Are individuals with chronic moderate-to-severe traumatic brain injury able to safely walk in the community? Exploring the challenges of dual-task walking while avoiding virtual pedestrians

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STATEMENT OF AUTHORSHIP

I, Thiago de Aquino Costa Sousa, certify that I am the primary author of this thesis. I claim full responsibility for the content and style of the text included herein.

STATEMENT OF ORIGINALITY

This thesis contains no material that has been published elsewhere, except where specific references are made. The study presented in Chapter 3 is original material and represents contributions to knowledge in the fields of chronic (> 6 months post- injury) moderate-to-severe traumatic brain injury (m/sTBI), obstacle circumvention, locomotor-cognitive interference, gaze behaviour, virtual reality, and rehabilitation. Currently, most studies investigating obstacle avoidance strategies adopted by individuals with m/sTBI have focused on stepping over obstacles rather than circumventing them, either in single- or dual-task conditions. To our knowledge, no study has yet investigated gaze behaviour as a marker of attention allocation during pedestrian interactions among individuals with m/sTBI. Thus, this study used a virtual reality paradigm to fill this gap in the literature, comparing the locomotor and cognitive costs associated with the concurrent performance of a circumvention task involving virtual pedestrians (VRPs) and an auditory-based cognitive task between individuals with m/sTBI and healthy individuals. We also characterized the gaze behaviour associated with the circumvention of pedestrians performed under single and dual-task conditions in both groups. The results of this study will provide clinicians with valuable information on persistent locomotor, cognitive, and attentional deficits after the rehabilitation of individuals with chronic m/sTBI, aiming for their safe community ambulation. The data presented in this thesis were collected and analyzed at the Feil & Oberfeld Research Centre of the CISSS-Laval at the Jewish Rehabilitation Hospital site of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR), affiliated with McGill University. The study presented in this thesis was approved by the Research Ethics Board in réadaptation et en déficience physique of the CIUSSS du Centre-Sud-de-l'Île-de-Montréal.

DEDICATION

First of all, I dedicate this thesis to God. I believe with all my heart that the opportunity to pursue a master's degree at the best university in Canada would never have happened without His intercession. Feeling His inexplicable presence in moments of fear and uncertainty, when it was just Him, me, and the guitar, comforted me, renewed my faith, and assured me that victory was on the way. Thank you, God!

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CONTRIBUTION OF AUTHORS

This thesis is presented in a manuscript format and includes one research manuscript which will be submitted to a peer-reviewed journal. I, Thiago de Aquino Costa Sousa, am the main contributor and lead author of all chapters and manuscript included in this thesis. My contribution extends to the research design, experimental set up, data collection, data analysis, statistical analysis, interpretation of findings, preparations of figures/tables, writing of this thesis and revisions.

The research study and manuscript presented here were developed under Dr. Anouk Lamontagne and Dr. Bradford James McFadyen's supervision. Dr. Lamontagne and Dr. McFadyen oriented the selection of the research design, experimental set up, data analysis, statistical analysis, interpretation of findings and critically reviewed and provided constructive feedback on the manuscript and this thesis. Dr. Karen Li and Dr. Isabelle Gagnon provided feedback on the protocol, contributed to the interpretation of findings and reviewed the manuscript prior to its submission to the journal.

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LIST OF ABBREVIATIONS

10MWT	10m Walk Test
ABC	Activities-Specific Balance Confidence Scale
AP	Antero-Posterior
CB&M	Community Balance and Mobility Scale
CDT	Coût De La Double Tâche
CoM	Center of Mass
CTL	Healthy Controls or/ou *Individus Contrôles*
DT	Dual Task
DTC	Dual-Task Cost
ETDRS	Early Treatment of Diabetic Retinopathy Study
GCS	Glasgow Coma Scale
GEE	Generalized Estimating Equations
HMD	Head-Mounted Display
LSD	Least Significant Difference
m/sTBI	Moderate-To-Severe Traumatic Brain Injury

ML	Medio-Lateral
MoCA	Montreal Cognitive Assessment
MPD	Minimum Predicted Distance
PTA	Post-Traumatic Amnesia
PV	Piétons Virtuels
SD	Standard Deviation
ST	Single Task
TBI	Traumatic Brain Injury
TCCm/g	Traumatisme Crânio-Cérébral Modéré à Grave
TMT	Trail Making Test
TPC	Theoretical Point of Collision
TUG-Cog	Timed Up and Go Cognitive
VE	Virtual Environment
VR	Virtual Reality
VRP	Virtual Pedestrian

ABSTRACT

Background: Individuals with moderate-to-severe traumatic brain injury (m/sTBI), despite good locomotor recovery greater than six months post-injury, face challenges in adapting locomotion to contextual demands. They also present with altered cognitive functions, which may impact dual-task walking abilities. Whether they present collision avoidance strategies with moving pedestrians that are altered under dual-task conditions, however, remains unclear. This study aimed to: (1) compare, between individuals with m/sTBI and age-matched healthy individuals, the locomotor and cognitive costs associated with the concurrent performance of a circumvention task involving virtual pedestrians (VRPs) and an auditory-based cognitive task and; (2) characterize the gaze behaviour associated with the circumvention task performed under single vs. dual-talk condition. **Methodology:** Twelve individuals with m/sTBI (age=43.3±9.5 yrs) and 12 healthy controls (CTLs) (age=41.8±8.3 yrs) were assessed while walking in a virtual subway station viewed in a head-mounted display. They performed a collision avoidance task with VRPs, as well as auditory-based cognitive tasks (pitch discrimination and auditory Stroop), both under single and dual-task conditions. Measures and dual-task cost (DTCs) for onset distance of trajectory deviation, minimum distance from the VRP, maximum lateral deviation, walking speed, gaze fixations and cognitive task accuracy were contrasted between groups using generalized estimating equations. **Results:** In contrast to the strategy adopted by CTLs who showed locomotor DTCs only, individuals with m/sTBI showed DTCs for both the locomotor and the cognitive tasks. While both groups walked slower under dual-task conditions, individuals with m/sTBI, unlike CTLs, failed to modify their onset distance of trajectory deviation and maintained smaller minimum distances and smaller maximum lateral deviation compared to single-task walking. Both groups further showed shorter gaze fixations on the approaching VRP under dual-task conditions, but this reduction was

less pronounced in the individuals with m/sTBI. A reduction in cognitive task accuracy under dual-task conditions was found in the m/sTBI group only. **Conclusion:** Individuals with m/sTBI present altered locomotor, gaze behaviour and cognitive performances when executing a collision avoidance task involving moving pedestrians, especially under dual-task conditions. Potential mechanisms explaining those alterations are discussed. Present findings raise concerns about potential collisions in crowded community environments in individuals with m/sTBI, while highlighting the compromised complex walking abilities in this population who otherwise present a good locomotor recovery.

Keywords – circumvention, cognition, gaze behaviour, locomotion, Moderate-to-severe TBI, multitasking, obstacle avoidance, virtual reality.

ABRÉGÉ

Contexte : Les personnes ayant subi un traumatisme crânio-cérébral modéré à grave (TCCm/g), malgré une bonne récupération locomotrice, sont confrontées à des défis pour adapter leur marche aux exigences contextuelles. Elles présentent également des fonctions cognitives altérées qui peuvent avoir un impact sur leurs capacités de marche en double tâche. Cependant, on ne sait pas encore si elles présentent des stratégies d'évitement de collisions avec des piétons en mouvement qui sont modifiées dans des conditions de double tâche. Cette étude visait à : (1) comparer, entre des individus ayant un TCCm/g et des individus sains du même âge, les coûts locomoteurs et cognitifs associés à l'exécution simultanée d'une tâche de contournement de piétons virtuels (PV) et d'une tâche cognitive basée sur l'audition et; (2) caractériser le comportement du regard associé à la tâche de contournement exécutée en conditions de simple et double tâche. **Méthodologie** : Douze personnes ayant subi un TCCm/g (âge = 43,3±9,5 ans) et 12 individus contrôles (CTLs) en bonne santé (âge = 41,8±8,3 ans) ont été évalués alors qu'ils marchaient dans une station de métro virtuelle affichée à l'aide d'un casque de réalité virtuelle. Ils ont effectué une tâche d'évitement de collision avec des PV, ainsi que des tâches cognitives auditives (discrimination tonale et Stroop auditif), en conditions de tâche simple et double. Les variables et le coût de la double tâche (CDT) en termes de distance d'apparition de la déviation de la trajectoire, distance minimale par rapport au PV, déviation latérale maximale, vitesse de marche, fixations du regard et précision des réponses lors de la tâche cognitive ont été comparés entre les groupes à l'aide d'équations d'estimation généralisées. **Résultats** : Contrairement à la stratégie adoptée par les CTLs qui n'ont montré que des CDT locomoteurs, les individus avec TCCm/g ont montré des CDT à la fois pour les tâches locomotrices et cognitives. Alors que les deux groupes marchaient plus lentement en conditions de double tâche, les individus ayant subi un TCCm/g, contrairement aux CTLs, n'ont

pas réussi à modifier la distance à laquelle ils effectuaient une déviation de la trajectoire de marche et ils ont maintenu des distances minimales plus petites ainsi qu'une déviation latérale maximale plus petite par rapport à la marche en simple tâche. Les deux groupes ont également utilisé des fixations du regard plus courtes sur le PV approchant dans des conditions de double tâche, mais cette réduction était moins prononcée chez les personnes ayant subi un TCCm/g. Une réduction de la précision lors des tâches cognitives dans des conditions de double tâche a été constatée uniquement dans le groupe TCCm/g. **Conclusion** : Les personnes ayant subi un TCCm/g présentent un changement au niveau de la locomotion, du comportement du regard et des performances cognitives lors de l'exécution d'une tâche d'évitement de collision impliquant des piétons en mouvement, en particulier dans des conditions de double tâche. Les mécanismes potentiels expliquant ces altérations sont discutés. Les résultats actuels soulèvent des préoccupations quant aux risques de collisions dans les environnements communautaires très fréquentés chez les personnes ayant subi un TCCm/g, tout en mettant en évidence les capacités compromises en termes de marche complexe chez cette population qui présente par ailleurs une bonne récupération locomotrice.

THESIS ORGANIZATION AND OVERVIEW

The organization of this manuscript-based thesis adheres to the guidelines for thesis preparation published by McGill Graduate and Postdoctoral Studies. Chapter 1 includes a literature review. Chapter 2 outlines the rationale, objectives and hypotheses of the study. Chapter 3 presents a research manuscript that includes an abstract, introduction/background, methodology of the experiment, results, discussion of the findings, conclusion and journal required declarations. Chapter 4 summarizes the findings of the study and discusses the contribution of these findings to rehabilitation and future research. The last chapter of this thesis, Chapter 5, provides references to all studies discussed in the thesis.

CHAPTER 1: INTRODUCTION

1.1 TRAUMATIC BRAIN INJURY (TBI)

Acquired brain injuries include traumatic brain injuries (TBI) as well as non-traumatic brain injuries like cerebral vascular accidents. These injuries result in non-progressive damage to the brain and are not present at birth or caused by congenital diseases.[1, 2] TBI is defined as a brain dysfunction caused by an external mechanical force, a severe acceleration and deceleration of the head, or a penetrating head injury.[3-5] Traumatic brain injury can result in primary injuries, as a direct result of head shock, or secondary neural tissue damage due to oxygen restriction, infection, or inflammatory processes.[5]

Traumatic brain injury is often referred to as the "silent epidemic" due to underreporting, particularly in low- and middle-income countries (which altogether account for 89% of the head trauma population worldwide), where consistent data recording is lacking.[6-9] An estimated 69.0 million people worldwide suffer from TBI each year and the global incidence rate is 939 cases per 100,000 individuals.[6] Between 1990 and 2016, the worldwide prevalence of TBI increased by 8.4%, with 55.5 million cases in 2016, 62.7% of which involved males. In Canada, the incidence of TBI in 2016 was 302 new cases per 100,000 individuals yearly (age-standardised).[10] While falls are the most common cause of TBI worldwide, the causes vary across age groups and regions of the globe.[4, 10] For instance, transportation collisions as well as sports and recreation injuries are the leading causes of TBI among adolescents and young adults in Canada, while falls are the primary cause among infants, young children and older adults.[11]

Proper medical care and rehabilitation approaches for TBI survivors depend on the severity of the injury, which is classified as mild, moderate or severe based on indicators present in the acute

stage of injury (see Table 1.1).[12] These indicators include loss or reduced consciousness, loss of memory, muscle weakness, disrupted vision and abnormal findings on structural brain imaging.[5] The Glasgow Coma Scale (GCS)[13] is the main clinical measure used to determine TBI severity,[5, 11, 14-16] but some authors have recommended using a combination of measures due to GCS scores being influenced by factors such as sedation, pain, motor impairments and others.[5, 12, 17]

TBI is a leading cause of death and disability globally, with estimated costs of US$ 400 billion per year.[3, 18, 19] In Canada, the cost associated with preventable injuries, including TBI and other types of injury such as poisoning, near drowning, burns, fractures, concussions, neck whiplash exceeds $26.8 billion annually.[11] The mortality ratio for TBI survivors is 2.18 times greater than people without TBI.[20] Survivors of a TBI face sequelae that can be serious and long-lasting, given that it often affects those with a long life expectancy.[11] Traumatic brain injury can lead to deficits in the physical, cognitive, behavioural, and communicative domains, with the physical and cognitive domains being the focus of this research due to their relevance to complex locomotor tasks such as dual-task walking.[16]

The main physical deficits observed after TBI are muscle weakness (paresis or paralysis), abnormal muscle tone (spasticity), reduced joint range of motion, movement incoordination or ataxia, as well as deficits in balance and mobility.[16] Cognitive deficits encompass difficulties in understanding or producing speech as well as deficits in attention and memory, reasoning, judgement, initiation, planning, problem-solving and decision-making.[16] Although some deficits might resolve completely, others such as deficits in cognitive executive function and attention,[21] in community walking[22, 23] and obstacle avoidance,[24] especially following a moderate-to-severe TBI (m/sTBI), can be long-lasting and result in partial or permanent disability.[5] Despite the negative consequences of cognitive and locomotor dysfunctions on the daily life of individuals

with m/sTBI, there is a lack of research examining how these affect their ability to engage in complex locomotor tasks that are essential for independent community living.

Criteria	Mild	Moderate	Severe
Structural Imaging	Normal	Normal or abnormal	Normal or abnormal
Loss of Consciousness	< 30 minutes	30 minutes to 24 hours	>24 hours
Alteration of Consciousness / Mental State	A moment to 24 hours	>24 hours	>24 hours
Post-traumatic Amnesia	0–1 day	>1 and <7 days	>7 days
Glasgow Coma Scale (best available score in 24 hours)	13–15	9–12	3–8

Table 1.1. Criteria for traumatic brain injury classification. Adapted from Brasure et al., 2012.

1.2 COMMUNITY WALKING

Walking is a daily living activity that goes beyond a simple automated motor activity and requires a true "symbiosis" between gait physiology and biomechanics, higher-level cognition (e.g. executive function and attention), postural control and cardiorespiratory function.[25, 26] Factors related to the individual (e.g., age, personality, mood, culture, and diseases), but also factors related to the physical environment (e.g. terrain and lighting conditions, presence of obstacles, etc.) and the social environment (e.g., sociocultural context, interactions with others) influence the locomotor behaviour when ambulating in the community.[26, 27]

Patla and Shumway-Cook (1999) presented a conceptual framework for community walking comprised of eight dimensions.[28] These dimensions, which were later confirmed as being essential for independent community walking by individuals with and without physical disability,[29] are as follows: (1) distance of walking, (2) temporal factors (e.g. speed), (3) ambient conditions (e.g., lighting, weather), (4) physical load, (e.g., carrying an object), (5) terrain (e.g., incline), (6)

attentional demands (e.g., cognitive load), (7) traffic density (e.g., obstacles in the environment) and (8) postural transitions. One of the requirements that is being addressed in the context of this thesis is that of obstacle avoidance which, according to Patla (2001),[30] requires an adequate interaction between two main dimensions, i.e. attentional demands and traffic density.

1.3 UNDERSTANDING OBSTACLE AVOIDANCE

1.3.1 BEHAVIOURAL AND INFLUENTIAL FACTORS

The ability to successfully avoid obstacles while walking is crucial for safe and efficient locomotion in everyday life. Stepping over an obstacle requires adjustments to the horizontal and vertical trajectories of the foot in order to avoid contact with the obstacle.[31] In contrast, circumvention involves transiently reorienting the center of mass in a new direction and making adjustments to ongoing stepping patterns to go around and avoid the obstacle,[32] and will be further discussed in this thesis.

Obstacle circumvention is a complex task that relies on sensory information and the subsequent locomotor adaptations required to prevent collisions. Past research studies have described obstacle circumvention as a two-phase process. The first phase is the anticipatory locomotor phase, which begins approximately 3 to 4 m or even 6 from the obstacle.[33-35] During this phase, individuals engage in the early planning stage, making initial lateral adjustments to their path deviation. As they approach the obstacle, they enter the late planning stage, where final adjustments are made in the last stride before crossing the obstacle. The second phase is known as the clearance phase, which starts when individuals are approximately one stride preceding obstacle crossing. In this phase, individuals modify their locomotor behaviour to ensure successful clearance. This includes taking wider and shorter crossing steps and maintaining a given distance or clearance from the

obstacle. The clearance phase is influenced, amongst others, by factors such as the movement and position of the obstacle.[33] While some anticipatory adjustments are made, the strategy to avoid an obstacle can still change in real time based on environmental constraints. [36-39]

The ability to perceive and respond to obstacles while walking depends on the integration of various sensory information, including vision, vestibular and proprioceptive information.[40] However, vision plays a crucial role in providing information about distant environmental features, including obstacle properties (nature, size, shape, etc.), location and motion characteristics (providing information on speed and direction), which are essential for successful obstacle avoidance.[41-47] Researchers have proposed numerous models, theories, and control variables to elucidate the intricate process of integrating sensory information, planning, and executing obstacle navigation. One of them is the Bearing Angle Model, which suggests that humans use the angle between their self-motion direction and an approaching obstacle to guide their avoidance actions. A constant bearing angle indicates that the walker and obstacle are on a collision route. By monitoring changes in the bearing angle, individuals can make real-time adjustments to avoid collisions with the obstacle.[48] Another model proposed by Fajen (2013), which arises from Gibson's theory,[49] is the Affordance-based Model and focuses on how individuals perceive and interact with environmental affordances, that is the action possibilities offered by the environment. In the context of obstacle avoidance, individuals perceive the affordances of passable paths and adjust their movements accordingly.[48] The Behavioral Dynamics Model by Fajen and Warren (2003) explains how humans control their movements to avoid collisions. It emphasizes the dynamic interaction between perceptual information and behavioural responses. Individuals continuously update information about the obstacle's location and compute a "theoretical point of collision" (TPC). They adjust their heading and speed to maintain a safe distance from the obstacle

based on the real-time perception of this TPC.[50] The Time-to-Contact Theory (or Time-to-Collision) suggests that individuals use the rate of change of visual angle (tau) between themselves and the obstacle to time their movements and determine when to initiate an avoidance behaviour.[34, 51] Olivier et al. (2012) investigated collision avoidance between two walkers and proposed a control variable called Minimum Predicted Distance (MPD). The authors hypothesized that a reciprocal interaction would occur between walkers and found that locomotor adjustments usually occurs when MPD is below a threshold of 1m. They concluded that walkers have the capacity to assess and adjust their motions based on the anticipated crossing distance.[52]

While theories to explain the control of obstacle circumvention behaviour are multiple, the concept of obstacle clearance is one of that is recurrent in the literature and that has been extensively studied. The general concept of clearance refers to the distance maintained between an individual and an obstacle.[53, 54] This concept has been investigated through various variables, including the minimum clearance (the smallest distance between the walker and the obstacle),[54, 55] and dynamic clearance (the weighted average of minimal clearance at every time point during the entire avoidance strategy).[56] The terms personal space, that is an elliptical flexible clearance zone maintained around the body during walking[33, 57] and safety margin or zone, that is the distance prompting individuals to alter actions when an object enters it,[58-60] are other variables that describe this concept of clearance in different studies.

Another well-studied control variable is the distance at the onset of trajectory deviation, which expresses the antero-posterior distance between the walker and the obstacle at the onset of the walking trajectory deviation, also commonly referred as 'onset distance'.[33, 55, 61] Although no data are available correlating both clearance measures and onset distance with the risk of collision, it can be intuitively inferred that they are associated, as smaller values reflects greater proximity with

the obstacle. However, studies have demonstrated that a minimal predicted distance inferior to 1 m is associated with risk of collision.[52, 62]

In addition to analyzing space-related control variables, the examination of time-related variables, including walking speed and the time duration from the onset of trajectory deviation to obstacle crossing, sometimes referred as onset time of trajectory deviation,[32, 54, 63] holds significant importance in the analysis of obstacle circumvention. Speed reflects the rate at which an individual is moving through the environment and can play a crucial role in determining maneuverability during obstacle avoidance.[64] Reductions and increases in walking speed during the avoidance of an obstacle have often been interpreted as reflecting "safer" vs. "riskier" collision avoidance strategies, respectively.[57, 59, 65] Similarly, onset time of trajectory deviation indicates the moment when the walker initiates the process of avoiding an obstacle in reference to the time at obstacle crossing.[54] A larger onset time indicates an earlier deviation or reorientation in relation to the time of obstacle crossing. Conversely, a smaller onset time suggests a later onset that is closer in time to the point of obstacle crossing.[54] Slower walking speed and earlier onset time of trajectory deviation provides the individual more time to process the interaction with the obstacle and to implement the necessary locomotor adaptations, in a safer manner.[54]

The literature shows that circumvention strategies, as reflected by the variables described above, are influenced by individual factors. Older adults, for instance, adopt a larger personal space compared to younger adults.[66, 67] In an ongoing study on inactive lifestyle behaviour, Boulo et al. (2023) also showed that inactive healthy young adults presented a larger distance from the obstacle at the onset of walking trajectory deviation compared to active healthy young adults.[68] In studies that investigated sensorimotor deficits due to stroke, Darekar et al. (2017) further showed that individuals post-stroke assumed a riskier behaviour by maintaining a smaller obstacle clearance

when avoiding obstacle coming from head-on compared to healthy controls.[69] Aravind and Lamontagne (2017) further showed that individuals with post-stroke visuospatial neglect maintained smaller minimum distances from obstacles approaching from the neglected (contralesional) side; this reduction in minimum distance was further compromised by the addition of a concurrent cognitive task, leading to high rates of collision.[70]

Perceived characteristics of the obstacle can also influence the circumvention strategy. For example, Souza Silva et al. (2018)[55] and Lynch et al. (2018)[71] found smaller clearances when obstacles were humans compared to cylinders. In addition, in presence of a human interferer approaching from head-on, healthy young adults were shown to avoid the collision primarily by deviating to the right, which was not the case when the obstacle was a cylinder.[55] It is evident that obstacles resembling humans prompt distinct clearance strategies, possibly influenced by social interactions and the preservation of a safety zone in relation to others. Nevertheless, variations in clearance across studies may arise from specific obstacle characteristics, including their stationary[60] or dynamic[55, 71] nature, their physical[60] versus virtual[55, 71] representation, amongst other factors. In the study of Bourgaize et al. (2020), the size of the obstacle has also been associated with clearance, wherein greater clearance was seen for larger vs. smaller obstacles.[44]

The motion properties of the obstacle, such as global (whole body) vs. local motion (body component) cues, were also shown to influence the circumvention behaviour. For instance, Lynch et al. (2018) found that participants maintained smaller clearances when the obstacle presented local motion cues (trunk oscillations or leg movements) as opposed to only global motion cues (cylinders and sphere).[71] Similarly, Fiset et al. (2020) showed that in the presence of an interferer displaying local motion cues (normal locomotor movements of the limbs), participants maintained

smaller clearances compared to when the interferer only offered global motion cues (i.e. moving in space with limbs fixed).[72]

The stationary vs. moving nature of the obstacle is another factor that may affect the circumvention behaviour. Indeed, and while Gérin-Lajoie et al. (2005)[66] found no differences in clearance among healthy young adults when avoiding a collision with stationary vs. moving obstacles, Darekar et al. (2017)[69] noticed a larger dynamic clearance for moving vs. stationary obstacles in healthy older adults. The authors in the first study suggested that the locomotor control system might have taken into consideration a specific distance around the body and kept it constant while navigating all conditions. In return, the authors in the latter study proposed that a cautious avoidance strategy for safe clearance was adopted when the individuals were further challenged by an approaching (moving) obstacle.

