Virtual Reality For Rehabilitation: Enhancing The Transition to Wheelchair Use

A Thesis submitted to the University of Kent
for the degree of
Doctor of Philosophy
in Biomedical Engineering

by

Chantal Zorzi
School of Engineering, University of Kent

Word Count: 47,134
March, 2024

"Working hard is important. But there's something that matters even more. Believing in yourself." — J.K. Rowling, Harry Potter and the Order of the Phoenix

Abstract

Whether arising from neurological or orthopaedic conditions acquired at birth, in infancy, or later in life, the use of a wheelchair becomes a necessity for some. The journey of transitioning from non-disabled to relying on a wheelchair can be disheartening, requiring adaptation to new physical, practical, and emotional needs in order to navigate the challenges of everyday life. To facilitate this transition, support and training programs play an important role. In recent years, Virtual Reality (VR) has gained widespread popularity in rehabilitation. For wheelchair adaption programs, VR is able to address challenges found in real-life programs such as resource constraints and time limitations. Consequently, for new wheelchair users, VR can serve as a valuable environment for acclimating to newfound physical restrictions and learning to navigate daily life.

This thesis investigates the opportunities VR can offer to support the transition to wheelchair use, with a particular focus on improving wheelchair driving skills training. The work presented in the thesis is built upon a review of the literature, to identify the gaps in existing research and contribute to the knowledge of the field. In particular, the following gaps are identified: lack of VR applications for wheelchair rehabilitation beyond driving skills training, lack of a standard framework and cost-effective system for VR driving skills training programs, and lack of insights about the effects of VR driving skills training programs on the participants' physiological well-being.

Consequently, this thesis presents three main contributions: general suggestions of how VR could assist the transition to wheelchair use after an exploration into the daily life of wheelchair users; general and technological suggestions on how VR wheelchair skills training programs can be maximised for powered wheelchair users; technological suggestions on how to monitor a user's physiological well-being during VR training. Specifically, experienced wheelchair users were individually interviewed about the challenges they face in daily life, with the findings used to suggest different potential VR applications that can mitigate them. For wheelchair driving skills training, a framework is proposed for the standardisation of these applications within VR, with suggestions about the environment design, tasks to be performed, and the assessment of skills acquisitions. A controller was developed and used for the navigation in VR, which allows participants to use the joystick of a real wheelchair to perform the tests in VR. This controller was developed with the consideration of the need for cost-efficient and ergonomic technology for a successful VR driving skills training program. Further, the physiological signals of the participants, specifically the heart rate (HR), were monitored throughout the two studies to analyse the effect VR has on the user's well-being. The results underscore the necessity for VR applications to aid new wheelchair users across various aspects of their transition, extending beyond physical assistance. Regarding driving skills training, the

results indicate that VR programs can be optimised through: the implementation of a standardised framework for the assessment of skill acquisition; the use of cost-effective technology; and the thoughtful consideration of environmental design choices. Additionally, the results highlight that monitoring participants' HR provides an implicit measure of their well-being.

Hence, this thesis contributes to the research community's enhanced comprehension of the effective application of VR as a rehabilitation tool for individuals transitioning to wheelchair use. It incorporates the valuable lived experiences of wheelchair users. It proposes and develops a system aimed to maximise the effectiveness of VR wheelchair driving training programs. Additionally, it monitors the well-being of participants throughout their VR experiences.

Acknowledgments

First, I would like to thank my supervisory team. Importantly, my main supervisor, Dr. Gianluca Marcelli, for supporting me throughout my academic career. From being my academic advisor, lecturer and supervisor in my undergraduate degree, to motivating me to pursue a PhD and supporting me throughout my PhD; he never failed to be a great mentor and academic role model. Without his motivation and faith in me, I would not have been able to accomplish this. I will be eternally grateful. Next, my joint main-supervisor, Prof. Konstantinos Sirlantzis, provided invaluable support and guidance, necessary to complete this PhD. Dr. Alexandra Covaci, my secondary supervisor, helped and advised me throughout my PhD, thus playing an important role in completing my PhD. I would also like to thank the last member of my supervisory team, Dr. Luma Tabbaa. Her guidance, advice and support, helped me with my PhD and to grow as a researcher. I am also grateful to my internal examiner, Dr. Rocio von Jungenfeld, and external examiner Prof. Mihai Duguleană for their feedback on my work.

The work carried out in the thesis would not have been possible without the support of the funding agencies. This work was supported by the Assistive Devices for empowering dis-Abled People through robotic Technologies (ADAPT) project. ADAPT was selected for funding by the INTERREG VA France (Channel) England Programme which is co-financed by the European Regional Development Fund (ERDF). The European Regional Development Fund (ERDF) is one of the main financial instruments of the European Unions (EU) cohesion policy. The work was also supported by the Engineering and Physical Science Research Council (EP/T518141/1).

I would also like to thank the members of the University of Kent, School of Engineering, technical support team, for helping when needed. All other University of Kent students and staff, with whom I crossed paths throughout this journey, also merit to be recognised. You were all part of my experience. Specifically, I would like to thank the friends I made throughout this journey, and who, like me, were completing a PhD; in particular, the members of my lab, for fun lunches and perhaps too many coffee breaks. Special thanks to Dr. Rania Kolaghassi, Pavlos Nicolaou, Dr. Paula Delgado-Santos and Jenna Seetohul. I was lucky to have shared this journey with you.

Now, to my family. I would like to thank my parents, Christiane Planche and Francesco Zorzi, for not setting limits to my academic career and giving me the tools and opportunities to make the most of it. For this, and much more, I am grateful. I would also like to thank my brother, René Zorzi, and my dog, Whiskey Zorzi; a pet's companionship is all that is needed sometimes. It is important to me that I also thank my grandparents, Jean-Claude Planche and Hilde Planche, for all their love and support throughout my life. You played a significant role into making me the person that I am today.

Finally, thank you to my friends outside my academic endouvers and across the world. In particular, I would like to thank Camilla Meneghetti, whom I have had the pleasure to have by my side for most of my life. Our friendship has pervailed years of long-distance and time differences, yet it always remained strong. I am very thankful for you. Next, I would like to thank Julia Leenders, who has been by my side for many years. Your friendship has been to me more like a sisterhood. No matter where in the world we have been, we have always had each other. Thank you for your friendship, support and for Loua. I am grateful to have you in my life. Lastly, I would like to thank someone very dear to my heart. Dylan Bansi, since we met, you brightened my days with love, joy, kindness and positivity, all key ingredients I needed to complete this PhD. I will always be thankful for you.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

VR	**V**irtual **R**eality
HMD	**H**ead **M**ounted **D**isplay
WSTP	**W**heelchair **S**kills **T**raining **P**rogram
WST	**W**heelchair **S**kills **T**raining
HR	**H**eart **R**ate
IPQ	**I**group **P**resence **Q**uestionnaire
SSQ	**S**imulator **S**ickness **Q**uestionnaire
SoP	**S**ense **o**f **P**resence
RCT	**R**andomized **C**ontrol **T**rial
QoE	**Q**uality **o**f **E**xperience
CNS	**C**entral **N**ervous **S**ystem
EEG	**E**lectro**e**ncephalo**g**raphy
PNS	**P**eripheral **N**ervous **S**ystem
RR	**R**espiration **R**ate
OCD	**O**bsessive **C**ompulsive **D**isorder
bpm	**b**eats **p**er **m**inute
HRV	**H**eart **R**ate **V**ariability
ANS	**A**utonomic **N**ervous **S**ystem
EDA	**E**lectrodermal **A**ctivity
SCL	**S**kin **C**onductance **L**evel
SCR	**S**kin **C**onductance **R**esponse
EMG	**E**lectromyogram
GSR	**G**alvanic **S**kin **R**esponse
ECG	**E**lectro**c**ardio**g**ram
HCI	**H**uman **C**omputer **I**nteraction
CEAG	**C**entral **E**thics **A**dvisory **G**roup
AT	**A**ssistive **T**echnology
IMU	**I**nertial **M**easurment **U**nit
FoV	**F**ield **o**f **V**iew

I2C	**I**nter **I**ntegrated **C**ircuit
PCB	**P**rinted **C**ircuit **B**oard
BT	**B**lue**T**ooth
IDE	**I**ntegrated **Development** **E**nvironmenr
m	**m**eters
MI-BCI	**M**otor **I**magery **B**rain-**C**omputer **I**nterfaces
AI	**A**rtificial **I**ntelligence

Chapter 1

Introduction

This research was motivated by the compelling surge in virtual reality's (VR) versatile applications and the intention to harness the benefits of VR in a biomedical setting, to enhance the well-being of individuals in need. The growing number of individuals relying on wheelchairs for mobility, fueled also by an increasing population, set the grounds for this work. Given the challenges of rising living costs, this research prioritises developing affordable VR rehabilitation solutions for new wheelchair users, thus aiming to address economic constraints. This thesis embarks on a journey to explore and innovate VR solutions for individuals transitioning to wheelchair use while aligning with the evolving needs of our society.

This chapter introduces the thesis by discussing the background information (section 1.2), the problem statement (section 1.3), and how this work attempts to offer solutions to the problem statement through its aim and research questions (section 1.4). This chapter also provides an overview of the research methodology that has been implemented (section 1.5) and the key contributions of this work (section 1.6), followed by the contributions made by the research team (section 1.7). This chapter concludes with a description of the structure of the thesis (section 1.8).

1.1 SARS COVID-19 Statement

The research carried out for the thesis was started September 2020 and ended September 2023 during the COVID-19 pandemic in Canterbury, UK. Various restrictions and lockdown rules were in place for the general public between March 2020 and December 2021, with additional measures for vulnerable populations, including wheelchair users, continuing as necessary. Consequently, the pandemic greatly affected the inclusion of wheelchair users in the studies, limiting both the number of participants and the methods of their participation. This situation necessitated the development and adaptation of the research questions to ensure compliance with the law while allowing for feasible participation and data collection.

1.2 Background

It is estimated that 1.85% of the world population requires a wheelchair for mobility [1]. The need to use a wheelchair stems from neurological or orthopaedic conditions acquired at birth, as an infant, or later in life [2]. Furthermore, each person needs a different type of wheelchair, one that appropriately meets the individual's needs. However, even when an appropriate wheelchair is found, getting acquainted with it can be a challenging experience.

When someone goes from being a non-disabled person to using a wheelchair later in life, the transition can be discouraging, especially for more severe cases that require a powered wheelchair. Powered wheelchair users face more barriers, such as relying more on others for cognitive assistance [3] and being less likely to be employed compared to manual wheelchair users [4]. To help ease this transition, assistive technologies (AT) have been developed, some of which are based on VR [5]. VR has been defined as a "set of technologies that enables people to immersively experience a world beyond reality" [6, 7]. VR available to consumers for purchase can be in the form of a non-immersive (using monitor screens), a semi-immersive (using CAVE systems; a system that projects the virtual environments on walls), or a fully immersive (using head-mounted displays (HMDs)) experience. HMDs can either be mobile or stationary and are operated through controllers [8]. To create a higher sense of immersion, HMDs can be accompanied by feedback mechanisms such as haptic, auditory, or multi-sensory [8].

