Gaze and body kinematics of healthy young adults walking and avoiding pedestrians in a virtual community environment

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STATEMENT OF AUTHORSHIP

I, Trineta Mohan Bhojwani 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 pedestrian interactions, vision, virtual reality, and rehabilitation. In this study, we analyzed the gaze behaviour of healthy young adults during pedestrian interactions, including quantification of fixation durations on pedestrians, their body segments, and environmental features under both single and dual-task conditions. The influence of varying directional conditions of pedestrian approach and task complexity on gaze behaviour has never been analyzed before although it holds immense relevance for safe community ambulation. This study was conducted using a previously validated virtual reality paradigm which allowed us to systematically control for task-relevant variables such as the direction and speed of pedestrian approach, and to repetitively present them to yield consistent patterns of behavioral responses amongst participants. The data presented in this thesis was collected and analyzed at the Feil & Oberfeld Research Centre of the CISSS-Laval and Jewish Rehabilitation Hospital Site of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR), which is affiliated to McGill University. The study presented in this thesis was approved by the Research Ethics Board of CRIR.

DEDICATION

I dedicate this thesis to Krishna, my guru, my friend, and my everything. From a very young age through your teachings in the Gita, you have influenced my life in profound ways. You taught me the importance of compassion for all beings and this very quality stemmed my passion for neurorehabilitation and the desire to help populations with a neurological disorder live a fulfilled life to the best of my abilities. This Master's journey was full of challenges often extremely overwhelming. There were moments I lost faith in myself and the ability to do justice to the work in front of me and at times quitting felt like the only right thing to do. Through Gita, you taught me that my only focus should be to give the work presented to me my 100%, and that the results on which we can never really have control I must leave to fate. This very teaching has now become the principle of my life in all aspects. Being away from the people closest to my heart was the hardest aspect of this journey especially during uncertain times of the Covid-19 pandemic but you sent in my life wonderful humans that made a little bit of home feel alive around me. I can never thank you enough for all your blessings, I can only hope to make the most of them and be a reflection of your love in this world.

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CONTRIBUTION OF AUTHORS

This thesis is presented in a manuscript format and includes one research manuscript, which has been formatted for publication in a peer-reviewed journal (Annals of Physical Medicine and Rehabilitation Medicine). I, Trineta Mohan Bhojwani, am the main contributor and lead author of all chapters and the manuscript included in this thesis. My contribution extends to the research design, experimental setup, data collection, data analysis, interpretation of findings, preparations of figures/tables, and writing of this thesis. In the weeks and months following this thesis submission, I will also contribute to the submission of the manuscript for publication and revisions following the peer review process.

The research project and manuscript presented here were developed under the supervision of Dr. Anouk Lamontagne and in collaboration with Dr. Sean Lynch. Dr. Lamontagne oriented the selection of the research design, experimental setup, data analysis, statistical analysis, interpretation of findings, and critically reviewed and provided constructive feedback on this thesis. Dr. Sean Lynch provided constructive inputs on the experimental design, data collection, data analysis and interpretation of findings.

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LIST OF ABBREVIATIONS

3-D : Three dimensional

CAVE : Cave automatic virtual environment

CRIR : Centre for Interdisciplinary Research in Rehabilitation

DCA : Distance to closest approach

DT : Dual task

DTC : Dual task cost

DTW : Dual task walking

EDI : Edinburgh handedness inventory

GEE : Generalised estimating equation

HMD : Head mounted display

MoCa : Montreal cognitive assessment

SD : Standard deviation

SE : Standard error

SPOT : School of Occupational and Physical Therapy

ST : Single task

STC : Cognitive single task

STW : Single task walking

TA : Teaching assistant

TPC : Theoretical point of collision

TtCA : Time to closest approach

VR : Virtual reality

VRP : Virtual pedestrian

ABSTRACT

The two essential dimensions of community ambulation of interest in this thesis were circumvention of approaching pedestrians and performance of cognitive tasks while walking. Visual information acquired by coordinated eye-head movements is known to guide avoidance strategies. Thus, the primary focus of this thesis was to analyze visuomotor behaviour during such pedestrian interactions. Previous work indicates that during pedestrian interactions, gaze is likely to be fixated on surrounding pedestrians posing a greater risk of collision, after which it is reoriented towards the end goal to assist with locomotor steering. However, which specific visual cue(s) about an approaching pedestrian is used to guide the collision avoidance strategy and how the acquisition of such visual cue(s) may vary according to the direction of pedestrian approach remains to be determined. Furthermore, it is unclear how a concurrent cognitive task that imposes an additional attentional load while walking impacts on the ability to attend to visual cues essential for successful collision avoidance. Such knowledge is needed to explain the challenges and higher collision rates encountered while walking by patient populations such as stroke, especially under dual-task conditions. As a first step towards the understanding of behaviours presented by older adults and patient populations, this work focused on characterizing successful collision avoidance strategies implemented by healthy young adults. To allow testing participants in safe, controlled, and ecologically-valid conditions, a previously validated virtual reality (VR) paradigm was used.

Sixteen healthy young adults were instructed to ambulate towards a target while circumventing pedestrians approaching from the left, middle or right in a virtual community environment. Participants were exposed to both single and dual-task (DT) conditions, wherein the dual-task condition involved performing a simple (auditory pitch discrimination) or a complex (auditory Stroop) cognitive task while walking. Participants viewed the virtual environment through a head

mounted display (HTC Vive Pro Eye) that is enabled with an eye-tracking system. Gaze variables such as percent duration of fixation on the approaching pedestrian and their body segments, the end goal, other pedestrians, and the environment were analyzed across different directions of pedestrian approach and task conditions. In addition, locomotor outcomes such as the number of collisions, walking speed, onset distance of trajectory deviation and minimum distance maintained with respect to the approaching pedestrian were quantified. Cognitive performance was assessed using the percentage of accuracy on the cognitive tasks. Generalized estimating equation (GEE) models were used to compare gaze, cognitive and locomotor outcomes across conditions with a significance level set to $p<0.05$.

Our results revealed that the average duration of fixation on the approaching pedestrian (34-50%) was longer compared to that on other pedestrians (13-35%) and on the end goal (17-32%). Maximal fixations were seen on the upper trunk (28-48%) followed by the head (18-33%) of the approaching pedestrian. A significant effect of direction was also observed wherein longer fixations were seen on the pedestrian and target for the middle pedestrian approach compared to diagonally approaching pedestrians ($p=0.006$ to 0.01). Likewise, a significant effect of direction was observed on locomotor outcomes ($p=0.001$ to 0.03), with faster walking speeds, larger onset distances of trajectory deviation and smaller minimum distances for the middle vs. diagonal pedestrian approaches. No significant differences were observed between single and dual-task conditions for any of the gaze or locomotor outcomes ($p>0.05$). The accuracy of response on both the simple and complex cognitive tasks, however, was found to significantly deteriorate in dual-task conditions compared to the single-task conditions ($p<0.01$).

The higher risk of collision associated with the approaching pedestrian compared to other pedestrians in the environment likely explains why it received longer gaze fixations. Participants may have further fixated mainly on the upper trunk and head of the approaching pedestrian to anticipate its locomotor trajectory, as the reorientation of both of these two body segments is known to precede one's change in walking direction. Thus, these segments likely provided reliable cues for the participants to predict the future walking trajectory of the virtual pedestrian. The longer gaze fixation on the central pedestrian is also consistent with previous studies suggesting that this direction of approach is more challenging and riskier compared to other directions of obstacle approach, an interpretation that is further substantiated by findings of this study which show that the central pedestrian approach led to faster walking speeds, larger onsets of trajectory deviation, and yet smaller minimum distances with respect to the pedestrian. The longer duration of gaze fixation on the central pedestrian may also be explained by the fact that it lied in the line of sight of the end goal. Lastly, the lack of dual task effects on both locomotor and gaze behaviour coupled with significant deterioration of performance on the cognitive tasks suggests that healthy individuals prioritize the locomotor task and the acquisition of visual information needed for its successful completion.

This study fills important knowledge gaps in terms of the specific visual cues that guide pedestrian interactions and how the uptake of such cues is modulated as a function of the direction of pedestrian approach. It also provides new knowledge on the impact of dual tasking on the gaze behaviour associated with collision avoidance. The healthy patterns of visuomotor behaviour unveiled in this study will further serve as a basis for comparison to understand altered collision avoidance strategies observed in older adults and populations with neurological disorders such as stroke or traumatic brain injury.

ABRÉGÉ

Les deux dimensions essentielles de la marche en communauté d'intérêt dans cette thèse sont le contournement de piétons en approche et la réalisation de tâches cognitives pendant la marche. Les informations visuelles acquises par les mouvements coordonnés œil-tête sont connues pour guider les stratégies de contournement. Ainsi, l'objectif principal de cette thèse était d'analyser le comportement visuomoteur pendant ces interactions avec les piétons. Des études antérieures indiquent que lors d'interactions piétonnes, le regard est plus susceptible de se fixer sur les piétons environnants qui posent un plus grand risque de collision, après quoi il est réorienté vers la destination finale pour aider au contrôle de la trajectoire de marche. Cependant, il reste encore à déterminer quel(s) indice(s) visuel(s) spécifique(s) concernant un piéton en approche est (sont) utilisé(s) pour guider la stratégie d'évitement de collisions et comment l'acquisition de cet(s) indice(s) visuel(s) peut varier en fonction de la direction d'approche du piéton. De plus, nous ne savons pas si une tâche cognitive concomitante, qui ajoute une charge attentionnelle supplémentaire pendant la marche, a un impact sur la capacité à se concentrer sur les indices visuels essentiels à l'évitement de collisions. Ces connaissances sont nécessaires afin d'expliquer les difficultés rencontrées ainsi que les taux de collision plus élevés observés lors de la marche chez certaines populations de patients tel que les personnes ayant subi un accident vasculaire cérébral, en particulier dans des conditions de double tâche. Comme première étape vers une compréhension des altérations de comportements locomoteurs présentés par certaines populations de patients et les personnes âgées, cette étude s'est concentrée sur la caractérisation des stratégies d'évitement de collisions mises en œuvre par de jeunes adultes en bonne santé. Pour permettre de

tester les participants dans des conditions sécuritaires, contrôlées et écologiquement valides, un paradigme de réalité virtuelle (RV) précédemment validé a été utilisé.

Seize jeunes adultes en bonne santé ont reçu pour instruction de marcher vers une cible tout en contournant des piétons approchant par la gauche, le milieu ou la droite, dans un environnement virtuel représentatif de la communauté. Les participants ont été exposés à des conditions de simple tâche et de double tâche (DT), la condition de double tâche impliquant l'exécution d'une tâche cognitive simple (discrimination de la hauteur du son) ou complexe (Stroop auditif) tout en marchant. Les participants ont visualisé l'environnement virtuel à l'aide d'un casque de RV (HTC Vive Pro Eye) équipé d'un système d'oculométrie. Les variables se rapportant au regard, telles que le pourcentage de durée de fixation sur le piéton en approche ainsi que ses segments corporels, sur l'objectif final, sur les autres piétons et sur l'environnement, ont été analysées en fonction des différentes directions d'approche du piéton et des conditions de tâche. De plus, les variables locomotrices telles que le nombre de collisions, la vitesse de marche, la distance de début de déviation de la trajectoire de marche et la distance minimale maintenue par rapport au piéton en approche ont été quantifiés. Les performances cognitives ont été évaluées à l'aide du pourcentage de précision des réponses lors des tâches cognitives. Des modèles d'équation d'estimation généralisée (GEE) ont été utilisés pour comparer les résultats du regard, de la cognition et de la locomotion entre les conditions, avec un niveau de signification de $p<0.05$.

Nos résultats ont révélé que la durée moyenne de fixation du regard sur le piéton en approche (34-50%) était plus longue que sur les autres piétons (13-35%) et que sur la cible (17-32%). Les plus longues fixations du regard ont été observées pour la partie supérieure du tronc (28-48%), suivi de la tête (18-33%) du piéton en approche. Un effet significatif de la direction d'approche du piéton a également été observé. En effet, des fixations plus longues ont été observées sur le piéton ainsi que sur la cible pour l'approche centrale (du milieu) en comparaison aux approches diagonales ($p=0.006$ à 0.01). De même, un effet significatif de la direction d'approche a été observé sur les variables locomotrices ($p=0.001$ à 0.03), avec des vitesses de marche plus rapides, des distances de début de déviation de trajectoire plus grandes et des distances minimales plus petites pour les approches du milieu par rapport aux approches diagonales. Aucune différence significative n'a été observée entre les conditions de tâche simple et de tâche double pour les résultats relatifs au regard ou à la locomotion ($p>0.05$). Cependant, la précision des réponses aux tâches cognitives s'est considérablement détériorée dans les conditions de double tâche par rapport aux conditions de simple tâche ($p<0.01$).