Obstacles can also vary in their location, and dynamic obstacles can come from different directions and at different speeds. Huber et al. (2014)[73] demonstrated that adjustments in the direction and speed of walking of healthy young adults depended on the angle of approach (orthogonal, diagonal or head-on) of the interferer. When the interferer approached orthogonally or diagonally, participants adjusted their trajectory by laterally displacing their center of mass (CoM) and/or adjusting their walking speed. However, when the obstacle approached from head-on, lateral trajectory adaptations are absolutely required to avoid a collision. Souza Silva et al. (2018)[55] further showed that when encountering a head-on approaching obstacle, individuals exhibit larger onset distances of trajectory deviation and a greater maximum medio-lateral displacement compared to when the obstacle is approaching diagonally. However, in that same study, no differences in walking speed were observed due to the direction of obstacle approach. Collectively,

these studies suggest that avoiding a head-on (middle) approaching obstacle is more challenging as it necessarily requires trajectory adaptations.

Therefore, it is crucial to consider individual characteristics of the participants as well as the nature of the obstacle and its motion properties when conducting obstacle circumvention experiments, as these factors play a key role in shaping the circumvention behaviour.

1.3.2 IMPACTS OF TBI ON OBSTACLE CIRCUMVENTION

While the prognosis for regaining independent walking is generally good for those with m/sTBI, with 73% recovering within six months after injury,[74] and 72% of them reporting subjective ease in performing ambulatory tasks,[75] their ability to perform complex locomotor tasks in the community remains compromised.[75, 76] The available literature on the topic, however, is scarce and mainly focusses on stepping over obstacles.[21, 24, 77-79] In fact, the only published studies that have investigated circumvention strategies in the population with TBI have focused on elite athletes following mild TBI.[80, 81] In those studies, participants who were symptom-free at the time of testing showed residual locomotor-cognitive impairments such as slower response reaction time, larger obstacle clearance (except in Fait et al., 2009)[80] and decreased maximum walking speed compared to healthy controls, even 30 days after the concussion. Furthermore, findings from an unpublished thesis by Fait et al. (2011)[82] demonstrated that individuals with m/sTBI when circumventing static or moving obstacles adopt reduced walking speeds and increased minimal clearances compared to healthy controls. Thus, individuals after m/sTBI show altered locomotor adaptations during obstacle avoidance, which could impact their safety when walking in the community.

1.4 GAZE BEHAVIOUR IN OBSTACLE CIRCUMVENTION

The visual information gathered through gaze behaviour (where the person is looking at) allows modulating the walking pattern in a feedforward manner in anticipation of features and potential perturbations in the environment.[43] The main gaze behaviours described in the human locomotion literature are: (1) fixation, defined as the stabilization of the gaze on a location in the environment (continuously from 80 to 150ms);[41] (2) saccade, that is a rapid shift in gaze between two locations[41, 43] and; (3) travel fixation, where the gaze is held stable in front of the travel surface and move at the speed of locomotion.[41, 43, 83] The latter term, travel fixation, however, is debated and not commonly used such that most will simply refer to fixation.

Few studies have investigated gaze behaviour during obstacle circumvention. Recent studies from Joshi et al. (2021)[42] and Bühler et al. (2023)[84] demonstrated that healthy young individuals modulate their gaze as a function of the location and/or direction of approach of pedestrians present in the environment. In fact, longer and/or more frequent fixations appear to be devoted to pedestrians in the environment that are posing a greater risk of collision.[42, 85, 86] Joshi et al. (2021) further suggested that other factors such as pedestrian overall visibility (lying in the middle of the individuals' field of view), the presence of leaders in the environment (walking in the same direction but ahead of the observer) and social conventions (e.g., right-sided circulation) could modulate the attraction of gaze towards pedestrians in the environment.[40] Barbieri et al. (2018)[45] and Simieli et al. (2017)[87] found that healthy individuals, when circumventing a static obstacle (cylinder) in a laboratory setting, presented gaze fixations mainly on the ground (20%), with only 5% of fixation time devoted to the obstacle. In contrast, in Bühler et al. (2023)[84], Fiset et al. (2023)[67] and Bhojwani et al. (2022),[88] which involved the circumvention of moving pedestrians, the proportion of gaze fixation time on the 'obstacle' reached 30-50%, 50-55% and 34-50%,

respectively. Thus, longer fixation times on the obstacle may emerge in presence of moving vs. static obstacles, possibly because the moving obstacles entail a higher collision risk.

Gaze behaviour following TBI can be affected due to oculomotor[75] and vestibulo-ocular deficits.[89] Impaired oculomotor control involves issues with the muscles of the eyes and their movement, which can result from damage to cranial nerves such as the oculomotor, trigeminal, and abducens.[75] In turn, trauma to the head and neck can damages the peripheral vestibular system in the inner ear or the vestibular nuclear complex in the central nervous system, causing problems with the processing and integration of vestibulo-ocular sensory information.[89] All together, these deficits cause gaze instability (i.e. maintaining fixation of images on the fovea during head motion), vertigo, dizziness, blurry vision, nauseas, unsteadiness and/or balance problems.[90-93] Another disfunction experienced by individuals with TBI is in the visuo-spatial processing,[94] mainly when occurs a mismatch between shifting the visual midline and the proprioceptive base of support and center of mass, affecting balance and posture and increasing the risk of falling in individuals with TBI.[95] Furthermore, during locomotion, Lirani-Silva et al. (2021) showed that people with mild TBI have impaired saccadic eye movements during walking, which likely limits their ability to visually scan their environment.[96] According to the authors, it is unclear whether such alterations in gaze behaviour are due to the cognitive demands associated with walking or result from an attempt to reduce or prevent symptoms such as dizziness that can be triggered by ocular movements in this population.

As gaze behaviour and attentional processes are tightly integrated at the neural level,[97] the allocation of gaze can be indicative of "what and where" an individual is paying attention to. Based on this idea, Bhojwani et al. (2022) recently examined the impact of performing a cognitive task during a collision avoidance task with other pedestrians on the gaze behaviour of healthy young

adults.[88, 98] They observed that the allocation of gaze on features such as the approaching pedestrians, the target, or the environment remained the same as when the collision avoidance task was performed in isolation. As for individuals with m/sTBI, it was shown that they can present difficulties with selective attention,[99] divided attention[100, 101] and sustained attention.[102] Thus, performing a cognitive task while walking could further affect their ability to attend to and allocate their gaze to critical features of the environment such as obstacles in the environment. In the next section, the concept of dual-task walking and dual-task interference will be discussed in more details, while focusing more specifically on the literature that has examined obstacle circumvention.

1.5 DUAL-TASK WALKING

Cognition contributes to the execution of locomotion[25] and complex maneuvers such as obstacle circumvention.[38] Dual-task walking adds another layer to this and, in the present context, refers to when someone is walking while simultaneously performing another task, such as cognitive task (e.g., counting or remembering items of a shopping list). Such dual-task walking abilities are highly relevant to everyday life and independent community ambulation.[38]

Attention refers to the cognitive finite capacity of selectively focusing mental resources on specific information, stimuli, or tasks while filtering out or ignoring irrelevant or less important information.[103] Several models explaining the use of human attentional resources in dual-task context have been proposed, such as the filter (bottleneck) model,[104] capacity sharing,[105, 106] and multiple resources.[107] For instance, Woollacott and Shumway-Cook (2002) defined total attentional capacity as "the information processing capacity of an individual".[108] If a motor task and a cognitive task are executed concurrently and they demand more than the total capacity of

the shared attentional resources, (capacity sharing model)[105, 106] the execution of one or both tasks will deteriorate, causing what is referred to as interference.[108] Plummer et al. (2013)[109] proposed nine patterns of interference when simultaneously executing a motor and a cognitive task: a) no interference, b) cognitive-related motor interference (cognitive interference), c) motor-related cognitive interference (motor interference), d) motor facilitation, e) cognitive facilitation, f) cognitive-priority trade off, g) motor-priority trade off, h) mutual interference (cognitive-motor interference) and i) mutual facilitation. Amongst those patterns, the most reported in the walking literature are the cognitive and the motor interferences, whereby one of the tasks (either the cognitive or the motor tasks) is negatively affected by dual tasking but not the other, as well as the 'mutual motor-cognitive interference' that is characterized by a deterioration in both the motor and cognitive tasks. These patterns of interference are dependent on factors such as the nature of tasks performed, their level of difficulty, instructions with respect to task prioritization and the characteristics of the person (for in-depth reviews, see[109, 110]). Dual-task interferences can be quantified by calculating the locomotor and cognitive dual-task costs, which compare the relative differences in the individuals' performances during dual-task condition versus the single-task conditions.[111]

The few studies that have investigated the impact of dual tasking on the circumvention of moving obstacles (pedestrians or objects) in healthy young adults have found a cognitive interference, that is a deterioration in the cognitive task but no differences in the locomotor task in the dual- vs. single-task conditions.[39, 59, 111] In a study on the use of mobile phones while walking, Souza Silva et al. (2019) also showed that a visually-based cognitive task (text messages) caused a larger dual-task cost than a task that involved auditory stimuli (audio message).[59] In addition, Deblock-Bellamy et al. (2021), in a systematic review, identified that the complexity of the motor and

cognitive tasks matters and impacts the magnitude of locomotor and cognitive dual-task interferences. In other words, as tasks become more complex, cognitive response accuracy decreases, walking speed slows down, and other locomotor measures may be modified as well.[111]

Individuals with a neurological condition typically present larger dual-task costs while walking compared to healthy individuals, likely due to a combination of locomotor and executive function deficits.[25] A study from Aravind and Lamontagne (2017)[70] and the systematic review from Deblock-Bellamy et al. (2020)[110] both reported that individuals with an acquired brain injury due to stroke experience mutual (cognitive-motor) interferences in dual-task walking conditions. Aravind et al. also also demonstrated that the dual-task performance further deteriorated when performing a complex (Auditory Stroop) vs. a simpler (simple pitch discrimination) cognitive task.[70]

As for the population with TBI, Vallée and McFadyen et al. (2006) observed that despite a good recovery of locomotor function, individuals with m/sTBI stepping over obstacles under dual-task conditions presented a mutual dual-task interference.[24] Cossette and McFadyen et al. (2014) further showed that individuals with a mild TBI have deficits in stepping over an obstacle under dual task conditions.[112] Fait (2011) tested a small sample of eight high functioning m/sTBI participants performing concurrently an obstacle circumvention task and a visual Stroop task and found that the individuals with m/sTBI were slower and made more errors on the Stroop task while walked slower and with greater minimal obstacle clearance compared to healthy individuals, especially under the dual-task condition.[82] These findings, however, remain to be confirmed in a larger sample of participants, and while using a cognitive task that does not interfere with the sense of vision, the latter being required for the obstacle circumvention task. It will also be of interest to examine such dual-task walking behaviour under more ecological conditions, i.e. while ambulating

in a community environment and avoiding pedestrians, as opposed to moving objects such as cylinders. Furthermore, by employing an auditory-based cognitive task, it can minimize potential conflicts with the visual demands of obstacle circumvention.

1.6 VIRTUAL REALITY FOR STUDYING HUMAN LOCOMOTION

Virtual reality (VR) is a tool that can be defined as the "use of interactive simulations created with computer hardware and software to present users with opportunities to engage in environments that appear and feel similar to real world objects and events" (Weiss et al., 2006, p. 183).[113] Virtual reality has been increasingly used as an assessment and intervention tool in rehabilitation.[53] Virtual environments (VE) are created by the use of 2-D or 3-D computer graphics in which individuals are able to immerse themselves by the use of visual displays (e.g., head-mounted display or CAVE systems) and interact in real time with images, manipulate virtual objects and perform actions that reproduce activities of daily living by the use of input or motion capture devices (e.g., cybergloves, joysticks, etc.).[53, 114] Virtual reality affords researchers with the unique opportunity to safely expose and assess individuals in ecological and controlled VEs, while allowing to quantify one's performance using movement sensors, an eye tracker, etc.[53]

Previous studies comparing locomotor strategies while circumventing static obstacles[57, 115, 116] or moving pedestrians[61] in the VE vs. physical environment have shown that individuals adopt slightly larger clearances (mean differences range from 0.05 to 0.35 m) and slower walking speeds (mean differences range from 0.03 to 0.13 m/s) in the VE, and that strategies are qualitatively similar between the two environments. It was concluded that while more conservative circumvention strategies are adopted in the VE, differences with the physical environment are small and thus VR can be used as an ecologically-valid tool to assess obstacle circumvention.[61] As

a result, VR allows researchers to bring the complexity of the daily physical environments into the controlled setting of the laboratory.

CHAPTER 2: RATIONALE, RESEARCH OBJECTIVES AND HYPOTHESES

2.1 RATIONALE

The present research aims to address several gaps in the current literature regarding the ability of persons with m/sTBI to perform complex locomotor tasks in community-like settings. Specifically, while previous studies have reported an impaired capacity to step over an obstacle under dual-task conditions, only one unpublished study[82] with a small sample size has investigated the strategies used by people with m/sTBI to circumvent obstacles. Thus, it is necessary to expand on that preliminary study with a larger sample size to further understand not only how m/sTBI affects obstacle circumvention, but also how such a task is affected when concurrently performing a cognitive task with multiple levels of complexity, as is common in daily life. The present project also differentiates from the unpublished one by the use of an auditory-based cognitive task instead of a visual-based cognitive task, as the latter likely interfered with the acquisition of visual information needed for the execution of the locomotor task.

In addition, the present project is novel by examining, amongst people with m/sTBI, collision avoidance strategies in response to human-like interferers (as is encountered when walking in the community), and by collecting information on gaze behaviour as a marker of visual attention. Participants with m/sTBI and healthy individuals were recruited and tested while performing, concurrently and in isolation, a VR-based collision avoidance task involving virtual pedestrians approaching from different directions (locomotor task) and a pitch discrimination task of varying complexity (cognitive task). The study focused on dual-task costs as the main measure, in both the locomotor and cognitive domains.

2.2 OBJECTIVES

The research question sought to be answered in this study was: "What are the dual-task costs of combining a cognitive task of different complexities to a pedestrian circumvention task in individuals with m/sTBI as compared to age-matched healthy participants?". Therefore, the first objective of this study was to compare, between individuals with m/sTBI and age-matched healthy individuals, the locomotor and cognitive dual-task costs (DTCs) associated with the concurrent performance of a circumvention task involving virtual pedestrians (VRPs) and an auditory-based cognitive task. The second objective was to characterize the gaze behaviour associated with the circumvention task performed under single vs. dual-talk condition in both groups.

2.3 HYPOTHESES

In relation to the first objective, it was hypothesized that individuals with m/sTBI would present DTCs in both the locomotor and cognitive tasks, while the healthy individuals would only show a small cognitive DTC. For the second objective, longer gaze fixations on the approaching VRPs were expected in the dual- vs. single task condition. Such change, however, would be more pronounced in the m/sTBI group than in the healthy control group.

CHAPTER 3: RESEARCH MANUSCRIPT

Exploring the challenges of avoiding collisions with virtual pedestrians using a dual-task paradigm in individuals with chronic moderate to severe traumatic brain injury

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3.1 ABSTRACT

Background: Individuals with a moderate-to-severe traumatic brain injury (m/sTBI), despite good locomotor recovery, face challenges in adapting locomotion to contextual demands. They also present with altered cognitive functions, which may impact dual-task walking abilities. Whether they present collision avoidance strategies with moving pedestrians that are altered under dual-task conditions, however, remains unclear. This study aimed to: (1) compare, between individuals with m/sTBI and age-matched healthy individuals, the locomotor and cognitive costs associated with the concurrent performance of a circumvention task involving virtual pedestrians (VRPs) and an auditory-based cognitive task and; (2) characterize the gaze behaviour associated with the circumvention task performed under single vs. dual-talk condition. **Methodology:** Twelve individuals with m/sTBI (age=43.3±9.5 yrs; >6 mo. post injury) and 12 healthy controls (CTLs) (age=41.8±8.3 yrs) were assessed while walking in a virtual subway station viewed in a head-mounted display. They performed a collision avoidance task with VRPs, as well as auditory-based cognitive tasks (pitch discrimination and auditory Stroop), both under single and dual-task conditions. Dual-task cost (DTCs) for onset distance of trajectory deviation, minimum distance from the VRP, maximum lateral deviation, walking speed, gaze fixations and cognitive task accuracy were contrasted between groups using generalized estimating equations. **Results:** In contrast to CTLs who showed locomotor DTCs only, individuals with m/sTBI displayed both locomotor and cognitive DTCs. While both groups walked slower under dual-task conditions, individuals with m/sTBI, unlike CTLs, failed to modify their onset distance of trajectory deviation and maintained smaller minimum distances and smaller maximum lateral deviation compared to single-task walking. Both groups showed shorter gaze fixations on the approaching VRP under dual-task conditions, but this reduction was less pronounced in the individuals with m/sTBI. A

reduction in cognitive task accuracy under dual-task conditions was found in the m/sTBI group only. **Conclusion:** Individuals with m/sTBI present altered locomotor, gaze behaviour and cognitive performances when executing a collision avoidance task involving moving pedestrians, especially under dual-task conditions. Potential mechanisms explaining those alterations are discussed. Present findings highlight the compromised complex walking abilities in individuals with m/sTBI who otherwise present a good locomotor recovery.

Keywords – circumvention, cognition, gaze behaviour, locomotion, moderate-to-severe TBI, multitasking, obstacle avoidance, virtual reality.

3.2 BACKGROUND

Walking in the community is a daily living activity that goes beyond a simple automated motor activity and requires a true "symbiosis" between sensorimotor, higher-level cognitive (e.g. executive function and attention) and cardiorespiratory systems.[25, 26] This complex activity also demands one to perform adaptations of their locomotor behaviour as a function of the physical and social environmental factors.[28] Among the essential adaptations necessary for safe and independent community walking, obstacle avoidance stands out as a crucial skill, particularly in busy environments where other pedestrians walking in different directions must be avoided.[52] Successfully navigating such situations entails executing circumvention maneuvers. These maneuvers involve a temporary center of mass deviation to a new direction by concurrent adjustments to one's ongoing stepping patterns and/or speed, all with the purpose of smoothly going around and avoiding a collision with the obstacle.[32, 33, 73] The analysis of obstacle circumvention can be segmented into two phases: an anticipatory locomotor phase involving the initiation of lateral trajectory adjustments, and a clearance phase where individuals regulate their crossing distance from the obstacle.[33, 52, 61] Understanding the circumvention maneuver requires the analysis of spatial measures, such as walking trajectories (onset distance of trajectory deviation, maximum lateral displacement) and relative distances to the obstacle (minimum distance, clearance, personal space, etc.),[33, 54, 61, 70] as well as temporal measures, such as the onset time of trajectory deviation (i.e. the time duration from the onset of trajectory deviation to obstacle crossing), or even a combination of spatial and temporal dimensions through the analysis of the walking speed.[32, 54, 63] The literature shows that circumvention strategies can be influenced by personal factors,[66-70] as well as situational factors, such as perceived characteristics of the obstacle.[55, 60, 66, 69, 71, 73]

Obstacle circumvention becomes notably challenging in situations where attention is divided, such as in dual-task walking (e.g. walking and performing a cognitive task at the same time), increasing the risk of collisions[70] and falls.[117] Possible explanations can be sought in theories of dual-task interference, such as the bottleneck (filter) theory,[104] which suggests that mental processes are conducted sequentially, and information can be processed on only one task at a time. Another theory is the capacity sharing,[105, 106] which proposes that the processing of simultaneous tasks occurs in parallel, and where each task competes for a limited total capacity for attention. A third theory, called multiple resources,[107] posits that the competition between tasks depends on whether or not the same neural resources are required. All these theories indicate that if a motor task or a cognitive task demands more attentional resources or compete for the same attentional structures, exceeding an individual's total attentional capacity,[105] it can result in interference within one or both tasks, potentially leading to a decline in the performance of one or both tasks.[109]

Traumatic brain injury (TBI), a brain damage caused by an external mechanical force,[5] is considered a leading cause of death and disability worldwide.[19] It can lead to sensorimotor and cognitive impairments[5] that negatively impact the completion of activities of daily living. The severity of a TBI can be classified as mild, moderate or severe, depending on both the presence and extent of signs such as loss or reduced consciousness, loss of memory, motor response, verbal response, eyes opening, disrupted vision, and abnormal findings on structural brain imaging.[5] Once rehabilitation is completed, individuals with moderate-to-severe TBI (m/sTBI) often present a good recovery of independent walking[74] but walking in the community remains compromised.[75] When it comes to complex walking tasks, such as stepping over an obstacle,[24] hopping, or walking on irregular terrains,[75, 76] limitations become even more obvious. Longitudinal studies that followed individuals with m/sTBI over time revealed a progressive improvement in functional

independence within the first 12 months post-injury, but a subsequent decline between the 2nd and 7th years post-injury. [118, 119] Cognitive function in individuals with m/sTBI also generally improves in the first year post-injury, but a substantial proportion of individuals (27%) later experience a decline between 12 and 30 months post-injury.[120] Individuals with m/sTBI also struggle to divide their attention effectively between walking and a concurrent cognitive task,[21, 24, 76] which also seems to be dependent on locomotor and cognitive task complexity. For instance, Vallée et al. (2006)[29] observed that individuals with m/sTBI, when stepping over obstacles under dual-task conditions with varying levels of complexity, demonstrated mutual cognitive-locomotor dual-task interference for the more complex condition which involved the wider obstacle and a Stroop word task.

While previous studies have allowed uncovering the presence of locomotor and cognitive deficits in individuals with m/sTBI, there is a paucity of research on complex locomotor tasks involving obstacle circumvention in this population, both under single and dual-task conditions. To date, only one unpublished study has investigated the strategies used by individuals with m/sTBI to circumvent obstacles while walking.[82] In that study, Fait (2011) compared a high-functioning sample of 8 participants with m/sTBI (average time since the injury was 5 months) to a group of age-matched healthy individuals, as they circumvented a static or orthogonally-approaching cylinder with or without performing a visually-based Stroop-word task. Under dual-task conditions, individuals with m/sTBI presented slower response reaction times and made more errors on the cognitive task compared to healthy individuals. They also showed alterations in the walking task, with slower walking speeds and larger obstacle clearances. The use of a visually-based cognitive task, however, might have impacted the performance on the obstacle circumvention task, as both tasks heavily rely on the sense of vision, thereby creating interference

by dividing visual attention. Further investigation is also necessary to generalize the results to a larger sample of individuals with m/sTBI in an ecologically-valid community setting, which would involve pedestrians approaching from unpredictable directions as obstacles or interferers.

Research also shows that attentional processes and gaze behaviour (where a person is looking) are closely linked at the neural level, making gaze allocation indicative of an individual's focus of attention.[97] In recent locomotor studies, gaze fixation duration was shown to be modulated according to factors such as the location and/or direction of displacement of pedestrians present in the environment,[42, 88] suggesting that visually acquiring information about the spatial properties of the obstacle plays a role in successful collision avoidance. Additionally, a study involving stepping over an obstacle while performing a cognitive task showed that individuals with m/sTBI, unlike healthy individuals, presented a larger cognitive dual-task cost when performing a visual vs. auditory-based cognitive task.[21] Although gaze behaviour was not measured in that study, the findings were interpreted as individuals with m/sTBI allocating greater visual attention to the obstacle during the avoidance task. A meta-analysis further revealed that individuals with TBI experience deficits in higher-order visual-spatial attentional processing, particularly in cases of moderate-to-severe and severe injury.[121] Characterizing gaze behaviour during obstacle circumvention and how it may be affected by the addition of a cognitive task may thus provide further insight into underlying mechanisms explaining dual-task walking abilities in individuals with m/sTBI. To our knowledge, there is no research examining circumvention strategies of individuals with chronic m/sTBI avoiding pedestrians as interferers (like encountered when walking in the community), particularly using gaze behaviour as a marker of visual attention. Therefore, the first objective of this study was to compare, between individuals with m/sTBI and age-matched healthy individuals, the locomotor and cognitive costs associated with the concurrent

performance of a circumvention task involving virtual pedestrians (VRPs) and an auditory-based cognitive task. The second objective was to characterize the gaze behaviour associated with the circumvention task performed under single vs. dual-talk condition in both groups. In relation to the first objective, it was hypothesized that individuals with m/sTBI would present dual-task costs (DTCs) in both the locomotor and cognitive tasks, while the healthy individuals, based on previous work involving similar obstacle circumvention tasks,[98, 111] would only show a small cognitive DTC. For the second objective, longer gaze fixations on the approaching VRPs were expected in the dual- vs. single task condition. Such change, however, would be more pronounced in the m/sTBI group than in the healthy control group.