Fully immersive VR offers advantages over other non-immersive VR for computer-based rehabilitation programs by making the relevant rehabilitation exercises more motivating and engaging thanks to its increased degrees of immersion and interaction [9]. Further, it provides an immersive virtual space to perform exercises otherwise too dangerous, difficult, or time-consuming to do in the real world [9]. VR can be used for physical and cognitive rehabilitation, but also for psychological assistance (such as to treat anorexia nervosa [10] or to stimulate self-compassion [11]). Thus, VR can be used as a tool to allow people new to wheelchair use to get acquainted with their new physical restrictions; in fact, VR has been used since the 1990s as an alternative way to in-person wheelchair skills training programs, where it serves as a potential solution to overcome the problems currently faced in traditional real-life training such as lack of time and resources [12].

1.3 Problem Statement

If an individual goes from being non-disabled to requiring a wheelchair for mobility, new unavoidable costs are incurred. Firstly, wheelchair costs start at £100 for basic manual models [13], while powered wheelchairs can range from £2,000 to more than £10,000 [14] and multiple wheelchairs might be needed for different activities (e.g. inside driving, outside driving and sports). Further, in most cases rehabilitation is required, and adjustments need to be made in one's home such as stair lifts, accessible showers, and adjustable kitchens [15]. As such, alleviating the financial strain associated with transitioning to wheelchair mobility is important. An area where costs can be reduced is rehabilitation/training programs, where cost-effective measures can be implemented by utilising VR.

There has been extensive research in VR for wheelchair driving skills training [5, 12, 16]; in this field, a variety of techniques have been developed, which differ in the design of the environment, the interaction methods, the type of trained skills and the assessment methods of acquired skills [5, 12, 16]. There are many VR techniques used for these applications; thus, there may be a need for the standardisation of how these techniques are developed and how their effectiveness is assessed. This is important, as currently it is unclear for researchers and clinicians how to most effectively train wheelchair driving skills in VR and how to best assess whether they have been transferred to real life [5, 12]. This is in contrast to real-life training methods, for which a standardised and renowned program has been developed, the Wheelchair Skills Training Program (WSTP) [17].

Further, VR technology for wheelchair users has primarily concentrated on addressing the physical needs, specifically learning to operate a wheelchair, while neglecting other crucial areas where individuals new to wheelchairs might require assistance. To create VR applications that comprehensively support newcomers to wheelchair living, it is essential to consider the entire experience of adapting to life with a wheelchair. Additionally, the involvement of wheelchair users in the design process is crucial; however, co-design initiatives with this user group for VR applications are not always done when developing applications.

Finally, the effect VR technologies have on a user's well-being need to be considered in order to limit the side effects that are common in VR. In particular, prolonged use of VR can lead to cybersickness, which occurs due to sensory conflict between vestibular and visual motion cues [18], meaning that while a person immersed in a VR experience can see the movement, the person does not feel it. Cybersickness leads to various discomforts such as nausea, disorientation, oculomotor disturbances, and drowsiness [18]. For a

VR application to be sustainable, cybersickness needs to be limited, especially in an application developed for people with disabilities.

1.4 Aim And Research Questions

This thesis aims to explore the use of VR technology in smoothing the transition to wheelchair use, to uncover better approaches to skills training methodologies, and to examine how VR training can affect the user's physiological responses. A thorough investigation of all the aims requires research conducted beyond a single PhD. As such, this thesis addresses specific problems, by answering the following three main research questions:

R1: In what ways can the insights and experiences of long-term wheelchair users contribute to the development of solutions tailored for individuals new to using wheelchairs?

This question is addressed in Chapter 3. To effectively answer the question, a two-phase process was used; interviews were conducted with wheelchair users, followed by a workshop with researchers. As the research carried out throughout the thesis aims to address how VR could sustain the transition to wheelchair use, it was important to include wheelchair users as participants in this study. Thus, the interviews were conducted with individual wheelchair users and shed light on the diverse challenges they encounter across various aspects of their daily lives. The workshop was conducted with a team of researchers as participants, to help generate ideas for VR applications that could alleviate the challenges identified from the interviews. The workshop was conducted in person to more effectively collaborate amongst researchers; however, this posed as a challenge for the participants of the interviews to be present and thus they were unable to partake in it. Nonetheless, Chapter 3 importantly takes into account the specific needs of wheelchair users to propose VR solutions.

R2: How can VR be used to develop an affordable wheelchair driving skill training system, and can a methodology be implemented to assess its effectiveness?

This question is addressed in Chapter 4. To effectively answer the question, a system made of a controller and a VR environment was developed. The low-cost and non-invasive controller could be placed on any ordinary wheelchair joystick, for the control of the navigation in VR. The VR environment was designed based on the WSTP [17], and a methodology to assess the effectiveness of the system was proposed also based on the WSTP [17]; this methodology aims to standardise the assessment of the acquisition of real-life driving skills from VR training. The developed system was tested in two studies with non-disabled participants, due to the potential safety risks and unproven reliability of the system, which could have posed more harm or discomfort to wheelchair users as participants.

R3: How can the impact of the VR training be implicitly assessed in relation to participant's well-being?

This question is addressed in Chapter 5. To effectively answer this question, the heart rate (HR) of participants was measured throughout the VR experience, using a chest strap, to implicitly assess how the training affected their well-being, in terms of psychophysical load of task in VR and cybersickness. The well-being of the participants was also assessed explicitly, through two well-established questionnaires, specifically the perceived presence was assessed (using the Igroup Presence Questionnaire (IPQ) [19]) and the cybersickness (using the Simulator Sickness Questionnaire (SSQ) [20]).

1.5 Research Methodology

The research questions were addressed over the course of the PhD journey by performing a review of the available literature on the specific topics related to the questions (see Chapter 2) and through three empirical studies (see Chapters 3, 4, 5). As detailed in Chapter 2, the literature review covers, amongst others, the following three topics: *VR Applications For Wheelchair Users*, *VR For Wheelchair Skills Training*, and *Physiological Measurements in VR*. The literature review highlighted the existing limitations in each of the three topics, setting the stage for novel research to be conducted throughout this PhD.

The topic, *VR Applications For Wheelchair Users*, addresses the background information required to develop and answer R1. This review explores challenges related to wheelchair adaptation and existing VR applications for wheelchair users, pinpointing gaps in the literature. Following the review, various ways to include wheelchair users in the project were thought of. It was important to include wheelchair users as they would be the primary stakeholders benefitting from the research conducted. However, the project was started during the COVID-19 pandemic and therefore a major determinant on how to include wheelchair users was the constant change in restriction rules. Thus, to adhere to the regulations, R1 was developed in a way that allowed the interviewing of wheelchair users without infringing any safety regulations, as the possibility was given to the participants to partake remotely or to adhere to appropriate social distancing rules. Subsequently, a study was conducted (presented in Chapter 3) which involved interviewing experienced wheelchair users to gain insights into their daily challenges and their perceptions of VR. In order to facilitate recruitment, and to adhere to any government policy, the setting of the interviews was based on the participant's preferences (i.e. in person or remote). The interviews offered valuable perspectives into the lives of the individuals the research aims to assist, making them a crucial component of the work conducted in this thesis. These interviews were followed by a workshop with a group of researchers as participants, in which how VR could be used to mitigate the challenges highlighted by the interviewees was discussed. Though it may have been beneficial to have the interviewees also partake in the workshop, due to the nature of the workshop being carried out in person no wheelchair user was able to attend it.

The topic, *VR For Wheelchair Skills Training*, addresses the background information required to develop and answer R2. This review investigates existing VR applications to train wheelchair driving skills and how these skills are taught in real life. The review served to identify gaps in the literature about VR training, and to identify successful real-life training methods which could help improve the effectiveness of VR training. Amongst others, the following gaps were identified: high-costs of training methods, the lack of a validated training program for powered wheelchair users, and the lack of standardised methods to assess the effectiveness of VR training systems. These gaps served as the rationale of R2, thus defining this research question at the beginning of the research. Subsequently, two studies as described in Chapter 4 were conducted, with the aim of resolving those gaps. First, a low-cost VR controller adaptable to various wheelchair joysticks was developed. Then, its effectiveness in training wheelchair driving skills was validated in the first study, by following the standardised assessment methodology proposed in Chapter 4. Following this validation, a second study was conducted that compared two different VR environments (one with elements of gamification and the other without) to assess how the design of the VR environment affects the VR experience and if it leads to differences in acquired skills. The two studies were carried out with non-disabled participants, to mitigate potential safety risks posed to wheelchair users as a result from testing a newly developed system with unproven reliability.

The topic, *Physiological Measurements in VR*, addresses the background information required to develop and answer R3. As the research conducted in the thesis is intended to be used for rehabilitation, it was important to study any potential adverse effects of the employed technology objectively. Thus, this review investigates what physiological signals have been measured during VR experiences, highlighting the effectiveness of HR as an indicator of physiological responses caused by VR. Following the success of the literature in monitoring physiological signals in VR experiences, R3 was defined. Subsequently, the HR of participants during the VR experience, of the two studies conducted to answer R2, was measured as described in Chapter 5. Specifically, in the first study the HR was analysed as an indicator of psychophysical load of VR tasks and in the second study the HR was analysed as an indicator of cybersickness.

1.6 Key Contributions of The Thesis

The contribution of this thesis is to explore how VR can be applied in the rehabilitation of new wheelchair users. The thesis contributes to a larger project, namely the Assistive Devices for empowering dis-Abled People through robotic Technologies (ADAPT) project. This thesis focuses primarily on how to improve the efficacy of wheelchair driving skills training in VR for powered wheelchair users. Further, the thesis investigates how VR affects the well-being of individuals using it. The key contributions are as follows:

- Exploring how VR can mitigate challenges faced by wheelchair users (Chapter 3).
- Proposing an affordable and adaptable VR controller for wheelchair driving skills training applications (Chapters 4).
- Proposing a standardised way of assessing the effectiveness of VR wheelchair driving skills training applications in teaching skills transferable to real life (Chapter 4).
- Investigating the effect of the developed VR system on a user's well-being through physiological measurements (Chapter 5).

The thesis resulted in the following publications:

Peer-reviewed journal articles:

C. Zorzi, L. Tabbaa, A. Covaci, K. Sirlantzis and G. Marcelli, "A Standardized and Cost-Effective VR Approach for Powered Wheelchair Training," in IEEE Access, vol. 11, pp. 66921-66933, 2023, doi: 10.1109/ACCESS.2023.3288424.