Le risque de collision plus élevé associé au piéton en approche par rapport aux autres piétons présents dans l'environnement explique probablement pourquoi celui-ci a été l'objet de plus longues fixations du regard. Il est également possible que les participants aient fixé principalement la partie supérieure du tronc et la tête du piéton en approche afin d'anticiper sa trajectoire locomotrice, puisque des évidences dans la littérature démontrent que la réorientation de ces deux segments corporels précède le changement de direction de la marche. Ces segments ont donc probablement fourni aux participants des indices visuels fiables pour prédire la future trajectoire de marche du piéton virtuel. La fixation prolongée du regard sur le piéton central est également cohérente avec des études antérieures qui suggèrent que cette direction d'approche est plus difficile et plus risquée que les autres directions d'approche d'obstacles, une interprétation qui est également corroborée par les résultats de cette étude qui démontrent que l'approche du piéton central entraîne des vitesses de marche plus rapides, des déviations de trajectoire plus importantes et des distances minimales plus petites par rapport au piéton. La plus longue durée de fixation du regard sur le piéton central peut également s'expliquer par le fait qu'il se trouvait dans la ligne de mire de la cible vers laquelle les participants marchaient. Enfin, l'absence d'effet de la double tâche sur le comportement locomoteur ainsi que sur le regard, associée à une détérioration significative des performances dans les tâches cognitives, suggère que les individus en bonne santé priorisent la tâche locomotrice et l'acquisition des informations visuelles nécessaires à sa bonne réalisation.

Ce projet de maîtrise comble des lacunes importantes quant aux connaissances se rapportant aux informations visuelles spécifiques qui guident les interactions entre piétons et sur la façon dont l'acquisition de ces informations est modulée en fonction de la direction d'approche des piétons. Il apporte également de nouvelles connaissances sur l'impact de la double tâche sur le comportement du regard associé à l'évitement de collisions. Les patrons de comportement visuomoteur sains observés dans cette étude serviront de base de comparaison pour comprendre les altérations au niveau des stratégies d'évitement de collisions observées chez les adultes plus âgés et les populations souffrant de troubles neurologiques tels qu'un accident vasculaire cérébral ou un traumatisme crânio-cérébral.

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 and rationale of the study. Chapter 2 outlines the objectives and hypotheses of the study. Chapter 3 presents a research manuscript which includes an abstract, introduction, methodology of the experiment, results and discussion of the findings. 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 of all studies discussed in the thesis.

CHAPTER 1: INTRODUCTION

1.1 COMMUNITY AMBULATION

The ability to walk from one place to another and move about safely in varying surroundings is an integral component of independent living and thus a crucial determinant of quality of life (1, 2). Although intrinsic factors such as cardiovascular endurance, lower limb strength, neuromuscular generation of cyclic lower limb movement patterns, upright posture, and balance play a crucial role in optimal locomotion (3), physical and social environmental factors cannot be ignored when studying requirements of community ambulation (4). Complex outdoor settings pose task-specific challenges that are not limited to variables of distance, speed, and terrain (1). Patla et al. (2002) presented a conceptual model that classifies environmental demands into 8 dimensions, which represent the challenges that an individual must overcome to be an independent community walker. The dimensions include distance (e.g. minimum walking distance needed to ambulate outside home), temporal factors (e.g. minimum walking speed needed to negotiate traffic lights), ambient conditions (light and weather conditions), physical load (e.g. carrying a child), terrain (e.g. inclines, stairs, curbs), attentional demands (e.g. walking and talking), traffic density (e.g. avoiding other pedestrians), and postural transitions (e.g. changing position, turning while walking) (5).

The first dimension of interest to my MSc project is traffic density. Traffic density is defined as the average number of people in an arms range (5). It determines the need for collision avoidance. Circumventing dynamic obstacles such as pedestrians moving about in a community environment is a task that represents this dimension and it was the object of my research project. Successful avoidance of static and dynamic obstacles encountered in community settings involves gathering sensory information to plan and then perform necessary motor adaptions to avoid a collision (6). Due to impairments (e.g., sensory and motor deficits) commonly seen in older adults and individuals with neurological disorders (e.g., stroke), the ability to perform this task can be compromised (7-9). To encourage daily mobility, it is crucial to understand the defective mechanisms preventing such populations from meeting the requirements of this task. Analyzing strategies adopted by healthy individuals was the first step towards this.

The second dimension of interest to my MSc project was attentional demands. Enhanced attentional demands while walking can be caused by the several distractions present in the environment as well as by multitasking which entails the completion of more than one task concurrently (5). In fact, community ambulation rarely involves the performance of only one task at a time. Talking on the phone while walking, remembering grocery items while shopping in a supermarket, or recalling the route of an unfamiliar location are dual-task conditions routinely performed in everyday life (10). By placing an additional load on the attentional resources, such simultaneous tasks may hamper different aspects of locomotion such as balance and velocity (5). Thus, it is necessary to account for attentional demands during the assessment and training of mobility in patient populations. Of specific interest in my project was the interaction of attentional demands and traffic density. Previous studies have shown that circumventing obstacles while simultaneously executing a cognitive task results in motor and/or cognitive interferences, thereby affecting the performance of either or both the locomotor (e.g., reduced walking speed or increased collisions) and cognitive task (deciphering text/audio messages) (11-13). Dual-tasking is especially found to be challenging in older adults and stroke populations due to higher information processing demands (14, 15). It is thus necessary to investigate the two dimensions of traffic density and attentional demands not only individually but also when they interact.

1.2 GAZE AND OBSTACLE CIRCUMVENTION

Locomotion is known to be guided primarily by visual information (6, 16-18). In the context of obstacle circumvention vision provides key information such as the location of an obstacle at a distance, speed of movement of that obstacle, and obstacle characteristics such as shape and size (16, 19-21). When circumventing pedestrians in a community, anticipating an approaching pedestrian's path and accordingly making directional (veering left or right) and speed adjustments (slowing, stopping, or accelerating) in a coordinated manner is necessary (22). Huber et al. (2014) studied the adjustments of path and speed when a participant is crossing a human interferer (trained actor acting as a pedestrian) at different angles and speeds (23). They found that crossing at acute angles (i.e., 45° and 90°) requires more complex collision avoidance strategies involving both path and speed adjustments while crossing at obtuse angles (closer to 0°) required only path adjustments. Another widely accepted model for interception and avoidance of moving obstacles is the bearing angle model (24). The bearing angle is the angle subtended between the instantaneous heading of the individual and that of the obstacle, at a given point of observation. A constant bearing angle implies that the individual and obstacle are on a collision course. Observation of this constant bearing angle should initiate locomotor changes such as trajectory (direction of heading) or speed adaptations to avoid a collision (24). Such studies reflect that visual information acquired at a distance is used in a feedforward manner to plan avoidance strategies.

The array of visual information used to guide locomotion is vast, and it is difficult to process all the information in the visual field (25). Thus selection mechanisms that enable the extraction of task-relevant information are crucial. One such mechanism is the coordination of eye and head movements also known as gaze (26). Gaze orientation is the sum of eye and head orientation and it aids an individual to bring an image of interest onto the region of the retina with the highest visual acuity, namely fovea (27). Gaze behavior during locomotion has been characterized so far using the following outcomes: (a) fixation on a location or object, (b) travel fixation, or (c) a shift in gaze from one location to another (28). In our study, we focus on fixation which can be defined as the stabilization of gaze on a location or feature in the environment which lasts 80 ms or longer (29, 30). Analyzing patterns of fixation enables us to understand the precise nature of the visual information that is used to plan and execute kinematic adaptions for a given locomotor task.

Hollands et al. (2002) studied gaze behavior when changing direction while walking locomotion (by 30° or 60° left and right) and observed that for the majority of the time, gaze was aligned with the plane of progression. They also observed an invariable shift of gaze in the direction of the future path prior to the walking turns. Such findings of an anticipatory gaze shift in alignment with the desired travel destination via coordinated eye and head movements are supported by other studies in the literature (31-33). Boulanger et al. (2017) studied gaze behaviour patterns in healthy young adults during obstacle circumvention in a controlled environment and observed similar patterns wherein eye movements were initiated ahead of mediolateral trajectory displacements, possibly to locate the obstacle to be circumvented (34). Gaze fixation patterns are known to be highly task-specific (35-37), and some studies have also looked at gaze fixation patterns to understand how individuals plan future actions or modulate gaze fixation patterns to acquire the necessary information. Concerning pedestrian interactions, Croft and Panchuk et al. (2017) found that looking behaviour was a reliable predictor of avoidance strategies wherein participants were likely to go behind an orthogonally approaching interferer when they were looked at earlier and for a longer duration in the trial (38). Joshi et al. (2021) analyzed gaze behavior during pedestrian interactions in the physical world where pedestrians were ambulating in varying directions. They observed a pattern of a fixation on central pedestrians during forward walking and longer fixations on the pedestrians going in the same direction as participants(39), Berton et al. (2020) had similar findings in a virtual reality paradigm wherein they observed that with increasing crowd density, participants focused their gaze on pedestrians in front and closest to them. Such studies support the above-mentioned findings that gaze is usually congruent with the direction of walking (39). Literature on gaze and pedestrian interactions also consistently suggests that longer (30, 39-41), more frequent (39, 41, 42), and earlier gaze (40) fixations are observed on those pedestrians which pose the maximal risk of collision. For instance, Meerhoff et al. (2018) studied pedestrian interactions in a virtual interactive neighborhood (41). They aimed to understand how walkers prioritized their avoidance strategy when walking through a crowded environment based on gaze activity. The risk of collision of each virtual walker was quantified by combining distance and time-based metrics such as ‘distance at closest approach’ (DCA) and ‘time to closest approach’ (TtCA). Specifically, Pareto ranking was used to rank each virtual walker based on their combination of DCA and TtCA. A virtual walker with a high rank (i.e., closer to 1) would demand to be interacted with as the risk of collision would be high relative to the walkers with lower rankings. Results revealed that gaze was consistently attracted to virtual walkers with a high Pareto walking (i.e., the smallest values of DCA and TtCA), indicating a higher risk of collision. This is translated by longer duration and frequency of fixations on those risker virtual walkers. These results led them to conclude that humans navigate through crowds by selecting only a few interactions and that gaze reveals how a walker prioritizes these interactions. Little is known, however, about how the direction of a pedestrian coming from the opposite direction influences the gaze behavior of individuals. Since circumvention strategies are modulated as a function of the direction of pedestrian approach (23) and since vision is crucial to guide locomotion(16), it would be interesting to explore if such directional effects are observed in the gaze strategies deployed during pedestrian interactions.

There is also very little information in terms of which visual information (i.e., which body part) about another pedestrian one uses to plan and execute an avoidance strategy. For instance, Nummenmaa et al. (2001) analyzed whether the orientation of gaze of an approaching pedestrian influenced the avoidance strategy of participants and found that participants skirted to the side opposite to the gaze orientation of the pedestrian (43). In contrast, Lynch et al. (2018) found no significant differences in avoidance strategies in conditions of mutual vs. no mutual gaze interaction between participants and an orthogonally approaching virtual pedestrian. They concluded that visual information about the orientation of body segments of an approaching pedestrian probably sufficed for participants to anticipate the locomotor trajectory of that pedestrian and plan a circumvention accordingly (44). Which specific body segments of an approaching pedestrian is fixated upon, however, remains unclear. Thus, in my MSc project, I aim to understand the precise nature of visual information acquired by quantifying the extent of gaze fixations on task-relevant features of the environment (e.g., approaching vs. other pedestrians, end goal), as well as on specific body segments of the approaching pedestrian. I further aim to examine whether the gaze behaviour is modulated by the direction of pedestrian approach.

1.3 GAZE AND ATTENTIONAL DEMANDS

Everyday life often involves the concurrent performance of multiple tasks, which is referred to as dual tasking (45). Performing another task with walking is useful if not essential as it allows communication between people, changing directions, recalling shopping lists while walking, etc. (46). Dual-task walking is also crucial from a safety perspective, for example crossing a road involves the maintenance of a minimum walking speed while monitoring pedestrian signage, vehicular traffic, and other pedestrians (47). Dual tasking is thus immensely relevant when considering independent and safe community ambulation. However, all populations be it healthy young adults (48, 49), elderly individuals (15, 50), or patient populations such as stroke (11, 14, 51) or Parkinson's Disease (52, 53), can experience a deterioration in the performance of one or both tasks performed simultaneously, a phenomenon referred to as 'dual-task interference' (54). The literature describes three theories or models that could explain the mechanisms of this interference, including i) the capacity sharing model; ii) the bottleneck (task-switching) model, and iii) the crosstalk model (55). The widely accepted capacity sharing model suggests that central resources are limited and during the execution of multiple tasks simultaneously these attentional resources are shared parallelly amongst the tasks (56, 57). Since the available central resources are divided, less capacity for each individual task leads to deterioration of performance. This model also suggests that while sharing the resources, individuals are likely to prioritize the performance of one task over the other (55). In contrast, the bottleneck (task-switching) model suggests that individuals dedicate central resources to tasks sequentially (as opposed to parallelly) and one of the tasks is delayed or impaired during this sequential performance (55). The cross-talk model implies that interference is a function of the content of the tasks to be performed wherein it is easier to concurrently perform tasks with similar processing requirements (55). Some studies, however, have in fact supported the opposite probability (58).

