INVESTIGATION OF VIRTUAL REALITY LOCOMOTION TECHNOLOGY EFFECTS ON SIMULATOR SICKNESS AND APPLICATION FOR NEURO-COGNITIVE TRAINING FOR PARTICIPANTS WITH MEMORY PROBLEMS

by

Cassandra Aldaba

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

Department of Biomedical Engineering

University of Manitoba

Winnipeg

Copyright © 2018 by Cassandra Aldaba

ABSTRACT

This thesis investigated the effects of virtual reality locomotive controllers with a head-mounted display on a user's simulator sickness and controller's intuitiveness. The investigation included two types of controllers: seated static methods (TiltChair and game pad joystick) and mobile methods (omni-directional treadmill and our manual wheelchair joystick, VRNChair). Initially, young adult participants selected the TiltChair that caused the most severe simulator sickness due to its asynchronous rotation between the participants' necks and torsos. Thus, a second experiment investigated the effect of synchronous neck rotation via utilizing the TiltChair with a neck brace. Overall, participants that spent more time in virtual reality had significantly higher simulator sickness. Additionally, the joystick and TiltChair had the highest level of intuitiveness and the omni-directional treadmill had the lowest level of intuitiveness among the young adult participants. Since we recruited young adult participants, researchers should design virtual reality experiments based on their sample population's susceptibility to simulator sickness and ability to utilize the virtual reality technology. Therefore, elderly participants with minimal computer experience would find the naturalistic motion of the VRNChair intuitive with minimal simulator sickness.

To further investigate the feasibility of the virtual reality locomotive controllers, the thesis investigated participants with memory problems utilizing the VRNChair or TiltChair during a neuro-cognitive rehabilitation program. The participants had no difficulties with the virtual reality locomotive controller and neuro-cognitive training shopping task, but the participants did not have any significant memory improvements. Therefore, the virtual reality neuro-cognitive tasks should be re-designed to minimize simulator sickness and to optimize mental stimulation for any potential cognitive or memory improvements.

ACKNOWLEDGEMENTS

This thesis has been supported by the Natural Sciences and Engineering Research Council of Canada and the Alzheimer's Society of Manitoba.

First, I wish to thank Churchill Park United Church for allowing me to conduct my neuro-cognitive rehabilitation program in their gym. I do not know what I would have done without this space. Also, I extend my gratitude towards all my participants who completed my experiments. Sometimes there were bouts of simulator sickness or sometimes there were bouts of boredom, however thank you for your participation.

Thank you to everyone in the virtual reality group: Paul, Ahmad and Kazu. We had many discussions that did not solely focus on our work but with times of laughter. I like to extend my appreciation to Paul because he provided his expertise in designing the omni-directional treadmill, the virtual Water Morris Maze, the virtual Radial Arm Maze and his virtual reality software Unity 3D packages. I could not have completed my thesis without his hard effort and work. Also, thanks to everyone in Dr. Moussavi's research group for reminding me that graduate studies includes beyond one's cubicle.

To Dr. Zahra Moussavi, my advisor, I am gracious for you providing me an opportunity to discover biomedical engineering in my undergraduate career. During my undergraduate research position, I became motivated to continue in my studies and pursue graduate studies. I truly appreciated all the opportunities: past, present and future.

Lastly, I graciously like to thank my family and friends for supporting me throughout my academic career. I love everyone very much. Even though it seems that I played video games the entire time, all my hard work and effort would had not existed without knowing that you were by my side.

DEDICATION

To my family and friends, especially my grandfather,

thank you for continuously being right by my side

as I embarked on this adventure.

TABLE OF CONTENTS

ABSTRACT i
ACKNOWLEDGEMENTS ii
DEDICATION iii
TABLE OF CONTENTS iv
LIST OF FIGURES vii
LIST OF TABLES ix
LIST OF ABBREVIATIONS xi
CHAPTER 1 – Introduction 1
1.1. Rationale 1
1.2. Objectives 2
1.3. Hypotheses 3
1.4. Summary and Organization of Thesis 4
CHAPTER 2 – Literature Review and Background 5
2.1. Virtual Reality Technological History 5
2.2. Simulator Sickness 7
2.3. Simulator Sickness Measurements 12
2.4. Simulator Sickness Individual Susceptibility 13
2.5. Simulator Sickness Remedies 15
2.5.1. Pharmaceuticals 15
2.5.2. Electrical Stimulation 16
2.5.3. Timely Breaks 16
2.5.4. Virtual Reality Environment Design 17
2.5.5. Software Solutions 17
2.5.6. Hardware Solutions 19
2.6. Virtual Reality Applications 20
2.6.1. Psychological Treatments 20
2.6.2. Occupational Training 21
2.6.3. Neuro-cognitive Rehabilitation 22
2.7. Summary 23
CHAPTER 3 – Methodology 24
3.1. Virtual Reality Platform 25
3.2. Virtual Reality Navigational Controllers 25
3.2.1. Head-Mounted Displays 26
3.2.2. TiltChair 27
3.2.3. Omni-directional Treadmill 28

3.2.4. VRNChair 32
3.2.5. Joystick 33
3.3. Virtual Reality Task 34
3.4. Experiment 1 35
3.4.1. Procedures 35
3.4.2. Participants 35
3.5. Experiment 2 35
3.5.1. Procedures 35
3.5.2. Participants 36
3.6. Simulator Sickness Measurements 36
3.6.1. Postural Sway 36
3.6.2. Simulator Sickness Questionnaire 39
3.7. Intuitive Utilization Measurements 40
3.8. Experiment Assumptions 41
3.9. Data Analysis 42
3.9.1. Data Analysis Assumptions 43
3.10. Summary 45
CHAPTER 4 – Results 46
4.1. Experiment 1 Results 46
4.1.1. Simulator Sickness 46
4.1.2. Intuitiveness 52
4.2. Experiment 2 Results 55
4.2.1. Simulator Sickness 55
4.2.2. Intuitiveness 59
4.3. Summary 60
CHAPTER 5 – Discussion 62
5.1. Experiment 1 Discussion 62
5.2. Experiment 2 Discussion 65
5.3. Exposure Time 66
5.4. Inadequacy of Simulator Sickness Measurements 66
5.5. Head-Mounted Displays 69
5.6. Intuitiveness 70
5.7. Observations in our Other Studies 71
5.7.1. VRNChair with Laptop Display 71

5.7.2. VRNChair with Oculus Rift DK2 73
5.7.3. TiltChair with Oculus Rift CV1 75
5.8. Summary 78
CHAPTER 6 – Application: Neuro-cognitive Training for Participants with Memory Problems 79
6.1. Aging Brain and Alzheimer's disease 79
6.2. Brain Plasticity 81
6.3. Brain Stimulation 82
6.4. Neuro-Cognitive Rehabilitation Programs 84
6.5. Methods 86
6.5.1. Training Sessions 87
6.5.2. Testing Sessions 90
6.6. Data Analysis 96
6.7. Participants 96
6.8. Results 97
6.8.1. Shopping Task 98
6.8.2. Primary Measures 99
6.8.3. Secondary Measures 102
6.8.4. Simulator Sickness 104
6.9. Discussion 105
6.10. Limitations 107
6.11. Summary 109
CHAPTER 7 – Conclusion and Future Works 111
7.1. Conclusion 111
7.2. Future Work 112
7.3. Summary 113
References 114

LIST OF FIGURES

Figure 1 – Most recent virtual reality technologies with head-mounted displays and hand controllers 6

Figure 2 – Vestibular apparatus 10

Figure 3 – Motion stimuli pathways 11

Figure 4 – Dynamic depth of field on virtual scene 18

Figure 5 – Simulator sickness measurement protocol 24

Figure 6 – Head mounted displays utilized in thesis 26

Figure 7 – TiltChair set-up 27

Figure 8 – TiltChair set-up with neck brace 28

Figure 9 – Omni-directional treadmill set-up 29

Figure 10 – Omni-directional treadmill walking algorithm of left foot 30

Figure 11 – Virtual omni-directional treadmill model 31

Figure 12 – VRNChair set-up 32

Figure 13 – Virtual model of VRNChair 33

Figure 14 – Joystick set-up 33

Figure 15 – Virtual reality navigation task for simulator sickness experiments 34

Figure 16 – Wii Balance Board calibration set-up 37

Figure 17 – Wii Balance Board manufacturer coefficient calibration 38

Figure 18 – Wii Balance Board center of pressure diagram 39

Figure 19 – Center of pressure path length sex × controller interaction effect with eyes-closed. 48

Figure 20 – Experiment 1 simulator sickness questionnaire mean difference trends 51

Figure 21 – Experiment 2 simulator sickness questionnaire mean difference score trends 58

Figure 22 – Initial virtual reality set-up with projection screen and joystick 72

Figure 23 – Initial VRNChair set-up as push cart controller 73

Figure 24 – Elderly participant with VRNChair and Oculus Rift DK2 set-up 74

Figure 25 – TiltChair v3 utilized by elderly participant 76

Figure 26 – Resolution comparison between Oculus Rift CV1 and DK2 77

Figure 27 – Brain anatomical comparison between Alzheimer's diseased brain (top) and healthy brain (bottom) 80

Figure 28 – Neuro-cognitive rehabilitation schedule 86

Figure 29 – Neuro-cognitive rehabilitation assessment order 86

Figure 30 – Shopping district neuro-cognitive rehabilitation task 88

Figure 31 – Virtual shopping district map 89

Figure 32 – Virtual Water Morris Maze 92

Figure 33 – Virtual Radial Arm Maze 93

Figure 34 – Word-Association Test 94

Figure 35 – 1-Back Test 95

Figure 36 – Participant's shopping task performances 98

Figure 37 – Word-Association forward score 102

Figure 38 – Word-Association backward score 102

LIST OF TABLES

Table 1 – Virtual reality locomotive controllers and head-mounted display motion stimuli 25

Table 2 – Simulator sickness questionnaire symptom categories [32] 40

Table 3 – Experiment 1 center of pressure path length with eyes closed 47

Table 4 – Experiment 1 center of pressure path length with eyes open 49

Table 5 – Experiment 1 traversed distance results..... 52

Table 6 – Experiment 1 execution times..... 53

Table 7 – Experiment 1 eyesight effects on execution time 54

Table 8 – Experiment 2 center of pressure path length with eyes-closed..... 56

Table 9 –Experiment 2 center of pressure path length with eyes-open 56

Table 10 – Simulator sickness traversed distances 59

Table 11 – VRNChair comparison to all TiltChair versions 59

Table 12 – Experiment 2 execution times..... 60

Table 13 – Oculus DK2 and CV1 hardware specifications comparison [78], [99], [100] 76

Table 14 – Neuro-cognitive rehabilitation's participant demographics 97

Table 15 – MoCA scores 99

Table 16 – Morris Water Maze average trial traversed error..... 100

Table 17 – Morris Water Maze average trial execution time 100

Table 18 – Radial Arm Maze average trial traversed error 101

Table 19 – Radial Arm Maze average trial execution time 101

Table 20 – Radial Arm Maze average trial reference memory error 101

Table 21 – Summary of MoCA scores 104

Table 22 – Summary of Word-Association forward scores..... 105

Table 23 – Summary of Word-Association backward scores..... 105

LIST OF ABBREVIATIONS

Abbreviation	Definition
VR	Virtual Reality
HMD	Head-Mounted Display
DK2	(Oculus Rift) Developer Kit 2
CV1	(Oculus Rift) Consumer Version 1
SSQ	Simulator Sickness Questionnaire
AD	Alzheimer's disease
MoCA	Montreal Cognitive Assessment

CHAPTER 1 – Introduction

1.1. Rationale

Our research group utilizes virtual reality (VR) technology with our spatial navigation games to investigate the application for diagnosing [1], [2] and neuro-rehabilitation of [3] Alzheimer's disease at a very early stage. VR allows us to replicate naturalistic scenarios in a controlled environment. Initially, participants utilized a joystick to play the games, but many elderly participants struggled to utilize the joystick and some developed simulator sickness. To resolve these issues, in a past research study of our team, a manual wheelchair joystick called the VRNChair was developed and utilized with a laptop display [4]. As participants viewed the virtual environment on the laptop display, they moved in the virtual environment by walking and pushing the VRNChair in the physical environment. Elderly participants had no difficulties utilizing the VRNChair and the simulator sickness reduced significantly.

Currently in our studies, participants utilize the Oculus Rift DK2 head-mounted display (HMD) with the VRNChair. Participants become fully immersed in virtual environment to have a naturalistic experience. A pilot study, showed more efficient target finding (shorter traversed distance in shorter duration) in the this version compared to utilizing the VRNChair and laptop display [5]. However, the number of simulator sickness incidents increased (further discussed in Section 5.7.2). Consequently, the current thesis tried to find the most feasible VR locomotive controller with the highest level of comfort in terms of simulator sickness and the highest level of intuitiveness in terms of user usability. The thesis investigated different VR locomotive controllers with a HMD first among young adult participants and then we evaluated the most feasible controller among elderly participants.

To further investigate the feasibility of the VR locomotive controller among elderly participants, the second part of the thesis investigated the application through a neuro-cognitive rehabilitation program with a VR brain exercise based on working and spatial types of memory. An individual's memory capability decreases with age and with neuro-degenerative diseases like dementia. The number of people diagnosed with dementia including most commonly Alzheimer's disease is 46.8 million worldwide in 2015. [6]. This number will continue to grow as the seniors population grows to 131.5 million by 2050 [6]. However, there is no effective treatment or cure for this neurodegenerative disease yet. Therefore, in recent years there have been a few studies that investigated the potential benefits to innovative non-conventional treatments such as repetitive transcranial magnetic stimulation (rTMS) [7] and cognitive stimulation by mental exercises [8]. These stimulating treatments utilize the brain's plasticity to strengthen the communication links between neurons and brain regions to improve cognition.

1.2. Objectives

The study's first objective investigates the feasibility of different VR locomotive controllers based on the lowest level of user simulator sickness and the highest level of controller intuitiveness among young adult participants. Simulator sickness occurs with participants utilizing immersive VR technology, while intuitiveness occurs when a user does not have difficulties utilizing the VR technology. Once we determine the most feasible controller(s) among young adult participants, the other objective investigates a VR application of neuro-cognitive rehabilitation for participants with memory problems.

1.3. Hypotheses

There are separate hypotheses for each experimental investigation of this thesis, one for the feasibility of the locomotive controllers and another for the application of a neuro-cognitive rehabilitation program. These hypotheses are summarized as followed:

- A feasible locomotive controller will have the highest level of comfort in terms of simulator sickness and highest level of intuitiveness for usability. We believe that controllers providing users with the most matching motion stimuli will have the lowest level of simulator sickness (measured by lowest Simulator Sickness Questionnaire scores) and provide the highest level of intuitiveness (measured by shortest traversed distance and shortest execution time).
- The neuro-cognitive rehabilitation program over a course of 2 months will either improve or maintain (avoid decline in) the cognitive status of participants with memory problems compared to baseline. Through such program, participants will execute mental stimulation that increases their brain activity to stimulate the brain's plasticity. The plausible improvements may be translated to their daily living.

1.4. Summary and Organization of Thesis

This thesis consists of seven chapters. Within this first chapter, the thesis project's rationale, objectives and hypotheses are explained. Chapter 2 presents the literature review and background information regarding VR and simulator sickness. Chapter 3 describes the methodology of the locomotive controller, simulator sickness and intuitiveness experiments. Chapter 4 presents the results and Chapter 5 interprets the results and discusses the locomotive controller(s) minimizing simulator sickness and maximizing the level of intuitiveness. Afterwards, Chapter 6 discusses the utilization of the locomotive controller during a neuro-cognitive rehabilitation program. Lastly, Chapter 7 concludes the thesis with a discussion of future work and final remarks.

CHAPTER 2 – Literature Review and Background

This thesis investigates the feasibility of VR locomotive controllers based on users' simulator sickness and controllers' intuitiveness. This chapter discusses current VR technology and its association with simulator sickness. Most importantly, one should learn the mechanisms that cause, measure, change and mediate simulator sickness before discussing the effects of VR locomotive technologies. Furthermore, the chapter discusses current VR applications.

2.1. Virtual Reality Technological History

The first VR technologies were created over 50 years ago. Morton Heilig submitted a patent in 1961 for his Sensorama invention in 1962 [9]. Users went on a virtual bike ride with an enclosing 3D display of a city. The first head mounted display (HMD) was created in 1968 by Ivan Sutherland called the Sword of Damocles [10]. This HMD had a pair of glasses with small screens that integrated a user's vision together to create a 3D image. Then, users could change the 3D image view by changing their own head's orientation. However, these initial VR technologies were unaccepted by the general consumer because of the low naturalistic fidelity from premature computer software and hardware technologies.

Current computer software and hardware technologies provide a more naturalistic and immersive VR experience. The Oculus Rift CV1 (Figure 1a) and HTC Vive (Figure 1b) HMDs immerse users in a virtual environment with a quick frame rate with 90 Hz and a high-resolution display with a pixel density of 455.63 pixels/inch for each eye. Additionally, the main computer processor receives help from a powerful graphics card (Eg. NVIDIA GeForce GTX 980 or higher) to update the next 3D image frame. Faster frame rates reduce the noticeable flicker and the 3D vision provides users with a naturalistic environmental view.



(a) (b)

Figure 1 – Most recent virtual reality technologies with head-mounted displays and hand controllers
(a) Oculus Rift CV1 (b) HTC Vive Consumer version

To further immerse users in the virtual environment, users can interact with the environment via hand controllers, VR tracking hardware sensors and locomotive game controllers. The hand controllers allow users to manipulate virtual objects. Users can pick up, put down and move objects through the grasp of their own hands with natural physic interactions. These hand controllers' and the HMDs' positions are determined by different tracking methods by the Oculus Rift and HTC Vive. The Oculus Rift utilizes a combination of internal inertial sensors, imbedded infrared LEDs and an external camera to determine the device position [11, p. 20]. In contrast, the HTC Vive utilizes external beacons illuminating the HMD and hand controllers' photodetectors to determine the device position [12].

Additionally, the Oculus Rift and HTC Vive allow users to navigate in a small space defined by an external camera or a few beacons. To navigate past these boundaries, different methods have been developed such as teleportation [13], joysticks and omni-directional treadmills [14]. A former member of our research team also developed a manual wheelchair that acts as a computer joystick called the VRNChair [4]. The VRNChair converts a user's physical translations into virtual

translations as a user freely walks around. However, VR users are still susceptible to developing simulator sickness, which will be described in the next section.

2.2. Simulator Sickness

Simulator sickness along with seasickness, carsickness and space sickness can all be generalized as motion sickness. Thus, this section will explain the simulator sickness mechanisms utilizing the general term, motion sickness. However, all other sections will utilize the term simulator sickness when users develop motion sickness from VR [15]. Generally, people can develop symptoms such as nausea, dizziness and fatigue in varying severities [16]. Additionally, animal studies observed motion sickness among different species such as cats [17], house musk shrews [18], squirrel monkeys [19], rats [20] and dogs [21]. These studies observed motion sickness through vertical oscillations [17], rotations [18]–[20], or vehicular motions [21]. To measure motion sickness among animals, these studies can look at measurements associated with the subjective feeling of nausea such as stomach activity [17], [22]. Otherwise, an overall indication of motion sickness among animals include an emetic response [17]–[19], [21] or a pica response in rats [20]. Therefore, humans and animals subjected to similar conditions can experience motion sickness with similar symptoms. However, researchers debate about the mechanism that initiates motion sickness. These mechanisms have been hypothesized by various theories: eye-movement, postural stability and sensory conflict.

S. Ebenholtz explained how eye-movement can initiate motion sickness in 1994 [23]. The eye-movement theory describes the associations between the visual and the vestibular systems. One association includes the vestibular nystagmus that describes our heads rotating to stimulate the vestibular system by acceleration and then producing involuntary eye movement. On the other

hand, another association includes the optokinetic reflex that describes our eyes tracking a moving object and stimulating the vestibular receptors and the vagus nerve [23]. The vagus nerve relays parasympathetic signals to the heart, stomach and intestines. Thus, Ebenholtz believes motion sickness symptoms derive from the stimulation of the vagus nerve due to eye-movement. However, motion sickness can generally be developed without the visual system. For instance, a blind person or a person with his or her eyes closed in a moving car or cruise ship can still develop motion sickness.

Alternatively, Riccio and Strofregen in 1991 [24] presented the postural stability theory. The postural stability theory states a person develops motion sickness because he or she are unable to maintain his/her balance within the environment. As a person spends more time in the unbalanced state, the severity of the motion sickness symptoms increases. To reduce motion sickness, one should learn to maintain his/her balance in an unstable environment. However, a person laying down and maintaining his or her balance can still exhibit motion sickness such as vertigo. Since counter arguments can be created against the eye-movement theory and postural stability theory, the sensory conflict theory is the most accepted.

The sensory conflict theory associated with the sensory rearrangement theory was presented by J.T. Reason in 1978 [25]. The sensory rearrangement theory describes the discrepancy between the vestibular, visual and proprioceptive systems that receive abnormal motion stimuli from the external environment. Then, the sensory conflict theory describes the occurrence when the brain receives this abnormal motion stimuli that conflict with its past motion experience. Therefore, the sensory conflict between the past motion experience and current abnormal motion stimuli causes a person to develop motion sickness. For example, when a seated user watches a video of a rider on a roller coaster they will start to develop simulator sickness. He or she develops simulator

sickness because the brain only receives motion stimuli from the visual system and did not receive the expected motion stimuli from the vestibular and proprioceptive systems. All the above mentioned three theories try to explain the mechanism that initiate motion sickness, but the theories do not explain the reason why humans develop motion sickness; also, there are circumstances that each theory fails to explain the mechanism.

Evolution provides a reason to explain the importance of humans developing motion sickness. Motion sickness development may had occurred by an indirect chance from an original poison response [26]. For example, intoxication causes a person to become imbalanced and nauseated. Similar symptoms also occur when a person experiences motion sickness. Therefore, a person tries to remove him or herself from the toxic situation or tries to remove the toxin by an emetic response from the body. During these bouts of motion sickness, abnormal motion stimuli propagate to the brain from conflicting motion receptors.

To perceive sensory mismatching motion stimuli, a person's body receives external motion stimuli from the visual, vestibular and proprioceptive systems' receptors. The visual system receptors consist of rods and cones cells found in the eye's retina [27, pp. 325–326]. Rods detect low light vision and cones refine our vision with the finer details and colour. The visual system allows humans to perceive their own egocentric frame of reference with themselves relative to external objects. The vestibular system consists of the vestibular apparatus with hair cell receptors found in the inner ears [27, pp. 289–291] (

Figure 2). The apparatus consists of the otolith organs, which include the utricle and saccule, and three semicircular canals. The utricle and saccule detect gravity and linear motion, while the semicircular canals detect rotational motion. Lastly, the proprioceptive system consist of receptors with neuronal afferents synapses in the muscles, joints and tendons [28]. This allows the brain to

know the bodily limb orientation, position and motion occurrence. These three systems send the external motion stimuli to be integrated within the brain for one to perceive his/her motion [28].



CC Image courtesy of ***BruceBlaus on wikimedia without any changes.***

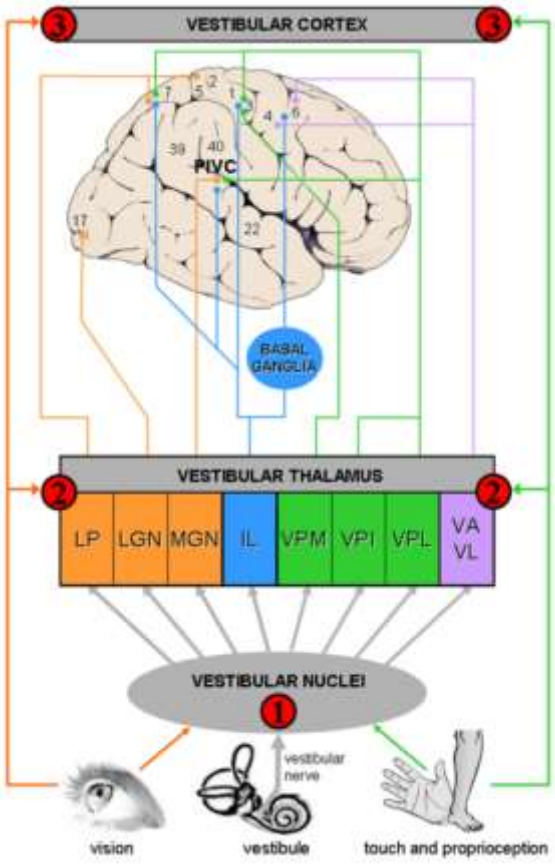
Figure 2 – Vestibular apparatus

The vestibular apparatus of the inner ears is responsible for detection accelerations.

To perceive self-motion, the brain processes vestibular, proprioceptive and visual stimuli through different neuronal pathways that converge at regions within the cerebral cortex [29]. The overall neuronal pathway can be seen in Figure 3 [29]. First, vestibular, visual and proprioceptive stimuli are processed at the vestibular nuclei of the brainstem. Afterwards the signals leave the brainstem and enter the thalamus for a secondary processing. Lastly, a tertiary processing occurs in the cerebral cortex for the integration of self-motion perception. In a human brain, these cerebral regions are similar to a monkey's parieto-insular vestibular cortex whose neurons respond to vestibular, proprioceptive and visual motion stimuli [30]. In summary, the integration for all three motion stimuli in normal circumstances (for example, when a person is walking) travels to the

brain stem and then to higher thought processes of the cerebral cortex and the cerebellum that regulates a person's balance and rhythmic motion.

Motion sickness occurs when the brain integrates abnormal motion stimuli. From the abnormal motion stimuli, the autonomic nervous system induces an abnormal stress response [31]. This stress response causes individuals to feel fatigue, nauseous and individuals have a strong desire to remove themselves from the motion sickening experience. Therefore, it is important to congruently stimulate the proprioceptive, visual and vestibular systems to reduce simulator sickness. Furthermore, researchers can monitor participants with simulator sickness measurements to prevent any significant negative effects such as vertigo or vomiting.



Reprinted with permission from C. Lopez [29]

Figure 3 – Motion stimuli pathways

The pathway of motion stimuli from the visual, vestibular and proprioceptive systems to the brain's cerebral cortex

2.3. Simulator Sickness Measurements

Simulator sickness can be measured with different methods. In most VR studies, they utilize the subjective simulator sickness questionnaire. However, there are not many studies that utilize objective physiological measurements.

Subjectively, a simulator sickness questionnaire (SSQ) developed by Kennedy et al. has been most commonly used in VR studies [32]. The study recruited thousands of army personnel to determine the effects of flight simulators on simulator sickness symptoms. Participants rated the severity of 16 different symptoms categorized as nausea, oculomotor and disorientation. Afterwards, scores based on each category or a weighted total score were calculated to describe the participants' subjective simulator sickness.

Objectively, simulator sickness can be measured through physiological measurements and postural body sway. Dennison, Wisit and D'Zmura conducted a simulator sickness experiment to compare the effects of a laptop display and Oculus Rift HMD on the participants' physiological measures from the electrical activity of the heart and stomach, eye movement, pulse oximetry, breathing rate and galvanic skin response and on the participants' simulator sickness from the SSQ [22]. Their results showed electrical activity of the heart and stomach, eye movement and verbal indication of sickness after 4-6 minutes of virtual exposure could differentiate between the computer monitor and the HMD; furthermore, the physiological measures from the autonomic response of stomach activity, blinking and breathing were associated with the SSQ scores.

Postural body sway measurements could be utilized to measure simulator sickness. In some postural sway studies, participants virtually experienced either an active drive [33] or active walk [34], or a passive view of a first person shooter game [35]. The study completed by Reed-Jones et al had a significant negative correlation between postural sway during a single leg stance with eyes

open and the SSQ scores [33]. Participants with lower SSQ scores had significantly more postural sway than participants with higher SSQ scores. The authors suggested the amount of postural sway may be associated with the adaptation processes to reduce simulator sickness. Lower SSQ scoring participants may have had more postural sway because they adapted to the mismatching visual stimuli. In contrast, higher SSQ scoring participants may had less postural sway trying to mediate the simulator sickness symptoms based on Riccio and Strofregen's postural stability theory [24] (See 2.2). However, other studies discovered there were insignificant association between simulator sickness and postural sway during double leg stance [34], [35]. Overall, participants in a double leg stance should have less sway than participants in a single leg stance because a double leg stance provides more stability compared to a single leg stance. Thus, a single leg stance may be a better method for evaluating participant adaptation to simulator sickness instead of measuring the severity of the participants' simulator sickness.