C. Zorzi, L. Tabbaa, A. Covaci, K. Sirlantzis and G. Marcelli, "Train vs. Play: Evaluating the Effects of Gamified and Non-Gamified Wheelchair Skills Training Using Virtual Reality", in Bioengineering, 10, 1269, 2023, doi: 10.3390/bioengineering10111269

Conferences:

C. Zorzi, L. Tabbaa, A. Covaci, K. Sirlantzis and G. Marcelli, "Standardisation of Virtual Reality Wheelchair Skills Assessments" , BioMedEng 2022, UCL (poster).

C. Zorzi, L. Tabbaa, A. Covaci, K. Sirlantzis and G. Marcelli, "Development of a Virtual Environment to Train Wheelchair Users" BioMedEng 2021, The University of Sheffield (poster).

1.7 Contributions to The Thesis Made by The Research Team

The author of this thesis, Chantal Zorzi (CZ), was the primary researcher of all the studies conducted throughout the project. However, also the members of CZ's supervisory team and some members of the University of Kent body of students and staff contributed to the development of work reported in the thesis and they must be acknowledged accordingly. The main supervisor, Dr. Gianluca Marcelli (GM), helped shaping the research questions, supported the planning and analysis of the studies presented in Chapter 4 and 5, and provided feedback for all the publications and the writing of the thesis. The joint main supervisor, Prof. Konstantinos Sirlantzis (KS), helped with the planning and conducting of the studies presented in Chapter 4 and 5, through supporting the development of the ideas and the shaping of R2 and R3, the ethics application, providing the required equipment and finding the space to conduct the studies, as well as offering feedback to the publications. The secondary supervisor, Dr. Alexandra Covaci (AC), helped shaping R1 and R2, specifically assisting the study conducted to answer R1 (as presented in Chapter 3); she further provided support for any VR related research and for the publications. The additional supervisor, Dr. Luma Tabbaa (LT), specifically helped shaping R1 by assisting the study conducted to answer that research question (as presented in Chapter 3); she further provided support for the ethics application, the publications and the writing of Chapter 3 of this thesis. Travis Sharp (TS), University of Kent undergraduate student (Digital Design), developed the environments used for Study 2 described in Chapter 4. To ensure appropriate statistical tests were conducted for the analysis of the data presented in Chapter 4 and Chapter 5, the statistics clinic of the University of Kent was consulted with specific support provided by Dr. Bruno Santos (BS). Finally, technical support related to the development of the controller was provided by the University of Kent, School of Engineering, team of technicians. Throughout the thesis, contributions made by specific researchers will be referred by using their initials.

1.8 Thesis Structure

The thesis is structured in the following way:

- *Chapter 2*: This chapter presents a review of the literature focused on topics related to the thesis. It is divided in three sections, each addressing the background literature of one experimental chapter. First, a general overview of existing VR applications for wheelchair users, including their limitation, is presented. Second, VR applications focusing specifically on wheelchair skills training are explored. Third, how VR affects physiological signals is investigated.

- *Chapter 3*: This chapter presents a study conducted following the first section of the literature review. This study was conducted in a two-phase process, including interviews with wheelchair users and a workshop with researchers. First, the findings of the individual interviews conducted with wheelchair users are presented, highlighting the challenges faced by the interviewees and their opinions on VR technology. Then, the results of a workshop, conducted with researchers to explore how VR can be used to mitigate the identified challenges, are described. This is followed by a brief proposal, in the form of a creative catalogue of ideas, of how VR applications could be useful to wheelchair users.

- *Chapter 4*: This chapter presents two studies conducted following the second section of the literature review. To address the limitations identified in the literature, a VR training system made of an affordable VR controller and different VR environments was developed, as described in this chapter. This system was used to conduct two studies. In the first study, the system was validated through a proposed standardisation framework for the assessment of acquired driving skills. In the second study, whether the system can be improved through different approaches in VR environment design was explored. The two studies are followed by an overall conclusion which ties them together.

- *Chapter 5*: This chapter presents the results of two studies conducted following the third section of the literature review. In particular, this chapter describes how the well-being of the participants, doing the VR training throughout the two studies presented in Chapter 4, was assessed. Both explicit measures in the forms of questionnaires (two), and an implicit measure (the HR) were used. After presenting the two studies, the relationship of their results is discussed, which is followed by an overall conclusion.

- *Chapter 6*: This chapter presents the overall findings, contributions to knowledge, and limitations of thesis, as well as avenues of future work that could follow the thesis. In particular, first, each research questions defined in section 1.4 is answered through a discussion of the outcomes of their respective conducted experiments. This is followed by an overall discussion, the contributions to knowledge (describing both the general and technological contributions), the limitations, proposed future work and conclusion.

Chapter 2

Literature Review

This chapter provides a review of the literature pertaining to key elements central to address the research questions of the thesis. Firstly, it delves into the use of VR to facilitate wheelchair adaption, meaning the process of adapting to a wheelchair-dependent lifestyle, with an analysis of the challenges inherent in adapting to a wheelchair and an introduction to VR applications tailored for wheelchair users (section 2.1). This first section establishes a foundation for the thesis and specifically motivates the study described in Chapter 3. Then, the chapter focuses on the specific subject of VR for wheelchair skills training (section 2.2), with the findings in this section used to inform the design of the studies presented in Chapter 4. Finally, the chapter concludes by exploring the impact of VR on physiological responses (section 2.3), with the findings in this section used to inform the studies presented in Chapter 5.

2.1 VR For Wheelchair Adaption

This section describes the potential use of VR technology in alleviating the challenges associated with transitioning to a wheelchair-dependent lifestyle. The section starts with an analysis of the challenges inherent to the adaption of using a wheelchair, including the physical, psychological, and social barriers encountered during this transition (subsection 2.1.1). Subsequently, the focus shifts towards an examination of VR applications available to wheelchair users (subsection 2.1.2), followed by an investigation of the diverse interaction methods employed within VR applications (subsection 2.1.3). Another essential aspect addressed is the representation of wheelchair users within VR applications (subsection 2.1.4). Conclusively, the section presents the limitations inherent in current VR applications (subsection 2.1.5) which hinder them to be used by wheelchair users. This overview, covering the challenges of wheelchair adaption, VR applications, interaction methodologies, representation, and limitations, serves as the foundation for the thesis, specifically for Chapter 3.

2.1.1 Challenges of Wheelchair Adaption

The process of transitioning to needing a wheelchair presents multiple challenges, both physical and psychological. Throughout the journey of becoming en-wheeled, people find barriers relating to accessibility, free movement in public and how they are perceived [21]. These previously not encountered challenges psychologically impact new wheelchair users to an altered sense of self-perception, as a result of the new physical, emotional and practical needs, as well as an increased awareness of societal perceptions, as a result of worrying about the public's opinion of them [22]. Individuals grappling with this transition, who may still be able to walk at times, often exhibit initial tendencies to avoid the use of their wheelchair in settings where they may be recognised [22]. Overcoming these challenges and gradually integrating the wheelchair into one's identity, shaping how individuals move, perceive, and connect with their surroundings, is a continuous journey [23, 24]. As such, the incorporation of a wheelchair into one's life significantly impacts various aspects including the physical adjustments and the complex process of integrating the wheelchair into one's self-identity, while also coping with the reactions from the public [24].

Current research underscores the important role of offering support and training to facilitate acceptance of using a wheelchair [25]. In fact, to fully realise the inclusiveness and empowerment wheelchairs can offer to individuals relying on them, wheelchair users should be surrounded by a positive and supportive environment [26]. Importantly, the prescription of a wheelchair should be part of a comprehensive intervention program that includes an assessment of factors associated with successful adaption, training in using the device, assessment of the user's physical and social context, and exhaustive follow-up to ensure that the device remains appropriate to the changing needs of the user [27]. Further, to maximise the benefits provided by wheelchairs, wheelchairs should have more adaptable hardware regulations in accordance with personal preference [26].

Additional barriers to wheelchair adaption include limited access to equipment, lengthy funding processes and lack of funding for home and vehicle modifications [28]. As such, when developing solutions to ease the wheelchair adaption process, a variety of aspects that tend to one's physical and emotional needs should be considered, while being mindful of the financial implications that accompany adjusting to a wheelchair-dependent lifestyle.

2.1.2 Exploring VR Applications For Wheelchair Users

VR for wheelchair users has been developed primarily as a tool for rehabilitation, suggesting its potential application in facilitating the transition to using a wheelchair. In fact, VR technology has been utilised for the instruction of wheelchair driving skills since the 1990s [12], serving as a viable alternative to conventional real-life training methodologies. In this regard, research has shown that VR could be utilised as a tool that can mitigate the costs and lack of resources associated with real-life driving applications [12]. Further, VR driving skills applications can be tailored to the needs of the user, varying in hardware design, software design and assessment methods for their effectiveness [5, 12, 16]. Given the pre-eminence of these rehabilitative applications in the existing literature, they warrant a dedicated section for a comprehensive exploration (see section 2.2).

While VR technology is most notably known for gaming, inclusive applications designed specifically for wheelchair users often receive limited attention. In fact, there is a lack of gaming applications that adequately address the unique requirements essential for accommodating the diverse needs of wheelchair users [29]. The designs of VR games need to represent individuals, including those with diverse physical attributes and abilities, in a more inclusive and equitable manner. Though limited, some applications specific to wheelchair users have been developed, mainly for sporting games such as badminton [30] and basketball [31] (as seen in Figure 2.1) which show promising results by allowing the users to feel like real-life athletes [31]. In fact, when designed correctly, a VR game "has potential to move the person into the foreground and stigma into the background" [29].

Another field in which VR has grown in popularity for wheelchair users is virtual tourism, as it facilitates visiting certain attractions. Accessibility issues encountered in traditional tourism such as transportation modalities, infrastructure design, service amenities, adaptability, staff and public empathy, and the availability of pertinent information, among others [32], pose major barriers for people with restricted mobility to enjoy tourism. The utilisation of VR technology to furnish comprehensive information about tourist destinations and to enable virtual exploration, could be a plausible solution to mitigate these challenges [32]. Furthermore, the development of VR applications to facilitate virtual visits to archaeological sites, enhanced by haptic feedback for an immersive experience, contributes significantly to the social integration of wheelchair users [33, 34]. For people new in a wheelchair who may be struggling with their mental health, these applications could be especially beneficial as VR tourism has been shown to enhance the psychosocial well-being of individuals unable to travel [35].