3.3 METHODS

3.3.1 STUDY DESIGN

This experimental study used a within-between repeated measure design and involved two groups of participants, i.e., participants with m/sTBI and healthy controls, who were compared across different experimental conditions.

3.3.2 PARTICIPANTS

The present study recruited a convenience sample of 24 participants who were divided equally into two groups involving healthy control participants and individuals with chronic m/sTBI. The sample size was estimated based on changes in 'minimum distance' from the obstacle previously documented as the main measure in a study using a similar paradigm in participants with stroke and healthy control participants,[70] and for which a large effect size was observed (0.8). The sample size calculation, estimated in G*Power version 3.1.9.6, was based on a repeated measures ANOVA with one between-subject factor (group: m/sTBI and healthy) and two within-subject factors (task

and direction). Considering a significance level of 0.05 and a power of 80%, a sample size of 12 participants per group was recommended.

The m/sTBI participants were recruited from the discharge list of the Trauma rehabilitation program of the Jewish Rehabilitation Hospital (JRH) and via the Association Québécoise des Traumatisés Crâniens (AQTC) of Laval, a local association supporting individuals with TBI and their family. Healthy controls were recruited from McGill graduate students, family members and friends of participants, as well as from JRH clinical personnel and through online advertisement on social media.

To be eligible for participation in the study, individuals in the m/sTBI group had to meet the following inclusion criteria: have experienced a chronic TBI at least 6 months earlier; have had their brain injury classified as moderate or severe, based on meeting at least two of three of the following criteria: Glasgow Coma Scale (GCS) ≤ 12, post-traumatic amnesia (PTA) >1 day, and abnormal brain image;[12] be aged between 18 and 55 years; be able to perform the 10m Walk Test[122] at a speed of 0.7 m/s or greater[23, 24] without a walking aid and; have sufficient cognitive function to follow instructions and provide autonomous consent. The age cut-off of 55 years was selected in order to minimize the impact of older age and associated comorbidities on mobility and cognitive functions. For the healthy group, age and sex-matched participants with no known history of TBI or concussion and intact cognitive function (Montreal Cognitive Assessment (MoCA) score > 25)[123] were recruited. Individuals in both groups further had to receive primary education in either the English or French language, in order to avoid language barriers when performing the cognitive task. In addition, they had to present normal or corrected-to-normal visual and auditory acuity. For this study, we considered a visual acuity result of logMAR of 0.4 or greater on the ETDRS chart,[124] which is the minimum visual acuity required for driving in Québec.[125] The

auditory acuity was tested subjectively by assessing if the participants could hear and repeat an audio message at 50dB played through the head-mounted display (HMD) headset, with 100% accuracy on 5 trials.[55] Exclusion criteria for both groups included any conditions that could interfere with locomotion, other than the TBI for the m/sTBI group.

Prior to the study, all participants provided written informed consent, after being fully informed about the details and potential risks and benefits of the experiment. The study was approved by the Research Ethics Board en réadaptation et en déficience physique of the CIUSSS du Centre-Sud-de-l'Île-de-Montréal, and all procedures were conducted in accordance with the ethical standards set forth by the board.

3.3.3 EXPERIMENTAL SETUP AND PROCEDURES

The study took place at the Virtual Reality and Mobility Laboratory located at the JRH in Laval, QC, Canada. It comprised of two evaluation sessions taking place on the same day and lasting 2-2.5 hours each. In the first session, eligible participants underwent a clinical assessment of balance, mobility and cognition. In the second session, participants completed a comprehensive laboratory evaluation that included multiple task conditions. These tasks consisted of: (1) a single walking task (ST walking); (2) a single cognitive task with two complexity levels (a simple pitch discrimination task and a complex Auditory Stroop task) and; (3) dual task conditions that combined the walking task with both complexity levels of the cognitive task, resulting in a simple (DT Simple) and a complex dual-task (DT Complex) condition. To minimize potential order and learning effects, the order of the tasks was randomized. Participants were offered breaks as needed, with a mandatory long break of approximately 1 hour between evaluation sessions.

3.3.3.1 CLINICAL ASSESSMENT

First, participants were interviewed to obtain demographic data and information on the following: time since the onset of TBI and cause, determined using medical chart information and reconfirmed by administering The Ohio State University Traumatic Brain Injury Identification Method,[126] level of education (i.e., number of years of school completed) and prior experience with immersive VR environments (i.e., yes or no). Handedness was determined using the Edinburgh Handedness Inventory.[127] Overground walking speed was measured using the 10m Walk Test (10MWT)[122] and ambulatory skills were characterized using the Community Balance and Mobility Scale (CB&M).[128] The ability to dual task while walking and balance confidence were assessed using the Timed Up and Go Cognitive (TUG-Cog)[129] and Activities-specific Balance Confidence (ABC) Scale,[130] respectively. Cognitive function was characterized using the Montreal Cognitive Assessment (MoCA), the Digit Span Test[131] as well as the Trail Making Test A (TMT-A) and B (TMT-B).[132]

3.3.3.2 SINGLE OBSTACLE AVOIDANCE TASK

Participants were assessed while walking overground and immersed in an ecological VE representing a subway station in Montreal, (QC), Canada (see Figure 3.1-A), created in Autodesk Maya and controlled using the Unreal game engine 4.27.2. Participants were positioned at a designated starting position marked at one end of the walking area. They faced the target (Montreal subway map) located straight ahead (0°) in the far space (8.5 m). Three female (aged 35-45 years) VRPs acting as interferers were created using motion capture data from healthy female individuals.[61] The VRPs were positioned in an arc fashion at 0° (straight ahead), 30° to the right and 30° to the left from a theoretical point of collision located 3.25m in front of the participant, with a radius of 3m. The theoretical point of collision is a point where a collision with an

approaching VRP would occur if the participant does not perform any locomotor adjustments (see figure 3.1-B).

The VRPs were non-reactive and walked with a neutral gait pattern at a speed set to 1.2m/s, replicating the average comfortable walking speed of healthy female adults.[133] The choice of female VRPs walking with a neutral gait pattern was guided by research indicating that gender and emotions of gait are factors that can influence perception on the part of the observers.[134, 135] The participants viewed the VE using the HTC VIVE Pro Eye, an HMD that has an integrated binocular eye tracker and audio headset. This HMD weighs 550 grams and has a field of view of 110°, a resolution of 2880x1600 pixels and a refresh rate of 90 Hz. Using SteamVR Base Station 2.0 units, the HMD was tracked over an area of 7m x 7m. The HMD is equipped with tracking sensors that provides information on position and orientation of the head. This information was supplied in real-time to the Unreal Game engine to update the camera view of the participants within the virtual scene according to their head position and orientation. The eye tracker within the HMD has an accuracy of 0.5 to 1.1° across the entire 110-degree field of view. Participants' head, eye and gaze position data were recorded in Unreal at 90Hz.

An initial calibration process was conducted to align the virtual and the physical environments, as per a procedure described earlier.[61] A calibration of the VIVE Pro Eye for the eye tracker was also conducted. This calibration was repeated prior to every block of ten (10) walking trials, or at any point in time if the HMD was repositioned or removed from the participant's head. During data collection, participants were instructed to begin walking at a comfortable speed towards the target after the words 'Get ready' disappeared from the screen, and to stop walking when seeing the words 'Stop'. They were further instructed to avoid any collision with an approaching VRP if present. Once participants reached 0.5 m of forward walking, the three VRPs located in the far

space started walking toward the theoretical point of collision. After taking one step, two of the VRPs turned around and walked away while the remaining one continued walking towards the theoretical point of collision.

Five VRP directions were presented in a random order, including (1) a right and (2) left approach (±30°), (3) a middle approach (0°), (4) an all-back condition where all VRPs turned around and walked away (catch trials) and (5) a control trial without any VRPs. Trials without VRPs served the purpose of evaluating the participants comfortable walking speed in the VE and were used as a reference of straight-ahead trajectory to calculate the onset time/distance of trajectory deviation. In the event of a collision, the word 'Collision' flashed on the screen and the participants had to stop and walk back towards the starting point. Six trials for each of the 5 VRP directions were randomly performed, for a total of 30 trials.

3.3.3.3 SINGLE COGNITIVE TASK

Participants were assessed while seated and observing the static VE in the HMD. The cognitive task was an auditory pitch-discrimination task with 2 levels of complexity, for which sound stimuli were delivered through the audio headset of the HMD. In the simple task, the word "Cat" (or "Chat" in French) was presented in a high or low pitch while in the complex task, the words "High" or "Low" ("Haut" and "Bas" respectively in French) were presented in a high or low pitch (i.e., an Auditory Stroop Task). The Auditory Stroop or "High-Low" task is considered to be a more intricate task than the simple pitch discrimination task, especially when the trial presents an incongruent condition (e.g. word 'high' in low pitch), as greater attention and inhibition is required to correctly identify the pitch without being influenced by the meaning of the word.[38] The intensity

of the sound stimulus was set to 70 dB, a level that was considered enough and comfortable based on a study associating TBI severity with audiometric measures.[136]

Participants were instructed to verbally report the pitch of the words as accurately as possible (2 alternatives: high or low) while ignoring the meaning of the words as needed. The single cognitive task conditions, delivered in a random order, were tested by means of 6 trials (3 for the simple and 3 for the complex task) each lasting 50s. For each trial, multiple sound stimuli were delivered at variable interstimulus intervals of 1.5 s to 1.9 s. The 50s duration of the trials was based on the duration and number of the walking trials, considering an average adult walking speed of 1m/s to 1.2m/s,[133] in order to get a similar number of auditory stimuli in the single vs. dual-task condition. The participants' answers (including missed responses) were entered by the experimenter in Unreal for each sound stimuli and saved for offline analysis. The answers were also digitally recorded for future validation.

3.3.3.4 DUAL-TASK CONDITIONS

The dual-task conditions required participants to perform simultaneously the walking (avoiding collision with a VRP) and the cognitive tasks (either simple or complex), resulting in the DT simple and DT complex conditions. The auditory cognitive task was presented at the same time intervals as in the single cognitive task conditions. Instructions given to participants were to walk towards the target and to avoid VRPs as needed while reporting the pitch of the words simultaneously. The dual-task conditions comprised of 30 trials and their order of presentation was randomized.

The perception of difficulty for the single cognitive and dual-task conditions were assessed after each long single-task trials and after each block of 10 dual-task trials, with a 10-point numeric rating scale, from 0 (no difficulty) to 10 (extreme difficulty). At the very end of the experiment,

the VR motion sickness was measured through the Fast Motion Sickness Scale[137] while the feeling of presence in the virtual environment (VE) was measured through the Single-Item Measure of Presence in VR.[138]

3.3.4 DATA ANALYSIS

Data recorded in the Unreal engine were exported to Matlab (MathWorks, USA) and used to calculate the measures related to the locomotor and cognitive tasks. Because participants exhibited very similar behaviour when navigating VRP interferers approaching from the left vs. right, as also seen in other studies,[54, 84, 88] data from the left and right VRP directions were combined into a single 'diagonal' condition. There were no missing data in this study, with the exception of one trial for one participant that was not recorded due to technical issues.

Locomotor measures for this study encompassed the number of collisions, minimum distance, walking speed (minimum, average, and maximum), onset distance, onset time, maximum lateral displacement and side of deviation. The number of collisions was calculated by counting the number of times the distance between the lateral edges of the participant and the VRP was less than the sum of the radii of the participant and VRP (42.5 cm). Minimum distance was calculated as the minimum distance maintained between the center of the participant's head and the VRP's centre of the neck over a time window spanning from when VRPs were triggered to walk to the point of VRP crossing, that is the point when the antero-posterior position of the participant was the same as that of the VRP. Walking speed was calculated using the first derivative of the participant's head trajectory over a distance starting at 1m of anteroposterior displacement of the participant (to avoid initial acceleration) until the point of VRP crossing. Minimum, mean and maximum walking speed values were then extracted. Onset distance of trajectory deviation was

calculated as further detailed in Buhler et al. (2018, 2022 and 2023).[61, 84, 139] Briefly, it was obtained by first identifying the point where the participant's mediolateral displacement was greater than what was observed in control trials and, from this point, the trace was scanned backward to identify the first preceding point where the participant's mediolateral speed was equal to zero. From the latter point, the onset distance of trajectory deviation was calculated as the Euclidean distance between the participant and the VRP. As for onset time of trajectory deviation, it was calculated as the time between the onset distance of trajectory deviation and the point of VRP crossing. Maximum lateral displacement was defined as the maximum lateral excursion occurring in a window that spanned from the onset distance of trajectory deviation to the point of VRP crossing. Side of trajectory deviation was defined as the direction the participant veered in relation to the VRP (i.e., to the left or right).

Gaze-related measures included the percent duration of gaze fixations directed toward objects of interest which included the approaching VRP, other VRPs, the goal, and the environment. Gaze fixation instances were identified for every data frame at which a participant's gaze vector collided on the respective object of interest in a time window that began at the onset of VRP movement and ended at the point of VRP crossing. The total of instances of gaze fixation on a given object of interest was then expressed as a percentage of the total number of data frame in that time window. Given that the metro map was far and often occluded by a VRP, the goal for this analysis was considered as the combination of the subway map and subway entrance.

Response accuracy during the cognitive tasks was assessed by means of percent correct responses. These were calculated as the percentage of correct responses with respect to the total number of auditory stimuli. All measures that presented a significant main effect of task or a group X task

interaction effect had their DTC calculated by the use of the following formula: DTC = 100 * (single-task score – dual-task score) / single-task score.[140]

3.3.5 STATISTICAL ANALYSIS

Clinical assessment measures, perception of difficulty, presence and motion sickness questionnaires were compared between groups using two-sided independent-sample T-tests for continuous variables and two-sided Pearson Chi-square tests for categorical variables. Locomotor, gaze behaviour and cognitive measures were contrasted between groups and across tasks using generalized estimating equations (GEE). For the locomotor and gaze behaviour measures, our model incorporated an exchangeable correlation matrix, with two within-subject factors, namely direction of VRP approach (diagonal and middle) and task (ST walking, DT simple, and DT complex), along with one between-subject factor, which was the group (healthy and m/sTBI). As for the cognitive measure, the model featured one within-subject factor, that is the task (ST simple, ST complex, DT simple, and DT complex) and group as the between-subject factor. The DTCs were analyzed by means of a GEE model comprising of complexity (simple vs. complex) as the within-subject factor and group as the between-subject factor. Post-hoc comparisons were carried out when appropriate using least significant difference (LSD) with Bonferroni adjustments. Except for the number of collisions, all measures were calculated using collision-free trials. Statistical analyses were performed in SPSS Statistics 29.0.0.0 (241) with an alpha level of significance set to $p<0.05$.

3.4 RESULTS

3.4.1 CHARACTERISTICS OF PARTICIPANTS

In this study, 83.3% (10 out of 12) of the traumatic brain injuries were caused by vehicle accidents, with the remaining two cases attributed to one assault and one fall. Table 3.1 provides an overview of the characteristics of participants from each group. Notably, no significant differences emerged between the groups concerning age, sex, handedness, level of education, prior experience with immersive VR environments, single and dual-task performance on the Timed Up and Go, memory assessed through the Digit Span test (both forward and backward), and self-reported sense of presence within the virtual environment, as measured by the Single-Item Measure of Presence. Individuals with m/sTBI, however, demonstrated alterations in their balance and mobility, as indicated by significantly reduced scores on the ABC and CB&M tests and slower overground walking speed on the 10MWT compared to the healthy group. In terms of cognitive function, participants with m/sTBI scored significantly lower on the MoCA and showed longer completion times for TMT-A and TMT-B tests. Furthermore, they reported small but significantly higher motion sickness ratings (3.2 out of 20) on the Fast Motion Sickness Scale compared to the healthy group (0.2 out of 20).

3.4.2 LOCOMOTOR MEASURES

When considering both groups, 1295 walking trials with a VRP as an interferer were analyzed. Among these trials, 16 collisions occurred (1.25% of the total; 9 in the m/sTBI group, 7 in the healthy group). Seven of these collisions occurred during ST walking, while 3 and 6 occurred during the simple and complex DT conditions, respectively. As indicated earlier, results below are for collision free trials.

In Figure 3.2, representative walking trajectories from one healthy participant and one participant with m/sTBI are depicted for each locomotor condition. A noticeable modulation of the onset of trajectory deviation can be observed in the healthy participant across conditions, with a progressively earlier onset (or at a further distance from the VRP, not shown) during simple and complex DT conditions compared to ST walking. Such modulation, however, was less pronounced in the participant from the m/sTBI group. For the diagonal VRP approaches, it can also be observed that both representative participants consistently veered on the same side as the VRP was approaching from. In other words, they chose to pass behind the VRP, which was the case for 99% of trials when considering the whole sample of participants. When negotiating a VRP approaching from the middle, participants veered either right or left, with a preference to circumvent towards the right side (healthy group: 55.9%; m/sTBI group: 54.7%).

Results of the analyses of the anticipatory phase (onset distance of trajectory deviation), clearance phase (minimum distance and maximum lateral deviation) and maximum walking speed are illustrated in Figure 3.3. In general, all measures were significantly modulated by the direction of approach of the VRP and most demonstrated an interaction effect between group and task. More specifically, onset distance of trajectory deviation exhibited a main effect of direction ($x^2(1,1150) = 62.798$, $p<0.001$) and an interaction effect between group and task ($x^2(2,1150) = 8.893$, $p=0.012$). Post-hoc analyses revealed that, overall, participants initiated their trajectory deviation at a larger distance from the VRP when circumventing a VRP approaching from the middle vs. diagonally ($p<0.001$). Additionally, participants in the healthy group initiated their trajectory deviation at a larger distance from the VRP in both the simple ($p<0.001$) and complex ($p<0.001$) DT conditions vs. ST walking. Such effect of task complexity, however, was not present in the m/sTBI group (p-values: ST walking vs. DT simple = 0.362; ST walking vs. DT complex = 0.754).

Of note, similar effects of direction ($x^2(1, 1150) = 4.646$, $p=0.031$) and group X task interaction ($x^2(2, 1150) = 17.424$, $p<0.001$) were observed for onset time of trajectory deviation (not shown in Figure 3.3). In agreement with onset distance results, healthy participants were found to initiate their trajectory deviation earlier in both the simple ($p<0.001$) and complex ($p=0.012$) DT conditions vs. ST walking, while onset time values remained unchanged across levels of task complexity in the m/sTBI group (p-values: ST walking vs. DT simple = 0.025; ST walking vs. DT complex = 0.257).

For minimum distance, a main effect of direction ($x^2(1,1271) = 27.015$, $p<0.001$) and interaction effects between group and task ($x^2(2,1271) = 9.213$, $p=0.010$), as well as between group and direction ($x^2(1,1271) = 4.244$, $p=0.039$), were found. Post-hoc analyses showed that individuals adopted smaller minimum distances from the VRP for the middle vs. diagonal VRP approaches ($p<0.001$) but this difference was less pronounced in the healthy group than in the m/sTBI group (Healthy:$\Delta=0.09$; m/sTBI:$\Delta=0.21$m, $p<0.001$). Furthermore, while the healthy group increased their minimum distances in the simple DT walking condition compared to ST walking ($p=0.005$), the m/sTBI group showed a reduction in minimum distance due to task complexity, with significantly smaller values for the complex DT condition vs. ST walking ($p=0.009$).

The analysis of maximum lateral deviation revealed main effects of group ($x^2(1,1150) = 5.322$, $p=0.021$) and direction ($x^2(1,1150) = 259.389$, $p<0.001$), as well as an interaction effect between group and task ($x^2(2,1150) = 10.779$, $p=0.005$). Post-hoc analyses demonstrated larger maximal lateral trajectory deviations for middle vs. diagonally approaching VRPs ($p<0.001$). Between-group differences were further observed but only for DT walking conditions, with the healthy group displaying greater lateral deviation than the m/sTBI group (DT simple: $p=0.006$; DT complex: $p=0.013$). The influence of task complexity also differed between the two groups, as the

healthy group displayed larger maximum lateral deviations in the simple DT walking vs. ST walking condition ($p=0.007$) while the m/sTBI group showed smaller values in the complex DT walking vs. ST walking condition ($p=0.002$).

Main effects of group ($x2(1,1266) = 4.355$, $p=0.037$), task ($x2(2, 1266) = 6.607$, $p=0.037$) and direction ($x2(1, 1266) = 43.480$, $p<0.001$), as well as an interaction effect between task and direction ($x2(2, 1266) = 9.968$, $p=0.007$), were observed for maximum walking speed. Post-hoc comparisons showed that participants with m/sTBI adopted slower maximal walking speeds compared to the healthy group ($p<0.037$), and smaller values were also observed for diagonally approaching VRP vs. those approaching from the middle ($p<0.001$). Concerning the effect of task complexity, participants decreased their maximum speed during the complex DT condition vs. the two other conditions (simple DT: $p<0.001$; ST walking: $p<0.001$), but only for the diagonal approach. Although not illustrated in Figure 3.3, a main effect of direction was also observed for minimum walking speed ($x2(1, 1266) = 33.059$, $p<0.001$) and average walking speed ($x2(1, 1266) = 79.148$, $p<0.001$), whereby participants walked with slower minimum and average walking speeds when circumventing a VRP approaching from a diagonal direction vs. from the middle.

3.4.2 GAZE BEHAVIOUR MEASURES

Figure 3.4 illustrates the percentages of gaze fixation duration on the approaching VRP, the other VRPs, the goal and the rest of the environment. The percentage of gaze fixation duration on the approaching VRP was affected by the task ($x2(2, 1217) = 75.463$, $p<0.001$) and direction of approach of the VRP ($x2(1, 1217) = 18.868$, $p<0.001$), while showing an interaction effect of group and task ($x2(2, 1217) = 11.301$, $p=0.004$). Post-hoc analyses showed that participants gazed on the approaching VRP for longer durations during the ST walking condition vs. both the simple

($p<0.001$ for the healthy group and $p=0.023$ for the m/sTBI group) and complex ($p<0.001$) DT conditions, as well as when the approaching VRP was coming from a middle direction vs. diagonal ($p<0.001$). The between group differences were more pronounced in the ST walking ($p=0.022$) where the healthy group gazed the approaching VRP 8.5% more than the m/sTBI group did. As for the percentage of gaze fixation directed toward the other VRPs, it showed a main effect of direction ($x2(1, 1217) = 208.985$, $p<0.001$) and an interaction effect of task and direction ($x2(2, 1217) = 9.010$, $p=0.011$). Overall, participants gazed at other VRPs for longer durations when the approaching VRP was coming from a diagonal vs. the middle direction ($p<0.001$). The task and direction interaction effect were explained by a small but significant increase in the percentage of gaze fixation on other VRPs during the simple DT condition vs. ST walking ($p=0.017$) for the middle approach only.

The percentage of gaze fixation on the environment was only affected by the direction of VRP approach ($x2(1, 1217) = 10.662$, $p= 0.001$), with participants gazing at the environment for longer durations while avoiding a middle vs. a diagonally approaching VRP. As for the percentage of gaze fixation on the goal, it was only affected by the task ($x2(2, 1217) = 13.102$, $p=0.001$), with smaller values for ST walking vs. both the simple ($p=0.002$) and complex DT ($p<0.001$) conditions.