2.4. Simulator Sickness Individual Susceptibility

User susceptibility to developing simulator sickness depends on the interaction effects between a user's sensitivity and adaptability to mismatching motion stimuli [36]. Some studies investigated different effects such as vestibular disorders [37], sex [38], [39] and age [39]. Vestibular disorders (e.g. Meniere's disease, vertigo, migraines, etc.) may contribute to have higher simulator sickness susceptibility [37]. Sex has been investigated by Munafo et al. utilizing the Oculus Rift DK2 during a navigation task [38]. They found significantly more simulator sickness incidences among females than males. Moreover during a driving simulator, significantly more females would drop out in comparison to males due to simulator sickness [39]. With age, the same study in [39] had significantly more older adult drop outs compared to the number of young adult drop outs.

However, there were insignificant association between age and SSQ scores after exposure to the driving simulator [39]. Overall, individual characteristics, which include vestibular disorders, sex and age, can increase one's simulator sickness susceptibility. To reduce simulator sickness susceptibility, a person can undergo adaptation processes.

Adaptation to mismatching motion stimuli can occur when a person experiences a simulator sickening scenario many times. Eventually, a person's susceptibility to simulator sickness decreases because a person's brain and body learn to recognize and to adapt during a simulator sickening experience [40]. The ability to recognize and adapt occur among his or her neurons through the brain's plasticity [25]. Afterwards, the severity of the symptoms may lessen until these symptoms become unobservable. Contrarily, some people may become more susceptible to future simulator sickening experiences [40]. This can be explained through the motion sickness amplification theory [40] when a person tries to avoid any motion sickening experiences. From the avoidance, both of a person's brain and body will not adapt to future simulator sickening experiences. The person will be highly sensitive to mismatching simulator motion stimuli and more susceptible to develop severe simulator sickness. Regardless of variable individual susceptibilities, researchers should focus on the cases of the amplification theory because it can influence the attrition rate for a study's participation and results.

Overall, there are many factors contributing to a person's susceptibility to simulator sickness. To predict a person's simulator sickness susceptibility we could utilize a general short motion sickness questionnaire [41], but the questionnaire does not predict susceptibility to simulator sickness specifically. During VR experiments, researchers need to monitor the most susceptible participants. Otherwise, these susceptible participants' performances will be affected by trying to minimize the simulator sickness symptoms. If the symptoms become severe, the participants may

withdraw from the study. Therefore, researchers should design VR experiments in a naturalistic environment, while minimizing simulator sickness for the most susceptible participants (i.e. seniors and female participants).

2.5. Simulator Sickness Remedies

Since users may develop simulator sickness during a VR exposure, many studies investigated different solutions that can reduce or prevent the symptoms. These solutions include pharmaceuticals, electrical stimulation, timely breaks, VR design, software methods and hardware methods. Overall, these solutions try to reduce simulator sickness to prevent any attrition of their sample population. If VR studies try to reduce simulator sickness, participants can focus on the VR task. Therefore, a study should consider one or a combination of these simulator sickness remedies.

2.5.1. Pharmaceuticals

Pharmaceuticals target brain centers responsible of developing the general simulator sickness symptoms. The most effective pharmaceuticals are anti-histamines, scopolamine and amphetamine [42]. Anti-histamines block histamine H_1 receptors that receive signals from the histaminergic nervous system in the emetic system of the brain stem. Scopolamine reduces the neuronal simulator stimuli mismatch signal. Lastly, amphetamine opposes the suppression of norepinephrine during sensory mismatching motion stimuli. However, these drugs can have some negative side effects, which most commonly include drowsiness, dry eyes, dry mouth or sensitivity to light [43]. Transdermal scopolamine has serious adverse effects especially among elderly people such as toxic psychosis, difficulties with urination, headaches, skin redness and rashes, moreover prolonged usage may lead to memory impairments [44]. Due to these adverse effects

that may be detrimental to a person's daily living activities, pharmaceuticals solutions would not be suitable for long-term VR applications, such as rehabilitation programs. Furthermore, the pharmaceutical short-term effects like drowsiness may affect participants' performance. In addition, they may affect participant safety outside the experiment (e.g. driving or heavy equipment operation).

2.5.2. Electrical Stimulation

Simultaneous transcutaneous electrical nerve stimulations can be utilized to reduce simulator sickness. To significantly reduce simulator sickness, using surface electrodes, studies stimulated either the posterior neck and distal to the right knee [45], bilaterally on top of the sternocleidomastoid muscles [46], or bilaterally on the mastoid processes [47], [48]. Stimulation over the neck and sternocleidomastoid muscles stimulates the neck proprioceptive receptors [45], [46], while stimulation over the mastoid processes stimulate the auditory-vestibular cranial nerve [47], [48]. The stimulations try to provide matching motion stimuli. However, users may find the electrical stimulation and additional equipment uncomfortable. Also, these stimulations can reduce users' immersion in the VR experience.

2.5.3. Timely Breaks

Not only does VR influence a user's simulator sickness, but VR exposure time also influences a user's simulator sickness. As a user spends more time in VR, the user's simulator sickness would worsen [49]–[52]. One solution involves multiple interventions throughout a VR task to provide a user with adequate breaks. During these breaks, the user can receive naturalistic motion matching stimuli from the physical environment to reduce simulator sickness. The study in [50] designed a fuzzy controller based on a user's exposure time and movement to intervene during a VR task.

This significantly reduced a user's simulator sickness compared to a user without any intervention method.

2.5.4. Virtual Reality Environment Design

Some studies investigated how virtual environmental design can affect a user's simulator sickness related to scene complexity, ramp/stairs utilization, and pleasant sounds and odors integration. Scene complexity describes the level of realism as a user views a VR environment. A scene that looks more realistic associated with higher simulator sickness, when users wore an Oculus Rift DK2 HMD and experienced a virtual roller coaster ride [53]. Similarly, virtual stairs create an experience with significantly higher simulator sickness compared to virtual ramps [54]. As users navigate along the virtual stairs, they receive oscillating visual stimuli of an un-naturalistic head bobbing motion. Naturalistically, the users should receive visual stimuli of stable images as one navigates along a set of stairs. In comparison, as users navigate along a virtual ramp, users receive smooth visual stimuli. Therefore, the virtual ramps provide matching motion stimuli from a naturalistic experience that minimizes user simulator sickness. Also, virtual experiences can integrate pleasant sounds (E.g. Instrumental music) [55] and pleasant odors (E.g. Floral scents) [56] to help reduce simulator sickness. Therefore, careful virtual environmental design may allow users to have a comfortable VR experience with minimal simulator sickness.

2.5.5. Software Solutions

Software solutions try to reduce photon-to-eye latencies by optimizing computation time and try to simulate naturalistic visual filters by creating a dynamic field of view. The computation time should be minimal such that a user does not notice any latency between their intended interaction and actual interaction with the virtual environment. The HMD latency was reported to be at an average delay of 147.64 ± 84.91 ms [57]. However, simulator sickness does not significantly differ

with a HMD latency between 48 ms to 250 ms [58]. If a user notices any latency, then the user's body would receive mismatching motion stimuli. Most importantly, varying latency times in-between HMD updates cause more severe user simulator sickness compared to a constant latency time [59], [60]. Therefore, all computations should be executed between the HMD updates or be executed by a parallel processor to reduce simulator sickness with a constant and minimal latency.

The simulation of a natural visual filter should replicate a user's accommodation-vergence reflex that focuses and merges a binocular image [61]. However, the Oculus Rift decouples this reflex by fixing the accommodation due to the Oculus lenses kept at a constant distance away from a user's eyes [62]. By fixing the accommodation, the eyes try to continuously verge [62] that may lead to eye strain and simulator sickness. To reduce simulator sickness, the naturalistic accommodation-vergence reflex can be replicated by a dynamic depth field of view [61]. As shown in Figure 4, this provides a central focal point with the peripheral blurred to reduce eye strain and simulator sickness.



(a) (b)

Figure 4 – Dynamic depth of field on virtual scene
(a) Application of dynamic depth of field (b) No application of dynamic depth of field

2.5.6. Hardware Solutions

Hardware device design focuses on providing motion stimuli to users via the integration of vibrations, application of airflow or construction of controllers. Vibrations and air flow can provide additional proprioceptive stimuli to reduce simulator sickness. To reduce simulator sickness, vibrations can be produced by motors applied to the head rest of a chair as users experienced rotation about the yaw axis [63]. Another study reduced simulator sickness by applying vibrations against the lower gluteus maximum muscles to mimic a slight forward imbalance during motion [64]. Alternatively, a different study reduced simulator sickness by applying air flow from a fan with a speed of 3.2 km/h and at a distance of 0.2 m away from a user's face to mimic forward vection [65]. Overall, the hardware devices providing vibrations or airflow may sufficiently reduce simulator sickness, but the user still receives conflicting vestibular and visual motion stimuli.

Motion matching stimuli can be provided by VR locomotive controllers as a user navigates throughout a VR environment. The user may utilize a controller either in static or mobile locations. Controllers in a static location include gamepad controllers, leaning methods, head tilting methods, hand gesturing and walking in place [66], [67]. In contrast, controllers in a mobile location includes an ultrasonic tracking system [68], VirtuSphere treadmill system [14] or VRNChair [4]. The controllers with a mobile location allow users to move around freely. These controllers mimic naturalistic locomotion and provide the most motion matching stimuli. However, the above-mentioned studies investigated the utilization of the static [66], [67] or mobile [4], [14], [68] controller methods separately. They do not investigate the different combinations of motion stimuli for the vestibular, visual and proprioceptive systems altogether. Therefore, the current thesis tried to investigate different locomotive VR controllers such as seated static methods (TiltChair, with or without a neck brace, and gamepad joystick) and mobile methods (omni-directional treadmill

and VRNChair) along with a HMD. The thesis investigated the controller effects on simulator sickness and intuitiveness to determine the controller's feasibility. We expected the VRNChair with a HMD to be the most feasible controller because users receive the most sensory matching motion stimuli to reduce the level of simulator sickness and to increase the level of intuitiveness.

2.6. Virtual Reality Applications

VR allows users to experience naturalistic scenarios. Thus, researchers and designers utilize VR because they have the capabilities to control environmental variables and to replicate naturalistic environments. Some application developers hope users can transfer their VR experiences into their daily routine. Some examples include psychological treatments, occupational training and neuro-cognitive rehabilitation.

2.6.1. Psychological Treatments

Psychological treatments utilized VR for post traumatic stress disorders, spider phobia and flight anxiety with various outcomes. McLay et. al in 2001 investigated the utilization of VR among past army personnel to treat post traumatic stress disorder [69]. Their participants utilized a HMD and joystick to experience similar sounds and visuals as in their past service country. The participants in the VR-therapy group improved 30% or greater on a clinical post-traumatic stress disorder scale in comparison to the control group.

For people with flight anxiety, all related scenarios such as packing for a flight, airport arrival and the actual flight can raise anxiety. To reduce flight anxiety, one study utilized VR to provide these flight scenarios with a HMD and a mouse for navigation [70]. The study discovered participants in the VR therapy improved similarly to the control group. However, participants in

the VR group subjectively expressed that they were less anxious and their fears and severity on flights no longer interfered with their daily lives.

Additionally, VR can be utilized for exposure theory involving a spider phobia [71]. After their VR therapy program, the results suggested that showcasing multiple spiders had short term benefits. To have potential long-term benefits, the authors [52] suggested showing the phobia in sufficiently different environments may reduce the participants' expectations of a similar phobic experience.

2.6.2. Occupational Training

Occupational training utilizes VR for workers to practice their skills and to reduce any risk in a naturalistic environment. Users can interact with naturalistic VR scenarios by customized industrial specific tool hardware controllers. Additionally, the novelty of a VR training can help maintain a trainee's enthusiasm to learn new essential work skills. However, VR may not be sufficient to replace and to maintain all occupational types of training. VR has shown to have greater skill transfer in some aspects of industry specific construction safety training [72] and orthopaedic surgical training [73] compared to conventional naturalistic training that will be discussed below.

The construction industry has many on-site dangerous risks to their workers. To prevent any harm, VR can safely train workers in a controlled environment. The study in [72] utilized VR in safety training for concrete and stone cladding work. Workers and the instructor utilized an Xbox controller and HMD with a 2.4 m by 1.8 m curved display to identify unsafe practices in different workspace scenarios. Participants involved with the VR program had significantly better safety performance with concrete and stone cladding works immediately after the training program, and concrete works only one month after the training program compared to participants involved with

the traditional program (presentations, videos and demonstrations). Overall, the study suggests VR safety training can help prevent specific industry related safety risks, but cannot help preventing general safety risks.

The medical industry requires minimizing the risk to patients especially in the surgical field. VR can train resident surgeons to improve their surgical skills during stressful situations in a naturalistic scenario. One study [73] trained orthopaedic residents utilizing VR to simulate an arthroscopic knee surgery. Students utilized a computer monitor and a haptic feedback probe. After training, the VR group performed significantly better during an actual arthroscopic knee surgery compared to control group in procedural checklist and probing skills. Therefore, VR can train residents to acquire a better surgical skill set for the medical industry.

2.6.3. Neuro-cognitive Rehabilitation

Neuro-cognitive rehabilitation programs try to improve a person's cognition in hopes of the transfer of improvements into a person's daily living activities. Some examples focus on training in social cognition and spatial navigation applications. Social cognition involves the interaction between two or more people. An autistic person may have difficulties reading another person's body language or emotion. One study utilized VR to have eight young high functioning autistic young adults interact with a virtual avatar via a computer display, arrow keys and mouse [74]. Overall, the participants significantly improved on their social interactions with their ability to respond to other people's thoughts and desires and able to recognize facial emotion.

Secondly, spatial navigation involves path finding to reach a target destination. One study had two elderly subjects improve their attention and orientation cognition by executing cognitive exercises focused on attention, perception and visuo-spatial cognition in various daily environments (e.g. supermarket, park, office or city center) and also in their attention and

orientation cognition [75]. In our research group, a member created two different individual programs for participants at an early stage or later stage of Alzheimer's disease separately. The participants received spatial cognitive training as they utilized our VRNChair and Oculus Rift DK2 HMD [76]. There were significant improvements only with the participant at the early stage in comparison to the later stage participant. The current thesis will also discuss the investigation that determined the feasibility of a VR locomotive controller(s) that was utilized by participants with memory problems through a neuro-cognitive rehabilitation program in CHAPTER 6 – Application: Neuro-cognitive Training for .

2.7. Summary

Chapter 2 discussed the development of VR technologies from the first virtual bike ride of Sensorama to today's Oculus Rift and HTC Vive HMDs and hand controllers. However, these VR technologies make users susceptible to simulator sickness due to the mismatching the brain's expectations of normal motion stimuli to the abnormal sensory mismatching motion stimuli. Many studies try to determine an adequate measure for simulator sickness, and try to reduce and to prevent simulator sickness. In fact, if simulator sickness can be mediated, VR applications may branch into psychological treatments, occupational training or neuro-cognitive rehabilitation due to its ability to simulate naturalistic scenarios. We expect the VRNChair with the HMD will decrease a user's simulator sickness and increase its own intuitiveness because it provides users with sensory matching motion stimuli as they navigate a VR environment. This was the motivation for this thesis's experiments to investigate the locomotive controllers that decrease user's simulator sickness and increase controller's intuitiveness in the latter chapters.

CHAPTER 3 – Methodology

We investigated the VR locomotive controller(s) effects on a user's simulator sickness and controller's intuitiveness in two experiments. In Experiment 1 young healthy adults were recruited to utilize all locomotive controllers (TiltChair without a neck brace, Omni-directional treadmill, VRNChair and joystick) with an HMD [52]. The controllers and HMD provided different motion stimuli. The TiltChair without a neck brace might have caused simulator sickness for a few participants because the controller assumed that participants would synchronously rotate their heads and torsos, when it was possible that some users rotated their heads and torsos asynchronously to induce simulator sickness. Therefore, in Experiment 2, we investigated the effects of neck rotation on simulator sickness. This chapter describes the simulator sickness experimental methodologies with descriptions of the different navigational controllers, simulator sickness measurements and experimental procedures.

All experimental sessions measured simulator sickness before exposure to the virtual task, after the 1st trial, 4th trial and last 8th trial. Simulator sickness was measured by utilizing sway measurements with eyes open and eyes closed and by the SSQ. Within each VR trial, the participant's trajectories were recorded to calculate the total traversed distance. Before any exposure to the VR task, participants learned to utilize the locomotive controller. The simulator sickness measurement protocol can be visualized in Figure 5.

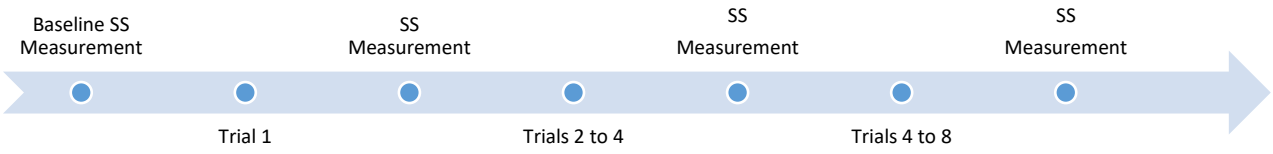


Figure 5 – Simulator sickness measurement protocol
Where SS: simulator sickness

3.1. Virtual Reality Platform

The VR simulator sickness experiments utilized the Unity 5 game engine on two laptops with a NVIDIA GEFORCE GTX 970m graphic processor and Intel® Core™ i7-6700K CPU processor with 8.00 gigabytes of RAM. The laptop had quick computations that provided unobservable latency between the users' interactions with the virtual environment. We verified the latency by a frame rate counter in the experiment's VR task environment. These laptops could meet the Oculus and HTC specifications with an average frame rate of 90 Hz. This laptop hardware allowed users to continuously feel comfortable while immersing users in the virtual environment.

3.2. Virtual Reality Navigational Controllers

The simulator sickness experiments utilized four different locomotive controllers with an HMD to provide users with different motion stimuli; they are summarized in Table 1. In the following individual sections, each device and their motion stimuli are further described.

Table 1 – Virtual reality locomotive controllers and head-mounted display motion stimuli

VR Technology	Stimuli Type			
	Visual	Acceleration		Proprioception
		Rotation	Translational	
Head-Mounted Display	✓			
TiltChair		✓	✓	
Omni-directional treadmill		✓		✓
VRNChair		✓	✓	✓
Joystick				

3.2.1. Head-Mounted Displays

The experiment utilized two types of HMDs to fulfill different requirements for the omni-directional treadmill and the other locomotive controllers (Figure 6). The omni-directional treadmill utilized the HTC Vive hand controllers that were only available at the time of the study. These hand controllers were strapped onto the user's feet to translate the user forward for the walking algorithm. All other controllers utilized the Oculus Rift CV1 with its internal orientation tracking ability via gyroscope, accelerometer and magnetometer sensor fusion and without the need for an external camera tracker [77]. Both HMDs stimulated the visual receptors by updating motion within the virtual environment through their lenses. The HMDs had the same resolution 2160 x 1200, and a frame rate of at least 90 Hz [78], [79]; hence, their differences should not had significantly contributed to a user's overall simulator sickness.

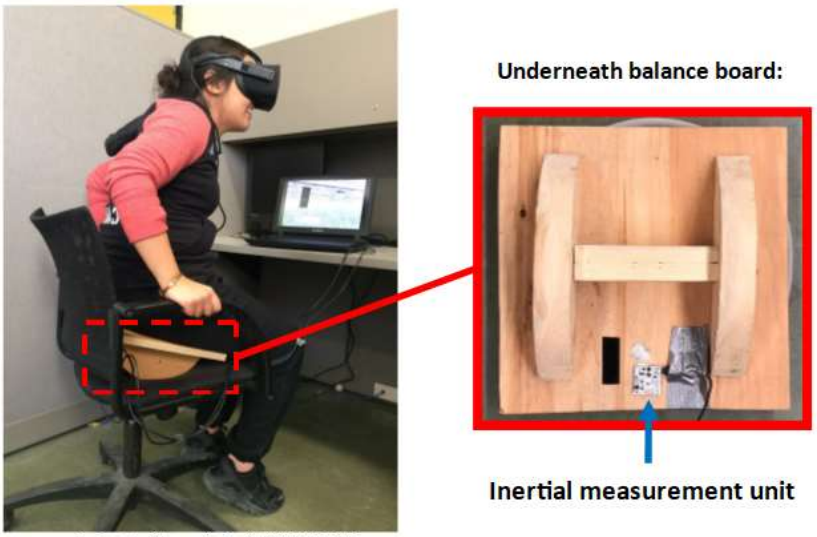


(a) (b)

Figure 6 – Head mounted displays utilized in thesis
(a) Oculus Rift CV1 (b) HTC Vive Developer Kit

3.2.2. TiltChair

The TiltChair consists of a swivel chair with a balance board seat (Figure 7) that can rotate along the yaw and pitch axes respectively. The balance board seat has a Bosch Sensortec's BNO055 inertial measurement unit to determine its orientation angles. The orientation angles represented a user pivoting in place to change his/her heading direction, or a user translating forward. These angles navigated the user throughout the virtual environment in a virtual wheelchair while providing motion stimuli.



Reprinted with permission © 2017 IEEE [35]

Figure 7 – TiltChair set-up

The TiltChair stimulated the vestibular receptors by providing rotation and acceleration stimuli. However, the results of Experiment 1 [52] suggested that the initial design assumed a user's head and torso rotates synchronously. Therefore, some participants received mismatching motion stimuli when their head rotated asynchronously with their own torso and developed simulator sickness. To reduce simulator sickness while utilizing the TiltChair, participants in Experiment 2 wore a neck brace (Laerdal Stifneck Select Extrication Collar) to synchronize the rotation between the head, torso and TiltChair (Figure 8).



Figure 8 – TiltChair set-up with neck brace

3.2.3. Omni-directional Treadmill

The omni-directional treadmill consists of a wooden structure with a carpeted concave bowl (Figure 9). Users strapped HTC Vive hand controllers and friction reducing slippers on his or her feet to walk or run along the walls of the bowl. Also, users wore the Bosch Sensortec's BNO055 inertial measurement on their lower backs to determine their forward heading direction. To translate this physical to virtual motion, the Unity game engine utilized the HTC Vive hand controllers to determine each foot's distance from the center of the concave bowl that started the walking algorithm.

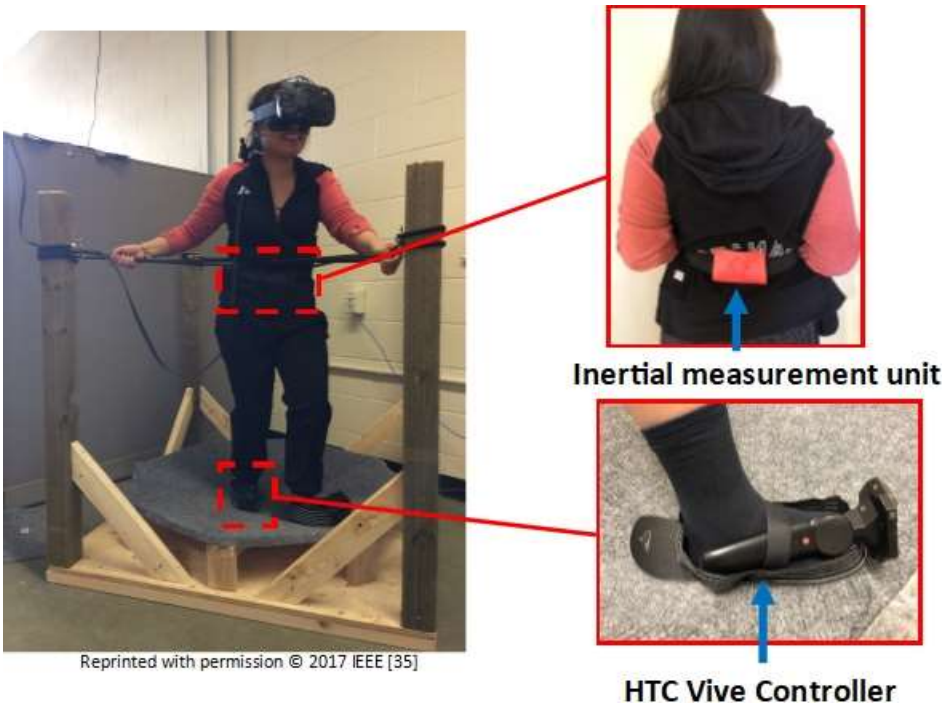


Figure 9 – Omni-directional treadmill set-up

The walking algorithm was based on the "Walking Velocity Update" method [80] that utilized the user feet's positions to identify different gait phases and then to translate the user forward. First, an average moving filter of 100 feet position samples created separate sinusoidal waveforms of a foot's position and velocity (Figure 10). The algorithm calculated velocity as a simple differentiation approximation from the foot's position. From the sinusoids, one could separate different phases as alternating stance and swing phases between each foot. The swing phase began when a user moved a foot at the edge of the concave bowl, which the 'o' identifies on the peak of the sinusoid. Then, the stance phase began as the user slid the foot back towards the center of the concave bowl that moved the user forward in the virtual environment. This translation ended at the 'x' on the velocity sinusoid that identifies when the foot's velocity changed from negative to

positive as the foot stopped at the bowl's center. Afterwards, the user started the next swing phase with the other foot.

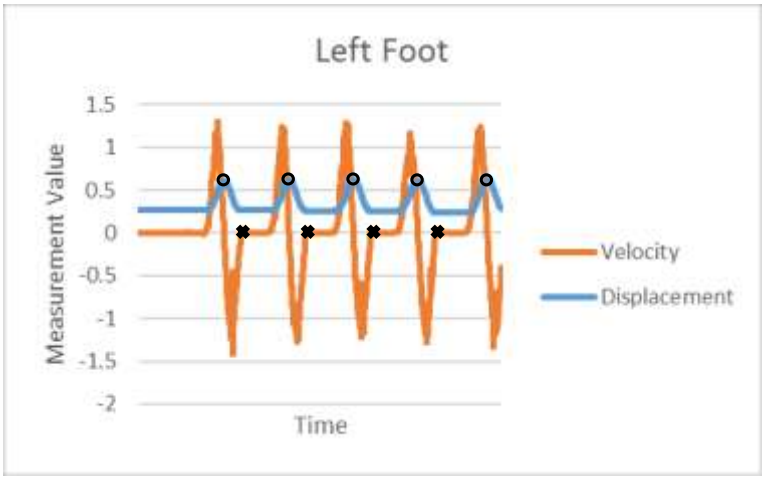


Figure 10 – Omni-directional treadmill walking algorithm of left foot
Where 'o' symbolizes the start of swing phase and 'x' symbolizes the end of stance phase

In the virtual environment, users saw a virtual representation of the physical omni-directional treadmill structure (Figure 11). The virtual structure aligned with the physical structure. A red arrow pointed to the forward heading direction. However, the red arrow sometimes became unaligned with the IMU on a user's lower back due to drift. To re-align the red arrow, a user turned to face a post by a 3-D virtual cake reference point as a research assistant pressed a keyboard button.