Despite the advancements in making VR applications more accessible, the spectrum of applications specifically designed for wheelchair users remains limited. VR applications for wheelchair skills training have great variability in their approaches, while the development of VR solutions in other areas is scarce. VR for gaming and for virtual tourism shows promise for enhancing the well-being of wheelchair users, however research in these fields is still relatively unexplored. Moreover, even in areas where VR has made significant strides, such as mental health, there is an absence of applications that are specifically tailored to the needs of wheelchair users. Nonetheless, VR technology has shown promising results in skills training, gaming, and virtual tourism; thus, it stands to reason that VR applications could be extended to other areas wheelchair users could benefit from. VR could be applied to address the challenges faced by wheelchair users, ranging from education and employment to social interaction and beyond. The adaptability of VR technology, coupled with its ability to tailor experiences to meet the specific needs of individuals with mobility challenges, opens up new possibilities for its application. Hence, further exploration of VR applications for wheelchair users merits research.

FIGURE 2.1: Example of an inclusive VR game (by Macedo et al. [31]).

2.1.3 VR Interaction Methods For Wheelchair Users

A big limitation to current VR applications for wheelchair users are the interaction methods. When using a VR application, a user has two main pieces of technology to interact with: the head-mounted display (HMD), worn on the user's head to be immersed in the virtual world, and the controllers, used to navigate in the virtual world. Both of these pieces of hardware can pose a barrier to wheelchair users wanting to use VR. This is caused by the different mobility requirements of people using wheelchairs, which are often not met by the hardware of most commercially available VR applications. Due to this, it can be said that VR is inherently an ableist application [36]. Further, the few applications that are accessible are also not well-known, as wheelchair users believe that they cannot use VR to the full experience because of the inaccessibility of the controls [37].

Considering VR is an exponentially growing field, it is imperative to research ways to make VR applications more accessible. For wheelchair users, it must be taken into account that full-body interactions can be challenging, and that the weight of carrying the VR headset may be uncomfortable [29]. This discomfort is a result of some users not having the head or neck strength to carry the HMD, and as such they may find it uncomfortable to put it on and to remove it on their own; they may also already be wearing glasses or other devices on their head which would make it uncomfortable to wear a HMD as well [37]. Further, some VR headsets are wired and dealing with a cable while moving in a wheelchair can be challenging [29]. To solve this issue, ergonomic hardware for wheelchair users needs to be developed.

Moreover, when it comes to controlling the movement in VR, the controllers are often not accessible for wheelchair users as they require the user to be able to comfortably hold two controllers, and press buttons, which is a concern for people who have mobility restrictions [37] (see Figure 2.2 for an example). As such, controllers must be developed that do not require the user having one or both hands available, but that are adapted to one's motor abilities [38]. For some wheelchair users, it would suffice to use sensors built-in the headset such as eye-gaze, motion and audio sensors [38], without needing to develop a new controller. Further, alternative VR controllers have been developed in the context of wheelchair skills training where some applications use sensors that meet their end users' specific requirements such as sensors on wheels [39], eye trackers [40], or electroencephalography (EEG) signals [41]. These latter methods, being tailored to a person's motor abilities, may allow for VR to be more accessible.

FIGURE 2.2: Example of Oculus Touch Controllers. As seen, they require two hands. Image taken from: https://www.vrfitnessinsider.com/replace-worn-out-vr-gear-6-vive-rift-accessories/oculus-controller/

2.1.4 Representation of Wheelchair Users in VR

Another important aspect for an appropriate integration of accessible VR applications is the correct use of avatars. Avatars represent an online user's physical self, which allow the user to experience the activities and adventures of the virtual world and are an online user's interface to other humans [42]. First impressions in the virtual world are important [43], and consequently, the depiction of one's avatar is important.

The kind of avatar a person would want to represent oneself with is based on the type of application, task and personal preference [38]. Thus, to allow for an avatar representation that meets the user's satisfaction, options to customise the avatar according to different designs and information on the virtual environment must be provided [43]. For an accessible application, one of the avatar's customisable features should be physical disabilities, which the user may decide to apply based on the game [29].

Giving the option of custom avatars based on one's disability is important, as wheelchair users are eager to lead with their disability in social VR interactions, some even wanting to include fine details [44]. It has also been found that when wheelchair users are in a wheelchair during a VR application, their sense of presence increases and their perception of passing through gaps is more accurate [45]. Further, simulating a VR experience of being in a wheelchair, with an appropriate virtual representation, for non-disabled people increases empathy and tolerance towards people in a wheelchair [46], and reduces implicit bias of the disability [47]. Bias towards the disability can also be reduced by receiving instructions of virtual tasks by an avatar in a wheelchair [47]. However, it must be noted that other wheelchair users may be more selective regarding the information they like to disclose through their avatars [44].

As such, more efforts need to be made for an inclusive representation in VR. For individuals new to using a wheelchair, custom avatars offer a means of taking control over how and when to disclose their disability, potentially helping them to mitigate internalised biases. In this way, the careful consideration of avatar design emerges as a crucial element in creating a truly inclusive and empowering VR experience for users of all abilities.

2.1.5 Limitations of VR

In the above sections, various constraints of VR technology to be used by wheelchair users were discussed, such as inaccessible interaction methods, restricted representation, and limited accessible applications. However, it's important to note that VR has general limitations across different applications that may affect wheelchair users more significantly.

The elevated expenses associated with VR technologies create a hurdle for certain individuals considering their purchase. These high costs should be lowered, especially if VR is intended to serve as a rehabilitation tool for someone transitioning to a wheelchair, as during this process individuals already face additional financial burdens. Specifically, procuring a wheelchair can be costly, ranging from £100 for basic manual models [13] to over £10,000 for powered ones [14]. Moreover, throughout the transition process, there are ongoing medical expenses, and modifications to one's home, such as installing stair lifts, accessible showers, and adjustable kitchens [15]. Therefore, it is crucial to mitigate the expenses associated with VR, if possible, especially as a rehabilitation tool.

Through all the limitations, perhaps the most important one is VR's impact on physiological responses to the experience. Stress-induced physiological responses as a result of VR interactions include heightened skin conductance, heart rate variability (HRV), subjective stress and anxiety [48]. Of particular concern is the influence on physiological responses that lead to cybersickness, a phenomenon arising from sensory conflict between vestibular and visual motion cues [18]. This conflict gives rise to alterations in physiological parameters, including elevated heart rate (HR), heightened cortisol levels, increased body temperature, diminished systolic and diastolic blood pressure, and augmented finger temperature [49, 50]. The resultant physiological alterations associated with cybersickness are marked by visual fatigue, nausea, disorientation, and headaches, thereby diminishing the overall enjoyment of the VR experience [51]. Therefore, the impact of VR on an individual's physiological well-being should be carefully controlled to prevent any user discomfort, particularly in applications intended for rehabilitation.

2.2 VR And Wheelchair Skills Training

This section of the literature review delves into the methodologies employed for training wheelchair driving skills in VR. It starts by explaining the significance of learning these skills, followed by an examination of real-life training approaches along with their respective advantages and constraints. Subsequently, it delves into VR techniques for driving skills training and concludes with suggestions on how to use VR in a way that could also complement real-life training. Specifically, this section serves as a foundation for Chapter 4.

2.2.1 Overview of Wheelchair Skills Training

To maximise participation in society of new wheelchair users, it is important they undergo some sort of driving skills training [2], which should be implemented during initial rehabilitation [52]. These sorts of training enable wheelchair users to drive the wheelchair safely, manage their daily activities, participate in society [53, 54], and therefore, to improve their independence [52, 55, 56]. As a result, various training methods have been developed, both in real life and in VR applications [16].

To train a new wheelchair user in real-life, the Wheelchair Skills Training Program (WSTP) can be adopted [17]. The WSTP is a training method that provides a standardised way of enhancing and assessing the skills of manual or powered wheelchair users, or mobility scooters users. Other types of training (different from the WSTP) exist, which are set within controlled environments, where users have to undergo obstacle courses or follow a track on the floor [16, 57–60]. There are also training methods in less controlled environments, where users learn their skills by driving through rehabilitation centres, homes, schools, or outdoors while having to interact with the environment, like by approaching objects [16, 61, 62].

Real-life training methods are often time and resource intensive [12, 63]; this is something VR training can mitigate [12, 64]. Training in VR environments can have further numerous benefits: it can be more motivating, it lacks the danger of having collisions [65], it increases safe and independent learning opportunities, and it enhances engagement with tasks [64]. VR has also been successfully used to simulate driving of other vehicles such as cars, trains, aircrafts and ships [5]. VR can be highly realistic through stimulating the users' senses to enhance the learning experience by targeting various feedback mechanisms such as auditory, visual, vestibular and force feedback [5]. The immersion and involvement in a VR environment elicits the Sense of Presence (SoP), defined as "experiencing the computer-generated environment rather than the actual physical locale", which positively correlates with the effectiveness of VR-based training [5, 66]. With the exponential growth of VR, these methods are likely to increase in popularity although there are aspects of real-life training methods that might not be replaceable with technology. Thus, it is important to develop VR training systems that could best complement real-life ones.

2.2.2 Introduction to Traditional Training Methods

Real-life wheelchair skills training methods can vary in nature, and often consist in completing tasks within controlled environments, such as obstacle courses, and measure speed and completion time to assess improvement [16]. Other methods, though less popular, are 'ecological' in nature where the user drives through real environments, such as schools and homes, and interacts with these settings [16, 67]. The interactions can mimic what someone would do daily like reaching for objects, writing, and opening doors [16]. Due to the heterogeneity of real-life training, a way to standardise them has been developed, namely the WSTP [17]. This programme can be used for manual and powered wheelchair users and mobility scooters. The programme consists of a set of tasks that a person has to be able to successfully complete to be deemed able to drive a wheelchair independently. Specifically, it tests the wheelchair users on individual tasks (e.g. driving forward, backward, through obstacles, and turning), with the aim of teaching users to deal with various situations such as going shopping [17].

The efficacy of the WSTP [17] was analysed by Tu et al. [68] which reviewed 10 randomised controlled trials (RCTs), and 7 non-RCTs to analyse the short-term effects and long-term effects of the WSTP [17]. In RCTs, participants undergoing the WSTP [17] showed higher improvement in the short-term (immediately to one-week after) retention of skills than those undergoing other methods, for manual wheelchair users. For long-term effects (after 3-12 months), instead, no significant difference was noticed compared to other training methods. These results were similar to what was found in non-RCTs, where manual wheelchair users undergoing the WSTP [17] showed better improvement within 5 weeks as compared to other methods. Although the results show the effectiveness of the WSTP [17] for short-term improvement of skills of manual wheelchair users, insufficient evidence was reported for powered wheelchair users. A similar review was conducted by Keeler et al. [69], who reviewed 13 RCTs and concluded that the WSTP

[17] has a meaningful effect on the improvement of skills compared to no training or other methods. Besides being an effective training method, the WSTP [17] consists in performing tasks in a safe and controlled environment, thus allowing manual wheelchair users to be more confident during the training [69]. These reviews show that real-life training for manual wheelchair users is particularly effective when using the WSTP [17].