3.4.3 COGNITIVE MEASURES

All participants made errors in at least one of the cognitive tasks. The perceived level of difficulty on the cognitive tasks was significantly higher in the m/sTBI group than in the healthy control group for all conditions (ST simple: m/sTBI = 3.76±2.59, healthy = 0.92±1.14, $p=0.002$; ST complex: m/sTBI = 4.86±2.75, healthy = 2.06±1.83, $p=0.008$; DT simple: m/sTBI = 4.03±2.68,

healthy = 1.48±1.28, p=0.007; DT complex: m/sTBI = 5.47±2.12, healthy = 2.00±1.42, p=0.000). We observed twice as many participants making errors in the m/sTBI group vs. the healthy group for the simple ST condition (n=8 vs. 4), the complex ST condition (n=12 vs. 6) and the simple DT condition (n=12 vs. 6). For the complex DT condition, the number of individuals making errors was the same between groups (11 for each).

As a whole, participants demonstrated proportions of correct response on the cognitive tasks that ranged from 81.0% (DT complex for the m/sTBI group) to 99.6% (ST simple for the healthy group), as depicted in Figure 3.5. Statistical analyses revealed a main effect of group ($x^2(1, 96) = 8.060$, $p=0.005$) and task ($x^2(3, 96) = 16.950$, $p<0.001$), as well as an interaction effect between group and task ($x^2(3, 96) = 8.029$, $p=0.045$). Except for the simple ST condition, the healthy group showed higher proportions of correct response than the m/sTBI group on all task conditions (DT simple, p=0.014; ST complex, p=0.01; DT complex, p=0.003). In addition, only the m/sTBI group experienced a decrease in performance in the complex cognitive task performed in single vs. dual-task condition (p=0.008).

3.4.4 DUAL-TASK COSTS

The analyses of dual-task costs (DTCs) related to locomotor, gaze behaviour, and cognitive measures are summarized in Table 3.2. In general, statistically significant main effects of group and/or complexity were identified, but no statistically significant interactions between group and complexity were found for any of the DTC measures (p-value = 0.109 - 0.935). Regarding locomotor DTCs, significant main effects of group emerged for onset time ($x^2(1, 48) = 10.260$, $p=0.001$), onset distance ($x^2(1, 48) = 10.347$, $p=0.001$), minimum distance ($x^2(1, 48) = 10.140$, $p=0.001$), and maximum lateral deviation ($x^2(1, 48) = 10.381$, $p=0.001$). In fact, while the healthy

group displayed negative DTCs for all of those measures, the m/sTBI group instead showed relatively small but positive DTCs. In practical terms, this means that healthy participants performed a trajectory deviation earlier and at a greater distance from the VRP, while increasing their minimum distance and maximum lateral deviation during dual- vs. single-task conditions. Conversely, the m/sTBI group initiated a trajectory deviation later and a closer distance from the VRP and showed reduced minimum distance and maximum lateral deviation in the dual- vs. the single-task condition, although those changes were generally of small magnitude. A main effect of task complexity was also identified for both maximum speed ($x2(1, 48) = 6.626$, $p=0.01$) and maximum lateral deviation ($x2(1, 48) = 7.434$, $p=0.006$). For both of these measures, an increase towards a more positive cost was observed in the complex vs. simple DT condition, implying a reduction in maximum speed and maximum lateral deviation in the complex vs. simple DT condition.

Gaze behaviour measures showed the largest DTCs amongst all measures, reaching values as high as 47% and -43%, respectively, for gaze fixation duration on the approaching VRP and the goal. While both groups exhibited a positive DTC for gaze fixation duration on the approaching VRP, this DTC was significantly smaller ($x2(1, 46) = 4.572$, $p=0.033$) in the m/sTBI group than in the healthy group. In other words, while dual tasking induced shorter fixation durations on the approaching VRP, such reduction was significantly less pronounced in the m/sTBI group than in the healthy group. Of note, negative DTCs were observed for gaze fixation on the goal and, to some extent on the other VRPs (as seen in the m/sTBI group), indicating that participants fixated more on those elements in DT conditions. For the latter two measures, however, there were no differences between groups. A significant main effect of complexity was observed in relation to DTC in gaze fixation duration on the approaching VRP ($x2(1, 46) = 6.405$, $p=0.011$). The cost was

higher in the complex vs. simple dual-task condition (Δ=8.57%), which means that the reduction in gaze fixation duration on the approaching VRP was more pronounced for the complex vs. simple dual-task condition.

Lastly, the m/sTBI group exhibited positive DTCs in cognitive task accuracy reaching at most 6.91%, indicating a modest overall reduction in cognitive performance in dual-task conditions, while values for the healthy controls remained close to zero (0.78-0.79%). A statistically significant main effect of group was observed for DTC in cognitive accuracy ($x^2(1, 48) = 4.293$, $p=0.038$), with the m/sTBI group experiencing a larger DTC compared to the healthy group. Task complexity did not significantly impact on this measure.

3.5 DISCUSSION

This study was the first to examine the dual-task costs in locomotor and cognitive measures in individuals with chronic m/sTBI simultaneously performing a collision avoidance task involving pedestrians and a cognitive task while ambulating in a virtual community environment. The individuals with m/sTBI recruited in this study showed, as expected,[75] alterations in their clinical tests of balance and mobility and executive functions. However, they were still relatively high functioning and walked on average at a comfortable speed of 1.2m/s, which is equal or greater than the speed required for independent community ambulation.[22, 23, 141] Yet, when exposed to a complex walking task such as avoiding a collision with pedestrians approaching from different directions, they did show differences in their collision avoidance strategies compared to healthy controls. Furthermore, under dual-task conditions, they not only showed a mutual cognitive-locomotor interference that contrasted with the single locomotor interference observed in the

healthy individuals, but they also adopted collision avoidance strategies that markedly differed from that of their healthy counterpart.

3.5.1 DUAL TASK-INDUCED ADAPTATIONS IN COLLISION AVOIDANCE STRATEGY

The present study highlights between-group differences in both the anticipatory and clearance phases when executing the collision avoidance task under dual-task conditions. Healthy controls exhibited slower walking speeds, earlier and more distant onsets of trajectory deviation in the anticipatory phase, along with increased maximum lateral deviations and larger minimum distances in the clearance phase for the dual- vs single-task conditions. Individuals with m/sTBI also walked slower for the dual-task conditions, but they maintained similar distances and times at onset of trajectory deviation between dual- and single-task conditions, indicating a lack of modulation of the anticipatory phase of obstacle circumvention. This lack of modulation likely resulted in the closer proximity to pedestrians observed in the clearance phase for this group when dual tasking, which was reflected by smaller maximum lateral deviations and minimum distances.

The dual-task adaptations observed in healthy controls apparently contrast with a recent study by Bhojwani et al. (2022), which used a protocol similar to the one used in the present study[88] and where no dual-task adaptations in terms of locomotor measure were observed. The healthy individuals included in the present study, however, were aged-matched to the m/sTBI group and older (average 41.8 years, range 24-53) than those tested earlier (24.9 years, range 18-29).[88] Age-related changes in sensorimotor and cognitive functions,[142-144] as well as in dual-task walking abilities,[145, 146] likely explain differences between the two studies. Earlier onsets of trajectory deviations,[67, 84] but also larger minimum distances[55] were observed in previous obstacle circumvention studies when participants were exposed to riskier or unfamiliar obstacle conditions,

suggesting such adaptations to reflect the use of a conservative circumvention strategy. Such adaptations on the part of healthy individuals in the present study may thus reflect the use of a conservative or safer avoidance strategy, which aimed to minimize the risk of collision as cognitive resources were drawn upon to complete the concurrent cognitive task.

While a similar dual-task induced conservative behaviour was recently reported in the context of an obstacle circumvention study involving individuals with Parkinson's disease and age-matched healthy individuals,[147] individuals from the m/sTBI group in the present study rather seemed to exert a riskier collision avoidance behaviour, as they failed to modulate the onset of trajectory deviation and adopted smaller obstacle clearances under dual-task conditions. Past studies related to obstacle crossing (stepping over) under dual-task conditions have reported both reduced [21] and increased toe clearance[24] in individuals with m/sTBI. While reasons for such difference between studies remain unclear, we do suggest that the task involved in the present study, where participants circumvented moving interferers approaching from different directions, is more demanding than stepping over a static obstacle in terms of planning and execution. It would thus require more cognitive resources, possibly exceeding a total cognitive capacity that is already comprised after m/sTBI and resulting in a riskier as opposed to a safer collision avoidance behaviour.

Given the divergent dual-task induced locomotor adaptations between the two groups, it is not surprising that the groups exhibited DTCs of different polarity (i.e., negative vs. positive DTCs) for most locomotor measures. Those positive and negative DTCs reflect, respectively, a decrease and an increase in a given measure under dual-task conditions. It is important to note, however, that some DTC values in the m/sTBI group were modest (e.g., 1.5% and 2.12% for onset distance), reflecting a lack of adaptation rather than an actual change. Overall, such alterations in the pattern of DTCs in the individuals with m/sTBI did not result in more collisions. A heightened risk of

collisions in busier community environments (e.g., shopping mall with multiple pedestrians walking in different directions), however, cannot be excluded.

Interestingly, the measures that displayed the largest DTCs in the present study were those related to gaze behaviour. Indeed, both groups showed a marked reduction in gaze fixation on the approaching VRP and an increased gaze fixation on the goal during dual-task conditions. Several studies have suggested gaze behaviour to be an indicator of attention allocation, with longer and/or more frequent fixations being devoted to objects or cues that are being focussed on.[42] In the present study, the fact that a non-visually based cognitive task modified the relative gaze fixation duration on visual cues (approaching VRP and goal) that are essential for the successful completion of the locomotor task suggests an interference with the allocation of attention. Yet, as participants did not experience more collisions under dual-task conditions, it is possible that quickly looking at the approaching pedestrian was sufficient to make the proper adjustments in the locomotor trajectory and avoid a collision. Other elements such as peripheral vision[148, 149] and eye proprioceptive information provided through gaze shifts[150] may have further assisted with the localization of the interferer. As for the prolonged fixation on the goal, it may have served the purpose of fulfilling the goal-oriented component of the walking task.[88] It is also possible that in response to the increased attentional load, individuals reduced their visual scanning of the environment, resulting in a gaze orientation towards the midline where the goal was located. This hypothesis, however, would need to be verified through spatial-temporal analysis of gaze allocation on the different features present in the virtual simulation.

As for the gaze behaviour of individuals with m/sTBI, the reduction in gaze fixation on the approaching pedestrian was up to twice as small in the m/sTBI group as in the healthy group. As suggested earlier, it could be hypothesized that individuals with m/sTBI are more reliant on visual

information to perform an obstacle avoidance task while walking.[21] In the present study, however, they exhibited shorter gaze fixations on the approaching pedestrian compared to healthy controls in the single task condition. It is possible that the m/sTBI group, who already showed short visual fixations on the approaching VRP in single-task walking, could not afford to reduce this gaze fixation to the same extent as healthy controls in the dual-task conditions, in order to provide adequate visual information about the obstacle and successfully complete the collision avoidance task. As for the individuals with m/sTBI displaying shorter gaze fixations on the approaching VRP in the single task condition compared to their healthy counterpart, it is likely attributed to them focussing on other elements in the environment, although none of those elements (goal, environment, other pedestrians) considered in isolation came out as significantly different between the two groups. Whether they were focusing on other visual cues that helped them planned their trajectory or on other elements of the scene that were irrelevant to the task (e.g., buildings, trash bins, etc.) remains an open question.

The complexity of the cognitive task had overall a minimal impact on locomotor DTCs, except for maximum walking speed and maximum lateral deviation, for which both groups increased their DTCs towards more positive values in the more complex dual-task condition. This indicates that individuals from both groups experienced slower maximum walking speeds and less maximum lateral deviations in the complex vs. simple dual-task condition. Such findings are consistent with the larger DTCs observed for various locomotor measures due to increased task complexity in other populations such as stroke.[70, 151] Such effect of task complexity is likely due to participants' cognitive resources being further 'taxed' when performing the more complex cognitive task.

Present findings also showed that the direction of obstacle approach modulated locomotor measures. Such modulation, observed in earlier studies, is show to be characterized by one or

several of the following changes, including earlier onsets of trajectory deviation, smaller minimum distance, greater maximum lateral displacement, faster walking speeds and longer duration of gaze fixation on the approaching VRP in the presence of obstacles/interferers approaching from the middle vs. diagonally. [59, 61, 84, 88] It was suggested that negotiating with a middle obstacle approach is more challenging than with a diagonal approach, as the former absolutely requires a trajectory change to prevent a collision, whereas the latter can also be avoided through walking speed adjustments.[61, 73, 88] In the present study, an interaction of group and direction also indicated that individuals with m/sTBI maintained smaller minimum distances from the interferer compared to healthy controls for the middle approach specifically, both in single and dual-task conditions. This illustrates the increased difficulty experienced by individuals with m/sTBI in negotiating this more challenging or riskier obstacle condition.

3.5.2 DUAL TASK COGNITIVE PERFORMANCE

Individuals with m/sTBI showed alterations in both locomotor and cognitive performances during dual-task walking, in contrast to healthy controls whose alterations in performance were limited to the locomotor task. Although not statistically different from the simple dual-task condition, the cognitive DTC in the m/sTBI group was especially pronounced for the complex dual-task condition. These findings, which suggest the presence of a cognitive-motor interference, align with previous studies carried out in individuals with m/sTBI[21, 24] and other populations with neurological conditions such as stroke.[70, 109, 110] They also align with the fact that individuals with m/sTBI in the present study gave higher subjective ratings of task difficulty for the dual-task condition than for the single-task condition, and generally higher ratings than healthy controls.

Altered executive functions could explain, at least in part, this DTC in cognitive performance, as individuals with m/sTBI exhibited a reduced performance on clinical tests of cognitive executive functions to start with, as well as on the Auditory Stroop Task performed as a single task. In fact, individuals with m/sTBI can experience a variety of cognitive deficits, including slowed information processing, impaired long-term memory, attention, working memory, executive function, mental flexibility, inhibitory control and mental fatigue.[152] Thus, while individuals with m/sTBI may possess sufficient cognitive abilities to successfully perform simple cognitive tasks under single-task conditions, their performance is compromised when exposed to cognitive tasks with higher demands in terms of executive functions, or when attention is divided as in dual-task walking. More specifically, alterations in visuospatial processing, as indicated in the present study by results of m/sTBI participants on TMT-A and TMT-B, could be at cause, since such alterations were shown to correlate with smaller toe clearance when stepping over an obstacle under both single and dual-task conditions in individuals with m/sTBI.[153]

As for the healthy individuals in the present study, who were in their middle adulthood, they presented a locomotor-only interference that contrasts with the cognitive-only interference previously reported for healthy young adults tested under identical experimental conditions.[88] In fact, their levels of accuracy on the cognitive tasks (97.30 to 99.55%) appear to surpass that of the healthy young adults (range 88.53 to 97.65),[88] with a 9% difference in accuracy on the complex dual-task condition. This enhanced performance on the cognitive task, along with the locomotor-only interference, suggest that the middle-aged adults in the present study were more focused on the cognitive tasks at the expense of the locomotor task, for which they showed a more conservative behaviour.

3.5.3 CLINICAL IMPLICATIONS

Our study indicates that individuals with a chronic m/sTBI, in spite of a good locomotor recovery, exhibit residual deficits in obstacle circumvention that are especially pronounced in dual-task conditions, possibly increasing the risk of collisions and interfering with community walking abilities. Dual-task walking training could be integrated early in the process of rehabilitation, while exposing individuals to scenarios of various complexities that simulate real-life locomotor challenges. Additionally, and as observed in a recent study involving stroke survivors,[151] our study revealed that standardized clinical assessments such as TUG-Cog may overlook dual-task walking difficulties related to complex daily locomotor tasks. Such observation highlights the potential of VR as a tool for the evaluation and training of dual-task walking abilities in individuals with m/sTBI.

3.5.4 LIMITATIONS

We acknowledge some limitations in our study. This protocol was conducted during the Covid-19 pandemic, and therefore participants circumvention strategies may have been influenced by the unique context of social distancing and heightened anxiety levels.[84] Such an effect, however, would be expected to be similar in both groups. In addition, the use of a VR-based protocol may have impacted on the locomotor behaviour, inducing larger obstacle clearances and slower walking speeds compared to what would be observed in the real world; these differences, however, were shown to be of small magnitude (10-13%).[61] Furthermore, the ability to control experimental conditions and the safety of VR outweigh this limitation, making it a valuable tool for studying complex locomotor tasks.

3.6 CONCLUSION

This study revealed that individuals with chronic m/sTBI present alterations in both locomotor and cognitive performances when circumventing pedestrians under dual-task conditions, as opposed to healthy individuals who only show an alteration in their locomotor performance. In addition, the nature of the dual-task induced alterations differed between groups, the m/sTBI group showing riskier collision avoidance that contrasts with the more conservative locomotor behaviour displayed by healthy individuals. The extent of gaze behaviour modulation under dual-task condition also differed between the two groups, possibly reflecting alterations in the allocation of attention. Present findings raise concerns about potential collisions in crowded community environments in individuals with m/sTBI, while highlighting the compromised complex walking abilities in this population who otherwise present a good locomotor recovery. Collectively these findings emphasize the pressing need to assess and enhance these abilities as integral components of rehabilitation.

AVAILABILITY OF DATA AND MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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AUTHOR'S CONTRIBUTION

TACS is the primary author of this manuscript and contributed to the research design, data collection and analysis, interpretation of findings, preparation of figures/tables, and writing of the manuscript. AL and BJM contributed to design of the study and oversaw all steps leading to this publication, while critically reviewing the manuscript. KZHL and IJG provided feedback on the protocol, contributed to the interpretation of findings and reviewed this manuscript prior to its submission to the journal.

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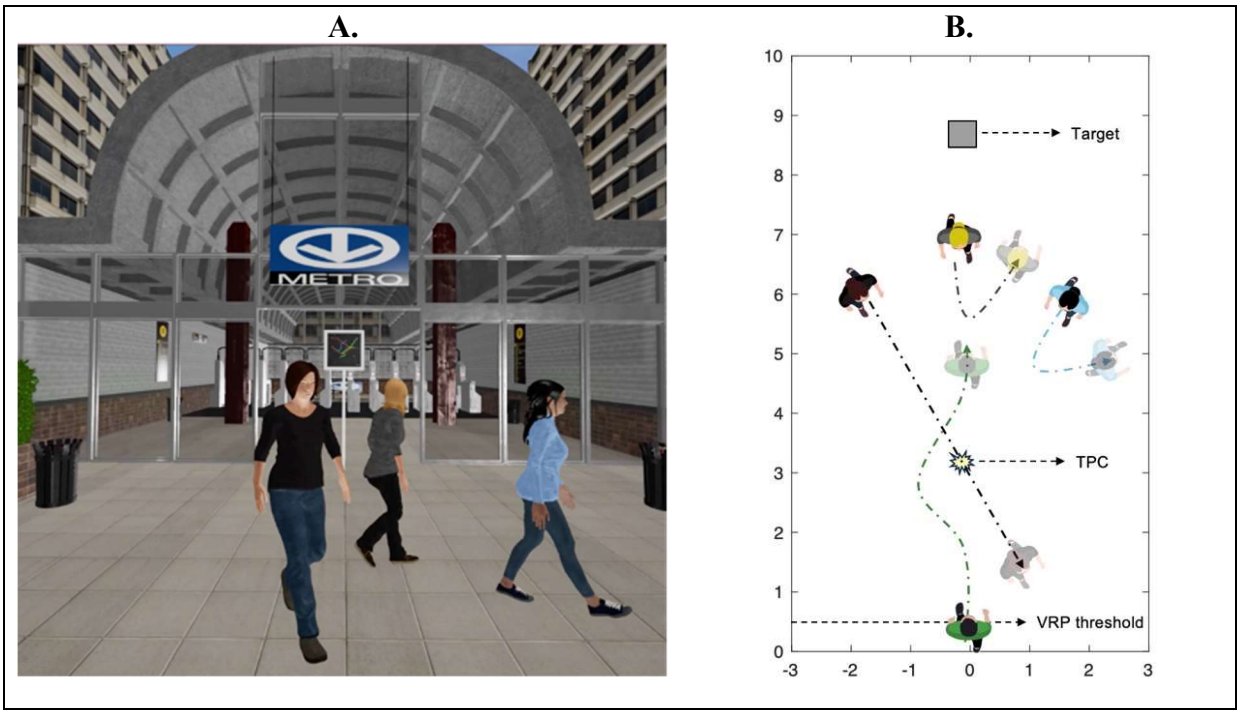

Figure 3.1. A. Virtual environment representing a subway station with pedestrians, as viewed by the participants during a diagonal virtual pedestrian (VRP) approach (left). **B.** Schematic representation of the obstacle circumvention task from a bird's eye view, when avoiding a left VRP approach.

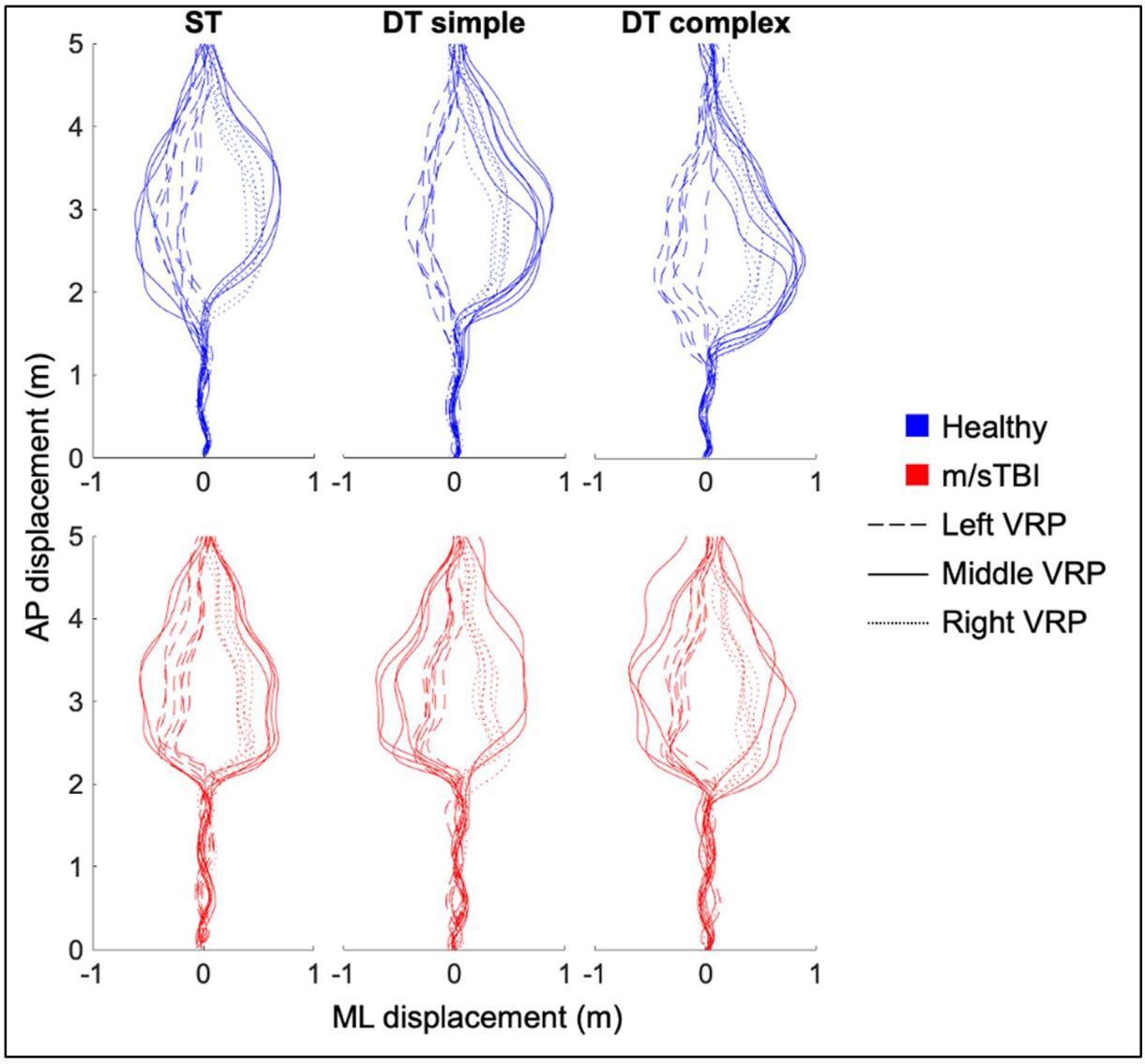

Figure 3.2. Walking trajectories of one healthy participant and one participant with m/sTBI for each locomotor task. Different scales were used for AP and ML displacement in order to better represent the walking trajectories. m/sTBI – Moderate-to-severe traumatic brain injury; AP – Antero-posterior; ML – Medio-lateral; VRP – Virtual pedestrian.