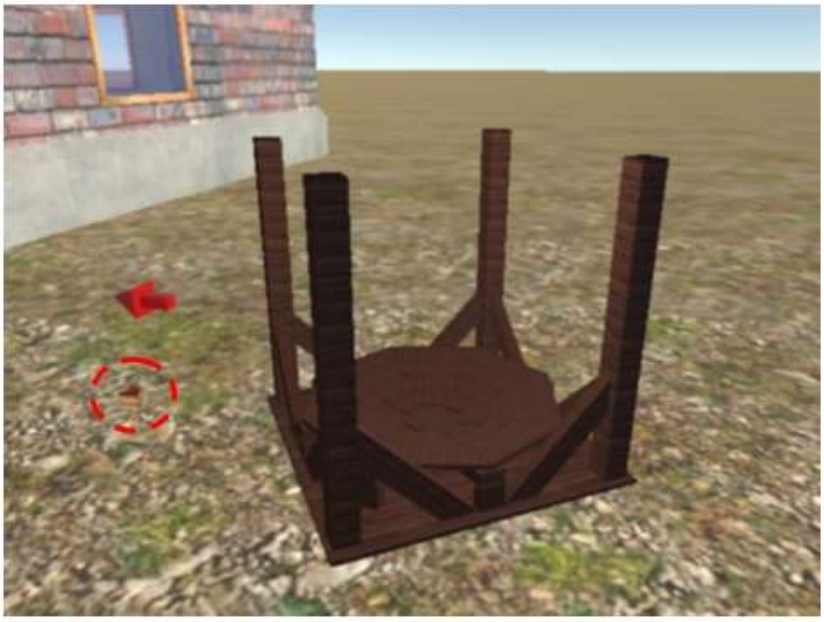


Figure 11 – Virtual omni-directional treadmill model
With encircled virtual cake for user re-alignment

The omni-directional treadmill contributed to users' simulator sickness as they were not walking naturalistically. This provided a mismatch between motion stimuli and the proprioceptive and vestibular receptors' responses. Forward walking users' proprioceptive receptors received mismatching stimuli as their muscles contracted to move each foot to the edge of the concave bowl and then their muscles contracted to slide the foot back to the center in the alternating stance and swing phases. Additionally, the alternating phases caused the vestibular acceleration receptors to receive mismatching stimuli from the user's head sliding forward and backward. Contrarily, during a naturalistic gait, a walking user feels translation during the transition from stance to swing phases when his or her center of mass projects forward to translate forward. Therefore, the foot and head movements during the utilization of the omni-directional treadmill caused the proprioceptive and vestibular receptors to receive mismatching stimuli compared to a naturalistic gait that may had contributed to a user's simulator sickness.

3.2.4. VRNChair

The VRNChair consisted of a manual wheelchair joystick developed by a past research member [4] (Figure 12). Seated users moved within the virtual environment by walking. As the wheels turned with the VRNChair movement, a magnetic encoder detected the magnetic changes from the wheels with a multi-pole magnetic ring. Then, a microcontroller detected these magnetic changes from electrical pulses from the magnetic encoder. From the electrical pulses, the microcontroller estimated the velocity of the wheelchair. Additionally, an IMU on the VRNChair's tray estimated the forward heading direction. The microcontroller and IMU sent the velocity and heading direction respectively to the Unity game engine. In the virtual environment, users saw themselves seated in a virtual manual wheelchair to increase immersion (Figure 13). Overall, the VRNChair stimulated a user's vestibular and proprioceptive receptors as they freely moved around.



Reprinted with permission © 2017 IEEE [52]

Figure 12 – VRNChair set-up



Figure 13 – Virtual model of VRNChair

3.2.5. Joystick

Seated users utilized the joystick from an Xbox Controller to move within the virtual environment (Figure 14). Similarly, to the VRNChair, the user saw a virtual wheelchair to simulate driving an electrical wheelchair. The joystick did not stimulate any proprioceptive or vestibular receptors.

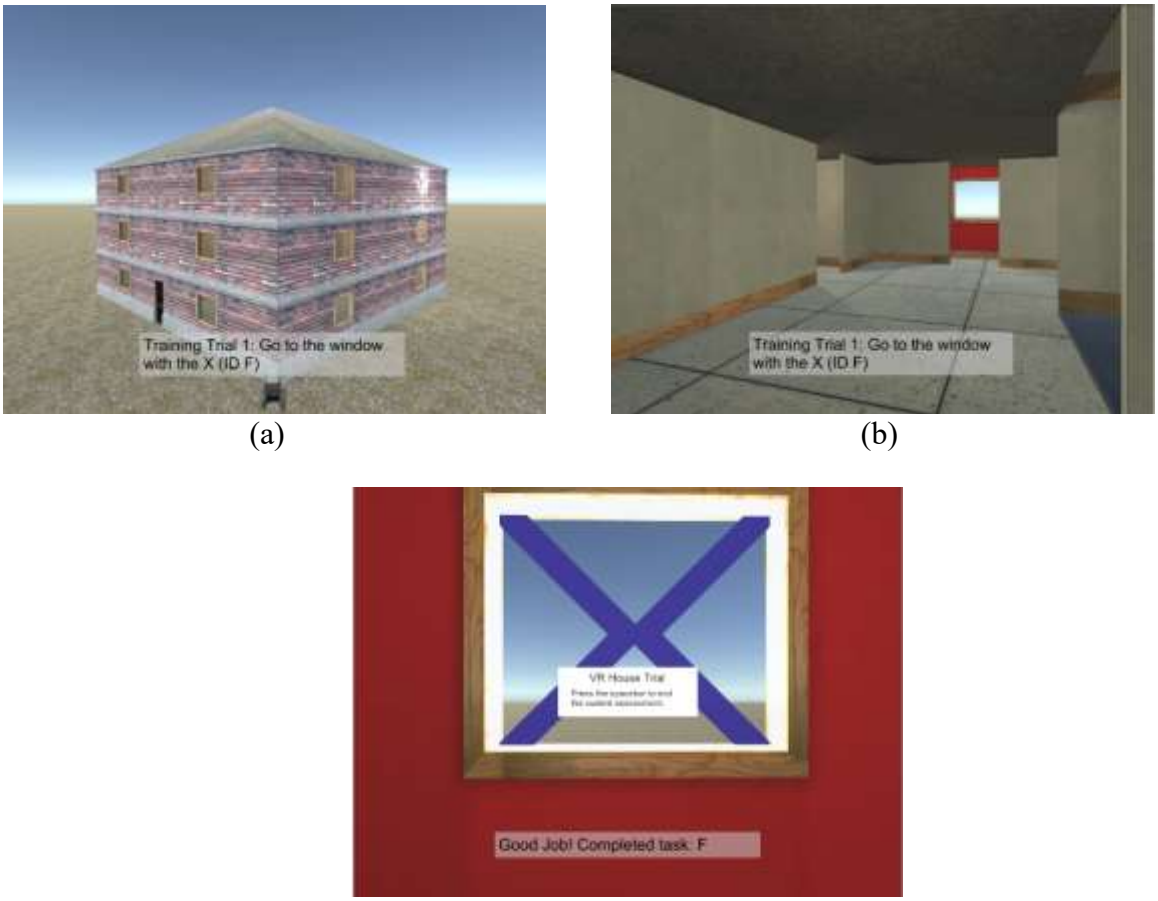


Reprinted with permission © 2017 IEEE [52]

Figure 14 – Joystick set-up

3.3. Virtual Reality Task

The experimental VR task has been initially designed to investigate early onset detection of Alzheimer's disease [2], [76]. The overall task had 8 trials. For each trial, the task had participants find a target room with an 'X' on its window observed outside a 3-storey cubic building (Figure 15). Afterwards, participants entered the building to find the target room. In each trial, participants sought new target locations. This minimized the opportunity for participants to adapt and to try reducing any simulator sickness. Since the primary outcome measure included simulator sickness and not spatial navigation, participants had the option to ask the research assistant for help to find the specific target.



(a) (b)

(c)

Figure 15 – Virtual reality navigation task for simulator sickness experiments
Different user views of the virtual reality task, (a) External building rotation to encode target's location (b) Inside the building (c) End of successful trial finding the target

3.4. Experiment 1

3.4.1. Procedures

Experiment 1 investigated the effects of combining different motion stimuli provided by locomotive VR controllers (TiltChair, omni-directional treadmill, VRNChair and joystick) with all using an HMD. Participants utilized each controller individually during separate sessions. After a session, a participant had at least one rest day to minimize any cross over simulator sickness effects on the next VR controller session. Some studies had few participants feeling simulator sickness until 2 to 4 hours [81], until the evening of the same day [82], or 24 hours [38] after the VR experiments. Once a participant completed the four sessions and tried all four different controllers, the participants ranked each controller based on what was the most comfortable in terms of simulator sickness and the most intuitive in terms of ease of VR task execution.

3.4.2. Participants

For Experiment 1, 20 participants were recruited: 10 males (mean age of 22.9 ± 2.6 years) and 10 females (mean age of 22.8 ± 3.7 years). The participants did not have any pre-existing conditions that may affect a user's susceptibility to simulator sickness (Eg. Vertigo, or vestibular issues) and a controller's perceived intuitiveness (Eg. Physical disability). In regard to the participants' experience with a computer joystick and VR, seventeen participants had utilized a joystick in the past and only one participant had experienced VR once before Experiment 1.

3.5. Experiment 2

3.5.1. Procedures

Experiment 2 investigated the effects of synchronous neck and torso rotation by comparing two TiltChair versions with and without the neck brace and the VRNChair all using an HMD.

Participants from Experiment 1 were invited to participate in Experiment 2. However, two males were unavailable at the time of the study and were replaced by two males with similar ages. Previous Experiment 1 participants executed an extra session to utilize the TiltChair with a neck brace. However, new participants executed three separate sessions to utilize the three different locomotive controllers. After a session, these new participants also had at least one rest day to minimize and carry over effects from any simulator sickness on the next locomotive controller session.

3.5.2. Participants

For Experiment 2, 20 participants were recruited: 10 males (mean age of 22.0 ± 2.5 years old) and 10 females (mean age of 23.0 ± 3.7 years old). Similarly, to Experiment 1, these participants did not have any pre-existing conditions that may affect a user's susceptibility to simulator sickness and a controller's perceived intuitiveness.

3.6. Simulator Sickness Measurements

As participants completed an experiment session, a participant's simulator sickness may had been influenced by different variables such as navigational controller type, sex and time. Simulator sickness measurements included an objective postural sway measure via a center of pressure path length and then a subjective overall symptom severity measure via SSQ scores.

3.6.1. Postural Sway

The experiments utilized postural sway from a center of pressure path length measurement. The center of pressure path length may be derived from dizziness due to simulator sickness by quantifying the participant's postural sway as the participant's center of mass changed to maintain his or her balance for one minute. Two separate measurements with eyes open and eyes closed had participants standing with their feet at a comfortable and consistent distance apart on a Nintendo

Wii Balance Board. The Wii Balance Board is an inexpensive and valid alternative to the standard force plate [83]. This balance board quantified postural sway as a center of pressure path length from 4 force strain gauge sensors on each of its corners labelled as top right (TR), top left (TL), bottom right (BR) and bottom left (BL).

To calculate the center of pressure path length, the values from the force sensors required calibration and filtration. The force sensor calibration values derived from manufacturer coefficients. These manufacturer coefficients were validated via student t-tests that showed insignificant differences compared to the actual calibrated weight values. This validation test applied different calibration weights to each different force strain sensor by a customized weight applicator (Figure 16) as a similar process described in [84]. The results are shown in Figure 17.



Figure 16 – Wii Balance Board calibration set-up

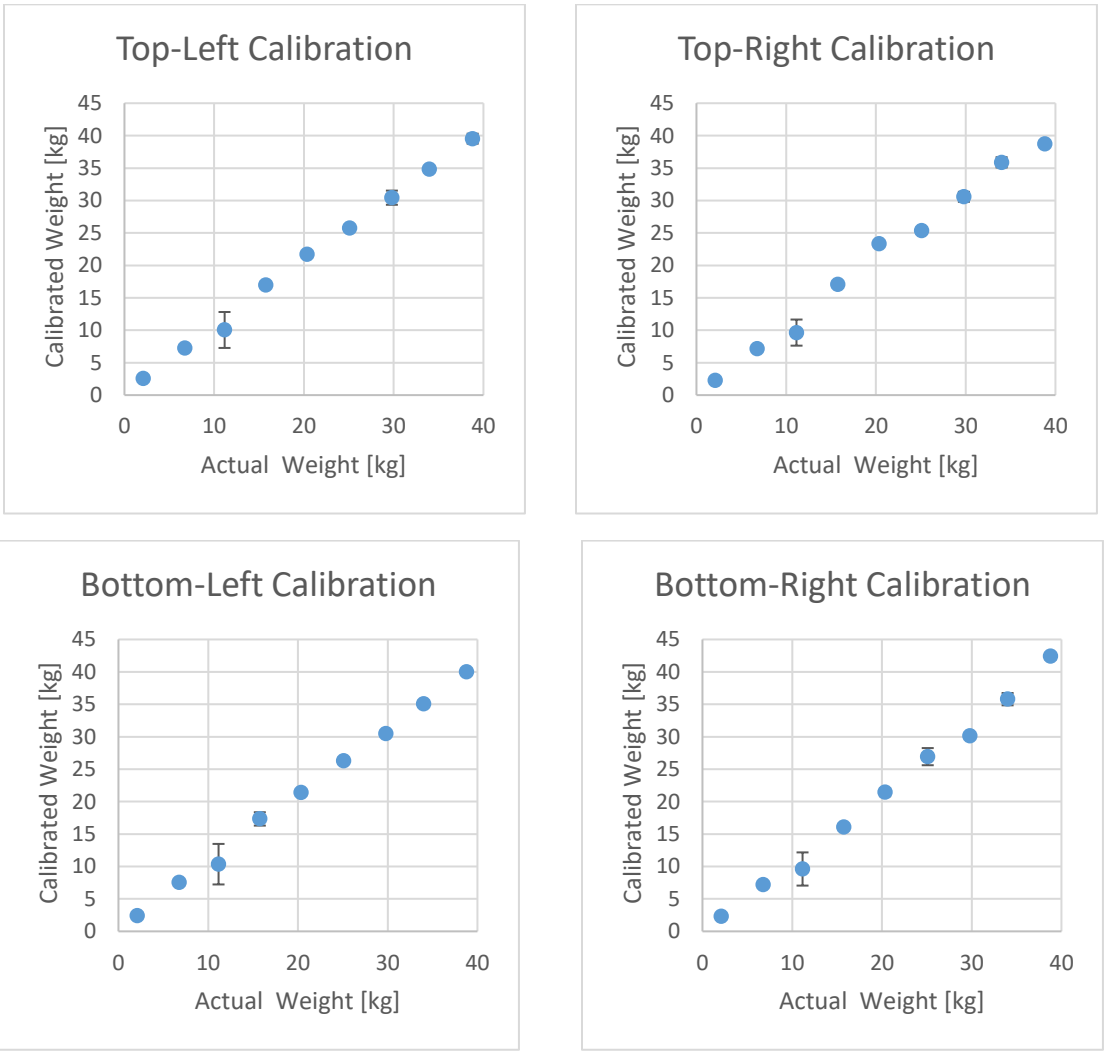


Figure 17 – Wii Balance Board manufacturer coefficient calibration
With standard deviation bars

Signal processing occurred with a 4th order low pass filter and a cut-off frequency of 12 Hz [85]. Based on Figure 18, these sensor values calculated the center of pressure as an x- and y-coordinate. From these coordinates, the center of pressure path length was calculated as followed:

$$COP_x = 21 \times \frac{(TR + BR) - (TL + BL)}{TR + TL + BR + BL} [cm]$$

$$COP_y = 12 \times \frac{(TR + TL) - (BR + BL)}{TR+TL+BR + BL} [cm]$$

$$\text{Path length} = \sqrt{(COP_{x2} - COP_{x1})^2 + (COP_{y2} - COP_{y1})^2}[cm]$$

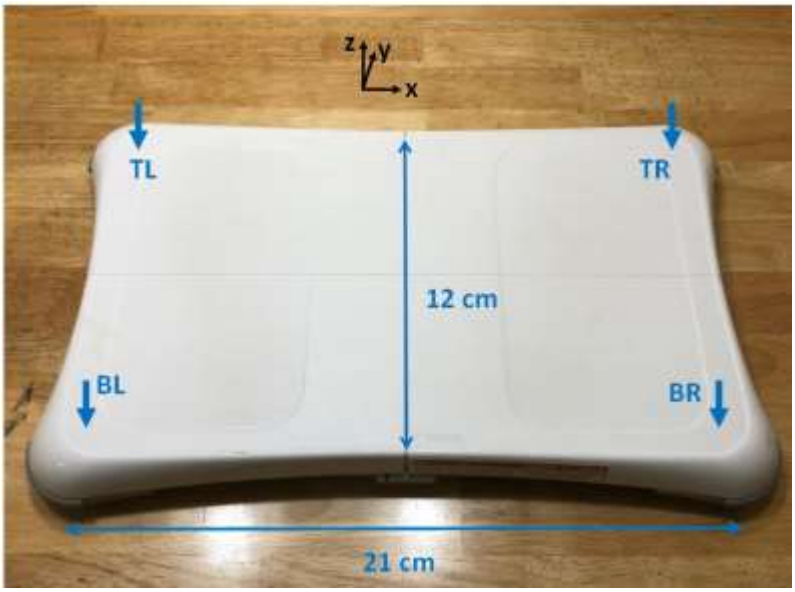


Figure 18 – Wii Balance Board center of pressure diagram

3.6.2. Simulator Sickness Questionnaire

After both postural sway measurements, participants completed a Simulator Sickness Questionnaire (SSQ) [32]. The SSQ consisted of 16 different symptoms: general discomfort, fatigue, headache, eyestrain, difficulty focusing, increased salivation, sweating, nausea, difficulty

concentrating, fullness or head, blurred vision, dizziness with eyes open, dizziness with eyes closed, vertigo, stomach awareness and burping. These symptoms are grouped together in overlapping categories of nausea, oculomotor and disorientation (Table 2). For each symptom, participants rated the severity on a scale between 0 (no symptom) to 4 (severe symptom) they felt at that moment of time. The weighted sum of these symptom severities described the participant's overall subjective feeling of simulator sickness [32]:

$$Total\ SSQ\ Score = 9.54 \times N + 7.58 \times O + 13.92 \times D,$$

where N: nausea sub-score, O: oculomotor sub-score and D: disorientation sub-score

The weighting coefficients were derived to create a baseline distribution with a minimum score of zero and a standard deviation of 15 from about 1200 observations. Data analysis utilized the mean differences between the baseline measurement and the measurement after the 1st trial, 4th trial, or 8th (last) trial.

Table 2 – Simulator sickness questionnaire symptom categories [32]

Category	Symptoms
Nausea	General discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, burping
Oculomotor	General discomfort, fatigue, headache, eyestrain, difficulty focusing, difficulty concentrating, blurred vision
Disorientation	Difficulty focusing, nausea, fullness of head, blurred vision, dizziness with eyes-closed, dizziness with eyes-open, vertigo

3.7. Intuitive Utilization Measurements

Intuitive utilization measurements consisted of the traversed distance and execution time for each trial in the VR navigation task. The data analysis utilized a sum of the last four trials' traverse distances and execution times to remove any learning effects from the controller utilization or VR

task execution. Afterwards, participants ranked all the controllers that were the most comfortable regarding simulator sickness and the most intuitive regarding VR task execution.

3.8. Experiment Assumptions

As we executed Experiments 1 and 2, we had assumptions that would not have a significant effect on our simulator sickness and intuitiveness measurements. These assumptions were based on the user susceptibility to simulator sickness and controller usability by all young adult participants. The experiment assumptions were:

- All young adult participants have similar susceptibility to simulator sickness.
- A participant naïve to VR or a participant with minimal VR experience cannot reduce simulator sickness during the experimental sessions because of their inexperience with VR mismatching motion stimuli. Additionally, differences on VR and joystick experiences does not influence the user's simulator sickness and controller's intuitiveness.
- A participant's eyesight (normal vision or uncorrected vision) does not contribute to his or her overall simulator sickness or the controller's intuitiveness.
- A participant's height does not affect a participant's ability to utilize a locomotive controller. Also, a participant's height does not affect a participant's susceptibility to simulator sickness. Thus, the participant's height does not affect the simulator sickness measurements (i.e. SSQ scores and postural sway) and intuitiveness measurements (i.e. Traversed distances and execution times).

3.9. Data Analysis

All data analyses utilized IBM SPSS Statistics version 24 to investigate the experimental condition effects on a user's simulator sickness and on a locomotive controller's intuitiveness and to verify the assumptions for participant's eyesight and height effects.

To compare the affect on the participants' simulator sickness via SSQ mean difference scores and center of pressure path lengths, individual three-way mixed analysis of variance (ANOVA) were utilized. The ANOVA investigated any significant interactions among the different factors. This statistical analysis required a continuous dependent variable (SSQ scores or center of pressure path length), two independent within-subject factors (time points and controller type) and an independent between-subject factor of sex. In contrast, to compare the affect on the traverse distance and execution time sums for intuitiveness, individual two-way mixed ANOVAs were executed. This analysis required a continuous dependent variable (traverse distance), an independent within-subject factor (controller type) and an independent between subject factor (sex). For all ANOVA analyses, the following hypotheses were:

- H_O: All groups should have the same mean measurement values
- H_A: All groups do not have the same mean measurement values

Also, Bonferroni corrected pairwise comparisons were executed for any ANOVAs with a significant main effect. The pairwise comparisons investigated any significant differences within the categorical level.

To verify the validity of experimental assumptions, we executed Spearman's correlation and ANOVAs. These statistical analyses determine whether height has any correlation with simulator sickness and intuitiveness, while user's characteristics such as eyesight and naivety (joystick and VR experience) have any effects with simulator sickness and intuitiveness. Correlations between

the participant's height and experiment measurements were verified through the non-parametric Spearman's correlation. For all Spearman's correlation analyses, the following hypotheses were:

- H_O: There is no correlation between the two variables
- H_A: There is a correlation between the two variables

User characteristic's effects was verified with a three-way ANOVA for any interacting user characteristic effects on postural sway and SSQ scores, and with a two-way ANOVA for any interacting user characteristic effects on intuitiveness measures (traversed distances and execution time).

3.9.1. Data Analysis Assumptions

ANOVA Assumptions

All ANOVAs have the same assumptions of outliers, normality, homogeneity of variances, homogeneity of covariance and sphericity [86]. These assumptions are summarized as followed with the statistical test to check for any violations:

Outliers

There should not be any significant outliers among the data set. For any outliers, this will affect the differences between cells of the ANOVA design that can lead to with problematic results. To remove outliers, the dependent variable may be transformed.

Normality

The data should be approximately normal validated by the Shapiro-Wilk's test for quality of variances with a statistically insignificant result. For a violation of normality, one may transform the dependent variable. However, the ANOVA is generally robust against any normality violations and does not require any transformations to fix any abnormalities.

Homogeneity of Variances

This describes that the variances of the residuals are equal. The homogeneity of variances was validated by the Levene's Test with a statistically insignificant result. For a homogeneity of variances violation, you may transform the dependent variable.

Homogeneity of Covariances (Two-way mixed ANOVA only)

The homogeneity of covariances was validated by the Box's test of equality of covariances matrices with a statistically insignificant result. For a homogeneity of covariances violation, separate repeated measures ANOVA may be executed without any investigation of an interaction term, or the two-way mixed ANOVA may be executed with the violation noted.

Sphericity

Lastly, the assumption of sphericity states the variance between each ANOVA within-subject factor levels should be equal. The assumption of sphericity was validated by the Mauchly's test of sphericity with a statistically insignificant result. For any sphericity violation, Greenhouse-Geisser or Hyunh-Feldt corrections were utilized based on the ε value. If $\varepsilon < 0.75$, then the Greenhouse-Geisser correction was utilized; while, if $\varepsilon > 0.75$, then the Huynh-Feldt correction was utilized [87].

Spearman's Correlation Assumptions

For the non-parametric Spearman's correlation, the statistical analysis assumptions include: 1) paired observations that measure two variables on an ordinal or continuous scale, and 2) the two variables have an underlying monotonic relationship [88].

3.10. Summary

Chapter 3 described the methodologies for the locomotive controller feasibility experiments. In Experiment 1, participants utilized different locomotive controllers with all using HMDs to investigate their effects on a user's simulator sickness and a controller's intuitiveness; while in Experiment 2, participants utilized a neck brace with the TiltChair to investigate the effects of synchronous neck and torso rotations on a user's simulator sickness and a controller's intuitiveness. All participants completed a VR navigation task as their simulator sickness was measured by the postural sway's center of path length and SSQ scores, and intuitiveness via the participant's traverse distances, execution times and controller ranking. The statistical analysis results from these experiments are presented in the next chapter.

CHAPTER 4 – Results

Chapter 4 presents the results for the two experiments. Experiment 1 investigated the effects of different motion stimuli combinations provided by a locomotive controller with an HMD. In contrast, Experiment 2 investigated the effects of neck rotation with or without a neck brace while users utilized the TiltChair. Both experiment investigated the effects of user characteristics like height and eyesight. Overall, we investigated the effects of these conditions on a user's simulator sickness (postural sway and SSQ scores) and a controller's intuitiveness (traversed distance, execution time and controller ranking).

4.1. Experiment 1 Results

4.1.1. Simulator Sickness

Experiment 1's simulator sickness results for postural sway center of path lengths and SSQ scores had different significant results. Table 3 and Table 4 summarize the center of pressure path lengths for the eyes closed and eyes open conditions respectively. During the eyes-closed condition, controller type and sex had a significant interaction effect on the center of pressure path lengths ($F(3, 54) = 3.25, p = 0.03$). Figure 19 shows the center of pressure path length's estimated mean differences with standard errors based on this significant interaction effect between controller type and sex. This means the effects of controller type on the center of path lengths depends on the participant's sex. During the eyes-open condition there were insignificant interaction effects and main effects of controller type, sex and time on the center of path lengths.

The individual effects of height and eyesight on the center of path lengths had significant correlations and interaction effects respectively. The significant correlation occurred between the participant height and the center of path length during the eyes closed condition for the joystick

after trial 1 ($r_s = 0.616, p = 0.004$) and after trial 4 ($r_s = 0.574, p = 0.008$). When the participants utilized the joystick, taller participants had more postural sway compared to shorter participants. Additionally, there was a significant interaction effect between eyesight and time on the center of path lengths during the eyes-closed condition ($F(2,36) = 0.534, p = 0.009$).

Table 3 – Experiment 1 center of pressure path length with eyes closed

Sex	Controller Type	Trial 1	Trial 4	Trial 8
Males	VRNChair	-3.77 ± 18.17	-4.82 ± 16.77	-5.17 ± 15.69
	Omni-directional treadmill	-8.53 ± 11.17	-1.09 ± 17.14	4.79 ± 8.88
	TiltChair without a neck brace	-5.69 ± 19.83	-0.51 ± 20.21	-0.98 ± 20.13
	Joystick	9.47 ± 20.59	14.88± 24.57	8.64 ± 16.99
Females	VRNChair	-2.93 ± 12.24	2.32 ± 13.08	-1.79 ± 16.79
	Omni-directional treadmill	-0.34 ± 18.56	16.60 ± 51.94	1.93 ± 23.65
	TiltChair without a neck brace	-1.17 ± 7.75	-1.21 ± 10.34	3.50 ± 16.23
	Joystick	-6.40 ± 12.05	-10.46 ± 13.00	-2.01 ± 23.56
Total	VRNChair	-3.35 ± 15.09	-1.25 ± 15.09	-3.48 ± 15.91
	Omni-directional treadmill	-4.43 ± 15.49	7.75 ± 38.72	3.36 ± 17.45
	TiltChair without a neck brace	-3.43 ± 14.83	-0.86 ± 15.63	1.26 ± 17.95
	Joystick	1.54 ± 18.32	2.21 ± 23.13	3.31 ± 20.73

Values shown are mean differences between baseline and specified trial (cm) with their standard deviation. There was only a significant interaction effect ($p < 0.05$) of Sex × Controller Type on the center of path lengths.

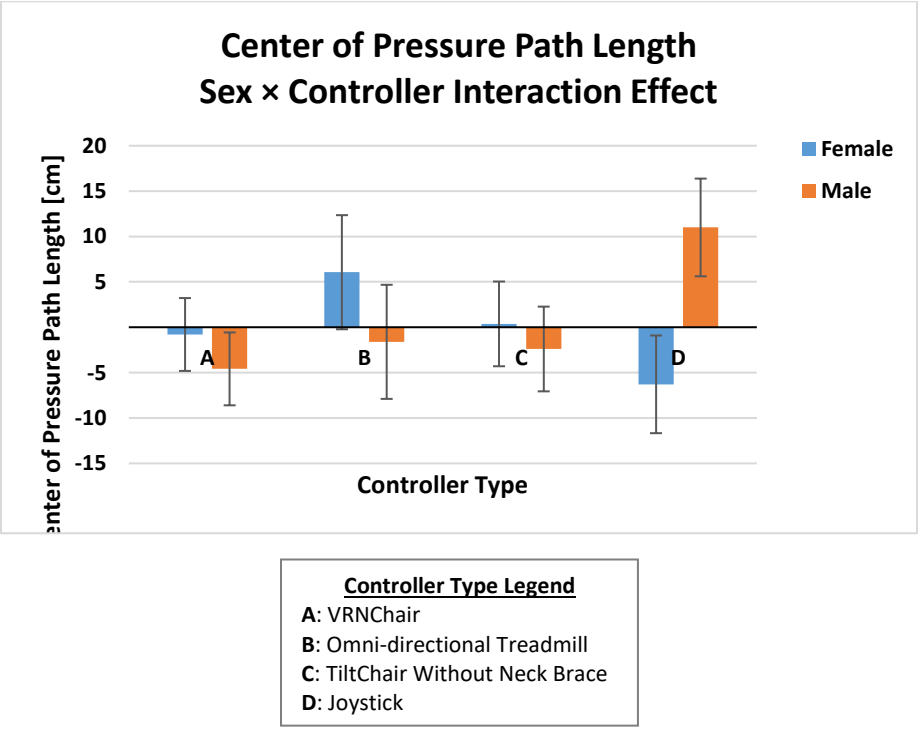


Figure 19 – Center of pressure path length sex × controller interaction effect with eyes-closed
Center of pressure path length [cm] estimated mean difference with standard error for significant sex × controller type interaction effect.