Though the WSTP [17] is an efficient method to train new wheelchair users, it has its limitations. Its long-term effects are not significantly higher compared to other methods, and due to the limited evidence available, no final conclusions can be drawn on its effectiveness for powered wheelchair users. Further, real-life training rarely contains tasks that mimic real world driving experiences such as driving in different environments and interacting with them [16]. Importantly, real-life training requires a lot of time and resources which are not available to everyone [12]. Powered wheelchairs are also heavier than manual ones, and can go at moderately high speeds, thus incidents during real-life training can be very harmful, meaning training must be conducted in a careful manner.

2.2.3 Introduction to VR Methods

Contrary to real life driving methods, VR has more freedom in the design of tasks as it does not need to consider safety concerns to the extent of real-life training. Thus, the tasks to complete in the different training environments can have various levels of difficulties, some of which are relatively basic such as passing through doorways [70, 71], mazes [70, 72], or obstacle courses [41, 71, 73], while others are more complex such as collecting blue balls in a room while avoiding red balls to teach hand-eye coordination [72]. Interestingly, though the tasks are performed in a virtual environment (VE) they are often designed to be realistic representing for example a laboratory room [40], or a virtual replica of a rehabilitation unit of a hospital [64]. On occasion, however, studies purposely develop unrealistic environments, like Rodriguez et al. [74] did, to meet the needs of their target users as they were children with multiple disabilities. Yet, due to the heterogeneity of environment designs it is unclear whether one has benefits over another. Further, different environment designs also lead to different tasks to be completed and different methods of assessing the effectiveness of the training. Nonetheless, the effectiveness of the training is commonly measured through collision [39, 41, 70, 72, 73, 75, 76], completion time [39–41, 72, 73, 75, 76], pre and post-training evaluation [39, 70, 72], controller events [70, 73, 76], cybersickness [40, 70, 72, 76], and user experience [40, 71].

Unlike for real-life training methods, a standardised program to follow both for the environment design and for the assessment of skills does not exist for VR. Some studies have attempted to base their work on the WSTP [17], such as Devigne et al. [73] who used the program as a pre-training assessment of skills prior to allowing their study participants to complete their developed VR training. Further, Archambault et al. [77], based their system on the following tasks of the WSTP [17]: driving backward 5m in a straight line, opening a door, moving through the door-way and closing it (in both directions, pushing and pulling), turning 180° within the limits of a 1.5m square (left and right), turning 90° forward (left and right), turning 90° backward (left and right), and moving sideways from one wall to another in a 1.5m square (left and right). All the tasks were performed five times in each direction (i.e. left and right). The tasks were conducted in a virtual replica of a clinical setting, developed using the miWe simulator and shown on a desktop display. To validate the effectiveness of VR, two groups of participants took place in the study, one performing said tasks in VR and one in real life, with their performances being compared in terms of joystick amplitude, trajectory and completion time. Their results seemed promising, with the authors suggesting their simulator has the potential to be used in rehabilitation centres. However, the results were not validated in terms of improvement of driving manoeuvres after conducting the VR training, and the use of a desktop monitor for training has been found to be less effective than the use of a HMD [72].

The WSTP [17] tasks were also employed in a study conducted by Fraudet et al. [78] in which the authors aimed at evaluating the user tolerance and driving performance of a powered wheelchair in VR versus real life. Participants came in for three separate sessions, each in growing levels of difficulty, and completed a set of tasks both in VR and in real life. The VR tasks were modelled using Unity3D[79]and were a replica of the ones conducted in real life. The session included tasks such as driving forward (10m) and backward (2m) and turning in place while moving forwards (90°). The second session was more difficult and included getting through a hinged door, ascending and descending a 5° access ramp, rolling on a soft surface (2m), crossing a threshold and driving through narrow corridors. The third session was the most difficult where participants had to avoid moving obstacles and ascend and descend a 10° access ramp. This study was not used to teach participants wheelchair driving skills, as the participants were already expert wheelchair users. However, it validates the use of the WSTP [17] in VR as its results demonstrate participants adapted quickly to VR and their performance was similar to real-life. The authors also concluded that the use of VR can be a beneficial tool to acquire powered wheelchair driving skills for patients unable to practice these skills safely in real life.

However, most studies do not have any guidelines to follow when it comes to VR training, which makes it difficult for researchers, clinicians, and designers to understand the design requirements of an effective VR program. Further, a lot of environments are realistic which may not take full advantage of all the benefits VR has to offer. In fact, in a study conducted by Torkia et al. [71] (also shown in Figure 2.3), participants (clinicians and children who are wheelchair users) were asked for feedback about their VR training experience (driving through a replica of a rehabilitation centre); they suggested increasing the interaction with the VR environment and adding sounds to improve the sense of presence and training efficacy. To achieve these two goals, aspects of gamification could be added to the VR training to enhance the motivation and engagement of the participants [80]. Furthermore, Lam et al. [12], pointed out in their systematic review that a lot of studies do not explicitly describe the environment, rather they referred to images instead. Thus, a standardisation framework should be proposed, outlining the essential details a program should include, and studies should thoroughly describe their methods allowing other researchers to replicate them and expand their work further.

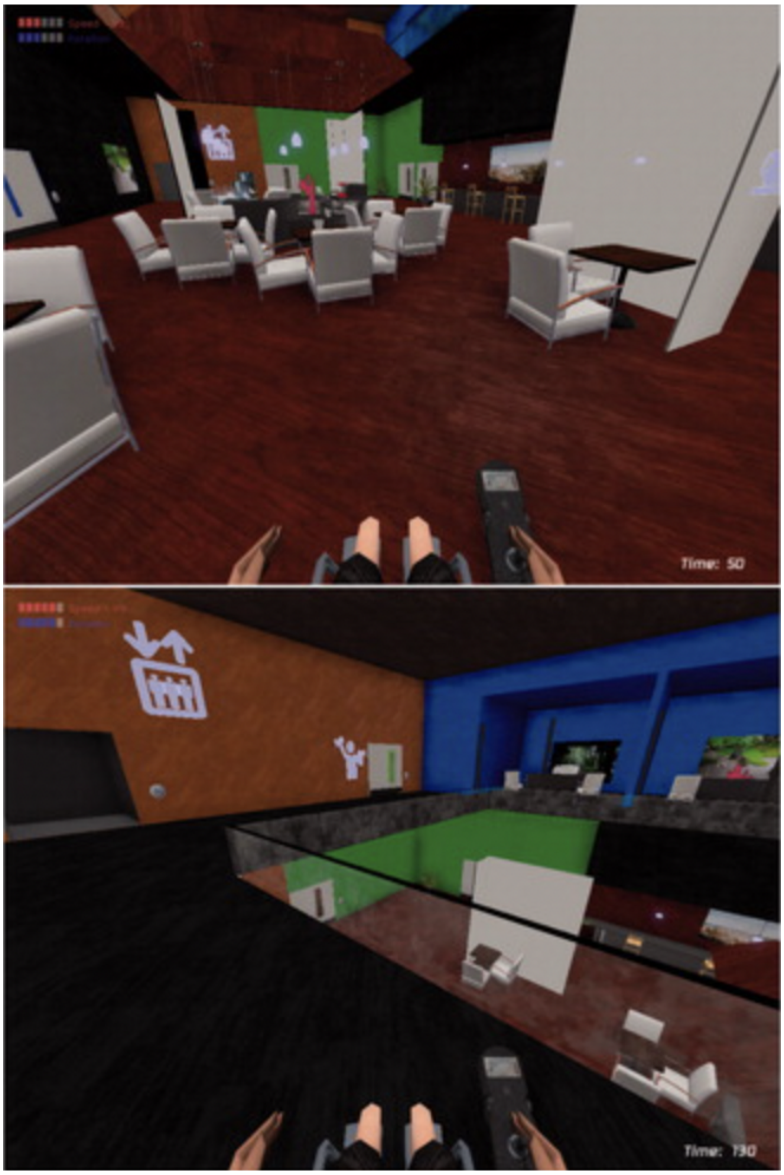

Figure 2.3: Example of VR wheelchair skills training by Torkia et al. [71]

2.2.4 Hardware of VR Systems

To allow for a smooth use of a VR training system, appropriate interaction methods that take into account a user's motor abilities need to be considered. For an immersive VR experience, HMDs are commonly used [39–41, 64, 70, 72, 76] as the visual hardware. Although they provide a greater degree of immersion and sense of presence, compared to monitor screens [72], they cause cybersickness. Less popular methods are monitor screens [71, 74, 75], or CAVE systems [73]. However, these methods are not as effective in training skills transferable to real life. In fact, Nigel et al. [72] had participants split into three groups (a control group, a HMD group and a monitor screen group), and the group using the HMD had the highest retention of driving skills transferred to the real world, even though participants showed more symptoms of cybersickness. Further, Hernandez-Hossa et al. [40], split its participants into two groups, one using a HMD and one using just a projector screen, and they found that the HMD group had a higher feeling of general presence, spatial presence and involvement. Similar results were shown by Govindarajan et al. [81], where they found that HMDs resulted in a higher sense of presence, though they provoked more intense symptoms of cybersickness.

Controllers used to interact with the VR environments also differ from one study to another. Commonly, a joystick is used to conduct navigation [5, 12, 40, 41, 64, 70–75], which can vary from a real powered wheelchair joystick or an adapted gaming joystick. Further, alternative ways to drive the VR simulation for powered wheelchair users exist, such as eye-trackers [40, 74]. For manual wheelchair users to drive the VR simulation, on the other hand, sensors attached to the wheels can be used, such as what was done by Li et al. [39] who placed VIVE trackers on the wheels to drive the simulation in VR; alternatively, the wheelchair can be placed on a wooden frame with two pairs of rollers fitted with angular speed sensors, which translate the user's movements of the wheels in VR [81]. Each of these controllers takes into account the user's motor abilities for the VR interaction. Nevertheless, it's essential to note that powered wheelchair joysticks exhibit substantial variation across different wheelchair models. Therefore, when contemplating solutions involving joysticks, it's crucial to account for the diverse characteristics among different joystick designs.

2.2.5 Data Analysis Performed in VR Studies

It is important to highlight the ways different studies measure their participants' performance, as improvements in driving performance could be used to assess the success of their training system. In order to analyse the acquired data, which most commonly includes collision [16, 39, 64, 70, 73, 74], completion time [41, 72–74, 76], pre and post

VR-training evaluation [39, 70], controller events [40, 73], cybersickness [70, 72, 76] (for which commonly the Simulator Sickness Questionnaire (SSQ) [20] is administered), and user experience [71, 73, 76] (for which commonly the iGroup Presence Questionnaire (IPQ) [19] is administered), statistical analysis is often performed [39, 40, 70, 72]. A lot of studies also perform an evaluation of their systems through interviews and questionnaires [41, 70, 71, 73, 76]. Thus, the most popular type of data acquired is quantitative, which can be objectively analysed and interpreted; however, at times qualitative data collection is needed for a better understanding of the participants' subjective experience of the VR application.