Although it is known that dual tasking during complex locomotor tasks can lead to either or both motor and cognitive interference, literature on the impact of dual tasking on gaze behaviour is sparse, if not inexistent for pedestrian interactions specifically. Gaze and attention are tightly linked, as a shift of gaze indicates a shift in attention (59). Competing attentional demands under dual-task conditions may thus alter visuomotor behavior and the uptake of critical visual information. Ellmers et al. (2016) analyzed the impact of increasing cognitive load on visual search behavior during locomotion (60). Participants in this study were instructed to ambulate on a walking path while performing a serial subtraction task. Significantly shorter durations of fixations on task-relevant areas and longer fixations on task-irrelevant environmental features coupled with greater stepping errors and slower completion of walking were observed with dual tasking. Such findings of widespread gaze fixations (meaning shorter fixations on task-relevant elements) are supported by other studies that involved simple forward walking and texting or walking while performing a letter fluency task (61, 62). Miyasike-daSilva et al. (2012) analyzed the gaze behavior of healthy young adults ascending stairs and performing secondary visual or auditory cognitive tasks. They observed significantly reduced fixations on crucial stair elements with dual tasking (63). Such studies suggest that the additional load imposed by dual tasking may interfere with the allocation of attention and gaze towards the visual cues that are important for successful task completion. To the best of our knowledge, no experiments so far have analyzed the modulation of gaze behavior with dual tasking in more challenging locomotor tasks such as pedestrian interactions. Given that the acquisition of visual information in a feedforward manner is crucial for the successful negotiation of pedestrians, it is thus necessary to understand how the gaze strategies deployed are altered in such competing situations. While such information will be especially helpful to explain poor dual-task performances displayed by older adults and populations with neurological disorders, it is however necessary to first identify strategies adopted by healthy individuals. For this purpose, I am thus proposing to characterize gaze behavior (and obstacle avoidance strategies) in healthy young adults performing a collision avoidance task with a pedestrian under dual vs. single task conditions. To further understand the impact of task complexity on gaze behaviour, I am further proposing to expose participants to a simple and a more complex dual task condition.

1.4 USE OF A VIRTUAL REALITY PARADIGM

The term virtual reality (VR) describes a computer-generated scenario of objects (virtual environment) with which the user can interact in real-time (64). The combination of three-dimensional computer graphics (3-D), special display techniques (head-mounted display, stereo glasses), specific input devices (data glove, space ball, etc.) allows intuitive manipulation of objects in the scenario thus giving the user the impression of being in the scenario (65). VR is a promising assessment and interventional tool in research and clinical practice due to its numerous advantages. Indeed, the computer-generated environments allow for control over a large number of physical variables that influence behaviour, and stimuli can be presented in a consistent manner over repeated trials and modified as per the user’s abilities (66). Such interactions also allow for real-time performance feedback (67). Distractions to performers' attention can be easily employed in virtual environments without posing any real danger, as collisions with virtual objects or pedestrians for instance do not pose any threats to safety (68, 69). Virtual environments can effectively be designed to resemble real-life scenarios including those seen in the community (70).

VR thus offers us the opportunity to bring the complexity of the physical world into the controlled environment of the laboratory.

Buhler et al. (2018) compared pedestrian interactions of healthy young participants walking in virtual and physical environments (71). They found similar avoidance strategies, with slightly larger minimal distances maintained with respect to other pedestrians (0.01m) and slightly slower walking speeds (0.01m/s) in the virtual condition. The authors concluded that VR is a valid tool and, bearing in mind the advantages, it is a desirable tool to study complex locomotor tasks such as pedestrian interactions. Gerin-Lajoie et al. (2008) recorded compliant results wherein no significant differences in personal space or path curvatures were observed between physical and virtual conditions (9).

Different types of VR systems exist such as a Cave Automatic Virtual Environment (CAVE), a head-mounted display (HMD), or a rear-projection screen (72). The level of immersion and visual display are the distinguishing factors between these systems. Berton et.al (2019) analyzed the influence of the VR systems on gaze behaviour and kinematic strategies during joystick-driven collision avoidance tasks (29). Gaze behaviour and locomotion strategies were found to be qualitatively similar in VR and real conditions. The authors also suggested that gaze behavior in helmet-mounted displays (HMD) was more in line with real-world conditions as compared to other VR systems. With respect to my MSc project, I am thus proposing to use an HMD-based VR system as a valid and safe tool to study gaze behavior and collision avoidance strategies during a pedestrian interaction task.

CHAPTER 2: OBJECTIVES AND HYPOTHESES

This thesis was developed in a manuscript format and includes a full experiment which is presented in chapter 3. The specific objectives and hypotheses of the thesis and manuscript are outlined below.

2.1 SPECIFIC OBJECTIVES

(1) To characterize gaze behavior, as reflected by the nature and duration of fixation on approaching pedestrians and specific body segments, of healthy young individuals circumventing pedestrians approaching from different directions.

(2) To estimate the extent to which the addition of a simultaneous cognitive task of varying complexity alters the gaze behavior and locomotor strategies adopted by healthy young adults during the circumvention of virtual pedestrians.

2.2 HYPOTHESES

(1) Pedestrians posing a greater risk of collision would be fixated for longer durations, translating by longer durations of fixations for i) approaching vs. other pedestrians present in the environment and ii) pedestrians approaching from the middle (i.e., head-on) vs. other directions.

(2) Upper body segments (i.e., head and/or trunk) would be the body segments fixated upon for longer durations, due to those segments providing information about the current and future direction of walking. It is unclear, however, if these fixations on specific body segments would be modulated as a function of the direction of pedestrian approach.

(3) Dual-task walking, compare to single-task walking, would lead to shorter durations of gaze fixation on the approaching pedestrians, as well as possible dual-task interference in locomotor and/or cognitive outcomes. Larger changes in gaze fixation as well as in other locomotor and cognitive outcomes would be observed in the complex vs. simple dual task condition.

CHAPTER 3: RESEARCH MANUSCRIPT

Impact of dual tasking on gaze behaviour and locomotor strategies adopted while circumventing virtual pedestrians during a collision avoidance task

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3.1 ABSTRACT

Background: Community walking requires the ability to circumvent pedestrians and perform multiple tasks simultaneously. While vision plays a key role in the control of walking, which specific body cues about approaching pedestrians guide collision avoidance strategies remains to be elucidated. In addition, how the additional attentional load imposed by dual tasking may impact the acquisition of visual information needed for successful collision avoidance is unclear. This study thus aimed to analyze gaze behaviour and collision avoidance strategies while exposed to pedestrians approaching from different directions, under single and dual-task task conditions.

Methods: Sixteen healthy young adults walked towards a goal while avoiding virtual pedestrians (VRPs) approaching from the left, center or right. The locomotor task and an auditory-based cognitive task were performed in isolation (single task) and concurrently (dual task). Gaze (percent durations of gaze fixation on approaching VRP and its body segments, on other pedestrians, and the goal) and locomotor outcomes (walking speed, onset distance of trajectory deviation and minimum distance) were contrasted between directions of pedestrian approach and task conditions. Cognitive task accuracy was further compared between single and dual-task conditions.

Results: Longer duration of gaze fixations were observed on the approaching vs. other VRPs, with longer fixations on the upper trunk and head of the VRP compared to other body segments. Gaze and locomotor patterns differed across the directions of pedestrian approaches wherein longer fixations on the VRP, faster walking speeds, larger onsets of avoidance and smaller minimum distances were observed for the central approach. Gaze and locomotor behaviour did not differ between single and dual task conditions. However, significant dual task costs were observed on both the simple and complex cognitive tasks.

Discussion: The longer gaze fixations on approaching vs. other pedestrians align with previous literature suggesting that increased visual attention is devoted to pedestrians posing a greater risk of collision. Likewise, longer gaze fixations for the centrally vs. diagonally approaching pedestrians may be explained by the greater risk of collision imposed by this condition, as well as by the fact that it lied in the line of sight of the goal. Longer fixations on the pedestrian's trunk and head may have served the purpose of anticipating its walking trajectory. Lastly, the dual-task effects which were limited to cognitive outcomes suggest that healthy young adults prioritized the locomotor task and associated acquisition of visual information. The healthy patterns of visuomotor behaviour unveiled in this study will serve as a basis for comparison to further understand altered collision avoidance strategies in older adults and patient populations.

Keywords: Eye movements, cognitive load, collision avoidance, locomotion, pedestrian interactions, virtual reality

3.2 INTRODUCTION

Safe and effective community ambulation is a crucial determinant of quality of life (1, 5). Various activities of daily living such as crossing a street, grocery shopping, walking in crowded spaces, etc., involve locomotion in complex environmental settings (2). Successfully fulfilling the challenges associated with locomotion in such settings relies on various extrinsic factors classified by Patla et al. (2002) into 8 dimensions that include distance and speed of walking, ambient conditions, physical load, changing terrains, postural transitions, attentional demands (e.g. coping with distractors and dual-tasking) and traffic density (e.g. static and moving obstacles) (1). The first dimension of interest to this paper is traffic density. Traffic density accounts for the need to perform an avoidance strategy in order to negotiate obstacles such as other pedestrians present in the environment (1). Previous work has shown that with sensorimotor deficits due to older age or stroke, such populations face challenges in successfully negotiating obstacles while walking (8, 73). It is thus crucial to understand healthy behavioural patterns necessary for safe and optimal locomotor performance.

Locomotion has long been known to be guided primarily by visual information (6, 16, 19). Vision provides key information such as location, dimension, and speed of obstacles in the environment (6, 20). Such information is used in a feedforward manner for planning appropriate kinematic adaptations (20, 35). The visual array is vast and it is not possible for all visual information to be processed, thus selection mechanisms that extract relevant information from the environment are required (25). One such mechanism is the coordination of eye and head movements that orients the gaze towards appropriate visual cues (26). Previous studies that have looked at gaze behaviour during locomotion indicate that participants tend to fixate their gaze in the direction of the end goal when walking straight ahead and, when changing direction, an anticipatory shift of gaze orientation occurs prior to the change in heading direction (28, 31, 32). A similar pattern was observed during the circumvention of moving pedestrians, wherein a gaze reorientation occurs in the direction of the side of circumvention and prior to walking trajectory adjustments (34). Gaze fixation patterns also provide crucial information about how individuals plan future actions. Existing research indicates that gaze fixations are usually focused on task-relevant elements like surfaces to be stepped upon to guide safe foot placement (36), obstacle to be circumvented prior to approach (35), curbs, and crosswalk lines during intersection crossing (37). When it comes to pedestrian interactions specifically, gaze fixations would be primarily focussed on pedestrians posing a greater risk of collision (i.e. perceived as being on a collision path if no action is taken), which translates by longer (30, 39-41), more frequent (39, 41, 42) and/or earlier fixations (40) on those 'risky' pedestrians compared to the others. Croft & Panchuk et al. (2017) observed that looking behaviour was a reliable predictor of locomotor strategies wherein participants were more likely to pass behind vs. in front of an interferer approaching orthogonally when the interferer is fixated upon earlier in the trial and for a longer duration (38). The direction of gaze of the interferer was also shown to influence obstacle avoidance behaviour, resulting in individuals looking away from the gaze of the interferer and skirting on that side (43). While this observation suggests that individuals are looking amongst others at the head of the approaching pedestrian, which exact body segment is being looked at by individuals to anticipate the pedestrians' walking direction and perform an informed avoidance strategy accordingly remains unclear. Furthermore, how gaze allocation on different body segments may vary according to the direction of pedestrian approach remains to be elucidated.