Table 4 – Experiment 1 center of pressure path length with eyes open

Sex	Controller Type	Trial 1	Trial 4	Trial 8
Male	VRNChair	-6.15 ± 13.20	-2.84 ± 15.29	3.08 ± 14.42
	Omni-directional treadmill	10.17 ± 17.13	6.84± 18.92	7.01 ± 13.23
	TiltChair without a neck brace	2.67 ± 16.15	-0.54 ± 15.16	-0.17 ± 14.43
	Joystick	-0.85 ± 26.40	-0.23 ± 21.62	1.84 ± 22.46
Female	VRNChair	2.12 ± 16.85	-0.67 ± 18.51	4.88 ± 16.03
	Omni-directional treadmill	-0.68 ± 21.16	4.00 ± 27.01	4.78 ± 17.94
	TiltChair without a neck brace	-7.11 ± 12.38	-2.47 ± 15.65	-6.66 ± 16.24
	Joystick	-0.73 ± 12.01	3.52 ± 12.93	2.33 ± 16.59
Total	VRNChair	-2.01 ± 15.33	-1.76 ± 16.56	3.98 ± 14.87
	Omni-directional treadmill	4.75 ± 19.55	5.42 ± 22.75	5.89 ± 15.39
	TiltChair without a neck brace	-2.22 ± 14.88	-1.51 ± 15.03	-3.42 ± 15.31
	Joystick	-0.79 ± 19.96	1.64 ± 17.45	2.08 ± 19.22

Values shown are mean differences between baseline and specified trial [cm] with their standard deviation. There were insignificant interaction effects and main effects for sex, controller type and trial.

For the SSQ total score mean difference, only time had a significant effect on a participant's simulator sickness ($F(1.21, 21.80) = 21.23, p < 0.0005$) . As shown in Figure 20, the SSQ total score mean differences increased with time regardless of the controller type. The nausea, disorientation and oculomotor SSQ sub-score mean difference results varied. Nausea had separate main effects of controller ($F(3,57) = 4.49, p = 0.007$) and VR exposure time ($F(2,38) = 15.61, p < 0.0005$). In contrast, disorientation and oculomotor sub-scores had VR exposure time as the only significant main effect: $F(1.25,23.82) = 12.25, p = 0.001$, and $F(1.27,24.16) = 26.51, p < 0.0005$ respectively. Overall, there were no sex differences on the SSQ scores.

User characteristics, which included participant height and eyesight, had different effects on the SSQ scores. Height had a significant correlation with the omni-directional treadmill SSQ disorientation sub-score after trial 4 ($r_s(18) = -0.525, p = 0.018$). When participants utilized the omni-directional treadmill taller participants had lower SSQ disorientation sub-scores after trial 4 compared to shorter participants. In contrast, eyesight had insignificant interaction and main effects on the SSQ scores.

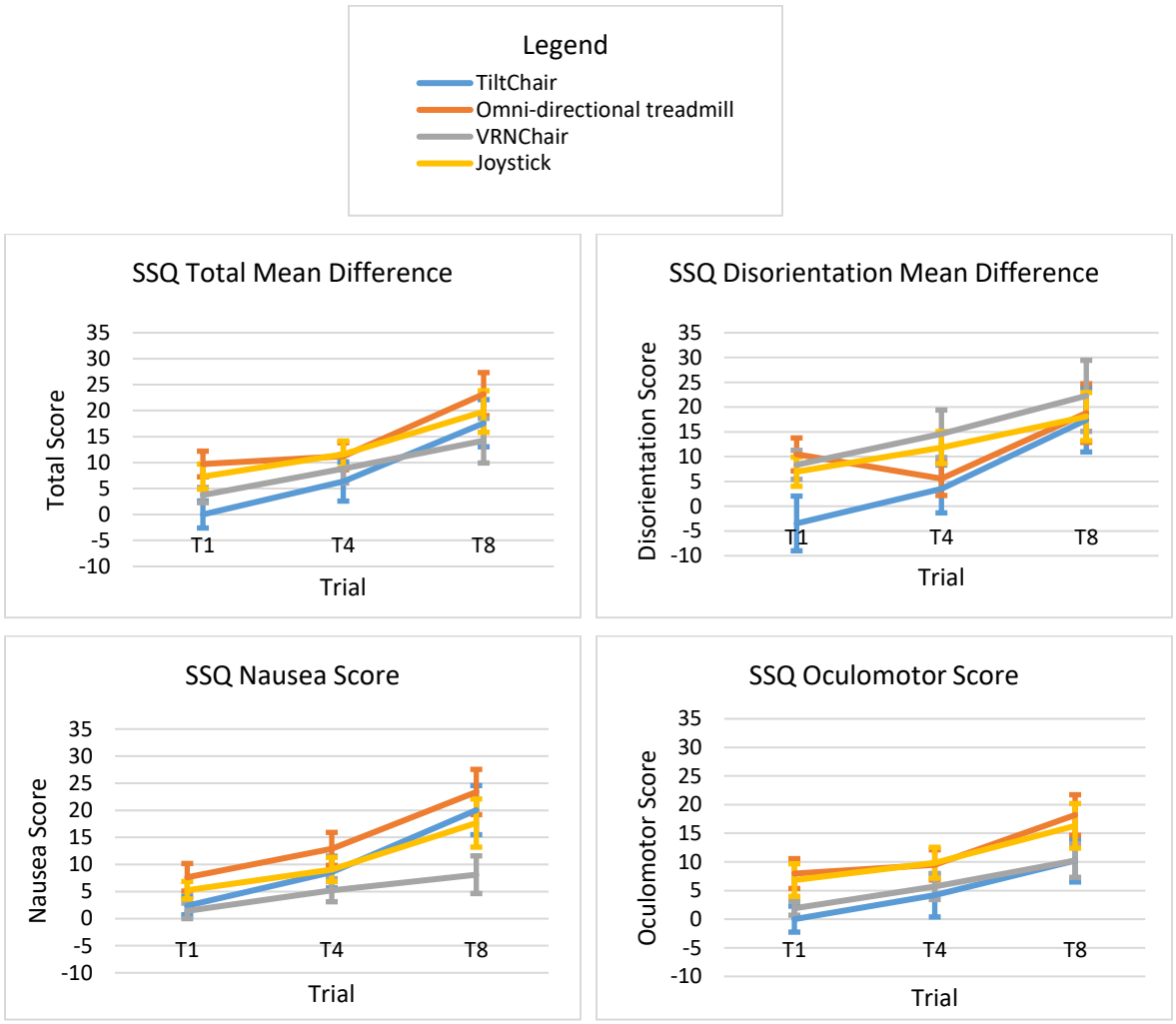


Figure 20 – Experiment 1 simulator sickness questionnaire mean difference trends

With mean difference and standard deviation bars for 20 participants Total score, disorientation sub-score and oculomotor sub-score were significantly affected by exposure time. Nausea sub-score had a significant main effect for both controller type and exposure time.

4.1.2. Intuitiveness

The results of the traversed distances are shown in Table 5. There was a significant interaction between sex and controller type on the traversed distances ($F(3,27) = 6.42, p = 0.002$). Within sex, controller type significantly affected the female's traversed distance ($F(3,27) = 6.42, p = 0.002$). Within controller type, there were significant differences for sex. Generally, females traversed significantly shorter distances than males utilizing the TiltChair ($F(1,18) = 5.00, p = 0.038$) and omni-directional treadmill ($F(1,18) = 7.26, p = 0.015$). Overall, on average, participants traversed significantly shorter distances on the TiltChair without a neck brace ($p < 0.03$).

Table 5 – Experiment 1 traversed distance results

Controller Type	Males	Females	Total
VRNChair	160.42 ± 5.47	159.01 ± 4.21	159.72 ± 4.81
Omni-directional treadmill*	165.64 ± 8.14	157.57 ± 4.84	161.60 ± 7.72
TiltChair without a neck brace*	158.81 ± 6.50	152.59 ± 5.92	155.70 ± 6.83*
Joystick	161.88 ± 8.27	164.18 ± 7.93	163.03 ± 7.98

All units are in meters. * indicates significance with $p < 0.05$. There was a significant interaction between sex and controller type on traversed distances. Within sex, males and females had significant differences while utilizing the omni-directional treadmill and TiltChair without a neck brace. Overall, on average participants traversed significantly shorter distances while utilizing the TiltChair without a neck brace.

The execution time results are shown in Table 6. There was only a significant main effect of controller type ($F(1.28,23.02) = 61.83, p < 0.0005$). Overall, the participants had significantly shorter execution times when utilizing the joystick when compared to the other controllers, while the participants had significantly longer execution times when utilizing the omni-directional treadmill compared to the other controllers. All participants had similar execution times when utilizing the VRNChair and the TiltChair.

Table 6 – Experiment 1 execution times

Controller Type	Mean ± Standard Deviation [s]
VRNChair	266.11 ± 35.49
Omni-directional treadmill*	450.14 ± 105.27
TiltChair without a neck brace	276.48 ± 26.28
Joystick*	225.15 ± 22.89

All units are in seconds. * indicates significance with $p < 0.05$. The joystick had the significant shortest execution time and the treadmill had the significant longest execution time. There were insignificant differences between the VRNChair and TiltChair execution times.

For the user characteristics, height and eyesight had a significant correlation and interaction effect respectively. Participant height and the omni-directional treadmill's traverse distance had a significant correlation ($r_s(18) = 0.527, p = 0.017$). However, participant height and the controller types' individual execution times had insignificant correlations. This means when the participants utilized the omni-directional treadmill taller participants had longer traverse distances compared to shorter participants. Eyesight and controller type had a significant interaction effect on execution time ($F(1.47,26.47) = 6.84, p = 0.008$). Thus, execution times depended on a participant's eyesight and the controller they utilized to complete the VR task. In fact, when participants utilized the omni-directional treadmill there was a significant difference between eyesight groups ($F(1,18) = 8.49, p = 0.009$). Participants with normal or corrected to normal vision had significantly shorter execution times compared to participants with uncorrected vision (Table 7). Eyesight had an insignificant effect on the controller types' individual traversed distances.

Table 7 – Experiment 1 eyesight effects on execution time

Controller Type	Eyesight	Mean ± Standard Deviation
VRNChair	Normal Vision / Corrected Vision	265.26 ± 31.08
	Uncorrected Vision	267.70 ± 45.31
Omni-directional treadmill	Normal Vision / Corrected Vision	407.53 ± 56.35
	Uncorrected Vision	529.28 ± 132.28
TiltChair without a neck brace	Normal Vision / Corrected Vision	277.34 ± 27.51
	Uncorrected Vision	274.88 ± 25.84
Joystick	Normal Vision / Corrected Vision	223.20 ± 23.92
	Uncorrected Vision	228.79 ± 22.14

All units are in seconds. From a two-way mixed ANOVA, there was a significant interaction between eyesight and controller type on a participant's execution time ($F(1.47,26.47) = 6.84, p = 0.008$).

After a participant completed all the sessions, they ranked all locomotive controllers. Most participants selected the joystick and VRNChair as the most intuitive and most comfortable controllers to utilize. In contrast, most participants selected the TiltChair and omni-directional treadmill as the least intuitive and least comfortable to utilize. For computer experience, three participants had not utilized a joystick before the experiment, while two participants experienced VR once before the experiment. Therefore, we could assume joystick and VR experience should not have any effects on the simulator sickness and intuitiveness measures.

.

4.2. Experiment 2 Results

4.2.1. Simulator Sickness

Similar to Experiment 1, Experiment 2's simulator sickness results varied for center of path length and SSQ mean score differences. Table 8 and Table 9 summarize the center of pressure path lengths for the eyes closed and eyes open conditions respectively. For center of pressure path length, controller type, sex and time did not significantly interact on either the eyes open and eyes closed conditions. Individually, these factors did not have any significant main effect.

In contrast, the individual effects of height and eyesight had significant correlations and interaction effects on the center of path lengths respectively. The significant correlation occurred between participant height and the center of path length during the eyes-closed condition and when participants utilized the TiltChair without a neck brace after trial 8 ($r_s(18) = 0.508, p = 0.02$). For eyesight, there was a significant interaction effect between eyesight and time during the eyes-open condition ($F(2,36)=3.73, p = 0.03$).

Table 8 – Experiment 2 center of pressure path length with eyes-closed

Sex	Controller Type	Trial 1	Trial 4	Trial 8
Male	VRNChair	-6.41 ± 17.66	- 6.36 ± 15.54	-7.47 ± 14.80
	TiltChair without a neck brace	-7.21 ± 20.20	-4.87 ± 21.58	-5.23 ± 19.84
	TiltChair with a neck brace	-5.82 ± 11.39	-2.67 ± 15.52	-0.63 ± 17.88
Female	VRNChair	-2.93 ± 12.24	2.32 ± 13.08	-1.79 ± 16.79
	TiltChair without a neck brace	-1.17 ± 7.75	-1.21 ± 10.34	3.50 ± 16.23
	TiltChair with a neck brace	0.87 ± 13.05	3.78 ± 17.91	1.89 ± 14.82
Total	VRNChair	-4.67 ± 14.90	-2.02 ± 14.67	-4.63 ± 15.68
	TiltChair without a neck brace	-4.19 ± 15.21	-3.04 ± 16.58	-0.86 ± 18.20
	TiltChair with a neck brace	-2.47 ± 12.40	0.56 ± 16.65	0.63 ± 16.04

Values shown are mean differences between baseline and specified trial [cm] with their standard deviation. There were insignificant interaction effects and main effects for sex, controller type and trial.

Table 9 –Experiment 2 center of pressure path length with eyes-open

Sex	Controller Type	Trial 1	Trial 4	Trial 8
Male	VRNChair	-5.15 ± 12.96	0.65 ± 11.22	2.41 ± 15.05
	TiltChair without a neck brace	5.97 ± 19.57	2.29 ± 16.47	4.46 ± 13.41
	TiltChair with a neck brace	-0.25 ± 9.32	0.89 ± 12.51	3.16 ± 14.40
Female	VRNChair	2.12 ± 16.85	-0.67 ± 18.51	4.88 ± 16.03
	TiltChair without a neck brace	-7.11 ± 12.38	-2.47 ± 15.65	-6.66 ± 16.24
	TiltChair with a neck brace	0.45 ± 10.87	5.51 ± 12.98	8.61 ± 22.11
Total	VRNChair	-1.51 ± 15.10	-0.01 ± 14.92	3.65 ± 15.19
	TiltChair without a neck brace	-0.57 ± 17.30	-0.09 ± 15.83	-1.10 ± 15.58
	TiltChair with a neck brace	0.10 ± 9.86	3.20 ± 12.63	5.89 ± 18.37

Values shown are mean differences between baseline and specified trial [cm] with their standard deviation. There were insignificant interaction effects and main effects for sex, controller type and trial.

For the SSQ scores, the mean score differences can be seen in Figure 21. Time had a significant main effect on the total SSQ score mean difference ($F(1.71, 30.77) = 17.25, p < 0.0005$). However, the comparison among sub-scores, disorientation, oculomotor and nausea had different results. Disorientation had individual significant main effects of controller type ($F(2,36) = 7.42, p = 0.002$) and time ($F(1.30, 23.30) = 11.86, p < 0.0005$). When comparing the different controller types with Bonferroni corrections, the VRNChair had a significantly higher disorientation sub-score compared to the TiltChair with a neck brace ($M = 13.688, SD = 3.483, p = 0.003$). Contrarily, the nausea and oculomotor sub-score mean differences only had a main effect of VR exposure time: $F(2,36) = 13.15, p < 0.0005$, and $F(1.61, 29.01) = 17.28, p < 0.0005$ respectively.

Additionally, participant height had a significant correlation with the SSQ scores, but eyesight had insignificant interaction and main effects on the SSQ scores. The significant correlations occurred between height and the SSQ oculomotor sub-score after trial 1 ($r_s(18) = 0.511, p =0.021$) and between height and the SSQ disorientation sub-score after trial 4 ($r_s(18) = 0.452, p =0.046$) as participants utilized the TiltChair without a neck brace. In general, taller participants compared to shorter participants that utilized the TiltChair without a neck brace had higher oculomotor sub-scores after trial 1 and higher disorientation sub-scores after trial 4.

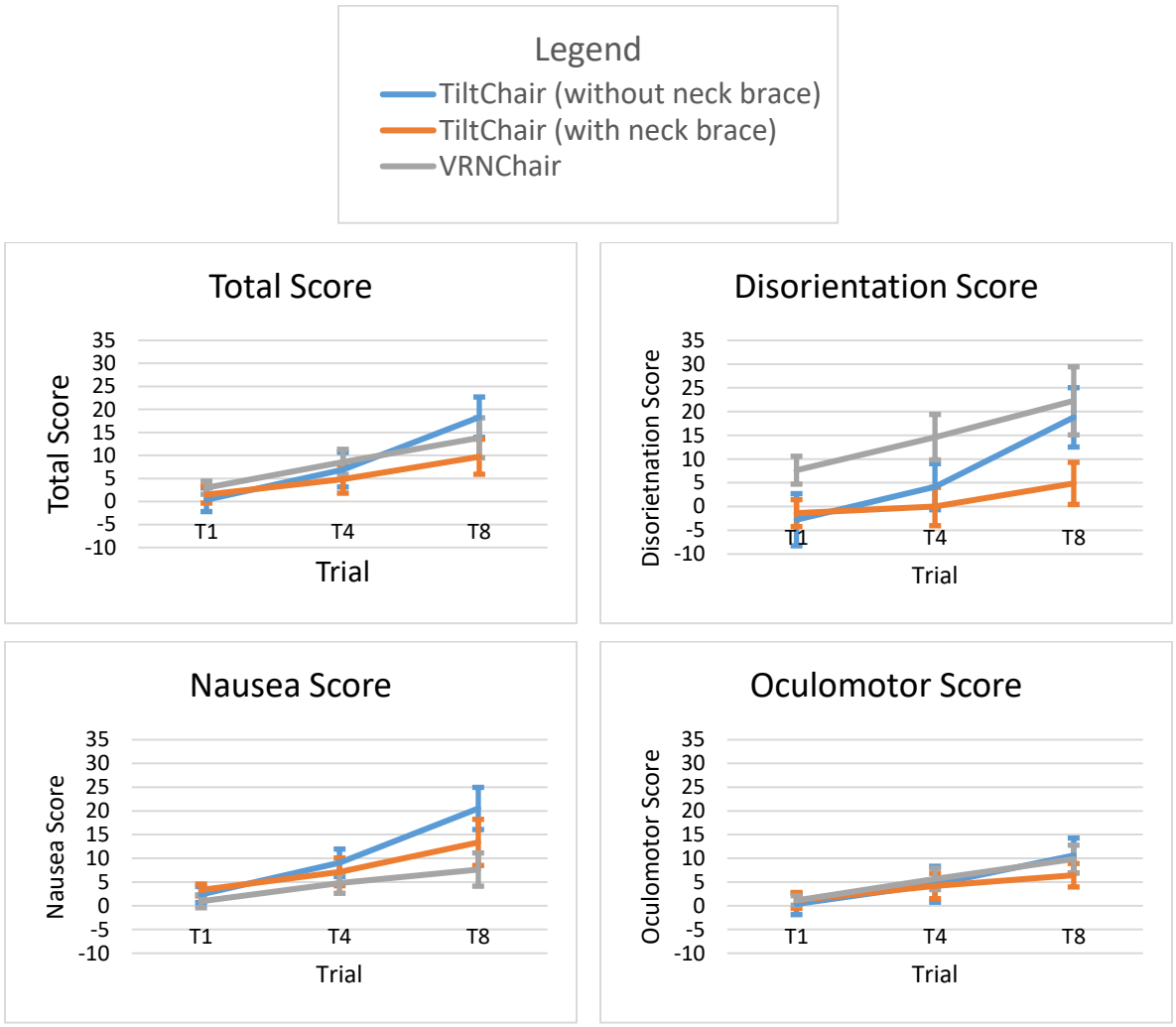


Figure 21 – Experiment 2 simulator sickness questionnaire mean difference score trends
With mean difference scores and standard deviation bars for 20 participants. Total Score, nausea sub-score and oculomotor sub-score had a significant effect of time. Disorientation sub-score had a significant effect of controller and type with significant differences between VRNChair and TiltChair with neck brace.

4.2.2. Intuitiveness

Experiment 2 measured intuitiveness via the traverse distances and execution times. For the traverse distances, the interaction among the controller type and sex factors had an insignificant effect ($F(2,36) = 1.57, p = 0.22$). However, the main effect of controller type had a significant effect on the total traversed distance ($F(2,36) = 10.52, p < 0.0005$). The controller type main effects can be summarized in Table 10. In contrast, sex did not have a significant main effect on the traversed distance.

Table 10 – Simulator sickness traversed distances

Controller Type*	Mean ± Standard Deviation [m]
VRNChair	159.87 ± 5.09
TiltChair without neck brace	155.10 ± 6.21
TiltChair with neck brace	154.79 ± 5.06

* indicates significance with $p < 0.05$. There was a significant main effect of controller type.

When analyzing the main effect of controller type with Bonferroni corrections, there were significant differences when comparing the VRNChair to both TiltChair with and without a neck brace. From Table 11, participants that utilized the VRNChair traversed further distances.

Table 11 – VRNChair comparison to all TiltChair versions

Controller	Mean Difference	Standard Error	p-value	95% Confidence Interval
TiltChair without neck brace	4.77	1.35	0.007	1.21 to 8.32
TiltChair with neck brace	5.39	1.05	<0.0005	2.63 to 8.16

Note: All table values (except for the p-value) are in meters.

The results for the execution times are shown in Table 12. There were an insignificant interaction between sex and controller type ($F(2,36) = 3.02$, $p = 0.06$), and an insignificant main effect of controller type ($F(2,36) = 2.44$, $p = 0.10$).

Table 12 – Experiment 2 execution times

Controller Type	Mean ± Standard Deviation [s]
VRNChair	268.40 ± 34.03
TiltChair without neck brace	274.14 ± 28.19
TiltChair with neck brace	256.63 ± 33.90

There was an insignificant interaction between controller type and sex, and an insignificant main effect of controller type.

Also, user characteristics, user joystick experience and user VR experience had insignificant effects on the traverse distances and execution times. Overall, participant height and eyesight had insignificant correlation and main effects on the traverse distances and execution times respectively. Similar to Experiment 1, seventeen participants utilized a joystick and two participants experienced VR once before the experiments. Therefore, the experience with a joystick and VR before the experiment should not have a significant effect on the SSQ scores, traverse distances and execution times.

4.3. Summary

Chapter 4 presented the results for the VR locomotive technology feasibility experiments. Experiment 1 investigated the effects of different motion stimuli combinations provided by a VR locomotive controller with a HMD. Experiment 2 investigated the effects of neck rotation freedom by participants utilizing the TiltChair with or without a neck brace. For both experiments, participant's simulator sickness SSQ scores were significantly affected by VR exposure time. In Experiment 1, participants selected the joystick and VRNChair as the most comfortable controllers

in terms of simulator sickness, while participants selected the TiltChair and omni-directional treadmill as the least comfortable and least intuitive. In Experiment 2, the participants' necks were restrained while utilizing the TiltChair. This resulted with the participants having less severe simulator sickness symptoms that significantly affected the disorientation sub-score. Participants could efficiently and intuitively traverse at significantly shorter distances with the TiltChair. Also, the participants had significantly shorter execution times utilizing the joystick and significantly longer execution times utilizing the omni-directional treadmill. The comparison between sexes had male participants with longer traversed distances than female participants when they utilized the omni-directional treadmill and TiltChair without a neck brace. These experiment results will be discussed in the next chapter.

CHAPTER 5 – Discussion

Chapter 5 includes a discussion of the results from Experiment 1 and Experiment 2. Even though they had different experimental conditions, there were some overlapping effects such as VR exposure time, inadequate simulator sickness measurements and HMD utilization that affected a user's overall simulator sickness. Furthermore, the current chapter discusses observations from the research group's other studies that utilize VR.

5.1. Experiment 1 Discussion

In Experiment 1, participants selected the joystick and VRNChair as the most comfortable in terms of simulator sickness and most intuitive in terms of utilization [52]. This may be due to the young adult participants' past computer experiences with the joystick and the naturalistic movement with the VRNChair. Since seventeen participants had utilized a joystick and only one participant experienced VR before Experiment 1, we could not perform any statistical analysis to cross-correlate between different experiences with a joystick and VR. However, participants utilizing the joystick had significantly shorter execution times because they could easily move at the maximum speed with the maximum joystick tilt. In general, participants did not have any difficulties utilizing these controllers and could focus on completing the VR task.

Nevertheless, participants selected the TiltChair without a neck brace and the omni-directional treadmill as the least comfortable in terms of simulator sickness and the least intuitive in terms of utilization [52]. Even though the TiltChair without a neck brace had similar SSQ scores, similar execution times and shorter traversed distances compared to the other controllers, participants complained about their discomfort from utilizing the TiltChair. This may be due to the TiltChair providing mismatching motion stimuli and a lack of stability. The mismatching motion stimuli

occurred between the visual and vestibular system as participants rotated to change their heading direction. The controller design assumed that participants would rotate their necks and torsos synchronously because the HMD would update via the participant's torso rotation. Instead, some participants may have rotated their necks and torsos asynchronously to develop simulator sickness. Lastly, the lack of stability may have occurred when participants leaned to move forward in the virtual environment. Some participants leaning forward felt that they could almost fall off the TiltChair. To conclude, when participants utilized the TiltChair without a neck brace they received mismatching motion stimuli and had a lack of stability that may led to their decision to select the TiltChair without a neck brace as the least comfortable and least intuitive without any statistical significance.

Secondly, the omni-directional treadmill caused participants to have higher nausea scores and longer execution times compared to all other controllers. SSQ nausea scores include symptoms such as general discomfort, sweating and nausea [32]. The participants may have had some discomfort because several wires from the HMD and IMU surrounded their bodies, the HTC VIVE controllers were strapped onto their feet and tight bungee cords surrounded their torsos for support. We observed increased perspiration on the participant's foreheads because participants had more dynamic movements utilizing the omni-directional treadmill than the joystick and TiltChair. Additionally, as described in 3.2.3, higher nausea scores may had derived from the mismatching motion stimuli provided to the vestibular and proprioceptive receptors from the non-naturalistic gait.

Participants also had longer execution times while utilizing the omni-directional treadmill due to slower navigation speeds. We calibrated the omni-directional treadmill to move the user two virtual meters forward when the user slid his or her foot one meter along the omni-directional

treadmill's concave bowl. However, participants described moving at a slower speed than their expected speed. Interestingly, participants with uncorrected vision utilizing the omni-directional treadmill had significantly longer execution times compared to participants with normal or corrected to normal vision. These participants with uncorrected vision perhaps had poor perception on their distances between themselves and the walls of the virtual building or the entrances to the elevators and rooms. Therefore, they moved at a slower speed to traverse at a similar distance compared to participants with normal vision.

Overall, participants did not have any difficulties utilizing the controllers, but when participants utilized the TiltChair without a neck brace and omni-directional treadmill there were significant traversed distance differences among males and females. As the participants utilized these controllers, males had significantly longer traversed distances compared to females. However, other studies that investigated the feasibility of other novel VR locomotive controllers had predominantly more male participants recruited for their sample population [14], [66], [68]. Therefore, these studies could not execute statistical analyses to investigate any sex effects. Our results suggest males utilized the omni-directional treadmill and TiltChair less cautiously to inefficiently traverse longer distances.

