Multi-Tasking in Adults with Traumatic Brain Injury: Examining the Impact of Concurrent Motor and Cognitive tasks

by

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Rehabilitation Science Institute
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Abstract

After moderate-severe traumatic brain injury (TBI), community reintegration is a well-documented challenge. A focus of this dissertation is the role of balance in community integration: Balance impairments, shown to correlate with poorer community integration, are a common and enduring consequence of TBI; moreover, even in patients who appear to be well-recovered in balance control, residual impairment can be revealed when examined with multi-tasking paradigms. Multi-tasking is a particularly important capacity for community integration because so many activities that enable people to successfully engage in the community require concurrent performance of motor and cognitive tasks. To date, limited research has examined static postural control and cognitive performance after moderate-severe TBI, and no studies have examined postural control in the context of facial emotion perception (FEP). However, this combination is particularly relevant to community integration because many inter-personal activities (e.g., having coffee with a friend, speaking with an employer) require both. Therefore the overall aims of this dissertation were to examine the relationship between multi-tasking and community integration, and better characterize multi-tasking impairment after TBI, employing postural control measures designed to simulate real-world functioning plus a conventionally used cognitive test (the Stroop), and a newly developed measure of FEP designed to provide a more
ecologically valid assessment of this capacity in TBI. We first demonstrated that balance correlated with early, but not later community integration, and balance functioning that necessitated multi-tasking in the earlier stages of recovery correlated with community integration in the later stages. We developed an FEP task using an indirect test format to permit implicit processing that employed dynamic faces and provided environmental context; we demonstrated preliminarily that it was feasible for brain-injured adults. Finally, in comparing adults with TBI to controls, we found that when combining postural control and Stroop tasks, only postural control was affected in TBI. These findings extended to the indirect FEP task. Taken together, the findings suggest that early identification of multi-tasking impairment and targeted intervention might improve long-term community integration. Further research is required to better understand the mechanisms that underlie multi-tasking impairment after TBI in order to design such targeted interventions.
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List of Abbreviations

A/P – anterior-posterior

BFRT – Benton Face Recognition Test

CB&M – Community Balance and Mobility Scale

CIQ – Community Integration Questionnaire

CNS – central nervous system

COM – centre of mass

COP – centre of pressure

DTC – dual-task cost

FEP – facial emotion perception

FEP-dci – facial emotion perception with dynamic stimuli, contextual information and implicit processing

FAM – Functional Assessment Measure

FIM – Functional Independence Measure

GCS – Glasgow Coma Scale

HC – healthy control

HiMAT – High-level Mobility Assessment Tool

LT - left

M/L – medial-lateral

MPF\textsubscript{A} – mean power frequency for acceleration

MPF\textsubscript{C} – mean power frequency for centre of pressure
MVC – motor vehicle crash

NA – narrow stance

NAC – narrow stance plus cup

PTA – post-traumatic amnesia

\( \text{RMS}_A \) – root mean square for acceleration

\( \text{RMS}_C \) – root mean square for centre of pressure

RT – right

ST – standard stance

STC – standard stance plus cup

TASIT – The Awareness of Social Inference Test

TBI – Traumatic brain injury

TSI – time since injury

WTAR – Wechsler Test or Adult Reading
1 Introduction

1.1 Traumatic brain injury

Traumatic brain injury (TBI) is an alteration in brain function or other evidence of brain pathology due to forces exerted on the brain, such as from a direct blow to the head or by the exertion of linear or rotational accelerational/decelerational forces; motor vehicle crashes, falls, sporting injuries and assaults are among the most common causes [1, 2]. TBI, a ubiquitous injury sustained by many people in the prime of life [3, 4], is the primary cause of disability in Canadians under 40 years of age [3, 5, 6], which can mean decades of disability and lost productivity. Not surprisingly, the annual burden of acute care and rehabilitation in North America is estimated to be in the billions of dollars [5, 7].

Moderate-severe TBI, the focus of this thesis, can result in significant and intrusive impairments to cognitive, motor and emotional functioning ([8-10], see [11-13] for a review). Predominant and persisting deficits to executive functioning, attention, memory and speed of processing compromise psychosocial functioning and quality of life [10, 14-16]. In addition, residual balance and mobility impairment has been reported as one of the most common and chronic concerns after TBI [17, 18]. These deficits prevent many TBI survivors from returning to pre-injury levels of participation [19-21] and community integration [22, 23], with commensurately reduced quality of life [9, 16, 24-27]. Community integration is, thus, recognized as a primary goal of rehabilitation for persons with brain injury [28]. Understanding how impairments mediate community integration, a focus of this thesis, is an area of research that offers important prospects for treatment.
1.2 Community integration and traumatic brain injury

Community integration has been described as the experience of being a part of the community, being accepted, and not being unduly disadvantaged because of disability [29]. McColl et al. [29] suggested that ideal community integration has three main components: (1) activities to fill one’s time, (2) independence in one’s living situation, and (3) relationships with other people. Winkler et al. [23] reported that community integration constructs relate closely to the ‘participation’ concept, outlined in the International Classification of Function [30] as involvement of a person in all areas of life.

Poor community integration after TBI has been associated with depression, isolation, and decreased quality of life [15, 16, 22, 24, 26, 31], and reduced community integration is observed even years post injury [32]. Commonly reported examples of reduced community integration include increased idle time, boredom, and little-to-no engagement in meaningful activities [33-37]. Wise et al. [34] found that TBI survivors reported less participation in leisure activities, more sedentary and less social lifestyles, and many felt dissatisfied with these changes. Furthermore, with respect to reduced community integration, psychosocial functioning (e.g., employment, social relationships, independent living, and recreation) has been shown to be negatively affected after TBI [15, 26, 38, 39]. Research has demonstrated that by one year after injury, problems with psychosocial functioning appear to be greater than problems in basic activities of daily living [40] and may persist many years after TBI [41]. Struchen et al. [42] demonstrated that social communication abilities and affective/behavioural functioning, including the ability to express and regulate emotions [31, 41-44], as well as the ability to read emotions in faces [45, 46], make a substantial contribution to social integration outcomes after TBI. In addition to cognitive and psychosocial impairment after TBI, research has demonstrated a relationship between high-level balance and community integration, such that those with poorer postural control report lower levels of community integration [25, 47]
A range of barriers, physical, attitudinal [48], financial [49-53], and functional (see [54] for a review), have been shown to play a role in community integration, and many individuals with TBI and their family members report feeling inadequately prepared for the transition from hospital to home, particularly with respect to behavioural sequelae [35, 49, 55-58]. In Rochat et al.’s [59] examination of executive disorders and perceived socio-emotional changes after TBI, the authors reported that lower multi-tasking performance (as measured by the Modified Six Elements Test [60]) was related to greater externalizing behaviours, including increased irritability, impulsivity, lack of planning, insensitivity, social inappropriateness, impatience, aggression and inappropriate affect. They suggested that disturbances in self-regulation - the inability to flexibly direct attention to internal and external representations - may lead to behaviour that is maladjusted in unconstrained situations. Such findings raise the broader question whether multi-tasking impairments might lead to the observed difficulties in community integration after TBI. To date, as indicated by a comprehensive review of the literature, no studies have explicitly asked this question.

The ability to multi-task likely plays an important role in community integration given that many everyday activities require that multiple processes operate at once. Even seemingly simple tasks like walking and holding a cup require the concurrent operation of motor, sensori-perceptual and cognitive processes [61-64], let alone inter-personal situations that additionally necessitate communication and the interpretation of emotions [65-67]. Given that many studies have demonstrated that the ability to multi-task is affected after TBI (e.g., [8, 68, 69]), logically, it follows that multi-tasking impairment may be implicated in community integration difficulties.
1.3 Multi-tasking, traumatic brain injury and community integration

Burgess and Simons [70] define the mental processes of multi-tasking as:

“...the creation, maintenance and execution of delayed intentions; the ability to recognise the need for self-initiative and carry out complex meta-strategies; dovetailing of tasks to be time effective; prioritisation of tasks and deciding for oneself in the absence of feedback whether a result is satisfactory.” (p.228)

It has also been more broadly defined as the ability to process and/or respond to information while concurrently performing more than one task [71]. Multi-tasking is important for many daily tasks because we are constantly dividing our attention, switching between tasks, and responding to internal or environmental stimuli. The ability to multi-task has been widely researched to determine to what extent humans can manage several processes online at once, and how performance changes when the system is overloaded.

A number of theoretical models have been proposed to explain performance deterioration when multi-tasking (see [72-74] for summary). In the aging and brain injury literature, there has been extensive support for the automaticity framework with respect to multi-tasking [73, 75-77]. Automaticity refers to the performance of a task with little demand on attentional resources [65, 72, 77], and is thought to be achieved by extended training, resulting in increased speed of processing and parallel processing, along with less effort and control [77]. The automaticity framework for multi-tasking purports that when the simultaneous performance of two tasks does not disrupt performance, we assume that one or both of the tasks requires minimal attention. However, if one or both tasks are novel and/or require conscious, effortful processing, the demand for attentional resources will be greater [78-81], and therefore, performance on either or both tasks will be affected. Central to this framework is the notion that attention has a finite capacity, and that tasks can be performed simultaneously without cost to either task until the limit in attentional resources is reached [82]; when this occurs, task performance deteriorates.
Multi-tasking studies have examined how performance might be affected by combining cognitive tasks, motor tasks, or by combining both cognitive and motor tasks. Level of interference, often referred to as dual-task cost (DTC) and measured by comparing single-task (or baseline) performance to dual-task performance, depends on variables including difficulty of the task(s) and level of automaticity in one or more tasks. The cost when tasks are combined is often exhibited as increased reaction time and/or errors on cognitive tasks [83-86], and slowed, more variable or less coordinated movements on motor tasks [75, 79, 87, 88] relative to performance of either of the respective tasks alone. DTCs may be found in one or both tasks [89-93], and influenced by factors such as task priority/focus [94-97], age [61, 66, 67, 85, 98-100] and sensory modality of the tasks [101-106].

When comparing multi-tasking abilities in brain-injured adults to healthy controls, studies have shown disproportionate impairment for those with TBI [71, 84, 102, 107-112]. Furthermore, there is evidence of altered brain activation in brain-injured adults when multi-tasking, as compared to healthy controls [113, 114]. Rasmussen et al. [113] demonstrated that adults with severe TBI had greater activation in areas involved with each task (i.e., a visual search task and a button-press motor task) when dual-tasking, and also activated areas of the prefrontal cortex that were not activated by either task alone. They suggested the differences in activation could represent a shift in automatic, parallel processing to a non-automatic, serial processing strategy. Sinopoli et al. [114] found similar differences in young athletes with mild TBI.

Interestingly, in healthy adults, combining tasks can also result in improved performance on one or both of the tasks as compared to their performance alone [115]. For example, Broglio et al. [116] found that when a cognitive task and a postural control task were performed in parallel, reaction time decreased and balance scores improved. When combining motor and cognitive tasks, researchers have suggested that the relationship between postural control and cognitive demands is explained by a U-shaped function (see [115] for a review), whereby performance of
one task is poorest at the lowest and highest levels of cognitive demand of the simultaneous task, and optimal when the cognitive demands are intermediate.

Wulf et al. [80] examined whether paying attention to one’s movement can disrupt performance of well-practiced skills while an external focus enhances performance. This might occur because postural control is thought to be mediated by automatic control processes, and conscious examination of postural control might interfere with relatively automatic processing. McNevin and Wulf [79] provided evidence to support this by demonstrating that when attention was directed away from participants’ focus of maintaining balance (by focusing on another task), participants reduced their sway. In accordance, Huxhold et al. [115] suggested that relatively low-difficulty cognitive activities improve postural performance by shifting the focus of attention away from a highly automatized activity. Task focus [79, 96, 104], age [66, 115, 117], visual spatial/perceptual properties of the tasks [66, 103, 105, 115, 117-120] and physiological responses like arousal [121-124] appear to mediate this relationship.

When combining relatively automatic and simple motor and cognitive tasks, studies have demonstrated effects on motor performance such as decreased variability in gait [117] and increased postural stability [79, 96, 103-105, 118-120, 124, 125]. The effects on cognitive performance often manifest as faster reaction time [66, 104, 126]. Huxhold et al. [115] suggest that the beneficial effects of combining certain tasks are more easily observed at lower levels of task difficulty because such levels are sufficient to shift attention away from the postural domain without causing resource competition. In addition, some researchers have suggested that supra-postural tasks (e.g., tasks or behavioural goals that are super-ordinate to postural control [119]) that require visual processing, and therefore require stabilization of the head (to support accurate visual fixation), play a large role in postural stabilization [103, 105, 118-120]. Early work by Gibson [127] suggested that information that is available to the eye can be influenced by movements of the head and body, and that such movements can be controlled so as to facilitate vision. Consistent with this concept of the visual system, Stoffegren et al. [119, 120]
demonstrated that visual performance, controlled by parameters of the oculomotor system such as focus and convergence, could be maintained by variations in body sway. The finding of increased postural stabilization in response to supra-postural tasks that require visual processing has been demonstrated in younger and older healthy adults [128].

With respect to brain injured adults, findings of improved performance have not been replicated, but rather evidence suggests that multi-tasking results in decrements to performance, possibly due to reduced attentional capacity [107, 109], lost ability to perform tasks that are automatic or a shift to controlled processing on tasks previously performed automatically [68], or damage to brain areas needed for multi-tasking, such as the pre-frontal cortex [112, 129, 130]. A number of studies of TBI have demonstrated that tasks performed normally in isolation show disproportionate disruption to one or all tasks when combined [112, 131-133].

The essential role that multi-tasking plays in everyday life raises the question of how multi-tasking deficits impact community integration after TBI. Foley et al. [134] demonstrated that 25% of their sample of TBI patients demonstrated DTCs when they simultaneously performed a digit span and a tracking task (i.e., paper and pencil task to connect circles), and those who had greater deficits in psychosocial functioning, as measured by the Functional Independence and Functional Assessment Measures (FIM+FAM), had worse dual-task performance. They concluded that this finding provides evidence of a relationship between impaired dual-task performance and diminished everyday functioning after TBI. These findings are the first to demonstrate a relationship between multi-tasking impairments and independence in daily living. However, a review of the literature reveals that to date, there are no published studies that have correlated multi-tasking performance with a valid and reliable measure of community integration in moderate-severe TBI patients.
One tool that has been established as a valid and reliable measure of participation in the community is the Community Integration Questionnaire (CIQ), developed by Willer and colleagues [135]. The FIM+FAM contains items that address functioning in the community, but was designed as a measure of disability, and moreover was developed to assess functioning in the early stages after injury rather than as a measure of later community-based functioning. The CIQ was designed to assess home integration, social integration and productive activity in brain-injured adults, and is currently the mostly widely used community integration measurement tool for people with TBI [136]. There are no studies to-date have examined the relationship between the CIQ and multi-tasking ability after TBI.

1.3.1 Postural control, traumatic brain injury and community integration

Balance control, necessary for independence in activities of daily living [137], is defined as the dynamics of body posture to prevent falling and is related to the inertial forces acting on the body [138]. It requires integration of visual, somatosensory, and vestibular information (see [139, 140] for a review) to maintain the body’s centre of mass ([COM] a point equivalent to the weighted average of the COM of each body segment in 3D space) over the base of support during quiet standing [138]. Human balance has been modelled as an inverted pendulum, where the body is controlled as a single rigid segment supporting the COM, which rotates about the ankle joints [141]. The inverted pendulum is controlled through the development of ground-reaction forces that can be recorded using a force plate. Centre of pressure (COP) represents a weighted average of all the pressures over the surface of the area in contact with the ground (e.g., under the foot) [138] and involves two different components: (1) the gravitational projection of COM, called centre of gravity; and, (2) torques generated at the ankle joints (dorsi-flexion/plantar-flexion) in the anterior–posterior (A/P) plane and the hip joints (abduction/adduction) in the medial–lateral (M/L) plane [142]. Postural sway, the seemingly random oscillation of the body during stance, can be caused by external forces (e.g., wind, vibrations, ground movements) and internal forces (e.g., breathing, blood flow, muscle activity), and it is has been postulated that a goal of the central nervous system (CNS) is to maintain equilibrium of the COM around a particular point when standing [141, 143]. Thus, the COP must
react to counteract movements of the COM; its movement is greater than that of the COM in order to create appropriate torque on the inverted pendulum to force the COM to a desired point or area. COP thus does not represent postural sway itself, but is used as a proxy measure of sway [141].

Impairments to postural control have been well-documented after TBI [144-146]. Given the importance of postural control to everyday activities – even apart from multi-tasking – an important scientific and clinical question is whether postural control deficits play a role in reduced community integration.

The Community Balance and Mobility Scale (CB&M) [47], a measure of high-level postural control, was designed to provide insight into the balance and mobility status of the TBI patient returning to the community environment. It includes a range of tasks that are sensitive to the abilities that underlie motor skills necessary for everyday functioning within the community [47], including aspects of movement and posture such as multi-tasking and sequencing of movement components. Moreover, the CB&M has been demonstrated to correlate with performance on the CIQ in TBI [25, 147]. Previous studies found that poor high-level balance was related to low ratings of community integration [25], and in examining the sub-scales of the CIQ (i.e., Home integration, Social integration, and Productivity), evidence suggested that high-level balance might be most important for return to productive activity [147]. However, methodological limitations of these studies (e.g., lack of control for injury severity and age), and differing timelines of measurement leave some uncertainty regarding the relationship between postural control and community integration in TBI, and further research is warranted.
1.3.2 Postural control, multi-tasking and traumatic brain injury

Conventionally, postural control was thought to be an automatic response to sensory input [148], but work in the past two decades has provided evidence that it may require attentional resources (e.g., [92]). This research has primarily employed multi-tasking paradigms. For example, Lajoie et al. [92] demonstrated that attentional costs increased as balance requirements of the postural task became more demanding, with reaction times to auditory stimuli longer for standing and walking than for sitting, and longer for walking than for standing. More recent work has found that a greater amount of attentional resources are needed as the postural stance becomes more challenging, for example wide versus narrow versus tandem stances [96, 104, 116, 126, 149]. Studies examining multi-tasking effects have demonstrated increases in measures of sway, including COP amplitude, frequency, velocity, path length, and variability [98, 103, 104, 106, 125, 126, 150].

Interestingly, some studies have demonstrated that the addition of a cognitive supra-postural task does not lead to changes to postural sway, [93, 96, 104, 123], and others have demonstrated stabilization of posture [103-105, 115, 116, 118, 120, 124, 128, 151, 152]. Explanations for why postural control was not affected by simultaneous performance of a cognitive task, include the following: (1) participants did not switch attention from one task to the other during the dual-task conditions [93]; (2) the additional task diverted attention from the postural task but did not elicit physiological arousal [123]; and (3) sufficient attention is automatically directed toward the maintenance of balance stability, even when participants focus on the cognitive task [96]. With respect to the stabilizing response seen in many multi-tasking studies, researchers suggest that the addition of a supra-postural task, particularly one that is visual in nature, directs attention away from balance-related cues, thereby reducing over-corrections [153], and thus allowing for more automatic or reflexive control processes to be utilized [79, 80]. Stoffregen and colleagues [105, 118] suggested that postural control does not compete with concurrent supra-postural tasks for central processing resources, but rather body sway is modulated to support visual performance.
Studies of multi-tasking that include postural control tasks in adults with mild to severe TBI have primarily examined the effects of adding a cognitive task to a gait task. Such studies have demonstrated slowed speed [90, 102, 154-158], smaller foot clearances [102, 156], increased COM variability [155], and greater sway [158] in dual- versus single-task conditions. However, few studies have used multi-tasking paradigms to better understand the attentional demands of maintaining standing balance after brain injury. Geurts and colleagues [159] examined 20 adults with mild to severe TBI, assessing concurrent performance of a balance task and a mental arithmetic task. While COP amplitude and frequency were significantly higher than the healthy control group at baseline, there were no DTC differences between the groups in COP amplitude or frequency, or in performance of the cognitive task. Conversely, Brauer et al. [109] compared 20 adults with severe TBI to a healthy control group, and found that baseline measures of COP excursion and velocity were higher in the TBI group, and they had significantly greater DTC to postural control, yet only when concurrently performing the easiest cognitive tasks (i.e., a control articulation task and a simple non-spatial task). They suggested that distractibility during these simple tasks likely contributed to an increase in COP motion and interference with postural stability. Brauer and colleagues [109] offered several explanations for the conflicting findings: (1) Geurts et al. [159] examined participants with mild to severe TBI, 75% of which were mild TBI, (Brauer et al. [109]: all severe TBI), (2) participants were on average 29 months post-injury, (Brauer et al. [109]: 4 months post-injury), and (3) the task that was used in the Geurts et al. study [159] may have been too easy.

Differences in multi-tasking ability when combining static postural control and cognitive tasks between adults with moderate-severe TBI and healthy adults, however, have not been widely examined, and studies to date have employed diverse experimental designs making assimilation of the findings difficult (see [160] for review). Given the importance that postural control plays in many daily activities, including the frequency with which postural control is needed while carrying out cognitive tasks, a better characterization of how postural control is affected by multi-tasking after TBI is warranted.
1.3.3 Cognitive tasks and multi-tasking

The effects of multi-tasking on cognitive outcome measures have been examined in healthy adults using several different attention-demanding tasks. When cognitive tasks are performed simultaneously, decrements in performance have been demonstrated on tasks requiring memory [64, 97], spatial processing [85, 97, 161], executive function [83, 161, 162], speed of processing tasks [83], speech [64, 85], and mental arithmetic [64, 162]. Combinations of cognitive and motor tasks have also demonstrated that cognitive performance can be disrupted with the addition of a motor task. Specifically, when combined with walking, studies have demonstrated disruptions to speech [61, 99], counting [89], speed of processing [63, 163, 164], semantic fluency [100], mental arithmetic [131], memory [67, 165] and attention [166]. Although, importantly, there is also evidence that combining different cognitive (e.g., semantic judgement tasks, visual processing and scanning tasks) and motor (e.g., walking, maintaining balance) tasks can also lead to improved cognitive performance (e.g., faster reaction time) [66, 94, 104, 116, 167]. Multi-tasking studies using cognitive tasks have discriminated between younger and older adults [61, 67, 99, 100, 117, 131, 168, 169], older adults with and without cognitive dysfunction [91, 166, 170, 171], and older adults that are fallers versus non-fallers [91, 166], a distinction that has direct implications for adults with TBI who often experience residual difficulty with high-level balance [18, 172].

In adults with TBI, findings of multi-tasking impairment have also been demonstrated with cognitive task combinations: decrements in performance, as compared to controls, have been observed for tasks requiring memory [108, 134], spatial processing [71, 109, 111, 134], executive function [84, 129, 130, 173], speed of processing [107, 112, 173, 174], speech [107, 175], driving [71], and mental arithmetic [174]. In cognitive-motor combinations, disruptions to gait have been widely demonstrated in adults with mild to severe TBI [90, 102, 133, 154-156, 158], using different cognitive tasks, but most often using the Stroop task [102, 133, 154-156]. The Stroop task [176] examines both speed of processing and selective attention/interference by requiring participants to name, as quickly as possible, the colours of words, where the word referents are also colours but ones that predominantly conflict with the colours in which the
words are presented. This task is widely used in neuropsychological assessments with brain-injured adults, and difficulty with this task may reflect poorer inhibitory control and/or selective attention. The direct generalizability of the task to everyday activities, however, has yet to be confirmed. Given the pervasiveness of multi-tasking in our daily lives, it is important understand whether cognitive tasks that are more experimental in nature generalize to everyday tasks when performed in parallel with postural control tasks. Simultaneous performance of a cognitive task and a postural control task that leads to a disruption in balance has direct functional implications. Disruption to a cognitive task that more closely resembles everyday activities that are important for community integration, like engaging in inter-personal interactions, has not been examined. Moreover, given evidence that multi-tasking is disrupted after TBI, as is community integration and social functioning, it would be clinically relevant to understand what role impaired multi-tasking plays in inter-personal interactions, and to do so, it is important use tasks that can generalize to such interactions.