The second dimension of interest to this paper is attentional demands. In the context of community walking, attentional demands refer to the addition of a cognitive load to locomotion, which usually involves walking and performing another task simultaneously (e.g. walking and remembering a list of shopping items) (1). Dual tasking is known to be challenging because locomotion places processing demands on the central nervous system and the addition of a simultaneous cognitive task is likely to further burden these resources, leading to a deterioration in the performance of one or both the tasks (45, 74). Of specific interest to our paper is the interaction of attentional demands and traffic density. Indeed, previous research has shown that adding a cognitive task to obstacle circumvention can result in significant cognitive-locomotor interference, that is a concurrent deterioration in locomotor (e.g. reduced walking speed and more collisions with obstacles), and cognitive performances (more errors on the cognitive task)(11, 13, 14, 51). Gaze and attention also are tightly linked, as a shift of gaze indicates a shift in attention (59). Competing attentional demands under dual-task conditions may thus alter visuomotor behaviour and the uptake of critical visual information. The few studies which looked at the impact of a cognitive task (backward counting) on visual scanning during locomotion in healthy young adults showed the presence of longer (60) and more frequent fixations (60, 62) on areas marked as task-irrelevant, as well as shorter duration of fixation on task-relevant areas with dual-tasking (61). Similar findings were seen on a stair climbing task with the addition of a concurrent visual task(63). Literature on gaze behaviour and dual-tasking remains sparse, especially the altered patterns of visuomotor behaviour during pedestrian interactions under such complex conditions remains to be explored.

Our study was conducted using a virtual reality (VR) based paradigm that was previously validated and which was shown to yield similar obstacle avoidance strategies compared to those observed in the physical world (75). Such VR paradigm further allowed testing participants in a safe, ecologically valid environment and to control for variables that influence collision avoidance behaviour and which must remain consistent across trials (66). Thanks to recent development in

VR technologies, it has also become easier to record gaze behaviour within immersive virtual environments. The ability to record gaze behaviour in an immersive virtual environment allows for understanding patterns of eye-head coordination across various dimensions of community mobility such as crowd navigation, crossing streets etc. which would otherwise be challenging in the physical world. Visuomotor control (27, 76, 77), dual-tasking abilities (14, 15, 51), and obstacle circumvention (8, 73) are known to be affected by older age and neurological conditions such as stroke. In order to better understand defective control mechanisms of gaze behaviour in these populations during locomotion, this study aimed as a first step to understand the patterns of gaze behaviour observed in healthy young individuals. Thus, the first objective of our study was to characterize the gaze behaviour, as reflected by the nature and duration of fixation on approaching pedestrians and specific body segments, of healthy young individuals circumventing pedestrians coming from different directions. The second objective was to analyze the impact of dual tasking on gaze behaviour outcomes in the same population. We hypothesized that pedestrians posing a greater risk of collision would be fixated for longer durations, translating by longer durations of fixations for i) approaching vs. other pedestrians present in the environment and ii) pedestrians approaching from the middle (i.e., head on) vs. other directions. We further hypothesized that upper body segments (i.e., head and/or trunk) would be the body segments fixated upon for longer durations, due to those segments providing information about current and future direction of walking. However, whether the latter pattern of gaze distribution would be modulated by the direction of pedestrian approach was at the time of study conception still unclear. Lastly, we expected shorter durations of gaze fixation on the approaching pedestrians in dual vs. single task walking, as well as a possible dual-task interference in locomotor and/or cognitive outcomes.

3.3 METHODS

3.3.1 STUDY DESIGN

This study uses an experimental, within-subject design where all behavioural data were collected in one session.

3.3.2 PARTICIPANTS

A convenience sample of 16 healthy young adults (11 females) aged 18-29 years (average ± 1SD: 24.93 ± 2.29 years) were recruited. This age range was selected based on previous work (78) and due to the fact that locomotor behavior changes in middle and older adults (79) (80). Due to lack of information on gaze behaviour and the impact of cognitive load on it, sample size was estimated using dual task cost on minimum distance as main outcome across obstacle avoidance studies (7, 14). Based on these studies, we postulated an effect size of 0.4. The statistical model that was considered in G*Power 3.1 involved a repeated ANOVA with two within subject factors (2 levels of complexity X 3 directions), as well as a power of 80% and statistical level of significance of 0.05. A sample of 14 participants was needed but given possible dropouts and technical issues in data collection, a sample size of 16 was planned. All participants had normal or corrected-to-normal visual acuity (equal to or above to logMAR of 0) on the EDTRS chart (81), intact cognition, as per their results on the Montreal Cognitive Assessment (≥ 26) (82), and intact audition tested subjectively by assessing if the participants could hear appropriately the task sounds while seated and while walking. As handedness was found to be significantly associated with spatial abilities and accident proneness (83, 84), only right-handed participants with a score equal to +40 or more as per the Edinburgh Handedness Inventory were included (85). Previous studies have also found an influence of traffic rules on avoidance strategies (e.g., side of circumvention), thus only participants raised in countries following a right-side traffic rule (e.g., North America) or participants with a driving experience of > 2 years in a right-side traffic rule country were recruited. Furthermore, to account for linguistic conflicts in the cognitive task, only participants with primary education in either French or English language were investigated. Participants were excluded if they presented any condition interfering with locomotion (e.g., orthopedic, rheumatologic, or neurological), lower limb or back pain, any visual condition interfering with 3D or color vision (e.g., strabismus, color blindness), or a history of eye surgery. The experiment was approved by the Research Ethics Board of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR) and all participants gave their written informed consent prior to entering the study.

3.3.3 EXPERIMENTAL SETUP AND PROCEDURE

After screening for eligibility, data collection took place at the Virtual Reality & Mobility Laboratory of Jewish Rehabilitation Hospital, a research site of CRIR. Participants were assessed for their performance in tasks categorized into 3 conditions, which were block randomized. The first condition involved single-task walking (STW) and required participants to walk towards a target while avoiding approaching virtual pedestrians (VRP). The second condition was a cognitive single task (STC) where the participants performed an auditory-based cognitive task. An auditory-based task, as opposed to a visual task, was selected to not interfere with gaze behavior. The cognitive task had two levels of complexity, that is a simple task involving a pitch discrimination task and a more complex task which consisted of an Auditory Stroop task. The third condition involved dual tasking (DT), that is a combination of tasks described in conditions 1 and 2.

Single task Walking (STW)

Participants were tested while walking in a virtual environment representative of a Montreal subway station and which was created in the Unreal 4.2 game engine (Figure 1). A previously validated VR paradigm was used for this study (71). The dimensions of the virtual room replicated those of the testing area (7.8m X 3.7m) that the participants walked in. Positioned at a designated starting position, the participants faced a target (metro map) located straight ahead (0°) at a distance of 10m. 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 (TPC) located 3.5m in front of the participant, with a radius of 3m. The TPC is a point where a collision with an interferer (i.e., approaching VRP) is to occur if the participants do not perform any locomotor adjustments. The VRPs were created based on real gait patterns of 3 female actors from a previously validated study in our lab (75). The walking speed of the VRPs was approximately 1.2m/s, replicating the average walking speed of healthy young individuals (86).

The participants viewed the virtual environment using the HTC Vive Pro Eye, head-mounted display (HMD). This HMD weighs 550 gm and has a field of view of 110° with a resolution of 2880 x 1600 pixels and a refresh rate of 90 Hz. The HMD is integrated with tracking sensors that provide information on the position and orientation of the head. This information was fed in real-time to the Unreal game engine to update the camera view of the participant within the virtual scene according to the head movements that were performed. The HTC Vive Pro Eye is enabled with an eye-tracking system that uses near-infrared light (NIR 850nm) to scan the wearer's movements for each eye. The headset tracks eye movements with an accuracy of 0.5 to 1.1° across the headset's entire 110-degree field of view (87). The eye position data was recorded in the Unreal game engine at 90Hz and stored for offline analysis.

The eye-tracking system was calibrated using a 3-point calibration process integrated into the headset, prior to starting the locomotor task and, in case the headset was removed or moved by participants, the calibration was repeated. For the locomotor task, participants were instructed to begin walking at a comfortable speed towards the target while avoiding collisions with approaching VRPS on seeing the words ‘Ready Set Go’ on the screen. They were further instructed to walk until the ‘STOP’ sign appeared on the screen, and in the event of a collision to stop walking and return to the starting point. Once the participants walked 0.5 m forward, the VRPs were triggered to walk towards the TPC. Two of the VRPs took a step forward, turned, and walked away, while one VRP continued to walk towards the TPC. Five directions of obstacle approach were randomly presented: (1) right obstacle approach; (2) left obstacle approach; (3) middle obstacle approach; (4) all back condition where all pedestrians turn back and (5) no obstacle condition where no VRPs were present in the virtual environment. Participants were allowed to take breaks as needed between the blocks.

Cognitive Single tasks (STC)

In the simple cognitive task, the word “cat” was presented in either a high or low pitch using the integrated headset of the HTC Vive Pro Eye. Participants were instructed to identify verbally the pitch of the sounds on hearing them. In the complex task, the words “high” or “low” were presented in a high or low pitch. In this task, participants were instructed to ignore the word and identify the pitch of the sound making it more complex as greater attention and inhibition is required. For both the simple and complex single cognitive tasks, participants were seated and observed the same virtual environment as in the locomotor (but static) in the HMD. The words were presented at a variable interstimulus interval of 1.5-1.9 seconds and were available in both

French and English. The answers of participants were entered manually by the experimenter in Unreal and stored for offline analysis.

Dual-task walking (DTW)

This condition was a combination of the locomotor and cognitive tasks (simple and complex), resulting in a simple and a complex DTW condition. Participants were instructed to walk towards the target and to avoid VRPs as needed while reporting the pitch of the words simultaneously. The sounds were played immediately after the 'Ready Set go' sign flashed and were spaced at a similar interstimulus interval as the SCT condition.

Three blocks of 10 trials (2 of each direction approach per block) were presented for each condition; STW, Simple DTW, and Complex DTW making it a total of 90 walking trials. One block of 24 trials for each Simple and Complex SCT were presented making it a total of 48 trials for this condition.

3.3.4 DATA ANALYSIS

In Unreal, the eye vector was compounded with the camera transformation and a function was applied to detect the scene components that intersected with the gaze vector at every sample frame. The data was loaded in Matlab R2018b for further analysis. In order to understand gaze behaviour, the following outcomes were analyzed: *Gaze fixation (%) on i) approaching virtual pedestrian (VRP) ii) target (subway map) iii) environment and iv) non-approaching pedestrians.* Gaze fixation was defined as a continuous gaze collision on the same object for a minimum duration of 80ms (88). Percentage of gaze fixation on these scene elements were looked at in the trial time starting at the onset of avatar movement i.e., 0.5m and up to point of VRP crossing (participant's position along the anteroposterior axis equals the VRP position). *Gaze fixation on the specific body* *segments*, that is on the head, upper and lower trunk, as well as bilateral arms and legs of the VRP, was analyzed similarly.

Locomotor outcomes included *minimum distance from the VRP, onset distance of trajectory deviation, average and peak walking speed, side of circumvention, and number of collisions*. These locomotor outcomes have been used previously to characterize the avoidance behaviour during the circumvention of pedestrians (7, 14, 71). Minimum distance was calculated as the shortest mediolateral distance in the walking trajectories between the VRP's sternum and participant from the start of VRP movement until the point of VRP crossing. To obtain the *onset distance* of trajectory deviation, a linear regression line was fitted to the data from the 0.5m mark until the first point, backtracking from the point of minimum distance at which the mediolateral displacement was smaller than 25% of the maximum within the same period. A deviation larger than the 99% confidence interval of this linear prediction determined the occurrence of a trajectory deviation. In trials with a trajectory deviation, the first frame preceding this deviation at which the first derivative of the lateral component of the participant's position was smaller than zero was obtained, and *onset distance* was defined as the Euclidean distance between the participant and VRP. To characterize the participant's speed adaptations, we first obtained the first point after the participant's initial acceleration. This point was defined as the first segment after the first step at which forward acceleration was equal or lower than zero. Subsequently, from this point to the point of VRP crossing, the average and maximum walking speeds were extracted. To identify collisions, a critical distance from the VRP calculated as the sum of the radius of the VRP and half the shoulder width of the participant was set. When the distance between the lateral borders of the participant and the obstacle dropped below this critical distance, a collision event was detected. Percentages of collision were calculated by dividing the number of collisions by the total number of trials per walking condition.

Accuracy of correct response on the cognitive tasks was reported in percentage and calculated for each condition by dividing the number of correct responses by the total number of trials.

Lastly, dual task cost was calculated for any variables that showed a statistically significant difference between single and dual-task conditions. The formula used for the calculation of dual-task cost was (100* [single-dual]/single).

3.3.5 STATISTICAL ANALYSIS

A generalized estimating equations model (GEE) built-in SAS 9.4 was used to compare gaze and locomotor outcomes across 2 within-subject factors, i.e., direction of obstacle approach (left, center, and right) and walking condition (STW, simple DTW, and complex DTW). For the cognitive outcomes, a GEE model was built to compare the accuracy of pitch discrimination across conditions 4 conditions(simple STC, complex STC, simple DTW, complex DTW). When the GEE returned a significant effect, Tukey post hoc tests with Bonferroni adjustments were conducted. Except for percentages of collision, all outcomes were calculated using collision-free trials. Statistics were performed with a statistical significance set at $\rho<0.05$.