Additionally, participants' heights were observed to affect their simulator sickness and traversed distance. Taller participants compared to shorter participants had significantly lower SSQ disorientation scores after trial 4 and significantly longer traversed distances with the omni-directional treadmill. Taller participants may have struggled to utilize the omni-directional treadmill with the numerous wires surrounding their own bodies. Consequently, the taller participants inefficiently traversed toward the target room or inefficiently turned around corners to achieve similar execution times as shorter participants. Therefore, these inefficient navigation

paths added to the longer traversed distances and may have contributed to the lower disorientation scores.

5.2. Experiment 2 Discussion

Experiment 2 had participants utilized the TiltChair with a neck brace to investigate the effect of restrained neck rotation on simulator sickness. The neck brace tried to reduce the participant's simulator sickness by enforcing synchronous rotation between the participant's neck and torso. As the HMD updated with the rotation of the participant's body, he or she received matching motion stimuli. However, some participants felt uncomfortable with the neck brace due to the restricted neck movement. Regardless, all participants felt less simulator sickness utilizing the TiltChair with the neck brace than the initial TiltChair without a neck brace.

Surprisingly, participants utilizing the VRNChair had significantly higher SSQ disorientation mean difference sub-scores compared to the two TiltChair conditions. We expected the VRNChair to not have any effects on a participant's simulator sickness because the VRNChair with the HMD provided the participant with sensory matching motion stimuli as he or she freely walked with the VRNChair. By analyzing the experimental protocol between the controllers, one participant described the draft in the VRNChair's physical play space created an illusion of self-motion called vection, which has been also described in the [65] study. However, this study described their participants had lower simulator sickness because they applied the air draft directly to the participants' individual faces that reduced their body temperatures [65]. In Experiment 2, the participants walked around a large open area that applied a draft not directly on the participants' faces at times. Therefore, this sensory mismatch between the air draft eliciting vection and a

participant walking around freely with the VRNChair may have led to a participant's simulator sickness.

5.3. Exposure Time

For both experiments, VR exposure time significantly affected the SSQ scores. As a user spent more time in VR, they had more severe simulator sickness with higher SSQ scores. This had been observed in many other studies [49]–[51]. By utilizing VR exposure time as one indicator for simulator sickness, one study developed an intervention identifier created from a fuzzy classifier [50]. The intervention identifier allowed the study to provide breaks for their participants that significantly reduced the SSQ scores. In my experiments, participants received breaks lasting a few minutes when we had to set up for the center of pressure pathlength simulator sickness measurements. We controlled the break effects by following the same experimental procedures and having the same set up time. During these breaks, the participants received matching motion stimuli from the physical environment that may have reduced the participants' simulator sickness. Overall, the reduction of simulator sickness may have attenuated the measurements and may have contributed to the insignificant results. This suggests our simulator sickness measurements may have been inadequate to measure some mild simulator sickness.

5.4. Inadequacy of Simulator Sickness Measurements

Some argued that the SSQ may be an inadequate measure for simulator sickness due to the scoring method, anxiety factor and a lack of physiological measurements. The SSQ total score derives from a weighted sum of the sub-scores with the sub-scores containing some of the same

symptoms. Due to these different weights, some symptom severity scores are emphasized more than other symptoms in the total score.

Also, Kennedy et al. derived the weights for the SSQ total score to produce a standard deviation of 15 among the initial military trainee sample population [32]. The sample population of military trainees may be problematic because they usually are more physically fit compared to a general population. One study observed young adults who did physical and sport activities, especially activities with complex motion stimuli integration (Eg. Karate, trampoline and gymnastics), had significantly lower susceptibility to general motion sickness than participants who did not participate in physical and sport activities [89]. Participants with lower susceptibility to motion sickness had their brains and bodies may adapt to the mismatching motion stimuli to reduce their SSQ scores. Therefore, my generalized young adult population may have been more susceptible to motion sickness compared to physically fit individuals that led to an exaggeration of my experimental results.

On the other hand, the SSQ total score may be influenced by a participant's anxiety to VR. Anxiety significantly associates with some SSQ categories with some of their symptoms that includes nausea (general discomfort, increased salivation and seating) and oculomotor discomfort (difficulty focusing and difficulty concentrating) [90]. In contrast, some SSQ symptoms insignificantly affected by anxiety include some from the nausea category (dizziness with eyes closed, headache and burping) [90]. These anxious feelings could further be enhanced when a research assistant explains the experimental procedures and potential risks to a participant that never experienced VR before. Also, pre-VR exposure to the potential risks with an initial baseline SSQ can lead to higher post VR exposure SSQ scores [91]. Overall, the SSQ inadequately measures simulator sickness due to its derived equation and participant anxiety.

To improve simulator sickness measurements, the current thesis experiments should have utilized physiological measurements. Similar to [92], my participants' postural sway did not significantly differ after their exposure to VR. This may be due to the experimental conditions (locomotive controllers and neck brace) designed to cause the least simulator sickness. We wanted to investigate the different experimental conditions to determine the most feasible VR controller that minimizes user simulator sickness and maximizes controller intuitiveness. Other physiological measurements such as heart rate, skin conductance changes or respiration rate may have been adequate to quantify simulator sickness [22]. Even though [22] did not significantly find any galvanic skin responses to measure any perspiration on their participants, more studies may want to investigate the utilization of the galvanic skin response because some of our participants showed perspiration on their foreheads post VR exposure and navigation.

Another physiological measurement for simulator sickness may include eye motion analysis because oculomotor discomfort is one of the SSQ sub-categories [32] and the eye-movement theory hypothesizes the onset of general motion sickness [23]. Possible measurements include gaze analysis, blink frequency, saccade amplitude and pupil dilation. Gaze analysis showed users with dynamic gazes had significantly higher SSQ oculomotor and disorientation scores than users with stable gazes [93]. Another study analyzed blink frequency and saccade amplitude between figure skaters and a control group using a HMD [94]. Their results showed figure skaters had a significantly higher blink frequency and a lower saccade amplitude while having a significantly lower SSQ total scores compared to the control group. The authors suggest the figure skaters had adapted to mismatching motion stimuli to lower their susceptibility to simulator sickness. Lastly, pupil dilation significantly changes when a user views a stereoscopic image [95] such as a user viewing a virtual environment through a HMD. A stereoscopic image produces a 2D image with

depth [95] that could cause simulator sickness from the HMD disrupting the accommodation-vergence reflex (discussed in Section 2.5.5). Even though a user's eye motion changes with simulator sickness, eye motion analysis still requires more studies to investigate any association with the SSQ symptoms. Overall, optimal simulator sickness measurements should include a combination of the SSQ and physiological measurements

5.5. Head-Mounted Displays

Among all the experimental conditions, the utilization of an HMD perhaps was associated with the significant VR exposure time effect. The HMD removed the user's vergence-accommodation reflex and peripheral vision. As the eyes try to track movement, vergence describes the internal rotation of our eyes to produce a singular binocular image; while, accommodation describes the lenses flexion to focus on the image [61]. However, the Oculus DK2 caused a user's eyes to continuously verge as accommodation remained static because the distance between the user's eyes and the Oculus DK2's lenses remained constant [62]. Hence, some users developed eye strain that contributed to their simulator sickness. To disable the eyes' vergence, one study resolved this issue by a dynamic depth of field to focus on the virtual scene [61].

Additionally, participants may have developed simulator sickness from the HMDs that occluded their peripheral vision. The lack of peripheral vision among HMDs in the [96] study had participants with an increased severity of simulator sickness. In my experiment, the HMDs enforced participants to rely only on their central vision information to receive mismatching motion stimuli. In contrast, a laptop screen enforces users to rely on both central and peripheral visual information to receive matching motion stimuli. Therefore, my participants had mismatching motion stimuli among their central and peripheral visual systems that contributed to

their simulator sickness. Even though this thesis did not compare the effects between HMD and laptop display, we compared these two devices through the research group's observations from our other studies discussed in 5.7.

5.6. Intuitiveness

The highest level of intuitiveness occurs when participants can easily utilize a locomotive controller to complete the VR navigation task. To evaluate the highest level of intuitiveness, participants should complete the task with the shortest traversed distances and shortest execution times. The shortest traversed distances occurred when participants utilized the TiltChair. The TiltChair had the slowest speed that helped participants efficiently traverse the shortest distance to find the target rooms. All other controllers (VRNChair, omni-directional treadmill and joystick) had similar traversed distances.

In contrast, the shortest execution times occurred with the joystick. The joystick had the fastest speed at its maximum tilt that helped participants quickly find the target rooms. The longest execution times occurred when participants utilized the omni-directional treadmill. Additionally, participants utilizing the omni-directional treadmill had males traverse significantly longer distances than females. During the utilization of the omni-directional treadmill, participants had difficulties with the un-naturalistic gait (Explained in 3.2.3) to inefficiently move around in the virtual environment. Overall, the omni-directional treadmill had the lowest level of intuitiveness, while the joystick and TiltChair had the highest level of intuitiveness among the young adult participants.

The amount of experience with computers may affect a user's perception of a VR locomotive controller's intuitiveness. For instance, young adult participants may have different computer

experience than elderly participants. Most of the young adult participants had experience with a computer joystick and only a few participants had one VR experience before starting the study. However, we could not perform any statistical analysis to cross-correlate between the different experiences and intuitiveness measures. In contrast, most elderly participants have minimal computer experience. The next section will discuss observations on elderly participants utilizing the joystick, VRNChair and TiltChair to complete the same VR navigation task. A VR controller with a low level of intuitiveness would cause the elderly participants to have difficulties utilizing the technology and not focus on executing the VR task. If researchers want to execute VR experiments, the researchers should select VR technology based optimizing controller intuitiveness and reducing user simulator sickness for their sample population to remove any of these effects on the study's results.

5.7. Observations in our Other Studies

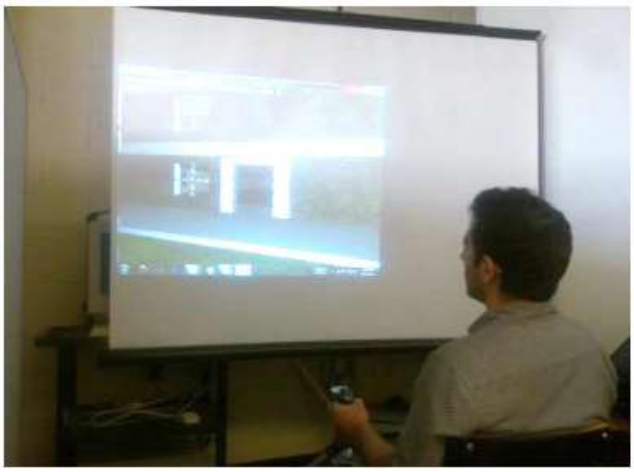
From the research group's other studies, participants utilized different VR technologies to execute the same VR navigation task. To complete a task, the participants utilized either the VRNChair with a laptop display, the VRNChair with an Oculus Rift DK2, or the TiltChair with an Oculus Rift CV1. However, some participants developed such severe simulator sickness that they had to quit the experimental session.

5.7.1. VRNChair with Laptop Display

The initial version of the research group's studies, prior to the VRNChair introduction in 2012, had participants utilizing an ordinary joystick while viewing the virtual task on a large projection screen [97, p. 80] (Figure 22). This resulted with 30% of the participants developing simulator sickness. Also, many elderly participants struggled to utilize the joystick due to their minimal

computer experience; hence, experience bias would affect the study's results. Experience bias involved participants struggling to utilize the experimental device and not focusing on the experimental task. To remove experience bias and reduce simulator sickness, the research group became motivated to design a locomotive controller.

The first locomotive controller design consisted of the VRNChair with a laptop display. Participants easily utilized this controller to complete the VR task while reducing the level of simulator sickness. As shown in Figure 23, the initial VRNChair design included a laptop placed onto a manual wheelchair's tray. Participants pushed the VRNChair to navigate as they viewed the virtual environment on the laptop display. With the VRNChair's high level of intuitiveness, elderly participants utilizing the VRNChair had shorter traversed distances and significantly improved performances [97, p. 95]. Moreover, 4 out of 333 participants (1.2%, mean age of 64.22 ± 9.13 years) that utilized the VRNChair with a laptop display quit the task due to severe simulator sickness [unpublished data].



Reprinted with permission of Ahmad Byagowi [97]

Figure 22 – Initial virtual reality set-up with projection screen and joystick



Figure 23 – Initial VRNChair set-up as push cart controller

5.7.2. VRNChair with Oculus Rift DK2

The next locomotive controller design consisted of seated participants that utilized the VRNChair with an Oculus Rift DK2 as they freely walked around (Figure 24). They performed better during the same VR navigation task with short traversed distances and less errors compared to a laptop display [5], [76, p. 39]. To traverse efficiently, the Oculus Rift DK2 allowed participants to better perceive their distances between the internal virtual walls; while the laptop display obstructed the participants' view of the virtual environment and they could not perceive their distances between the virtual internal walls. With the Oculus Rift DK2, participants automatically projected themselves into the 3D virtual environment and described the navigation task as intuitive. Therefore, this VR navigation task simulated a naturalistic scenario that helped participants to produce fewer errors.



Figure 24 – Elderly participant with VRNChair and Oculus Rift DK2 set-up

Even though the Oculus Rift DK2 improved the participants' performances, there were about 9 out of 81 participants (11.11%, mean age of 67.56 ± 9.28 years) that developed severe simulator sickness with the VRNChair and Oculus Rift DK2 and had to quit the experimental session [unpublished data]. The simulator sickness may have developed from the HMD visual stimuli, which was explained in an earlier section, decoupling mode or hardware drift. The HMD visual stimuli that contributed to a participant's simulator sickness included the removal of the vergence-accommodation reflex, and the removal of the user's peripheral vision.

Also, the VRNChair decoupling mode could have contributed to a participant's simulator sickness. A participant entered this mode when the participant approached an obstacle. Then, a research assistant pressed a button to pause the VR task and moved the participant away from the obstacle. During this motion, the participant saw a video feed of the physical space played to provide visual motion stimuli. However, the virtual scene juddered around the small video feed that mismatched with the motion stimuli to cause simulator sickness. To reduce simulator sickness, the decoupling mode could be removed by scaling the virtual environment to fit in the physical space or by implementing a redirected walking method [98]. The redirected walking method causes the virtual environment to slightly rotate about a user as the user navigates through the

virtual environment. For instance, when a user walks along a straight line in the virtual environment, the user walks along a curve line in the physical space. Overall, the user will not notice this slight rotation. Therefore, users can reduce simulator sickness by avoiding the decoupling mode along the boundaries of the physical play space.

Lastly, the hardware drift derived from the VRNChair's inertial measurement unit heading direction. The drift increased as the inertial measurement unit increased in temperature. Eventually, the physical and virtual motion became unaligned that created mismatching motion stimuli and led to simulator sickness. To re-align participants, the participants turned their heads in the forward direction as a researcher pressed a button on the keyboard. These hardware issues can be resolved by implementing automatic realignment. Automatic realignment can occur when a user's head orientates directly in front of the laptop screen.

5.7.3. TiltChair with Oculus Rift CV1

The latest locomotive controller design included fourteen elderly participants that utilized the TiltChair and Oculus Rift CV1 (Figure 25). Improvements to the TiltChair's software algorithm allowed participants to freely rotate their own necks without any synchronous rotation between the necks and torsos. Therefore, the HMD only updated via the user's neck rotation. However, 50% of the elderly participants developed severe simulator sickness and stopped their experimental session. In contrast, only one participant executed my entire neuro-cognitive rehabilitation program utilizing the TiltChair (further explained in the next chapter).



Figure 25 – TiltChair v3 utilized by elderly participant

The newer Oculus Rift CV1 includes improvements in comparison to the older Oculus Rift DK2. Table 13 compares the two devices with their frame rate, resolution and field of view. The new version reduced the latency time for the brain to receive visual motion stimuli, and increased immersion with complex details and a larger field of view. Moreover, the CV1's high resolution removed the noticeable pixels from the DK2 (Figure 26). For instance, a user wearing the DK2 could identify individual pixels that created the illusion of looking through a mesh screen. These improvements should help reduce cases of simulator sickness, but most elderly participants suffered from severe simulator sickness.

Table 13 – Oculus DK2 and CV1 hardware specifications comparison [78], [99], [100]

Hardware Specification	DK2	CV1
Resolution	1920 x 1080	2160 x 1200
Frame rate (Hz)	75	90
Field of view (degrees)	100	120



(a) (b)

Figure 26 – Resolution comparison between Oculus Rift CV1 and DK2
Image taken through lenses of head-mounted display (a) Oculus Rift CV1 (b) Oculus Rift DK2

Participants' simulator sickness may have been due to the TiltChair not utilizing the Oculus Rift CV1's position tracker. The position tracker updates the HMD's view when participants translate their heads in any direction. I removed the position tracker to prevent any issues when participants obstructed the position tracker's view. Without the position tracker, the HMD would not update with any translational movement when a participant leans forward on the TiltChair. Therefore, participants' eyes would not receive any translational stimuli.

Additionally, elderly participants may have had developed simulator sickness due to their difficulties with maintaining stability on the TiltChair. Typically, elderly participants have more difficulties with maintaining stability in comparison to young adult participants. They may have found the TiltChair unintuitive to utilize. Some elderly participants struggled to lean forward and to pivot in place due to their limited range of hip mobility or due to their taller heights. Like the young and taller male adult participants (discussed in 5.6), taller elderly participants were required to lean forward until they almost fell forward. Overall, many senior participants developed severe

simulator sickness and struggled to utilize the TiltChair; hence, the research group's other studies discontinued to utilize the TiltChair.

5.8. Summary

Experiment 1 and Experiment 2 investigated the feasibility of VR locomotive controllers from the effects on user's simulator sickness and controller's intuitiveness. Simulator sickness was significantly affected by VR exposure time. To minimize the VR exposure time effects, a participant's VR task can be intervened with breaks throughout a session. However, a HMD may have contributed to the participants' simulator sickness without any peripheral vision or vergence-accommodation reflex. Overall, the joystick and TiltChair had the highest level of intuitiveness and the omni-directional treadmill had the lowest level of intuitiveness among the young adult participants. Since elderly participants are susceptible to simulator sickness and have little computer experience, the elderly participants would find the VRNChair controller as the most intuitive to utilize with the least amount of simulator sickness. Therefore, Chapter 6 investigates the utilization of the VRNChair through a VR application of neuro-cognitive training with elderly participants.

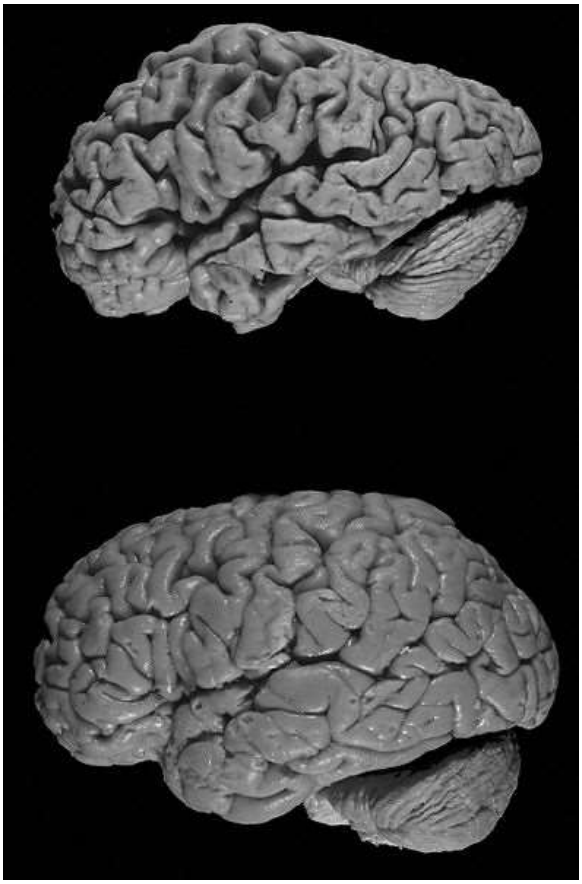
CHAPTER 6 – Application: Neuro-cognitive Training for Participants with Memory Problems

The thesis further investigates the utilization of the VRNChair, TiltChair and Oculus Rift CV1 HMD during a VR neuro-cognitive training for participants with memory problems. Memory and cognitive decline generally occurs as a natural process of aging, however significant declination can be observed with dementia or Alzheimer's disease (AD). To stop or slow this characteristic decline, elderly people may execute brain exercises to activate the brain's plasticity through mental stimulation. Therefore, the current neuro-cognitive training utilizes a brain exercise by a designed VR shopping task. This chapter will discuss the neuro-cognitive training rehabilitation program, participant's results and discusses the criticisms to the current designed program.

6.1. Aging Brain and Alzheimer's disease

There are some differences between normal aging and AD with cognitive functionality and physiology. Normal aging tends to describe some memory difficulties, while AD tends to describe more frequent memory difficulties. Furthermore, a person diagnosed with AD may forget daily essential activities such as eating meals, or taking medications that affect their ability to live independently. Physiologically, AD can be described as the ineffective communication between neurons leading to declination in memory and many more cognitive functions [101]. Some affected areas include the neocortex, entorhinal area, hippocampus, amygdala, nucleus basalis, anterior thalamus and parts of the brain stem nuclei [101] that contribute to the significant differences between a normal-aged and an AD brain (Figure 27). As the disease transitions from mild cognitive impairment to AD, the efficacy of the neuronal communication network (i.e. white matter)

diminishes significantly [102], [103] as well as the hippocampus atrophies and the ventricles enlarges significantly [104].



CC image courtesy of Hersenbank on wikimedia

Figure 27 – Brain anatomical comparison between Alzheimer's diseased brain (top) and healthy brain (bottom)

To explain the development of AD, there are theories that include the beta-amyloid cascade, blood flow impairment and microglial toxins. Hardy and Allsop created the most popular beta-amyloid cascade theory [105]. Initially, a gene mutation activates the metabolism of the amyloid precursor proteins, beta amyloid depositions and plaques. The accumulation of beta-amyloid proteins externally to a neuron causes tau phosphorylation and the creation of tangles that leads to neuronal death. However, recent studies suggest that beta-amyloid plaques and tau tangles are only biomarkers due to the presence of these proteins from a brain's stress response (E.g. A concussion) [106] or from inadequate blood flow to the brain [107] .

Lastly, microglial cells within the brain may cause AD [108]. Microglial cells produce toxic compounds in response to damage signals within the brain. These toxins cause the formation of the beta-amyloid plaques and tau tangles. Afterwards, neurons eventually die and release more damage signals. Thus, the microglial cells react in a positive feedback loop that continuously respond to damage signals within the brain that eventually leads to the characteristic cognitive decline among AD patients. The later stages of AD describe when the brain can no longer maintain homeostasis against these brain dysfunctions with the characteristic cognitive decline [106].

Overall, dementia, especially AD, affects many people every year. Alzheimer's Disease International estimates the number of people with AD will grow to 131.5 million worldwide by 2050 [6]. Meanwhile, the estimated worldwide cost of dementia will be $2 trillion USD by 2030 [6]. Not only does dementia and AD have functional burdens for sufferers and financial burdens for economies, there are also mental burdens for caregivers. The caregiver's mental wellbeing may be jeopardized trying to maintain their regular routine and to care for their significant other with dementia or AD. To diminish these burdens, many research interests include investigating novel treatments to replace the current non-effective pharmaceuticals by utilizing the brain's plasticity.

6.2. Brain Plasticity

Brain plasticity describes the improvement to the efficacy of the neuronal communication network from an increase functional demand. This can be described by Hebb's postulate from over 65 years ago that states, "Cells that fire together, wire together" [109], [110, p. 62]. Presynaptic neuron stimulating its postsynaptic neuron(s) may cause changes to one or all communicating neurons. These changes may include the neuron's excitability for a stimulus and the strength of synaptic communication due to chemical synaptic changes. Chemical synapses can change for

weeks or months via long term potentiation that strengthens synapses by brief burst of activity in presynaptic afferents [109]. Long term potentiation can strengthen memories. However, learning involves the increase or decrease in long term potentiation in specific localized regions. Therefore, targeting brain regions responsible for cognition may lead to observable improvements in an elderly person's cognitive abilities through different brain stimulations.

6.3. Brain Stimulation

The brain's plasticity motivates studies to investigate the utilization of brain stimulation as a treatment for dementia. Brain stimulation upon specific regions can strengthen the communication network to surrounding or interconnecting regions that may lead to cognitive or memory improvements. There are three non-invasive brain stimulations that studies investigated for their effectiveness as a treatment for dementia or AD. These stimulations include repetitive transcranial magnetic stimulation, transcranial direct current stimulation and mental stimulation.

Repetitive transcranial magnetic simulation applies a quick alternating electrical current in a coil onto a person's scalp. This creates a magnetic field that induces an electric field in the brain to increase neuronal activity via long term potentiation or depression [111]. Magnetic field applications include short bursts with an intermittent break. One study applied the stimulation bilaterally for 10 minutes on the dorsolateral prefrontal cortex with cognitive training [7]. In contrast, two studies applied the stimulation on the brain regions associated with AD clinical symptoms for 7 to 15 minutes [112], [113]. All studies resulted with improvements to their primary cognitive measurements.

Transcranial direct current stimulation works like repetitive transcranial magnetic stimulation. Instead of applying a magnetic field to create an electrical current, the stimulation applies a small

electrical current on a person's scalp via electrodes as he or she completes cognitive training. Contrarily, transcranial direct current stimulation does not affect the brain's plasticity, but affects the neuron's membrane potential and excitability [114]. Most commonly for AD studies, an anodal stimulation (2 mA of electrical current) had been applied on the left dorsolateral prefrontal cortex for 25 minutes [115], or bilaterally on the temporal cortices for 30 minutes [116]. These studies also resulted in cognitive improvements.

The above-mentioned external stimulation studies utilized cognitive assessments to investigate the overall indirect plastic-like effects. The studies may observe improvements not only in cognition and memory but also in depression symptoms. For example, other studies also showed improvements on depression symptoms by applying stimulation to the left dorsolateral prefrontal cortex [117], [118], which may include improvements on concentration and/or anxiety. These stimulations do not target specific neuronal synapses; instead, the stimulation applies to the target, surrounding and interconnecting regions. The regions can be a few millimeters to several centimeters for repetitive transcranial magnetic stimulation [119] or have a current density of 0.1 A/m^2 for a transcranial direction stimulation of 2.0 mA [120]. Since these stimulations can improve a participant's mood, the cognitive assessment may be inadequate to measure any indirect plastic-like effects because the participant's mood can affect the overall results especially in small samples for any treatment modality.

To investigate the effects on the brain's plasticity, studies may want to utilize objective measurements such as electroencephalography, functional near infrared spectroscopy and functional magnetic resonant images. Electroencephalography has shown changes to the brain's oscillatory electrical activity, which the study recorded at 15 minutes before, during and 15 minutes after repetitive transcranial magnetic stimulation [121]. Another study utilizing

electroencephalography after repetitive transcranial magnetic stimulation saw changes to the neuronal activity with the spectral power and neuronal connectivity through phase coherence [122]. Functional near infrared spectroscopy has the potential to investigate changes to superficial neuronal sensitivity and connectivity with transcranial repetitive stimulation [123]. Lastly, functional magnetic resonant images has shown changes to the brain's resting state connectivity with transcranial direct current stimulation [124]. Thus, studies applying magnetic or direct current stimulations as an Alzheimer's disease treatment, can utilize electroencephalography, functional near infrared spectroscopy and functional magnetic resonant images to investigate any changes to the brain's plasticity.

Lastly, mental stimulation does not utilize any external device to create the electrical currents among neurons. Instead, mental stimulation utilizes cognitive training completed by a participant. Cognitive training causes the brain to transmit electrical signals naturally to initiate the brain's plasticity for cognitive improvements. Mental stimulation can be applied via a neuro-cognitive rehabilitation program where participants complete cognitive training for a certain amount of time. Some neuro-cognitive rehabilitation program investigations will be discussed in the next section.

6.4. Neuro-Cognitive Rehabilitation Programs

Neuro-cognitive rehabilitation and its benefits had been investigated through strategy, paper-and-pen, and computer-based methods. In elderly neuro-cognitive rehabilitation, the most well cited study is the Advanced Cognitive Training for Independent and Vital Elderly (ACTIVE) trial [125]. During the ACTIVE 6-week intervention program with a follow-up maintenance, elderly participants learned and practiced different strategies focused on memory, reasoning and speed-processing cognitive performance. These participants had long term effects lasting after 5 years

[126] and only had reasoning and speed performances maintained after 10 years [127]. Most recently, a study incorporated conventional paper-and-pen with computer-based neuro-cognitive training exercises focused on visuospatial, working memory, and verbal and semantic fluency [128]. Their results showed that combining paper-and-pen exercises with computer-based exercises had significant improvements than only conventional paper-and-pen exercises [128].