2.2.6 VR Wheelchair Skills Training to Complement Real-Life Training

To appropriately harness the benefits of VR to complement the limitations of real-life training, the advantages and drawbacks of real-life training must first be understood. From reviewing the literature in subsection 2.2.2, it was found that real-life training is often very controlled, and the user is rarely exposed to environments that allow to practice everyday skills due to safety concerns and lack of resources such as time and money. Further, a standardised assessment method has been developed, the WSTP [17], which has been proven to be more effective than other training programs; however, the evidence only supports this for manual wheelchair users. There are fewer studies that used the WSTP [17] for powered wheelchair users, therefore there is the need to do more research on training methods for this population. Furthermore, the WSTP [17] does not train the user to navigate around real-life environments, and distractions and obstacles, like those found in real life, are minimal. VR could mitigate these limitations by being a more resource efficient training system, through being more cost effective and allowing the training of driving skills in "dangerous" environments without actually putting the user in danger.

However, due to the high design heterogeneity amongst VR studies, including differences between tasks and assessment methods, it is currently unclear what methods are more effective than others. The use of realistic VR environments is common [16, 40, 41, 71], suggesting that realism could be an important aspect to consider when developing VR applications for training. Nonetheless, engaging interactions with the VR environment are also important to make the training experience more enjoyable [71]. The end users' needs must be considered, and in some cases an abstract environment may be required due to the users' disability [74]. Though the hardware used in the different studies varies, a lot of studies [5, 12, 40, 41, 64, 70–75] use a joystick, or similar, as a controller for the VR navigation, given that VR training systems are predominantly developed for powered wheelchair users.

Another heterogeneity in current VR systems, lays in each study using their own assessment measures on which to base their conclusions regarding the effectiveness of their training system, making it challenging to compare the outcomes of different systems and, therefore, to design better ones in the future. Standardised assessments would be of great interest and can be achieved by identifying a list of parameters that can be measured by any VR system. For example, task completion time and number of collisions, would be good candidates given that they are commonly used to assess VR systems, and that collisions are also used to assess one's driving proficiency using the WSTP [17] in real life. Further, limited studies test their taught skills in real-life by having the user navigate in a specific real environment before and after the VR training [39, 70], and thus most studies cannot conclude that acquired skills can be transferred to real life.

Currently the WSTP [17] has been shown useful particularly for the retention of skills of manual wheelchair users [68, 69], while most existing VR training environments are designed for powered wheelchair users. This provides the opportunity to complement real-life training by developing VR systems based on the WSTP [17] for powered wheelchair users; this would enhance the reliability and usefulness of VR systems, by limiting their heterogeneity using the guidelines set by a validated program.

However, to successfully use VR, its limitations must be considered. A major limitation found by the different studies is cybersickness, a common side effect of VR, caused by the disorientation of the user's sense of motion [82]. This effect is mainly observed in studies using a HMD as the VR interface [72, 76], while studies using monitor screens [72] do not report significant effects. The assessment of cybersickness and the implementation of mitigating approaches should be incorporated in future VR training systems. At the moment, cybersickness is only assessed using self-reported questionnaires, as for SoP and user's comfort. However, studies in different fields have shown that these aspects can be measured using implicit performance metrics [83] such as users' HR during training.

In conclusion, VR has significant potential to be used for wheelchair skill training, ranging from activities of simple navigation to more complex tasks such as moving within restricted spaces and with moving obstacles. In addition, developing a VR interface for powered wheelchairs is more cost effective than for manual wheelchairs as to control the VR environment all that is needed is a joystick, while manual wheelchairs require platforms equipped with sensors to control navigation. Furthermore, VR has the potential to be used in conjunction with various navigation simulators, ranging from a classic joystick to eye tracking or EEG signals, thus allowing a wider group of powered wheelchair users to benefit from virtual training.

2.3 VR's Affect on Human Physiology

When developing a VR system for rehabilitation, special attention should be placed into studying the users' Quality of Experience (QoE) defined as "the degree of delight or annoyance of the user of an application or service" [84]. This can be assessed explicitly, through asking the user to assess their perceived QoE within a pre-defined rating scale, or implicitly. This latter method, a bio-inspired approach, can automatically recognise a user's perceived QoE through its physiological signals [85]. These signals originate from either the central nervous system (CNS), such as EEG, or from the peripheral nervous system (PNS), such as HR and respiration rate (RR), to name a few [85]. Besides being able to assess the QoE, these physiological responses, derived from changes in behaviour and bodily states, can be interpreted to define the emotional state of a person such as boredom, pain and surprise [86].

Due to their many possible applications, measuring a person's physiological signals in a VR system has become a topic of interest in many studies. In gaming, this data is often taken to determine the user's level of cybersickness or SoP in the games. On the other hand, for medical and rehabilitation applications this information has been used to objectively determine the effectiveness of VR in reducing pain during medical procedures, reducing obsessive compulsive disorder (OCD) symptoms, and relieving anxiety [87].

Due to VR's growth in popularity, and its large impact across a variety of fields, it is important to understand what physiological signal is most useful to study the QoE of a VR application. The following sections aim to provide an overview of what kind of physiological signals are taken and for what, to know which physiological signal is most common, and how this signal is taken and analysed.

2.3.1 Common Physiological Signals

Prior to understanding how to capture physiological signals in VR, what different physiological signals are must be understood. Below is a brief description of common physiological signals:

- Cardiovascular signals: Cardiovascular signals are all signals that derive from the cardiovascular system. The most well-known signal is the HR measured as beats per minute (bpm). This reflects responses to internal and external stimuli and is determined by the parasympathetic and sympathetic nervous system [88], both part of the autonomic nervous system (ANS) [89]. The interval between heart beats is known as the HRV, which indicates the heart's response to psychological and environmental stimuli [88] and can signal health impairments such as depression and anxiety, determined by low HRV [89].

- Respiratory rate: RR is controlled by the CNS and reflects the number of breaths a person takes per minute [90]. Abnormality in RR can indicate serious clinical complications [90]. As a result, RR has been associated to numerous pathological conditions [91]. However, various stressors including changes of emotional states, such as anxiety [92] and cognitive load [91], have also been shown to affect changes in RR.

- Skin temperature: Skin temperature changes in accordance to changes in the ANS such as stress [93]; specifically, acute stress results in vasoconstriction which leads to a drop in skin temperature [94]. This happens especially on the nose, as a direct result of reduction of blood flow in nasal capillaries [93]. As such, changes in skin temperature can indicate different mental and emotional states [93].

- Electrodermal activity: Changes in electrodermal activity (EDA) are related to changes in eccrine sweating, which is caused by the ANS as a result of psychological processes. The more the skin's sweat ducts and pores are filled with sweat, the more conductive the skin becomes. EDA is composed of a tonic and a phasic activity. The tonic one is defined as skin conductance level (SCL), and reflects overall arousal, thus it decreases when someone is relaxed. The phasic one is defined as skin conductance response (SCR) and is more commonly used to determine conscious and unconscious emotional processing [95].

2.3.2 Physiological Signals in VR

Across the various studies exploring the changes of physiological signals as a result of VR applications, researchers have employed different measurements. For instance, Jang et al. [96] examined the physiological reactions of nonphobic participants in two virtual environments, focusing on skin resistance, HR, and skin temperature. In a related field, Delahaye et al. [97] utilised VR technology to induce stress and to assess decision-making cognitive functions; the authors used HR as a physiological indicator of these. Meanwhile, Bassano et al. [98] assessed the usability of a VR ship simulator for nautical personnel training using skin conductance and HR parameters to measure the occurrence of cybersickness as a result of the simulation.

Similar to Bassano et al. [98], other studies have used physiological measurements to investigate cybersickness. Guna et al. [99] investigated the influence of video content on VR sickness, examining skin conductance, HR, skin temperature, and respiration rate. Stuaffert et al. [100], delved into the impact of latency jitter on cybersickness, measuring galvanic skin response and HR. Additionally, Gavgani et al. [83] measured cybersickness as a result of a VR roller-coaster ride, by assessing HR, RR, finger skin conductance, and forehead skin conductance.

Physiological signals have also been measured in VR applications developed for medical purposes. Keighrey et al. [101] aimed to develop AR and VR Speech and Language Therapy applications, analysing EDA and HR as objective measures of the user's QoE of the application. Meanwhile, Van Bennekom et al. [87] evaluated a VR game designed to provoke OCD symptoms by measuring the physiological arousal it caused through HR, HRV, and skin conductance level. Further, Wiederhold et al. [102] assessed the effectiveness of VR in reducing dental procedure-related pain and anxiety, employing a objective measurements, specifically electromyogram (EMG), skin temperature, galvanic skin response (GSR), EEG, HRV, HR, and RR. Salva et al. [103] attempted to improve cognitive deficits resulting from brain trauma, using a mixed reality system to stimulate cognitive functions and measuring HR, skin conductance, skin temperature, respiratory effort, and breaths per minute. As evident from this diverse array of studies, HR emerges as a commonly used metric across different research, showcasing its versatility and relevance in measuring various physiological responses in VR applications.

2.3.3 What Does HR Indicate?

In subsection 2.3.2 it was found that HR is commonly used as a physiological measure to assess VR studies; as such, understanding what different researchers believe it indicates is important. In examining the usability of a VR ship simulator, Bassano et al. [98] noted slightly higher HR values during fast trials suggesting it relates to the increased task difficulty and a higher level of participant involvement. The higher HR was not found to be correlated to specific emotional states that could compromise performance or learning. Higher HR was, however, also found in initial phases of simulations which the authors believe to be correlated to the excitement or anxiety of the participants. Similarly, Delahaye et al. [97] found significant differences in HR across various phases of a stress-inducing experiment.

In the context of VR sickness, Guna et al. [99] observed a decrease in HR when participants watched neutral videos, indicating a higher level of relaxation. Additionally, Stauffert et al. [100] established a significant correlation between HR and cybersickness. However, Gavgani et al. [83], found only minor changes in HR as a result of cybersickness.

Van Bennekom et al. [87] compared the HR of OCD patients and non-OCD controls in a VR simulation. While the HR of the control group decreased during the VR experience as the participants were getting adjusted to the simulation, the HR of OCD patients remained high. The authors believe the high HR to be related to the patient's fear of leaving the VR environment without doing a final check-up, due to their OCD.