1.3.4 Facial emotion perception and multi-tasking

The ability to perceive emotion, considered a highly automatic skill that we develop and hone as we age [177, 178], is necessary for inter-personal interactions. An inability to accurately and quickly perceive facial emotions is problematic because it can cause difficulty with work and social activities, affecting quality of life, all of which relates to anxiety, depression, and isolation [31, 39, 86, 179-182]. Multi-tasking performance with tasks involving facial emotion perception (FEP) demonstrate that it can be disrupted when combined with other cognitive tasks [86, 183-186]. Philips et al. [86] demonstrated that the addition of a working memory dual-task resulted in more errors and longer reaction time in the FEP task. Tomasik et al. [186] used locus-of-slack logic (used to determine which operations are subject to a processing bottleneck) to demonstrate that FEP may not be able to operate in parallel with attention-demanding central operations on another task. They suggested that people may be slow to perceive and act appropriately on emotions when they simultaneously perform another task.
Few studies have examined multi-tasking with FEP tasks in neurological populations that experience difficulty with emotion perception (e.g., Alzheimer’s disease [185] and Parkinson’s disease [184]) and none to-date have examined FEP multi-tasking performance in adults with TBI. Difficulty perceiving facial emotions has been widely demonstrated in brain-injured adults [45, 46, 179, 180, 187-189]. Some suggest that neural structures associated with FEP may be vulnerable to damage because of their location in the frontal and temporal lobes [45, 190, 191], and disruption to white matter tracts [192] has been linked with poor FEP performance in adults that have sustained a TBI [46]. Moreover, poor FEP performance after TBI has been related to poor social integration [31].

The most common method to examine FEP is to present participants with static, decontextualized images of faces (e.g., faces in which all background information has been removed [193-195]) and to ask them to explicitly identify the emotion expressed, whether to label it or to match it to a target [177]. Participants are given time to observe the stimulus, consider its properties, and make a judgment. A weakness of this paradigm is its dissimilarity to real world FEP, or low ecological validity, defined by Burgess et al. [196] as “the degree of ‘representativeness’ of a task (extent to which a clinical test corresponds in form and context to a situation encountered outside the laboratory), and the ‘generalisability’ of test results (degree to which poor performance on the test will be predictive of problems outside the laboratory)”. First, real world FEP is typically carried out in a specific context (e.g., within a conversation, while watching a film with a plot). Second, we are infrequently asked to label or to match facial emotions, nor to even explicitly identify an emotion in everyday life. Rather, facial emotions are typically processed implicitly. Third, in real world interpersonal communications, facial emotions are not presented in a static manner, but rather shift from neutral to emotional or emotional to emotional. Recent studies have demonstrated the benefits of using dynamic stimuli (e.g., videos or morphs of faces changing from, for example, a neutral face to an emotional face over time, usually milliseconds) over the more conventionally used static stimuli to assess FEP [197-200]. Behavioural studies using dynamic stimuli report that facial emotions are recognized more accurately than static versions of those expressions [199-205], and brain regions implicated
in processing facial affect (see [192, 206] for a review) have been shown to respond more to
dynamic versus static emotional expressions (primarily the amygdala) [192, 200, 207-209].
While some current assessment tools contain some of these elements, such as the TASIT [210],
there are no existing FEP tools with all of these components. Thus, a gap in the literature is a tool
that permits implicit processing of dynamic facial emotions in a meaningful context.

There is also a gap in the literature on multi-tasking studies that combine FEP and postural tasks.
Stins et al. [124] demonstrated that postural control was affected by the emotional valence of
social cues (i.e., happy and angry faces) when asking participants to step forward or backward in
response to each cue. D’Attillio et al. [211] showed similar findings, in that COP was affected
when participants viewed a series of emotion-eliciting images (e.g., scenarios, faces, events).
Other researchers have also shown that postural control is affected by fear and anxiety [122, 212,
213]; however, these findings have been demonstrated by eliciting such emotions through
challenging postural tasks such as elevated heights. Moreover, as the ability to read emotions in
faces is considered relatively automatic, it is unknown whether using a tool that relies on implicit
and automatic processing of facial emotions will elicit DTC when combined with other tasks,
particularly with postural control tasks. There are currently no studies, to our knowledge, that
examine the ability to read emotions in faces, particularly with FEP tasks the permit implicit
processing of dynamic facial emotions, and the ability to simultaneously maintain postural
control, which is important for inter-personal interactions in the community.

1.4 Summary

While it is well-known that community integration can be negatively impacted after moderate-
severe TBI, and that there may be several complex and multi-faceted contributing factors, little is
known about what role multi-tasking might play. The CB&M, a measure of high-level balance,
has been demonstrated to correlate with community integration after TBI; however, an
understanding of which aspects of balance and mobility (e.g., multi-tasking) may affect
community integration has not yet been undertaken. It may be possible that those who are better able to multi-task are also better able to participate more fully in their communities, and it would, therefore, be clinically important to examine if multi-tasking ability after TBI is a predictor of, or related to, community integration. Moreover, further research is needed to better characterize multi-tasking in adults with moderate-severe TBI using tasks that are relevant to community integration, such as inter-personal interactions, given the frequency of social contexts in which postural and cognitive multi-tasking is needed (e.g., preparing a meal, holding a drink and talking, giving a presentation). Currently, only two studies have examined multi-tasking after moderate-severe TBI using postural control and cognitive tasks, with differing results, and neither used tasks that generalize well to daily functioning. Whether adults with TBI also demonstrate reductions in sway with the addition of a task that requires visual processing has not been examined, nor has whether these findings extend to tasks that are important for everyday activities, such as reading emotions in faces. Understanding if the ability to interact with others in inter-personal settings is affected by the ability to multi-tasking can inform or direct therapies and interventions.

1.5 Research aims and objectives

1.5.1 Balance, community integration and multi-tasking

**Aim:** To better understand the relationship between postural control and community integration in adults with moderate-severe TBI. In order to begin to better understand the mechanisms by which high-level balance and mobility may impact community integration, the relationship between multi-tasking ability on the CB&M and community integration in adults with TBI was also assessed.

**Objective 1:** To examine if the relationship between the CB&M and the CIQ (total and subscales) changed over time. In order to reconcile past differences in the literature, we examined the impact of time post-injury on the relationship between high-level balance and community integration.
integration by correlating the CIQ total and sub-scale scores with the CB&M scores at 5 months following moderate-severe TBI and at 12 months after moderate-severe TBI, while controlling for severity of injury and age.

**Objective 2a:** To examine if a putative multi-tasking dimension existed within the CB&M. This was accomplished by undertaking an exploratory factor analysis of the items on the CB&M using data from a sample of adults with moderate-severe TBI.

**Objective 2b:** To examine if a relationship existed between the CB&M and the CIQ (total and sub-scales), employing two latent variables from the CB&M: the putative multi-tasking variable and a second non-multi-tasking variable. We explored the relationship between the putative multi-tasking dimension and the CIQ at 5 and at 12 months post-injury. The CIQ (but not the CB&M) had been collected at 2+ years post-injury, so we additionally correlated the CB&M factors at 5 and 12 months post-injury with the CIQ at 24 months post-injury, to ascertain any predictive relationships that might be of clinical prognostic value.

### 1.5.2 A novel approach to measure facial emotion perception

**Aim:** To introduce a more ecologically valid method of measuring FEP and to assess if this new task is feasible to use in a sample of adults with moderate-severe TBI.

**Objective 1:** To introduce a novel approach to assess FEP. We described the development and design of a novel approach to assess FEP created to enhance the ecological validity of testing, which: (1) employs dynamic stimuli, (2) incorporates contextual information, and (3) employs an indirect test paradigm.
Objective 2: To measure the feasibility of this novel task. To accomplish this, we preliminarily measured the feasibility of this novel task in a pilot study employing mild to severe TBI patients and matched controls. Here, we focussed on acceptability, implementation and adaptability, using the criteria of Bowen et al. [214], whereby *acceptability* refers to the extent to which a new measure is suitable, satisfying or attractive, *implementation* refers to the extent to which a new measure can be successfully delivered to intended participants, and, *adaptability* refers to the extent to which an existing measure performs when changes are made for a new format (e.g., degree to which similar outcomes are obtained in new format, compared to previous methods).

1.5.3 Concurrent performance of postural and cognitive tasks

Aim: To better characterize multi-tasking capacity after moderate-severe TBI by examining postural control and cognitive performance using a conventional cognitive/motor task combination (i.e., the Stroop task and postural control) and examining if findings extend to a cognitive task that is an important domain given its role in interpersonal communications and remains unexplored with respect to cognitive-postural control multi-tasking paradigms (i.e., FEP).

Objective 1: To examine whether adults who have sustained a moderate-severe TBI show disproportionate multi-tasking impairment relative to controls in a paradigm employing a cognitive and a postural control task. This was accomplished by examining postural control in four increasingly challenging postural stances that are similar to everyday situations (i.e., standing with feet in a comfortable stance, a narrow stance, and while holding a cup filled with liquid), while carrying out a cognitive task that required visual processing (i.e., the Stroop task). This comparison was undertaken to examine whether adults with TBI demonstrate a stabilizing response when concurrently performing a postural control task, or if increases in attentional load resulted in increased sway, reaction time, and/or errors.
Objective 2: To extend Objective 1 by determining if adults with TBI demonstrate disproportionate multi-tasking disturbances compared to controls (as measured by postural control and cognitive DTCs) where the cognitive task is FEP. This was achieved by examining postural control in four increasingly challenging postural stances that are similar to everyday situations (i.e., as described above), while carrying out the FEP task. This objective allows us to determine whether adults with TBI demonstrate similar behaviour on a task that is considered highly automatic and practiced, and relevant to daily functioning.
2 Examining the relationship between balance and community integration after traumatic brain injury

2.1 Introduction

Traumatic brain injury (TBI) is a ubiquitous injury that affects many people in the prime of life, and reintegrating patients to the community is often a central goal of rehabilitation after injury [28]. Mobility impairments are some of the most persistent and common long-term concerns after TBI [17, 18, 172], and extent of motor impairment has been correlated with participation and community integration [32, 215-219]. However, despite previous research, there are gaps in our understanding of the relationship between mobility impairments and community integration after TBI.

With regard to the assessment of mobility, Williams et al. [220], found that the measures typically used to assess mobility after TBI assess independent walking; however, mobility is a more comprehensive capacity for moving the whole body that additionally includes crawling, climbing, running, jogging, jumping, and swimming [30]. They also found that the Functional Independence Measure (FIM) was the measure of mobility most frequently used in studies of chronic TBI; however, the FIM was designed for acute and sub-acute functioning [221] and thus has less sensitivity in the chronic stages of injury due to ceiling effects [220]. In response to findings of dynamic instability that persist in high-functioning, ambulatory patients following TBI, Howe et al. [47] created an assessment tool called the Community Balance and Mobility Scale (CB&M) [47]. The scale was designed to provide insight into the real-world balance and mobility status of the TBI patient returning to the community environment and to measure change following intervention. The tool includes a range of tasks that are sensitive to the abilities that underlie motor skills necessary for everyday function within the community [47]. This includes aspects of movement and posture such as multi-tasking, sequencing of movement components, and complex motor skills, with both timed and untimed tasks, and with measures of both unilateral right and left limb movements as well as bilateral movements.
In their initial study, Howe et al. [47] examined a sample of 34 adults with TBI at a mean of 11 ± 23 months post-injury and they examined level of community integration as a function of performance on the CB&M. To assess community integration, they employed the Community Integration Questionnaire (CIQ) [135], the most widely used community integration measurement tool for people with TBI [136], with demonstrated validity and reliability for this population [222, 223]. They found that community integration in those scoring at the lower end of the CB&M was significantly lower than for those who scored at the higher end of the CB&M.

Building on the earlier findings of Howe et al. [47], Inness et al. [25] also examined the relationship between the CB&M and the CIQ in a sample of adults with TBI that were 10 ± 14 months post-injury. They found a correlation between scores on the CB&M and the CIQ, and they also replicated the significant difference in CIQ scores between those scoring at the high versus low end of the CB&M. Together, these studies underscore the relationship between residual high-level balance impairments and difficulties with community integration.

Further extending this line of research into the relationship between mobility and community integration, Perry et al. [147] correlated measures of motor functioning (i.e., the CB&M, as well as the Dynamic Gait Index and Ten-Meter Walk Test for gait speed), with the sub-scales of the CIQ, comprising home integration (i.e., participation in activities such as housework and shopping), social integration (i.e., participation related to visiting friends and engaging in leisure activities) and productive activity (i.e., participation in work, school, and volunteer activities) [135]. Such an examination of the relationship between mobility and the CIQ sub-scales allows for the determination of which domains of functioning are most affected by impaired motor functioning. In 34 adults with TBI that were 52 ± 44 months post-injury, Perry et al. [147] found a positive correlation between the CB&M and the productive activity sub-scale, but they did not find an association between the CB&M and either the total CIQ (in contrast to previous research, above) or the other sub-scales [25, 47]). Similarly, Williams et al. [224] examined 39 adults with severe TBI with a median length of 9.2 months (IQR 3.2 - 24.5) post-injury using another
measure of high-level balance (the High-level Mobility Assessment Tool [HiMAT]) and found a relationship with the CIQ productive activity sub-scale score, but not with the CIQ total or other sub-scale scores.

One key difference across studies examining the relationship between the CB&M and the CIQ was time post-injury. Howe et al. [47] and Inness et al. [25] examined adults with TBI that were, on average, just under a year post-injury, while Perry et al.’s [147] sample was, on average, 52 months post-injury. As such, the findings suggest that later after injury, high-level balance and mobility may play less of a role (or perceived role) in home and social community integration. Another possible interpretation is that the CB&M only exerts an influence on community integration in adults with TBI that have poorer balance and mobility, and since the participants in the Perry et al. [147] study were longer post-injury, there might have been greater motor recovery. However, the participants in the Perry et al. [147] study were actually more impaired on the CB&M as a group, scoring more than 15 points lower than the participants in the Inness et al. [25] study. Therefore, it is more probable that it is differences in time post-injury (affecting CIQ reporting) that explain the disparity between the studies rather than level of CB&M performance. Perry et al. [147] contended that as people accepted and adjusted to impairment in the years after injury, they were able to re-establish their social roles in the community. On the other hand, while their roles at home and in social settings could be supported by family (or other aids) to facilitate integration, these supports could not offset the liability (or perceived liability) of difficulties with balance and mobility in the workplace or school to the same extent. With further regard to differences across the studies, a second important difference was that the Howe et al. [47] and Inness et al. [25] studies did not control for age, while the Perry et al. [147] study did. Another limitation of past research was the lack of control for severity of injury [25, 47, 147, 224]. Thus, it is unclear to what extent other non-motor impairments (e.g., cognitive or emotional weaknesses) may have influenced CIQ scores. As well, age, an important contributor to community integration, was controlled for in only one [147] of the four prior studies examining the relationship between high-level balance the community integration [25, 47, 224].
Thus, the first objective of the current retrospective study was to examine the impact of time post-injury on the relationship between high-level balance and community integration by correlating the CIQ total and sub-scale scores with the CB&M scores at 5 months following moderate-severe TBI and at 12 months after moderate-severe TBI, while controlling for severity of injury and age.

We were also interested in gaining a more refined understanding of what elements of high-level balance might play a role in community integration. In particular, we were interested in the role of multi-tasking. Multi-tasking is often simply defined as the ability to process and/or respond to information while concurrently performing more than one task [71]. The ability to multi-task is an important aspect of community integration because most everyday activities, including interpersonal communication, require processing of multiple operations concurrently (e.g., walking while way-finding, communicating through social media, having a coffee with a friend) [61-67].

An inability to multi-task has been linked to lower functional independence [49, 50]. Therefore, in Objective 2a, we undertook an exploratory factor analysis of the items on the CB&M to identify a putative multi-tasking dimension. In Objective 2b, we then examined the relationships between the CB&M and community integration (CIQ total and sub-scales), employing two latent variables from the CB&M: the putative multi-tasking variable and a second non-multi-tasking variable. Here, we explored the relationship between the putative multi-tasking dimension and the CIQ at 5 and at 12 months post-injury. The CIQ (but not the CB&M) had been collected at 2+ years post-injury, so we additionally correlated the CB&M factors at 5 and 12 months post-injury with the CIQ at 24 months post-injury, to ascertain any predictive relationships that might be of clinical prognostic value.
2.2 Methods

2.2.1 Participants

Participants were drawn from a larger prospective study (n = 190) investigating the natural history of cognitive and motor recovery after moderate-severe TBI at multiple time points. This larger study took place within a large, urban inpatient, neurorehabilitation program at the Toronto Rehabilitation Institute.

Inclusion criteria for all participants for the larger study were as follows: (1) acute care medical diagnosis of TBI; (2) Post-traumatic amnesia (PTA) of 1 hour or more and/or Glasgow Coma Scale (GCS) score of 12 or less either at Emergency or the scene of accident and/or positive CT or MRI findings; (3) age between 17 and 80 years; (4) able to follow simple commands in English based upon speech language pathologist intake assessment; and, (5) competency to provide informed consent for study or availability of a legal decision maker.

Exclusion criteria for all participants for the larger study were as follows: (1) Orthopaedic injuries affecting both upper extremities; (2) diseases primarily or frequently affecting the central nervous system, including dementia of Alzheimer’s Type, Parkinson’s Disease, Multiple Sclerosis, Huntington’s Disease, Lupus, stroke – based on medical records and screening of family members for patients over 50; (3) history of psychotic disorder; (4) not emerged from PTA by 6 weeks post-injury, as measured by the Galveston Orientation Amnesia Test [225]; and, (5) failure on a test of symptom validity (e.g., Test of Memory Malingering [226]).

Additional inclusion criteria for objective 1 (relationship between CB&M and CIQ across time) were that participants had to have completed the CB&M and the CIQ at the 5- and 12-month assessments. There were 51 participants who completed the 5 and 12 month assessments.
For objective 2a (factor analysis), participants had to have completed the CB&M at the 12-month assessment. Data from 123 participants were included. This sample overlaps with those from objective 1 (n = 51), but additionally includes participants who were recruited to the larger study before the CIQ was introduced, as well as participants that were excluded in analyses for objective 1 due to missing CIQ data (n = 72). For objective 2b, we examined correlations between each factor and the CIQ using the same participants that were included in objective 1 (those with assessments at 5 and 12 months [n = 51] and plus a further 24 participants with data at approximately 24 months after TBI).

Table 1 provides demographic and injury characteristics of the larger sample that participated in the recovery study (n = 190), which was a typical sample of adults with moderate-severe TBI: predominantly male and the majority of injuries caused by motor-vehicle crashes. The table also characterizes participants that were included in the analyses for objectives 1 and 2.
Table 1. Demographic and injury characteristics for participants [Mean (SD)].

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Sex (m/f)</th>
<th>Age</th>
<th>Years of education</th>
<th>GCS score</th>
<th>PTA score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eligible sample</td>
<td>190</td>
<td>139/49</td>
<td>39.77</td>
<td>13.33</td>
<td>6.40</td>
<td>4.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(16.55)</td>
<td>(2.98)</td>
<td>(3.57)</td>
<td>(1.11)</td>
<td></td>
</tr>
<tr>
<td>Excluded patients (from larger sample)</td>
<td>67</td>
<td>47/20</td>
<td>41.67</td>
<td>12.72</td>
<td>6.31</td>
<td>4.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(17.46)</td>
<td>(2.74)</td>
<td>(3.63)</td>
<td>(1.38)</td>
<td></td>
</tr>
<tr>
<td>Objective 1</td>
<td>51</td>
<td>39/12</td>
<td>38.84</td>
<td>15.08</td>
<td>6.44</td>
<td>4.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(16.94)</td>
<td>(3.07)</td>
<td>(3.41)</td>
<td>(.73)</td>
<td></td>
</tr>
<tr>
<td>Objective 2a</td>
<td>123</td>
<td>96/27</td>
<td>38.76</td>
<td>13.75</td>
<td>6.60</td>
<td>5.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(15.94)</td>
<td>(3.71)</td>
<td>(3.71)</td>
<td>(2.38)</td>
<td></td>
</tr>
<tr>
<td>Objective 2b</td>
<td>51</td>
<td>39/12</td>
<td>38.84</td>
<td>15.08</td>
<td>6.44</td>
<td>4.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(16.94)</td>
<td>(3.07)</td>
<td>(3.41)</td>
<td>(.73)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>19/5</td>
<td>44.50</td>
<td>15.67</td>
<td>6.10</td>
<td>4.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(17.78)</td>
<td>(3.21)</td>
<td>(2.95)</td>
<td>(.72)</td>
<td></td>
</tr>
</tbody>
</table>

2.2.2 Measures

2.2.2.1 Outcome Variables

The Community Balance and Mobility Scale. The CB&M consists of 13 tasks, with six items performed on both the right (RT) and left (LT) sides, resulting in a total of 19 items (see Table 2). Of the 13 tasks, three are performed unilaterally (i.e., single-leg stance) and the remaining 10 tasks are performed bilaterally (i.e., with double-leg stance). Patients are scored on their ability to perform each task based on a 6-point scale (0 - 5) and criteria for scores are progressively demanding with regards to time, distance and quality of performance. Scores range from 0 to 96, with higher scores representing better function. For a full description of the CB&M, see Howe et al. [47]. The CB&M has demonstrated content and construct validity, and reliability, with intra-class correlation coefficients of .98 for both intra- and inter-rater reliability, .90 and .98 for test-retest reliability (5-day and immediate, respectively), and Cronbach’s alpha of .96 for internal
consistency [47]. Research has also demonstrated significant correlations with measures of gait, balance and participation in the community [25].

Table 2. Tasks of the CB&M.

<table>
<thead>
<tr>
<th>CB&amp;M tasks</th>
<th>RT/LT assessment</th>
<th>Unilateral assessment</th>
<th>Bilateral assessment</th>
<th>Timed task</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Unilateral stance</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2. Tandem walking</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>3. 180° tandem pivot</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4. Lateral foot scooting</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5. Hopping forward</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6. Crouch and walk</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7. Lateral dodging</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8. Walking and looking</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9. Running with controlled stop</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>10. Forward to backward walking</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>11. Walk, look and carry</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>12. Descending stairs</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>13. Step-ups x 1 step</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>

*Note:* Items are performed in order. Right columns indicate if task is timed and/or assessed on both left and right sides.

The Community Integration Questionnaire. The CIQ [135] is a 15-item measure developed for people with TBI to assess participation in the community. There are three sub-scales that assess home integration, social integration and productive activity. The Home Integration sub-scale includes five items associated with performing domestic activities such as household shopping, chores, caring for children, and preparing meals. The Social Integration sub-scale includes six items related to engaging in personal and leisure activities. Finally, the Productivity sub-scale contains four items related to engagement in work, school, and volunteer activities. The CIQ total score ranges from 0 - 29, and the sub-scale scores range from 0 - 10 (Home), 0 - 12 (Social) and 0 - 7 (Productivity). The instrument has established construct validity, and reliability, with intra-class correlation coefficients of .81 for both intra- and inter-rater reliability [223], Cronbach’s alpha of .76 - .84 for internal consistency [222, 223], and with sensitivity to distinguish between individuals with TBI and healthy adults [135].
2.2.2.2 Control Variable

To control for severity of injury, we used PTA score, which is based on the classification system
developed by Lezak [227], whereby a score of one represents a length of PTA less than 5 min;
two represents a length of PTA between 5 - 60 min; three, PTA = 1 - 24 hr; four, PTA = 1 - 7
days; five, PTA = 1 - 4 weeks; and six, PTA > 4 weeks. Length of PTA was extracted from
medical records and/or established through clinical interview and is considered a more
 uncontaminated measure of brain injury severity (e.g., not affected by alcohol consumption at
time of injury, or physical injury) [228, 229]. Moreover, research has demonstrated that length of
PTA is better at predicting long-term outcome than GCS [230-232].

2.2.3 Analyses

2.2.3.1 Objective 1: Relationship between CB&M and CIQ across time

Zero-order Pearson correlations and second-order partial correlations (controlling for age and
injury severity) were conducted to explore the relationships between performance on the CB&M
and the CIQ total and sub-scale scores at 5 and 12 months post-injury. To correct for multiple
comparisons, a Bonferroni-Holm correction was applied to each set of correlations. Using
Cohen’s guidelines, a moderate relationship was interpreted as \( r = .30 - .50 \) and a strong
relationship as \( r \geq .50 \) [233].

2.2.3.2 Objective 2a: Factor analysis of the CB&M

An exploratory factor analysis was conducted to determine whether the latent variable of multi-
tasking could be reduced to form a set of factors. Inter-correlations between items ranged from \( r = .47 - .79 \). The Kaiser-Meyer-Olkin measure of sampling adequacy was .93, above the
recommended value of .60. Bartlett’s test of sphericity was significant (\( \chi^2 [171] = 2004.46, \ p < .000 \)). Communalities were all above .45 (see Table 3). Overall, these indicators suggest that an
exploratory factor analysis would be suitable for all 19 items of the CB&M.
An exploratory factor analysis was used because the primary purpose was to identify and compute composite scores that may specifically relate to multi-tasking. The number of factors to be retained was determined using a parallel analysis, which is a Monte Carlo simulation that compares observed eigenvalues to those obtained from uncorrelated variables. Factors larger than the 95\textsuperscript{th} percentile of the distribution derived from random data were retained. The random data in our analysis were based on permutations of our obtained data, which typically guards against violations of normality [234]. Results indicated that a two factor solution best accounted for the total shared variance. Oblimin rotation of the factor loading matrix was employed given the likelihood of correlation between the two factors. Where an item from the CB&M loaded onto both factors, it was assigned to a single factor based on the highest loading, as well as by checking the reliability of each item per factor, and removing it if Cronbach's Alpha increased when the item was deleted.