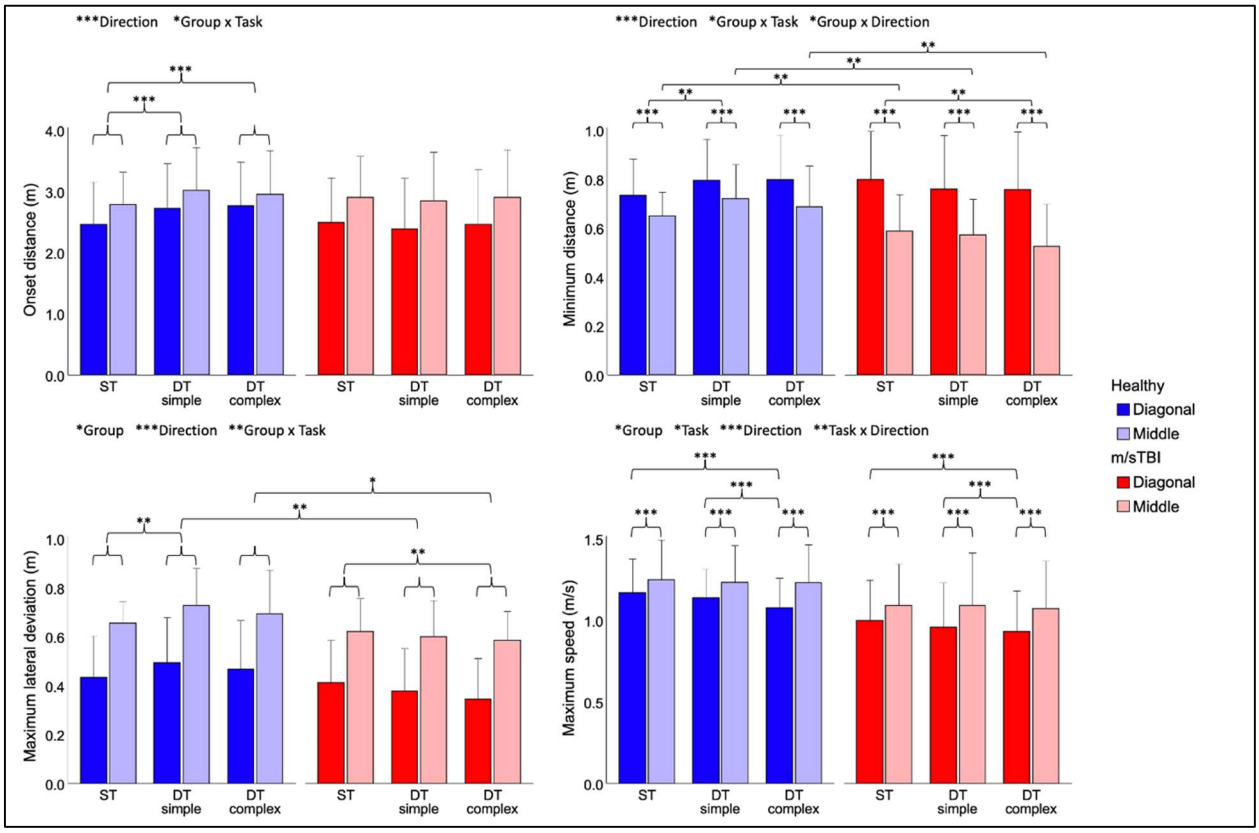

Figure 3.3. Locomotor measures (mean + 1 SD) for the healthy and m/sTBI participants across tasks and directions of pedestrian approach. Significant main and interaction effects are illustrated at the top of each graph, while results of post-hoc analyses are illustrated within each graph. m/sTBI – Moderate-to-severe traumatic brain injury; ST – single task; DT – dual task. Level of significance: *p-value < 0.05; **p-value < 0.01; ***p-value <0.001.

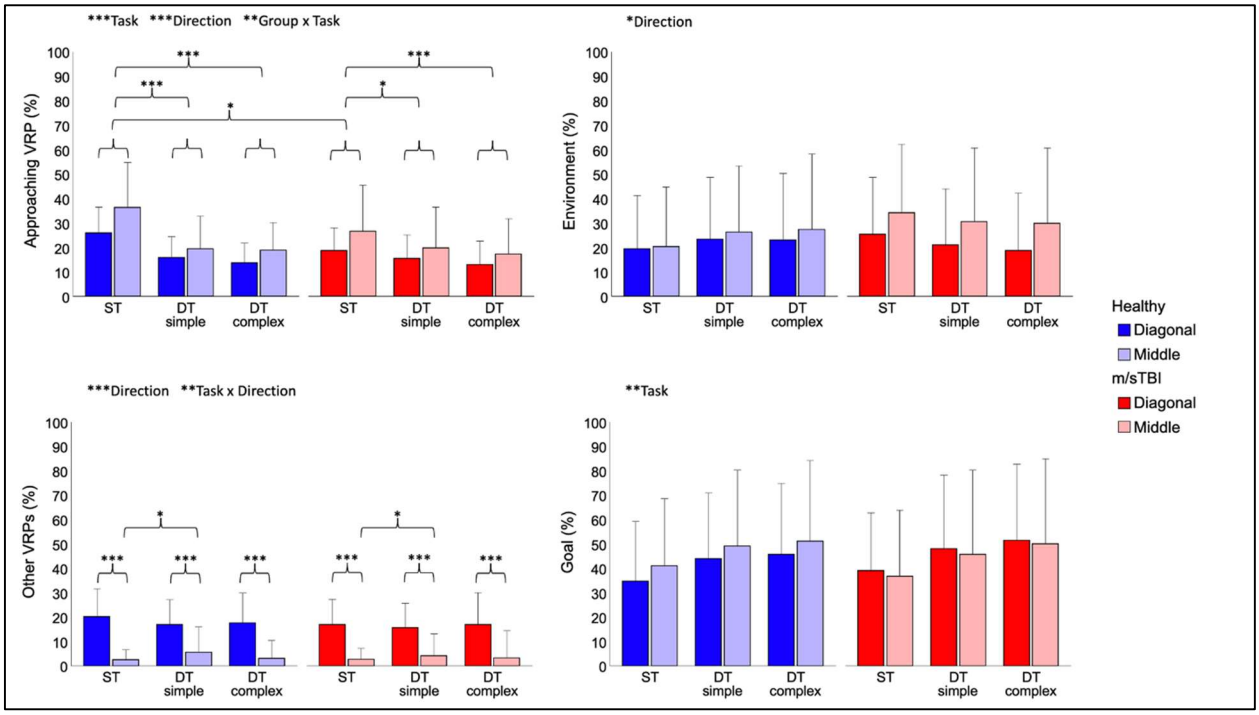

Figure 3.4. Gaze behaviour measures (mean + 1 SD) for the healthy and m/sTBI participants across tasks and directions of pedestrian approach. Significant main and interaction effects are illustrated at the top of each graph, while results of post-hoc analyses are illustrated within each graph. m/sTBI – Moderate-to-severe traumatic brain injury; ST – single task; DT – dual task. Level of significance: *p-value < 0.05; **p-value < 0.01; ***p-value <0.001.

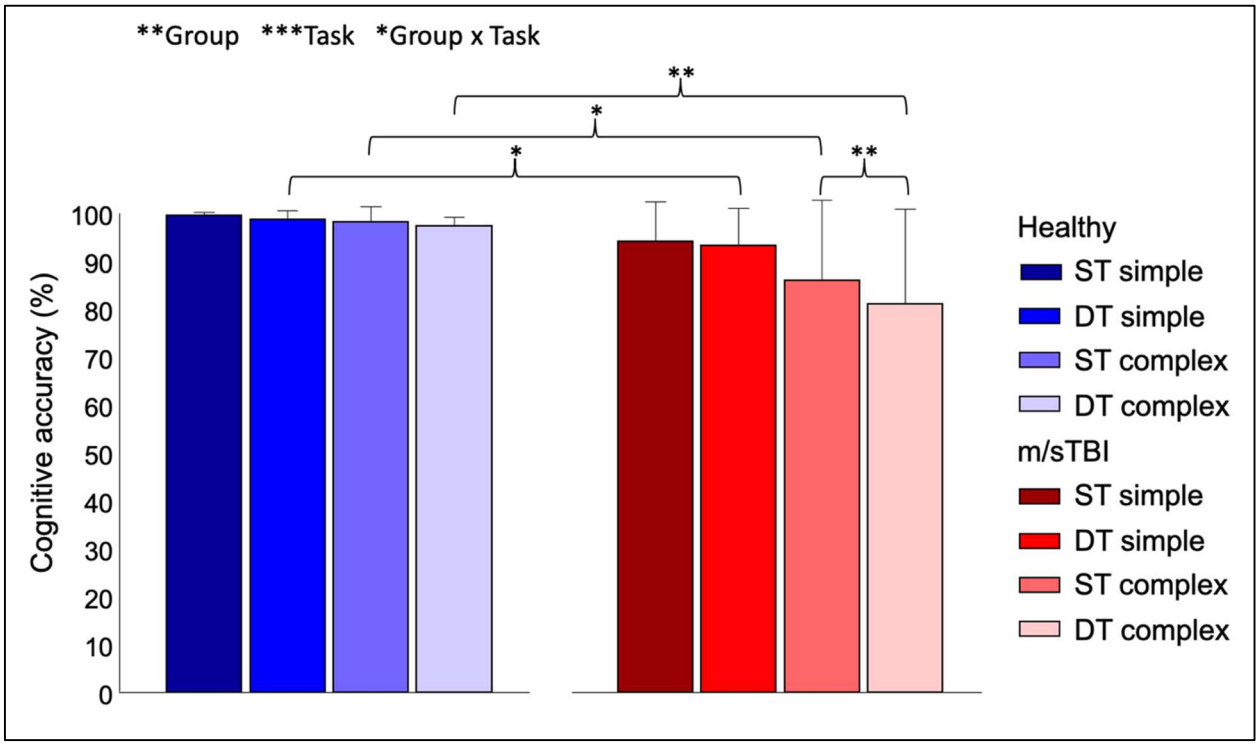

Figure 3.5. Percentages of correct response (mean + 1 SD) on the simple and complex cognitive tasks performed in single- and dual-task conditions in healthy and m/sTBI participants. m/sTBI – Moderate-to-severe traumatic brain injury; ST – single task; DT – dual task. Level of significance: **p*-value < 0.05; ***p*-value < 0.01; ****p*-value <0.001.

	Group		*P*-value
	Healthy (n=12)	**m/sTBI (n=12)**	
Demographics			
Age (years)	41.8 (8.3)	43.3 (9.5)	0.685
Sex (Female/Male)†	4/8	3/9	0.653
Handedness (Left/Ambidextrous/Right) †	0/0/12	0/2/10	0.14
Level of education (years of schooling)	17.0 (2.6)	16.3 (5.6)	0.710
VR experience (Yes/No) †	6/6	8/4	0.408
TBI severity (Moderate/Severe) †	-	4/8	-
Time since TBI (months) §	-	29 (49.8)	-
PTA duration (days) §	-	10.5 (25.5)	-
GCS (3-15)	-	7.1 (3.6)	-
Balance & Mobility			
ABC (%)	98.5 (3.0)	76.2 (15.0)	**<0.001**
CB&M (0-96)	88.4 (6.6)	63.4 (23.8)	**0.002**
Comfortable walking speed (m/s)	1.5 (0.2)	1.2 (0.2)	**0.032**
Maximum walking speed (m/s)	2.2 (0.3)	1.7 (0.4)	**<0.001**
TUG (s)	8.3 (1.0)	9.3 (2.3)	0.168
TUG-Cog (s)	9.9 (2.0)	11.4 (3.3)	0.2
TUG-DTC (%)	-18.7 (18.0)	-21.4 (13.5)	0.692
Cognition			
MoCA (max=30)	28.3 (1.5)	24.8 (3.2)	**0.002**
TMT-A (s)	22.7 (5.4)	40.1 (14.3)	**<0.001**
TMT-B (s)	62.2 (24.7)	99.4 (40.1)	**0.012**
Digit Span - Forward (s)	10.0 (1.9)	9.1 (3.6)	0.444
- Backward (s)	8.8 (2.9)	7.9 (2.7)	0.475
Post-experiment questionnaires			
Fast Motion Sickness Scale (0-20)	0.2 (0.6)	3.2 (4.4)	**0.028**
Single-Item Measure of Presence (0-10)	7.3 (2.5)	6.6 (3.0)	0.560

Table 3.1. Characteristics of participants. Mean (± 1 SD) are indicated, with the exception of variables with a † symbol for which numbers of participants are indicated, and § symbol for which the numbers represent the median. P-values for between-group comparisons are indicated when applicable and are in bold when < 0.05. VR – Virtual Reality; m/sTBI – Moderate-to-Severe Traumatic Brain Injury; PTA – Post-traumatic amnesia; GCS – Glasgow Coma Scale; ABC – Activities-Specific Balance Confidence Scale; CB&M – Community Balance and Mobility Scale; TUG – Timed Up and Go; MoCA – Montreal Cognitive Assessment; TMT – Trail Making Test.

Locomotor DTCs (%)	Group				*P*-value	
	Healthy		m/sTBI			
	Complexity					
	Simple	Complex	Simple	Complex	Group	Complexity
Onset time	-9.81 (10.22)	-7.79 (9.51)	5.49 (11.70)	4.53 (19.03)	**0.001**	0.850
Onset distance	-10.11 (11.21)	-10.03 (9.10)	1.50 (13.89)	2.12 (15.32)	**0.001**	0.915
Minimum distance	-9.24 (12.12)	-7.71 (14.70)	4.22 (12.01)	6.43 (9.26)	**0.001**	0.343
Maximum speed	1.84 (7.00)	5.42 (10.14)	3.08 (11.37)	5.19 (15.21)	0.906	**0.010**
Maximum lateral deviation	-12.57 (16.20)	-5.32 (15.22)	3.28 (15.66)	11.48 (11.97)	**0.001**	**0.006**
Gaze behaviour DTCs (%)						
Approaching VRP	42.29 (9.87)	46.95 (10.66)	20.62 (32.53)	33.11 (28.63)	**0.033**	**0.011**
Other VRPs	4.08 (20.98)	6.98 (25.53)	-5.90 (50.07)	-14.63 (56.20)	0.302	0.578
Goal	-32.72 (62.17)	-33.35 (39.16)	-27.52 (60.83)	-42.79 (79.99)	0.923	0.486
Cognitive DTCs (%)						
Cognitive accuracy	0.79 (1.48)	0.78 (4.56)	0.62 (6.01)	6.91 (9.82)	**0.038**	0.110

Table 3.2. Mean (1SD) for dual-task costs. DTC – Dual-task cost; VRP – Virtual pedestrian. Statistically significant p-values for the effect of group and complexity are shown in bold.

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CHAPTER 4: GENERAL DISCUSSION

This thesis examined locomotor-cognitive interferences in a dual-task obstacle circumvention paradigm, observing interactions between individuals with m/sTBI and virtual pedestrians in an ecological environment simulating a subway station. Additionally, we also characterized gaze behavior as an indicator of visuo-spatial attention. Comparisons with age and sex-matched healthy participants revealed different locomotor, cognitive and gaze strategies for individuals with m/sTBI. This chapter adds to the manuscript discussion above to go over the knowledge gaps addressed by this thesis, explores the clinical implications of the findings, and suggests directions for future studies.

4.1 MAIN FINDINGS

The findings of this MSc thesis confirmed some of the hypotheses originally proposed while refuting others. Notably, it was confirmed that individuals with m/sTBI exhibited mutual cognitive and locomotor interference during dual-task conditions. Such interference was expressed by a riskier obstacle avoidance behaviour, characterized by a lack of modulation in anticipatory adjustments of the locomotor trajectory and a closer proximity with the obstacle, as well as by a lower response accuracy on the cognitive task when combined with locomotor navigation. Such mutual interference aligns with what was observed previously in individuals with m/sTBI performing other locomotor tasks[21] or in other populations such as stroke.[70, 110] Mutual interference may be due to compromised cognitive executive functions responsible for locomotor judgment, planning, execution, and inhibition,[25] as well as to the presence of sensorimotor impairments, even if subtle, that impact the execution of the locomotor task itself.[5, 154-156] As a result, task demands likely exceeded the individuals' total attentional capacity, leading to a deterioration in dual-task

performance. In favor of such an explanation, it was shown that individuals with neurological conditions already demonstrate higher brain activation in cognitive performance during single-task conditions compared to healthy controls. This would compromise their ability to further adjust brain activation with increasing cognitive load in dual-task condition,[157] here leading to a riskier obstacle circumvention behavior and decreased cognitive task accuracy.

As for healthy controls, and in contrast to the initially hypothesized dual-task cognitive interference, only a locomotor interference was observed. This locomotor interference was characterized by earlier anticipatory adjustments of the locomotor trajectory and increased obstacle clearance during dual- vs. single-task conditions. Studies reporting similar findings classify these types of adaptations as a conservative/safe behaviour.[55, 67, 84] While similar dual-task adaptations are documented in the literature for older adults,[59] it is not the case for younger adults who, in the context of an identical VR-based circumvention study as this study, showed exclusively a cognitive DTC.[88] Given the age of the participants in the current study, it may be that this conservative locomotor adaptation in response to a dual-task context emerges in healthy adults around middle adulthood, coinciding with the onset of age-related cognitive decline.[143, 146] The adoption of a conservative strategy by middle-aged healthy controls in the present study likely aimed at safely navigating the obstacle while allowing them to allocate sufficient attention to the concurrent cognitive task. This strategy thus enabled them to be successful with the concurrent task demands, which were to avoid a collision with the interferer and to provide accurate answers on the cognitive task.

In contrast to what was hypothesized, the results of this MSc thesis work also revealed a pattern of shorter gaze fixations on the approaching pedestrian and longer fixations on the goal during the dual- vs. single-task condition for both groups. We suggest that such dual-task induced alterations

in gaze behaviour results from an interference with the allocation of attention, which shifted the attention from the obstacle towards other elements in the environment (such as the goal). It is possible that individuals may have successfully completed the task by the use of their peripheral vision[149] or with quick glances at the approaching pedestrian that was impossible to measure with the current set-up.[150]

It is also interesting to note that unlike the healthy middle-aged individuals in the present study, healthy young adults in a previous study were shown to not modify their gaze behaviour under similar dual-task walking conditions.[88] Gaze behaviour adaptations shown for the healthy individuals in the present study, similar to their locomotor adaptations, could be attributed to ageing. As for the individuals with m/sTBI, their reduction in gaze fixation on the approaching pedestrian during dual-task conditions was not as great as for healthy controls. However, they already had a lower gaze fixation duration during the single-task condition and thus ended up with similar gaze fixation durations as healthy controls during dual-task conditions. Given these observations, it is possible that individuals with m/sTBI could not afford to further reduce their gaze fixation on the approaching VRP in order to successfully execute the collision avoidance task. As for their shorter gaze fixation duration on the approaching pedestrian in single-task condition, suggesting an already reduced visual attention towards the 'obstacle', this could possibly be due to the poor visuo-spatial attention reported in this population,[94-96] as well as to alterations in oculomotor and vestibulo-oculomotor functions.[75, 89] The latter suggestions could be explored, in the future, through a comprehensive assessment of visuo-spatial abilities as well as oculomotor and vestibulo-oculomotor functions, and by exploring correlations between such functions and gaze behaviour in single and dual-task walking.

Both groups showed increased costs under more complex vs. simple dual-task conditions, as shown by slower speeds and reduced lateral deviations. This is consistent with similar observations in individuals with other acquired brain injuries such as stroke,[70, 151] suggesting that increased cognitive task complexity taxes participants' cognitive resources and impacts locomotor performance. However, the complexity of the task did not affect the onset of trajectory deviation and minimum distance (clearance). Such finding could be explained by a prioritization of selective locomotor variables. Indeed, participants might have prioritized the onset of trajectory deviation and obstacle clearance, as they are crucial control variables to ensure the successful execution of the obstacle avoidance task. In return, such prioritization may have been done at the expense of walking speed and lateral trajectory deviation. Further studies are needed, however, to confirm these hypotheses.

This study also confirmed the well-established observation that the direction of obstacle approach influences locomotor measures. [59, 61, 73, 84, 88] Indeed, obstacles approaching from the middle vs. the diagonal directions elicited earlier trajectory deviation, smaller minimum distance, greater lateral displacement, faster walking speeds, and prolonged gaze fixation in the present study, which was suggested to be caused by the increased risk of collision imposed by a head-on condition. As noted above, individuals with m/sTBI consistently maintained smaller minimum distances from pedestrians approaching from a middle direction, highlighting their increased challenge in negotiating this riskier obstacle condition compared to healthy controls.

4.2 SIGNIFICANCE AND FUTURE DIRECTIONS

The findings from the present study contribute to a more comprehensive understanding of the locomotor and cognitive behaviors exhibited by individuals with chronic m/sTBI when walking in

a simulated community environment while avoiding collisions with pedestrians approaching from multiple directions. Additionally, this study sheds light on the modulatory impact of dual-task conditions. Notably, this research marks the first characterization of gaze behavior during locomotion in this population when performing locomotor adaptations. Previous investigations into the dual-task modulation of obstacle avoidance among individuals with m/sTBI have also predominantly focused on stepping-over obstacles, with limited exploration into obstacle circumvention. A strength of this MSc project is the use of a VR paradigm to "extrapolate" beyond the limitations of a laboratory setting, "transporting" participants into an ecological representation of a dynamic community environment with moving pedestrians, as the literature shows it can influence measures.[55, 61] This also allowed exposure to both single and dual-task conditions that closely mimicked the daily reality of pedestrians, while simultaneously tracking participants' gaze fixation on elements of the scenario, which would be much more difficult to do in any other way.

The clinical significance of this study is multifold. First, despite a good locomotor recovery, individuals with chronic m/sTBI showed persistent residual deficits in dual-task walking, mainly when exposed to more complex locomotor and cognitive tasks. Thus, dual-task walking training should be incorporated more systematically into gait rehabilitation for individuals with m/sTBI, while exposing them to functional tasks that mirror the challenges and complexity of activities of daily living. Recent studies have demonstrated the benefits and superiority of dual-task walking training, compared to sequential locomotor and cognitive training, in improving balance, mobility, walking speed, and fear of falling in people with different neurological conditions, including TBI.[158, 159] Additionally, and as observed in a recent study involving stroke survivors,[151] our study revealed that standardized clinical assessments such as the TUG-Cog, which involves a locomotor and a cognitive task performed concurrently, may overlook dual-task walking difficulties related

to complex, daily locomotor tasks. Such observation highlights the potential of VR as a tool for the evaluation and training of dual-task walking abilities in individuals with m/sTBI. The use of VR provides means to expose individuals to safe, ecological and dynamic environments while grading the complexity of the tasks and offering the experimenter or clinician the opportunity to document performance with objective measures.

This project can be extended to investigate the locomotor and dual-task behaviour of individuals with m/sTBI in areas with higher population density, such as shopping malls where crowds and multiple distractors are present. Although not detecting a significant increase in the number of collisions when walking under dual-task conditions, we cannot not rule out the risk of collisions in such places due to the riskier behavior observed in individuals with m/sTBI in our study. Despite the abundance of literature investigating locomotion and cognition impairments on mild TBI (concussion), research on moderate-to-severe cases is limited, necessitating a focused effort to understand and address the specific challenges and long-term consequences these individuals face. This study showed that standard clinical assessments, such as TUG-Cog may overlook impairments of daily tasks, highlighting the effectiveness of VR in detecting between-group differences. Therefore, future studies should continue to explore the potential of new technologies such as VR and augmented reality as accurate tools for functional assessment.

4.3 CONCLUSION

Findings suggest that healthy individuals walking under dual-task conditions adopted safer avoidance strategies during circumvention without compromising cognitive performance. In contrast, individuals with chronic m/sTBI failed to modulate their locomotor performance and showed reduced cognitive performance in both simple and complex dual-task conditions, possibly

increasing the risk of collision with pedestrians. Altered dual-task walking abilities in m/sTBI may contribute to poor community walking in this population. Future studies are needed to expand our findings across other environments and across a wider sample of individuals with m/sTBI of differ locomotor capacities.