3.4 RESULTS

We recorded a total of 10 collisions out of the 864 trials for which a VRP was approaching (1.16 %). Eight of these collisions were seen in dual-task trials(6 simple and 2 complex) and 2 collisions in the walking only trials.

3.4.1 GAZE FIXATION OUTCOMES

Figure 2 shows the mean percentage of gaze fixation on the approaching VRP, target, other pedestrians, and the environment. Results indicate that participants looked between 34 to 50% of the time at the approaching VRP and between 13-35% at the at other VRPs present in the environment, compared to 17-32% at the target and 14-18% for other elements of the environment. A statistically significant main effect of direction was observed for the percentage of gaze fixation on approaching VRP (χ^2 (2,791 = 9.21, $\rho<0.05$), target (χ^2 (2,825) = 9.98, $\rho<0.05$), other pedestrians (χ^2 (2,678) = 12.60, $\rho<0.05$), and other elements of the environment (χ^2 (2,589) = 7.29, $\rho<0.05$). Post hoc analysis revealed that the percent duration of fixation was longer on the approaching VRP for the middle approach compared to the left (Δ = 14.04 % , $\sigma\overline{x}$ = 2.91, $\rho<0.01$) and right (Δ = 10.98 % , $\sigma\overline{x}$ = 2.00, $\rho<0.01$) approaches, while gaze fixation on other pedestrians was longer for the diagonal vs. middle approaches (left: Δ = 19.61% , $\sigma\overline{x}$ = 1.82, $\rho<0.01$| right: Δ = 16.15 % , $\sigma\overline{x}$ = 1.79, $\rho<0.01$). Longer duration of fixation was also observed on the target for the middle approach compared to left (Δ = 11.01 % , $\sigma\overline{x}$ = 2.37, $\rho<0.01$) and right (Δ = 12.98 %, $\sigma\overline{x}$ = 2.47, $\rho<0.01$). No significant effect of condition or interaction effect of condition X direction were observed for any of the gaze outcomes (condition : p = 0.53 - 0.74, condition X direction : p= 0.06 - 0.79)

Figure 3 shows the percentage of fixation on different body elements of the approaching VRP such as the head, upper and lower trunk, arms, and legs. For all walking conditions, participants maximally fixated at the upper trunk of the approaching pedestrian, followed closely by the head and then other body segments. The analysis of the frequency at which each body segment was fixated upon (Table 1) further shows that the upper trunk was looked at in 89.8% of the trials, followed by the head in 63.8% of the trials. In those trials in which where there was a fixation on the head and upper trunk, the percent duration of fixation did not vary across task conditions ((χ^2 (2,859) = 2.95, ρ=0.22), To identify differences due to the side of circumvention with respect to the VRP, a separate analysis was conducted comparing fixation durations on the left vs right hemi body of the VRP (i.e., combining arm and leg on the left vs. right side). This analysis revealed a significant effect of side of circumvention (χ^2 (1,859) = 9.21, ρ<0.05) due to longer percentages of fixation on the right hemi body when participants circumvented the VRP from the left vs. right side (Δ = 27.66%, $\sigma\overline{x}$ = 5.97, ρ<0.001).

3.4.2 LOCOMOTOR OUTCOMES

Figure 4 comprises of the bar graphs related to the locomotor outcomes. A statistically significant main effect of direction of approach was observed for average walking speed (χ^2 (2,845) = 9.98, ρ<0.05), minimum walking speed (χ^2 (2,845) = 11.26, ρ<0.05) minimum distance (χ^2 (2,845) = 7.46, ρ<0.05) and onset distance of avoidance (χ^2 (2,771) = 12.92, ρ<0.05), but not peak walking speed (χ^2 (2,845) = 0.46, ρ=0.79). Post hoc analysis showed that compared to the diagonal approaches, the middle obstacle approach caused participants to adopt faster average walking speeds (left: Δ = 0.02 m/s , $\sigma\overline{x}$ = 0.007, ρ<0.01 | right: Δ = 0.02 m/s, $\sigma\overline{x}$ = 0.01, ρ<0.05), faster minimum walking speed (left: Δ = 0.08 m/s , $\sigma\overline{x}$ = 0.01, ρ<0.01 | right: Δ = 0.14 m/s, $\sigma\overline{x}$ = 0.03, ρ<0.01) , smaller minimum distances (left: Δ = 0.07 m , $\sigma\overline{x}$ = 0.02, ρ<0.01 | right: Δ = 0.05 m , $\sigma\overline{x}$ = 0.02, ρ<0.01) and larger onset distances (left: Δ = 0.19 m, $\sigma\overline{x}$ = 0.03, ρ<0.01 | right: Δ = 0.15 m , $\sigma\overline{x}$ = 0.02, ρ<0.01). Average walking speed was also significantly slower for the right vs. left obstacle approach (Δ = 0.05 m/s, $\sigma\overline{x}$ = 0.01, ρ<0.01). A trend of reduced average walking speed and larger onset distances with dual-tasking was also observed, however, the results were not statistically significant. The analysis of the circumvention side further revealed that participants adopted a same-side strategy for diagonally approaching obstacles, i.e., they circumvented to the left side during the left obstacle approach (91.9 % of trials) and to the right during the right obstacle approach (89.73 % of trials). For the middle obstacle approach, a bias to circumvent from the left side was seen in the walking only (64.28%) and simple dual-task trials (64.35%) however a shift was seen in the complex dual-task condition wherein the participants circumvented more from the right side (55.67%).

3.4.3 COGNITIVE TASK OUTCOMES

Table 2 shows the results on the cognitive task in the simple and complex dual and single tasks. It was observed that the number of participants making errors was twice as high in the dual-task conditions compared to single-task conditions. A main effect of condition was seen for the percentage of accuracy on the cognitive task (χ^2 (3,64) = 10.31, $\rho<0.05$), with significantly higher accuracy under single- vs. dual-task conditions, both for the simple ($\Delta = 16.15$ %, $\sigma\overline{x} = 1.79$, $\rho<0.01$) and complex cognitive tasks ($\Delta = 16.15$ %, $\sigma\overline{x} = 1.79$, $\rho<0.01$). The difference in accuracy in the simple vs complex cognitive task was not statistically significant (p=0.08).

3.4.4 DUAL TASK COSTS

Dual task costs (DTC) were calculated for variables that showed significant differences due to condition that is the percent accuracy on the cognitive task, with all direction of approaches confounded the DTC for accuracy on simple cognitive task was 5.28% and on complex cognitive task was 10.19 %. No significant dual-task effect was seen on the gaze outcomes and locomotor variables

3.5 DISCUSSION

This study used a virtual reality-based paradigm to characterize gaze behaviour during a collision avoidance task involving pedestrians. Specifically, the effects of the direction of approach of pedestrians and of dual-tasking on gaze behaviour was systematically documented. We observed maximal durations of fixation on the approaching pedestrian in comparison to other pedestrians present in the environment. The upper trunk and head of the approaching pedestrian received longer and more frequent gaze fixations compared to other body segments. The direction of approach of the pedestrian was also found to modulate gaze behaviour and locomotor variables. Dual tasking did not affect the gaze and locomotor variables during the collision avoidance task. It resulted, however, in a reduced cognitive performance compared to the single task condition. Possible explanations for our results and their implications are further explored below.

3.5.1 GAZE AND LOCOMOTOR BEHAVIOUR MODULATED AS A FUNCTION OF DIRECTION

In the present study, participants exhibited longer gaze fixations on the approaching pedestrian compared to other pedestrians and compared to other features of the environment. Such finding aligns with previous literature on locomotion in 'complex' environments, which has shown that gaze is generally focused on task-relevant elements, such as obstacles on the floor that need to be stepped over or vehicles when standing at a curb before street crossing (35-37). Likewise, in a pedestrian interaction task like the one examined in this study, the approaching pedestrian represented a dynamic obstacle to be circumvented and was thus likely to garner maximal visual attention. Present findings further are in alignment with previous studies on pedestrian interactions which indicate that earlier (40), longer (30, 39-41), and/or more frequent gaze fixations (39, 41, 42) are observed for 'riskier' pedestrians, that is those posing a greater risk of collision. The fact that longer gaze fixations were observed for the middle approaching pedestrian also appears to support the notion of the perceived collision risk as playing a role. Indeed, the middle approach likely represents the most challenging approach as it necessitates a change in walking trajectory, as opposed to diagonal approaches where a change in speed (e.g., accelerating or decelerating) could suffice (23, 71, 89). Likely due to this additional challenge imposed by the middle pedestrian approach, and as reported in previous work, participants in this study displayed earlier onsets of trajectory deviation (15, 71, 90) and faster walking speeds (15), while achieving smaller minimum obstacle clearance (71) compared to diagonal pedestrian approaches. Other factors than the perceived collision risk, however, may also be at cause in the observed gaze behaviour. Indeed, as individuals are known to shift their gaze towards the future travel direction and end goal during locomotion (28, 31, 32), the middle pedestrian may have received longer fixation durations as it lied in the line of sight of the centrally-located end goal (i.e. the subway map). In favor of the latter hypothesis, the duration of gaze fixation on *other, non-approaching pedestrians* was found to be longer in presence of a diagonal pedestrian approach, and shorter in presence of the middle pedestrian approach, which in both cases implies that participants were fixating the middle pedestrian., Similar findings whereby individuals predominantly fixate in the central visual field were reported in a recent pedestrian interaction study performed in the physical world (39). We suggest that predominantly allocating gaze on the approaching (vs. non-approaching) pedestrians while maintaining a gaze centered towards the midline (or end goal) serves the purpose of fulfilling the two-fold task requirement of collision avoidance and goal-directed walking (i.e., steering).

We also analyzed which body segments of the approaching pedestrian were fixated upon maximally by participants. Although Nummennaa et al. (2009) suggested that the direction of gaze of an approaching pedestrian influences the side an individual skirts towards (43), a limitation of their study was that participants were instructed to observe the gaze of the approaching pedestrians and verbally indicate the side they would skirt to as opposed to analyzing the natural visuomotor behaviour of participants. Lynch et al. (2021) further found no significant effect of the gaze of an approaching virtual pedestrian on the collision avoidance strategy and suggested that body cues of the pedestrian alone influenced the locomotor behaviour of the participants (44). In our study, participants were found to primarily fixate on the upper trunk followed by the head, previous work has suggested that the trunk is a reliable indicator of the future walking direction (91). Literature also suggests that individuals orient their head in the direction of walking prior to kinematic adaptations and trajectory deviation (33, 92-96). Thus, participants may have maximally fixated on the upper trunk and head because the orientation of these segments provides important cues to anticipate the approaching pedestrian's locomotor behaviour. Further analysis of the timing at which head and trunk segments are looked at in the course of the circumvention task would help further understand when such visual information was gathered and potentially provide further information on their respective roles. With respect to body segments fixated upon, we also observed that during circumvention from the left side, participants fixated maximally on the right hemi body (right arms and legs). A symmetrical, opposite behaviour could be observed when circumventing from the right. When circumventing from the right, participants pass to the left of the approaching VRP and thus may have had greater exposure to the left hemi body of the VRP and vice versa during circumvention from the left side.

3.5.2 PERFORMANCE IN COGNITIVE TASK MODULATED AS A FUNCTION OF TASK COMPLEXITY

In our study, a dual task effect which led to a decreased performance was seen on both the simple and complex cognitive tasks. No dual-task effects, however, were observed on the locomotor task, including both kinematic and gaze outcomes. Such finding suggests, explanation for the lack of dual task effect on locomotion is that during dual-tasking there is known to be the presence of prioritization of one task (locomotor) over the other (cognitive), due to limited central resources (97, 98). Indeed, Yogev-seligmann et al. (2012) and Shumway-cook et al. (1997) suggested that healthy young adults are likely to prioritize locomotion/stability under complex walking or postural conditions, that is when safety is likely to be compromised (99, 100). Pedestrian interaction tasks are complex and given the risk of collision with an approaching pedestrian and ensuing negative consequences, it is likely that individuals prioritized safe ambulation over performance on the cognitive task. Deblock-Bellamy et al. (2021) and Kelly et al. (2013) also found locomotion to be prioritized during dual tasking with an increasing task complexity (101, 102).

Of primary interest to our paper was the effect of dual tasking on variables of gaze behaviour such as the duration of fixation on task-relevant elements like the approaching pedestrian, target, and other pedestrians. Although based on current literature we hypothesized that the duration of fixation on these elements would reduce with dual-tasking, such an effect was not observed. Past studies that have found an impact of dual-tasking on gaze behaviour in healthy young adults have done so in a simple forward walking task with either a secondary visual scanning or executive working memory (e.g., subtraction backwards) task (61, 62, 103). Our apparently contrasting results of no dual-task effect on gaze behaviour during locomotion may be due to the fact that visual information is key for successful collision avoidance (30, 39, 41, 42) and may thus reflect the prioritization of the pedestrian interactions task. Also, in contrast to the visual scanning and texting task performed in a previous study (62, 63), the current cognitive task did not interfere with the visual function. Lastly, it is also possible that our auditory pitch discrimination was not as challenging as the executive memory tasks deployed in a previous study that found a significant dual-task effect on gaze (60-62). These observations highlight the need to take into consideration the nature and complexity of the tasks involved when examining the impact of dual-task walking (101, 104). In the future, it would be interesting to analyze the impact of varying cognitive tasks on gaze during pedestrian interactions.