Table 3. CB&M factor analysis communalities

<table>
<thead>
<tr>
<th>CB&amp;M items</th>
<th>Initial</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 LT</td>
<td>1.00</td>
<td>.72</td>
</tr>
<tr>
<td>1 RT</td>
<td>1.00</td>
<td>.55</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>.65</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>.62</td>
</tr>
<tr>
<td>4 LT</td>
<td>1.00</td>
<td>.71</td>
</tr>
<tr>
<td>4 RT</td>
<td>1.00</td>
<td>.66</td>
</tr>
<tr>
<td>5 LT</td>
<td>1.00</td>
<td>.72</td>
</tr>
<tr>
<td>5 RT</td>
<td>1.00</td>
<td>.71</td>
</tr>
<tr>
<td>6</td>
<td>1.00</td>
<td>.71</td>
</tr>
<tr>
<td>7</td>
<td>1.00</td>
<td>.46</td>
</tr>
<tr>
<td>8 LT</td>
<td>1.00</td>
<td>.50</td>
</tr>
<tr>
<td>8 RT</td>
<td>1.00</td>
<td>.70</td>
</tr>
<tr>
<td>9</td>
<td>1.00</td>
<td>.75</td>
</tr>
<tr>
<td>10</td>
<td>1.00</td>
<td>.69</td>
</tr>
<tr>
<td>11 LT</td>
<td>1.00</td>
<td>.71</td>
</tr>
<tr>
<td>11 RT</td>
<td>1.00</td>
<td>.68</td>
</tr>
<tr>
<td>12</td>
<td>1.00</td>
<td>.79</td>
</tr>
<tr>
<td>13 LT</td>
<td>1.00</td>
<td>.59</td>
</tr>
<tr>
<td>13 RT</td>
<td>1.00</td>
<td>.75</td>
</tr>
</tbody>
</table>

* Loadings that were less than .30 were suppressed.
2.2.3.3 Objective 2b: Relationship between CB&M factors and CIQ across time

Spearman rank-order correlations and partial correlations (controlling for age and injury severity) were then conducted to explore the relationships between the two CB&M factors and the CIQ total and sub-scale scores, at 5 and 12 months post-injury, as well to examine the relationship between the two CB&M factors at 5 months and the CIQ total and sub-scale scores at 12 and 24 months post-injury. Additionally, the two CB&M factors at 12 months were correlated with the CIQ total and sub-scales at 24 months post-injury. Spearman rank-order correlations were used due to the non-normal distribution of the aggregate scores developed for factors one and two.

2.3 Results

2.3.1 Participant Characterization

Of the 190 patients with moderate-severe TBI that participated in the larger study examining recovery, data for 123 patients were used in the current study. This sub-set of participants (n = 123) was similar to those not eligible to participate in terms of age and injury characteristics (n = 67), yet differed in years of education (eligible participants: $M = 13.66$ years, $SD = 3.07$; ineligible participants: $M = 12.72$ years, $SD = 2.74$; $t[185] = -2.08$, $p = .04$, $d = -.31$). Mean scores for the CB&M and the CIQ at each time point are presented for the 123 participants that were included in the present study in Table 4.

Of the 123 participants, 51 were eligible to examine the relationship between the CB&M and the CIQ at the 5 months ($M = 5.06$ months, $SD = 1.08$) and 12 months ($M = 12.48$ months, $SD = 1.74$) post-injury, and 24 of those 51 participants were additionally assessed (on the CIQ only) at 24 months post-injury ($M = 27.07$ months, $SD = 3.52$). The participants that were used for the correlational analyses differed from the additional 72 that were included in the factor analysis.
only in years of education ([n = 72]: M = 13.04, SD = 3.18 vs. [n = 51]: M = 14.52, SD = 2.70; t[119] = 2.70, p = .01, d = .50).

### Table 4. CB&M and CIQ total scores at 5, 12 and 24 months post-injury [Mean (SD)]

<table>
<thead>
<tr>
<th>Participants</th>
<th>5 months</th>
<th>12 months</th>
<th>24 months</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CB&amp;M</td>
<td>CIQ</td>
<td>CB&amp;M</td>
</tr>
<tr>
<td>Included in correlational analyses</td>
<td>n = 51</td>
<td>71.00 (19.56)</td>
<td>14.57 (4.61)</td>
</tr>
<tr>
<td>Included in factor analysis</td>
<td>n = 123</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### 2.3.2 Objective 1: Relationship between CB&M and CIQ across time

**CB&M and CIQ at 5 months post-injury.** A zero-order Pearson correlation found a significant moderate positive relationship between the CB&M and the CIQ total score (see Figure 1), as well as with the CIQ Home and Social sub-scale scores, but not the Productivity sub-scale score. The relationship was then subjected to a second-order partial correlation to control for the effects of age and injury severity. The CB&M and the CIQ total scores, as well as the CIQ Home and Social sub-scale scores, were strengthened, but remained moderate. Table 5 lists results from all correlational analyses conducted to examine the relationship between the CB&M and the CIQ score at 5 months post-injury.
Figure 1. Relationship between CB&M and CIQ at 5 months post-injury

A Pearson second order partial correlation, controlling for age and injury severity found a significant positive moderate relationship ($r = .44, p = .002$).

CB&M and CIQ at 12 months post-injury. A zero-order Pearson correlation found a weak, but significant, positive relationship between the CBM and the CIQ total score, and no significant relationship with any of the CIQ sub-scales (see Table 5). After controlling for age and injury severity, there were no significant relationships between the CB&M and any CIQ scores. Table 5 lists results from all correlational analyses conducted to examine the relationship between the CB&M and the CIQ score at 12 months post-injury.
Table 5. Relationships between the CB&M and the CIQ at 5 and 12 months post-injury

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Outcome variable</th>
<th>Pearson zero-order correlation with CB&amp;M</th>
<th>Pearson second-order partial correlation with CB&amp;M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>r</td>
</tr>
<tr>
<td>5 months post-injury</td>
<td>CIQ total</td>
<td>51</td>
<td>.39*</td>
</tr>
<tr>
<td></td>
<td>Home sub-scale</td>
<td></td>
<td>.34*</td>
</tr>
<tr>
<td></td>
<td>Social sub-scale</td>
<td></td>
<td>.36*</td>
</tr>
<tr>
<td></td>
<td>Productivity sub-scale</td>
<td></td>
<td>.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 months post-injury</td>
<td>CIQ total</td>
<td>51</td>
<td>.28</td>
</tr>
<tr>
<td></td>
<td>Home sub-scale</td>
<td></td>
<td>.10</td>
</tr>
<tr>
<td></td>
<td>Social sub-scale</td>
<td></td>
<td>.25</td>
</tr>
<tr>
<td></td>
<td>Productivity sub-scale</td>
<td></td>
<td>.27</td>
</tr>
</tbody>
</table>

Note. The relationship between the CB&M and the CIQ at 5 and 12 months post-injury was first examined using Pearson zero-order correlations. Age and injury severity were then controlled for using Pearson second-order partial correlations. Asterisks (*) indicate relationships that remained significant after applying a Bonferroni-Holm correction.

2.3.3 Objective 2a: Factor analysis of the CB&M

Results from the exploratory factor analysis with all 19 items using oblimin rotations yielded a solution that explained 66.80% of the shared variance. All items in this analysis had loadings over .40. Factor labels were determined based on the items that loaded onto each specific factor. The emergence of two factors provide support for a possible multi-tasking dimension, as factor one appeared to measure “single-task” balance items, and factor two appeared to measure “multi-tasking” balance items. Internal consistency for each of the two scales derived from the factors were examined using Cronbach’s α. Internal consistency for both factors was excellent (Single-task factor: α = .95; Multi-task factor: α = .91). No substantial increases in α for both factors could have been achieved by eliminating more items. Results from the two-factor solution with item-to-factor loadings for the CB&M are presented in Table 6 and CB&M items per factor in Table 7.
Table 6. Structure and pattern matrices with factor loadings per item

<table>
<thead>
<tr>
<th>CB&amp;M items</th>
<th>Structure matrix</th>
<th>Pattern matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Component</td>
<td>CB&amp;M Items</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5 LT</td>
<td>.85</td>
<td>.57</td>
</tr>
<tr>
<td>4 LT</td>
<td>.84</td>
<td>.56</td>
</tr>
<tr>
<td>5 RT</td>
<td>.84</td>
<td>.61</td>
</tr>
<tr>
<td>13 LT</td>
<td>.83</td>
<td>.71</td>
</tr>
<tr>
<td>1 LT</td>
<td>.83</td>
<td>.40</td>
</tr>
<tr>
<td>13 RT</td>
<td>.81</td>
<td>.76</td>
</tr>
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<td>9</td>
<td>.81</td>
<td>.66</td>
</tr>
<tr>
<td>2</td>
<td>.80</td>
<td>.52</td>
</tr>
<tr>
<td>4 RT</td>
<td>.80</td>
<td>.44</td>
</tr>
<tr>
<td>3</td>
<td>.78</td>
<td>.55</td>
</tr>
<tr>
<td>1 RT</td>
<td>.74</td>
<td>.43</td>
</tr>
<tr>
<td>7</td>
<td>.70</td>
<td>.54</td>
</tr>
<tr>
<td>6</td>
<td>.65</td>
<td>.57</td>
</tr>
<tr>
<td>11 RT</td>
<td>.59</td>
<td>.89</td>
</tr>
<tr>
<td>8 RT</td>
<td>.52</td>
<td>.86</td>
</tr>
<tr>
<td>8 LT</td>
<td>.50</td>
<td>.84</td>
</tr>
<tr>
<td>11 LT</td>
<td>.62</td>
<td>.82</td>
</tr>
<tr>
<td>10</td>
<td>.71</td>
<td>.80</td>
</tr>
<tr>
<td>12</td>
<td>.69</td>
<td>.70</td>
</tr>
</tbody>
</table>

Note. Where an item from the CB&M loaded onto both factors, it was assigned to a single factor based on its highest loading, as well as by checking the reliability of each item per factor, and removing it if Cronbach’s Alpha increased when the item was deleted.

Table 7. Single-task and Multi-task factors that emerged from the factor analysis of the CB&M

<table>
<thead>
<tr>
<th>Factor</th>
<th>CB&amp;M tasks</th>
<th>RT/LT assessment</th>
<th>Unilateral assessment</th>
<th>Bilateral assessment</th>
<th>Timed task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-task</td>
<td>1. Unilateral stance</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>2. Tandem walking</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3. 180º tandem pivot</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4. Lateral foot scooting</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5. Hopping forward</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>6. Crouch and walk</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>7. Lateral dodging</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>9. Running with controlled stop</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>12. Descending stairs</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>13. Step-ups x 1 step</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Multi-task</td>
<td>8. Walking and looking</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>10. Forward to backward walking</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>11. Walk, look and carry</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Note: Items are performed in order. Right columns indicate if task is timed and/or assessed on left and right sides.
Interestingly, there was a significant difference in mean scores between the two factors at 5 months post-injury (Single-task factor aggregate scores \([M = 3.63, SD = 1.09]\), Multi-task factor aggregate scores \([M = 4.08, SD = .93]\); \(t[50] = -5.29, p < .000, d = -1.50\)) and 12 months post-injury (Single-task factor aggregate scores \([M = 3.91, SD = .90]\), Multi-task factor aggregate scores \([M = 4.28, SD = .74]\); \(t[49] = -4.07, p < .000, d = -1.16\)).

2.3.4 Objective 2b: Relationship between CB&M factors and the CIQ

2.3.4.1 Relationship between the CB&M factors and the CIQ across time

CB&M and CIQ at 5 months post-injury. A Spearman rank-order correlation found a significant moderate positive relationship between the CB&M Single-task factor and the CIQ total scores, as well a moderate relationship with the Home sub-scale score and a weak relationship with the Social sub-scale score (see Table 9). The relationship was then subjected to a partial-rank correlation to control for the effects of age and injury severity. The relationship between the CB&M Single-task factor and the CIQ total scores, as well as the CIQ Home and Social sub-scale scores, were strengthened, yet remained weak to moderate. Similarly, Spearman rank-order correlations found significant moderate positive relationships between the CB&M Multi-task factor and the CIQ total and Social sub-scale scores. The relationships were then subjected to partial-order correlations to control for the effects of age and injury severity. The relationships between the CB&M Multi-task factor and the CIQ total and Social sub-scale scores were strengthened and remained moderate. Furthermore, the relationship between the CB&M Multi-task factor and the CIQ Home scale scores was strengthened and significant once we controlled for age and injury severity. Table 9 lists results from all correlational analyses conducted to examine the concurrent relationship between the CB&M factors and the CIQ score at 5 months post-injury.

CB&M and CIQ at 12 months post-injury. Spearman rank-order correlations found significant moderate positive relationships between the CB&M Single-task factor and the CIQ total, Social and Productivity sub-scale scores. However, after controlling for age and injury severity, the
relationship between the CB&M and the CIQ total scores, as well as the Social sub-scale score, were lessened (both weak in strength) and the relationship with the Productivity sub-scale score was no longer significant. Spearman rank-order correlations found no relationship between the CB&M Multi-task factor and any of the CIQ scores. The relationships remained non-significant when age and injury severity were held constant. Table 8 lists results from all correlational analyses conducted to examine the concurrent relationship between the CB&M factors and the CIQ score at 12 months post-injury.

Table 8. Relationships between the CB&M Single-task and Multi-task factors and the CIQ at 5 and 12 months post-injury

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Outcome variable</th>
<th>5 months post-injury</th>
<th>12 months post-injury</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>rs</td>
</tr>
<tr>
<td>5 months post-injury</td>
<td>CIQ total</td>
<td>.34</td>
<td>.014</td>
</tr>
<tr>
<td></td>
<td>Home sub-scale</td>
<td>.34</td>
<td>.016</td>
</tr>
<tr>
<td></td>
<td>Social sub-scale</td>
<td>.28</td>
<td>.049</td>
</tr>
<tr>
<td></td>
<td>Productivity sub-scale</td>
<td>.18</td>
<td>.208</td>
</tr>
<tr>
<td>12 months post-injury</td>
<td>CIQ total</td>
<td>.34</td>
<td>.017</td>
</tr>
<tr>
<td></td>
<td>Home sub-scale</td>
<td>.12</td>
<td>.427</td>
</tr>
<tr>
<td></td>
<td>Social sub-scale</td>
<td>.30</td>
<td>.036</td>
</tr>
<tr>
<td></td>
<td>Productivity sub-scale</td>
<td>.32</td>
<td>.025</td>
</tr>
<tr>
<td>Multi-task factor</td>
<td>CIQ total</td>
<td>.35*</td>
<td>.014</td>
</tr>
<tr>
<td></td>
<td>Home sub-scale</td>
<td>.28</td>
<td>.053</td>
</tr>
<tr>
<td></td>
<td>Social sub-scale</td>
<td>.36*</td>
<td>.010</td>
</tr>
<tr>
<td></td>
<td>Productivity sub-scale</td>
<td>.16</td>
<td>.271</td>
</tr>
</tbody>
</table>

Note. The relationship between each CB&M factor and the CIQ at 5 and 12 months post-injury was first examined using Spearman rank-order correlations. Age and injury severity were then controlled for using Spearman partial-order correlations. Asterisks (*) indicate relationships that remained significant after applying a Bonferroni-Holm correction.
2.3.4.2 Relationship between CB&M factors at 5 and 12 months and the CIQ at 12 and 24 months after injury

CB&M at 5 months and CIQ at 12 months post-injury. A Spearman rank-order correlation found no significant relationship between the CB&M Single-task factor score at 5 months and the CIQ (12 months) total or sub-scale scores (see Table 9). When age and injury severity were controlled for, the relationship between the CB&M Single-task factor and the CIQ remained non-significant. Similarly, the CB&M Multi-task factor score did not correlate with any CIQ scores, and these relationships remained non-significant when we controlled for age and injury severity. Table 10 lists results from all correlational analyses conducted to examine the relationship between the CB&M factors at 5 months and the CIQ score at 12 months post-injury.

CB&M at 5 months and CIQ at 24 months post-injury. A Spearman rank-order correlation found that the CB&M Single-task factor score at 5 months showed a significant moderate positive relationship at 24 months with only the CIQ Productivity sub-scale score. However, when age and injury severity were controlled for, this relationship was non-significant. Spearman rank-order correlations found that the CB&M Multi-task factor score showed a significant moderate positive relationship with the CIQ total score, and a strong positive relationship with the CIQ Productivity score. When these relationships were subjected to partial-order correlations, the relationship between the CB&M Multi-task factor and the CIQ total scores remained significant, and the relationship between the CB&M Multi-task factor and the CIQ Social sub-scale scores was strengthened and significant (Table 9).

CB&M at 12 months and CIQ at 24 months post-injury. When the relationships between the CB&M Single-task factor and the CIQ total and sub-scale scores were examined with Spearman rank-order correlations, a significant moderate positive relationship was found between the CB&M Single-task factor and the CIQ Productivity sub-scale scores. However, when the relationship was subjected to a partial-order correlation, there was no longer a significant relationship between the CB&M Single-task factor and the CIQ Productivity sub-scale scores.
Spearman rank-order correlations found a significant strong relationship between the CB&M Multi-task factor and the CIQ total scores (see Figure 2), as well as a moderate relationship between the CB&M Multi-task factor and the Home sub-scale scores. When age and injury severity were controlled for, the relationships both remained significant, and the relationship with the CIQ Home sub-scale score was strengthened. Table 9 lists results from all correlational analyses conducted to examine the relationship between the CB&M factors at 12 months and the CIQ score at 24 months post-injury.

![Figure 2. Relationship between the CB&M Multi-task factor scores at 12 months and the CIQ scores at 24 months post-injury](image)

A Pearson second order partial correlation, controlling for age and injury severity found a significant positive strong relationship ($r = .52, p = .007$).
Table 9. Relationships between the CB&M Single-task and Multi-task factors and the CIQ at 5 and 12 months post-injury

<table>
<thead>
<tr>
<th>CB&amp;M Single-task factor at 5 months</th>
<th>Spearman rank-order correlation</th>
<th>Spearman partial-rank correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment</td>
<td>Outcome variable</td>
<td>n</td>
</tr>
<tr>
<td>CIQ at 12 months post-injury</td>
<td>CIQ total</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>Home sub-scale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Social sub-scale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Productivity sub-scale</td>
<td></td>
</tr>
<tr>
<td>CIQ at 24 months post-injury</td>
<td>CIQ total</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Home sub-scale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Social sub-scale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Productivity sub-scale</td>
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</tbody>
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<table>
<thead>
<tr>
<th>CB&amp;M Single-task factor at 12 months</th>
</tr>
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<tbody>
<tr>
<td>CIQ at 24 months post-injury</td>
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<td>CIQ at 24 months post-injury</td>
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<td>CIQ at 24 months post-injury</td>
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<table>
<thead>
<tr>
<th>CB&amp;M Multi-task factor at 5 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIQ at 12 months post-injury</td>
</tr>
<tr>
<td>CIQ at 12 months post-injury</td>
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<td>CIQ at 12 months post-injury</td>
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<td>CIQ at 12 months post-injury</td>
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<tr>
<td>CIQ at 24 months post-injury</td>
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<td>CIQ at 24 months post-injury</td>
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<td>CIQ at 24 months post-injury</td>
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<table>
<thead>
<tr>
<th>CB&amp;M Multi-task factor at 12 months</th>
</tr>
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<tbody>
<tr>
<td>CIQ at 24 months post-injury</td>
</tr>
<tr>
<td>CIQ at 24 months post-injury</td>
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<tr>
<td>CIQ at 24 months post-injury</td>
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<td>CIQ at 24 months post-injury</td>
</tr>
</tbody>
</table>

Note: Relationships between each CB&M factor at 5 and 12 months and the CIQ at 12 and 24 months post-injury were first examined using Pearson zero-order correlations. Age and injury severity were then controlled for using Pearson second-order partial correlations. Asterisks (*) indicate relationships that remained significant after applying a Bonferroni-Holm correction.
2.4 Discussion

After TBI, many factors may contribute to successful community integration. The current study examined the relationship between balance and mobility and community integration in a sample of adults with moderate-severe TBI and was designed to obviate methodological weaknesses of previous research.

We extended previous research by demonstrating that the relationship between the CB&M and the CIQ differs at 5 and 12 months post-injury. We found that when age and injury severity were controlled for, there were moderate positive correlations between the CB&M and the CIQ total, Social and Home sub-scale scores at 5 months post TBI, but not the Productivity sub-scale score. By 1 year post-injury, however, there was no longer a relationship between the CB&M and the CIQ (total or sub-scale scores). These findings support previous findings of a relationship between high-level balance and community integration after TBI [25, 47], and are in contrast to findings of a relationship between high level balance and only productive activity after TBI [147, 224], suggesting that variables such as time after injury, age, and injury severity may play a role in the relationship between high-level balance and community integration after TBI.

In exploring the role of multi-tasking in high-level balance, we found that two factors emerged from an exploratory factor analysis of the CB&M: (1) items interpreted to measure single-task balance items (Single-task factor), and (2) items interpreted to measure multi-tasking performance (Multi-task factor). Interestingly, we demonstrated that items measuring single-task performance and items measuring multi-task performance, while significantly different, similarly correlated with the CIQ total, Social and Home sub-scale scores at 5 months post-injury. However, multi-tasking scores at 5 and 12 months post-injury additionally correlated with CIQ total, Social and Home sub-scale scores at 24 months after TBI. These findings highlight the importance of multi-tasking ability in high-level balance for many aspects of community integration, which had not been previously reported.
The findings from this study offer further insight into the role that balance and mobility play in community integration after TBI. Earlier after TBI, the correlation between the CB&M and social and home activity highlights the importance of balance and mobility for returning to the community and engaging with others in social settings, regardless of age and injury severity. It could be the case that early after injury, patients in this Canadian sample of moderate-severe TBI are not focused on returning to work, as they may be transitioning from hospital to home, and thus re-establishing social and home roles may be of greater concern [21, 26, 28, 136]. Evidence to support this hypothesis comes from a study by Strandberg [21], who examined the changeover process, support and consequences experienced by adults after TBI. They found that a common theme that emerged was the significance of social interactions: the importance of social interactions with professional care providers, relatives and friends, as well as the difficulty in dealing with lost or changed relationships, and therefore decreased social networks.

One might expect that as awareness of deficits improves over time, those with poorer balance and mobility might rate their level of community integration as lower, and thus, strengthen the relationship between CB&M and the CIQ. However, in the current study, the CIQ total score showed little change across time, which would not support this hypothesis. This suggests that those with lower CB&M scores either improved in balance and mobility, or adaptations to impairment-related limitations improved over time, as has been previously suggested by Brown et al. [17]. Furthermore, Willemse-van Son et al. [32], who examined community integration in a large sample of adults with moderate-severe TBI up to 36 months after injury, found that clinical characteristics (e.g., GCS, length of hospital stay, FIM+FAM scores) were predictive of outcome early after injury (i.e., up to 6 months), but suggested that they might be less important than personal or environmental factors in predicting long-term outcome. Therefore, the CB&M may be related to community integration early after injury, but not later after recovery or adaptation.
Based on previous work examining the CB&M and the CIQ [147], we expected to find a relationship between high-level balance and productive activity in the later stages after TBI. In the current study, a longitudinal examination of high-level balance and community integration allowed us to examine the relationship between the CB&M and CIQ at different time points within the same sample. The relationship between the CB&M and the CIQ Productivity sub-scale was initially supported; however, after controlling for the effects of age and injury severity, this relationship was weaker and no longer significant. This suggests that in previous studies, age and injury severity may have been driving the relationship between high-level balance and productive activity after TBI. Therefore, previous results should be interpreted with caution until findings can be replicated with large sample sizes, where age and injury severity are controlled for.

While both single-task and multi-task ability were related to community integration early after injury, multi-task ability was more strongly related to level of engagement in social settings, perhaps because of the multi-tasking demands that logically cut across social situations. Social situations (e.g., walking and talking with a friend; holding a cup of coffee and chatting) require communication, social cognition (e.g., perception of emotions) and postural stability. Moreover, multi-tasking ability was the only variable that correlated with community integration 2 years after injury. The implications of these findings are that assessment and rehabilitation of high-level balance, particularly multi-tasking, is important earlier after injury, particularly for those who perform more poorly on the CB&M, as it may impact the ability to successfully return to community in the later stages of TBI.