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APPENDIX

Appendix 1: English consent form for participants without TBI

INFORMED CONSENT FORM

Participants without traumatic brain injury

1. STUDY TITLE

Impact of dual-task walking when avoiding collision with a virtual pedestrian in individuals with moderate-to-severe traumatic brain injury.

2. PRINCIPAL INVESTIGATORS

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5. Funding agency

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6. Introduction

We invite you to participate in a research project that examines the strategies you use while walking to avoid colliding with virtual pedestrians. In addition, this study will assess your ability to perform a pedestrian avoidance task and a mental task simultaneously. Before agreeing to participate in this project, please take the time to read and carefully consider the following information.

This consent form explains the aim of this study, the procedures, advantages, risks, and inconveniences, as well as the persons to contact, if necessary.

This consent form may contain words that you do not understand. We invite you to ask any question that you consider useful to the investigator and the other staff members assigned to the research project and ask them to explain any word or information that is not clear to you.

7. Description of the project and its objectives

Avoiding collisions with obstacles around us is essential to walking safely in everyday life. When we walk in a shopping mall or a park, for example, we encounter objects and people on our path that we must avoid by going around them. To do this, we mainly use our sense of vision which allows us to locate obstacles on our path. We then modify our trajectory and walking speed to avoid colliding with these obstacles.

People with moderate to severe traumatic brain injury (m/s TBI) may have different strategies for avoiding obstacles on their path. They may also have difficulty when they have to perform a mental task at the same time as avoiding obstacles. This difficulty may affect their ability to walk safely in the community.

Therefore, the main objective of this research project is to compare how individuals with m/s TBI avoid virtual pedestrians in a single-task situation (bypassing pedestrians only) and in a double-task situation (performing the pedestrian avoidance and the mental task at the same time). The results obtained in terms of walking and eye movements, as well as those obtained

during the mental task, will be compared to those of healthy individuals who have not undergone a TBI.

8. NATURE OF PARTICIPATION

If you agree to participate in this study, you will attend two (2) assessment sessions of 2 to 2.5 hours each. These 2 sessions will ideally take place in the same week. They will take place at the Virtual Reality & Mobility Laboratory of the Jewish Rehabilitation Hospital in Laval-QC, located at 3205 Place Alton-Goldbloom, Laval (Qc), H7V 3R6. A contact person and one of the researchers will be present during the evaluations to greet you and help you move around as needed.

Session 1 (2.5 hours):

At the beginning of this first session, you will have ample time to read and sign the consent form. All questions that you may have regarding the experiment will be answered. At this stage, you will be invited to perform clinical tests, to fill in questionnaires and to answer short questions that will be used either to confirm your eligibility to the study (screening evaluation) or to gather data needed the project (clinical evaluation). Your results on the screening evaluation will dictate whether you will proceed to the next phases.

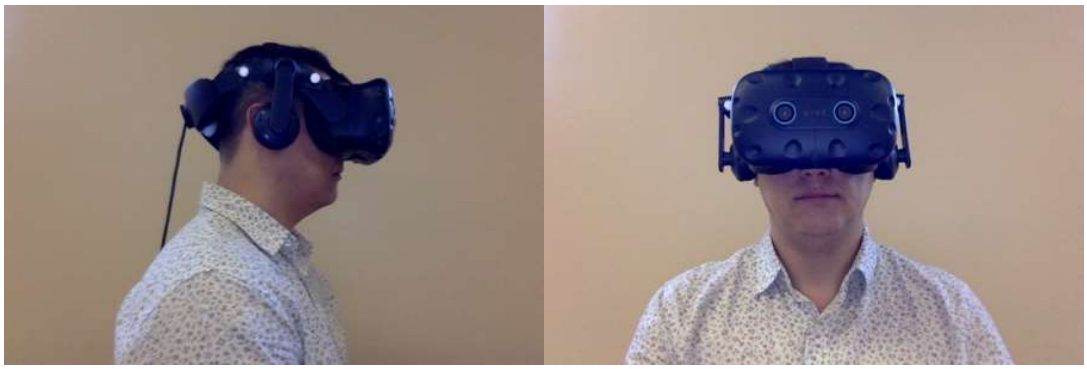
1. Screening Evaluation: Your comfortable walking speed will be assessed. Your vision and audition will also be confirmed with visual and auditory tests, and by asking you to identify visual or auditory elements in a virtual environment.

2. Clinical Evaluation: If you meet the eligibility criteria, we will further proceed with the following evaluation. Clinical tests will be used to assess your handedness, cognitive function, balance confidence, walking function, and maximal walking speed. We will also assess your eye movements using a virtual reality tool developed by Saccade Analytics. In addition, we will ask you if you have ever driven in countries with left-hand traffic, and if you have had a Covid-19 infection that has left any after-effects.

Overall, and including breaks, evaluation session 1 should last 2.5 hours.

Session 2 (2.5 hours):

Preparation and set-up: The second evaluation session will be done while you walk in a virtual environment representing a metro station in Montreal. You will view the metro station through a comfortable, light-weight virtual reality headset equipped with an eye tracker allowing to record eye movements (see picture). Small reflective markers will be attached to different parts of your body (head, thorax, arms and legs) with hypoallergenic tape in order to track your movements. Your voice will also be recorded in order to collect your answers on the pitch discrimination task. Note that all recordings will be stored confidentially, and these recordings will not include any personal information and will not be used for any other purpose than check the accuracy of your answers. Your height, weight and a few body dimensions will be measured to assist with the data analysis.



Evaluation You will be asked to walk in a virtual environment along a 10m long path. You will have to avoid virtual pedestrians approaching from different directions. During some of the trials, you will also be asked to perform a mental task that consists of distinguishing the pitch of certain sounds (low vs high). This pitch discrimination task will also be repeated while seated. You will be completing about 30 trials for each condition, based on your ability, comfort and endurance. You shall rest as often as needed in between trials. A longer break will be inserted between the conditions. During the walking trials, a member of the research team will walk next to you for additional safety and will assist you back to the starting position.

Overall, including all breaks, evaluation session 2 should take about 2.5 hours.

9. PERSONAL BENEFITS OF PARTICIPATING IN THE STUDY

You will not benefit personally from taking part in this study. However, you might contribute to the advancement of science in the fields of rehabilitation, mobility and virtual reality, because the results from this study will provide information that will help in developing focused rehabilitation programs and assessment tools for dual-task walking deficits in persons sustaining a moderate-to-severe traumatic brain injury.

10. RISKS AND INCONVENIENCES ASSOCIATED WITH PARTICIPATING IN THE STUDY

Risks

Your participation in this research project involves minimal risks for you. There is a risk of losing balance during the walking trials which cannot be eliminated completely. To limit the risk of falling, a person will be at your side to ensure your safety.

Inconveniences

Your participation in this research project may present some inconveniences for you.

1) Travel/participation time: The travel time from your home to the research site as well as the participation time in the research project may represent an inconvenience for some people.
2) Use of markers: Hypoallergenic tape will be used to affix the reflective markers on the skin. Despite of this, there is a possibility of skin irritation where the markers are attached. In such case, a soothing lotion will be applied to your skin.

3) Cybersickness: You may experience some nausea while exposed to the virtual scenarios. The feeling of nausea will disappear when taking off the headset and with rest. It is also possible that the equipment used during the experiments might cause you a bit discomfort at times, which can also be solved with periods of rest.

4) Fatigue: You may experience fatigue following the evaluation, but this will be temporary. If you become tired during the session, you will be able to rest before continuing. The feeling of fatigue will wear off with rest.

11. ACCESS TO THE RESULTS AT THE END OF THE RESEARCH

At the end of the study, do you want to have access to the general results of this research project.

Yes ☐

No ☐

email or address: _____

12. CONFIDENTIALITY

All personal information collected concerning you during the study will be coded to ensure its confidentiality. Only the members of the research team will have access to it. However, for research project control purposes, your research record could be consulted by a person mandated by the REB of the CRIR institutions or by the Direction de l'éthique et de la qualité du ministère de la Santé et des Services sociaux du Québec. This person adheres to a policy of strict confidentiality. The research data (forms, questionnaires, written tests, and results sheets) will be kept under lock and key by Anouk Lamontagne, PhD, at the Jewish Rehabilitation Hospital, and the electronic data related to your evaluation will be transferred onto a password-protected hard drive. After a period of 7 years following the end of the project, all the research data will be destroyed. In the event that the results of this study are presented or published, no information that can identify you will be included.

As part of the partnership in this project, portions of your anonymized data will be shared with Saccade Analytics. They will receive information related to your TBI (time since accident, severity), sex, age and experimental data through password-protected drives. From the oculomotor assessment recorded with Saccade Analytics own virtual reality assessment tool, this data will be sent online using the company's online security measures.

13. VIDEO RECORDING AND/OR TAKING PHOTOGRAPHS

It is possible that certain sessions will be recorded via videos or that photographs will be taken of you. We would like to use these recordings or photographs, with your permission, for the purpose of training and/or scientific presentation purposes. However, it is unnecessary to consent to this in order to participate in this project. If you refuse, the recordings and photographs concerning you will be destroyed at the end of the project to respect your confidentiality. If you accept, your face will be blurred.

Do you authorize us to use your photographs or recordings for the purpose of training or scientific presentations and to keep these recordings with your research data?

Yes ☐ No ☐

14. VOLUNTARY PARTICIPATION AND RIGHT OF WITHDRAWAL

You are free to accept or refuse your participation in this research project. You can withdraw from the study at any time without giving any reason or being subjected to prejudice of any kind. You simply must notify the contact person of the research team.

If you withdraw or are withdrawn from the study, you may also request that the data already collected about you be removed from the study. In this case, all documents concerning you, or that can be identified as yours, will be destroyed if that is your decision. If the data has been anonymized (i.e., does not contain any information that can be used to identify you), the data will continue to be used in the analysis of the study. Please note that all anonymized data sent to Saccade Analytics cannot be destroyed by the principal investigators.

15. SECONDARY USE OF INFORMATION FOR RESEARCH PURPOSES

The information you provide may be used, before the expected date of its destruction, in other research projects that will focus on the different facets of the topic for which you are solicited today. These possible projects will be the responsibility of the principal investigator and will be authorized by the Research Ethics Committee of CRIR establishments. The research team is committed to maintaining and protecting the confidentiality of your data under the same conditions as for this project. Do you agree that your data can be used in this context?

☐ Yes ☐ No *

16. SUBSEQUENT STUDIES

It is possible that the results of this study will give rise to another research project. In this context, do you authorize the persons in charge of this project to contact you again and ask if you would like to participate in this new project?

☐ no
☐ yes, for one year *
☐ yes, for two years *
☐ yes, for three years *

* Note, if you check off one of these three options, your personal contact information will be kept by the Lead Investigator for the period which you have selected.

17. RESPONSIBILITY OF THE RESEARCH TEAM

By agreeing to participate in this study, you do not give up any of your legal rights nor release the researchers or institutions involved of their legal and professional obligations.

18. COMPENSATORY INDEMNITY

You will receive an amount up to a maximum of $30 to cover your travel and parking costs.

19. RESOURCE PERSONS

If you have questions about the research project, if you wish to withdraw from the study or if you want to speak with the research team, please contact: Dr. Anouk Lamontagne at 450-688-9550 extension 84168 or by email at the following address: anouk.lamontagne@mcgill.ca.

If you have any questions regarding your rights and responsibilities or your participation in this research project, you may contact the Research Ethics Coordinator of the REB, by email at the following email address: cercrir@ssss.gouv.qc.ca

Regarding complaints, you can also contact the Local Quality of Service and Complaints Commissioner of the Jewish Rehabilitation Hospital at the following phone number (450) 668-1010, ext. 23628, or by e-mail at plaintes.csssl@ssss.gouv.qc.ca

20. CONSENT

I declare that I have read and understood this project, the nature and the scope of my participation, as well as the risks and inconveniences to which I may be exposed, as presented in this document. I have had the opportunity to ask all my questions regarding the different aspects of the study and to receive answers to these questions. A signed copy of this information and consent form must be provided to me.

I, undersigned, voluntarily accept to participate in this study. I can withdraw my participation in this study at any time without prejudice of any kind. I certify that I was allowed all the time necessary to make my decision.

Participant's Name: SIGNATURE

_____ _____

Signed on _____ of _____, 20_____

THE RESEARCHER MUST GIVE A SIGNED COPY OF THE CONSENT FORM TO THE PARTICIPANT AND KEEP ANOTHER ONE IN THE RECORD

21. COMMITMENT OF THE INVESTIGATOR OR HER/HIS REPRESENTATIVE

I, undersigned, _____, certify:

(a) that I have explained to the signatory the terms of the present form;
(b) that I have answered any questions that she/he asked me in this regard;

(c) that I have clearly indicated that she/he remains, at any time, free to terminate her/his participation in the research project described above;
(d) that I will provide her/him a signed and dated copy of this form.

_____
Signature of the Lead Investigator or his representative

Signed on _____ of _____, 20_____

APPENDIX

LOCAL COMPLAINTS COMMISSIONNER OF THE CRIR INSTITUTIONS AND THEIR PARTNERS

Centre de réadaptation Lethbridge-Layton-Mackay
- **Centre de réadaptation Constance-Lethbridge**
- **Centre de réadaptation MAB-Mackay**

CIUSSS du Centre-Ouest-de-l'Île-de-Montréal
Phone: 514-340-8222, extension 24222
Email: ombudsman.ccomtl@ssss.gouv.qc.ca

Institut universitaire sur la réadaptation en déficience physique de Montréal
- **Centre de réadaptation Lucie-Bruneau**
- **Institut Raymond-Dewar**
- **Institut de réadaptation Gingras-Lindsay de Montréal**

CIUSSS du Centre-Sud-de-l'Île-de-Montréal
Phone: 514-593-3600
Email: commissaireauxplaintes.ccsmtl@ssss.gouv.qc.ca

Hôpital juif de réadaptation
CISSS de Laval
Phone: 450-668-1010, extension 23628
Email: plaintes.csssl@ssss.gouv.qc.ca

Institut Nazareth et Louis-Braille
CISSS de la Montérégie-Centre
Phone: 450-466-5434 of toll free 1-866-967-4825, extension 8884
Email: commissaire.cisssmc16@ssss.gouv.qc.ca

Centre de réadaptation en déficience physique des Laurentides
CISSS des Laurentides
Phone: 450-432-8708
Email: info-plaintes@ssss.gouv.qc.ca

Centre de réadaptation en déficience physique de Lanaudière
CISSS de Lanaudière
Phone: 450-759-5333, extension 2133 or toll-free 1-800-229-1152, extension 2133
Email: plaintes.cissslan@ssss.gouv.qc.ca

Appendix 2: French consent form for participants without TBI

FORMULAIRE D'INFORMATION ET DE CONSENTEMENT

Participant sans traumatisme cranio-cérébral

22. TITRE DU PROJET

Impact de la marche en double tâche lors de l'évitement de collision avec des piétons virtuels chez des personnes souffrant d'un traumatisme cranio-cérébral modéré à sévère.

23. RESPONSABLES DU PROJET

Anouk Lamontagne, PT, PhD
Professeure agrégée
École de physiothérapie et d'ergothérapie
Hôpital Juif de réadaptation, site de CRIR, CISSS-Laval
Tel: 450-588-9550, poste: 84168; courriel: anouk.lamontagne@mcgill.ca

Thiago de Aquino Costa Sousa
Étudiant à la maîtrise
École de physiothérapie et d'ergothérapie
Hôpital Juif de réadaptation, site de CRIR, CISSS-Laval
Tel: 450-588-9550, poste: 84654; courriel: thiago.sousa@mail.mcgill.ca

Bradford J. McFadyen, PhD
Professeur agrégé
Département de réadaptation, Université Laval.
Chercheur à CIRRIS
Tel: 418-529-9141, poste: 6584; courriel: brad.mcfadyen@fmed.ulaval.ca

24. COLLABORATEURS

Association Québécoise des Traumatisés Crâniens (AQTC)
220, Parc Avenue
Laval (Quebec) H7N 3X4
Tel: 514-274-7447
Website: https://www.aqtc.ca/

25. ORGANISATIONS PARTENAIRES

Saccade Analytics
Isabel Galiana, CEO
400 rue Montfort,
Montréal, H3C 4J9
isa.galiana@saccadeanalytics.com

26. ORGANISMES SUBVENTIONNAIRES

Ce projet de recherche est financé par l'Initiative de recherche intersectorielle *Société Inclusive*.

27. PRÉAMBULE

Nous vous invitons à participer à un projet de recherche qui examine les stratégies que vous utilisez en marchant pour éviter de rentrer en collision avec des piétons virtuels. De plus, cette étude évaluera votre capacité à exécuter simultanément une tâche de contournement de piétons et une tâche mentale. Avant d'accepter de participer à ce projet de recherche, veuillez prendre le temps de lire, de comprendre et de considérer attentivement les renseignements qui suivent.

Ce formulaire de consentement vous explique le but de cette étude, les procédures, les avantages, les risques et inconvénients, de même que les personnes avec qui communiquer au besoin.

Le présent formulaire de consentement peut contenir des mots que vous ne comprenez pas. Nous vous invitons à poser toutes les questions que vous jugerez utiles au chercheur et aux autres membres du personnel affecté au projet de recherche et à leur demander de vous expliquer tout mot ou renseignement qui n'est pas clair.

28. DESCRIPTION DU PROJET ET DE SES OBJECTIFS

Éviter d'entrer en collision avec les obstacles qui nous entourent est essentiel pour marcher de manière sécuritaire dans la vie de tous les jours. Lorsque nous marchons dans un centre commercial ou un parc, par exemple, nous rencontrons sur notre chemin des objets et des personnes que devons éviter en les contournant. Pour ce faire, nous utilisons principalement le sens de la vision qui nous permet de localiser les obstacles sur notre chemin. Nous modifions ensuite notre trajectoire et notre vitesse de marche pour éviter d'entrer en collision avec ces obstacles.

Les personnes ayant subi un traumatisme crânien modéré à sévère (TCC m/s) peuvent adopter des stratégies différentes pour éviter les obstacles présents sur leur chemin. Elles peuvent également éprouver des difficultés lorsqu'elles doivent effectuer une tâche mentale en même temps que l'évitement d'obstacles. Cette difficulté peut affecter la capacité à marcher de façon sécuritaire dans la communauté.

Par conséquent, l'objectif principal de ce projet de recherche est de comparer la façon dont les personnes ayant subi un TCC m/s contournent des piétons virtuels en situation de tâche simple (contourner les piétons seulement) et en situation

de double-tâche (effectuer en même temps le contournement de piéton et la tâche mentale). Les résultats obtenus en termes de mouvements de marche et des yeux, de même que ceux obtenus lors de la tâche mentale, seront comparés à ceux d'individus en bonne santé n'ayant pas subi un TCC.

29. NATURE DE LA PARTICIPATION

Si vous acceptez de participer à cette étude, vous assisterez à deux (2) sessions d'évaluation d'une durée de 2 à 2,5 heures chacune. Ces 2 sessions se dérouleront idéalement la même semaine. Elles auront lieu au Laboratoire de réalité virtuelle et de mobilité de l'Hôpital juif de réadaptation de Laval-QC, situé au 3205 Place Alton-Goldbloom, Laval (Qc), H7V 3R6. Une personne contact et l'un des chercheurs seront présents lors des évaluations pour vous accueillir et vous assister lors de vos déplacements au besoin.

Session 1 (2.5 heures):

Au début de cette première session, vous aurez tout le temps de lire et de signer le formulaire de consentement. Nous répondrons à toutes les questions que vous pourriez avoir concernant l'étude. Ensuite, vous serez invité à effectuer des tests cliniques, à remplir des questionnaires et à répondre à de brèves questions qui serviront soit à confirmer votre admissibilité à l'étude (évaluation de dépistage), soit à recueillir des données nécessaires au projet (évaluation clinique). Vos résultats à l'évaluation de dépistage détermineront si vous pourrez passer aux phases suivantes.

1. Évaluation de dépistage : Votre vitesse de marche confortable sera évaluée. Votre vision et votre audition seront également confirmées par des tests visuels et auditifs, ainsi qu'en vous demandant d'identifier des éléments visuels ou auditifs dans un environnement virtuel.

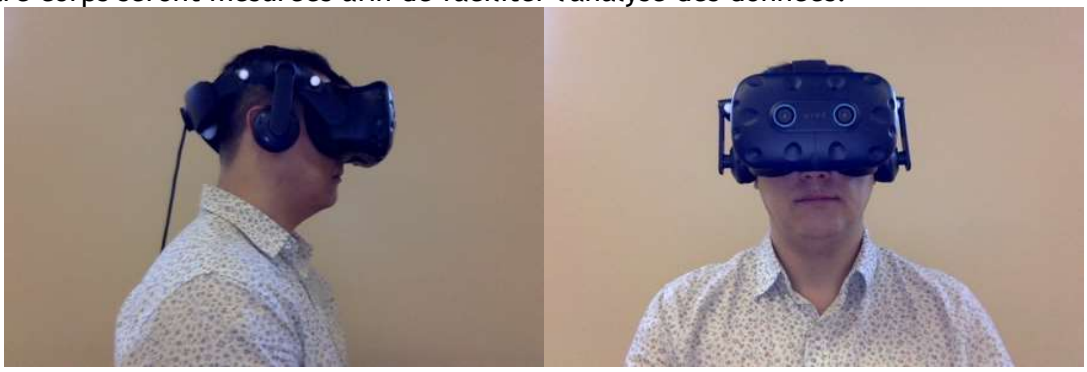
2. Évaluation clinique : Si vous répondez aux critères d'éligibilité, nous procéderons à l'évaluation suivante. Nous utiliserons des tests cliniques pour évaluer votre dominance manuelle, votre fonction cognitive, votre confiance en votre équilibre, votre fonction de marche et votre vitesse de marche maximale. Nous évaluerons également les mouvements de vos yeux à l'aide d'un outil de réalité virtuelle développé par Saccade Analytics. De plus, nous vous demanderons si vous avez déjà conduit dans des pays où la circulation se fait à gauche, et si vous avez eu une infection à la Covid-19 qui a laissé des séquelles.

Au total, en incluant les pauses, la session d'évaluation 1 devrait durer 2,5 heures.

Session 2 (2.5 heures):

Préparation et mise en place : La deuxième session d'évaluation se déroulera alors que vous marcherez dans un environnement virtuel représentant une station de métro de Montréal. Vous visualiserez la station de métro à travers un casque de réalité virtuelle confortable et léger équipé d'un système permettant d'enregistrer les mouvements de vos yeux (voir photo). De petits marqueurs réfléchissants seront fixés à différentes parties de votre corps (tête, thorax,

bras et jambes) avec du ruban adhésif hypoallergénique afin de suivre vos mouvements. Votre voix sera également enregistrée lors de certaines tâches pour nous aider à vérifier vos réponses. Notez que tous les enregistrements seront conservés de manière confidentielle et ne contiendront aucune information personnelle. Votre taille, votre poids et quelques segments de votre corps seront mesurées afin de faciliter l'analyse des données.



Évaluation : On vous demandera de marcher dans un environnement virtuel le long d'une allée de 10 m. Vous devrez éviter les piétons virtuels qui s'approchent de différentes directions. Lors de certains des essais, on vous demandera également d'effectuer une tâche mentale qui consiste à distinguer la hauteur de certains sons (graves vs aigüs). Cette tâche de discrimination des sons sera également répétée en position assise. Vous effectuerez environ 30 essais pour chaque condition, en fonction de vos capacités, de votre confort et de votre endurance. Vous pourrez vous reposer aussi souvent que nécessaire entre les essais. Une pause plus longue sera également prise entre les différentes conditions. Pendant les essais de marche, un membre de l'équipe de recherche marchera à vos côtés pour s'assurer de votre sécurité et vous aidera à revenir à la position de départ.

Au total, en incluant toutes les pauses, la session d'évaluation 2 devrait durer environ 2,5 heures.