The amount of interest grew for novel computer-based exercises in the past few years especially with VR. As discussed in the prior chapters, VR can be intuitive for elderly participants with little computer experience. They can utilize the VRNChair with minimal experience because of the naturalistic locomotion within the virtual environment. Therefore, the intuitiveness removes experience bias such that elderly participants can focus on the neuro-cognitive training task. As the participants focus on the neuro-cognitive training task, optimal mental stimulation allows participants to have probable improvements in their memory and/or cognitive abilities.

Our research group investigated the utilization of computer-based and immersive VR for neuro-cognitive training. The first computer-based neuro-cognitive training focused on associative memory word-image and animal-shape exercises [8]. Participants completed 3 sessions per week for a total of 8 weeks and significantly improved their short-term and logical memory compared to a no-treatment control group. Afterwards, we investigated the application of immersive VR in two case studies utilizing the VRNChair and Oculus Rift DK2 [76]. The two case studies included a participant at an early-onset stage of AD and another participant at a later stage of AD. The VR exercise's difficulty matched the cognitive abilities of the participants. Overall, this VR program had only observed cognitive improvement for the participant at an early stage of AD. Therefore, my neuro-cognitive rehabilitation program should result with cognitive improvements among the recruited participants with memory problems.

6.5. Methods

The neuro-cognitive rehabilitation program included 8 weeks of 45-minute training sessions with 3 testing sessions in a large quiet room. Training sessions occurred 3 times per week utilizing our customized VR shopping task exercise. Each training session was separated by at least 48 hours to minimize any simulator sickness from prior sessions. As described in section 3.4.1, some studies had few participants feeling simulator sickness after the experiment until 2 to 4 hours [81], until the evening of the same day [82], or 24 hours later [38]. Testing sessions occurred at baseline, on the 4th and 8th week of the program. After the program, follow-up testing sessions occurred at 4 and 12 weeks. Testing sessions utilized the Montreal Cognitive Assessment, Water Morris Maze and Radial Arm Maze as primary outcome measures, while testing sessions utilized the Word-Association and 1-Back tests as secondary outcome measures. An overview of the rehabilitation program can be seen in Figure 28.

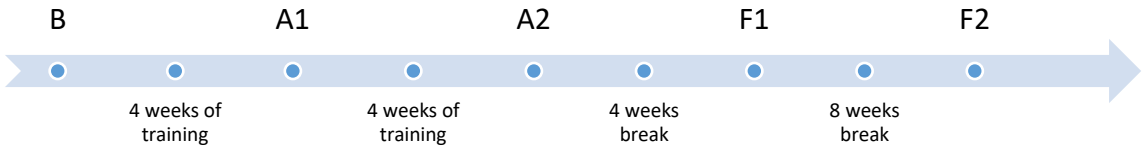


Figure 28 – Neuro-cognitive rehabilitation schedule

Testing sessions ensured that a participant received an adequate break in between each VR task of the Morris Water Maze and the Radial Arm Maze, which will be further explained in 6.5.2. This break in between the VR tasks helped reduce simulation sickness as suggested in Chapter 5. The order of the primary and secondary measures during a testing session is shown in Figure 29.

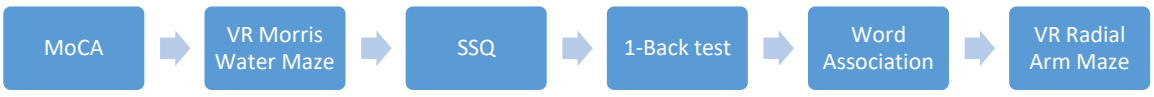
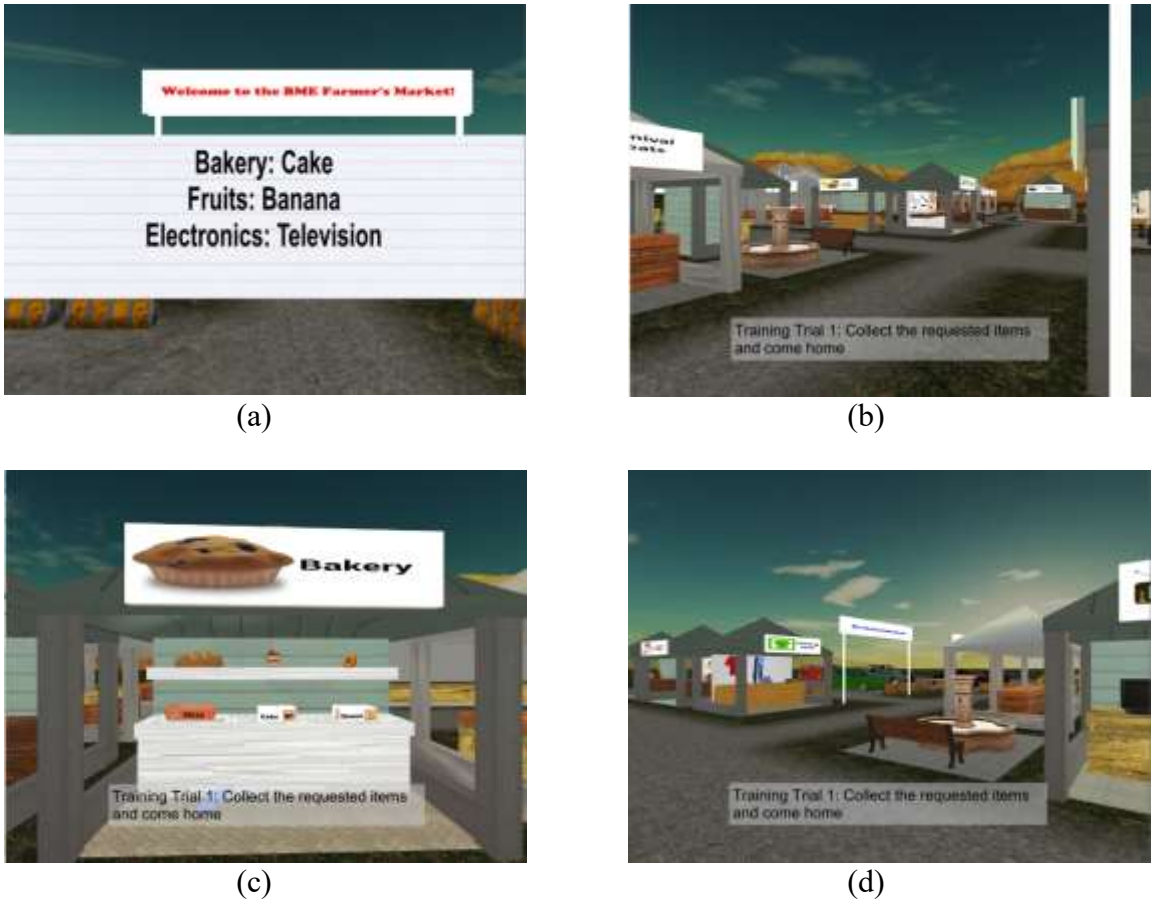


Figure 29 – Neuro-cognitive rehabilitation assessment order

6.5.1. Training Sessions

The training sessions consisted of a VR shopping task neuro-cognitive brain exercise focusing on spatial and working types of memory. These types of memory are significantly affected by old age and dementia [109]. The brain exercise utilized the Unity 5 game engine to immerse participants utilizing the VRNChair or TiltChair with an Oculus Rift CV1 in a virtual shopping district farmer's market (Figure 30 and Figure 31). In this environment, participants tried to memorize a shopping list as they navigated a path to pick up the items in order. As a participant picked up an item, a research assistant pressed the corresponding button as he or she walked beside the participant. If a participant forgot an item, or forgot the shopping path, the participant had the option to ask for a list hint or a path hint respectively.

Overall, participants received two training trials with errorless learning. Errorless learning can provide more improvements than an erroneous method, which allows a participant to freely explore around the environment to find each listed item [129]. In a training trial, a research assistant provided them visual and verbal guidance to each store. After two training trials, participants completed a test trial by executing the shopping task independently.



(a) (b)

(c) (d)

Figure 30 – Shopping district neuro-cognitive rehabilitation task

Different user views of the shopping district with shopping list, store layout and store front with items
(a) Start of task with shopping list (b) View of shopping district (c) Store front with items (d) End of task back at entrance

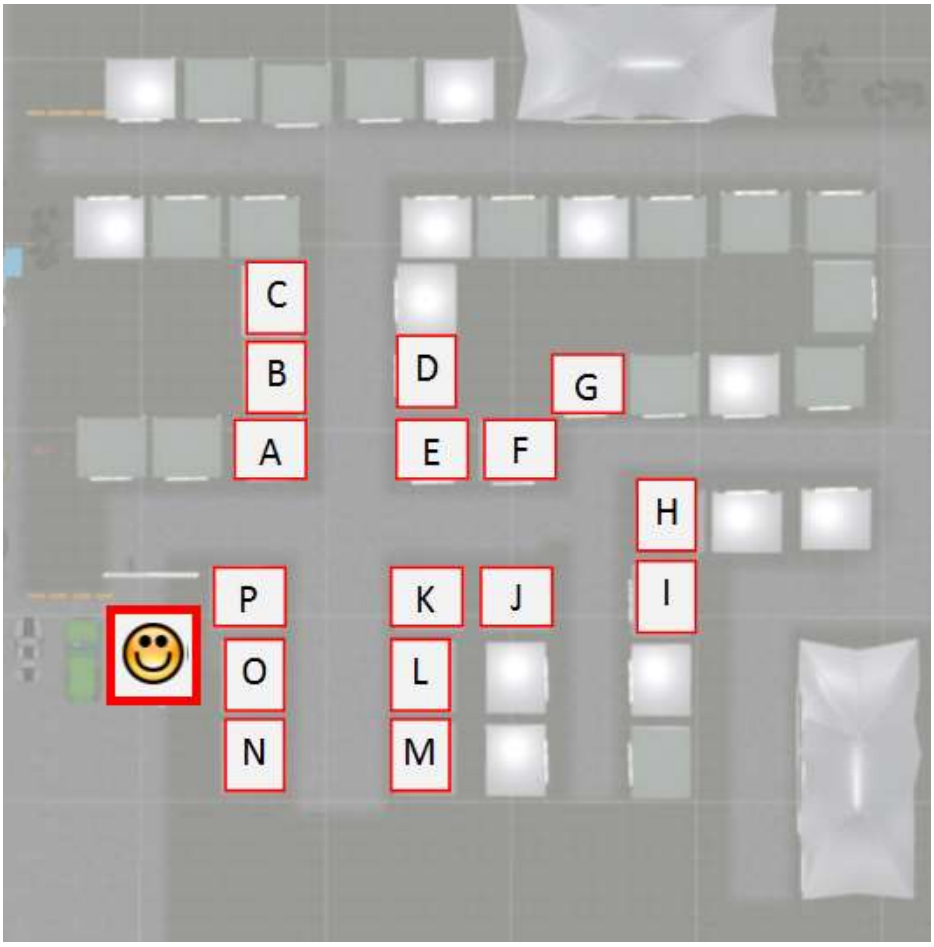


Figure 31 – Virtual shopping district map
The shopping district with store layout. Each letter indicates a possible store location that may be included in a shopping list training task.

A shopping task's difficulty changed due to a participant finding the task too easy or too difficult. A task being too easy meant a participant can perform three consecutive errorless individual task test trials; hence, the shopping task increased in difficulty by increasing the shopping list by one item. However, a task being too difficult meant a participant required a list hint or path hint, or they forgot an item for more than half of the previous session's tasks; hence, the shopping task decreased in difficulty by decreasing the shopping list by one item. To describe a participant's overall performance, a score was derived from a weighted sum, which included the number of correct items picked up in order and the number of errors (incorrect item, forgotten item, or required a hint). We selected the weighting coefficients to reward more points for remembering to pick up list items in the correct order and to penalize more points for entering an incorrect store, selecting an incorrect item or requiring a hint. We allowed participants to prematurely stop the trial if they forgot a list item or they did not know where to go. The overall performance shopping task score was calculated as follows:

$$\begin{aligned} Score = {} & 2 \times (no.of\ items\ remembered\ and\ correct\ order) \\ & + (no.of\ items\ remembered\ and\ incorrect\ order) \\ & -2\ \times (\ no.of\ incorrect\ stores\ entered) \\ & -2\ \times (no.of\ incorrect\ items\ picked) \\ & -2 \times (no.of\ list\ and\ path\ hints) \end{aligned}$$

6.5.2. Testing Sessions

In addition to the VR shopping task performance, testing sessions throughout the rehabilitation program investigated the potential benefits via primary and secondary outcome measures. Primary outcome measures included the Montreal Cognitive Assessment (MoCA), and VR Morris Water and Radial Arm mazes. To complete the VR mazes, participants utilized the VRNChair or

TiltChair with the Oculus Rift CV1. Secondary measures included the research group's Word-Association and 1-Back tests. To evaluate any effects to the participants' daily routine, caregivers completed a Bayer Activities of Daily Living Scale at baseline and after the program with a documentation of their own observations. Additionally, participants completed an SSQ to observe any simulator sickness from the VR technology.

Primary Measures

Montreal Cognitive Assessment (MoCA)

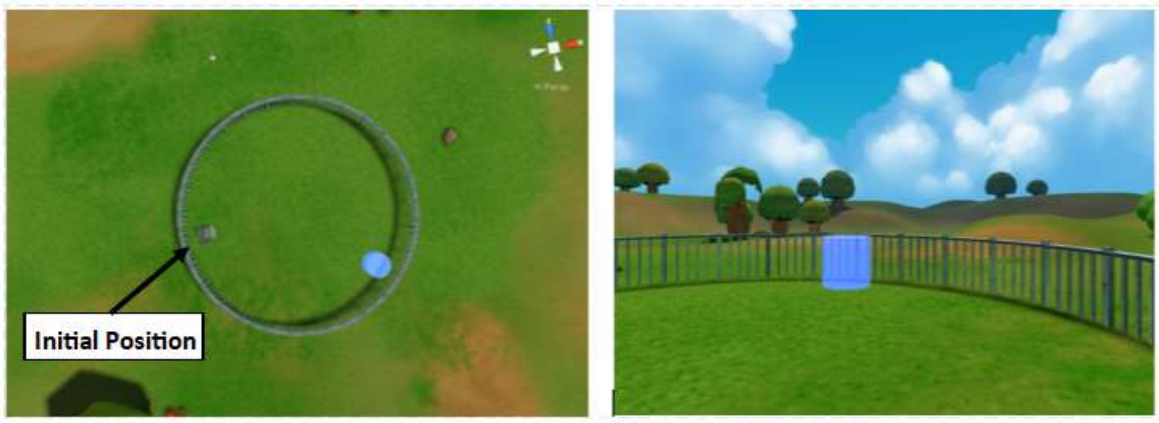
The Montreal Cognitive Assessment (MoCA) assessed a participant's cognitive ability [130]. This assessment consisted of questions that focused on different cognitive domains such as executive function, visuo-spatial ability, memory, attention, abstraction and verbal fluency. Any score below 26 indicated cognitive impairment. All participants had a baseline score below 26 to indicate some cognitive impairment to be eligible for the study. To remove any practice effects, three different English versions of the MoCA were randomized throughout the testing sessions.

Virtual Reality Morris Water Maze

During the VR Morris Water Maze, participants relied on their allocentric spatial memory and utilized the surrounding landmark cues of the environment. This had been utilized in other animal [131] and human [132] studies. In the initial Morris Water Maze animal study [133], researchers had rats swim to a submerged platform in a water tank utilizing surrounding landmark cues in the lab. In contrast, the human study recreated the Morris Water Maze utilizing VR [132]. Our virtual maze immersed participants in a circular enclosed area with surrounding geographical cues, which included trees, flowers, rocks and hills (Figure 32). The participants utilized the geographical cues to encode a visible target blue cylinder's location in the first two practice trials. Afterwards, the

target became invisible. Participants sought the invisible target based on the encoded geographical cues during five test trials with different starting positions. The maze recorded the participant's trajectories and execution times. For the data analysis, we calculated the traversed error defined as the ratio between the difference of a participant's traversed distance and optimal traversed distance to the optimal traversed distance:

$$Traversed\ error = \frac{(Participant\ traversed\ distance) - (optimal\ traversed\ distnace)}{optimal\ traversed\ dsitance}$$



(a) (b)

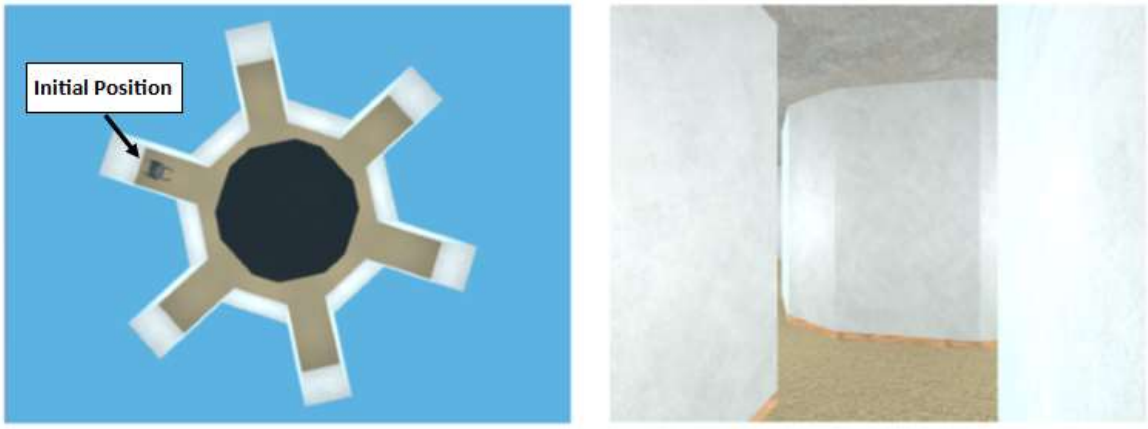
Figure 32 – Virtual Water Morris Maze
Different perspectives of the Water Morris Maze with a visible blue target cylinder. (a) Bird's eye view (b) User's view.

Virtual Reality Radial Arm Maze

During the VR Radial Arm Maze, we assessed the participants' egocentric spatial memory, which had been utilized to assess participants with amnesic mild cognitive impairment or AD [134]. The Radial Arm Maze comprised of a central circular hallway with 6 hallways branching from it (Figure 33). In the original Radial Arm Maze, users explored the various hallways to find numerous targets [134]. Since the neuro-cognitive rehabilitation program recruited participants with memory problems, we made the task easier by having participants find a single target hallway.

Initially, participants completed a practice trial as they explored each different hallway until they found the target hallway that plays music. Participants tried to memorize the direct path from

their starting hallway to the target hallway. Participants' starting location and the target's location never changed between trials. Participants continued to execute a new trial until they successfully found the target hallway directly without going into an incorrect hallway for three consecutive trials. However, a participant that completed 7 trials without a direct path to the target hallway meant he or she unsuccessfully encoded the specific path egocentrically. Thus, the Radial Arm Maze was terminated. The Radial Arm Maze recorded the participants' tracjectories, execution times and average reference memory error. The average reference memory error described the number of incorrect hallway visits divded by the total number of executed trials. Similar to the Morris Water Maze, we calculated the average traversed error distance, average execution time and average reference memory error for our data analysis.



(a) (b)

Figure 33 – Virtual Radial Arm Maze
Different perspectives of the radial arm maze. (a) Bird's eye view, (b) User's view

Secondary Measures

Word-Association Test

The Word-Association test evaluated a participant's associative memory. A past research member first developed the Word-Association test as a brain exercise to improve a participant's associative memory [8]. For the neuro-cognitive rehabilitation program's assessments, each

participant completed a separate Word-Association test to memorize the words in either the forward or backward order. First, a participant saw individual words consecutively and then the participant saw a matrix of images, which included images of the previously shown words as well as others (Figure 34). Afterwards, a participant tried to select the images in the correct order. If a participant selected the images in the correct order, the next trial's difficulty would increase with one more word. Otherwise if a participant selected the images in the incorrect order, the difficulty decreased with one less word. For our data analysis, we utilized the Word-Associate Test's total score based on the number of correct words remembered and the number of words selected in the correct order.

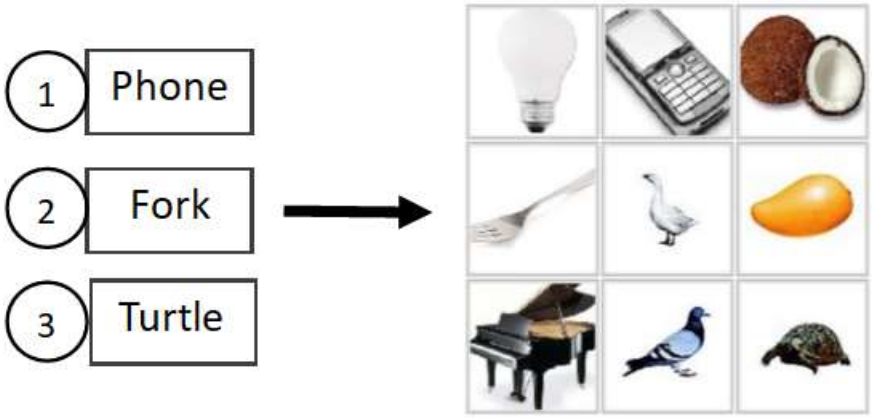
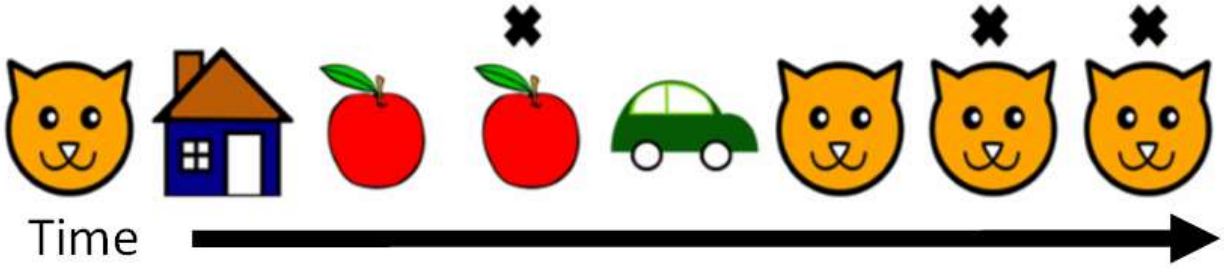


Figure 34 – Word-Association Test
Participant views a series of words and then a matrix of images that includes those words

1-Back Test

The 1-Back test evaluated the working memory and processing speed of elderly participants with mild cognitive impairment or AD in prior studies [135], [136]. Participants saw a series of individual images consecutively (Figure 35). If a participant saw that the current image matched the previous image, or the same image appeared more than two times consecutively, the participant quickly pressed the enter key. To assess a participant's cognitive processing in our data anaylsis, the 1-Back Test recorded the number of correct reactions, number of errors and reaction times.



Images in public domain. Cat by gammillian, House by Anonymous, Apple by Gerald_G and Car by oldifluff

Figure 35 – 1-Back Test
In 1-Back test, individual images are show and an 'X' indicates a correct reaction by user

Bayer Activities of Daily Living Scale

The Bayer Activities of Daily Living Scale assessed the participant's capability to execute daily living activities [137]. A participant's caregiver completed a Bayer Activities of Daily Living Scale before and after completion of the program. The caregiver rated 25 different daily living activities on a scale between a score of 1 to 10. A score of 1 described that the participant had no difficulties with the activity; while, a score of 10 described that the participant always had difficulties with the activity. Afterwards, a total score was calculated by summing all the activity ratings and then dividing by the number of activities rated. The Bayer Activities of Daily Living

scale provided a normalized value to evaluate the transfer of any effects from the neuro-cognitive rehabilitation program to activities of daily living.

Simulator Sickness

Participants completed the same SSQ [32], which has been discussed thoroughly in the previous chapters, immediately after the first VR task, the Morris Water Maze. The SSQ evaluated a participant's susceptibility to simulator sickness and ability to complete the VR shopping task. If an elderly participant developed simulator sickness after the short VR task, then this indicated that the participant would not be eligible to complete the cognitive VR training sessions.

6.6. Data Analysis

The experiment executed descriptive statistics due to the small sample size. For a proper study with comparisons between a control non-training group and a neuro-cognitive training group, power of 0.8 and medium effect size of f = 0.25, there should be a total sample size of 22 participants with 11 participants in each group as indicated with the software program GPower*.

6.7. Participants

To be eligible for the study, participants met a few criteria. They had no depression indicated with a Montgomery and Åsberg Depression Rating Scale score below 6 [138], had been diagnosed with early onset of AD or had memory problems indicated with a MoCA below 26, and were physically capable of utilizing the different VR technologies. Afterwards, eligible participants provided consent to this study approved by the University of Manitoba Biomedical Research Ethics Board.

Overall, four participants (3 males and 1 female) between the ages of 67 to 87 completed the neuro-cognitive rehabilitation program with two follow-up assessments. Seven other participants

completed the baseline assessment, but they had different reasons for their withdrawals. Two participants developed simulator sickness while utilizing the VR technology. Another two participants did not have any cognitive issues because their MoCA scores were 27/30. Two participants quit because they did not enjoy the neuro-cognitive rehabilitation program. Lastly, one participant attended less than half the rehabilitation training sessions and her data was not included in the results. Table 14 summarizes the participants' demographics, the amount of training that the participants completed and the locomotive controller the participants utilized throughout the program. Most participants utilized the VRNChair, but one participant utilized the TiltChair because he had no issues with the TiltChair in terms of simulator sickness and intuitiveness.

Table 14 – Neuro-cognitive rehabilitation's participant demographics

Participant	Sex	Age	Baseline MoCA Score	VR Locomotive Controller	Amount Completed
S1	M	75	24	TiltChair	92%
S2	M	67	25	VRNChair	79%
S3	F	87	22	VRNChair	88%
S4	M	79	20	VRNChair	88%

Amount completed indicates the amount of training sessions completed

6.8. Results

The results among all primary and secondary measures produced incongruent results. Every participant either improved or declined on the VR shopping task and the different assessments. Due to the small sample size, we could not perform any statistical analysis for the MoCA, Morris Water Maze, Radial Arm Maze, Word-Association and 1-Back Test performances.

6.8.1. Shopping Task

For the VR shopping task, the participants' performances are shown in Figure 36 with their average weekly score. Generally, participants improved their scores throughout the entire rehabilitation program. The general trend lines had various R^2 values ranging from 0.48 to 0.88.