3.6 LIMITATIONS

One of the main limitations of our study was that we did not analyze the timing of gaze fixations in relation to the time course of the locomotor task, which could have provided further information on the role of those fixations (planning vs. execution of collision avoidance vs. steering). This aspect of timing will be the object of a future manuscript on the coordination of gaze and body segments. The present study was also conducted in a virtual reality setting. While this allowed for a systematic manipulation of visual stimuli, and while collision avoidance behaviours were shown to be similar in the virtual vs. physical environment (9, 68, 71), our experimental conditions do not reflect the richness and diversity of scenarios one would encounter in a real, complex community setting such as shopping mall, which comprises of various visual and auditory distractors and where pedestrians of different characteristics ambulate from and towards varying directions.

3.7 CONCLUSIONS

We analyzed healthy patterns of gaze behaviour during a collision avoidance task involving pedestrians approaching from different directions, under single and dual-task conditions. Our findings indicate that participants fixated maximally on the approaching pedestrian, and more specifically its upper trunk followed by its head. This pattern of fixation on the trunk and head may have served the purpose of anticipating the pedestrian's trajectory. Gaze was also found to be largely fixated centrally, that is on the middle pedestrian and goal. Such pattern of fixation may be explained by factors that are linked to the two-fold requirement of the task, namely the avoidance of an obstacle for which the middle approach pose a greater risk of collision, and the implementation of a steering strategy which involves the orientation of gaze towards the end goal. The fact that dual tasking affected cognitive but not gaze or locomotor outcomes suggests a prioritization of the locomotor task and associated acquisition of visual cues needed for its successful completion. The healthy patterns of visuomotor behaviour unveiled in this study will serve as a basis for comparison to further understand altered collision avoidance strategies in older adults and patient populations.

3.8 ACKNOWLEDGEMENTS

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Figure 3-1. Virtual subway scene with pedestrians at beginning of a trial.

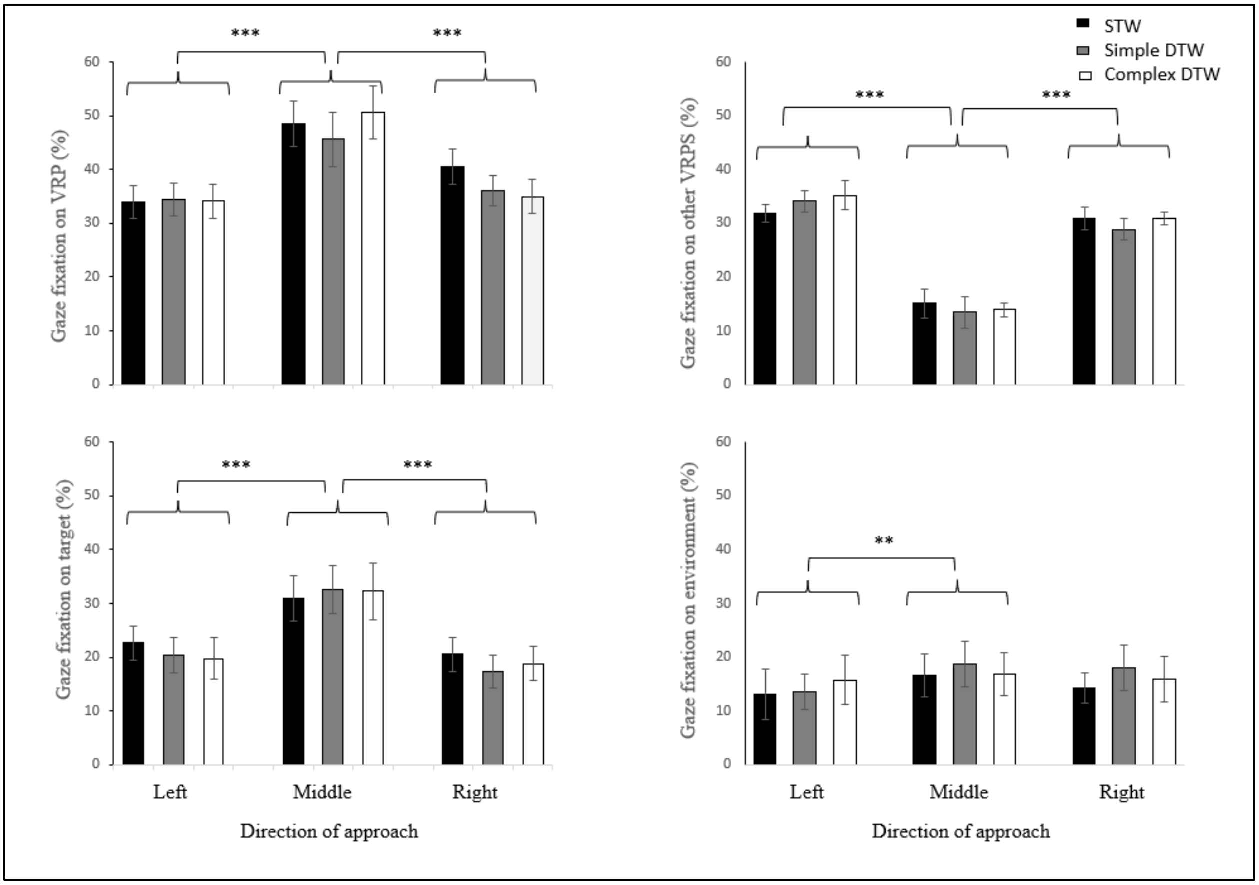

Figure 3-2. Group mean ± 1SE value for gaze fixation on approaching VRP(left upper panel), target (left lower panel), other VRPS (right upper panel), and environment (right lower panel). Statistically significant main and interaction effects are indicated, as applicable. Likewise, post-hoc comparisons that were statistically significant are also illustrated.

* $p < 0.05$. ** $p < 0.01$. ***$p < 0.001$

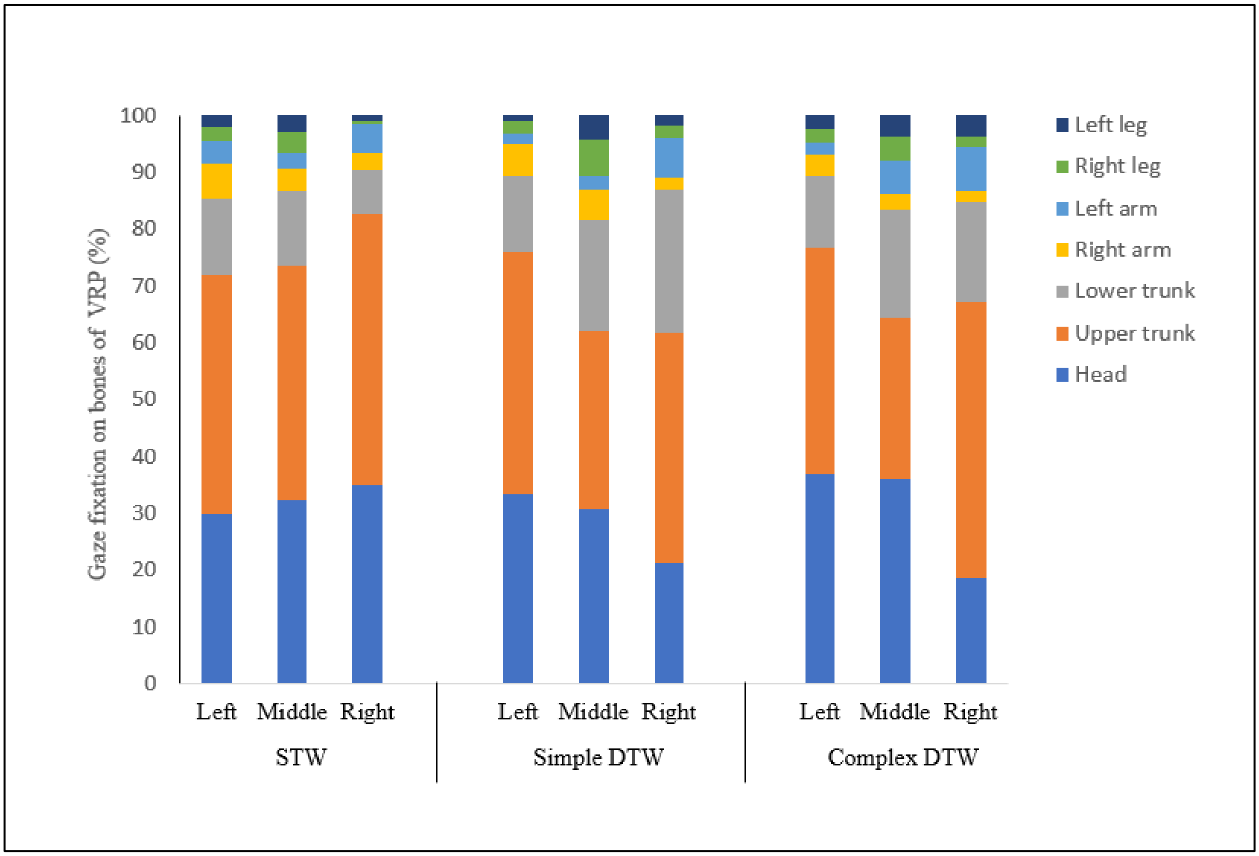

Figure 3-3. Percentage of gaze fixation on specific body segments of the approaching pedestrian across all direction and task conditions.

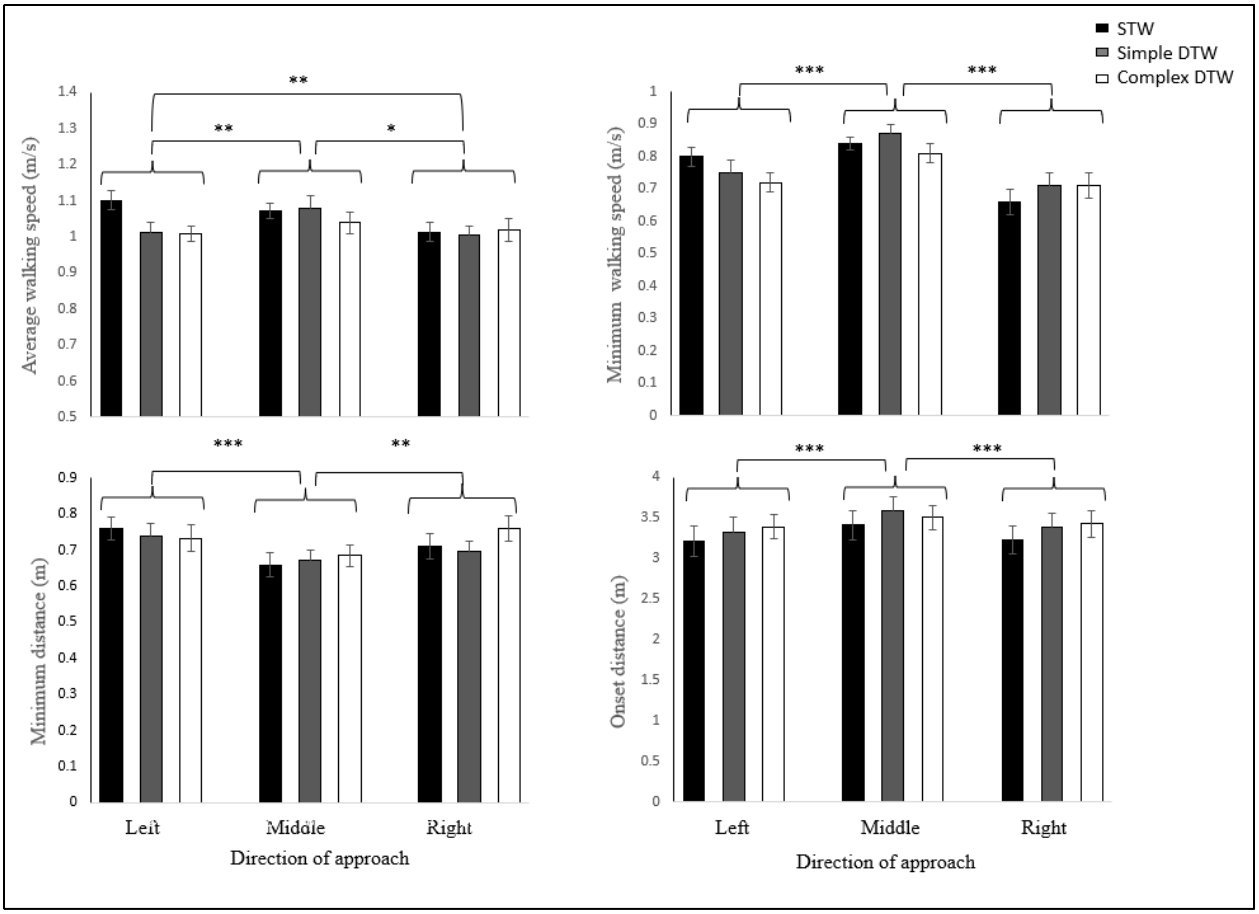

Figure 3-4. Group mean ± 1SE value for gaze fixation for average walking speed(left upper panel), minimum distance (left lower panel), minimum walking speed (right upper panel), and onset distance (right lower panel). Statistically significant main and interaction effects are indicated, as applicable. Likewise, post-hoc comparisons that were statistically significant are also illustrated. * $p < 0.05$. ** $p < 0.01$. ***$p < 0.001$

Table 3-1. Percentage of trials with fixation on the specified body segments as per direction (left, middle and right) and task conditions (single-task walking (STW), simple dual-task walking (DTW) and complex DTW).