With respect to the two factors that emerged from the exploratory factor analysis, items in the Multi-task factor appeared to map well onto multi-task items, in that they required patients to perform more than one task at a time (e.g., walk and look). Moreover, items 8 and 11 were identified by Howe et al. [47] as tasks that assessed multi-tasking ability. While items in the Single-task factor appeared to map well onto single-task items, an additional dimension to this
factor may be that of difficulty. Anecdotal reports from clinicians in our study indicated that patients found items from the first half of the CB&M more challenging (i.e., items 1 - 6, all of which load onto the Single-task factor in the current study). Perry et al. [147] offered empirical support for this observation: items 4, 5, 6, 9, 13 on the CB&M were the most difficult (i.e., lowest mean score) for their sample of TBI participants, and all of those items loaded onto the Single-task factor in the current study. Perry et al. [147] suggested that items on the CB&M that require quick movements (and therefore, rapid centre of mass movement and deceleration) may be particularly challenging after brain injury. In examining content validity of the CB&M, Howe et al. [47] asked physical therapists to rate the relevance of the items in measuring balance and reported that the items that were rated as most highly relevant tended to be those that were most closely related to functional mobility activities. The five most highly rated items included 2 of 3 items that comprise the Multi-task factor: walking and looking (item 8), and forward to backward walking (item 10). If we presume that Single-task factor items may also represent a dimension of difficulty (supported by the finding in the current study that the Single-task factor scores were significantly lower than the Multi-task factor scores), then this suggests that the relationship between multi-tasking and community integration may not be driven by whether patients can simply do more difficult balance tasks and, therefore, are better able to participate in the community. Rather, it suggests there may be a unique relationship between multi-tasking and community integration for people with TBI.

2.4.1 Limitations

Potential limitations of this work include the use of retrospective analyses and sample size. The retrospective nature of the current study may have introduced bias into sample selection, as many participants did not complete the CIQ or the CB&M at all time-points, which also directly impacted sample size. Reasons for missing data or use of alternative assessments were not available in all cases, and may have, therefore, lead to selection of a sample that was not representative of all TBI patients. However, participants that were eligible for the current study were similar in age and injury characteristics to those with incomplete data. Additionally, other
factors (e.g., cognitive level) may have influenced the relationship between balance and mobility and community integration, but were not controlled for in our analyses.

Future examinations of the relationship between the CB&M and the CIQ for the TBI population could be extended in several ways. Using a prospective research design, larger sample sizes and assessment of other variables (e.g., cognitive function), future studies can examine if other factors also impact the relationship between the CB&M and the CIQ. Research is currently underway to assess item difficulty for the CB&M; confirmatory analyses could be undertaken to see if the two factors that emerged from our analyses are consistent.

2.5 Conclusion

The findings of this study further underscore the relationship between residual high-level balance impairments and their deleterious impact on community integration early, but not later after injury. Multi-tasking (but not single-tasking) correlates with community integration at two years after injury. Given these findings, rehabilitation professionals should focus therapies on high-level balance, incorporating activities related to multi-tasking. Future studies examining the relationship between multi-tasking and CIQ could be undertaken to better understand how performing daily tasks that require multiple processes (e.g., walking, talking, attending to traffic) relates to community integration.
2.6 Next steps

The findings from this study provide further evidence of the impact that TBI can have on high-level balance, as well as multi-tasking ability, and how this relates to community integration. The CB&M, however, was not solely designed to measure multi-tasking ability in the context of balance and mobility, and the multi-tasking items on the CB&M have little cognitive demand beyond maintaining visual fixation. Moreover, these findings are correlational and retrospective in nature; a prospective experimental design would allow us to better characterize multi-tasking impairment in adults with TBI. By using tasks that are similar to inter-personal interactions, and thus more generalizable to everyday activities, we can examine if difficulty with multi-tasking may play a role in the level of community integration after TBI. In order to examine how people multi-task in the community, we focused on the concurrent performance of postural stability and FEP tasks, as this would be essential for successful interactions with others (e.g., engaging at a family dinner or out for coffee with friend). In order to assess FEP in an ecologically valid manner, we developed a task that used an indirect test format to permit implicit processing that employed dynamic faces and provided environmental context, and then examined if using such a task would be feasible in a sample of adults with moderate-severe TBI. The following chapter details this work.
3 Development and preliminary feasibility testing of an ecologically valid paradigm for assessment of facial emotion perception in brain injury

3.1 Introduction

From an evolutionary perspective, emotion perception is important for survival (e.g., perceiving fear or anger in others) [235]. The ability to perceive emotion is important for maintaining relationships, succeeding in our careers, and for daily social interactions [177]. We perceive emotion via different modalities: faces, voices, and body language and gestures. Facial emotion perception (FEP) has been the most widely examined modality as it is assumed to be the primary method of exhibiting emotion [4, 193, 236, 237]. Occasionally, misinterpretations and failures in the perception of facial expressions can occur in healthy adults [238, 239]; however, for others, this is a persistent and pathological problem [45, 46, 179, 180, 187-189, 191, 240-247]. Difficulty with FEP has been identified across people with focal lesions [191, 240, 241], schizophrenia [242, 246], Parkinson’s disease [243], autism [244-246], and traumatic brain injury (TBI) [45, 46, 179, 180, 187-189, 248, 249]. An inability to accurately and quickly perceive facial emotions has been shown to affect quality of life, and has been related to increased anxiety, depression, and isolation [31, 39, 86, 179-182].

The most common paradigm used to examine FEP, both experimentally and clinically, has been to present participants with decontextualized, static images of faces (e.g., [193-195, 248, 250-252]), and to ask them to explicitly identify the emotion or to match it to a target emotion [177]. Participants are given time to observe the stimulus, consider its properties, and make a judgment. Recently, more ecologically valid paradigms for assessing facial emotion perception have emerged [253, 254], which aim to increase (1) the extent to which clinical tests correspond in form and context to a situation encountered outside the laboratory, as well as (2) the degree to which poor performance on the test will be predictive of problems outside the laboratory [196]. One shift to a more ecologically valid approach to assessment that more closely matches the
expression of emotions in the real world concerns the use of dynamic faces. Several studies have employed stimuli that are not static representations of emotions (e.g., a photograph of a face) but rather, faces in motion (e.g., [199-205]).

Dynamic stimuli are videos or morphs of faces changing from, for example, a neutral face to an emotional face over time, usually milliseconds. Recent studies have demonstrated the advantages of using dynamic stimuli over the more conventionally used static stimuli to assess FEP [197-200]. For instance, brain regions already implicated in processing facial affect (see [192, 206] for a review) have been subsequently shown to respond more strongly to dynamic versus static emotional expressions (primarily the amygdala) [192, 200, 207-209]. As well, behavioural studies of healthy adults using dynamic stimuli have found that facial emotions are recognized more accurately than static versions of the same expressions [199-205].

A second development towards a more ecologically valid approach to assessment concerns the context in which emotions are conveyed. Previous studies have typically presented decontextualized faces (e.g., faces with all background details removed) [46, 86, 179, 181, 187, 189, 239, 246]. However, evidence suggests that people routinely encode context (e.g., social situation, scenes, body posture, voices, and/or words) when asked to make a specific inference about a target emotion [121], consistent with the conceptual-act model of emotion, in which emotion perception happens within conceptualizations of affective information that is available in the environment [255]. Social interactions require the ability to quickly integrate facial emotion cues and contextual information, including prior world knowledge [256-258]. Studies examining FEP have demonstrated that while people with TBI show significant impairment in identifying facial emotions, when more context is given (e.g., information about the situation or environment in which the emotion is being expressed), they are better able to identify the emotions [179, 190, 199, 259, 260]. For example, The Awareness of Social Inference Test (TASIT; [210]) is an audiovisual tool designed for the clinical assessment of social perception in people with TBI. The TASIT employs dynamic stimuli and contextual information to examine
emotion perception. It is comprised of several videoed vignettes wherein emotional expressions are portrayed dynamically by professional actors (via facial expression, body language and tone) and participants are allocated ample time to explicitly categorize the emotion of the actor.

A third movement towards the more ecological assessment of facial emotion concerns task demands with respect to implicit and explicit processing. Implicit processing refers to the rapid and automatic processing of information [261, 262] that is involved in ‘primary emotion’, which comprises unconscious or pre-organized responses to stimulus features such as size, motion, and sound [262]. In contrast, explicit processing of emotion is thought to be effortful, involving conscious attention, and may impact more controlled cognitive functions reliant on inhibition [261-263]. Studies have shown that different neural pathways underlie implicit and explicit processing of socially important facial expression: implicit processing activates the amygdala, whereas explicit processing (e.g., labelling emotions) activates the middle temporal gyrus [263] and can result in deactivation of the amygdala, mediated by the frontal cortex [192, 199]. Thus, there is evidence of dissociation between implicit and explicit FEP at both behavioural and brain levels. There is evidence that FEP tasks can be performed using implicit and/or explicit processes [263]. In TBI, like most other neurological populations, there is evidence of disproportionate impairments to explicit as compared to implicit processing [264-267]. Therefore, a task that with relatively greater demands for explicit than implicit processing of FEP (e.g., a direct assessment of FEP that requires emotion labelling) may disadvantage patients and overestimate FEP impairments given that real world FEP depends – arguably in large part – on implicit processing [199, 261-263, 268].

Thus, using an FEP task that allows for implicit perception of stimuli may allow for a more accurate examination of real world levels of functioning in TBI patients. While the TASIT assesses emotion perception with dynamic stimuli and contextual information, the task relies on explicit processing as participants are required to label the emotion presented in each vignette. As well, the TASIT uses facial and other forms of emotional information (e.g., voices, body
language and gestures). To date, there are no published indirect measures of FEP wherein tasks can be performed without explicit processing of facial emotions.

The purposes of this study, therefore, were twofold. First, we introduce a novel approach to assess FEP designed to enhance the ecological validity of testing, which: (1) employs dynamic stimuli, (2) incorporates contextual information, and (3) employs an indirect test paradigm. We refer to this new task as the FEP-dci (dynamic, contextualized, indirect). Secondly, we preliminarily measured the feasibility of this novel task in a pilot study employing mild to severe TBI patients and healthy controls. Here, we focussed on acceptability, implementation and adaptability, using the criteria of Bowen et al. [214], whereby acceptability refers to the extent to which a new measure is suitable, satisfying or attractive, implementation refers to the extent to which a new measure can be successfully delivered to intended participants, and, adaptability refers to the extent to which an existing measure performs when changes are made for a new format (e.g., degree to which similar outcomes are obtained in new format, compared to previous methods).

3.2 Methods

3.2.1 Introduction of novel protocol

Several phases of pilot work were conducted to develop the final version of the FEP-dci task.

Stimulus development: Consultation with Experts. In order to develop a series of questions for the indirect assessment of FEP, we consulted with experts in identifying an initial corpus of 40 questions based on recurring themes from the expert respondents within each emotional category (i.e., anger, disgust, fear, happiness, sadness, and surprise). Examples of questions that allowed for implicit perception of a target emotion were: “Is this person stuck behind a slower driver in
the fast lane? (target emotion = anger)” and “Is this person smelling rotten eggs? (target emotion = disgust)”.

**Empirical validation of stimuli.** In order to validate the questions that provided the clearest contextual information to capture a target emotion, we recruited 30 healthy adults (15 males/15 females) from the Greater Toronto area who were on average 31.2 years old ($SD = 9.1$). Participants were presented sentences one at a time that were paired with one emotion (i.e., anger, disgust, fear, happiness, sadness, surprise). They were asked to simply respond ‘Yes’ if the emotion word that followed the question was the correct emotional response and ‘No’ if it was not correct. The computerized task was developed and implemented using Experiment Builder (SR Research Ltd., Ottawa, ON, Canada). Both response (‘Yes’ or ‘No’) and time per trial was recorded.

The top two questions for each emotion were retained for the experiment based on the following criteria: (1) percentage of correct responses for the question, including both true positives (responding ‘Yes’ when a question was paired with its congruent target emotion) and true negatives (responding ‘No’ when a question was paired with an incongruent emotion); and (2) reaction time within one standard deviation of the mean for its respective emotional category. The top two questions per emotion are presented in Table 10.
Table 10. Contextual questions that were developed for the FEP-dci task

<table>
<thead>
<tr>
<th>EMOTION</th>
<th>QUESTION</th>
<th>True Positives</th>
<th>True Negatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>%</td>
<td>Reaction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>correct</td>
<td>time (ms)</td>
</tr>
<tr>
<td>Anger</td>
<td>Is this person stuck behind a slower driver in the fast lane?</td>
<td>96.7</td>
<td>1667.1</td>
</tr>
<tr>
<td></td>
<td>Is this person still waiting for an appointment that was over 2 hours ago?</td>
<td>96.6</td>
<td>1322.0</td>
</tr>
<tr>
<td>Disgust</td>
<td>Is this person smelling rotten eggs?</td>
<td>96.7</td>
<td>1211.9</td>
</tr>
<tr>
<td></td>
<td>Is this person drinking milk that has gone bad?</td>
<td>96.7</td>
<td>1271.0</td>
</tr>
<tr>
<td>Fear</td>
<td>Is this person face to face with a speeding truck on a one-way road?</td>
<td>100</td>
<td>1329.8</td>
</tr>
<tr>
<td></td>
<td>Is this person trapped in a snake pit?</td>
<td>100</td>
<td>1343.3</td>
</tr>
<tr>
<td>Happiness</td>
<td>Is this person in love?</td>
<td>100</td>
<td>1483.1</td>
</tr>
<tr>
<td></td>
<td>Is this person donating to their favourite charity?</td>
<td>93.3</td>
<td>1440.8</td>
</tr>
<tr>
<td>Sadness</td>
<td>Is the veterinarian telling this person that their dog needs to be put to sleep?</td>
<td>100</td>
<td>1357.0</td>
</tr>
<tr>
<td></td>
<td>Is this person at the bedside of their dying spouse?</td>
<td>96.7</td>
<td>1562.0</td>
</tr>
<tr>
<td>Surprise</td>
<td>Is this person the winner of the draw?</td>
<td>96.7</td>
<td>1732.0</td>
</tr>
<tr>
<td></td>
<td>Is this person suddenly seeing a naked fan run across the soccer field?</td>
<td>96.7</td>
<td>1785.1</td>
</tr>
</tbody>
</table>

Note. Questions were selected based on the percentage of true positives (indicating the question matched the target emotion), true negatives (correctly identifying that the target emotion did not match the emotion), and reaction time.

Task design. The above questions were then paired with the relevant emotion from the STOIC dynamic stimulus set [74]. Here, emotional videos – or morphs – displayed an emotion that moved from neutral into the target emotion. Each morph showed a black and white face of Caucasian models, and took approximately 500 ms to unfold. The top two questions for each of the six emotions were paired with a morph to create five sets of stimuli (18 trials each). The stimulus sets were matched for convergence ratings for the stimuli (i.e., how well a video conveyed the intended emotion, determined by Roy et al., [74]), the number of male versus female actors, and the emotions that were represented.

To empirically confirm the equivalence of the sets, nine healthy adults (four males/five females) from the Greater Toronto Area, who were on average 25.3 years old (SD 4.7) completed a
computerized task where they were asked to respond as quickly as possible to each question. Each trial began with the presentation of one of the 12 questions for 4 s, followed by the target dynamic stimulus. Once the participant responded, the image would be replaced with a blank display for 1 s before the onset of the next trial (see Figure 3). They were instructed to say ‘Yes’ if they thought the video that followed the question was the correct emotional response and ‘No’ if they thought it was not correct. A series of analysis of variance revealed no significant differences between blocks for reaction time or error rate.

![Figure 3. Example of one trial of the FEP-dci task](image)

*Figure 3. Example of one trial of the FEP-dci task*

Example of one trial in our newly adapted FEP-dci task. A question is presented for 4 s, along with gaze fixation crosshair to indicate where the dynamic stimulus will appear. A stimulus then appears, first displaying a neutral expression, then changing dynamically to an emotional expression (progresses as a fluid video). Once the participant responds, a blank screen appears for 1 s, and then the next trial begins.

### 3.2.2 Pilot feasibility study

#### 3.2.2.1 Participants

**TBI group.** Eleven adults with mild to severe TBI (7 males/4 females), aged between 29 and 54 years, were recruited from the Greater Toronto Area and the Toronto Rehabilitation Institute. Participants were included in the study if they were at least four months post-injury, and if their score on the Benton Face Recognition Test (BFRT - short form [269]) fell within the normal range (i.e., 41-54). Participants were excluded if they had (1) a neurologic disorder other than TBI or a systemic disorder known to affect brain function (e.g., diabetes, Lupus) or (2) a history of psychotic disorder. Medical records were accessible through Toronto Rehabilitation Institute for 7 of the 11 participants, and for these individuals, injury severity was based on the Glasgow

Coma Scale (GCS) score and/or length of post-traumatic amnesia (PTA). The remaining 4 participants were screened with demographic questionnaires to determine eligibility and injury severity was based on self-report. Causes of injury included motor vehicle crashes, falls, and sporting accidents. Time since injury ranged from 4 to 324 months.

**Healthy control (HC) group.** All participants were recruited from the Greater Toronto Area. Eleven healthy adults were recruited (6 males/5 females), aged between 28 and 55 years. Participants were screened with a demographic questionnaire prior to participating, and were excluded if they reported (1) previous neurologic disorders (e.g., stroke, TBI), or systemic disorders (e.g., diabetes); or (2) active clinically significant psychiatric illness (depression, psychosis, anxiety).

All participants took part in a larger study examining multi-tasking ability for which the FEP-dci task was designed. For the current study, performance on the FEP-dci task was assessed when participants completed the task while seated (i.e., single-task). Informed consent was obtained from all participants and the study was approved by the research ethics boards of the Toronto Rehabilitation Institute and the University of Toronto. Participant demographics are presented in Table 11.
Table 11. Demographic information for TBI and HC groups [Mean (SD)]

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (years)</th>
<th>Education (years)</th>
<th>WTAR</th>
<th>BFRT</th>
<th>TSI (months)</th>
<th>Severity</th>
<th>Etiology</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>001*</td>
<td>29</td>
<td>17</td>
<td>100</td>
<td>50</td>
<td>22</td>
<td>Severe</td>
<td>MVC</td>
</tr>
<tr>
<td>003*</td>
<td>54</td>
<td>13</td>
<td>114</td>
<td>49</td>
<td>4.5</td>
<td>Severe</td>
<td>MVC</td>
</tr>
<tr>
<td>004*</td>
<td>36</td>
<td>17</td>
<td>122</td>
<td>49</td>
<td>4.5</td>
<td>Severe</td>
<td>Fall</td>
</tr>
<tr>
<td>005*</td>
<td>58</td>
<td>17</td>
<td>96</td>
<td>50</td>
<td>11.5</td>
<td>Moderate</td>
<td>Fall</td>
</tr>
<tr>
<td>006*</td>
<td>53</td>
<td>20</td>
<td>89</td>
<td>47</td>
<td>4.5</td>
<td>Severe</td>
<td>MVC</td>
</tr>
<tr>
<td>009*</td>
<td>47</td>
<td>17</td>
<td>113</td>
<td>54</td>
<td>5</td>
<td>Moderate</td>
<td>Sporting accident</td>
</tr>
<tr>
<td>010+</td>
<td>55</td>
<td>19</td>
<td>123</td>
<td>51</td>
<td>9</td>
<td>Moderate</td>
<td>Sporting accident</td>
</tr>
<tr>
<td>012+</td>
<td>51</td>
<td>14</td>
<td>104</td>
<td>45</td>
<td>324</td>
<td>Severe</td>
<td>Fall</td>
</tr>
<tr>
<td>013+</td>
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<th>TSI (months)</th>
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Note. Asterisk (*) denotes availability of medical records; (+) indicates clinical information based on self-report.
Abbreviations: WTAR (Wechsler Test of Adult Reading), BFRT (Benton Face Recognition Test); TSI (time since injury), MVC (motor vehicle crash).

3.2.3 Design and procedures of preliminary feasibility study

The feasibility study used qualitative measures to determine acceptability and implementation (operationally defined below), and quantitative between-group comparisons between patients and controls to assess adaptation. Participation in the study required one 1 - 1.5 hours and testing was carried out at the Toronto Rehabilitation Institute. All participants first underwent screening tests (i.e., demographic questionnaire, WTAR, BFRT) and then completed the FEP-dci task.
Operational definitions of feasibility indices

Acceptability. The dependent variables were completion rate, acceptance of breaks offered at the testing mid-point, spontaneous breaks requested due to reported fatigue or discomfort, and spontaneous complaints about the procedure.

Implementation. The dependent measures were mean time to complete the task and reported difficulties with execution that arose during testing. We also noted equipment needed to carry out the task, and recorded other factors that might affect implementation, such as technical difficulties and ambient noise.

Adaptation. The independent measure was group (TBI vs. HC) and our dependent measures were mean reaction time and errors. Previous studies have reported slower response times for incongruent trials than congruent trials in healthy adults [177]; we examined if the HC group replicated this response time pattern, and additionally explored whether adults with TBI demonstrated similar patterns.

The findings from further comparisons were intended to generate hypotheses for future research because it was unpredictable whether patients would show preserved or impaired performance on this indirect measure of FEP. Previous findings of FEP impairment in adults with TBI with dynamic stimuli [31, 180, 189, 270] and contextual information [179] (but using an explicit processing approach), reported slower reaction times and more errors compared to healthy adults.
3.2.4 Materials

3.2.4.1 Screening Measures

Facial Recognition Impairments. The BFRT-short form was administered to screen participants for any impairment in facial recognition (i.e., score below 41). The short-form version of the test has 13 items and on each item, participants are presented with a target and are asked to indicate which of the six images match the target face. Male and female faces are used, and the faces are closely cropped so that no clothing and little hair are visible. For items 1 - 6, one of the six test faces displays the target individual, and the target image and the test image are identical. For items 1 – 7, three of the test faces match the target face, and the poses for the test images are different from the target image.

Estimated (pre-morbid) IQ. The Wechsler Test of Adult Reading (WTAR) [271] was used to estimate pre-morbid IQ. The test is composed of 50 irregularly spelled words that participants are asked to pronounce. Lists of acceptable pronunciations and tape recordings are provided by the publisher to account for words with multiple pronunciation variants. Each correct pronunciation is given a score of 1, with 50 as the maximum raw score. The raw scores are then standardized by age.

3.2.4.2 Experimental Task and Protocol

The FEP-dci task was developed using E-Builder and was displayed on a 127.0 cm plasma display. The display centre was raised to approximate eye level, positioned at a height of 165.2 cm and at a distance of 182.9 cm away from participants. Participants were required to make verbal responses. A shotgun condenser microphone, suspended overhead, was used to record verbal responses. The microphone was connected to a tube microphone preamplifier to increase the signal required to trigger the voice-key (used to record response time) when participants responded to the stimuli that were presented.
The FEP-dci task began with a preparation session to familiarize participants with the task demands and the questions that were paired with the dynamic stimuli, and thus eliminate novelty of contextual questions during experimental trials. Each emotional question (12 in total) was randomly paired with three different static stimuli (Pictures of Facial Affect [195]), for a total of 36 trials. Participants were instructed to respond ‘Yes’ if they thought the image showed the correct emotional response to the question and ‘No’ if they thought it did not. Participants were told that the preparation session was not timed and they were encouraged to ask questions if they were unsure of the task demands at any point. For the experimental trial, participants began with one practice trial, which only differed from the preparation session in that the stimulus that followed the question was dynamic. For task details, refer to section 3.2.1. Participants completed 10 trials, were offered a break, and then completed an additional 10 trials. Order of stimuli (i.e., question + morph) was randomized for each participant. Each of the six emotions (i.e., anger, disgust, fear, happiness, sadness, and surprise) was presented three times, with happiness and sadness stimuli presented one additional time, as the larger multi-tasking study employed blocks of 20 trials. There were an equal number of congruent and incongruent trials, as well as male and female actors presented.

3.2.5 Analyses

To compare performance between the TBI and HC groups, non-parametric statistical tests were used because they are more conservative than their parametric counterparts and because of the heterogeneity of variance among the groups. Tests of normality determined that the data were not normally distributed; therefore, between-group differences in reaction time and error rates between groups were tested with the Mann-Whitney U test. Exploratory analyses were conducted to examine between-group (Mann-Whitney U test) and within-group (Wilcoxon test) differences between congruent and incongruent trials.
3.3 Results

3.3.1 Acceptability

The TBI and control participants achieved a completion rate of 100%. All but one participant (from the HC group) tolerated the protocol without a break, which was offered to each participant. The HC group participant that accepted a break at the half-way point indicated the break was for personal purposes (to check his cell phone) and was not related to any type of onerousness of the protocol (e.g., fatigue or discomfort). There were no spontaneous negative comments about the procedure. Spontaneous comments were focussed on the amusingness of the trials (e.g., the question and video pairings), and what might be interpreted as ambiguity of certain stimuli. For example, one individual commented that the pairing of a video of a person becoming angry with the question ‘is this person smelling rotten eggs?’ could be the correct response if the person was angry that someone had let eggs spoil.