30. AVANTAGES POUVANT DÉCOULER DE VOTRE PARTICIPATION

Vous ne bénéficierez pas personnellement de votre participation à cette étude. Cependant, vous pourriez contribuer à l'avancement de la science dans les domaines de la réadaptation, de la mobilité et de la réalité virtuelle, car les résultats de cette étude fourniront des informations qui aideront à développer des programmes de réadaptation ciblés et de meilleurs outils d'évaluation des déficits de la marche en double tâche chez les personnes ayant subi un traumatisme cranio-cérébral modéré à sévère.

31. RISQUES ET INCONVÉNIENTS POUVANT DÉCOULER DE VOTRE PARTICIPATION

Risques

Votre participation à ce projet de recherche comporte des risques minimes pour vous. Il existe un risque de perte d'équilibre pendant les essais de marche qui ne peut être totalement éliminé. Pour limiter le risque de chute, une personne sera à vos côtés pour assurer votre sécurité.

Inconvénients

Votre participation à ce projet de recherche peut présenter certains inconvénients pour vous.

1) Temps de déplacement/participation : Le temps de déplacement de votre domicile au site de recherche ainsi que le temps de participation au projet de recherche peuvent représenter un inconvénient pour certaines personnes.
2) Utilisation de marqueurs : Du ruban adhésif hypoallergénique sera utilisé pour fixer les marqueurs réfléchissants sur la peau. Malgré cela, il existe une possibilité d'irritation de la peau à l'endroit où les marqueurs sont fixés. Dans ce cas, une lotion apaisante sera appliquée sur votre peau.
3) Mal des transports : Il est possible de ressentir une certaine nausée lorsque vous êtes exposé aux scénarios virtuels. La sensation de nausée disparaîtra en retirant le casque et en se reposant. Il est également possible que l'équipement utilisé pendant les essais vous cause parfois un léger malaise, ce qui peut également être résolu par des périodes de repos.
4) Fatigue : Il est possible que vous ressentiez de la fatigue après l'évaluation, mais celle-ci sera temporaire. Si vous êtes fatigué pendant la session, vous pourrez vous reposer avant de continuer. La sensation de fatigue s'estompera avec le repos.

32. ACCÈS AUX RÉSULTATS À LA FIN DE LA RECHERCHE

À la fin de l'étude, vous aurez la possibilité d'avoir accès aux résultats généraux découlant de ce projet de recherche.

Oui ☐

Non ☐

Courriel ou adresse : _____

33. CONFIDENTIALITÉ

Tous les renseignements personnels recueillis à votre sujet au cours de l'étude seront codifiés afin d'assurer leur confidentialité. Seuls les membres de l'équipe de recherche y auront accès. Cependant, à des fins de contrôle du projet de recherche, votre dossier de recherche pourrait être consulté par une personne mandatée par le CÉR des établissements du CRIR ou par la Direction de l'éthique et de la qualité du ministère de la Santé et des Services sociaux du Québec, qui adhère à une politique de stricte confidentialité.

Les données de recherche (formulaires, questionnaires, tests écrits et feuilles de résultats) seront conservées sous clé par Anouk Lamontagne, PhD, à l'Hôpital juif de réadaptation, et les données électroniques liées à votre évaluation seront transférées sur un disque dur protégé par un mot de passe. Après une période de 7 ans suivant la fin du projet, toutes les données de recherche seront détruites. Dans le cas où les résultats de cette étude seraient présentés ou publiés, aucune information permettant de vous identifier ne sera incluse.

Dans le cadre du partenariat de ce projet, une partie de vos données anonymisées sera partagée avec Saccade Analytics. Ce dernier recevra des informations relatives à votre TCC (temps écoulé depuis l'accident, sévérité), votre sexe, votre âge de même que des données de l'expérience via des disques durs protégés par un mot de passe. Les données découlant de l'évaluation oculomotrice enregistrée avec l'outil d'évaluation en réalité virtuelle propre à

Saccade Analytics seront envoyées en ligne en utilisant les mesures de sécurité en ligne de l'entreprise.

34. ENREGISTREMENT VIDÉO ET / OU PRISE DE PHOTOGRAPHIES

Il est possible que certaines séances soient enregistrées sur support vidéo ou que des photographies soient prises. Nous aimerions pouvoir utiliser ces dernières, avec votre permission, à des fins de formation et/ou de présentations scientifiques. Il n'est cependant pas nécessaire de consentir à ce volet pour participer au présent projet. Si vous refusez, les enregistrements et les photographies vous concernant seront détruits à la fin du projet dans le respect de la confidentialité.

Nous autorisez-vous à utiliser vos photographies ou enregistrements à des fins de formations ou de présentations scientifiques et à les conserver avec vos données de recherche ?

Oui ☐ Non ☐

35. PARTICIPATION VOLONTAIRE ET DROIT DE RETRAIT

Vous êtes libre d'accepter ou de refuser de participer à ce projet de recherche. Vous pouvez vous retirer de cette étude à n'importe quel moment, sans avoir à donner de raison, ni à subir de préjudice de quelque nature que ce soit. Vous avez simplement à aviser la personne ressource de l'équipe de recherche.

Si vous vous retirez ou êtes retiré de l'étude, vous pouvez également demander que les données déjà recueillies à votre sujet soient retirées de l'étude. Si vous demandez que vos données soient retirées et que les informations déjà recueillies vous concernant peuvent être identifiées comme étant les vôtres, elles seront détruites. Si les données ont été anonymisées (c'est-à-dire qu'elles ne contiennent aucune information permettant de vous identifier), elles continueront à être utilisées dans l'analyse de l'étude. Veuillez noter que toutes les données anonymisées envoyées à Saccade Analytics ne peuvent être détruites par les responsables du projet.

36. UTILISATION SECONDAIRE D'INFORMATIONS À DES FINS DE RECHERCHE

Les informations que vous fournissez pourront être utilisées, avant la date prévue de leur destruction, dans d'autres projets de recherche qui porteront sur les différentes facettes du sujet pour lequel vous êtes sollicité aujourd'hui. Ces éventuels projets seront sous la responsabilité de l'investigateur principal et seront autorisés par le Comité d'éthique de la recherche des établissements du CRIR. L'équipe de recherche s'engage à maintenir et à protéger la confidentialité de vos données dans les mêmes conditions que pour ce projet. Acceptez-vous que vos données soient utilisées dans ce contexte ?

☐ Oui☐ Non *

37. ÉTUDES ULTÉRIEURES

Il se peut que les résultats obtenus à la suite de cette étude donnent lieu à une autre recherche. Dans cette éventualité, autorisez-vous les responsables de ce projet à vous contacter à nouveau et à vous demander si vous souhaitez participer à cette nouvelle recherche ?

☐ non,
☐ oui pour une durée d'un an *
☐ oui pour une durée de deux ans *
☐ oui pour une durée de trois ans *

* Notez que si vous cochez l'une de ces trois cases, vos coordonnées personnelles seront conservées par le chercheur principal pour la période à laquelle vous avez consenti.

38. RESPONSABILITÉ DE L'ÉQUIPE DE RECHERCHE

En acceptant de participer à cette étude, vous ne renoncez à aucun de vos droits ni ne libérez les chercheurs, les commanditaires ou l'établissement de leurs responsabilités civiles et professionnelles.

39. INDEMNITÉ COMPENSATOIRE

Vous recevrez un montant maximal de $30 afin de couvrir vos frais de déplacement.

40. PERSONNES RESSOURCES

Si vous avez des questions concernant le projet de recherche, si vous souhaitez vous retirer de l'étude ou si vous voulez faire part à l'équipe de recherche d'un incident, vous pouvez contacter Anouk Lamontagne au 450-588-9550 poste 84168, ou par courriel à l'adresse suivante : anouk.lamontagne@mcgill.ca

Si vous avez des questions sur vos droits et recours ou sur votre participation à ce projet de recherche, vous pouvez communiquer avec la coordonnatrice du CER par courriel à l'adresse suivante : cer.rdp.ccsmtlr@ssss.gouv.qc.ca

Pour formuler une plainte, vous pouvez contacter le commissaire local aux plaintes de l'Hôpital juif de réadaptation au 450-688-1010 poste 23628, ou par courriel à l'adresse suivante : plaintes.csssl@ssss.gouv.qc.ca

41. CONSENTEMENT

Je déclare avoir pris connaissance et compris le présent projet, la nature et l'ampleur de ma participation, ainsi que les risques et les inconvénients auxquels je m'expose tel que présenté dans le présent formulaire. J'ai eu l'occasion de poser toutes les questions concernant les différents aspects de l'étude et de recevoir des réponses à mes questions. Une copie signée de ce formulaire d'information et de consentement doit m'être remise.

Je, soussigné(e), accepte volontairement de participer à cette étude. Je peux me retirer en tout temps sans préjudice d'aucune sorte. Je certifie qu'on m'a laissé le temps voulu pour prendre ma décision.

NOM DU PARTICIPANT _____ SIGNATURE _____

Fait à _____, le _____, 20_____

LE CHERCHEUR REMET UNE COPIE SIGNÉE DU FORMULAIRE DE CONSENTEMENT AU PARTICIPANT ET EN CONSERVE UNE AU DOSSIER

42. ENGAGEMENT DU CHERCHEUR OU DE SON REPRÉSENTANT

Je, soussigné (e), _____, certifie
(a) avoir expliqué au signataire les termes du présent formulaire;
(b) avoir répondu aux questions qu'il m'a posées à cet égard;
(c) lui avoir clairement indiqué qu'il reste, à tout moment, libre de mettre un terme à sa participation au projet de recherche décrit ci-dessus;
(d) que je lui remettrai une copie signée et datée du présent formulaire.

_____
Signature du responsable du projet
ou de son représentant

Fait à _____, le _____ 20____

.

ANNEXE

COMMISSAIRE LOCAL AUX PLAINTES DES INSTITUTIONS DU CRIR ET DE LEURS PARTENAIRES

Centre de réadaptation Lethbridge-Layton-Mackay
- **Centre de réadaptation Constance-Lethbridge**
- **Centre de réadaptation MAB-Mackay**

CIUSSS du Centre-Ouest-de-l'Île-de-Montréal
Téléphone: 514-340-8222, poste 24222
Courriel: ombudsman.ccomtl@ssss.gouv.qc.ca

Institut universitaire sur la réadaptation en déficience physique de Montréal
- **Centre de réadaptation Lucie-Bruneau**
- **Institut Raymond-Dewar**
- **Institut de réadaptation Gingras-Lindsay de Montréal**

CIUSSS du Centre-Sud-de-l'Île-de-Montréal
Téléphone: 514-593-3600
Courriel: commissaireauxplaintes.ccsmtl@ssss.gouv.qc.ca

Hôpital juif de réadaptation
CISSS de Laval
Téléphone: 450-668-1010, poste 23628

Courriel: plaintes.csssl@ssss.gouv.qc.ca

Institut Nazareth et Louis-Braille
CISSS de la Montérégie-Centre
Téléphone: 450-466-5434 ou 1-866-967-4825, poste 8884
Courriel: commissaire.cisssmc16@ssss.gouv.qc.ca

Centre de réadaptation en déficience physique des Laurentides
CISSS des Laurentides
Téléphone: 450-432-8708
Courriel: info-plaintes@ssss.gouv.qc.ca

Centre de réadaptation en déficience physique de Lanaudière
CISSS de Lanaudière
Téléphone: 450-759-5333, extension 2133 ou 1-800-229-1152, poste 2133
Courriel: plaintes.cissslan@ssss.gouv.qc.ca

Appendix 3: English consent form for participants with TBI

INFORMED CONSENT FORM

Participants with traumatic brain injury

43. STUDY TITLE

Impact of dual-task walking when avoiding collision with a virtual pedestrian in individuals with moderate-to-severe traumatic brain injury.

44. PRINCIPAL INVESTIGATORS

Anouk Lamontagne, PT, PhD
Professor
School of Physical and Occupational Therapy, McGill University.
Jewish Rehabilitation Hospital site of CRIR, CISSS-Laval.
Tel: 450-588-9550, ext.: 84168; Email: anouk.lamontagne@mcgill.ca

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Researcher at CIRRIS
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45. COLLABORATORS

Association Québécoise des Traumatisés Crâniens (AQTC)
220, Parc Avenue
Laval (Quebec) H7N 3X4
Tel: 514-274-7447
Website: https://www.aqtc.ca/

46. PARTNER ORGANIZATIONS

Saccade Analytics
Isabel Galiana, CEO
400 rue Montfort,
Montreal, H3C 4J9
isa.galiana@saccadeanalytics.com

47. FUNDING AGENCY

This study is funded by the *Initiative de recherche intersectorielle Société Inclusive*.

48. INTRODUCTION

We invite you to participate in a research project that examines the strategies you use while walking to avoid colliding with virtual pedestrians. In addition, this study will assess your ability to perform a pedestrian avoidance task and a mental task simultaneously. Before agreeing to participate in this project, please take the time to read and carefully consider the following information.

This consent form explains the aim of this study, the procedures, advantages, risks, and inconveniences, as well as the persons to contact, if necessary.

This consent form may contain words that you do not understand. We invite you to ask any question that you consider useful to the investigator and the other staff members assigned to the research project and ask them to explain any word or information that is not clear to you.

49. DESCRIPTION OF THE PROJECT AND ITS OBJECTIVES

Avoiding collisions with obstacles around us is essential to walking safely in everyday life. When we walk in a shopping mall or a park, for example, we encounter objects and people on our path that we must avoid by going around them. To do this, we mainly use our sense of vision which allows us to locate obstacles on our path. We then modify our trajectory and walking speed to avoid colliding with these obstacles.

People with moderate to severe traumatic brain injury (m/s TBI) may have different strategies for avoiding obstacles on their path. They may also have difficulty when they have to perform a mental task at the same time as avoiding obstacles. This difficulty may affect their ability to walk safely in the community.

Therefore, the main objective of this research project is to compare how individuals with m/s TBI avoid virtual pedestrians in a single-task situation (bypassing pedestrians only) and in a double-task situation (performing the pedestrian avoidance and the mental task at the same time). The results obtained in terms of walking and eye movements, as well as those obtained during the mental task, will be compared to those of healthy individuals who have not undergone a TBI.

50. NATURE OF PARTICIPATION

If you agree to participate in this study, you will attend two (2) assessment sessions of 2 to 2.5 hours each. These 2 sessions will ideally take place in the same week. They will take place at

the Virtual Reality & Mobility Laboratory of the Jewish Rehabilitation Hospital in Laval-QC, located at 3205 Place Alton-Goldbloom, Laval (Qc), H7V 3R6. A contact person and one of the researchers will be present during the evaluations to greet you and help you move around as needed.

Session 1 (2.5 hours):

At the beginning of this first session, you will have ample time to read and sign the consent form. All questions that you may have regarding the experiment will be answered. At this stage, you will be invited to perform clinical tests, to fill in questionnaires and to answer short questions that will be used either to confirm your eligibility to the study (screening evaluation) or to gather data needed the project (clinical evaluation). Your results on the screening evaluation will dictate whether you will proceed to the next phases.

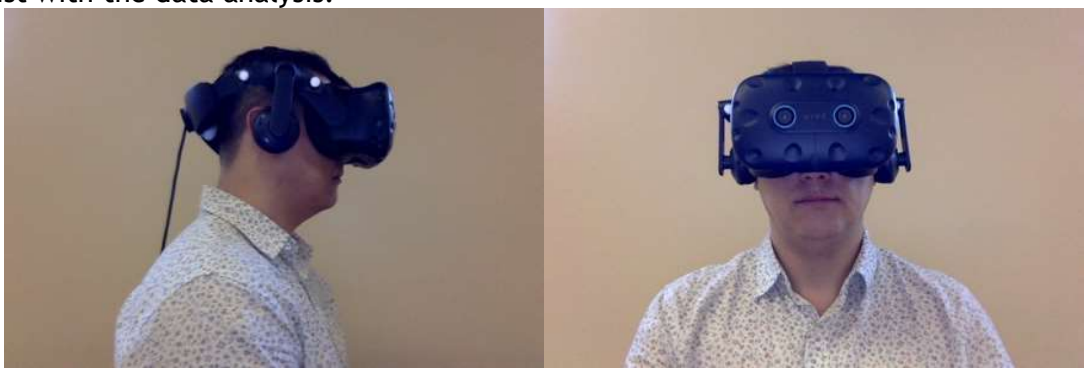
1. Screening Evaluation: Your comfortable walking speed will be assessed. Your vision and audition will also be confirmed with visual and auditory tests, and by asking you to identify visual or auditory elements in a virtual environment.

2. Clinical Evaluation: If you meet the eligibility criteria, we will further proceed with the following evaluation. Clinical tests will be used to assess your handedness, cognitive function, balance confidence, walking function, and maximal walking speed. We will also assess your eye movements using a virtual reality tool developed by Saccade Analytics. In addition, we will ask you if you have ever driven in countries with left-hand traffic, and if you have had a Covid-19 infection that has left any after-effects.

Overall, and including breaks, evaluation session 1 should last 2.5 hours.

Session 2 (2.5 hours):

Preparation and set-up: The second evaluation session will be done while you walk in a virtual environment representing a metro station in Montreal. You will view the metro station through a comfortable, light-weight virtual reality headset equipped with an eye tracker allowing to record eye movements (see picture). Small reflective markers will be attached to different parts of your body (head, thorax, arms and legs) with hypoallergenic tape in order to track your movements. Your voice will also be recorded in order to collect your answers on the pitch discrimination task. Note that all recordings will be stored confidentially, and these recordings will not include any personal information and will not be used for any other purpose than check the accuracy of your answers. Your height, weight and a few body dimensions will be measured to assist with the data analysis.



Evaluation: You will be asked to walk in a virtual environment along a 10m long path. You will have to avoid virtual pedestrians approaching from different directions. During some of the trials, you will also be asked to perform a mental task that consists of distinguishing the pitch of certain sounds (low vs high). This pitch discrimination task will also be repeated while seated. You will be completing about 30 trials for each condition, based on your ability, comfort and endurance. You shall rest as often as needed in between trials. A longer break will be inserted between the conditions. During the walking trials, a member of the research team will walk next to you for additional safety and will assist you back to the starting position.

Overall, including all breaks, evaluation session 2 should take about 2.5 hours.

51. PERSONAL BENEFITS OF PARTICIPATING IN THE STUDY

You will not benefit personally from taking part in this study. However, you might contribute to the advancement of science in the fields of rehabilitation, mobility and virtual reality, because the results from this study will provide information that will help in developing focused rehabilitation programs and assessment tools for dual-task walking deficits in persons sustaining a moderate-to-severe traumatic brain injury.

52. RISKS AND INCONVENIENCES ASSOCIATED WITH PARTICIPATING IN THE STUDY

Risks

It is understood that your participation in the study will not affect the care and services you receive or will receive from your rehabilitation institution, if applicable.

Your participation in this research project involves minimal risks for you. There is a risk of losing balance during the walking trials which cannot be eliminated completely. To limit the risk of falling, a person will be at your side to ensure your safety.

Inconveniences

Your participation in this research project may present some inconveniences for you.

1) Travel/participation time: The travel time from your home to the research site as well as the participation time in the research project may represent an inconvenience for some people.
2) Use of markers: Hypoallergenic tape will be used to affix the reflective markers on the skin. Despite of this, there is a possibility of skin irritation where the markers are attached. In such case, a soothing lotion will be applied to your skin.
3) Cybersickness: You may experience some nausea while exposed to the virtual scenarios. The feeling of nausea will disappear when taking off the headset and with rest. It is also possible that the equipment used during the experiments might cause you a bit discomfort at times, which can also be solved with periods of rest.
4) Fatigue: You may experience fatigue following the evaluation, but this will be temporary. If you become tired during the session, you will be able to rest before continuing. The feeling of fatigue will wear off with rest.

53. ACCESS TO THE RESULTS AT THE END OF THE RESEARCH

At the end of the study, do you want to have access to the general results of this research project.

Yes ☐

No ☐

email or address: _____

54. ACCESS TO MEDICAL RECORDS

We kindly ask that you authorize the research team to consult your medical chart and rehabilitation record in order to collect information in relation to your traumatic brain injury that is necessary to conduct this research project.

Specifically, we would like to access information regarding your neuropsychological scores, the initial diagnosis of condition severity (e.g., Glasgow Coma Scale score, structural brain imaging report if available, post-traumatic amnesia, and coma duration) and other potential co-morbidities that may limit your ability to participate in this study.

Yes ☐ No ☐

55. CONFIDENTIALITY

All personal information collected concerning you during the study will be coded to ensure its confidentiality. Only the members of the research team will have access to it. However, for research project control purposes, your research record could be consulted by a person mandated by the REB of the CRIR institutions or by the Direction de l'éthique et de la qualité du ministère de la Santé et des Services sociaux du Québec. This person adheres to a policy of strict confidentiality. The research data (forms, questionnaires, written tests, and results sheets) will be kept under lock and key by Anouk Lamontagne, PhD, at the Jewish Rehabilitation Hospital, and the electronic data related to your evaluation will be transferred onto a password-protected hard drive. After a period of 7 years following the end of the project, all the research data will be destroyed. In the event that the results of this study are presented or published, no information that can identify you will be included.

As part of the partnership in this project, portions of your anonymized data will be shared with Saccade Analytics. They will receive information related to your TBI (time since accident, severity), sex, age and experimental data through password-protected drives. From the oculomotor assessment recorded with Saccade Analytics own virtual reality assessment tool, this data will be sent online using the company's online security measures.

56. VIDEO RECORDING AND/OR TAKING PHOTOGRAPHS

It is possible that certain sessions will be recorded via videos or that photographs will be taken of you. We would like to use these recordings or photographs, with your permission, for the purpose of training and/or scientific presentation purposes. However, it is unnecessary to consent to this in order to participate in this project. If you refuse, the recordings and photographs concerning you will be destroyed at the end of the project to respect your confidentiality. If you accept, your face will be blurred.
Do you authorize us to use your photographs or recordings for the purpose of training or scientific presentations and to keep these recordings with your research data?

Yes ☐ No ☐

57. VOLUNTARY PARTICIPATION AND RIGHT OF WITHDRAWAL

You are free to accept or refuse your participation in this research project. You can withdraw from the study at any time without giving any reason or being subjected to prejudice of any kind. You simply must notify the contact person of the research team.

If you withdraw or are withdrawn from the study, you may also request that the data already collected about you be removed from the study. In this case, all documents concerning you, or that can be identified as yours, will be destroyed if that is your decision. If the data has been anonymized (i.e., does not contain any information that can be used to identify you), the data will continue to be used in the analysis of the study. Please note that all anonymized data sent to Saccade Analytics cannot be destroyed by the principal investigators.

58. SECONDARY USE OF INFORMATION FOR RESEARCH PURPOSES

The information you provide may be used, before the expected date of its destruction, in other research projects that will focus on the different facets of the topic for which you are solicited today. These possible projects will be the responsibility of the principal investigator and will be authorized by the Research Ethics Committee of CRIR establishments. The research team is committed to maintaining and protecting the confidentiality of your data under the same conditions as for this project. Do you agree that your data can be used in this context?

☐ Yes ☐ No *

59. SUBSEQUENT STUDIES

It is possible that the results of this study will give rise to another research project. In this context, do you authorize the persons in charge of this project to contact you again and ask if you would like to participate in this new project?

☐ no
☐ yes, for one year *
☐ yes, for two years *
☐ yes, for three years *

* Note, if you check off one of these three options, your personal contact information will be kept by the Lead Investigator for the period which you have selected.

60. RESPONSIBILITY OF THE RESEARCH TEAM

By agreeing to participate in this study, you do not give up any of your legal rights nor release the researchers or institutions involved of their legal and professional obligations.

61. COMPENSATORY INDEMNITY

You will receive an amount up to a maximum of $30 to cover your travel and parking costs.

62. RESOURCE PERSONS

If you have questions about the research project, if you wish to withdraw from the study or if you want to speak with the research team, please contact: Dr. Anouk Lamontagne at 450-688-9550 extension 84168 or by email at the following address: anouk.lamontagne@mcgill.ca.

If you have any questions regarding your rights and responsibilities or your participation in this research project, you may contact the Research Ethics Coordinator of the REB by email at the following email address: cercrir@ssss.gouv.qc.ca

Regarding complaints, you can also contact the Local Quality of Service and Complaints Commissioner of the Jewish Rehabilitation Hospital at the following phone number (450) 668-1010, ext. 23628, or by e-mail at plaintes.csssl@ssss.gouv.qc.ca

63. CONSENT

I declare that I have read and understood this project, the nature and the scope of my participation, as well as the risks and inconveniences to which I may be exposed, as presented in this document. I have had the opportunity to ask all my questions regarding the different aspects of the study and to receive answers to these questions. A signed copy of this information and consent form must be provided to me.