2.3.4 How is The HR Measured And Analysed?

Another convenience of using HR is it can be measured using a variety of systems, that do not disrupt the VR experience. In fact, in VR studies, it has been measured with systems ranging from expensive equipment such as the JandJ Engineering's I-330-C2-system [103], the Procomp+ biofeedback device by Thought Technology [102], or an Empatica E4 Wristwatch [100], to more affordable equipment such as the Scosche Rhythm armband [98] or a Fitbit device [101]. Expensive equipment is convenient to use when other physiological measurements are taken as well. In fact, the Procomp+ biofeedback, though costing above 4,000USD measures EMG, temperature, GSR, EEG, HRV, HR, and RR. Similarly, the JandJ Engineering's I-330-C2-system [103], though costing around 2,000USD measures EMG, electrocardiogram (ECG), EEG, skin temperature, skin resistance, and RR, as well as performs some data processing. However, when only interested in the HR, affordable devices are just as reliable. In fact, the Polar H10[104] chest strap, has been validated against medical equipment for its accuracy. The strap uses ECG sensors, and outputs HR in bpm at a sampling rate of 1Hz. The literature [105] demonstrates that it offers the best accuracy for the HR measurements compared to other similar sensors. Specifically, the Polar H10[104] was validated by Schaffarczyk et al. [106] against a 12-channel ECG, where it was found that in terms of R-R intervals and HR the Polar H10[104] gave similar results to an ECG device. It must also be noted that the Polar H10[104] has been proven to be as accurate as the gold standard HR monitor, the ECG Holter device, during low and moderate intensity activities [107].

After measuring the HR in VR scenarios, it has to be analysed. Commonly, the average HR is looked at [83, 99, 101–103, 108], then compared between the different groups of a study [98], or between different study conditions [103]. For instance, Bassano et al. [98] examined bpm and assessed peaks, averaging the HR across participants with and without experience in VR. Similarly, Otsuka et al. [108] focused on HR changes in bpm. Mean HR was further explored by Keighrey et al.[101], who examined mean HR and standard deviation, and Van Bennekom et al. [87], who investigated baseline and reactivity of mean HR. Additionally, Wiederhold et al. [102] and Salva et al. [103] delved into average HR during and between baseline and scenario periods. Additionally, Gavgani et al. [83] averaged HR signals at 1-minute intervals. The statistical analysis across these studies commonly involved One-way ANOVAs for repeated measures [83], with statistical significance set at $p < 0.05$. Alternatively, Delahaye et al. [97] employed a repeated-measures *t*-test to analyse differences in HR.

2.3.5 Summary of HR Benefits

In conclusion, the exploration of physiological signals within VR environments underscores the pivotal role these measurements play in enhancing our understanding of human responses to simulated realities. In particular, the widespread use of HR as a physiological marker in VR research, highlights its significance in assessing a range of reactions, from cognitive load and emotional stress to the onset of VR-induced cybersickness. The methods employed to measure and analyse HR, range from high-end medical equipment to consumer-grade devices, demonstrating the versatility and accessibility of this metric in various research contexts. By analysing HR and other physiological signals, researchers can tailor VR experiences to better suit educational, therapeutic, and entertainment purposes, ensuring that users gain the most benefit while minimising adverse effects.

Chapter 3

Harnessing VR Technology to Facilitate The Journey From Non-Disabled to Wheelchair User

The previous chapter, Chapter 2, presented a review of the literature about VR available to wheelchair users, and its potential implications in rehabilitation. Specifically, section 2.1, highlighted current challenges in adapting to wheelchair use and limitations in wheelchair user friendly VR applications. Besides wheelchair skills training applications, there was found to be a lack of VR applications that aim to support the transition to wheelchair use. To address this gap the research question investigated throughout this chapter was defined as follows: *In what ways can the insights and experiences of long-term wheelchair users contribute to the development of solutions tailored for individuals new to using wheelchairs?* Thus, the current chapter explores the challenges faced by wheelchair users and proposes potential applications of VR technology to address them.

3.1 Introduction

To address some of the challenges faced by wheelchair users (as outlined in 2.1.1), mainstream technologies can be used such as smart home appliances [109], voice-controlled appliances [110], or VR [12]. Extensive research has been done on using VR technologies for wheelchair users as a rehabilitation device to improve the driving skills [5, 12] of new wheelchair users. However, the transition to wheelchair use involves adaptations beyond mastering driving techniques, including new emotional and practical needs [21]. Limited research investigates the potential of VR to address these additional barriers faced by wheelchair users and explores the wider context in which people with disabilities perceive VR [36]. Given the uncharted landscape within the realm of VR and its immense potential for positive impact, the author of this thesis believes that drawing insights from those who have gone through similar challenges, by exploring the views and lived experiences of long-term wheelchair users in the design process of VR for rehabilitation, can better inform the development of useful applications that aim to meet the needs of the end-users. In fact, evidence shows that including end-users in research can benefit researchers, practitioners, research processes and research outcomes [111].

Therefore, this chapter aims to find how VR can be used to facilitate the transition to wheelchair adaption. The study conducted in this chapter follows a co-design approach carried out in a two-phase process. The first phase involved finding the primary challenges experienced by wheelchair users in their daily lives through interviewing experienced wheelchair users; while the second phase involved investigating how VR can be utilised as an intervention that supports new wheelchair users in overcoming these challenges, by conducting a workshop held between engineering and Human-Computer-Interaction (HCI) researchers. The structure of this chapter is as follows: study design; ethical approval; phase one; phase two; creative catalogue of ideas; and an overall conclusion.

3.2 Study Design

This study sought to investigate the potential role of VR in assisting individuals transitioning to a wheelchair-dependent lifestyle, by considering the experiences of long-term wheelchair users and the benefits of VR technology. To achieve this aim, a two-phase process was used in the study, namely *Phase 1* and *Phase 2*. In *Phase 1*, the aim was to identify the challenges commonly encountered by individuals when using wheelchairs. Subsequently, in *Phase 2*, the focus was on proposing VR-based solutions to mitigate these challenges and to ultimately facilitate a smoother transition to life as a wheelchair user. The two-phase process was necessary as it allowed to first understand the specific experiences of wheelchair users, such as challenges, views on the available support and wheelchair users' opinions on technology, and then suggest tailored VR interventions to effectively address these challenges; this in turn lead to a creative catalogue of ideas (section 4.22). The two-phase process is presented in Figure 3.1.

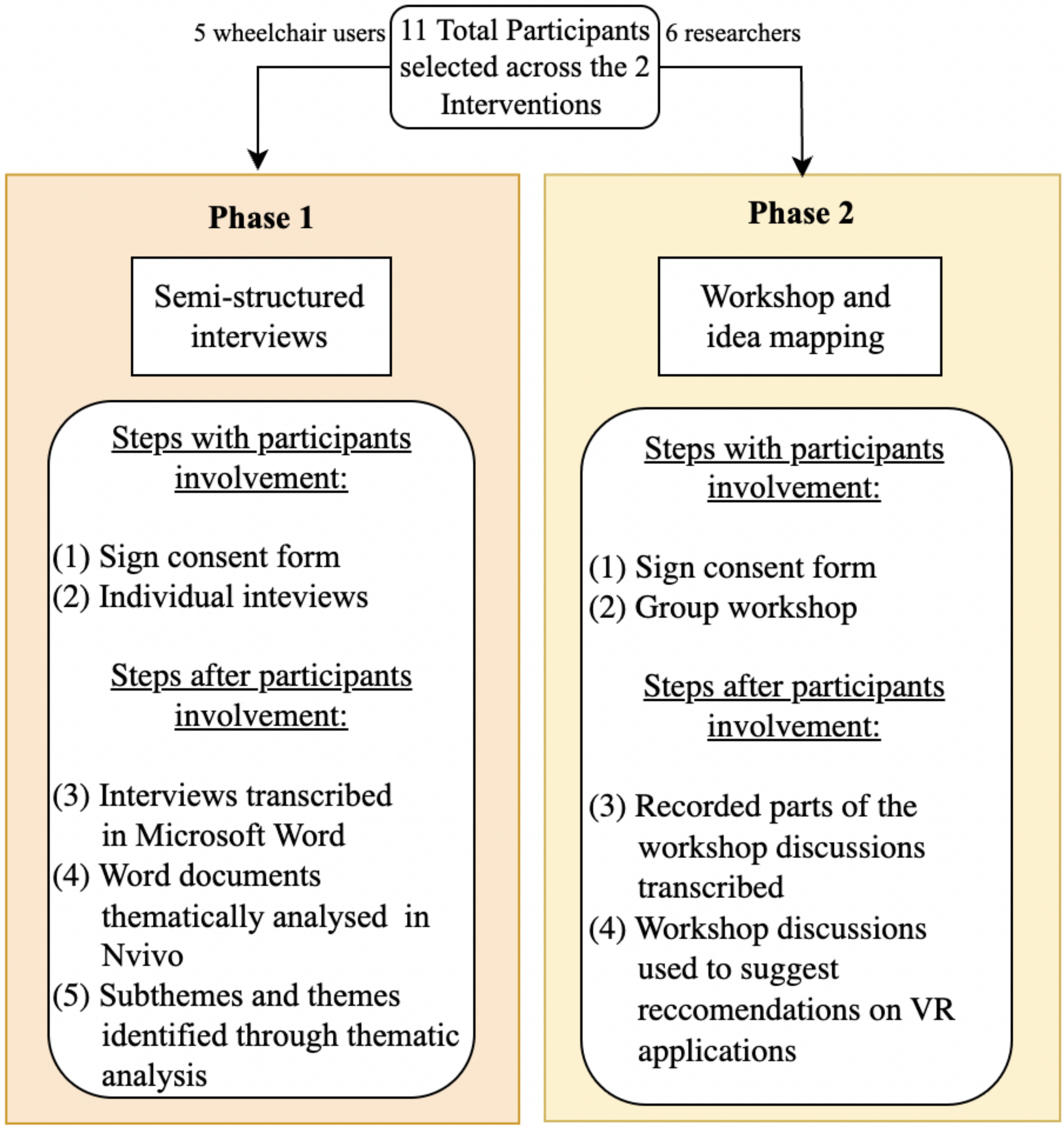

FIGURE 3.1: Flowchart of the set-up of the study.

3.3 Ethical Approval

Participants were recruited via word of mouth and email. Ethical approval was sought from the Central Ethics Advisory Group (CEAG) of the University of Kent. To ensure the anonymity of the participants of *Phase 1*, the data collected from each participant was saved under a coded name and stored on a University password-protected computer. To ensure the anonymity of the participants of *Phase 2*, the outcomes produced by participants individually were saved without any identifiable information on a University password-protected computer, while for the outcomes produced by participants as a group, the data was saved under the group name and stored on a University password-protected computer.