3.3.2 Implementation

Test administration was resource non-intensive: one laptop, one monitor and one microphone were required to collect data. One block of 20 trials took approximately 149.32 s ($SD = 10.43$ s) to complete. The program used to present the stimuli, E-Builder, provides an Excel spreadsheet with reaction times and responses per trial and therefore there was no scope for experimenter error in recording of responses. However, post-processing of the data was undertaken to verify that responses and reaction times were properly recorded. Time to process the data took approximately 20 min per participant. Experimental noise affecting data acquisition included low volume of participants’ voices and literal noise in the environment. Participants with low voices occasionally resulted in failure of data acquisition because their voice did not trigger the voice-key; loud (non-ambient) noises in the environment (e.g., elevator bells, construction) caused data acquisition errors by triggering the voice-key. These data acquisition problems were addressed during the experiment by increasing or decreasing levels on the microphone amplifier.

Importantly, for trials that did not trigger the voice-key (or triggered the voice-key prematurely), response time could still be calculated with information and audio recordings provided by E-
Builder as every trial was recorded and audible, regardless of whether the voice-key was triggered. Data, therefore, was not lost, nor was it compromised by these acquisition impediments. Moreover, these acquisition impediments occurred in less than half of the participants.

3.3.3 Adaptability

The TBI and HC groups were matched on demographic parameters except for age ($p = .07, d = .83$), with the TBI group on average 8 years older than the HC group. Previous work examining the effects of age on FEP has shown that performance differences are observed only between very wide age disparities (i.e., 20 – 30 vs. 60 – 70 years of age) [272]. Moreover, age effects are less pronounced on indirect than direct tests in general [273].

With regard to congruency findings, Wilcoxon tests showed that the HC group took longer to respond to incongruent trials than congruent trials ($Z = -2.27, p = .02$), while the TBI group did not show this response pattern ($Z = -.35, p = .73$). See Figure 4 for TBI and HC group mean response times across congruent and incongruent trials.

With regard to accuracy, 100% (11/11) of HC participants achieved a score of 80% or better on the FEP task, while 72% (8/11) of the TBI participants achieved this level of accuracy. This difference was not statistically significant (Fisher’s Exact test, $p = .11$). Mean total errors for the TBI group was 2.73 ($SD = 2.15$) and 2.00 ($SD = 1.26$) for the HC group; this difference was not significant ($Z = -.61, p = .55$).

With regard to reaction time, Mann-Whitney U tests showed significant differences between the groups ($Z = -5.55, p < .000$), with the TBI group performing faster ($M = 1376.29$ ms, $SD =$
965.62 ms) than the HC group (\(M = 1534.53\) ms, \(SD = 650.00\) ms). Further investigation demonstrated that the TBI group was also faster than the HC group for both congruent [TBI: \(M = 1396.67\) ms, \(SD = 1085.95\) ms vs. HC: \(M = 1454.50\) ms, \(SD = 621.74\) ms; \(Z = -3.14, p = .002\)] and incongruent [TBI: \(M = 1356.28\) ms, \(SD = 835.35\) ms vs. HC: \(M = 1611.52\) ms, \(SD = 670.01\) ms; \(Z = -4.71, p < .000\)] trials.

Findings of faster responses in the context of absolute (but not statistically significant) differences in error rates raised the question of a speed accuracy trade-off. Correlations between speed and error rates were non-significant in both groups, however.

![Figure 4](image)

*Figure 4*. Mean reaction time (total), CON trials, and INCON trials

Note. Grey bars show mean reaction time for the FEP-dci task per group, as well as mean reaction time for congruent (CON) trials and incongruent (INCON) trials. Error bars represent SD.
3.4 Discussion

We introduced a novel approach to the study of FEP in TBI because a survey of the literature revealed a need for an approach to FEP assessment that incorporated the use of dynamic over static faces [197-200], the provision of contextual information during measurement of FEP [179, 190, 199, 259, 260] and an indirect test of FEP with sensitivity to implicit FEP. These modifications all arguably allow processing of emotional faces that is more generalizable to real-world FEP. We also carried out a pilot feasibility study of the approach in healthy controls and a small sample of TBI patients.

All measures of feasibility were encouraging. The task was resource non-intensive. Test administration was brief, requiring approximately 2.5 minutes to complete. Limitations of implementation were high non-ambient noise level and low participant voice volume, which resulted in failure to trigger the voice-key or false-triggering of the voice key. However, this could be easily addressed during testing, and without loss of data, because all responses and reaction times were collected by the software apart from voice-key triggering. These limitations lead to an increase in post-processing time, but did not affect data integrity. In a future study, the microphone can be placed directly in front of participants or audio can be collected using wireless headsets.

With regard to adaptability, the findings indicated that participants performed largely as expected. Contrary to some but not all previous findings, the TBI group performed faster than the HC group (consistent with findings of reduced inhibitory control [274]), although it should be noted that this is a finding typically observed in concussion/milder TBI patients [275]. While the HC group demonstrated slower response times for incongruent trials compared to congruent trials, replicating previous findings [177], the TBI group did not allocate the extra time for these more challenging items. This finding is again consistent with findings of increased impulsivity and inhibitory control that is a common feature of TBI ([276, 277]); the quick responses
regardless of the task demand may reflect an inability to inhibit automatic or pre-potent response tendencies, which is critical for flexible goal-directed behaviour.

With respect to accuracy, the TBI and HC groups did not differ in mean error rate. However, a clear limitation of the current protocol was the ceiling effects in performance. This may have precluded detection of group differences. On the other hand, the modifications of the current paradigm may have optimized performance in our TBI group. McDonald et al. [278] provided evidence for this when they used the TASIT to show that TBI patients were not impaired when categorizing emotions based on dynamic stimuli and contextualized information (compared to a control group), but were impaired when asked to judge decontextualized static stimuli. They suggested that dynamic FEP may not be reliant on general cognitive processes (e.g., information processing, visual processing) but may represent a qualitatively distinct skill that is relatively spared in TBI. Another explanation is simply attributable to the heterogeneity of TBI, with the possibility that the patients in the current small sample did not have FEP impairments. Future research employing structural and functional imaging would help to control for this confound.

3.4.1 Limitations

There were several limitations to this first step at the development and pilot testing of a novel FEP assessment tool. The sample sizes were relatively small and heterogeneity of variance was high, limiting the types of analyses that could be performed, and the strength of conclusions that could be drawn. The TBI sample was a convenience sample, and some medical information was unavailable to us. Therefore, biases may have been introduced by selecting participants with varying levels of impairment. Furthermore, the lack of statistically significant differences in accuracy may be the reflection of a ceiling effect. Future modifications of the task could increase the difficulty by using facial emotion stimuli that are more ambiguous, as Zupan et al. [279] demonstrated that low intensity emotions are harder for TBI patients to perceive correctly. Likewise, modification of the contextual information provided could examine the effects of less or more subtle details. Finally, a direct comparison of the FEP task performance using implicit
and explicit approaches with a larger sample size, particularly with a sample that includes patients with known difficulty recognizing emotions on conventional FEP measures, would be an informative next step. With respect to ecological validity, such next steps would be required to establish the extent to which results on the FEP-dci task are related to scores on other measures that predict the performance of real-world tasks.

3.5 Conclusion

We introduced a measure that employs an indirect test paradigm to ensure sensitivity to implicit processing of facial emotions, which used dynamic stimuli and incorporated contextual information to indirectly assess FEP in adults with moderate-severe TBI, and we found that the task was feasible to use with TBI patients. It may be the case that conventional methods that have long been used to measure FEP may not be providing the most sensitive assessment of how people, particularly those with brain injury, are processing facial emotion in everyday life.

Developing a tool to examine emotion perception that is more similar to how people interact on a daily basis in the community, at work, at school, or when in any social setting is important to further our knowledge of emotion perception and, importantly, to potentially identify those who might benefit from specific interventions. Consistent with the suggestions of Bowen et al. [214] and Van Teijlingen et al. [280], initial feasibility studies such as this help to determine whether a new approach is worthy of further, more extensive testing. The encouraging preliminary findings from this study provide an impetus for further examination into the construct validity and other psychometric properties of this novel tool.
3.6 Next Steps

The findings from this study provide preliminary evidence that using a newly-developed task to assess FEP in an ecologically valid manner is feasible in a sample of adults with moderate-severe TBI. Therefore, the FEP-dci task was deemed suitable to use in the following study, which itself is an exploratory study that returns to questions about multi-tasking, and about impediments to real-world functioning. The following manuscript will describe the methods and results we obtained when examining multi-tasking with a task that is relevant to multi-tasking in interpersonal interactions, the FEP-dci task.
4 Characterizing multi-tasking after traumatic brain injury: concurrent performance of balance and cognitive tasks

4.1 Introduction

Multi-tasking, the ability to process and/or respond to information while concurrently performing two or more tasks [71], requires the co-activation of multiple brain regions, along with rapid allocation of attention. The widespread injury to brain structures, networks and connective structures (i.e., white matter tracts) following moderate-severe TBI [281-285], and the high prevalence of attentional impairments, particularly divided attention, in this population, give rise to the high prevalence of multi-tasking impairments [8, 68, 69].

To date, most studies of multi-tasking in TBI employ two cognitive tasks, and examine decrements in performance that exceed multi-tasking-related effects seen in healthy adults (e.g., [71, 84, 107, 110-112, 134, 173]). While a number of mild TBI multi-tasking studies have combined cognitive and motor tasks (e.g., [90, 155, 156, 158, 286, 287]), there are considerably fewer such studies in moderate-severe TBI (e.g., [102, 109, 154, 157, 159]). Of these, most have examined gait [102, 154, 157] and only two have examined static postural control (i.e., standing balance) [109, 159]. Postural control is of particular interest in the context of multi-tasking because of the many day-to-day activities that combine postural control with other cognitive tasks, for example, standing while talking to a friend or deciding on an order while waiting in line at a store.

Brauer and colleagues [109] examined concurrent performance of balance and cognitive tasks in adults with severe TBI. They found that baseline measures of centre of pressure (COP) excursion and velocity were higher in the TBI group, and these measures of postural control demonstrated greater multi-tasking-related changes (i.e., disproportionately greater increases), as compared to
healthy adults. This effect was only significant, however, when the postural control task was combined with the easiest cognitive tasks (i.e., articulation control and tone detection tasks). They also found that cognitive performance on those tasks was not affected by the addition of a postural control task. Interestingly and in contrast, Geurts et al. [159], who examined postural control and cognitive performance in adults with mild to severe TBI, found that while COP velocity and amplitude were higher in the TBI group at baseline, multi-tasking performance was not disproportionately worse in the patients as compared to controls. Accuracy on the cognitive task did decrease from single- to multi-task trials, but did not differ between groups. There were several differences between the studies that may have contributed to these dissimilar findings.

With respect to time since injury, patients from the Geurts et al. study [159] were on average two years post-injury and predominantly mild (in terms of injury severity), while the Brauer et al. [109] participants were examined at four months post-injury and predominantly severe. While Geurts et al. [159] only recruited patients who were still complaining of postural instability, the later stage of recovery and milder TBIs nonetheless may have allowed for a milder deficit to attentional functions, as well as brain structures and networks more generally, allowing for better multi-tasking.

Another contributing factor to the contrasting results may be differences in experimental design, which is common in posture-cognition multi-tasking studies (see [160] for review). Brauer et al. [109] assessed postural control while participants stood in a “step stance” (e.g., heel to toe) and Geurts et al. [159] in a “comfortable stance” (e.g., feet shoulder-width apart). Moreover, Brauer and colleagues [109] measured baseline performance of cognitive tasks (two spatial tasks [line orientation, spatial pattern discrimination], two non-spatial tasks [word generation, tone detection], and one control articulation task) while participants stood with postural support (i.e., holding a railing). Conversely, Geurts et al. [159] measured baseline performance of a cognitive task (mental math) while seated, which is a more common method of assessing baseline performance of a cognitive task in multi-tasking studies. Research examining multi-tasking demonstrates that performance can be differentially effected by the sensory modality of the cognitive task [102, 105, 106, 151], as well as level of difficulty for both postural [92, 94, 126,
Brauer et al. [109] used a more difficult postural stance (i.e., a narrow base of support) as compared to Geurts et al. [159] and found the strongest multi-tasking effect for the easiest task, the control articulation task, where participants were required to repeat the word ‘yes’. They suggested a possible explanation was that the task did not require concentrated focus, and therefore, the TBI group could have been more distractible during these trials.

Alternatively, the increase in postural sway could have been because that task had no visual component and stabilizing balance would have had no effect on performance of the cognitive task. Literature on multi-tasking with postural control tasks in healthy adults suggests that adding a supra-postural task (e.g., tasks or behavioural goals that are super-ordinate to postural control [119]) often results in spontaneous reductions to postural sway to facilitate the goals of the supra-postural task [79, 81, 124, 153, 288, 289]. This effect is often interpreted as the postural system trying to stabilize the head, particularly when the supra-postural task is one that requires visual processing [96, 103, 105, 118-120] and is thought to be mediated by automatic control processes [80].

In the aging and brain injury literature, there has been extensive support for the automaticity framework with respect to multi-tasking [73, 75-77]. Automaticity refers to activities or behaviours proceeding without conscious control and not requiring attention or capacity/processing resources [72]. With respect to the stabilizing response seen in many multi-tasking studies, researchers suggest that the addition of a supra-postural task directs attention away from balance-related cues, thereby reducing over-corrections [153], and thus allowing for more automatic or reflexive control processes to be utilized [79, 80]. Similarly, research has demonstrated that directing conscious attention to automatic motor skills can disrupt performance of that skill [290]. Mulder et al. [291] suggested that any type of damage that violates the integrity of the central nervous system (CNS) and creates novel constraints, in principle, may lead to the breakdown of automaticity, such that tasks that may have been
performed without conscious control before injury now require additional attentional resources [76, 113, 132]. While tasks may be performed relatively well in isolation, attentional resources required to perform multiple tasks in parallel may exceed capacity [112, 131, 133], leading to disruptions in performance. Therefore, disproportionate multi-tasking-related changes to performance that are observed after TBI may be due to increased attentional load required to perform tasks that require conscious control.

With regard to implications for everyday life, previous multi-tasking research in adults with moderate-severe TBI has focussed on ecologically valid motor tasks (i.e., walking, balance), and have typically employed lab-based measures of cognitive function, such as the Stroop task [176]. To date, no studies have investigated dual-tasking with measures of social cognition, such as facial emotion perception (FEP), a capacity with important ramifications for everyday life and considered a highly automatic skill that we develop and hone as we age [177, 178]. Interpersonal communications in our personal and professional lives demand a combination of FEP and postural control (e.g., talking, maintaining balance, holding an object) to be performed in parallel [65-67]. Furthermore, poor social communication abilities after TBI [42], and in particular poor FEP [31], have been related to reduced social integration. The mechanisms that underlie poor community integration are not well-understood, and one could speculate that increases in attentional resources required to multi-task in everyday activities might play a role in the challenges experienced with community integration after TBI. To date, no studies have examined the effects of multi-tasking with FEP in TBI, and therefore, it is unknown whether postural control-cognitive multi-tasking impairments extend to this domain or whether the automaticity of FEP or even its biological importance [235] might confer increased resilience against multi-tasking impairments.

Thus, in order to better characterize multi-tasking ability after TBI, our first objective was to examine whether adults who have sustained a moderate-severe TBI showed multi-tasking-related changes to performance when concurrently performing a traditional experimental cognitive task
and a postural control task, as compared to healthy adults. Extending previous work, we enhanced real-world validity by examining postural control in four increasingly challenging postural stances that are similar to everyday situations (i.e., standing with feet in a comfortable stance, a narrow stance, and both of these while holding a cup filled with liquid), as well as cognitive performance on a task that required visual processing (e.g., the Stroop) while seated. We then examined performance when tasks were executed concurrently (i.e., standing while performing the Stroop). Applying the automaticity framework, we expected that increased attentional demands required to perform the postural and cognitive tasks concurrently would result in disturbances to postural control (i.e., greater sway) and cognitive performance (i.e., increased speed, reduced accuracy), as compared to healthy adults.

Our second objective was to examine performance of an FEP task in the same group of adults with TBI and controls, while maintaining postural control, with the aim of determining if adults with TBI demonstrate disproportionate dual-task costs as compared to controls, such as disturbances to postural control (i.e., greater sway) and/or cognitive performance (e.g., increased reaction time and/or errors). To further enhance the implications of the multi-tasking paradigm to real-world functioning, we used a novel approach to the assessment of FEP developed in our lab. This approach employed an indirect test of FEP that is sensitive to the implicit FEP that is likely better preserved in TBI [264-267] and is an important component of real-world FEP [253, 254] (conventional paradigms ask people to explicitly label emotions, for example, which is not a feature of real-world FEP). The novel FEP approach additionally employed dynamic facial emotion stimuli rather than static faces, again to more closely approximate real world displays of facial emotion, and it incorporated contextual information (i.e., information about the context in which the emotion is being expressed), another important facet of real world FEP. Given findings of decreased postural sway with the addition of a supra-postural task in healthy adults, we expected to observe similar reductions in fluctuations to postural stability without changes to performance on the FEP task, as it is considered an automatic, well-practiced skill. We expected, however, to find that multi-tasking performance would be poorer in adults with TBI than healthy
controls, given evidence of decreased automaticity after TBI and the consequent increase in attentional resources necessary to complete both tasks.

4.2 Methods

4.2.1 Participants

**TBI group.** Eleven adults with mild to severe TBI (7 males/4 females), aged between 29 and 54 years, were recruited from the Greater Toronto Area and the Toronto Rehabilitation Institute. Participants were included in the study if they were at least four months post-injury, and if their score on the Benton Face Recognition Test (BFRT - short form [269]) fell within the normal range (i.e., 41-54). Participants were excluded if they had (1) a neurologic disorder other than TBI or a systemic disorder known to affect brain function (e.g., diabetes, Lupus) or (2) a history of psychotic disorder. Medical records were accessible through the Toronto Rehabilitation Institute for 7 of the 11 participants, and for these individuals, injury severity was based on the Glasgow Coma Scale (GCS) score and/or length of post-traumatic amnesia (PTA). The remaining four participants were screened with demographic questionnaires to determine eligibility and injury severity was based on self-report. Causes of injury included motor vehicle crashes, falls, and sporting accidents. Time since injury ranged from 4 to 324 months.

**Healthy Control (HC) group.** Twenty-seven healthy adults were recruited from the Greater Toronto Area (12 males/15 females), aged between 20 and 55 years. Participants were screened with a demographic questionnaire prior to participating, and were excluded if they reported (1) previous neurologic disorders (e.g., stroke, TBI), or systemic disorders (e.g., diabetes); or (2) active clinically significant psychiatric illness (depression, psychosis, anxiety).
Informed consent was obtained from all participants and the study was approved by the research ethics boards of the Toronto Rehab Institute and the University of Toronto. Participant characteristics are presented in Table 12.

Table 12. Participant demographic information

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (years)</th>
<th>Education (years)</th>
<th>WTAR</th>
<th>BFRT</th>
<th>TSI (months)</th>
<th>Severity</th>
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<td>18</td>
<td>117</td>
<td>45</td>
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<td>Severe</td>
<td>Fall</td>
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<td></td>
<td>Mean</td>
<td></td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td>45.00</td>
<td>16.63</td>
<td>109.00</td>
<td>48.36</td>
<td>51.36</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(9.89)</td>
<td>(2.06)</td>
<td>(11.00)</td>
<td>(3.14)</td>
<td>(102.49)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HC</td>
<td>29.64</td>
<td>16.20</td>
<td>109.28</td>
<td>48.80</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(9.17)</td>
<td>(1.58)</td>
<td>(9.30)</td>
<td>(2.38)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note. Asterisk (*) denotes availability of medical records; (+) indicates clinical information based on self-report. Abbreviations: WTAR (Wechsler Test of Adult Reading), BFRT (Benton Face Recognition Test); TSI (time since injury), MVC (motor vehicle crash).

4.2.2 Materials and apparatus

4.2.2.1 Cognitive outcomes

Screening tests

Facial Recognition Impairments. The BFRT-short form was administered to screen participants for any impairment in facial recognition. The short-form version of the test has 13 items and on each item, participants are presented with a target and are asked to indicate which of the six images match the target face. Male and female faces are used, and the faces are closely cropped
so that no clothing and little hair are visible. For items 1 - 6, one of the six test faces displays the target individual, and the target image and the test image are identical. For items 1 – 7, three of the test faces match the target face, and the poses for the test images are different from the target image.

*Estimated (pre-morbid)IQ.* The Wechsler Test of Adult Reading (WTAR) [271] was used to estimate pre-morbid IQ. The test is composed of 50 irregularly spelled words that participants are asked to pronounce. Lists of acceptable pronunciations and tape recordings are provided by the publisher to account for words with multiple pronunciation variants. Each correct pronunciation is given a score of 1, with 50 as the maximum raw score. The raw scores are then standardized by age.

*Vision.* A Snellen Eye Chart was used to measure visual acuity to ensure that participants were able to see all stimuli presented to them. In addition, a computerized version of the Stroop Colour and Word tests were used prior to testing to measure participants’ ability to read colour words (i.e., red, green, and blue) and to identify colours (i.e., red, green, and blue).

**Experimental tasks**

Both the Stroop and the FEP tasks were developed in Experiment Builder (SR Research Ltd., Ottawa, ON, Canada) and were displayed on a 127.0 cm plasma display. The display was raised to approximate eye level, positioned at a height of 165.2 cm and 182.9 cm away from the participants. The Stroop task was selected because it provides a visual task not requiring memory and has demonstrated reliability and validity [292, 293]. For the current study, the Stroop task was modified from the paper pencil original test. The FEP task was developed and tested for feasibility to use in a TBI population. The task paired questions that provided participants with contextual information to facilitate FEP with dynamic stimuli (i.e., 1 s videos of faces morphing
from a neutral face into an emotional face) from the STOIC data base [294]. Participants were required to process the emotions being displayed indirectly, while responding ‘yes’ or ‘no’ to each question.

For both tasks, participants were required to make verbal responses, and so a shotgun condenser microphone was used to record responses, suspended overhead of participants from a bar 226.8 cm above the force plates. The microphone was connected to a tube microphone preamplifier to increase the signal required to trigger the voice key.

### 4.2.2.2 Postural control outcomes

To measure postural control, COP was recorded from two force plates (Advanced Medical Technology Inc., Watertown, MA, USA) that were arranged side-by-side, separated by approximately 1 mm. Ground reaction forces and moments from each plate were synchronously sampled at 256 Hz, using custom software. Linear acceleration of the head was measured along two orthogonal axes [anterior-posterior (AP) and medial-lateral (ML)] using a tri-axial piezo-resistant accelerometer (G-Link Wireless Accelerometer Node, Microstrain, Inc, USA). The accelerometer had a range of ± 2 g and was mounted on the side of a lightweight hard hat suspension system. The accelerometer weighed 46 grams and the dimensions were 58 mm x 43 mm x 26 mm. The acceleration signal was sampled at a rate of 256 Hz using an inbuilt 12-bit analogue to digital converter, and stored to the on-board microprocessor. Three accelerometers in total were used (head, trunk and cup), but for the purposes of this study, we only examined acceleration of the head.

The force plates were connected to all apparatuses used to collect data so that data collection was synchronized: a TTL signal (i.e., a 5 V synchronization pulse) was emitted to initiate trials and allow for simultaneous data collection from force plates, accelerometers and laptop.
Participants were required to hold a cup filled with liquid for half of the trials (see Figure 5). The cup was designed so that participants could visibly see if water had been spilled without actually spilling any water. A small clear plastic cup (height – 10.2 cm, diameter – 7.6 cm) was fixed to the inside of a larger plastic cup (height – 12.7 cm, diameter – 10.2 cm) and a lid was placed on the larger cup. Green liquid (400 ml) was poured to the rim of the smaller cup and rim of the smaller cup was tinted black to increase visibly of both the liquid and top of the cup.

![Dual-cup system](image)

Figure 5. Dual-cup system

Note. The cup was used in multi-task trials to increase difficulty of the postural task, as well as to simulate everyday inter-personal interactions, such as going out with friends to a party.