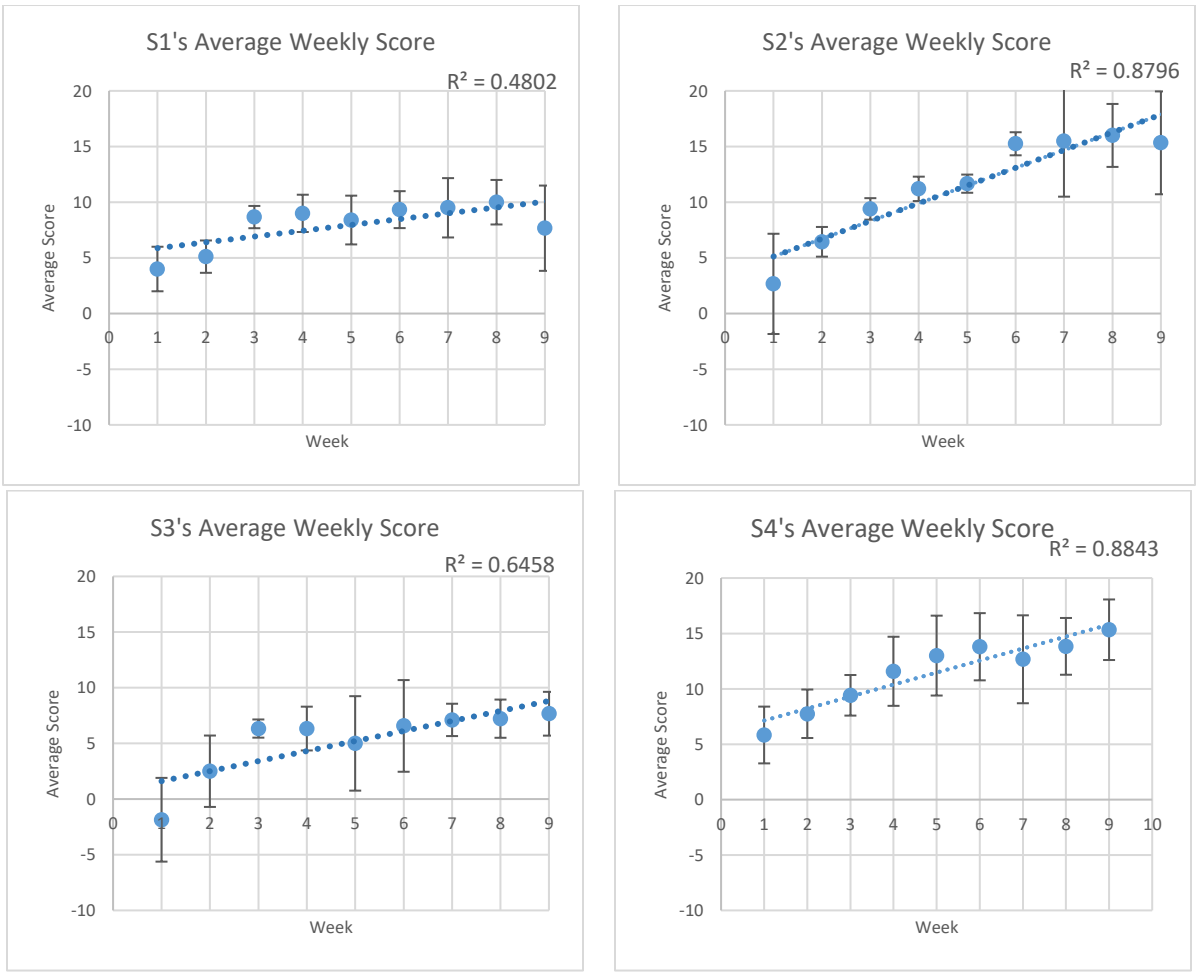


Figure 36 – Participant's shopping task performances
The average weekly score with standard deviation bars for each point and the R^2 values.

6.8.2. Primary Measures

Montreal Cognitive Assessment Score

For the MoCA, Table 15 shows all the participants' scores throughout the program. After completing all the training sessions at Assessment 2, S2 and S4 increased their MoCA scores, S1 did not change in MoCA score and S3 decreased in MoCA score. Overall, only S4 had consistent MoCA score throughout his participation in the neuro-cognitive program and follow-up sessions.

Table 15 – MoCA scores

Participant	Baseline	Assessment 1	Assessment 2	Follow-up 1	Follow-up 2
S1	24	22	24	24	22
S2	25	24	26	24	21
S3	22	23	20	22	22
S4	20	25	24	24	26

Morris Water Maze

For the VR Morris Water Maze, Table 16 and Table 17 show the participant's traversed error and execution time respectively. At the end of the rehabilitation program and during Assessment 2, only S2 and S3 on average were more efficient to find the targets with a shorter execution time. However, at the last Follow-up, only S2 and S4 decreased their average traversed error and execution time compared to their baseline testing session.

Table 16 – Morris Water Maze average trial traversed error

Participant	Baseline	Assessment 1	Assessment 2	Follow-up 1	Follow-up 2
S1	0.02 ± 0.03	0.22 ± 0.22	1.95 ± 3.38	1.38 ± 1.32	7.95 ± 7.36
S2	4.75 ± 2.87	1.07 ± 1.52	2.15 ± 2.72	0.92 ± 1.20	2.05 ± 1.72
S3	1.54 ± 1.66	0.88 ± 1.09	0.76 ± 0.62	5.39 ± 5.61	2.19 ± 1.88
S4	2.60 ± 4.17	2.73 ± 1.57	5.63 ± 3.79	0.81 ± 0.08	1.77 ± 1.72

All mean values with their standard deviations are in meters

Table 17 – Morris Water Maze average trial execution time

Participant	Baseline	Assessment 1	Assessment 2	Follow-up 1	Follow-up 2
S1	48.61 ± 10.95	40.43 ± 8.76	55.58 ± 26.61	38.97 ± 14.11	171.56 ± 63.48
S2	141.66 ± 11.07	46.66 ± 53.81	34.93 ± 27.28	18.91 ± 8.09	34.94 ± 31.48
S3	77.66 ± 57.01	59.07 ± 29.80	50.51 ± 36.33	114.57 ± 73.92	109.23 ± 80.79
S4	54.10 ± 33.97	69.56 ± 47.82	58.70 ± 11.10	24.55 ± 6.43	38.47 ± 26.47

All mean values with standard deviation are in seconds

Radial Arm Maze

For the VR Radial Arm Maze, Table 18 and Table 19 show the participant's traversed error and execution time respectively. At the end of the rehabilitation program, all participants decreased their traversed errors and decreased their execution time. They efficiently traversed at shorter distances to the target with a shorter execution time. However, at the last Follow-up 2, S1 and S3 traversed at a longer distance to find the target. Also, S3 had to stop after the 5th trial because she started to feel dizzy.

Table 18 – Radial Arm Maze average trial traversed error

Participant	Baseline	Assessment 1	Assessment 2	Follow-up 1	Follow-up 2
S1	0.05 ± 0.01	0.10 ± 0.01	0.09 ± 0.01	0.11 ± 0.01	0.60 ± 0.62
S2	1.27 ± 0.30	0.18 ± 0.02	0.30 ± 0.24	0.89 ± 0.02	0.30 ± 0.23
S3	1.04 ± 0.59	1.28 ± 0.97	0.88 ± 0.05	3.42 ± 3.49	2.57 ± 0.18
S4	0.42 ± 0.28	0.18 ± 0.03	0.18 ± 0.004	1.04 ± 0.33	0.22 ± 0.01

All mean values with standard deviation are in meters

Table 19 – Radial Arm Maze average trial execution time

Participant	Baseline	Assessment 1	Assessment 2	Follow-up 1	Follow-up 2
S1	57.48 ± 5.14	33.26 ± 8.30	33.87 ± 5.10	25.24 ± 1.21	34.63 ± 12.17
S2	42.70 ± 11.75	15.82 ± 1.14	21.29 ± 1.16	22.74 ± 1.13	19.64 ± 5.37
S3	97.57 ± 35.59	80.13 ± 40.84	36.39 ± 5.32	79.98 ± 63.53	95.58 ± 10.62[1]
S4	41.99 ± 21.43	18.30 ± 0.83	17.53 ± 1.22	22.68 ± 5.11	18.16 ± 0.67

All mean values with standard deviation are in seconds. [1]Participant S3 had to stop after 5th trial because she started to feel dizzy.

Additionally, Table 20 shows the participants' reference memory error. Only S4 reference memory error increased at the last Follow-up. In contrast, other participants' reference memory errors did not change with a score near zero. A score of zero meant that these participants could remember the path to the target hallway for at least three consecutive trials.

Table 20 – Radial Arm Maze average trial reference memory error

Participant	Baseline	Assessment 1	Assessment 2	Follow-up 1	Follow-up 2
S1	0	0	0	0	0.4
S2	0.33	0	0.25	0	0.25
S3	1	1.83	1	2.67	3
S4	0.5	0	0	0.25	0

6.8.3. Secondary Measures

Word-Association

For the Word-Association test, Figure 37 and Figure 38 show the participant's forward and backward scores respectively. At the end of the rehabilitation program, only S4 had decreased word association scores compared to baseline. The other participants increased their word association scores compared to baseline. At the last Follow-up, S1 and S4 had an increased forward score compared to baseline, plus S2 and S3 increased their backward scores compared to baseline.

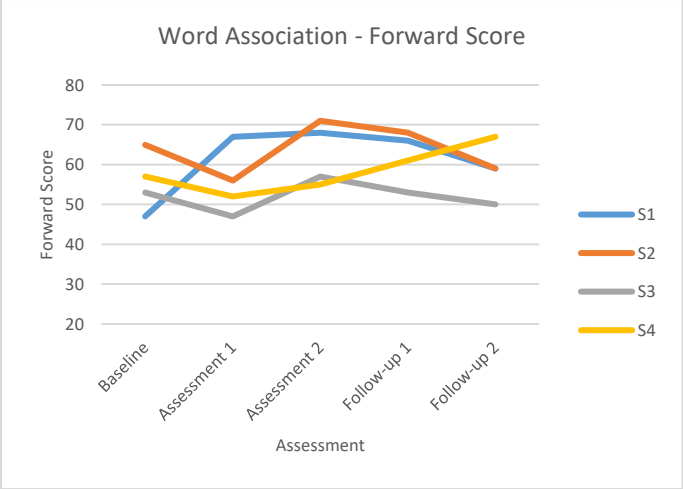


Figure 37 – Word-Association forward score

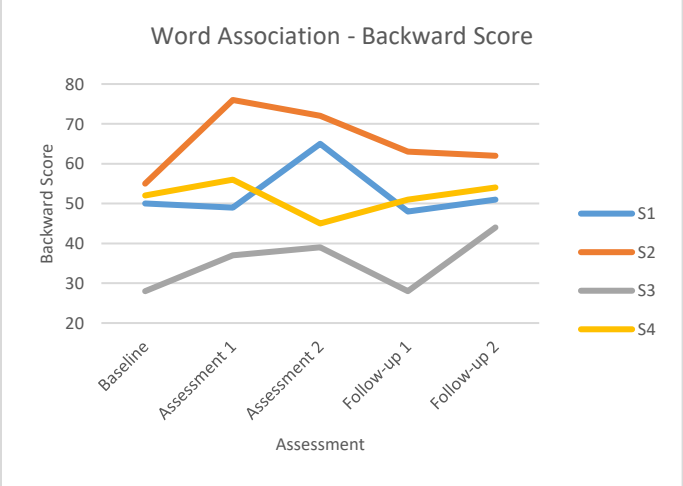


Figure 38 – Word-Association backward score

1-Back Test

For the 1-Back Test, the average reaction time did not significantly vary between baseline and all other assessments. Participants on average had a reaction time of 490 ms. The participants could identify at least 6 correct reactions.

Bayer Activities of Daily Living Scale

Caregivers completed a Bayer Activities of Daily Living Scale at baseline before and after the program. These scores did not largely differ before and after the program. Only S4's caregiver provided a 5-point improvement, while the other participants' scores only differed by about one point. Overall, the caregivers did not notice any significant changes to the participants and provided the following comments:

- S1: There were no noticeable changes. He did not enjoy the rehabilitation program because he disliked shopping. The participant was also executing the research group's brain exercises at the same time of the program that may have affected his assessment scores.
- S2: There were no changes. Partner described that his logic has declined. During the program, he recently moved to a new home that may have had affected his performance in the study.
- S3: There were no significant changes. During the program, she was more engaged in life because she went out 3 times a week. After last follow-up assessment, she felt more anxious to leave her home, forgot more easily and felt more overwhelmed with daily activities.

- S4: There was a noticeable change in the participant's behaviour, but not his memory. He felt happier, not stressed about his memory problems and more comfortable with his daughter.

6.8.4. Simulator Sickness

There were zero incidents of severe simulator sickness with zero participants prematurely quitting a training session. On average, the participants had an SSQ total score of 54.77 after completing the VR Morris Water Maze. However, S3 complained that the HMD made her dizzy after a short acclimatization period. To reduce her simulator sickness, she completed the VR shopping task, Morris Water Maze and Radial Arm Maze with the VRNChair while she viewed the virtual environment on the laptop display.

Summary of Participant Results

Overall, participants had variable performances with the assessments. Table 21,Table 22 and Table 23 summarize the improvements or diminishments in performance compared to baseline for the MoCA scores and the Word Association forward and backward scores. For these scores, a more than 1-point increase or decrease on a participant's Assessment 2, Follow-up 1 or Follow-up 2 scores meant participants improved or diminished from their baseline scores. Alternatively, scores with only a 1-point change from their baseline scores meant participants had no changes to their baseline scores.

Table 21 – Summary of MoCA scores

Participant	Assessment 2	Follow-up 1	Follow-up 2
S1	–	–	▼
S2	–	–	▼
S3	▼	–	–
S4	▲	▲	▲

–: No changes, ▲: improvement, ▼: decline

Table 22 – Summary of Word-Association forward scores

Participant	Assessment 2	Follow-up 1	Follow-up 2
S1	▲	▲	▲
S2	▲	▲	▼
S3	▲	–	▼
S4	▼	▲	▲

–: No changes, ▲: improvement, ▼: decline

Table 23 – Summary of Word-Association backward scores

Participant	Assessment 2	Follow-up 1	Follow-up 2
S1	▲	▼	–
S2	▲	▲	▲
S3	▲	–	▲
S4	▼	–	▲

–: No changes, ▲: improvement, ▼: decline

6.9. Discussion

In this study, we investigated the utilization of mental stimulation with an immersive neuro-cognitive training VR shopping task for participants with memory problems. To resolve these memory problems, participants completed an 8-week neuro-cognitive rehabilitation training program focusing on spatial and working types of memory. However, the results are inconclusive due to small sample size. Therefore, the discussion describes some observations based on only one participant that had severe simulator sickness. Overall, all the participants found the VR shopping task intuitive and improved their shopping task performance.

Only one participant (S3) experienced severe simulator sickness when utilizing the VRNChair with an Oculus Rift CV1 HMD that she completed the entire program with a laptop display instead of the HMD. This participant's simulator sickness may have been due to her pre-existing conditions, the HMD immersion and the VRNChair decoupling mode. S3 had vestibular issues and cataracts. She described taking medications and performing vestibular exercises to help reduce her regular bouts of dizziness. Moreover, she had cataracts without any corrective glasses that diminished her vision and caused her to see blurry images. With these pre-existing conditions, the

participant utilizing the HMD further mismatched the visual motion stimuli via the removal of accommodation-vergence reflex and peripheral vision (See 5.5). Therefore, S3 found the HMD uncomfortable and said it made her feel dizzy.

Additionally, her simulator sickness may have developed from the VRNChair's decoupling mode. During decoupling mode, a research assistant paused and turned the participant away from a physical obstacle (as described in VRNChair with Oculus Rift DK2). Since the physical space was too small for the VR shopping task, the participant experienced many decoupling modes. Even though the participant received some visual stimuli from a video feed of the physical space during her rotation, the participant had no control over her own movement that led to a nauseating feeling.

To reduce the above effects of simulator sickness, S3 completed the VR shopping task, Morris Water Maze, and Radial Arm Maze utilizing the laptop display with numerous of breaks (as suggested in the previous chapter). S3 could not use the HMD during a short acclimatization trial to become familiar with the VR technology because she complained about simulator sickness. Thus, she utilized the laptop display for her entire participation in the rehabilitation program. Also, the participant independently rotated herself away from obstacles during decoupling mode. Therefore, she had control over her own movement to receive sensory matching motion stimuli that reduced her simulator sickness during the VR tasks.

Throughout the neuro-cognitive rehabilitation's VR tasks, all participants found our VR shopping task to be intuitive and naturalistic. Participants easily utilized the VRNChair manual wheelchair joystick as described in the previous Chapter 5. Also, one participant found the TiltChair intuitive to utilize and did not develop any simulator sickness. To minimize any struggles when utilizing the VR technology, participants learned how to navigate and manipulate items with

the VRNChair or TiltChair before executing any VR tasks. This opportunity allowed participants to focus on the task for any possible improvements in their cognition or memory.

At the end of the neuro-cognitive rehabilitation program, participants improved their shopping task performances focused on spatial and working types of memory. Similar results with other cognitive and physical integrative programs had improved working memory [139] and navigation [140]. Our participants utilized naturalistic locomotive VR technology to interact with a realistic environment. This suggests that VR tasks may provide the same benefits as a naturalistic environment. The benefits of VR tasks can provide future research with easy manipulation on the task environment. VR can be designed with various difficulties to provide continuous mental stimulation and further cognitive improvements.

6.10. Limitations

Despite VR being a potential tool for neuro-cognitive training, our current program only had small insignificant cognitive improvements. This may have derived from users developing simulator sickness that led to short mental stimulation. Each participant executed at least 3 different shopping tasks in about 45 minutes. This training time was selected to reduce any simulator sickness because severity increases with VR exposure time [52] as well as noted in the previous chapters. To further reduce simulator sickness, participants took breaks throughout the sessions. These breaks disrupt the mental stimulation of the neuronal pathway responsible for spatial and working types of memory. To induce plasticity within the brain, mental stimulation should last 30 to 60 minutes [141]. To minimize simulator sickness and optimize mental stimulation, future VR cognitive and physical tasks should have a short execution time for numerous tasks in a session. Participants in our program did not have the benefit to complete

numerous tasks because a single task took too much time and they required breaks to minimize simulator sickness; thus, the participants only had small improvements.

Additional mental stimulation depends on the difficulty of the training task. All participants were highly functional with three participants living independently and one participant living with his wife. Some may argue that they did not have any mild cognitive impairment, but only memory complaint because the studies in [142], [143] indicated a MoCA cut-off score of 26 was too high. Also, we designed the VR shopping task for individuals at an early stage of AD. Therefore, the VR shopping task may have been too easy for our recruited participants with only memory problems. To provide continuous mental stimulation, a neuro-cognitive rehabilitation program should have challenging brain exercises that focus on different cognitive functionalities with varying difficulties.

Moreover, participants could have significant cognitive or memory improvements by learning and practicing different strategies to aid their diminished spatial and working types of memory. For instance, in the ACTIVE study participants practiced categorizing items in meaningful categories, organizing main ideas and visualization and associating items to be remembered that led to significant effects lasting up to 10 years [125], [127]. For our VR shopping task, navigational strategies may include map utilization and mental representation of the path [140]. A memorization strategy may include visual imagery that was utilized by one of our participants. He tried to remember the shopping list by visualizing an entire picture that contains all the listed items. By having participants practice different strategies during the VR shopping task, the participants may transfer these strategies into their daily routine.

Additionally, the program's small memory effects during a short time period may have been inadequately measured by the MoCA test. The MoCA test assessed different cognitive

functionalities. However, the VR shopping task focused on spatial and working types of memory. Instead of utilizing the MoCA, the program should have utilized the Weschler Memory Scale [144] that assesses different types of memory. The Weschler Memory Scale would allow us to observe any potential improvements to a participant's memory.

Overall, our small sample size did not fully investigate the effects of a neuro-cognitive rehabilitation program. This study suggests that VR can be utilized with elderly participants. To investigate any potential significant memory effects, we required a larger sample size of 22 participants with a statistical power of 0.8. It was difficult to recruit participants due to a lack of time, funds and availability of a physical space. Additionally, the participant performances were influenced by their disinterests, simulator sickness and logistics of the elderly. To increase recruitment, the neuro-cognitive rehabilitation training's brain exercises should be executed through an application for a tablet or a smart phone because most of the general population does not have access to VR technology. Thus, the neuro-cognitive training would be easily accessible to more participants with memory problems as they complete mentally challenging and engaging brain exercises.

6.11. Summary

This chapter discussed a VR neuro-cognitive rehabilitation application. Four participants completed an 8-week program (3 sessions per week) with training and testing sessions. Three participants found the VRNChair intuitive to utilize, while one participant found the TiltChair intuitive to utilize. For simulator sickness, only one participant developed such severe symptoms that she utilized a laptop display instead of a HMD with the VRNChair. Overall, the small sample size of our study provided inconclusive results and provided only speculations. The rehabilitation

program effects may have been influenced by participant disinterests, simulator sickness and logistics of the elderly. To investigate the benefits of a VR neuro-cognitive rehabilitation program, the shopping task should be redesigned to minimize simulator sickness and to optimize mental stimulation.

CHAPTER 7 – Conclusion and Future Works

7.1. Conclusion

Researchers utilize innovative VR technologies during experiments to investigate psychological human behavior in a naturalistic environment with controlled settings. However, current VR technology has common pitfalls including user simulator sickness and controller intuitiveness that contributes to a participant's overall performance. To reduce simulator sickness, this thesis investigated different motion stimuli combinations by participants utilizing locomotive controllers with an HMD. Initially, young adult participants selected the TiltChair as the most uncomfortable locomotive controller in terms of simulator sickness (Experiment 1). The increased simulator sickness may have derived from asynchronous rotation between a participant's neck and torso. Therefore, Experiment 2 investigated the effects of synchronous neck rotation by participants utilizing the TiltChair with a neck brace. Afterwards, participants significantly reduced simulator sickness with the TiltChair and neck brace by synchronizing the rotation (vestibular stimuli) and HMD updates (visual stimuli). To reduce simulator sickness further, short VR exposure times with numerous breaks should be applied. Overall, the joystick and TiltChair had the highest level of intuitiveness and the omni-directional treadmill had the lowest level of intuitiveness among the young adult participants. For an optimal VR experience, the VRNChair allowed young adult and elderly participants to easily navigate throughout an environment with little simulator sickness. Thus, researchers should consider their target sample population's susceptibilities to develop simulator sickness and capabilities to utilize VR technology.

The latter half of the thesis investigated the feasibility of utilizing VR in a neuro-cognitive training application with participants who had memory problems. Four participants completed the

8-week program utilizing a VR shopping task. The results suggested that VR can be utilized among elderly participants because our participants found the VR shopping task with the VRNChair, or TiltChair to be intuitive. However, we had a small sample size with insignificant effects on their memory problems. For a larger sample population with low attrition rates, researchers should investigate different neuro-cognitive training applications via VR, smartphone, tablet, computer and paper-and-pen brain exercises.

7.2. Future Work

The investigation of locomotive controllers (TiltChair, omni-directional treadmill, VRNChair and joystick) with a HMD insignificantly differed with their effects on a user's simulator sickness and its own intuitiveness among young adult participants. However, more participants developed simulator sickness utilizing the VRNChair with an Oculus Rift DK2 in comparison to the VRNChair with a laptop display (discussed in Observations in our Other Studies). To reduce simulator sickness among participants, future studies should investigate the effects of HMD with participants. Moreover, to reduce simulator sickness, the VRNChair's decoupling mode needs to be replaced by a better solution to minimize interference with the VR task. To minimize this interference, the decoupling mode could be removed if a virtual environment fits inside the VR physical play space or the VRNChair implements an algorithm similar to redirected walking [98].

In contrast, the investigation of a neuro-cognitive rehabilitation program utilizing a VR shopping exercise with a small sample size suggests that the training may be ineffective due to participant's disinterest, simulator sickness and logistics of the elderly. New brain exercises should be designed for better engagement and enjoyment with strategy learning to mentally challenge a participant. Further recruitment could increase through the ease of accessibility by providing brain exercises on a tablet or smart phone application that can be executed at the participant's home.

Therefore, future studies may investigate any differences between a tablet, or smart phone application to a VR brain exercise.

7.3. Summary

In summary, the main points from the current thesis are:

- Participants that receive vestibular, visual and proprioceptive matching motion stimuli and timely breaks during a VR task help reduce the participants' simulator sickness.
- Participants found the VRNChair with a HMD intuitive to utilize.
- When we compare young adults to elderly participants regarding simulator sickness elderly participants had more severe simulator sickness while utilizing the VRNChair with HMD. Thus, future studies need to investigate the effects of a HMD with elderly participants.
- The decoupling mode needs to be replaced with a solution that minimizes VR interference such as scaling the environment to fit in the physical space or implementing a directed walking method.
- Participants enrolled in our VR neuro-cognitive rehabilitation program had insignificant or zero improvements in the primary and secondary outcome measures. Future studies should investigate the utilization of brain exercises on a tablet or smart phone.

References

[1] O. R. Pouya, A. Byagowi, D. M. Kelly, and Z. Moussavi, "Introducing a new age and cognition-sensitive measurement for assessing spatial orientation using a landmark-less virtual reality navigational task," *The Quarterly Journal of Experimental Psychology*, vol. 70, no. 7, pp. 1406–1419, 2017.

[2] A. Byagowi and Z. Moussavi, "Design of a virtual reality navigational (VRN) experiment for assessment of egocentric spatial cognition," *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, San Diego, CA, pp. 4812–4815, 2012.

[3] P. J. White and Z. Moussavi, "Neurocognitive treatment for a patient with Alzheimer's disease using a virtual reality navigational environment," *Journal of Experimental Neuroscience*, vol. 10, pp. 129–135, 2016.

[4] A. Byagowi, D. Mohaddes, and Z. Moussavi, "Design and application of a novel virtual reality navigational technology (VRNchair)," *Journal of Experimental Neuroscience*, vol. 8, no. 1, pp. 7–14, 2014.

[5] P. J. White, A. Byagowi, and Z. Moussavi, "Effect of viewing mode on pathfinding in immersive virtual reality," in *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Milan, 2015, pp. 4619–4622.

[6] M. Prince, A. Wimo, M. Guerchet, G. C. Ali, Y. T. Wu, and M. Prina, "World Alzheimer Report 2015," Alzheimer's Disease International, London, UK, 2015.

[7] G. Rutherford, B. Lithgow, and Z. Moussavi, "Short and long-term effects of rTMS treatment on Alzheimer's disease at different stages: A pilot study," *Journal of Experimental Neuroscience*, vol. 9, pp. 43–51, 2015.

[8] M. T. Garcia Campuzano, "Investing the effect of associative memory exercises in aging population," M.Sc. thesis, Department of Biomedical Engineering, University of Manitoba, WPG, MB, 2015.

[9] M. L. Heilig, "Sensorama simulator," US Patent 3050870A, Jan 10, 1962.

[10] I. E. Sutherland, "A head-mounted three dimensional display," in *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, part I*, San Francisco, CA, 1968, pp. 757–764.

[11] Oculus VR. (2018). "Oculus Best Practices," Oculus VR, Menlo Park, CA [Online]. Available: http://static.oculus.com/documentation/pdfs/intro-vr/latest/bp.pdf. [Accessed: 08-Aug-2018].

[12] S. Buckley, "This is how Valve's amazing lighthouse tracking technology works," *Gizmodo*, 2015. [Online]. Available: http://gizmodo.com/this-is-how-valve-s-amazing-lighthouse-tracking-technol-1705356768. [Accessed: 08-Aug-2018].

[13] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey, "Point & teleport locomotion technique for virtual reality," in *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*, Austin, TX, 2016, pp. 205–216.

[14] N. A. Skopp, D. J. Smolenski, M. J. Metzger-Abamukong, A. A. Rizzo, and G. M. Reger, "A pilot study of the VirtuSphere as a virtual reality enhancement," *International Journal of Human-Computer Interaction*, vol. 30, no. 1, pp. 24–31, 2014.

[15] L. Rebenitsch and C. Owen, "Review on cybersickness in applications and visual displays," *Virtual Reality*, vol. 20, no. 2, pp. 101–125, 2016.