	STW			**Simple DTW**			**Complex DTW**		
	Left	**Middle**	**Right**	**Left**	**Middle**	**Right**	**Left**	**Middle**	**Right**
Head	67.70	71	75.78	62.10	56.25	58.33	63.82	55.78	63.15
Upper trunk	93.75	96.90	95.78	89.47	88.54	91.66	87.23	76.84	87.36
Lower trunk	64.58	50.51	57.89	68.42	56.25	72.91	56.38	52.63	69.47
Arms	73.95	56.70	63.15	65.26	59.3	81.25	59.57	52.63	56.84
Legs	33.29	25.77	36.84	43.15	30.20	37.5	36.17	38.94	32.63

Table 3-2. Performance of participants in the cognitive task illustrated by the number of participants (out of a total of 16) that made errors in pitch discrimination and their percentage of accuracy in each of the tasks.

	Single task		**Dual task**	
	Simple	**Complex**	**Simple**	**Complex**
No of participants that made errors (out of 16)	6	7	12	14
Percentage of accuracy (Mean ± SD)	97.65 ±0.84	97.91±0.65	92.49±2.46	88.53±1.97

CHAPTER 4: GENERAL DISCUSSION

In this study, healthy patterns of gaze behaviour during pedestrian interactions and specifically the impact of dual tasking on this behaviour were analyzed. This chapter discusses knowledge gaps addressed by this thesis work and implications of findings for locomotor rehabilitation.

4.2 SUMMARY OF FINDINGS

Safely circumventing the approaching pedestrians was a crucial requirement of this experiment, thus participants tested as part of this thesis work fixated maximally on these pedestrians, specifically their upper trunk and head. These body segments being reliable indicators of the pedestrian's future direction of walking (91, 93-95), they likely represented useful cues for participants to plan their avoidance strategies. A significant effect of direction was also observed for gaze variables, wherein maximal fixation was seen on the pedestrian and goal during the middle approach. This centrally fixated gaze may be explained by the fact that gaze is known to orient towards the direction of the end goal (28, 34) and to be largely fixated on risky pedestrians in the environment (30, 39, 41, 42), both of which are situations that applied to our experiment. In alignment with previous studies, we also observed a significant effect of direction on locomotor variables which were reflected by smaller obstacle clearances (71, 90), faster average and minimum walking speeds (22), and larger onset of avoidance distances (71, 90) for the middle approach. Such observations are likely due to the challenging nature of the middle approach, which absolutely requires a trajectory deviation to avoid a collision (23, 89). With respect to task complexity, a significant effect of dual tasking was observed for both the simple and complex cognitive tasks but not for locomotor and gaze variables associated with the collision avoidance task. Given the complex nature of our walking task, it appears the participants prioritized safe ambulation and thus the acquisition of necessary visual information for collision avoidance. Although previous studies have observed significant dual task effects on gaze during locomotion (48, 60, 62, 63), our auditory pitch discrimination task may not have burdened the attentional resources of healthy young adults as significantly as the executive working memory tasks or visual scanning tasks incorporated in those studies.

4.2 SIGNIFICANCE AND FUTURE DIRECTIONS

To the best of our knowledge, the study completed as part of this thesis work was the first to quantify the fixations on specific body segments of the approaching pedestrian and the effects of varying directional and task conditions on gaze behaviour during pedestrian interactions. Although it is known in the literature that visual information is acquired in a feedforward manner to guide locomotion (16, 19) and that individuals are likely to fixate on task-relevant elements (35, 36), the specific body segments of an approaching pedestrian fixated upon maximally to plan and execute the avoidance strategies have not been previously examined. Literature also suggested that locomotor strategies are modulated as a function of the direction of obstacle approach (23, 89), but whether such modulation would be observed for gaze behaviour was until now unclear.

Another dimension we explored in our work was negotiating pedestrians while performing a secondary task simultaneously. It is well documented in the literature that dual tasking is a challenging aspect of community mobility for elderly adults (13, 15, 50, 73, 105) and patient populations (11, 14, 46), due to the burden it imposes on attentional resources. Gaze and attention are known to be tightly linked (59) and, given that visual information is crucial for collision avoidance, an exploration of the impact of dual tasking on gaze behaviour was needed. The present thesis work is thus the first to explore this perspective, starting with healthy gaze behavioural patterns under both single and dual task conditions. Such exploration has allowed a deeper understanding of gaze strategies that are likely to yield a successful performance on these tasks. Obstacle avoidance and dual tasking are challenging aspects of community mobility for elderly adults (50, 73), individuals with sensorimotor impairments (e.g., stroke) (7, 8), or those with visual-perceptual impairments (e.g., stroke with unilateral spatial neglect) (14). Present findings will be useful in future research to compare and understand the altered collision avoidance responses in these populations. Identifying these deficits in visuomotor control may better explain their challenges in carrying out these tasks effectively in the community. Results from this thesis will also support the development of an ecological VR-based assessment tool for identifying deficits in dual-tasking walking and gaze behaviour. Assessment of gaze behaviour in the form of fixation time on relevant scene objects, timing of fixation etc. through gaming virtual reality headsets could play a role in designing a holistic rehabilitation programs for complex locomotor tasks. Currently, clinical practice largely focuses on kinematic aspects of locomotion, and new evidence highlighting the importance of visuomotor control, collision avoidance and dual-tasking may better inform clinicians to incorporate these aspects in locomotor rehabilitation.

CHAPTER 5: REFERENCES

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APPENDIX 1: English Consent Form

CONSENT FORM FOR PARTICIPATING IN A RESEARCH PROJECT

1. TITLE OF THE PROJECT

Gaze control strategies during locomotion and dynamic obstacles avoidance: walking in the real-world vs in virtual reality

2. PROJECT LEADER

Anouk Lamontagne, Ph.D., PT
Associate Professor
School of Physical and Occupational Therapy
Jewish rehabilitation Hospital (JRH)
McGill University

3. FUNDING ORGANIZATION

The research program, of which the current project is a part of, is financed by funding from the Regroupement d'ingénierie de technologies interactives en réadaptation (INTER).

INTRODUCTION

The aim of this research project is to evaluate the performance and strategies used by elderly people to avoid collisions with one or multiple moving obstacles. 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 inconvenience, 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 deem useful to the researcher and the others members of the staff assigned to the research project and ask them to explain any word or information which is not clear to you.

4. DESCRIPTION AND OBJECTIVES OF THE PROJECT

Avoiding obstacles during walking is an important part of daily activities. To reduce the risk of any accident, you must be able to avoid colliding with objects in your path. Vision is predominantly used to avoid collision by allowing the detection of obstacles in the environment. Avoiding an obstacle also depends greatly on the capacity to modify your trajectory and speed during locomotion. It is currently not clear what walking and gaze shifting strategies are used by healthy people and people who had a stroke when confronted with multiple potential human interferers (pedestrians). Furthermore, we don't know how such strategies are influenced by the performance by a concurrent mental task.

Virtual reality is a technique that allows us to study obstacle avoidance during walking by recreating safe and realistic environments like those encountered in everyday life. The data collected here will allow a better understanding of the difficulties faced by both groups of participants during obstacle avoidance and will help with the development of new assessment and intervention tools in the context of rehabilitation.

5. NATURE OF YOUR PARTICIPATION

You will be asked to participate in two (2) separate evaluation sessions of 2 to 3 hours each. Those sessions will ideally take place in the same week. The **first session** will consist of a clinical evaluation to assess your performance during several cognitive, walking and eye and head movement tasks. The results of this first session will determine if a given participant will be asked to participate in the second session. The **second session** will evaluate your ability to walk around obstacles, as well as the eye movements that accompany those body movements during this task.

All evaluations will take place at the Jewish rehabilitation hospital in Laval, QC. A contact person and one of the researchers will be present during the evaluations to greet you and help you move about.

First evaluation session

At the beginning of this session the participant will be given ample time to read and sign the consent form. All questions that you may have regarding the experiments will be answered.

The participant will then be evaluated on certain clinical tests and must fill in questionnaires that will evaluate hand dominance, your ability to walk, the presence or absence of motion sickness, as well as your cognitive, visual, and visuospatial functions. Finally, eye movement accuracy and the vestibulo-ocular reflex will be evaluated.

Second evaluation session:

This session will assess your ability to circumvent pedestrians while walking in the real world and in virtual reality.

Preparation

Your height, weight and body dimensions will be measured and small reflective markers will be places on different parts of your body (head, torso, arms and legs). The movement of your body based on these markers will be recorded by cameras while you walk and this will be used to analyze your movements. During all experiments, your eye movements will also be recorded and analyzed using a video camera.

Evaluation

You shall walk several times along an eleven-meter walkway. You will be asked to walk and avoid virtual pedestrians approaching from different directions as you walk in virtual reality. You will view the virtual environment through a helmet mounted display. For some walking trials, you will further execute a mental task which consist of determining the pitch (high or low) of words you will hear through earphones. In a second set of experiments, you will be asked to perform the same experiment but this time in the real world. In these latter experiments, you will therefore be required to avoid real human pedestrians walking in the laboratory and coming from different directions.

The helmet used during the virtual reality experiments is relatively comfortable to wear. The miniature eye movement camera will be positioned outside of the helmet. To stabilize to helmet you will also be asked to bite on a custom-made oral prosthesis attached to the helmet. A therapist will walk next to you for additional safety and will assist you back to the starting position.

You will complete between 20 and 25 trials during each of the two experiments, based on your ability, comfort and endurance. You shall rest as often as needed in between trials. A long 45-minute break will be inserted between the two experiments. Overall, including all breaks, the evaluation should take about 3hours.

6. Benefits from your participation

This study does not guarantee any direct benefit. However, the results from this study will provide information that will help in developing better techniques for rehabilitation of persons with a stroke.

7. RISKS AND INCONVENIENCES ASSOCIATED WITH YOUR PARTICIPATION

Risks associated to your participation in this study are minimal. You may, however, feel tired following the evaluation. You may also experience nausea following exposure to the virtual scenarios. The feeling of fatigue or nausea will wear off with rest. It is also possible that the equipment used during the experiments might feel a bit uncomfortable at times due to its weight and the use of the oral prosthesis to stabilize the helmet.

8. ACCESS TO RESULTS AT THE END OF THE STUDY

At the end of the study, you may have access to the results if desired.

9. ACCESS TO MEDICAL RECORDS

For the participants who had a stroke, the research team might need to access certain information found in your medical records, such as: the onset date and localization of the stroke, the cognitive status, gait ability, measures of motor recovery, visual functions, absence or presence of unilateral spatial neglect, as well as orthopedic/rheumatological conditions interfering with locomotion.

10. CONFIDENTIALITY

Any personal information making it possible to identify you will be kept confidential, codified and will be filed in a locked cabinet (room D-0110), along with your movements recorded during the experiments and your answers to the questionnaires. The data relating to your evaluations will be transferred onto a computer file server where access is protected by passwords. Only members of the research team have access to the information collected during the project. However, for quality control purposes, your file may be consulted by a person mandated by the CRIR’s CÉR or by a member of “la Direction de l’éthique et de la qualité du ministère de la Santé et des Services sociaux du Québec”. The information will be preserved for a duration of 5 years, after which they will be destroyed. The data of this research will only be revealed in the form of scientific presentations or publications, without my name or identity exposed.

11. VIDEOTAPING AND OR PHOTOGRAPHY

It is possible that certain sessions will be recorded with video or audiotape and that photographs will be taken. We will only use these with your permission for the educational and/or scientific purposes. It is however not necessary to consent this section to participate in the current project. If you refuse to consent, the recordings and photographs concerning you will be destroyed at the end of the project to respect your confidentiality.