I, undersigned, voluntarily accept to participate in this study. I can withdraw my participation in this study at any time without prejudice of any kind. I certify that I was allowed all the time necessary to make my decision.

Participant's Name: SIGNATURE

_____ _____

Signed on _____ of _____, 20_____

THE RESEARCHER MUST GIVE A SIGNED COPY OF THE CONSENT FORM TO THE PARTICIPANT AND KEEP ANOTHER ONE IN THE RECORD

64. COMMITMENT OF THE INVESTIGATOR OR HER/HIS REPRESENTATIVE

I, undersigned, _____, certify:

(e) that I have explained to the signatory the terms of the present form;
(f) that I have answered any questions that she/he asked me in this regard;
(g) that I have clearly indicated that she/he remains, at any time, free to terminate her/his participation in the research project described above;
(h) that I will provide her/him a signed and dated copy of this form.

_____
Signature of the Lead Investigator or his representative

Signed on _____ of _____, 20_____

APPENDIX

LOCAL COMPLAINTS COMMISSIONNER OF THE CRIR INSTITUTIONS AND THEIR PARTNERS

Centre de réadaptation Lethbridge-Layton-Mackay
- **Centre de réadaptation Constance-Lethbridge**
- **Centre de réadaptation MAB-Mackay**

CIUSSS du Centre-Ouest-de-l'Île-de-Montréal
Phone: 514-340-8222, extension 24222
Email: ombudsman.ccomtl@ssss.gouv.qc.ca

Institut universitaire sur la réadaptation en déficience physique de Montréal
- **Centre de réadaptation Lucie-Bruneau**
- **Institut Raymond-Dewar**
- **Institut de réadaptation Gingras-Lindsay de Montréal**

CIUSSS du Centre-Sud-de-l'Île-de-Montréal
Phone: 514-593-3600
Email: commissaireauxplaintes.ccsmtl@ssss.gouv.qc.ca

Hôpital juif de réadaptation
CISSS de Laval
Phone: 450-668-1010, extension 23628
Email: plaintes.csssl@ssss.gouv.qc.ca

Institut Nazareth et Louis-Braille
CISSS de la Montérégie-Centre
Phone: 450-466-5434 of toll free 1-866-967-4825, extension 8884
Email: commissaire.cisssmc16@ssss.gouv.qc.ca

Centre de réadaptation en déficience physique des Laurentides
CISSS des Laurentides
Phone: 450-432-8708

Email: info-plaintes@ssss.gouv.qc.ca

Centre de réadaptation en déficience physique de Lanaudière
CISSS de Lanaudière
Phone: 450-759-5333, extension 2133 or toll-free 1-800-229-1152, extension 2133
Email: plaintes.cissslan@ssss.gouv.qc.ca

Appendix 4: French consent form for participants with TBI

FORMULAIRE D'INFORMATION ET DE CONSENTEMENT

Participant avec traumatisme cranio-cérébral

65. TITRE DU PROJET

Impact de la marche en double tâche lors de l'évitement de collision avec des piétons virtuels chez des personnes souffrant d'un traumatisme cranio-cérébral modéré à sévère.

66. RESPONSABLES DU PROJET

Anouk Lamontagne, PT, PhD
Professeure agrégée
École de physiothérapie et d'ergothérapie
Hôpital Juif de réadaptation, site de CRIR, CISSS-Laval
Tel: 450-588-9550, poste: 84168; courriel: anouk.lamontagne@mcgill.ca

Thiago de Aquino Costa Sousa
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École de physiothérapie et d'ergothérapie
Hôpital Juif de réadaptation, site de CRIR, CISSS-Laval
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Bradford J. McFadyen, PhD
Professeur agrégé
Département de réadaptation, Université Laval.
Chercheur à CIRRIS
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67. COLLABORATEURS

Association Québécoise des Traumatisés Crâniens (AQTC)
220, Parc Avenue
Laval (Québec) H7N 3X4
Tel: 514-274-7447

Website: https://www.aqtc.ca/

68. ORGANISATIONS PARTENAIRES

Saccade Analytics
Isabel Galiana, CEO
400 rue Montfort,
Montréal, H3C 4J9
isa.galiana@saccadeanalytics.com

69. ORGANISMES SUBVENTIONNAIRES

Ce projet de recherche est financé par l'Initiative de recherche intersectorielle *Société Inclusive*.

70. PRÉAMBULE

Nous vous invitons à participer à un projet de recherche qui examine les stratégies que vous utilisez en marchant pour éviter de rentrer en collision avec des piétons virtuels. De plus, cette étude évaluera votre capacité à exécuter simultanément une tâche de contournement de piétons et une tâche mentale. Avant d'accepter de participer à ce projet de recherche, veuillez prendre le temps de lire, de comprendre et de considérer attentivement les renseignements qui suivent.

Ce formulaire de consentement vous explique le but de cette étude, les procédures, les avantages, les risques et inconvénients, de même que les personnes avec qui communiquer au besoin.

Le présent formulaire de consentement peut contenir des mots que vous ne comprenez pas. Nous vous invitons à poser toutes les questions que vous jugerez utiles au chercheur et aux autres membres du personnel affecté au projet de recherche et à leur demander de vous expliquer tout mot ou renseignement qui n'est pas clair.

71. DESCRIPTION DU PROJET ET DE SES OBJECTIFS

Éviter d'entrer en collision avec les obstacles qui nous entourent est essentiel pour marcher de manière sécuritaire dans la vie de tous les jours. Lorsque nous marchons dans un centre commercial ou un parc, par exemple, nous rencontrons sur notre chemin des objets et des personnes que devons éviter en les contournant. Pour ce faire, nous utilisons principalement le sens de la vision qui nous permet de localiser les obstacles sur notre chemin. Nous modifions ensuite notre trajectoire et notre vitesse de marche pour éviter d'entrer en collision avec ces obstacles.

Les personnes ayant subi un traumatisme crânien modéré à sévère (TCC m/s) peuvent adopter des stratégies différentes pour éviter les obstacles présents sur leur chemin. Elles peuvent également éprouver des difficultés lorsqu'elles doivent effectuer une tâche mentale en même temps que l'évitement d'obstacles. Cette difficulté peut affecter la capacité à marcher de façon sécuritaire dans la communauté.

Par conséquent, l'objectif principal de ce projet de recherche est de comparer la façon dont les personnes ayant subi un TCC m/s contournent des piétons virtuels en situation de tâche simple (contourner les piétons seulement) et en situationde double-tâche (effectuer en même temps le contournement de piéton et la tâche mentale). Les résultats obtenus en termes de mouvements de marche et des yeux, de même que ceux obtenus lors de la tâche mentale, seront comparés à ceux d'individus en bonne santé n'ayant pas subi un TCC.

72. NATURE DE LA PARTICIPATION

Si vous acceptez de participer à cette étude, vous prendrez part à deux (2) sessions d'évaluation d'une durée de 2 à 2,5 heures chacune. Ces 2 sessions se dérouleront idéalement la même semaine. Elles auront lieu au Laboratoire de réalité virtuelle et de mobilité de l'Hôpital juif de réadaptation de Laval-QC, situé au 3205 Place Alton-Goldbloom, Laval (Qc), H7V 3R6. Une personne contact et l'un des chercheurs seront présents lors des évaluations pour vous accueillir et vous assister lors de vos déplacements au besoin.

Session 1 (2.5 heures):

Au début de cette première session, vous aurez tout le temps de lire et de signer le formulaire de consentement. Nous répondrons à toutes les questions que vous pourriez avoir concernant l'étude. Ensuite, vous serez invité à effectuer des tests cliniques, à remplir des questionnaires et à répondre à de brèves questions qui serviront soit à confirmer votre admissibilité à l'étude (évaluation de dépistage), soit à recueillir des données nécessaires au projet (évaluation clinique). Vos résultats à l'évaluation de dépistage détermineront si vous pourrez passer aux phases suivantes.

1. Évaluation de dépistage : Votre vitesse de marche confortable sera évaluée. Votre vision et votre audition seront également confirmées par des tests visuels et auditifs, ainsi qu'en vous demandant d'identifier des éléments visuels ou auditifs dans un environnement virtuel.

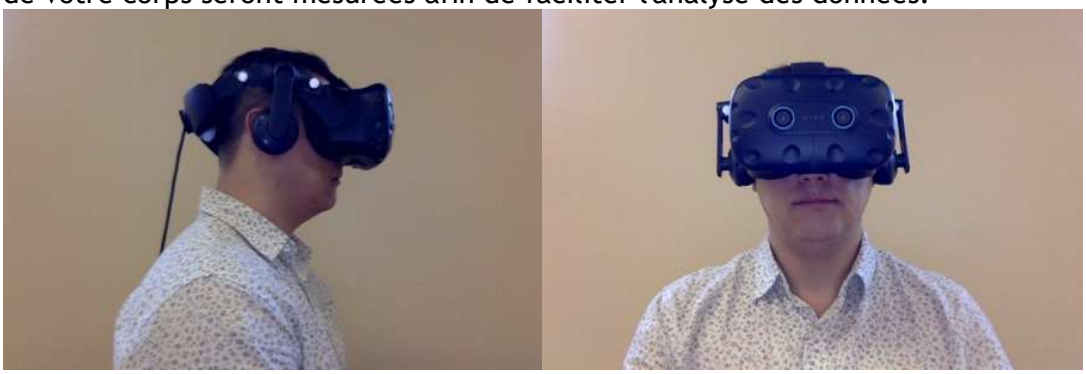
2. Évaluation clinique : Si vous répondez aux critères d'éligibilité, nous procéderons à l'évaluation suivante. Nous utiliserons des tests cliniques pour évaluer votre dominance manuelle, votre fonction cognitive, votre confiance en votre équilibre, votre fonction de marche et votre vitesse de marche maximale. Nous évaluerons également les mouvements de vos yeux à l'aide d'un outil de réalité virtuelle développé par Saccade Analytics. De plus, nous vous demanderons si vous avez déjà conduit dans des pays où la circulation se fait à gauche, et si vous avez eu une infection à la Covid-19 qui a laissé des séquelles.

Au total, en incluant les pauses, la session d'évaluation 1 devrait durer 2,5 heures.

Session 2 (2.5 heures):

Préparation et mise en place : La deuxième session d'évaluation se déroulera alors que vous marcherai dans un environnement virtuel représentant une station de métro de Montréal. Vous visualiserez la station de métro à travers un casque de réalité virtuelle confortable et léger équipé d'un système permettant d'enregistrer les mouvements de vos yeux (voir photo). De petits marqueurs réfléchissants seront fixés à différentes parties de votre corps (tête, thorax, bras et jambes) avec du ruban adhésif hypoallergénique afin de suivre vos mouvements. Votre voix sera également enregistrée lors de certaines tâches pour nous aider à vérifier vos réponses.

Notez que tous les enregistrements seront conservés de manière confidentielle et ne contiendront aucune information personnelle. Votre taille, votre poids et quelques segments de votre corps seront mesurées afin de faciliter l'analyse des données.



Évaluation : On vous demandera de marcher dans un environnement virtuel le long d'une allée de 10 m. Vous devrez éviter les piétons virtuels qui s'approchent de différentes directions. Lors de certains des essais, on vous demandera également d'effectuer une tâche mentale qui consiste à distinguer la hauteur de certains sons (graves vs aigus). Cette tâche de discrimination des sons sera également répétée en position assise. Vous effectuerez environ 30 essais pour chaque condition, en fonction de vos capacités, de votre confort et de votre endurance. Vous pourrez vous reposer aussi souvent que nécessaire entre les essais. Une pause plus longue sera également prise entre les différentes conditions. Pendant les essais de marche, un membre de l'équipe de recherche marchera à vos côtés pour s'assurer de votre sécurité et vous aidera à revenir à la position de départ.

Au total, en incluant toutes les pauses, la session d'évaluation 2 devrait durer environ 2,5 heures.

73. AVANTAGES POUVANT DÉCOULER DE VOTRE PARTICIPATION

Vous ne bénéficierez pas personnellement de votre participation à cette étude. Cependant, vous pourriez contribuer à l'avancement de la science dans les domaines de la réadaptation, de la mobilité et de la réalité virtuelle, car les résultats de cette étude fourniront des informations qui aideront à développer des programmes de réadaptation ciblés et de meilleurs outils d'évaluation des déficits de la marche en double tâche chez les personnes ayant subi un traumatisme cranio-cérébral modéré à sévère.

74. RISQUES ET INCONVÉNIENTS POUVANT DÉCOULER DE VOTRE PARTICIPATION

Risques

Il est entendu que votre participation au projet n'affectera pas les soins et services que vous recevez ou recevrez de votre établissement de réadaptation.

Votre participation à ce projet de recherche comporte des risques minimes pour vous. Il existe un risque de perte d'équilibre pendant les essais de marche qui ne peut être totalement éliminé. Pour limiter le risque de chute, une personne sera à vos côtés pour assurer votre sécurité.

Inconvénients

Votre participation à ce projet de recherche peut présenter certains inconvénients pour vous.

1) Temps de déplacement/participation : Le temps de déplacement de votre domicile au site de recherche ainsi que le temps de participation au projet de recherche peuvent représenter un inconvénient pour certaines personnes.
2) Utilisation de marqueurs : Du ruban adhésif hypoallergénique sera utilisé pour fixer les marqueurs réfléchissants sur la peau. Malgré cela, il existe une possibilité d'irritation de la peau à l'endroit où les marqueurs sont fixés. Dans ce cas, une lotion apaisante sera appliquée sur votre peau.
3) Mal des transports : Il est possible de ressentir une certaine nausée lorsque vous êtes exposé aux scénarios virtuels. La sensation de nausée disparaîtra en retirant le casque et en se reposant. Il est également possible que l'équipement utilisé pendant les essais vous cause parfois un léger malaise, ce qui peut également être résolu par des périodes de repos.
4) Fatigue : Il est possible que vous ressentiez de la fatigue après l'évaluation, mais celle-ci sera temporaire. Si vous êtes fatigué pendant la session, vous pourrez vous reposer avant de continuer. La sensation de fatigue s'estompera avec le repos.

75. ACCÈS AUX RÉSULTATS À LA FIN DE LA RECHERCHE

À la fin de l'étude, vous aurez la possibilité d'avoir accès aux résultats généraux découlant de ce projet de recherche.

Oui ☐

Non ☐

Courriel ou adresse : _____

76. ACCÈS À VOTRE DOSSIER MÉDICAL

Nous vous demandons d'autoriser l'équipe de recherche à consulter votre dossier de réadaptation afin d'y recueillir les renseignements relatifs à votre traumatisme cranio-cérébral, ce qui est nécessaire à la réalisation du projet de recherche.

Plus précisément, nous aimerions avoir accès à de l'information concernant vos résultats neuropsychologiques, le diagnostic initial de la gravité de votre état (p. ex., score du coma de Glasgow, amnésie post-traumatique et durée du coma) et d'autres comorbidités potentielles qui peuvent limiter votre capacité à participer à cette étude.

Oui ☐ Non ☐

77. CONFIDENTIALITÉ

Tous les renseignements personnels recueillis à votre sujet au cours de l'étude seront codifiés afin d'assurer leur confidentialité. Seuls les membres de l'équipe de recherche y auront accès. Cependant, à des fins de contrôle du projet de recherche, votre dossier de recherche pourrait être consulté par une personne mandatée par le CÉR des établissements du CRIR ou par la

Direction de l'éthique et de la qualité du ministère de la Santé et des Services sociaux du Québec, qui adhère à une politique de stricte confidentialité.

Les données de recherche (formulaires, questionnaires, tests écrits et feuilles de résultats) seront conservées sous clé par Anouk Lamontagne, PhD, à l'Hôpital juif de réadaptation, et les données électroniques liées à votre évaluation seront transférées sur un disque dur protégé par un mot de passe. Après une période de 7 ans suivant la fin du projet, toutes les données de recherche seront détruites. Dans le cas où les résultats de cette étude seraient présentés ou publiés, aucune information permettant de vous identifier ne sera incluse.

Dans le cadre du partenariat de ce projet, une partie de vos données anonymisées sera partagée avec Saccade Analytics. Ce dernier recevra des informations relatives à votre TCC (temps écoulé depuis l'accident, sévérité), votre sexe, votre âge de même que des données de l'expérience via des disques durs protégés par un mot de passe. Les données découlant de l'évaluation oculomotrice enregistrée avec l'outil d'évaluation en réalité virtuelle propre à Saccade Analytics seront envoyées en ligne en utilisant les mesures de sécurité en ligne de l'entreprise.

78. ENREGISTREMENT VIDÉO ET / OU PRISE DE PHOTOGRAPHIES

Il est possible que certaines séances soient enregistrées sur support vidéo ou que des photographies soient prises. Nous aimerions pouvoir utiliser ces dernières, avec votre permission, à des fins de formation et/ou de présentations scientifiques. Il n'est cependant pas nécessaire de consentir à ce volet pour participer au présent projet. Si vous refusez, les enregistrements et les photographies vous concernant seront détruits à la fin du projet dans le respect de la confidentialité.

Nous autorisez-vous à utiliser vos photographies ou enregistrements à des fins de formations ou de présentations scientifiques et à les conserver avec vos données de recherche ?

Oui ☐ Non ☐

79. PARTICIPATION VOLONTAIRE ET DROIT DE RETRAIT

Vous êtes libre d'accepter ou de refuser de participer à ce projet de recherche. Vous pouvez vous retirer de cette étude à n'importe quel moment, sans avoir à donner de raison, ni à subir de préjudice de quelque nature que ce soit. Vous avez simplement à aviser la personne ressource de l'équipe de recherche.

Si vous vous retirez ou êtes retiré de l'étude, vous pouvez également demander que les données déjà recueillies à votre sujet soient retirées de l'étude. Si vous demandez que vos données soient retirées et que les informations déjà recueillies vous concernant peuvent être identifiées comme étant les vôtres, elles seront détruites. Si les données ont été anonymisées (c'est-à-dire qu'elles ne contiennent aucune information permettant de vous identifier), elles continueront à être utilisées dans l'analyse de l'étude. Veuillez noter que toutes les données anonymisées envoyées à Saccade Analytics ne peuvent être détruites par les responsables du projet.

80. UTILISATION SECONDAIRE D'INFORMATIONS À DES FINS DE RECHERCHE

Les informations que vous fournissez pourront être utilisées, avant la date prévue de leur destruction, dans d'autres projets de recherche qui porteront sur les différentes facettes du sujet pour lequel vous êtes sollicité aujourd'hui. Ces éventuels projets seront sous la responsabilité de l'investigateur principal et seront autorisés par le Comité d'éthique de la recherche des établissements du CRIR. L'équipe de recherche s'engage à maintenir et à protéger la confidentialité de vos données dans les mêmes conditions que pour ce projet. Acceptez-vous que vos données soient utilisées dans ce contexte ?

☐ Oui ☐ Non *

81. ÉTUDES ULTÉRIEURES

Il se peut que les résultats obtenus à la suite de cette étude donnent lieu à une autre recherche. Dans cette éventualité, autorisez-vous les responsables de ce projet à vous contacter à nouveau et à vous demander si vous souhaitez participer à cette nouvelle recherche ?

☐ non,
☐ oui pour une durée d'un an *
☐ oui pour une durée de deux ans *
☐ oui pour une durée de trois ans *

* Notez que si vous cochez l'une de ces trois cases, vos coordonnées personnelles seront conservées par le chercheur principal pour la période à laquelle vous avez consenti.

82. RESPONSABILITÉ DE L'ÉQUIPE DE RECHERCHE

En acceptant de participer à cette étude, vous ne renoncez à aucun de vos droits ni ne libérez les chercheurs, les commanditaires ou l'établissement de leurs responsabilités civiles et professionnelles.

83. INDEMNITÉ COMPENSATOIRE

Vous recevrez un montant maximal de $30 afin de couvrir vos frais de déplacement.

84. PERSONNES RESSOURCES

Si vous avez des questions concernant le projet de recherche, si vous souhaitez vous retirer de l'étude ou si vous voulez faire part à l'équipe de recherche d'un incident, vous pouvez contacter Anouk Lamontagne au 450-588-9550 poste 84168, ou par courriel à l'adresse suivante : anouk.lamontagne@mcgill.ca

Si vous avez des questions sur vos droits et recours ou sur votre participation à ce projet de recherche, vous pouvez communiquer avec la coordonnatrice du CER par courriel à l'adresse suivante : cer.rdp.ccsmtl@ssss.gouv.qc.ca

Pour formuler une plainte, vous pouvez contacter le commissaire local aux plaintes de l'Hôpital juif de réadaptation au 450-688-1010 poste 23628, ou par courriel à l'adresse suivante : plaintes.csssl@ssss.gouv.qc.ca

85. CONSENTEMENT

Je déclare avoir pris connaissance et compris le présent projet, la nature et l'ampleur de ma participation, ainsi que les risques et les inconvénients auxquels je m'expose tel que présenté dans le présent formulaire. J'ai eu l'occasion de poser toutes les questions concernant les différents aspects de l'étude et de recevoir des réponses à mes questions. Une copie signée de ce formulaire d'information et de consentement doit m'être remise.

Je, soussigné(e), accepte volontairement de participer à cette étude. Je peux me retirer en tout temps sans préjudice d'aucune sorte. Je certifie qu'on m'a laissé le temps voulu pour prendre ma décision.

NOM DU PARTICIPANT SIGNATURE

_____ _____

Fait à _____, le _____, 20_____

LE CHERCHEUR REMET UNE COPIE SIGNÉE DU FORMULAIRE DE CONSENTEMENT AU PARTICIPANT ET EN CONSERVE UNE AU DOSSIER

86. ENGAGEMENT DU CHERCHEUR OU DE SON REPRÉSENTANT

Je, soussigné (e), _____, certifie

(e) avoir expliqué au signataire les termes du présent formulaire;
(f) avoir répondu aux questions qu'il m'a posées à cet égard;
(g) lui avoir clairement indiqué qu'il reste, à tout moment, libre de mettre un terme à sa participation au projet de recherche décrit ci-dessus;
(h) que je lui remettrai une copie signée et datée du présent formulaire.

_____
Signature du responsable du projet
ou de son représentant

Fait à _____, le _____ 20____

.

ANNEXE

COMMISSAIRE LOCAL AUX PLAINTES
DES INSTITUTIONS DU CRIR ET DE LEURS PARTENAIRES

Centre de réadaptation Lethbridge-Layton-Mackay

- **Centre de réadaptation Constance-Lethbridge**
- **Centre de réadaptation MAB-Mackay**

CIUSSS du Centre-Ouest-de-l'Île-de-Montréal
Téléphone: 514-340-8222, poste 24222
Courriel: ombudsman.ccomtl@ssss.gouv.qc.ca

Institut universitaire sur la réadaptation en déficience physique de Montréal

- **Centre de réadaptation Lucie-Bruneau**
- **Institut Raymond-Dewar**
- **Institut de réadaptation Gingras-Lindsay de Montréal**

CIUSSS du Centre-Sud-de-l'Île-de-Montréal
Téléphone: 514-593-3600
Courriel: commissaireauxplaintes.ccsmtl@ssss.gouv.qc.ca

Hôpital juif de réadaptation
CISSS de Laval
Téléphone: 450-668-1010, poste 23628
Courriel: plaintes.csssl@ssss.gouv.qc.ca

Institut Nazareth et Louis-Braille
CISSS de la Montérégie-Centre
Téléphone: 450-466-5434 ou 1-866-967-4825, poste 8884
Courriel: commissaire.cisssmc16@ssss.gouv.qc.ca

Centre de réadaptation en déficience physique des Laurentides
CISSS des Laurentides
Téléphone: 450-432-8708
Courriel: info-plaintes@ssss.gouv.qc.ca

Centre de réadaptation en déficience physique de Lanaudière
CISSS de Lanaudière
Téléphone: 450-759-5333, extension 2133 ou 1-800-229-1152, poste 2133
Courriel: plaintes.cissslan@ssss.gouv.qc.ca