A., & Oberg, K. (1993). Basic gait parameters: Reference data for normal subjects, 10-79 years of age. *Journal of Rehabilitation Research & Development, 30*(2), 210-223.

Ouchi, Y., Okada, H., Yoshikawa, E., Nobezawa, S., & Futatsubashi, M. (1999). Brain activation during maintenance of standing postures in humans. *Brain, 122*(Pt 2), 329-338.

Park, N. W., Moscovitch, M., & Robertson, I. H. (1999). Divided attention impairments after traumatic brain injury. *Neuropsychologia, 37*(10), 1119-1133.

Parker, T. M., Osternig, L. R., Van Donkelaar, P., & Chou, L. S. (2006). Gait stability following concussion. *Medicine and Science in Sports and Exercise, 38*(6), 1032-1040.

Parker, T. M., Osternig, L. R., Lee, H., Donkelaar, P. v., & Chou, L. (2005). The effect of divided attention on gait stability following concussion. *Clinical Biomechanics, 20*(4), 389-395.

Parker, T. M., Osternig, L. R., Van Donkelaar, P., & Chou, L. (2006). Gait stability following concussion.article. *Medicine & Science in Sports & Exercise, 38*(6), 1032-1040.

Ponsford, J., & Kinsella, G. (1995). Attentional deficits following closed-head injury: Erratum. *Journal of Clinical and Experimental Neuropsychology, 17*(4), 640.

Powell LE & Myers AM (1995). The Activities-specific Balance Confidence (ABC) Scale. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 50* (1), M28-M34

Powell, J. M., Machamer, J. E., Temkin, N. R., & Dikmen, S. S. (2001). Self-report of extent of recovery and barriers to recovery after traumatic brain injury: A longitudinal study. *Archives of Physical Medicine and Rehabilitation, 82*(8), 1025-1030.

Quant, S., Adkin, A. L., Staines, W. R., Maki, B. E., & McIlroy, W. E. (2004). The effect of a concurrent cognitive task on cortical potentials evoked by unpredictable balance perturbations. *BMC Neuroscience, 5*, 18.

Quinn, B., & Sullivan, S. J. (2000). The identification by physiotherapists of the physical problems resulting from a mild traumatic brain injury. *Brain Injury, 14*(12), 1063-1076.

Rankin, J. K., Woollacott, M. H., Shumway-Cook, A., & Brown, L. A. (2000). Cognitive influence on postural stability: A neuromuscular analysis in young and older adults. *The Journals of Gerontology: Series A, Biological Sciences and Medical Sciences, 55*(3), M112-9.

Redfern, M. S., Jennings, J. R., Martin, C., & Furman, J. M. (2001). Attention influences sensory integration for postural control in older adults. *Gait & Posture, 14*(3), 211-216.

Redfern, M. S., Muller, M. L., Jennings, J. R., & Furman, J. M. (2002). Attentional dynamics in postural control during perturbations in young and older adults. *The Journals of Gerontology: Series A, Biological Sciences and Medical Sciences, 57*(8), B298-303.

Regnaux, J. P., David, D., Daniel, O., Smail, D. B., Combeaud, M., & Bussel, B. (2005). Evidence for cognitive processes involved in the control of steady state of walking in healthy subjects and after cerebral damage. *Neurorehabilitation and Neural Repair, 19*(2), 125-132.

Regnaux, J. P., Roberston, J., Smail, D. B., Daniel, O., & Bussel, B. (2006). Human treadmill walking needs attention. *Journal of Neuroengineering and Rehabilitation, 3*, 19.

Reitan RM & Wolfson D (1985) The Halstead-Reitan Neuropsychological test battery. Tucson: Neuropsychology Press.

Riley, M. A., Baker, A. A., & Schmit, J. M. (2003). Inverse relation between postural variability and difficulty of a concurrent short-term memory task. *Brain Research Bulletin, 62*(3), 191-195.

Riley, M. A., Baker, A. A., Schmit, J. M., & Weaver, E. (2005). Effects of visual and auditory short-term memory tasks on the spatiotemporal dynamics and variability of postural sway. *Journal of Motor behavior, 37*(4), 311-324.

Rogers RD & Monsell S (1995) Costs of a predictable switch between simple and cognitive tasks. *Journal of Experimental Psychology*, 124 (2), 207-31

Rogers, R. D., Sahakian, B. J., Hodges, J. R., Polkey, C. E., Kennard, C., & Robbins, T. W. (1998). Dissociating executive mechanisms of task control following frontal lobe damage and parkinson's disease. *Brain, 121*(Pt 5), 815-842.

Schmitter-Edgecombe, M., & Langill, M. (2006). Costs of a predictable switch between simple cognitive tasks following severe closed-head injury. *Neuropsychology, 20*(6), 675-684.

Seaby L and Torrance G. (1989). Reliability of a physiotherapy functional assessment used in a rehabilitation setting. *Physiotherapy Canada, 41*: 264-71

Sheridan, P. L., Solomont, J., Kowall, N., & Hausdorff, J. M. (2003). Influence of executive function on locomotor function: Divided attention increases gait variability in alzheimer's disease. *Journal of the American Geriatrics Society, 51*(11), 1633-1637.

Shkuratova, N., Morris, M. E., & Huxham, F. (2004). Effects of age on balance control during walking. *Archives of Physical Medicine & Rehabilitation, 85*(4), 582-588.

Shumway-Cook, A., & Woollacott, M. (2000). Attentional demands and postural control: The effect of sensory context. *Journals of Gerontology Series A-Biological Sciences & Medical Sciences, 55*(1), M10-6.