4.2.3 Design

This study used a 2 x 2 x 4 between-group experimental design. The independent variables were group (HC vs. TBI), condition (single-task vs. multi-task) and postural task difficulty (standard stance [ST], standard plus cup [STC], narrow stance [NA], narrow plus cup [NAC] – see figure 6). The dependent variables for postural control were COP amplitude (root mean square [RMSc] over a 60 s recording period) and mean power frequency [MPFc], as well as head acceleration
amplitude (RMSA) and mean power frequency [MPFA] in both M/L and A/P directions. For cognitive performance, dependent variables were response reaction time and errors. We defined increases in COP sway as larger amplitudes and lower frequencies, and increased stability as lower amplitude with higher frequency. Poorer cognitive performance was related to increases in reaction time or increased errors as compared to baseline (i.e., single-task) measures.

![Figure 6. Postural stances](Image)

*Figure 6. Postural stances*

Note. Top left: standard (ST); Bottom left: standard with cup (STC); Top right: narrow (NA), Bottom right: narrow with cup (NAC). Participants were required to perform single- and multi-task trials in each postural stance, with and without holding the cup.

### 4.2.4 Procedures

Participants were required to come to the laboratory for one 1 - 1.5 hr testing session. Each session began with administration of the WTAR, the BFRT, and the Snellen Chart vision test. Participants were fitted with accelerometers and foot position was recorded on the force platforms. Participants were then asked to perform the four balance tasks, followed by either the Stroop trials first or the FEP trials first. Within each set of trials, participants performed a seated practice session first, then performed each of the five conditions with the cognitive tasks: single-task (seated), multi-task while in ST, STC, NA and NAC postural stances. During multi-task trials, participants were instructed to respond as quickly and accurately as they could while standing as still as they could, and were additionally told to keep their hand as still as they could.
so as to not spill any water in the cup-holding conditions. Order of single-task balance trials, cognitive tasks, and single versus multi-task sequence was counterbalanced between participants to minimize practice or learning effects.

**Balance.** Participants performed four trials of quiet standing during which they were asked to stand as still as possible for 60 s, with one foot on each force platform. For ST postural stance, foot position was standardised across all participants as per McIlroy and Maki [295], with feet positioned with 17 cm between heels and each foot externally rotated 14° from the median plane. For NA postural stance, feet were brought together as close as possible while still keeping each foot on separate force platforms. Participants performed two additional trials in each stance while holding the liquid-filled cup (STC, NAC), and were required to use their dominant hand to hold the cup, with their arm bent at a 90° angle. In the postural stances without the cup, participants were instructed to stand as still as possible while keeping their gaze on a crosshair, and when holding the cup, to keep their hand as still as possible so to not spill any water, while keeping their gaze on the crosshair. Water spillage was not measured, but the cup was refilled after every trial, allowing participants to see if any water had spilled from the smaller cup into the larger cup. This was done in response to pilot testing findings that the task was rated as subjectively easier when participants knew there was no consequence to hand movements (i.e., when using a single cup that was sealed, hand movements would not result in spillage).

**Cognitive.** The Stroop task began with a practice session where we first measured participants’ ability to read colour words (i.e., red, green, and blue) and identify colours (i.e., red, green, and blue). Participants then practiced three Stroop Interference trials, where they were instructed to identify the colour of each word while ignoring what was typed. For the experimental trials, participants were instructed to respond as quickly and accurately as they could. For each trial, a crosshair would orient participants’ gaze to the centre of the display for 1 s. Then a colour word that was typed in one of the three colours was presented (all incongruent pairings) and when participants made a response, the word was replaced with a blank display for 1 s, until the next
stimulus was presented (See Figure 7). Each block had 40 trials, divided into 2 sets of 20. Each block took approximately 2-3 min to complete.

The FEP task began with a practice session to familiarize participants with the questions that were paired with the dynamic stimuli. Each of the 12 questions was randomly paired with three different static stimuli (Pictures of Facial Affect [195]), for a total of 36 trials. Participants were instructed to respond ‘Yes’ if they thought the image showed the correct emotional response to the question and ‘No’ if they thought it did not. Participants were instructed that the practice session was not timed and were encouraged to ask questions if they were unsure of the task at any point. For the experimental trials, participants began with one further practice trial, which only differed from the practice session in that the stimuli that followed the questions were dynamic stimuli. Participants were instructed to respond as quickly as they could. Each trial began with the presentation of one of the 12 questions for 4 s, followed by the dynamic stimuli. Once the participant responded, the question and image would be replaced with a blank display for 1 s before the next trial would begin (see Figure 7). Each block had 20 trials, divided into 2 sets. Each block took approximately 2-3 min to complete.

Figure 7. Stroop (top) and FEP (bottom) tasks

Top - Stroop task. A cross-hair orients gaze to the centre of the display for 1s, stimuli appear and disappear when a response is made. A blank screen is presented for 1 s before the next trial. Bottom - FEP task. Question presented for 4 s. Stimuli appear as 1 s video of face changing from a neutral face to an emotional face, and disappear when a response is made. A blank screen is presented for 1 s before the next trial begins.
4.2.5 Data processing

COP. Raw COP data were low-pass filtered using a zero-lag, fourth-order, Butterworth filter with a cut-off frequency of 10Hz. A/P and M/L COP under each limb were calculated, in addition to the net-COP (COPnet) using custom-made programs in MatLab and Labview. For both A/P and M/L directions, RMS and MPF of the COPnet displacement were calculated over a 60 s trial. For multi-task trials, an average of two 60 s trials was taken. Due to technical difficulties with the equipment, COP data was not collected for two participants (1 TBI, 1 HC – force plates did not record trials due to tester error), and therefore, their COP data were excluded from analyses. Data for 10 participants from the TBI group and 25 participants from the HC group were analyzed.

Acceleration. Raw acceleration data were imported and converted to units of gravitational acceleration (g, or multiples of 9.81 m/s/s), corrected with appropriate gain and offset values. Using a custom-made program in MatLab, data were detrended to remove bias by applying a high-pass filter with a cut-off frequency of 0.05 Hz. This was done to eliminate any systematic increases or decreases in the data that might be attributable to drift variance. This cut-off was selected to reduce any low-frequency DC components and also because it has been suggested that low frequency body sway is likely not related to balance control, but high frequency excursions may be a more adequate measure [296]. The data were then low-pass filtered using a zero-lag, fourth-order, Butterworth filter with a cut-off frequency of 10Hz. RMS was then calculated, and MPF was calculated from the power spectral density of the signals. Due to technical difficulties with the equipment, acceleration data for 6 participants (1 TBI, 5 HC – accelerometers did not record trials properly due to tester error), and therefore, their acceleration data was excluded from analyses. Data for 10 participants from the TBI group and 22 participants from the HC group were analyzed.

Cognitive performance. Responses were examined with an audio editor to determine if reaction times reflected responses or artifacts (e.g., non-lexical utterances such as ‘uh’ or ‘um’) that may
have triggered the voice key, or if responses failed to trigger the voice key. In such situations, an audio editing program was used to measure reaction time based on start time and the voiced part of vowels (e.g., \( yEe \), \( blUe \)). Formulas were then used to determine reaction time based on stimulus display time. Each response was also compared to expected response to determine number of errors.

4.2.6 Statistical analyses

Between-group differences in demographic data and baselines measures (i.e., single-task performance) were determined using independent t-tests. All analyses were performed using SPSS v20.0. Significance was accepted at \( p < .05 \) for all tests.

Mixed-design ANOVAs were used to determine any group effects (TBI vs. HC), condition effects (single vs. multi-task), postural effects (ST vs. STC vs. NA vs. NAC), and associated interactions of each variable separately (reaction time, errors, and M/L and A/P RMS\( C \), MPF\( C \), RMS\( A \), MPF\( A \)). Post hoc t-tests were performed (adjusted for multiple comparisons by applying a Bonferroni correction) to identify specific differences between groups and tasks. Due to small sample size, a more conservative Bonferroni correction was not applied (to control for multiple ANOVAs), however, partial eta squared (\( \eta^2 p \)) was calculated to determine effect sizes between groups.

4.3 Results

4.3.1 Participant baseline measures

Participants were similar in terms of years of education, WTAR, and BFRT, but differed in age \( (p = .01, d = -1.41) \). Therefore, all ANOVAs were run with age as a covariate. When age was not significant in the ANCOVA, it was removed and an ANOVA (without age as a covariate) was used. Baseline cognitive and postural measures are summarized in Tables 13-16. Baseline values
for cognitive performance and postural control were similar between groups; only AP MPFC in ST postural stance differed between groups ($p = .01, d = .89$).

Tables 13 and 14 provide single-task (i.e., seated) mean reaction time and error rates for the TBI group (individual scores presented as well) and the HC groups for the Stroop and FEP tasks, respectively.

**Table 13.** Baseline Stroop reaction time and errors for TBI (individual and group performance) and HC groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Reaction time (ms)</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>685.14</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>693.55</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>775.14</td>
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<td>5</td>
<td>1366.82</td>
<td>1</td>
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<td>6</td>
<td>670.09</td>
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<td>9</td>
<td>828.12</td>
<td>0</td>
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<td>10</td>
<td>806.32</td>
<td>0</td>
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<td>12</td>
<td>1058.53</td>
<td>0</td>
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<td>13</td>
<td>597.36</td>
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<td>15</td>
<td>633.89</td>
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<td>16</td>
<td>680.21</td>
<td>0</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>799.55 (226.72)</td>
<td>.36 (.67)</td>
</tr>
<tr>
<td>HC</td>
<td>Mean (SD)</td>
<td>714.73 (94.17)</td>
</tr>
<tr>
<td></td>
<td>.27 (.57)</td>
<td></td>
</tr>
</tbody>
</table>
Tables 15 and 16 provide single-task (i.e., quiet standing) COP amplitude and frequency for the TBI and the HC groups in both A/P and M/L directions when in participants are in standard and narrow postural stances.

Table 14. Baseline FEP reaction time and errors for TBI (individual and group performance) and HC groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Reaction time (ms)</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
</tr>
<tr>
<td>1</td>
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</tr>
<tr>
<td>3</td>
<td>832.25</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>1267.07</td>
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<td>1922.59</td>
<td>6</td>
</tr>
<tr>
<td>13</td>
<td>953.78</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>973.66</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>1035.68</td>
<td>0</td>
</tr>
<tr>
<td>Mean  (SD)</td>
<td>1391.26 (587.09)</td>
<td>2.55 (2.12)</td>
</tr>
<tr>
<td>HC</td>
<td>Mean (SD)</td>
<td></td>
</tr>
<tr>
<td>1371.50 (359.86)</td>
<td>1.28 (1.27)</td>
<td></td>
</tr>
</tbody>
</table>

Note. Stroop baseline measures were taken while participants were seated.
Table 15. Baseline COP amplitude and frequency for TBI and HC groups

<table>
<thead>
<tr>
<th></th>
<th>RMSc (mm)</th>
<th></th>
<th></th>
<th>MPFc (Hz)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A/P</td>
<td>M/L</td>
<td>A/P</td>
<td>M/L</td>
<td>A/P</td>
<td>M/L</td>
</tr>
<tr>
<td>TBI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4.50</td>
<td>5.30</td>
<td>2.40</td>
<td>5.10</td>
<td>.41</td>
<td>.45</td>
</tr>
<tr>
<td>3</td>
<td>3.10</td>
<td>5.20</td>
<td>1.80</td>
<td>4.50</td>
<td>.58</td>
<td>.31</td>
</tr>
<tr>
<td>4</td>
<td>2.90</td>
<td>4.60</td>
<td>1.30</td>
<td>3.90</td>
<td>.41</td>
<td>.28</td>
</tr>
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<td>.19</td>
</tr>
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<td>6</td>
<td>4.70</td>
<td>6.00</td>
<td>1.50</td>
<td>4.50</td>
<td>.58</td>
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<td>8.30</td>
<td>4.70</td>
<td>2.40</td>
<td>3.60</td>
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<td>.45</td>
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<tr>
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<td>9.80</td>
<td>11.40</td>
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<td>.28</td>
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<td>12.20</td>
<td>4.90</td>
<td>2.30</td>
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<td>7.20</td>
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<td>16</td>
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<td>2.90</td>
<td>3.50</td>
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<td>.16</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>5.94 (3.10)</td>
<td>6.48 (2.13)</td>
<td>2.09 (.81)</td>
<td>4.59 (1.13)</td>
<td>* .35 (.14)</td>
<td>.34 (.13)</td>
</tr>
<tr>
<td>HC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>5.17 (2.51)</td>
<td>5.69 (1.92)</td>
<td>1.93 (.76)</td>
<td>4.52 (1.08)</td>
<td>* .25 (.09)</td>
<td>.28 (.12)</td>
</tr>
</tbody>
</table>

Note. Baseline measures were taken while participants stood quietly in standard and narrow stance, fixating on a target displayed on the monitor. Asterisks (*) indicate significant differences between the TBI and HC groups (p = .01). RMSc= centre of pressure root mean squared; MPFc= centre of pressure mean power frequency; A/P= anterior/posterior; M/L= medial-lateral; ST= standard stance; NA= narrow stance.

4.3.2 Postural control and the Stroop task

4.3.2.1 Stroop task performance

In order to evaluate multi-tasking effects on cognitive performance, we examined reaction time and errors on the Stroop task. A group (TBI vs. HC) by condition (single vs. multi-task) repeated measures ANOVA examining reaction time did not reveal any main effect of group (F[1,33] = 2.69; p = .11, $\eta^2_p = .08$), or condition (F[4,132] = 1.00; p = .41, $\eta^2_p = .03$), or group by condition interaction (F[4,132] = .31; p = .87, $\eta^2_p = .01$). Similarly, a group by condition repeated measures ANCOVA examining errors revealed no main effect of group (F[1,32] = .002; p = .97, $\eta^2_p = .000$), condition (F[4,128] = 1.66; p = .16, $\eta^2_p = .05$) or group by condition interaction (F[4,128] = 1.55; p = .19, $\eta^2_p = .05$). There was, however, a significant interaction between condition and age (F[4,128] = 2.85; p = .03, $\eta^2_p = .08$). When performing the Stroop task,
Table 16. Baseline acceleration amplitude (RMS) and frequency (MPF) for TBI (individual and group performance) and HC groups

<table>
<thead>
<tr>
<th></th>
<th>RMS(_\text{A} \text{ (g)})</th>
<th></th>
<th>MPF(_\text{A} \text{ (Hz)})</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>A/P</td>
<td>M/L</td>
<td>A/P</td>
<td>M/L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Group</strong></td>
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<td><strong>NA</strong></td>
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<td><strong>NA</strong></td>
<td><strong>ST</strong></td>
<td><strong>NA</strong></td>
<td></td>
</tr>
<tr>
<td>TBI</td>
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<td>.01</td>
<td>.01</td>
<td>.87</td>
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<td>.66</td>
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<td>.02</td>
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<td>.97</td>
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Note. Baseline measures were taken while participants stood quietly standard and narrow stance, fixating on a target displayed on the monitor. RMS\(_\text{A} \text{ = acceleration root mean squared; MPF}\_\text{A} = \text{acceleration mean power frequency}; \text{; A/P = anterior/posterior; M/L = medial-lateral; ST = standard stance; NA = narrow stance.}

reaction time and errors were not affected by the addition of a postural task (seated vs. ST, STC, NA, NAC).

4.3.2.2 Postural control performance

In order to examine multi-tasking effects on postural control, we examined COP amplitude and frequency, as well as head acceleration amplitude and frequency. For COP amplitude, there were main effects of condition (A/P RMSc: \(F[1,32] = 10.02; \ p = .003, \eta^2p = 0.24\)), as well as a main effect of postural stance (A/P RMSC: \(F[3,96] = 2.93; \ p = .04, \eta^2p = .08\); M/L RMSc: \(F[3,99] = 122.60; \ p < .000, \eta^2p = .79\)) and a condition by group interaction (M/L RMSc: \(F[1,33] = 16.61; \ p < .000, \eta^2p = .34\)). Post hoc analyses showed significantly higher values for narrow than standard
postural stances (A/P RMSc: NA vs. ST \(p = 0.02\); M/L RMSc: NA vs. ST, STC \(p < .000\), NAC vs. ST, STC \(p < .000\)). Additionally, the HC group significantly decreased M/L RMSc from single to multi-task trials \((p = .01)\), while the TBI group did not demonstrate any multi-tasking-related changes in COP amplitude \((p = .99)\).

In examining the effects of multi-tasking on COP frequency, there was a main effect of group (A/P MPFc: \(F[1,33] = 12.62; p = .001, \eta^2p = .28\)), and condition (A/P MPFc: \(F[1,33] = 24.71; p < .000, \eta^2p = .43\); M/L MPFc: \(F[1,32] = 8.84; p = .01, \eta^2p = .22\)), as well as a significant interaction between condition and age (M/L MPFc: \(F[1,32] = 5.93; p = .02, \eta^2p = .16\)). Post hoc analyses revealed there were significant increases in frequency from single to multi-task trials, and the TBI group had significantly higher A/P MPFc than the HC group during single-task \((p < .000)\) and multi-task trials \((p = .012)\).

In examining the effects of multi-tasking on acceleration amplitude at the head, there was a main effect of condition (A/P RMSA: \(F[1,27] = 4.90; p = 0.04, \eta^2p = .15\); M/L RMSA: \(F[1,27] = 8.91; p = .01, \eta^2p = .25\)), and a group by condition interaction (M/L RMSA: \(F[1,27] = 8.27; p = .01, \eta^2p = .24\)). Post hoc analyses revealed that the TBI group significantly increased M/L RMSA from single to multi-task trials \((p = .002)\), while the HC group did not \((p = .92)\).

For acceleration frequency, analyses revealed a main effect of posture (M/L MPFA: \(F[3,81] = 6.29; p = .001, \eta^2p = .19\)), as well as an interaction between group and condition (M/L MPFA: \(F[1,27] = 4.27; p = .05, \eta^2p = .14\)). Post hoc analyses revealed that frequency was significantly lower in narrow postural stances (NA vs. STC \([p = .02]\), NAC vs. STC \([p = .08]\)), and that the TBI group had significantly decreased their M/L MPFA from single to multi-task trials \((p = .03)\), while the HC group did not \((p = .86)\).
4.3.3 Postural control and the FEP task

4.3.3.1 FEP performance

A group (TBI vs. HC) by condition (single vs. multi-task) repeated measures ANOVA examining reaction time did not reveal any main effect of condition \( (F[4,136] = 1.65; \ p = .17, \ \eta^2 p = .05) \) or group \( (F[1,34] = .40; \ p = .532, \ \eta^2 p = .01) \), nor a group by condition interaction \( (F[4,132] = .36; \ p = .84, \ \eta^2 p = .01) \). An ANCOVA examining errors revealed no main effect of condition \( (F[3,132] = 2.22; \ p = 0.07, \ \eta^2 p = .06) \) or group \( (F[1,33] = 0.21; \ p = .65, \ \eta^2 p = .01) \), nor a group by condition interaction \( (F[4,132] = 1.83; \ p = .13, \ \eta^2 p = .05) \). Age, however, was significant in the model \( (F[1,33] = 6.96; \ p = .01, \ \eta^2 p = .17) \), and there was a significant interaction between condition and age \( (F[4,132] = 3.40; \ p = .03, \ \eta^2 p = .08) \).

4.3.3.2 Postural Control

For COP amplitude, there was a main effect of condition \( (A/P \ RMSc: \ F[1,33] = 12.04; \ p = .001, \ \eta^2 p = .27) \), a main effect of postural stance \( (A/P \ RMSc: \ F[3,99] = 4.52; \ p = .01, \ \eta^2 p = .12; \ M/L \ RMSc: \ F[3,99] = 137.12; \ p < .000, \ \eta^2 p = .81) \), and a condition by group interaction \( (M/L \ RMSc: \ F[1,33] = 9.30; \ p = .004, \ \eta^2 p = .22) \). Figure 8 displays single- and multi-task trial RMSc (A/P and M/L) for both TBI and HC groups. Post hoc analyses revealed that COP amplitude was significantly higher for narrow, compared to standard, postural stances \( (A/P \ RMSc: \ NA \ vs. \ STC \ [p = .02], \ NAC \ vs. \ STC \ [p = .004]; \ M/L \ RMSc: \ NA \ vs. \ ST, \ STC \ [p < .000], \ NAC \ vs. \ ST, \ STC \ [p < .000]) \). Also, the HC and TBI groups performed differently during multi-tasking trials: the HC group showed decreased M/L RMSc during multi-task trials, as compared to single-task trials \( (p = .01) \), while the TBI group showed no significant change \( (p = .97) \).
Figure 8. COP amplitude in each postural stance for TBI (left) and HC (right) groups

Note. Solid grey bars represent mean COP RMS (mm) for single-task trials, hatched bars represent multi-task trials in same postural stance. Error bars present SD. (Top) COP amplitude in AP plane: ANOVA found a main effect of condition ($p = .001$), and a main effect of postural stance ($p = .01$). (Bottom) COP amplitude in ML plane. ANOVA found a main effect of postural stance ($p < .000$), and a group by condition interaction ($p = .004$).

Analysis of COP frequency revealed a main effect of group (A/P MPFC: $F[1,33] = 8.28; p = .01$, $\eta^2_p = .20$), a main effect of condition (A/P MPFC: $F[1,33] = 11.87; p = .002$, $\eta^2_p = .27$; M/L MPFC: $F[1,32] = 7.65; p = .01$, $\eta^2_p = .19$), as well as an interaction between condition and age (ML MPFC: $F[1,32] = 6.00; p = .02$, $\eta^2_p = .16$). Figure 9 displays single- and multi-task trial MPFC (A/P and M/L) for both TBI and HC groups. Post hoc analyses found significant increases
in COP frequency from single to multi-task trials, and the TBI group had significantly higher A/P MPFe than the HC group during single-task \((p = .01)\) and multi-task trials \((p = .04)\).

**Figure 9.** COP frequency in each postural stance for TBI (left) and HC (right) groups

Note. Solid grey bars represent mean COP MPF (Hz) for single-task trials, hatched bars represent multi-task trials in same postural stance. Error bars present SD. (Top) COP MPF in AP plane: ANOVA found a main effect of group \((p = .01)\), and a main effect of condition \((p = .002)\). (Bottom) COP MPF in ML plane. ANOVA found a main effect of condition \((p = .01)\), and an age by condition interaction \((p = .02)\).
In examining acceleration amplitude, we found a main effect of group (M/L RMSA: \( F[1,26] = 5.11; p = .03, \eta^2 p = .16 \)), a main effect of condition (A/P RMSA: \( F[1,26] = 7.52; p = .01, \eta^2 p = .22 \); ML RMSA: \( F[1,26] = 8.54; p = .01, \eta^2 p = .25 \)), as well as interactions between condition and group (M/L RMSA: \( F[1,26] = 4.85; p = .04, \eta^2 p = .16 \)), condition and posture (M/L RMSA: \( F[1,27] = 4.38; p = .01, \eta^2 p = .14 \)) and condition, posture and group (A/P RMSA: \( F[3,78] = 3.32; p = .02, \eta^2 p = .11 \)). Figure 10 displays single- multi-task trial RMSA (A/P and M/L) for both TBI and HC groups. Post hoc analyses demonstrated significant increases in acceleration amplitude from single-task to multi-task trials for the TBI group (M/L RMSA: \( p = .004 \)), but not the HC group (M/L RMSA: \( p = .53 \)). Moreover, acceleration amplitude was greater for the TBI group, as compared to the HC group, in the single and multi-task trials for ST (A/P RMSA: \( p = .05 \) and \( p = .04 \), respectively), and in multi-task trials for STC (A/P RMSA: \( p = .001 \)) postural stances.