Do you authorize us to use the photographs or recordings for educational or scientific purposes and to conserve your research data?

Yes ☐ No ☐

13. VOLUNTARY PARTICIPATION AND 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. In case of withdrawal from the study, all documents concerning you will be destroyed if that is your decision.

14. FUTURE RESEARCH STUDIES

It may be that the results obtained following this study result in another research study. In this case, do you accept to be contacted by the same researchers to participate in other scientific studies done in a similar area of research?

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

* Note that if you select one of these three cases, your personal details will be kept by the principal investigator for the period to which you consent.

15. RESPONSIBILITY CLAUSE

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.

16. COMPENSATORY INDEMNITY

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

17. CONTACT PERSON

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 531 or by email at the following address: anouk.lamontagne@mcgill.ca.

If you have questions about your rights and recourse or your participation in this research project, you can contact Mme Mariama Touré, coordinator of the Research Ethics Committee of CRIR establishments (514) 527-9565 ext 3789 or by email at the following address: mariama.toure.ccsmtl@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

18. CONSENT

I state that I have read and understood this project, the nature and extent of my participation, as well as the benefits and risks/inconveniences to which I will be exposed as presented in this form. I have been given the opportunity to ask questions concerning any aspects of the study and have received answers to my satisfaction. A signed copy of this consent form will be given to me.

I, the undersigned, voluntary agree to take part in this study. I can withdraw from the study at any time without prejudice of any kind. I certify that I have had sufficient time to consider my decision.

NAME OF PARTICIPANT SIGNATURE

____________________________ ____________________________

Signed at ________________, the ___________, 20_____

19. COMMITMENT OF RESEARCHER OR REPRESENTATIVE

I, the undersigned ____________________________________, certify that I have

a) explained the terms of this form to the participant
b) answered the questions regarding this research study
c) explained clearly that the he/she remains, always free to end his/her participation in the research project described above.

____
Signature of the Principal Investigator or representative

Signed at___________________, the ______________ 20___

APPENDIX 2: French Consent Form

Formulaire d'information et de consentement

12. TITRE DU PROJET

Contrôle du regard lors de la marche et de l'évitement d'obstacles en mouvement : marcher dans le monde réel vs dans un monde virtuel

13. RESPONSABLE DU PROJET

Anouk Lamontagne, Ph.D., pht
Professeure agrégée
École de physiothérapie et d'ergothérapie
Université McGill
Hôpital juif de réadaptation

14. ORGANISME SUBVENTIONNAIRE

Le programme de recherche d'Anouk Lamontagne, Ph.D, dont le présent projet fait partie est financé par une subvention du Regroupement d'ingénieries intéractives en réadaptation (INTER)

15. PRÉAMBULE

Ce projet vise à évaluer la performance et les stratégies utilisées par les personnes durant une tâche qui consiste à marcher tout en évitant d'entrer en collision avec un ou des obstacles en mouvement. Avant d'accepter de participer à ce projet de recherche, veuillez prendre le temps de lire attentivement les renseignements qui suivent.

Ce formulaire de consentement explique le but de cette étude, les procédures, les avantages, les risques et les inconvénients ainsi que les personnes à contacter, si nécessaire.

Ce formulaire de consentement peut contenir des mots que vous ne comprenez pas. Nous vous invitons à poser toute question que vous jugez utile au chercheur et aux autres membres du personnel engagés dans le projet de recherche et de leur demander d'expliquer un mot ou une information qui n'est pas clair pour vous.

16. DESCRIPTION DU PROJET ET DE SES OBJECTIFS

La capacité d'éviter des obstacles tout en marchant est une compétence importante à maîtriser lors d'activités de la vie quotidienne. Pour réduire le risque d'accident, vous devez être capable d'éviter les collisions avec des objets ou des personnes présents dans votre environnement. L'évitement de collision repose en bonne partie sur le sens de la vision qui permet de détecter les obstacles sur votre chemin. Il dépend aussi de la capacité à modifier votre trajectoire ou votre vitesse de marche. À ce jour, nous possédons très peu d'information quant aux stratégies du contrôle de la marche et du regard utilisées par les personnes ayant eu ou non un AVC pour éviter d'autres personnes en mouvement (piétons). De plus, nous ne savons pas comment ces stratégies sont influences par l'exécution en simultané d'une tâche mentale.

La réalité virtuelle est une technique qui permet de recréer des environnements propices à l'évaluation de la capacité à contourner des obstacles pendant la marche, et ce, de façon sécuritaire. Les données recueillies dans le cadre de ce projet permettront de mieux comprendre les difficultés rencontrées par les personnes ayant eu ou non un AVC au cours de l'évitement d'obstacles et aideront au développement de nouvelles stratégies d'évaluation et de réadaptation.

17. NATURE DE LA PARTICIPATION

On vous demandera de participer à deux rencontres d'évaluation d'une durée de 2 heures à 3 heures chacune. Ces rencontres auront idéalement lieu durant la même semaine. La **première rencontre** consistera en une évaluation clinique qui permettra d'évaluer votre performance lors de différentes tâches cognitives, de marche et de mouvement des yeux et de la tête. Les résultats de cette première rencontre permettront de déterminer si oui ou non, il vous sera demandé de participer à une seconde rencontre. Le cas échéant, la **seconde rencontre** servira à évaluer votre démarche lors du contournement d'obstacles ainsi que les mouvements des yeux qui accompagnent ceux du corps lors de cette tâche.

Toutes les évaluations auront lieu à l'Hôpital juif de réadaptation à Laval, QC. Une personne ressource et l'un des chercheurs seront présents lors des évaluations pour vous accueillir et vous aider à vous déplacer.

Première rencontre d'évaluation

Au début de la première rencontre, vous aurez amplement le temps de lire et de signer le formulaire de consentement. Toutes questions seront répondues.

Vous serez ensuite évalué à l'aide de tests cliniques et serez invité à remplir quelques questionnaires qui mesureront la dominance manuelle, votre capacité de marche, la présence ou non de malaise de transport, vos fonctions cognitives, visuelles et spatiales, ainsi que la précision de vos mouvements des yeux et du réflexe vestibulo-oculaire.

<u>Deuxième rencontre d'évaluation</u>:

Cette seconde session servira à évaluer votre capacité à contourner des piétons en mouvement lors de la marche dans le monde réel et dans un contexte de réalité virtuelle.

Préparation. On prendra des mesures de vos dimensions corporelles et de votre poids et on apposera de petits marqueurs réfléchissants à différents endroits de votre corps (tête, torse, bras et jambes). Les déplacements de ces petits marqueurs seront enregistrés par des caméras pendant que vous marcherez et permettront d'analyser vos mouvements. Nous mesurerons aussi vos mouvements des yeux à l'aide d'une petite caméra vidéo.

Évaluation

Vous marcherez à plusieurs reprises le long d'une allée de 11 mètres. On vous demandera d'éviter des piétons virtuels provenant de différentes directions alors vous marcherez dans l'environnement virtuel que vous visualiserez à l'aide du casque de réalité virtuelle. Lors de certains essais de marche, vous effectuerai une tâche mentale qui consiste à déterminer la tonalité (haute ou basse) de mots que vous entendrez à travers à des écouteurs. Vous effectuerez aussi ces mêmes tâches dans le monde réel où vous devrez éviter des personnes réelles se déplaçant dans le laboratoire.

Le casque utilisé lors de la marche en environnement virtuel est relativement confortable. La caméra miniature qui permet de mesurer la position des yeux sera installée à l'extérieur du casque. Afin de stabiliser le casque et la caméra, vous devrez mordre légèrement une prothèse buccale. Un(e) thérapeute marchera à côté de vous pour plus de sécurité et vous aidera à retrouver votre position de départ après chaque essai de marche.

Durant chacune des deux tâches de marche (monde réel et monde virtuel), vous effectuerez entre 20 et 25 essais de marche, selon votre capacité et votre endurance. Vous prendrez des pauses aussi souvent que nécessaire entre les essais. Une plus longue pause d'environ 45 min séparera l'évaluation de la marche en monde réel de celle en mode virtuel. Incluant les pauses, la durée totale de la session sera d'environ 3 heures.

18. AVANTAGES POUVANT DÉCOULER DE VOTRE PARTICIPATION

Votre participation au projet ne comporte aucun avantage personnel direct. Cependant, les résultats de cette étude vont générer de l'information importante qui pourra aider au développement de meilleures techniques pour évaluer et entraîner des tâches de marche complexes telles que l'évitement de piétons.

19. RISQUES ET INCONVÉNIENTS POUVANT DÉCOULER DE VOTRE PARTICIPATION

Les risques reliés à votre participation sont minimes. Vous pourriez par contre ressentir une fatigue suite à cette évaluation. Il est également possible que vous ayez des nausées, dû au visionnement des images virtuelles Il est possible que l'appareillage occasionne un peu d'inconfort dû à son poids ou à la nécessité de mordre dans une prothèse dentaire pour stabiliser le casque. Si tel est le cas, cette fatigue, ces nausées et cet inconfort se résorberont avec du repos. Finalement, il y a un léger risque de chutes ou de perte d'équilibre. Une personne vous suivra donc de près lors de vos déplacements durant les expériences.

20. ACCÈS AUX RÉSULTATS À LA FIN DE LA RECHERCHE

Une fois l'étude terminée, vous pourrez avoir accès aux résultats si tel est votre désir.

21. ACCÈS À VOTRE DOSSIER MÉDICAL

Pour les personnes ayant eu un AVC, l'équipe de recherche pourrait avoir besoin d'accéder à certaines données contenues dans votre dossier médical, comme : la date et la localisation de l'AVC, l'état cognitif, le rétablissement des fonctions motrices, les fonctions visuelles, l'absence ou présence de négligence spatiale unilatérale, ainsi que la présence ou non de symptômes orthopédiques/rhumatologiques pouvant interférer avec la marche.

22. 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 autre 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, c'est-à-dire les enregistrements vidéo de vos mouvements et vos réponses aux différents questionnaires, seront conservées sous clé à l'Hôpital juif de réadaptation (Bureau D-0110) par le responsable de l'étude pour une période de 5 ans suivant la fin du projet, après quoi, elles seront détruites. En cas de présentation de résultats de cette recherche ou de publication, rien ne pourra permettre de vous identifier.

23. ENREGISTREMENT VIDÉO ET/OU PRISE DE PHOTOGRAPHIES

Il est possible que certaines séances soient enregistrées sur support vidéo ou audio et que des photographies soient prises. Nous aimerions pouvoir utiliser ces enregistrements et photographies, 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 enregistrements et photographies à des fins de formations ou de présentations scientifiques et à les conserver avec les données de recherche?

Oui ☐ Non☐

24. PARTICIPATION VOLONTAIRE ET DROIT DE RETRAIT

Vous êtes libre d'accepter ou de refuser de participer à ce projet de recherche. Il est possible de 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. En cas de retrait de votre part, les documents audiovisuels et écrits vous concernant seront détruits, à votre demande.

25. 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 pendant la période à laquelle vous avez consenti.

26. 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 ou l'établissement de leurs responsabilités civiles et professionnelles.

27. INDEMNITÉ COMPENSATOIRE

Les frais de transport et de stationnement encourus pour votre participation à ce projet vous seront remboursés, jusqu'à un montant maximal de 30 $ par visite, sur présentation de reçus.

28. Personnes-ressources

Pour obtenir réponse à toute question supplémentaire en rapport à cette étude, vous pourrez contacter Anouk Lamontagne au (450) 688-9550 poste 531 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 pourrez communiquer avec Mme Mariama Touré, coordonnatrice à l'éthique de la recherche des établissements du CRIR au (514) 527-9565 poste 3789 ou par courriel à l'adresse suivante: mariama.toure.ccsmtl@ssss.gouv.qc.ca. Pour toute plainte, veuillez communiquer avec le commissaire locale aux plaintes de l'Hôpital juif de réadaptation, au (450) 668-1010, poste 23628 ou par courriel à plaintes.csssl@ssss.gouv.qc.ca

29. Consentement

Je peux être assuré(e) que l'information que j'ai reçue concernant ce projet est exacte et complète. Ma participation à ce projet est entièrement volontaire. Mon refus de participer n'affecterait en rien le traitement que je reçois dans cet hôpital. De plus, je pourrai me retirer de cette étude à tout moment.

En acceptant de participer à cette étude, je ne renonce à aucun de mes droits ni ne libère les chercheurs, le commanditaire ou les institutions impliquées de leurs obligations légales et professionnelles**.**

Sujet: ______________________________ Date:___________________________

(Signature)

______________________________ Tél.: ________________________

(Nom)

30. 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; et (d) que je lui remettrai une copie signée et datée du présent formulaire.

______________________________ Date:___________________________

(Signature du chercheur principal)

______________________________ Tél.: ________________________

(Nom)