Shumway-Cook, A., Woollacott, M., Kerns, K. A., & Baldwin, M. (1997). The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *Journals of Gerontology Series A-Biological Sciences & Medical Sciences, 52*(4), M232-40.

Silsupadol, P., Siu, K. C., Shumway-Cook, A., & Woollacott, M. H. (2006). Training of balance under single- and dual-task conditions in older adults with balance impairment. *Physical Therapy, 86*(2), 269-281.

Sohlberg, M. M., & Mateer, C. A. (1987). Effectiveness of an attention-training program. *Journal of Clinical & Experimental Neuropsychology: Official Journal of the International Neuropsychological Society, 9*(2), 117-130.

Sparrow, W. A., Bradshaw, E. J., Lamoureux, E., & Tirosh, O. (2002). Ageing effects on the attention demands of walking. *Human Movement Science, 21*(5-6), 961-972.

Spreen, O., & Strauss, E. (1998). A compendium of neuropsychological tests: Administration, norms, and commentary (2nd ed.). *(1998). A Compendium of Neuropsychological Tests: Administration, Norms, and Commentary* (2nd ed.).xvi, 736 pp.New York, NY, US: Oxford University Press,

Staines, W. R., Brooke, J. D., & McIlroy, W. E. (2000). Task-relevant selective modulation of somatosensory afferent paths from the lower limb. *Neuroreport, 11*(8), 1713-1719.

Staines, W. R., Graham, S. J., Black, S. E., & McIlroy, W. E. (2002). Task-relevant modulation of contralateral and ipsilateral primary somatosensory cortex and the role of a prefrontal-cortical sensory gating system. *NeuroImage, 15*(1), 190-199.

Stuss, D. T., Stethem, L. L., Hugenholtz, H., Picton, T., Pivik, J., & Richard, M. T. (1989). Reaction time after head injury: Fatigue, divided and focused attention, and consistency of performance. *Journal of Neurology, Neurosurgery & Psychiatry, 52*(6), 742-748.

Swaine, B. R., & Sullivan, S. J. (1996). Longitudinal profile of early motor recovery following severe traumatic brain injury. *Brain Injury, 10*(5), 347-366.

Teasdale, N., & Simoneau, M. (2001). Attentional demands for postural control: The effects of aging and sensory reintegration. *Gait & Posture, 14*(3), 203-210.

Tornay, F. J., & Milan, E. G. (2001). A more complete task-set reconfiguration in random than in predictable task switch. *Quarterly Journal of Experimental Psychology A, 54*(3), 785-803.

Vallee, M., McFadyen, B. J., Swaine, B., Doyon, J., Cantin, J. F., & Dumas, D. (2006). Effects of environmental demands on locomotion after traumatic brain injury. *Archives of Physical Medicine and Rehabilitation, 87*(6), 806-813.

van Zomeren, A. H., & Deelman, B. G. (1976). Differential effects of simple and choice reaction after closed head injury. *Clinical Neurology & Neurosurgery, 79*(2), 81-90.

Vuillerme, N., Nougier, V., & Teasdale, N. (2000). Effects of a reaction time task on postural control in humans. *Neuroscience letters, 291*(2), 77-80.

Weeks, D. L., Forget, R., Mouchnino, L., Gravel, D., & Bourbonnais, D. (2003). Interaction between attention demanding motor and cognitive tasks and static postural stability. *Gerontology, 49*(4), 225-232.

Weerdesteyn, V., Schillings, A. M., van Galen, G. P., & Duysens, J. (2003). Distraction affects the performance of obstacle avoidance during walking. *Journal of Motor Behavior, 35*(1), 53-63.

Whyte, J., Fleming, M., Polansky, M., Cavallucci, C., & Coslett, H. B. (1998). The effects of visual distraction following traumatic brain injury. *Journal of the International Neuropsychological Society, 4*(2), 127-136.

Whyte, J., Schuster, K., Polansky, M., Adams, J., & Coslett, H. B. (2000). Frequency and duration of inattentive behavior after traumatic brain injury: Effects of distraction, task, and practice. *Journal of the International Neuropsychological Society, 6*(1), 1-11.

Wickens CK. Attention and Skilled Performance. In: *Human Skills*, Holding D, editor. New York: John Wiley & Sons 1989.

Williams, G., Robertson, V., & Greenwood, K. (2004). Measuring high-level mobility after traumatic brain injury. *American Journal of Physical Medicine & Rehabilitation, 83*(12), 910-920.

Williams, G., Robertson, V., Greenwood, K., Goldie, P., & Morris, M. E. (2006). The concurrent validity and responsiveness of the high-level mobility assessment tool for measuring the mobility limitations of people with traumatic brain injury. *Archives of Physical Medicine and Rehabilitation, 87*(3), 437-442.

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: A review of an emerging area of research. *Gait & Posture, 16*(1), 1-14.

Wylie, G., & Allport, A. (2000). Task switching and the measurement of "switch costs". *Psychological Research, 63*(3-4), 212-233.

Yang, Y. R., Chen, Y. C., Lee, C. S., Cheng, S. J., & Wang, R. Y. (2007). Dual-task-related gait changes in individuals with stroke. *Gait & Posture, 25*(2), 185-190.

Yardley, L., Gardner, M., Leadbetter, A., & Lavie, N. (1999). Effect of articulatory and mental tasks on postural control. *Neuroreport, 10*(2), 215-219.

Yeung, N., & Monsell, S. (2003). Switching between tasks of unequal familiarity: The role of stimulus-attribute and response-set selection. *Journal of Experimental Psychology: Human Perception and Performance, 29*(2), 455-469.