In examining acceleration frequency, there was a significant main effect of condition (A/P MPFA: \( F[1,26] = 9.78; p = .004, \eta^2 p = .27 \); M/L MPFA: \( F[1,26] = 39.97; p < .000, \eta^2 p = 0.61 \)) and interactions between condition and posture (M/L MPFA: \( F[3,78] = 3.00; p = .04, \eta^2 p = 0.10 \)), group and condition (M/L MPFA: \( F[1,26] = 10.30; p = .004, \eta^2 p = .28 \)) and condition, posture and group (A/P MPFA: \( F[3,78] = 2.78; p = .05, \eta^2 p = .10 \)). Figure 11 displays single- multi-task trial MPFA (A/P and M/L) for both TBI and HC groups. Post hoc analyses revealed that the HC group significantly decreased acceleration frequency from single to multi-task trials for ST (A/P MPFA: \( p = .05 \)) and NAC (M/L MPFA: \( p = .002 \)) postural stances, while the TBI group demonstrated significant decreases from single to multi-task trials in every postural stance (ST [M/L MPFA: \( p = .001 \)]; STC [A/P MPFA: \( p < .000 \), M/L MPFA: \( p < .000 \)]; NA [M/L MPFA: \( p = .03 \), NAC [M/L MPFA: \( p = .002 \)]. Moreover, the TBI group had significantly lower acceleration frequency in multi-task trials, compared to the HC group, in both standard postural stances (ST [M/L MPFA: \( p = .01 \)], STC [A/P MPFA: \( p = .04 \); M/L MPFA: \( p = .004 \)].
Figure 10. Acceleration amplitude in each postural stance for TBI (left) and HC (right) groups

Note. Solid grey bars represent mean acceleration RMS (g) for single-task trials, hatched bars represent multi-task trials in same postural stance. Error bars present SD. (Top) Acceleration RMS in AP plane: ANOVA found a main effect of condition ($p = .01$) and a group by postural stance by condition interaction ($p = 0.2$). (Bottom) Acceleration RMS in ML plane. ANOVA found main effects of group ($p = .03$) and condition ($p = .01$), and interactions between group and condition ($p = .02$), as well as postural stance and condition ($p = .04$).
Figure 11. Acceleration frequency in each postural stance for TBI (left) and HC (right) groups

Note. Solid grey bars represent mean acceleration MPF (Hz) for single-task trials, hatched bars represent multi-task trials in same postural stance. Error bars present SD. (Top) Acceleration MPF in AP plane: ANOVA found a main effect of condition ($p = .004$) and a group by postural stance by condition interaction ($p = 0.5$). (Bottom) Acceleration MPF in ML plane. ANOVA found main effects of condition ($p < .000$), and interactions between group and condition ($p = .004$), as well as postural stance and condition ($p = .04$).
4.4 Discussion

The primary aim of this study was to further explore and characterize multi-tasking performance in adults with moderate-severe TBI. Applying a framework of automaticity [72] and taking into consideration expected reductions in attentional resources after TBI [8, 68, 69], we expected to find that the TBI group would demonstrate greater disturbances to postural control and cognitive performance, whereas we expected healthy adults to demonstrate reduced sway and unaffected cognitive performance when multi-tasking. Our hypotheses were partially supported. When multi-tasking with the Stroop and postural control tasks, reaction time and accuracy were not affected by the addition of a postural task, nor by increases in the amount of postural control required (seated vs. ST, STC, NA, NAC) for either group. The effects of adding a supra-postural task affected the TBI and HC groups similarly in the A/P plane involving reduced sway (i.e., decreased COP amplitude and increased frequency). However, the groups differed in M/L postural control. While the HC group demonstrated reduced sway with the addition of the Stroop task, the TBI group demonstrated no change to COP, and they also increased acceleration amplitude (and decreased frequency) at the head.

Multi-tasking with the FEP and postural control tasks produced similar results. When comparing performance of the TBI group to the HC group, we found no differences in the effect of concurrently performing the FEP and postural tasks on reaction time or accuracy. Postural control was also similarly affected with the addition of the FEP task: reduced sway in the A/P plane but group differences in M/L postural control. While the HC group demonstrated reduced sway with the addition of the FEP task, the TBI group demonstrated no change to COP, and increased acceleration amplitude (and decreased frequency) at the head. Increases in acceleration amplitudes at the head were also demonstrated in the A/P plane for the TBI group, but only in standard stances.
With respect to baseline (i.e., single-task) differences in cognitive performance between the TBI and HC groups, they did not differ in reaction time or accuracy on either the Stroop or FEP tasks. This was somewhat surprising given findings of impairment on the Stroop task after TBI (as compared to healthy adults) [297]. However, the FEP task was designed to capture real-world performance, with adaptations to the conventional paradigms, including an indirect measure of FEP, intended to permit implicit processing, which is often spared after TBI [264-267]. In TBI, like most other neurological populations, there is evidence of disproportionate impairments to explicit as compared to implicit processing [264-266, 268]. The TBI group in the current study, therefore, may not have differed from the HC group during single-task cognitive tasks as they were able to perform the task relatively automatically.

We also did not see any baselines differences in M/L COP amplitude or frequency, nor acceleration amplitude or frequency in either direction. We did, however, find group differences in A/P COP frequency, with higher COP frequency in the TBI group for standard stance only. This finding was in contrast to Brauer et al. [109], who found no difference in baselines measures of COP acceleration or frequency, as well as Geurts et al. [159], who found baselines differences only in COP amplitude (both A/P and M/L). The overall lack of difference in postural control between the TBI and HC groups was interesting, considering subjective complaints of balance and mobility have been reported, in particular, as some of the most persistent and common long-term concerns after TBI [17, 18, 172]. This highlights the importance of using multi-tasking paradigms to examine residual impairment after TBI, because even with a group that seems well-recovered, we demonstrated multi-tasking-related changes to postural control.

The lack of differential multi-tasking-related effects on cognitive performance between groups, was not a novel finding as Brauer et al. [109] and Geurts et al. [159] had similar results with the cognitive tasks that were utilized in each study. McFadyen et al. [102] found that Stroop reaction time was more greatly affected for their TBI group, as compared to healthy controls, but they
examined gait and obstacle avoidance while concurrently performing the Stroop task, thus a more attention-demanding dynamic postural control task. We also found that cognitive performance was not affected by postural stance, which has been previously demonstrated in healthy adults [106, 124, 126, 149]. The high level of accuracy and fast reaction times could be a result of increased arousal due to concurrent performance of the cognitive and postural tasks [115]. However, without a measure of arousal in the current study, it is unknown whether arousal was indeed a factor for one or both groups.

Where we did see differences in multi-tasking-related changes to performance was in COP amplitude and acceleration of the head. While the HC group performed as we expected, by reducing postural sway to stabilize the head (to optimize performance of the visual cognitive tasks), the TBI group did not. Interestingly though, the lack of reductions in postural sway for the TBI group did not appear to affect performance on either of the cognitive tasks, as reaction time did not increase nor did error rates decrease in multi-tasking trials.

Revisiting the automaticity framework, it may be possible the TBI group did not reduce postural sway in response to a visual cognitive task due to a loss of automaticity when there is a competition for attention. If the stabilizing response is indeed an automatic response, then as suggested by Laessoe et al. [131], when automaticity is lost, more conscious attention is required to control posture, therefore postural control may be more vulnerable to cognitive distraction. Likewise, Huffman et al. [298] found that with increased stress or challenge, there was a switch to more conscious control of balance. This effect has also been observed at a neural level. Rasmussen et al. [113] found that for multi-tasking trials, adults with TBI not only showed greater activation for the areas activated by either task alone, but they also recruited additional prefrontal structures, as compared to healthy adults, with no differences in performance between the groups. They suggested that this represented more effortful processing, which was similar to serial rather than parallel processing. Furthermore, it has been suggested that a loss of automaticity that is often seen in older adults and different neurological populations may lead to
more cautious postural control [133, 157, 299]. It may be the case, then, that the TBI participants in the current study were trying to maintain a more cautious postural stance by not reducing postural sway, which would require greater conscious control. Therefore, they may be prioritizing posture in that they are putting safety first, while healthy adults are prioritizing the cognitive task by stabilizing the visual plateau. However, the finding of no change in cognitive performance, regardless of prioritization, requires further investigation.

Another interesting difference between the TBI and HC groups was in orthogonal control of posture. During multi-task trials, the TBI group demonstrated similar reductions in A/P postural sway as the HC group, but not in M/L postural sway. In examining multi-tasking in healthy older adults, Kang et al. [98] reported similar findings: greater postural sway and less postural stabilization in the M/L plane only. A possible mechanism for the difference between A/P and M/L control, as discussed by Kang et al. [98], may be that bipedal standing (particularly wide stances) affords more stability in the M/L plane, but not in the A/P plane. Thus, in multi-task trials, the CNS could be using limited attentional resources to maintain A/P postural control, at the expense of M/L control. In the current study, the TBI group may have had less attentional resources available to control sway in the M/L plane, and therefore, was not able to reduce sway. Research also suggests that deterioration of postural control seen in ageing populations and those with neurological impairment may be more pronounced in the M/L plane [300, 301]. However, Nagy et al. [152] demonstrated that in healthy older adults, after a balance training program, M/L sway increased. They suggested that training resulted in improved M/L postural control, which lead to an ability to control a greater degree of freedom from the hip. The TBI group in the current study were all at least 4 months post-injury and were either still participating or had completed physical therapy, and therefore it is possible that while postural control was improved, it lead to increased M/L sway. However, the TBI group did not demonstrate greater M/L sway during single-task trials. Further research is needed to better understand orthogonal control of postural control and how it is affected after brain injury.
Finally, an important impetus for examining whether findings of multi-tasking-related changes in performance extended to an FEP task was because of the implications for community integration of the combination of postural control and FEP. If adults with TBI are indeed being more cautious with postural control and less able to engage automatic processes (i.e., consciously controlling posture), then it would be logical to think that this will impact any inter-personal activities competing for attention, as such activities that require several cognitive processes (e.g., memory, attention, speed of processing, emotion perception) and motor processes (e.g., maintaining balance, manipulating objects) to be performed in parallel [65-67]. This may be particularly true for persons with TBI that have more severe balance issues than those recruited in the current study; if residual problems present in well-recovered persons, then those with greater sequelae will be bound to have more overt problems with multi-tasking. Although, it seems residual issues persist regardless of recovery. It could be the case, then, that the increase in attention that is required to multi-task after brain injury could be a possible mechanism mediating difficulty with community integration. The increase in activation of the brain [113], as well as reports of higher subjective mental effort (as compared to healthy adults) when multi-tasking [107], has been suggested as an explanation for why TBI patients frequently complain of mental fatigue. However, further research is required to better understand the generalizability of these findings to community integration.

4.4.1 Limitations

Several limitations of our study should be acknowledged. The sample size was relatively small, and participants may not have been representative of the large, heterogeneous population of adults with moderate-severe TBI. The study should be repeated with larger samples and across a larger range of severities. Also, while posters for recruitment were placed across the Greater Toronto Area, proximity to the University of Toronto resulted in many HC group participants that were between 20 and 30 years of age, and therefore a HC group that was significantly younger than our TBI group. While the difference in age was approximately 15 years [TBI = 45 vs. HC = 30 years], the literature does not suggest differences in multi-tasking ability between these age groups [100]. We did, however, control for age in our analyses, and few significant
interactions between age and multi-tasking performance highlight this limitation in our study. Additionally, while we did not control for multiple comparisons conservatively (by reducing \( p \) values for significance) for each ANOVA, we did calculate effect sizes for each comparison to understand the magnitude of differences found, and applied a Bonferroni correction for all post-hoc analyses.

4.5 Conclusion

The ability to perform two or more tasks simultaneously is critical for many daily activities that we participate in at home, at work or school, and socially. The current study replicated previous findings of a postural stabilizing response with the addition of a visual cognitive task in healthy adults, and extended these findings to a task that was generalizable to real-world functions. Moreover, we demonstrated that adults with moderate-severe TBI do not engage in such a postural stabilizing response, without effect to cognitive tasks that can be performed relatively automatically. Future studies should examine whether these findings can be replicated in larger samples, and if performance changes when either motor or cognitive task difficulty is increased. Finally, relating this performance to community integration will be most relevant as this can provide guidance on how to tailor therapies and interventions to improve community integration and quality of life after TBI.
5 General Discussion

The behavioural consequences of moderate-severe TBI affect many aspects of life, and these effects can be long-lasting. Returning to an independent and meaningful life has many obstacles, and difficulty with community integration has been linked to depression, anxiety, and poorer quality of life [15, 16, 22, 24, 26, 31]. A fuller understanding of enduring behavioural impairments, particularly those that are essential to everyday functioning (e.g., multi-tasking, postural control and FEP impairments) and how these might impede community integration can aid researchers and clinicians to foster a more successful return to meaningful activities after brain injury.

5.1 Summary of findings and rehabilitation implications

5.1.1 Balance, community integration and multi-tasking

In manuscript one, we examined the impact that time post-injury has on the relationship between high-level balance and community integration after TBI. To do so, we correlated CB&M and CIQ scores at 5 and at 12 months after injury, while controlling for age and injury severity, in a sample of adults with moderate-severe TBI. We found a positive relationship between high-level balance and community integration early after injury; however, this relationship did not persist later after injury. We then examined what role multi-tasking might play in successful return to participation in daily activities by identifying which items on the CB&M measure multi-tasking ability (using an exploratory factor analysis). Here, we found that two factors emerged: one factor that was interpreted to measure multi-task performance and one that was interpreted to measure single-task performance. Lastly, we correlated multi-tasking scores to community integration scores to explore relationships at 5 and 12 months post-injury, as well as relationships between multi-tasking at 5 and 12 months and community integration at 12 and 24 months post-injury. The purpose of examining the latter set of relationships was to determine if early multi-tasking impairments were related to later challenges with community integration. We found a positive correlation between multi-tasking ability and community integration early after injury, as well as positive correlations between multi-tasking at 5 and 12 months, and level of community integration 2 years after injury.
The above study made several novel contributions. We examined balance and community integration differently than has been done previously by (1) assessing the relationship between high-level balance and community integration longitudinally; (2) controlling for the effects of age and injury severity; and (3) providing preliminary evidence that certain items on the CB&M may be evaluating different functions, such as single- and multi-task abilities, and multi-tasking ability early after injury was related to community integration in the later stages after TBI. These additions to research were important because it shed light on the discrepancies in the literature around the relationship between high-level balance and community integration after TBI by looking at how time after injury affects the relationship, as well as the mediating roles of age and injury severity. Moreover, the findings from this study suggest that certain aspects of high-level balance, such as multi-tasking ability, are related to level of community integration in the later stages of recovery.

Evidence suggests that high-level mobility can be successfully trained for people with acute TBI [302], therefore, early identification and rehabilitation may have the potential to improve community integration. Moreover, given findings of a relationship between multi-tasking ability early after injury and community integration in the later stages of recovery, it may also be beneficial to include interventions that target concurrent performance of two or more tasks. While interventions that have been developed to improve multi-tasking ability after brain-injury are promising, and provide preliminary evidence of improvement on trained tasks [303, 304], there is little evidence to support generalizability to untrained tasks. However, a recent study by Dux et al. [305] found that multi-tasking ability was improved (in healthy adults) when speed of processing was increased, whereby training induced a switch from slow, deliberative processing in brain networks to fast, automatic processing in task-specific neural circuits. Moreover, evidence suggests that automaticity after brain-injury can be regained [73, 75, 76]. Future studies, therefore could examine the impact of improving speed of processing, and thereby automaticity, after TBI on multi-tasking in everyday activities.
If we know that people who have multi-tasking impairment early after injury will likely experience difficulty with community integration in the later stages post-TBI, then resources should be tailored to not only try to ameliorate impairments, but also to manage residual impairments by providing adequate preparation for returning to their daily activities despite their multi-tasking deficits. Interventions designed to improve community integration [306, 307] and participation in everyday life [308] after TBI have shown promise, and may therefore be beneficial for those demonstrating multi-tasking impairment by providing strategies and access to resources that allow them to participate in their roles more fully. Management options, such as modifications to the environment that would help people to cope or integrate into the community in the context of multi-tasking impairments could be provided to patients and their family members to facilitate the transition home after TBI. These might include enablement of “single-tasking” at work through serial approaches to task completion. In social situations, patients could be encouraged to sit (to reduce balance/postural control demands) and encouraged to focus on one task at a time, such as eating/drinking versus talking.

5.1.2 A novel approach to measure facial emotion perception

In manuscript two, we introduced a new FEP task and we preliminarily tested the feasibility of the task by comparing performance of a small convenience sample of patients with mild to severe TBI to a group of healthy controls. The newly developed task was created to address a gap in the literature for an ecologically valid measure of FEP with task demands that more closely resemble everyday life. There were three adaptations of previous FEP tasks to make it more ecologically valid. First, consistent with a recent development in the literature on emotion perception [179, 190, 199, 259, 260], we provided contextual information to more closely simulate real-world processing of facial emotions. Here, the contextual information briefly described the scenario or event in which the emotion was being expressed. The second adaptation was to use dynamic stimuli, as recent studies have demonstrated dynamic emotions are recognized more accurately than static versions of the same expressions [199-205]. Lastly,
we tested FEP with an indirect task with the aim of providing sensitivity to implicit processing of emotional dynamic stimuli and less requirement for explicit processing. There is evidence that implicit processing is more relevant to much of the facial emotion processing we do [199, 261-263, 268], and moreover, implicit processing tends to be better preserved in brain injury than explicit processing in other cognitive modalities [264-266, 268]. Therefore, the task was designed to give a more accurate reflection of the actual FEP capacity of a person with TBI in their everyday life. Based on the criteria of Bowen et al. [214] for examining feasibility, the task was considered acceptable as all participants completed the task without any subjective reports of fatigue, and it required a short amount of time and few resources to implement. Under the umbrella of feasibility, we examined preliminary efficacy. Here, we observed that adults with TBI did not differ from healthy adults in accuracy, but did differ in speed. Surprisingly, the TBI group performed significantly faster than controls, and did not appear to allocate more time to the harder task (i.e., incongruent trials), as the healthy control group did.

These findings added to the existing literature by introducing a novel task that combines dynamic stimuli, contextual information, and implicit processing, which was determined to be feasible to use with adults that have sustained a moderate-severe TBI. While this novel approach to assessing FEP needs to be validated and examined further, it may provide greater insight into the difficulty that persons with moderate-severe TBI experience with FEP, and a new approach to examine how people might engage in everyday situations.

In order for the tool to be used clinically, further research is required to determine the reliability and validity of the FEP-dci task. Once the psychometric properties of the tool are established, such a tool will have important implications for rehabilitation. A more accurate characterization of the ability to read emotions in faces after TBI will better assist in developing interventions to rehabilitate specific processes that might underlie impairment than existing tools.
5.1.3 Concurrent performance of postural and cognitive tasks

Existing literature examining concurrent performance of postural control and cognitive tasks in adults with moderate-severe TBI is sparse, and has provided inconsistent results. Therefore, in manuscript three, we aimed to better characterize multi-tasking ability in adults with TBI by examining performance using a paradigm that has been widely examined in healthy adults: combining postural control tasks with cognitive tasks that require external focus and visual processing to elicit a postural stabilization response. We found that while the HC group demonstrated a stabilizing response with addition of the Stroop task, and maintained stability of the head, the TBI group did not show these responses. While postural sway did not increase significantly, the TBI group did not demonstrate reduced sway (as did controls). There was also no evidence of dual-task costs to the Stroop task.

Furthermore, previous research on motor-cognitive multi-tasking research has largely employed lab-based cognitive tasks that do not have clear generalizability to everyday life. To date, no studies have investigated multi-tasking with measures of social cognition, such as FEP, a capacity with important ramifications for everyday life and considered a highly automatic skill that we develop and hone as we age [177, 178]. Inter-personal communications in our personal and professional lives demand a combination of postural control and FEP (e.g., talking, maintaining balance, holding an object) to be performed in parallel [65-67]. Thus, we also examined whether any multi-tasking differences between brain-injured adults and healthy controls extended to concurrent performance of maintaining postural control while reading emotions in faces. Here, we found that multi-tasking performance observed with the Stroop task extended to the FEP task.

These findings added to the existing literature by demonstrating that behavioural deficits in multi-tasking extended to tasks that were designed to be similar to everyday interactions. While the TBI group did not demonstrate disproportionately worse performance on what may be considered two relatively automatic tasks, they did perform differently than healthy adults.
Furthermore, the preserved cognitive performance for the TBI group when multi-tasking, despite not stabilizing the visual plateau, needs to be further examined. Previous findings of improved cognitive performance when multi-tasking suggests that increased arousal may play a role [121-124]; however, we did not include any measures of arousal, and thus, we do not know if such was the case in the current study.

By understanding the mechanisms that underlie poor community integration, we can develop interventions or resources to facilitate the transition from hospital to home. If multi-tasking ability plays a role in community integration, as was demonstrated in manuscript one, it is critical to understand how multi-tasking ability is affected after TBI so that we can design interventions to target impairments. The findings from the current study provide impetus for more research to better understand how multi-tasking ability relates to rehabilitation and community integration.

While previous work suggests that the effects of a cognitive task on postural control (i.e., reduced vs. increased sway) depends on whether the task requires visual stabilization (e.g., for reading) or not (e.g., mental math) [101-106], the findings from the current study suggest that further work is needed to understand if the type of cognitive task is relevant for generalizability to everyday activities. We found similar results between the TBI and HC groups when they were multi-tasking with the Stroop and FEP tasks. One interpretation is that difficulty with multi-tasking may be related to loss of automaticity, and therefore increased attentional load, rather than the type of activity in which they are engaged, which is consistent with the automaticity framework of multi-tasking. However, the implication for rehabilitation is that multi-tasking that is necessary for everyday interactions, and not only for tasks that have low generalization to daily activities, is affected after TBI. Studies have demonstrated that basal ganglia-frontal cortex-basal ganglia feedback loops play a critical role in regulating movement automaticity [87], and Rasmussen et al. [113] suggested that DTC might reflect a problem with sub-cortical connections due to diffuse axonal injury. Thus, if multi-tasking impairments arise from an inability to access
or engage automatic pathways, then we should see some form of disruption regardless of the tasks that are combined. Whether disruptions mean direct effects on behaviour (e.g., increased sway, increased reaction time, or decreased accuracy) or indirect effects (e.g., increased perceived effort or fatigue) needs to be investigated further.

One direct effect to behaviour that was observed during multi-task trials was the difference in A/P and M/L postural control. The TBI group demonstrated similar stabilization in A/P postural control as the HC group, but not in M/L postural control. Research suggests that deterioration of postural control seen in ageing populations and those with neurological impairment may be more pronounced in the M/L plane and has been associated with a high risk of falling [300, 301]. In upright bi-pedal postural control, motor responses in the M/L plane are believed to be dominated by a hip load/unload strategy (i.e., use of hip abductor/adductor muscles to control side-to-side motion), and because this strategy is orthogonal to A/P control (i.e., achieved by dorsi-flexion/plantar-flexion in the ankle to control front-to-back motion), it is seen to be completely independent of an ankle-control strategy [309]. There is also evidence to suggest that the CNS might use different strategies to control A/P versus M/L components of postural control. Slobounov et al.[310] found that there was more activation in frontal areas of the brain when participants swayed in the M/L plane, and EEG activation patterns suggested greater energetic demands and/or “neural working load” to preserve postural control in the M/L plane. As suggested by Kang et al. [98], bi-pedal standing affords more stability in M/L plane, and therefore, in multi-task trials, the CNS could be using limited attentional resources to maintain A/P postural control, at the expense of M/L control. However, Nagy et al. [152] demonstrated that in healthy older adults, after a balance training program, M/L sway increased. They suggested that training resulted in improved M/L postural control, which lead to an ability to control a greater degree of freedom from the hip. The subjects of the TBI group in the current study were all at least 4 months post-injury and were either still participating in, or had completed, physical therapy and therefore it is possible that this lead to increased postural sway. However, the TBI group did not demonstrate greater M/L sway during single-task trials. Further
research is needed to better understand orthogonal control of postural control and how it is affected after brain injury.

However, changes in postural control when multi-tasking could be interpreted as a compensatory or adaptive strategy after TBI. It has been suggested that a loss of automaticity that is often seen in older adults and different neurological populations may lead to more cautious postural control [133, 157, 299]. It may be the case then that the TBI participants in the current study were trying to maintain a more cautious postural stance by not stabilizing posture, which might allow them to better react to any physical perturbations in the environment. Therefore, they may have been prioritizing posture in that they were putting safety first, while healthy adults were prioritizing the cognitive task by stabilizing the visual plateau. As suggested by Mitra et al. [103], it is not clear whether a decrease in sway when visual information is presented during unperturbed stance reflects greater stability. While Winter et al. [141] suggested that a stiffness mechanism could be important in response to unexpected external perturbations, Nagy et al. [152] suggested that an increase in postural sway does not always mean a deterioration of the control mechanisms and that increased sway is not a good predictor of postural instability since many unstable patients (e.g., patients with Parkinson’s disease) show less sway than normal. In Mulder et al.’s [291] review of motor recovery, they discuss how the sensorimotor system can generate relatively unimpaired motor output despite the fact that the system may be damaged and postulate that it is due to strategic shifts in available modes of control, leading to compensatory motor patterns. However, whether these compensatory changes are maladaptive remains to be investigated.