[16] K. L. Koch and W. L. Hasler, *Nausea and Vomiting*. Cham, Switzerland: Springer

International Publishing, 2017.
[17] I. M. Lang, S. K. Sarna, and R. Shaker, “Gastrointestinal motor and myoelectric correlates of motion sickness,” *American Journal of Physiology-Gastrointestinal and Liver Physiology*, vol. 277, no. 3, pp. G642–G652, 1999.
[18] S. Ueno, N. Matsuki, and H. Saito, “Suncus murinus as a new experimental model for motion sickness,” *Life Sciences*, vol. 43, pp. 413–420, 1988.
[19] M. Igarashi, K. Kobayashi, W. B. Kulecz, and T. Himi, “Change in susceptibility to vestibular-visual conflict sickness in monkeys by repeated exposure,” *Acta Oto-Laryngologica*, vol. 102, no. 5–6, pp. 432–437, 1986.
[20] Y. L. Cai, J. Q. Wang, X. M. Chen, H. X. Li, M. Li, and J. S. Guo, “Decreased Fos protein expression in rat caudal vestibular nucleus is associated with motion sickness habituation,” *Neuroscience Letters*, vol. 480, no. 1, pp. 87–91, 2010.
[21] S. Cannas and M. Evangelista, “An epidemiology study on travel anxiety and motion sickness,” *Journal of Veterinary Behavior: Clinical Applications and Research*, vol. 5, no. 1, pp. 25–26, 2010.
[22] M. S. Dennison, A. Z. Wisti, and M. D’Zmura, “Use of physiological signals to predict cybersickness,” *Displays*, vol. 44, pp. 42–52, 2016.
[23] S. M. Ebenholtz, M. M. Cohen, and B. J. Linder, “The possible role of nystagmus sickness: A hypothesis,” *Aviation, Space and Environmental Medicine*, vol. 65, no. 11, pp. 1032–1035, 1994.
[24] G. E. Riccio and T. A. Stoffregen, “An ecological theory of motion sickness and postural instability,” *Ecological Psychology*, vol. 3, no. 3, pp. 195–240, 1991.
[25] J. T. Reason, “Motion sickness adaptation: A neural mismatch model,” *Journal of the Royal Society of Medicine*, vol. 71, no. 11, pp. 819–829, 1978.
[26] M. Treisman, “Motion sickness: An evolutionary hypothesis,” *Science*, vol. 197, no. 4302, pp. 493–495, Jul. 1977.
[27] N. L. Strominger, R. J. Demarest, and L. B. Laemle, *Noback’s Human Nervous System, Seventh Edition*. Totowa, NJ: Humana Press, 2012.
[28] D. M. Johnson, “Introduction to and review of simulator sickness research,” U.S. Army Rsearch Institute for the Behavioral and Social Sciences, Fort Rucker, AL, Research Report Number 1832, 2005.
[29] C. Lopez, “A neuroscientific account of how vestibular disorders impair bodily self-consciousness,” *Frontiers in Integrative Neuroscience*, vol. 7, p. 91, 2013.
[30] M. E. Shinder and S. D. Newlands, “Sensory convergence in the parieto-insular vestibular cortex,” *Journal of Neurophysiology*, vol. 111, no. 12, pp. 2445–2464, 2014.
[31] K. L. Koch, “Physiology of Nausea,” in *Nausea and Vomiting: Diagnosis and Treatment*, K. L. Koch and W. L. Hasler, Eds. Cham, Switzerland: Springer International Publishing, 2017, pp. 1–13.
[32] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, “Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness,” *The International Journal of Aviation Psychology*, vol. 3, pp. 203–220, 1993.
[33] R. J. Reed-Jones, L. A. Vallis, J. G. Reed-Jones, and L. M. Trick, “The relationship between postural stability and virtual environment adaptation,” *Neuroscience Letters*, vol. 435, no. 3, pp. 204–209, 2008.
[34] E. Sinitski, A. A. Thompson, P. C. Godsell, J. L. Honey, and M. Besemann, “Postural stability and simulator sickness after walking on a treadmill in a virtual environment with

a curved display," *Displays*, vol. 52, pp. 1–7, 2018.
[35] A. J. A. Lubeck, J. E. Bos, and J. F. Stins, "Motion in images is essential to cause motion sickness symptoms, but not to increase postural sway," *Displays*, vol. 38, pp. 55–61, 2015.
[36] J. T. Reason, "Motion sickness: Some theoretical and practical considerations," *Applied Ergonomics*, vol. 9, no. 3, pp. 163–167, 1978.
[37] J. F. Golding, "Motion sickness susceptibility," *Autonomic Neuroscience: Basic and Clinical*, vol. 129, no. 1, pp. 67–76, 2006.
[38] J. Munafo, M. Diedrick, and T. A. Stoffregen, "The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects," *Experimental Brain Research*, vol. 235, no. 3, pp. 889–901, 2017.
[39] B. Keshavarz, R. Ramkhalawansingh, B. Haycock, S. Shahab, and J. L. Campos, "Comparing simulator sickness in younger and older adults during simulated driving under different multisensory conditions," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 54, pp. 47–62, 2018.
[40] K. S. Hale and K. M. Stanney, *Handbook of Virtual Environments: Design, Implementation, and Applications*, 2nd ed. Boca Raton, FL: CRC Press, 2014.
[41] J. F. Golding, "Predicting individual differences in motion sickness susceptibility by questionnaire," *Personality and Individual Differences*, vol. 41, no. 2, pp. 237–248, 2006.
[42] F. Schmäl, "Neuronal mechanisms and the treatment of motion sickness," *Pharmacology*, vol. 91, no. 3–4, pp. 229–241, 2013.
[43] A. Brainard and C. Gresham, "Prevention and treatment of motion sickness," *American Family Physician*, vol. 90, no. 1, pp. 41-16, 2014.
[44] Z. Nachum, A. Shupak, and C. R. Gordon, "Transdermal scopolamine for prevention of motion sickness: Clinical pharmacokinetics and therapeutic applications," *Clinical Pharmacokinetics*, vol. 45, no. 6, pp. 543–566, 2006.
[45] H. Chu, M.-H. Li, Y.-C. Huang, and S.-Y. Lee, "Simultaneous transcutaneous electrical nerve stimulation mitigates simulator sickness symptoms in healthy adults: A crossover study," *BMC Complementary and Alternative Medicine*, vol. 13, no. 1, p. 84, 2013.
[46] G. Galvez-Garcia, M. Hay, and C. Gabaude, "Alleviating simulator sickness with galvanic cutaneous stimulation," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 57, no. 4, pp. 649–657, 2015.
[47] J. G. Reed-Jones, R. J. Reed-Jones, L. M. Trick, R. Toxopeus, and L. A. Vallis, "Comparing techniques to reduce simulator adaptation syndrome and improve naturalistic behaviour during simulated driving," in *Proceedings of the Fifth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, Big Sky, MT, 2009, pp. 276–283.
[48] M. J. Cevette *et al.*, "Oculo-vestibular recoupling using galvanic vestibular stimulation to mitigate simulator sickness," *Aviation Space and Environmental Medicine*, vol. 83, no. 6, pp. 549–555, 2012.
[49] S. Sharples, S. Cobb, A. Moody, and J. R. Wilson, "Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems," *Displays*, vol. 29, no. 2, pp. 58–69, 2008.
[50] C. L. Liu, "A study of detecting and combating cybersickness with fuzzy control for the elderly within 3D virtual stores," *International Journal of Human Computer Studies*, vol. 72, no. 12, pp. 796–804, 2014.
[51] B. Keshavarz, A. C. Novak, L. J. Hettinger, T. A. Stoffregen, and J. L. Campos, "Passive

restraint reduces visually induced motion sickness in older adults," *Journal of experimental psychology. Applied*, vol. 23, no. 1, pp. 85–99, 2017.
[52] C. N. Aldaba, P. J. White, A. Byagowi, and Z. Moussavi, "Virtual reality body motion induced navigational controllers and their effects on simulator sickness and pathfinding," in *2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Seogwipo, 2017, pp. 4175–4178.
[53] S. Davis, K. Nesbitt, and E. Nalivaiko, "Comparing the onset of cybersickness using the Oculus Rift and two virtual roller coasters," in *Proceedings of the 11th Australasian Conference on Interactive Entertainment (IE 2015)*, Sydney, 2015, pp. 27–30.
[54] J. L. Dorado and P. A. Figueroa, "Ramps are better than stairs to reduce cybersickness in applications based on a HMD and a gamepad," in *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, Minneapolis, MN, 2014, pp. 47–50.
[55] B. Keshavarz and H. Hecht, "Pleasant music as a countermeasure against visually induced motion sickness," *Applied Ergonomics*, vol. 45, no. 3, pp. 521–527, 2014.
[56] B. Keshavarz, D. Stelzmann, A. Paillard, and H. Hecht, "Visually induced motion sickness can be alleviated by pleasant odors," *Experimental Brain Research*, vol. 233, no. 5, pp. 1353–1364, 2015.
[57] J. D. Moss, E. R. Muth, R. A. Tyrrell, and B. R. Stephens, "Perceptual thresholds for display lag in a real visual environment are not affected by field of view or psychophysical technique," *Displays*, vol. 31, no. 3, pp. 143–149, 2010.
[58] M. H. Draper, E. S. Viirre, T. A. Furness, and V. J. Gawron, "Effects of image scale and system time delay on simulator sickness within head-coupled virtual environments," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 43, no. 1, pp. 129–146, 2001.
[59] M. E. St. Pierre, S. Banerjee, A. W. Hoover, and E. R. Muth, "The effects of 0.2 Hz varying latency with 20-100 ms varying amplitude on simulator sickness in a helmet mounted display," *Displays*, vol. 36, pp. 1–8, 2015.
[60] J. D. Moss, J. Austin, J. Salley, J. Coats, K. Williams, and E. R. Muth, "The effects of display delay on simulator sickness," *Displays*, vol. 32, no. 4, pp. 159–168, 2011.
[61] K. Carnegie and T. Rhee, "Reducing visual discomfort with HMDs using dynamic depth of field," *IEEE Computer Graphics and Applications*, vol. 35, no. 5, pp. 34–41, 2015.
[62] Oculus VR, "Binocular vision, stereoscopic imaging and depth cues," 2017. [Online]. Available: https://developer.oculus.com/design/latest/concepts/bp_app_imaging/. [Accessed: 22-Jun-2017].
[63] J. E. Bos, "Less sickness with more motion and/or mental distraction," *Journal of Vestibular Research*, vol. 25, no. 1, pp. 23–33, 2015.
[64] S. Arts, M. Sam, J. Plouzeau, D. Paillot, J. Chardonnet, and F. Merienne, "Effect of proprioceptive vibrations on simulator sickness during navigation task in virtual environment," in *International Conference on Artificial Reality and Telexistence Eurographics Symposium on Virtual Environments*, Kyoto, 2015.
[65] S. D'Amour, J. E. Bos, and B. Keshavarz, "The efficacy of airflow and seat vibration on reducing visually induced motion sickness," *Experimental Brain Research*, vol. 235, no. 9, pp. 2811–2820, 2017.
[66] D. Zielasko, S. Horn, S. Freitag, B. Weyers, and T. W. Kuhlen, "Evaluation of hands-free HMD-based navigation techniques for immersive data analysis," in *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, Greenville, SC, 2016, pp. 317–318.

[67] J. Lee, M. Kim, and J. Kim, "A study on immersion and VR sickness in walking interaction for immersive virtual reality applications," *Symmetry*, vol. 9, no. 6, p. 78, 2017.
[68] J. Shin, G. An, J. S. Park, S. J. Baek, and K. Lee, "Application of precise indoor position tracking to immersive virtual reality with translational movement support," *Multimedia Tools and Applications*, vol. 75, no. 20, pp. 12331–12350, 2016.
[69] R. N. McLay *et al.*, "A randomized, controlled trial of virtual reality-graded exposure therapy for post-traumatic stress disorder in active duty service members with combat-related post-traumatic stress risorder," *Cyberpsychology, Behavior, and Social Networking*, vol. 14, no. 4, pp. 223–229, 2011.
[70] M. Rus-Calafell, J. Gutiérrez-Maldonado, C. Botella, and R. M. Baños, "Virtual reality exposure and imaginal exposure in the treatment of fear of flying: A pilot study," *Behavior Modification*, vol. 37, no. 4, pp. 568–590, 2013.
[71] Y. Shiban, I. Schelhorn, P. Pauli, and A. Mühlberger, "Effect of combined multiple contexts and multiple stimuli exposure in spider phobia: A randomized clinical trial in virtual reality," *Behaviour Research and Therapy*, vol. 71, pp. 45–53, 2015.
[72] R. Sacks, A. Perlman, and R. Barak, "Construction safety training using immersive virtual reality," *Construction Management and Economics*, vol. 31, no. 9, pp. 1005–1017, 2013.
[73] W. D. Cannon *et al.*, "Improving residency training in arthroscopic knee surgery with use of a virtual-reality simulator," *The Journal of Bone and Joint Surgery*, vol. 96, no. 21, pp. 1798–1806, 2014.
[74] M. R. Kandalaft, N. Didehbani, D. C. Krawczyk, T. T. Allen, and S. B. Chapman, "Virtual reality social cognition training for young adults with high-functioning autism," *Journal of Autism and Developmental Disorders*, vol. 43, no. 1, pp. 34–44, 2013.
[75] E. Gadler, A. Grassi, and G. Riva, "A rehabilitation protocol for empowering spatial orientation in MCI. A pilot study," *Studies in Health Technology and Informatics*, vol. 144, no. 1, pp. 234–236, 2009.
[76] P. J. White, "An immersive virtual reality navigational tool for diagnosing and treating neurodegeneration," University of Manitoba, 2016.
[77] Oculus VR, "Tracking," 2017. [Online]. Available: https://developer3.oculus.com/documentation/intro-vr/latest/concepts/bp_app_tracking/. [Accessed: 20-Apr-2017].
[78] Oculus VR, "Rendering techniques," 2017. [Online]. Available: https://developer.oculus.com/design/latest/concepts/bp_app_rendering/. [Accessed: 22-Jun-2017].
[79] HTC Vive, "VIVE™ Canada." [Online]. Available: https://www.vive.com/ca/product/. [Accessed: 22-Jun-2017].
[80] C. C. Lo, C. P. Chiu, Y. C. Tseng, S. A. Chang, and L. C. Kuo, "A walking velocity update technique for pedestrian dead-reckoning applications," *2011 IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications*, Toronto, ON, 2011, pp. 1249–1253.
[81] E. R. Muth, "The challenge of uncoupled motion: Duration of cognitive and physiological aftereffects," *Human Factors*, vol. 51, no. 5, pp. 752–761, 2009.
[82] Ł. Dziuda, M. P. Biernacki, P. M. Baran, and O. E. Truszczyński, "The effects of simulated fog and motion on simulator sickness in a driving simulator and the duration of after-effects," *Applied Ergonomics*, vol. 45, no. 3, pp. 406–412, 2014.
[83] J. O. Chang, S. S. Levy, S. W. Seay, and D. J. Goble, "An alternative to the balance error

scoring system: Using a low-cost balance board to improve the validity/reliability of sports-related concussion balance testing," *Clinical Journal of Sport Medicine*, vol. 24, no. 3, pp. 256–262, 2014.
[84] H. L. Bartlett, L. H. Ting, and J. T. Bingham, "Accuracy of force and center of pressure measures of the Wii Balance Board," *Gait & Posture*, vol. 39, no. 1, pp. 224–228, Jan. 2014.
[85] T. E. Prieto, J. B. Myklebust, R. G. Hoffmann, E. G. Lovett, and B. M. Myklebust, "Measures of postural steadiness: Differences between healthy young and elderly adults," *IEEE Transactions on Biomedical Engineering*, vol. 43, no. 9, pp. 956–966, 1996.
[86] Laerd Statistics, "Two-way mixed ANOVA using SPSS Statistics: Statistical tutorials and software guides," 2015. [Online]. Available: https://statistics.laerd.com/premium/spss/twma/two-way-mixed-anova-in-spss.php. [Accessed: 14-May-2018].
[87] S. E. Maxwell and H. D. Delaney, *Designing Experiments and Analyzing Data: A Model Comparison Perspective*, 2nd ed. New York, NY: Psychology Press, 2004.
[88] Laerd Statistics, "Spearman's correlation using SPSS Statistics: Statistical tutorials and software guides," 2017. [Online]. Available: https://statistics.laerd.com/premium/spss/sroc/spearmans-rank-order-correlation-in-spss.php. [Accessed: 02-Jun-2018].
[89] G. Caillet, G. Bosser, G. C. Gauchard, N. Chau, L. Benamghar, and P. P. Perrin, "Effect of sporting activity practice on susceptibility to motion sickness," *Brain Research Bulletin*, vol. 69, no. 3, pp. 288–293, 2006.
[90] S. Bouchard, G. Robillard, P. Renaud, and F. Bernier, "Exploring new dimensions in the assessment of virtual reality induced side effects," *Journal of Computer and Information Technology*, vol. 1, no. 3, pp. 20–32, 2011.
[91] S. D. Young, B. D. Adelstein, and S. R. Ellis, "Demand characteristics in assessing motion sickness in a virtual environment: Or does taking a motion sickness questionnaire make you sick?," *IEEE Transactions on Visualization and Computer Graphics*, vol. 13, no. 3, pp. 422–428, 2007.
[92] M. S. Dennison and M. D'Zmura, "Cybersickness without the wobble: Experimental results speak against postural instability theory," *Applied Ergonomics*, vol. 58, pp. 215–223, 2016.
[93] S. Wibirama, H. A. Nugroho, and K. Hamamoto, "Depth gaze and ECG based frequency dynamics during motion sickness in stereoscopic 3D movie," *Entertainment Computing*, vol. 26, pp. 117–127, 2018.
[94] G. Menshikova, A. Kovalev, O. Klimova, A. Chernorizov, and S. Leonov, "Testing the vestibular function development in junior figure skaters using the eye tracking technique," *Procedia - Social and Behavioral Sciences*, vol. 146, pp. 252–258, 2014.
[95] S. A. Arsalan, N. Badruddin, and A. S. Malik, "Effects of stereoscopic screen disparity on pupil diameter," in *2013 IEEE Symposium on Computers & Informatics (ISCI)*, Langkawi, 2013, pp. 118–121.
[96] J. D. D. Moss and E. R. R. Muth, "Characteristics of head mounted displays and their effects on simulator sickness," *Human Factors*, vol. 53, no. 3, pp. 308–319, 2011.
[97] A. Byagowi, "Virtual reality platform designed for spatial cognition studies," Ph.D. dissertation, Department of Electrical and Computer Engineering, University of Manitoba, WPG, MB, 2016.

[98] S. Razzaque, Z. Kohn, and M. C. Whitton, "Redirected walking," in *Proceedings of EUROGRAPHICS*, Manchester, 2001, pp. 105–106.
[99] J. Popa. (2014, Aug. 10). "Oculus Rift: DK1 vs DK2," *in2gpu*. [Online]. Available: http://in2gpu.com/2014/08/10/oculus-rift-dk1-vs-dk2/. [Accessed: 22-Jun-2017].
[100] C. Hunt. (2016, July 25). "Field of view face-off: Rift vs Vive vs Gear VR vs PSVR," *VRHeads*. [Online]. Available: https://www.vrheads.com/field-view-faceoff-rift-vs-vive-vs-gear-vr-vs-psvr. [Accessed: 22-Jun-2017].
[101] D. L. Price, A. V. Savonenko, M. Albert, J. C. Troncoso, and P. C. Wong, "Aging of the brain and Alzheimer's disease," in *Handbook of the Neuroscience of Aging*, P. R. Hof and C. V Mobbs, Eds. Amsterdam ; Boston: Elsevier/Academic Press, 2009, pp. 409–417.
[102] Z. Yao, Y. Zhang, L. Lin, Y. Zhou, C. Xu, and T. Jiang, "Abnormal cortical networks in mild cognitive impairment and Alzheimer's disease," *PLoS Computational Biology*, vol. 6, no. 11, pp. 1–11, 2010.
[103] E. H. Seo *et al.*, "Whole-brain functional networks in cognitively normal, mild cognitive impairment, and Alzheimer's disease," *PLoS ONE*, vol. 8, no. 1, pp. 1–11, 2013.
[104] L. G. Apostolova *et al.*, "Hippocampal atrophy and ventricular enlargement in normal aging, mild cognitive impairment and Alzheimer's disease," *Alzheimer Disease and Associated Disorders*, vol. 26, no. 1, pp. 17–27, 2012.
[105] J. Hardy and D. Allsop, "Amyloid deposition as the central event in the aetiology of Alzheimer's disease," *Trends in Pharmacological Sciences*, vol. 12, no. 10, pp. 383–388, 1991.
[106] M. Castello and S. Soriano, "On the origin of Alzheimer's disease. Trials and tribulations of the amyloid hypothesis," *Ageing Research Reviews*, vol. 13, pp. 10–12, 2014.
[107] D. A. Drachman, "The amyloid hypothesis, time to move on: Amyloid is the downstream result, not cause, of Alzheimer's disease," *Alzheimer's & Dementia*, vol. 10, no. 3, pp. 372–380, 2014.
[108] R. B. Maccioni, G. Farías, I. Morales, and L. Navarrete, "The revitalized tau hypothesis on Alzheimer's disease," *Archives of Medical Research*, vol. 41, no. 3, pp. 226–231, 2010.
[109] P. R. Rapp and J. Bachevalier, "Cognitive development & aging," in *Fundamental Neuroscience*, L. Squire, D. Berg, F. Bloom, S. Du Lac, A. Ghosh, and N. Spitzer, Eds. Burlington, US: Elsevier Science & Technology, 2008, pp. 1039–1066.
[110] D. O. Hebb, *The Organization of Behavior: A Neuropsychological Theory*. New York, NY, USA: John Wiley & Sons Inc., 1949.
[111] J. M. Hoogendam, G. M. J. Ramakers, and V. Di Lazzaro, "Physiology of repetitive transcranial magnetic stimulation of the human brain," *Brain Stimulation*, vol. 3, no. 2, pp. 95–118, 2010.
[112] J. M. Rabey, E. Dobronevsky, S. Aichenbaum, O. Gonen, R. G. Marton, and M. Khaigrekht, "Repetitive transcranial magnetic stimulation combined with cognitive training is a safe and effective modality for the treatment of Alzheimer's disease: A randomized, double-blind study," *Journal of Neural Transmission*, vol. 120, no. 5, pp. 813–819, 2013.
[113] J. Lee, B. H. Choi, E. Oh, E. H. Sohn, and A. Y. Lee, "Treatment of Alzheimer's disease with repetitive transcranial magnetic stimulation combined with cognitive training: A prospective, randomized, double-blind, placebo-controlled study," *Journal of Clinical Neurology*, vol. 12, no. 1, pp. 57–64, 2016.
[114] C. J. Stagg and M. A. Nitsche, "Physiological basis of transcranial direct current

stimulation," *The Neuroscientist*, vol. 17, no. 1, pp. 37–53, 2011.
[115] E. M. Khedr *et al.*, "A double-blind randomized clinical trial on the efficacy of cortical direct current stimulation for the treatment of Alzheimer's disease," *Frontiers in Aging Neuroscience*, vol. 6, pp. 1–12, 2014.
[116] P. S. Boggio *et al.*, "Prolonged visual memory enhancement after direct current stimulation in Alzheimer's disease," *Brain Stimulation*, vol. 5, no. 3, pp. 223–230, 2012.
[117] J. P. O'Reardon *et al.*, "Efficacy and safety of transcranial magnetic stimulation in the acute treatment of major depression: A multisite randomized controlled trial," *Biological Psychiatry*, vol. 62, no. 11, pp. 1208–1216, 2007.
[118] A. R. Brunoni *et al.*, "Cognitive control therapy and transcranial direct current stimulation for depression: A randomized, double-blinded, controlled trial," *Journal of Affective Disorders*, vol. 162, pp. 43–49, 2014.
[119] S. M. Fitzpatrick and D. L. Rothman, "Meeting report: Transcranial magnetic stimulation and studies of human cognition," *Journal of Cognitive Neuroscience*, vol. 12, no. 4, pp. 704–709, 2000.
[120] P. C. Miranda, M. Lomarev, and M. Hallett, "Modeling the current distribution during transcranial direct current stimulation," *Clinical Neurophysiology*, vol. 117, pp. 1623–1629, 2006.
[121] A. Woźniak-Kwaśniewska, D. Szekely, P. Aussedat, T. Bougerol, and O. David, "Changes of oscillatory brain activity induced by repetitive transcranial magnetic stimulation of the left dorsolateral prefrontal cortex in healthy subjects," *NeuroImage*, vol. 88, pp. 91–99, 2014.
[122] L. Ding, G. Shou, H. Yuan, D. Urbano, and Y. H. Cha, "Lasting modulation effects of rTMS on neural activity and connectivity as revealed by resting-state EEG," *IEEE Transactions on Biomedical Engineering*, vol. 61, no. 7, pp. 2070–2080, 2014.
[123] F. A. Kozel *et al.*, "Using simultaneous repetitive transcranial magnetic stimulation/functional near infrared spectroscopy (rTMS/fNIRS) to measure brain activation and connectivity," *NeuroImage*, vol. 47, no. 4, pp. 1177–1184, 2009.
[124] D. Keeser *et al.*, "Prefrontal transcranial direct current stimulation changes connectivity of resting-state networks during fMRI," *Journal of Neuroscience*, vol. 31, no. 43, pp. 15284–15293, 2011.
[125] J. B. Jobe *et al.*, "ACTIVE: A cognitive intervention trial to promote independence in older adults," *Controlled Clinical Trials*, vol. 22, no. 4, pp. 453–479, 2001.
[126] S. L. Willis *et al.*, "Long-term effects of cognitive training on everyday functional outcomes in older adults," *Journal of the American Medical Association*, vol. 296, no. 23, pp. 2805–2814, 2006.
[127] G. W. Rebok *et al.*, "Ten-year effects of the advanced cognitive training for independent and vital elderly cognitive training trial on cognition and everyday functioning in older adults," *Journal of the American Geriatrics Society*, vol. 62, no. 1, pp. 16–24, 2014.
[128] R. De Luca *et al.*, "Cognitive training for patients with dementia living in a sicilian nursing home: A novel web-based approach," *Neurological Sciences*, vol. 37, no. 10, pp. 1685–1691, 2016.
[129] M. M. E. de Werd, D. Boelen, M. G. M. Olde Rikkert, and R. P. C. Kessels, "Errorless learning of everyday tasks in people with dementia," *Clinical Interventions in Aging*, vol. 8, pp. 1177–1190, 2013.
[130] Z. S. Nasreddine *et al.*, "The Montreal Cognitive Assessment, MoCA: A brief screening

tool for mild cognitive impairment," *Journal of the American Geriatrics Society*, vol. 53, no. 4, pp. 695–699, 2005.
[131] R. G. M. Morris, "Spatial localization does not require the presence of local cues," *Learning and Motivation*, vol. 12, no. 2, pp. 239–260, 1981.
[132] R. W. Skelton, S. P. Ross, L. Nerad, and S. A. Livingstone, "Human spatial navigation deficits after traumatic brain injury shown in the arena maze, a virtual Morris water maze," *Brain Injury*, vol. 20, no. 2, pp. 189–203, 2006.
[133] R. S. Astur, J. Tropp, S. Sava, R. T. Constable, and E. J. Markus, "Sex differences and correlations in a virtual Morris water task, a virtual radial arm maze, and mental rotation," *Behavioural Brain Research*, vol. 151, no. 1–2, pp. 103–115, 2004.
[134] J. Y. Lee *et al.*, "Spatial memory impairments in amnestic mild cognitive impairment in a virtual radial arm maze," *Neuropsychiatric Disease and Treatment*, vol. 10, pp. 653–660, 2014.
[135] V. Bragin, G. Shereshevsky, I. Bragin, A. Vaysman, E. Slobod, and A. Tsoy, "N-back task as a paradigm for working memory testing and training in dementia: Case studies," *Alzheimer's & Dementia*, vol. 11, no. 7, pp. 609–610, 2015.
[136] A. Borkowska, W. Drozdz, P. Jurkowski, and J. K. Rybakowski, "The Wisconsin card sorting test and the N-back test in mild cognitive impairment and elderly depression," *The World Journal of Biological Psychiatry*, vol. 10, no. 4, pp. 870–876, 2009.
[137] I. Hindmarch, H. Lehfeld, P. de Jongh, and H. Erzigkeit, "The Bayer activities of daily living scale (B-ADL)," *Dementia and Geriatric Cognitive Disorders*, vol. 9, no. suppl. 2, pp. 20–26, 1998.
[138] S. Montgomery and M. Asberg, "A new depression scale designed to be sensitive to change," *The British Journal of Psychiatry*, vol. 134, no. 4, pp. 382–389, 1979.
[139] P. Eggenberger, V. Schumacher, M. Angst, N. Theill, and E. D. de Bruin, "Does multicomponent physical exercise with simultaneous cognitive training boost cognitive performance in older adults? A 6-month randomized controlled trial with a 1-year follow-up," *Clinical Interventions in Aging*, vol. 10, pp. 1335–1349, 2015.
[140] M. Mitolo, E. Borella, C. Meneghetti, E. Carbone, and F. Pazzaglia, "How to enhance route learning and visuo-spatial working memory in aging: A training for residential care home residents," *Aging & Mental Health*, vol. 21, no. 5, pp. 562–570, 2016.
[141] C. Lüscher, R. A. Nicoll, R. C. Malenka, and D. Muller, "Synaptic plasticity and dynamic modulation of the postsynaptic membrane," *Nature Neuroscience*, vol. 3, no. 6, pp. 545–550, 2000.
[142] B. Waldron-Perrine and B. N. Axelrod, "Determining an appropriate cutting score for indication of impairment on the Montreal Cognitive Assessment," *International Journal of Geriatric Psychiatry*, vol. 27, no. 11, pp. 1189–1194, 2012.
[143] C. A. Luis, A. P. Keegan, and M. Mullan, "Cross validation of the montreal cognitive assessment in community dwelling older adults residing in the southeastern US," *International Journal of Geriatric Psychiatry*, vol. 24, no. 2, pp. 197–201, Feb. 2009.
[144] D. Weschler, "A standardized memory scale for clinical use," *The Journal of Psychology*, vol. 19, no. 1, pp. 87–95, 1945.