5.2 Limitations

Sample size and selection bias: The sample sizes in each manuscript were relatively small, and participants may not have been representative of the large, heterogeneous population of adults with moderate-severe TBI. With respect to sample bias, it may be possible that those who participated in the studies, particularly the FEP-dci and multi-tasking studies, were high-
functioning adults interested in partaking in research. Participants in the TBI group were also highly educated and had IQ scores that were slightly above average; previous work has demonstrated better pre-morbid intelligence and level of education have been shown to affect patterns of recovery [311], therefore, our sample may have been higher functioning than a typical sample of adults with moderate-severe TBI, and thus performed more similarly to the HC group. An alternative interpretation of the current findings in manuscript two is that the intact FEP performance, as compared to controls, was attributable to the high level of functioning of the group and not to preserved implicit processing, for example. How the findings from this dissertation apply to those who are less educated, have lower IQs and/or possibly have more severe injuries or cognitive impairment remains to be investigated.

Age effects: The possible effect of age was controlled for in manuscripts one and three, but non-parametric analyses and small sample size did not permit this in manuscript two. Previous work examining the effects of age on FEP has shown that performance differences are observed only between very wide age disparities (i.e., 20 – 30 vs. 60 – 70 years of age) [272]. Moreover, age effects are less pronounced on indirect than direct tests in general [273]. Therefore, the relatively small age difference (of 8 years) was not likely contributing to outcome variance, based on previous research. It is possible, however, that the difference in age between our groups may have accounted for some of the variance in reaction time and error rates on the FEP-dci task and thus results from manuscript two should be interpreted with caution until findings can be replicated using large sample sizes.

Experimental design: In manuscript one, the retrospective design may have introduced bias as many patients from the larger research study from which these participants were drawn had not completed the CIQ or the CB&M at all time-points, and reasons for missing data or use of alternative assessments were not available in all cases. Therefore, this may have led to the selection of a sample that was not representative of all TBI patients (e.g., those with greater high-level balance impairment due to orthopaedic injury, participants that may have suffered from
communication impairments). For our correlation between the CB&M factors at 5 and 12 months with the CIQ at 24 months, there were fewer participants, and therefore, the finding of a significant relationship should be interpreted with caution. It is possible that those who did not return for long term follow-up may have returned to work or school, which would have resulted in an inflated relationship between the CB&M and the CIQ Productivity sub-scale.

While we did control for multiple comparisons in manuscript one and three, we did not control for multiple comparisons conservatively in manuscript three. Due to small sample size and the conservative approach of the Bonferroni adjustment, we did not apply a correction for each ANOVA that was run, as this would have likely increased the chance of type II errors. We did, however, calculate effect sizes for each comparison to understand the magnitude of differences found, and applied a Bonferroni correction for all post-hoc analyses. In order to be confident that the findings from each study are not spurious, it would be necessary to replicate findings in large samples, using a lower alpha to adjust for multiple comparisons.

Outcome variables: The FEP-dci task that was developed for this study was intended to introduce a novel approach to assessing FEP, and thus there are limitations to using a task for which psychometric properties have not been established for either the healthy or TBI population. In manuscript two, the lack of statistically significant differences that we found in accuracy on the FEP-dci task may be the reflection of a ceiling effect, as accuracy levels were relatively high in both the TBI and HC groups. Thus, an alternative interpretation is that TBI patients are impaired at implicit FEP, but that we were not able to detect this impairment with the current protocol.
5.3 Future directions

5.3.1 Balance, community integration and multi-tasking

Future examinations of the relationship between the high-level balance and community integration for the TBI population could be extended in several ways. Using a prospective research design, larger sample sizes and assessment of other variables (e.g., cognitive function), future studies can examine if other factors also impact the relationship between the CB&M and the CIQ. This includes an examination of the role executive dysfunction, a common sequelae of TBI, might play in the relationship between the CB&M and the CIQ, as previous research has demonstrated that older adults with poorer executive functioning are more prone to falls [91, 166]. A future study of high-level balance after moderate-severe TBI could entail administration of the CB&M to a large sample of patients to permit a confirmatory factor analysis of the two factors that emerged from our analyses (i.e., single- vs. multi-task items). Another question to address is whether the CB&M correlates with other measures of community integration after TBI. While Williams et al. [224] found a relationship between the High-level Mobility Assessment Tool (HiMAT) and the CIQ, they demonstrated a stronger relationship between the HiMAT and the Brain Injury Community Rehabilitation Outcome scale (BIRCO-39 [312]). Therefore, a future study could similarly look at the relationship between the CB&M and the BICRO-39, or other more subjective measures of community integration.

5.3.2 A novel approach to measure facial emotion perception

In developing and examining the feasibility of the FEP task, we were not able to ascertain what role implicit task demands or task difficulty played. A useful follow-up study would be to use the same paradigm, but with several modifications. These include explicit labelling of emotions in order to compare speed and accuracy to the implicit task, as well as increasing the difficulty of the task by using stimuli that are more ambiguous, as Zupan et al. [279] demonstrated that low intensity emotions are harder for TBI patients to perceive correctly. This would allow us to more precisely elucidate a specific source of impairment after TBI. Previous research has suggested that configural processing of facial emotions can be equated with automatic processing, while
featural processing can be equated with more controlled or conscious processing [177]; an additional modification would be to examine if there are differences in strategy-use by examining eye-tracking when performing conventional tasks vs. FEP-dci task. Differences could provide evidence that either task relies more on explicit vs. implicit processing. Additionally, a direct comparison of the FEP task performance using implicit and explicit approaches with a larger sample size, particularly with a sample that includes patients with known difficulty recognizing emotions on conventional FEP measures, would be an informative next step.

5.3.3 Concurrent performance of postural and cognitive tasks

To address research questions that emerged from the multi-tasking study, several different approaches can be taken. Firstly, the results from the current study would need to be replicated using larger, well-matched groups to address issues related to age effects, sample bias and variability. A follow-up study that would address the effects of different types of cognitive task that are performed in parallel with a postural control task could compare how adults with TBI perform on cognitive tasks that involve visual processing (i.e., the Stroop task) to those that do not (i.e., serial subtractions, n-back), as such ‘non-visual’ supra-postural tasks have been found to increase postural sway in other populations [98, 106, 125, 126, 150]. Furthermore, multi-tasking performance could be related to diffuse axonal injury after TBI to examine the role that disruption to networks (particularly cortical-sub-cortical connections) after TBI plays in automaticity. Additionally, participants could rate levels of fatigue and mental effort, to better understand the implications for everyday functioning. To examine what role M/L postural control plays after brain injury, a follow-up study could examine multi-tasking ability when perturbations are administered, and compare A/P and M/L postural control. In order to examine if changes to M/L control could be due to physical therapy and possible strategic shifts in control, we could also measure M/L control using a multi-tasking paradigm before and after a physical therapy program. Whether these changes in postural control are compensatory and adaptive after TBI requires further examination: a longitudinal study using a multi-tasking paradigm could examine if automaticity is regained after TBI and if any factors facilitate this. Finally, findings could be extended to a more ecologically valid motor task, such as walking. An
ideal future study could utilize virtual reality, as is available at the Toronto Rehab Institute iDapt research centre, which would allow us to test participants while walking in front of a simulated social environment with visual or auditory distractors.
6 Conclusion

Early identification of individuals who have difficulty with balance and mobility after TBI is important given the finding of a relationship between high-level balance and community integration, particularly social and home integration, at 5 months post-injury. Furthermore, early identification is particularly important because brain-injured adults with higher levels of participation in everyday occupations report a higher perception of quality of life [9, 16, 24, 26, 27]. In the later stages of recovery, high-level balance may be less related to community integration due to recovery or compensation for impairments. However, given the evidence of a relationship between multi-tasking ability early after injury and community integration in the later stages of recovery, early identification of multi-tasking impairment after TBI may have the potential to improve later community integration. This is particularly important given previous findings of an association between poor community integration and depression, isolation, and decreased quality of life after TBI [15, 16, 22, 24, 26, 31].

In order to design interventions to address multi-tasking impairment, more research is needed to better understand the mechanisms that underlie such impairment. We demonstrated that after TBI, multi-tasking with postural control and cognitive tasks may be affected by an inability to engage automatic processes, which would mean greater conscious control and attentional resources required, and likely greater effort, to complete relatively automatic tasks. Furthermore, we demonstrated that this extended to a multi-tasking paradigm that had remained largely unexplored: concurrent performance of a postural task and an FEP task, relevant for many interpersonal interactions in the community, and clinically relevant for adults with TBI, as poor social communication abilities after TBI [42], and in particular poor FEP [31], have been related to reduced social integration. However, more research is needed to better understand the mechanisms that underlie difficulty with parallel processing or loss of automaticity, and to understand the implications for rehabilitation and community integration after TBI.
References


Appendices

Appendix 1. The Community Balance and Mobility scale [47]

Full CB&M guidelines must be reviewed to ensure accurate administration and scoring. To score 5, actions must appear coordinated and controlled without excessive equilibrium reactions.

<table>
<thead>
<tr>
<th>CB&amp;M Tasks</th>
<th>Notes</th>
<th>Initial</th>
<th>Mid</th>
<th>D/C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. UNILATERAL STANCE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>unable to sustain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.00 to 4.49 sec.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4.50 to 9.99 sec.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10.00 to 19.99 sec.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>≥ 20.00 secs.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>45.00 sec., steady and coordinated</td>
<td></td>
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</tbody>
</table>

“Look straight ahead”
Test is over if stance foot moves from start position or raised foot touches ground.

| **2. TANDEM WALKING** | | | | |
| 0 | unable | | | |
| 1 | 1 step | | | |
| 2 | 2 to 3 consecutive steps | heel-toe distance < 3” (for levels 2 & 3 only) | | |
| 3 | ≥ 3 consecutive steps | in good alignment = heel-toe contact and feet straight (for levels 4 & 3 only) | | |
| 4 | ≥ 3 consecutive steps | | | |
| 5 | 7 consecutive steps | | | |

“Look ahead down the track, not at your feet.”

| **3. 180° TANDEM PIVOT** | | | | |
| 0 | unable to sustain tandem stance | | | |
| 1 | sustains tandem stance but unable to unweight heels or initiate pivot | | | |
| 2 | initiates pivot but unable to complete 180° turn | | | |
| 3 | completes 180° turn but discontinuous pivot (e.g., pauses on toes) | | | |
| 4 | completes 180° turn in a continuous motion but cannot sustain reversed position | | | |
| 5 | completes 180° turn in a continuous motion and sustains reversed position | | | |

Test is over if touches heels down or steps out of position.

| **4. LATERAL FOOT SCOOTING** | | | | |
| 0 | unable | | | |
| 1 | 1 lateral pivot | | | |
| 2 | 2 lateral pivots | | | |
| 3 | ≥ 3 pivots but < 40 cm | | | |
| 4 | 40 cm in any fashion and/or unable to control final position | | | |
| 5 | 40 cm continuous, rhythmic motion with controlled step | | | |

Test is over if patient hops or opposite foot touches down.

| **5. HOPPING FORWARD** | | | | |
| 0 | unable | | | |
| 1 | 1 to 2 hops, uncontrolled | | | |
| 2 | 2 hops, controlled but unable to complete 1 metre | | | |
| 3 | 1 metre in 2 hops but unable to sustain landing (touches down) | | | |
| 4 | 1 metre in 2 hops but difficulty controlling landing (hops or pivots) | | | |
| 5 | 1 metre in 2 hops, coordinated with stable landing | | | |

Test is over if opposite foot touches down.

| **6. CROUCH AND WALK** | | | | |
| 0 | unable to crouch | | | |
| 1 | able to descend only | | | |
| 2 | descends and rises but hesitates, unable to maintain forward momentum | | | |
| 3 | crouches and walks in continuous motion, time ≤ 8.00 sec., protective step | | | |
| 4 | crouches and walks in continuous motion, time ≤ 8.00 sec., excess equilibrium reaction | | | |
| 5 | crouches and walks in continuous motion, time ≤ 4.00 sec. | | | |
|---------------------|----------------------|-------------------------------|-----------------------------|----------------------|---------------------|---------------------|
| 0                   | 0                    | 0                            | 0                           | 0                    | 0                   | 0                   |
| unable to perform 1 cross-over in both directions without support | unable to walk and look e.g. steps | unable to run | unable | unable | unable to step down | unable to step up, requires assistance or railing |
| 1 cross-over in both directions in any fashion | performs but loses visual fixation at or before 4 metre mark | runs, time > 5.00 sec | performs | performs | 1 step | requires assistance or railing to descend |
| 1 or more cycles, but does not contact line every step | performs but loses visual fixation after 4 metre mark | runs, time > 3.00 but ≤ 5.00 sec, unable to control stop | with reciprocal pattern | performs in ≤ 11.00 sec, performs | 3 steps | completes 5 cycles |
| 2 cycles, contacts line every step | performs and maintains visual fixation between 2-6 metre mark but protective step | runs, time > 1.00 but ≤ 3.00 sec, runs contacting stop | performs in ≥ 8.00 sec, and/or veers during backward walking | performs in ≤ 7.00 sec, maintains straight path | reciprocal or full tight in step-to-pattern | completes 5 cycles |
| 4 cycles, contacts line every step 11.00 to 15.00 sec. | performs and maintains visual fixation between 2-6 metre mark but protective step | runs, time ≤ 3.00 sec, unable to control stop | performs in ≥ 8.00 sec, and/or veers during backward walking | performs in ≤ 7.00 sec, maintains straight path | 3 steps | completes 5 cycles in > 6.00 but ≤ 10.00 sec |
| 2 cycles, contacts line every step ≤ 12.00 sec. coordinated direction change | performs, straight path, steady and coordinated ≤ 7.00 sec. | runs, time ≤ 3.00 sec, with controlled stop, both feet on line, coordinated and rhythmic | performs in ≤ 7.00 sec, maintains straight path | performs in ≤ 7.00 sec, maintains straight path | reciprocal or full tight in step-to-pattern | completes 5 cycles |
| “Do this as fast as you can yet at a speed that you feel safe.” | “Walk at your usual pace.” | “Run as fast as you can.” Hold position on finish line. | “Walk as quickly as you can yet at a speed that you feel safe.” | “Walk at your usual pace.” | “Do this as quickly as you can. Try not to look at your feet.” | “Do this as quickly as you can. Try not to look at your feet.” |

<table>
<thead>
<tr>
<th>Signature(s)</th>
<th>Date(s)</th>
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<tbody>
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</table>
Appendix 2. The Community Integration Questionnaire [223]

## COMMUNITY INTEGRATION QUESTIONNAIRE

<table>
<thead>
<tr>
<th>Subject:</th>
<th>Date:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Who usually does the shopping for groceries or other necessities in your household?</td>
<td>☐ Yourself alone  ☐ Yourself and someone else  ☐ Someone else</td>
</tr>
<tr>
<td>2. Who usually prepares meals in your household?</td>
<td>☐ Yourself alone  ☐ Yourself and someone else  ☐ Someone else</td>
</tr>
<tr>
<td>3. In your home who usually does the everyday housework?</td>
<td>☐ Yourself alone  ☐ Yourself and someone else  ☐ Someone else</td>
</tr>
<tr>
<td>4. Who usually cares for the children in your home?</td>
<td>☐ Yourself alone  ☐ Yourself and someone else  ☐ Someone else  ☐ Not applicable  ☐ No children under 17 in the home</td>
</tr>
<tr>
<td>5. Who usually plans social arrangements such as get-togethers with family and friends?</td>
<td>☐ Yourself alone  ☐ Yourself and someone else  ☐ Someone else</td>
</tr>
<tr>
<td>6. Who usually looks after your personal finances, such as banking or paying bills?</td>
<td>☐ Yourself alone  ☐ Yourself and someone else  ☐ Someone else</td>
</tr>
<tr>
<td>7. Approximately how many times a month do you usually participate in shopping outside your home?</td>
<td>☐ Never  ☐ 1 - 4 times  ☐ 5 or more</td>
</tr>
<tr>
<td>8. Approximately how many times a month do you usually participate in leisure activities such as movies, sports, restaurants, etc.</td>
<td>☐ Never  ☐ 1 - 4 times  ☐ 5 or more</td>
</tr>
<tr>
<td>9. Approximately how many times a month do you usually visit your friends or relatives?</td>
<td>☐ Never  ☐ 1 - 4 times  ☐ 5 or more</td>
</tr>
<tr>
<td>10. When you participate in leisure activities do you usually do this alone or with others?</td>
<td>☐ Mostly alone  ☐ Mostly with friends who have head injuries  ☐ Mostly with family members  ☐ Mostly with friends who do not have head injuries  ☐ With a combination of family and friends</td>
</tr>
</tbody>
</table>

Please complete page two
# Community Integration Questionnaire

11. Do you have a best friend with whom you confide?  
   - Yes  
   - No

12. How often do you travel outside the home?  
   - Almost every day  
   - Almost every week  
   - Sometimes/never  
   (less than once per week)

13. Please choose the answer that best corresponds to your current (during the past month) work situation:  
   - Full-time  
   (more than 20 hours/week)  
   - Part-time  
   (less than or equal to 20 hrs/week)  
   - Not working, but actively looking for work  
   - Not working, not looking for work  
   - Not applicable, retired due to age

14. Please choose the answer that best corresponds to your current (during the past month) school or training program situation:  
   - Full-time  
   - Part-time  
   - Not attending school, or training program  
   - Not applicable, retired due to age

15. In the past month, how often did you engage in volunteer activities?  
   - Never  
   - 1 - 4 times  
   - 5 or more

Comments:
Appendix 3. Recruitment posters for multi-tasking study

Are you interested in participating in a study of how people multi-task?

The Cognitive Neurorehabilitation Sciences Lab at the Toronto Rehabilitation Institute is conducting research on how people multi-task to help us better understand the effects of brain injury. The study is being supervised by Research Scientist, and Neuropsychologist, Dr. Robin Green. Participation will take a total of 1-1.5 hours and participation is voluntary.

To participate you must:

Be between 18 and 50 years old
Have no current or previous balance, neurological or systemic conditions, history of psychosis, substance abuse, or diagnosed development/congenital disorder
Have no current or previous diagnosis of clinical depression
Speak English fluently

If you are interested in participating, please contact:

Diana Frasca
Toronto Rehabilitation Institute
550 University Ave., Suite 11005
(416) 597-3422 ext. 7850
Frasca.diane@torontorehab.on.ca
Appendix 4. Consent form for multi-tasking study

Can difficulty with community integration be explained by multi-tasking impairments? An investigation of multi-tasking in traumatic brain injury

Principal Investigators: Dr. Robin Green, Toronto Rehab Institute, University of Toronto

Collaborative investigators: Dr. Brad McFadyen, University of Laval

Dr. Bill McIlroy, Toronto Rehab Institute, University of Toronto

Diana Frasca, University of Toronto, Toronto Rehab Institute

Introduction

You are being invited to participate in a study in the Cognitive Neuroscience Sciences lab at Toronto Rehab Institute. We want to look at “multi-tasking” - that is, doing two or more things at once - in people with traumatic brain injury. This consent form will give you a basic idea of what the research is about and what participation will involve. If you would like more information, please feel free to ask.

Study Procedures

If you agree to participate, we will ask you to do some paper and pencil tasks. We will also ask you to do some simple tasks on the computer. For these tasks you will need to read some words, look at pictures and answer some questions about your daily activities.

We will ask you to complete these tasks while seated and some while standing and keeping your balance. You will need to come to the Toronto Rehab Institute once for about 1 to 1.5 hours.

If you have participated in other studies with Dr. Green, we can use information collected in the present study so we do not have to ask some things twice. Only Dr. Green and Diana Frasca will have access to this information. If this applies to you, please check below.

- Yes  No  Demographic information (e.g. age, gender, years of education)
- Yes  No  Medical information from your chart (e.g. nature of injury, MRI findings)
- Yes  No  Neuropsychological test scores

Risks and discomforts
You may feel slightly tired after standing for about 20 minutes. You will have time to rest if you need to. In addition, you may find it hard to perform two tasks at the same time, which might make you feel frustrated.

Benefits

There will be no direct benefits to you by participating in this study. You may feel gratified that you are contributing to research and potentially helping other people with traumatic brain injury.

Confidentiality

We will keep information collected in a locked office at the Toronto Rehab Institute. Only researchers involved in the study will have access to the data. We will also remove any information that identifies you (e.g., your name or age) before results are published.

Participation

Participating in this study is voluntary. You are free to choose not to participate. You are also free to withdraw from the study at any time without consequence. Participating in this study will in no way affect your current or future care at Toronto Rehab.

Your Rights

Please call Diana Frasca or Dr. Robin Green if you have questions about the study. Please call the Research Ethics Board if you have questions about your rights as a participant. You will receive a copy of this consent form.

Diana Frasca (416) 597-3422 x 7850
Dr. Robin Green at (416) 597-3422 x 7871
Research Ethics Board (416) 597-3422 x 3081

I have had the chance to discuss this study and I am satisfied with the answers to my questions. I voluntarily consent to participate in this study.

Participant name: ____________________________________________
Signature: ____________________________________________ Date: _______

Legal decision maker name (if applicable): ____________________________
Signature: ____________________________ Date: _______

Person who obtained consent/assent: ____________________________
Signature: ____________________________ Date: _______
Appendix 5. REB approval from the Toronto Rehabilitation Institute.

June 9, 2011

Dr. Rebin Green
Toronto Rehabilitation Institute
University Centre
550 University Avenue
Toronto, Ontario
M5G 2A2

Dear Dr. Green:

RE: TRI REB #: 11-019
Can community integration deficits be explained by multi-tasking impairments?
An investigation of multi-tasking in traumatic brain injury (TBI)

The Toronto Rehabilitation Institute Research Ethics Board has reviewed the above-named submission. Any concerns and requested revisions have been addressed to the satisfaction of the REB. The protocol dated June 8, 2011 is approved for use for the next 12 months. If the study is expected to continue beyond the expiry date, you are responsible for ensuring the study receives re-approval. The REB must also be notified of the completion or termination of this study and a final report provided.

Also approved are the following documents:
- Appendix A - Recruitment Ad dated June 8, 2011
- Appendix B - Information Letter dated June 8, 2011
- Appendix C - Demographic Information Sheet dated June 8, 2011
- Appendix D - Consent Form dated June 8, 2011
- Appendix E - STOIC Emotional Faces dated June 8, 2011
- Appendix F - Berg Balance Scale dated June 8, 2011

If, during the course of the research, there are any serious adverse events, changes in the approved protocol or consent form or any new information that must be considered with respect to the study, these should be brought to the immediate attention of the Board.

TRI REB conforms with the Tri-Council Policy Statement (TCPS2): Ethical Conduct for Research Involving Humans and Ontario Privacy Legislation PHIPA

Toronto Rehab is a teaching and research hospital fully affiliated with the University of Toronto.
Best wishes for the successful completion of your project.

Yours sincerely,

[Signature]

[ ] Paul Oh MD, MSc, FRCPC, FACP
Chair, Research Ethics Board
Toronto Rehabilitation Institute

[ ] Ann Heesters BEd, BA, MA, PhD (ABD)
Vice Chair, Research Ethics Board
Toronto Rehabilitation Institute

June 9, 2011
Date of Initial REB Approval

June 9, 2012
Expiry Date of REB Approval

TRI REB conforms with the Tri-Council Policy Statement (TCPS2): Ethical Conduct for Research Involving Humans and Ontario Privacy Legislation PIHPA
Appendix 6. Demographic Questionnaire for multi-tasking study

DEMOGRAPHIC INFORMATION SHEET

Subject ID: ___________ Initials: ___________

Year of Birth: ___________________

Age: ________

Gender: ☐ M ☐ F

Handedness: ☐ R ☐ L ☐ Both

Education:
☐ Less than high school
☐ High school
☐ Technical or trade school
☐ College diploma
☐ University degree
☐ Post-graduate degree

Number of Years of Education: ______

Degree Obtained:
☐ Canada & U.S.
☐ Outside Canada or U.S.

Current (or previous) Occupation: __________________________________________________

First Language:
☐ English
☐ Other __________________________

If other, please specify number of years English spoken for: ___________________

Living Status:
☐ Single
☐ Married
☐ Common-law/living with someone
☐ Divorced
☐ Widowed
General Health Questionnaire:

1. Have you ever had an acquired brain injury, e.g., a traumatic brain injury or concussion, a stroke or encephalitis?
   □ N    □ Y
   If yes, please provide details (when, how long unconscious, circumstance)

2. Do you have any diagnoses of a medical disease/disorder, in particular neurological (e.g., Parkinson’s Disease or Multiple Sclerosis) or systemic (e.g., Diabetes, Lupus).

3. Have you received a diagnosis of a psychological disorder such as depression, anxiety or schizophrenia?
   □ N    □ Y
   If yes, are you currently taking medication for this? □ N    □ Y
   If yes, which ones and for how long? ___________________________________________________________________

4. Are you currently taking any medications? □ N    □ Y
   If yes, please indicate which ones and for how long? ___________________________________________________________________