3.4 Phase 1: Semi-Structured Interviews

The first part of the study consisted of conducting interviews with experienced wheelchair users. The primary aim of the interviews was to identify challenges faced by wheelchair users, while the secondary aim was to understand wheelchair users' acceptance of VR technology. The following sections present the methodology used, the findings, and a brief discussion.

3.4.1 Participants

The requirements for the participants of the interviews were: 18 years old or older, can speak, write, and read in English, have no known cognitive disability and be a wheelchair user. A total of 5 experienced wheelchair users were recruited for the study. The participants were powered wheelchair users (n = 4), manual wheelchair users (n = 1), identified as female (n = 3) and male (n = 2), and at the time of the interview had been using a wheelchair for minimum 10 years (specifically: 0-10 years (n = 1), 11-20 years (n = 1), 21-30 years (n = 3)). The participants of the individual interviews were given a £5 Amazon voucher as compensation for their time.

3.4.2 Interview Methodology

The interviews followed a semi-structured format aimed at learning about the challenges in the daily life of wheelchair users. As such, the interviews covered the following topics:

- *Initial wheelchair struggles*: In this topic, the struggles encountered by the interviewees at the beginning of the journey to using a wheelchair full-time and faced throughout their childhood were discussed.
- *Wheelchair struggles now*: In this topic, the struggles commonly encountered by the interviewees now and in adult life were discussed.
- *Users' knowledge of technology*: In this topic, different technologies used by the interviewees in their day-to-day life were discussed.
- *Users and VR*: In this topic, how the interviewees view VR and if they would be keen on trying it out was discussed.

One participant did not feel well enough to partake in the interview, and as such completed an open-ended questionnaire that covered the main themes discussed in the interviews (see Appendix A). One of the interviews was carried out in person (by CZ and AC), one was carried out over a video call via Zoom[112] (by CZ), one was carried out over an audio call via Microsoft Teams[113] (by CZ), and one was carried out over a regular call (by CZ). All interviews lasted between 23:59 minutes and 29:31 minutes and were audio-recorded. The interviews were transcribed and analysed using thematic analysis, following the approach outlined by Braun and Clarke [114] via the Nvivo[115] software. Thematic analysis consists in identifying patterns within a qualitative data set and interpreting them. Thus, the interview data was coded, and the codes were then grouped into sub-themes and themes.

3.4.3 Interview Data Collection And Processing

The interview data was collected employing a conventional recorder, integrated within a smartphone, by the author of this thesis. Subsequently, the recorded audio was manually transcribed into a digital textual format, on Microsoft Word[116]. Following the transcription phase, a thematic analysis using NVivo[115] was performed, a dedicated qualitative data analysis software platform. Anonymity of the interviewees was maintained by assigning each participant a coded name and saving all the data (both recorded and transcribed) under the respective coded name. Specifically, the software described below were used for the processing of the data.

3.4.3.1 Microsoft Word

Microsoft Word[116] was used for the data analysis as the platform for the transcription of the recorded interview data. The transcription process used a multifaceted approach with both automated and manual techniques, ensuring a comprehensive and accurate representation of the interview content. The automated transcription process was facilitated by voice writing technology, that seamlessly translates spoken words into text, included in the Microsoft Word[116] software. After the automated transcription, manual transcription, characterised by listening to the recorded interviews and typing them out, was also performed (by CZ) to ensure everything was accurately transcribed. The manual transcription included the identification of the speaker, distinguishing between the interviewer and interviewee, as well as timestamps denoting the chronological progression of the interviews. Furthermore, the transcription also included observations of interviewee behaviours, such as tone of voice, emotional expressions (e.g., laughter, expressions of distress), and other relevant behavioural cues. Subsequent to the transcription phase, the transcribed data underwent thematic analysis, with the qualitative analysis software NVivo[115].

3.4.3.2 Nvivo

The transcribed data derived from interviews underwent a thematic analysis process using NVivo[115], a dedicated qualitative data analysis software, following the guidelines set by Braun and Clarke [114]. To do so, the transcribed interview data represented as Word[116] documents was imported into the NVivo[115] software. Subsequently, the documents were initially coded (by CZ). The coded data was reviewed and validated by multiple researchers (n = 5), including biomedical engineers (n = 1, CZ), HCI specialists (n = 2, AC, LT), and digital media students (n = 2). Afterwards, the codes were organised into meaningful clusters. This clustering process, conducted by three researchers (CZ, LM, AC), led to the emergence of subthemes and, ultimately, overarching themes within the dataset. These subthemes and themes encapsulated higher-order patterns within the interview data, thereby facilitating the understanding of the interviews.

3.4.4 Interview Findings

To understand the daily life of wheelchair users, in order to be able to determine the primary challenges faced by them, three main themes were identified from the interviews: 1) Embracing Uniqueness: Navigating The Journey of Acceptance And Adaptation in Self And Society; 2) Fostering Connection: Building a Compassionate Community For Inclusion, Friendship, And Social Integration; 3) Empowering Independence: Navigating Daily Living. To inform *Phase 2* more accurately, the participants' opinion on VR technology was also analysed, and presented in a further theme: 4) VR: What Wheelchair Users Really Think. The subsections below present the results of each interview theme, while a graphical summary of the themes with their main sub-themes can be found in Figure 3.2.

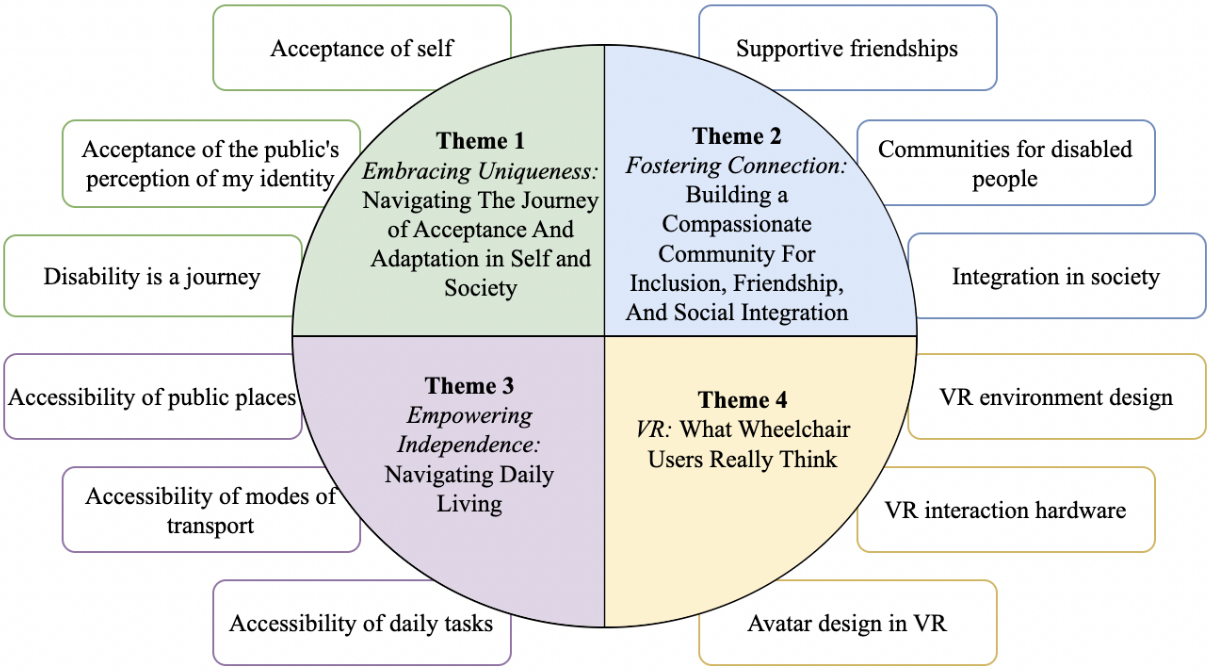

FIGURE 3.2: Main themes and sub-themes identified in the interviews.

3.4.4.1 Embracing Uniqueness: Navigating The Journey of Acceptance And Adaptation in Self And Society

The interviews gave an insight into the challenges of accepting one's disability. In particular, three main challenges were identified: accepting oneself, accepting how others view oneself, and how disability is a journey that changes over time. The findings indicate that acceptance is an ongoing process, not defined by the length someone has had their wheelchair for. Nonetheless, two participants stated initial acceptance as being more challenging:

"It's not so much an issue for me these days but accepting that help in the beginning when I first started was a lot harder." (P4)

"When I first started using a wheelchair I was still at primary school, so my biggest struggle was worrying about what all my friends and other people at school would think of me now that I was using a wheelchair every day." (P5)

This acceptance is defined not only by adjusting to the physical changes but also to the emotional ones. In fact, one participant stated:

"I would probably say that umm it's more of an emotional I mean more a psychological thing than a physical thing (mumbling) to be in a wheelchair." (P1)

Indeed, the feelings shared by P1 are not uncommon. Physical disabilities have been shown to impact the feelings and attitudes toward one's body [117, 118]. The societal stigma on disability may be at the root of this, as there is a lack of awareness about disabilities and how to appropriately behave towards those in a wheelchair.

"I think that's probably the biggest thing I've had to overcome was I guess just that you know people looking at you and that sort of thing." (P1)

"I just find there is not a lot of awareness about disabled people you know." (P1)

Researchers believe these behaviours towards people in wheelchairs vary based on the beauty standards of the societal settings of the people [117], with poorer countries having a higher stigma regarding disability [119]. These stigmas cause uncomfortable interactions between wheelchair users and others; they also cause wheelchair users being stared at, both of which lead to feelings of discomfort and insecurity [120]. Naturally, these stigmas affect one's acceptance of their own disability as social relationships are important for the mental health and well-being of people with disabilities [121]. As such, to ease the acceptance of the disability it is critical to have a support network. Taleporos and McCabe [117] conducted interviews with physically disabled people and found that every interviewee had struggled with their body image acceptance, and what has helped is positive feedback from their partners and others. Similarly, P4 agrees that social support is important:

"I got on with it really yea I suppose other than talking to my family getting support from them." (P4)

However, participants who would like professional help to aid them with their journey toward acceptance encountered difficulty in locating suitable support, as existing services are not tailored to accommodate those with disabilities:

"I think the umm stuff I've accessed in the past can be quite ableist in terms of how it comes across with alternatives, and you know it's all very led on look at yourself in the mirror and breakdown your appearance, and you know it doesn't really take into account the fact that there were days that I can't physically get to that mirror to do those things." (P2)

This could stem from a lack of awareness among professional services regarding the different ways in which disabled individuals may experience relationships with their bodies:

"Disabled people we have varying relationships with our bodies that tend to be very different to able bodied people's relationships with their bodies." (P2)

Further affecting the processes of acceptance is the fact that disability changes over time, it can get more severe or improve. As the physical limitations change, the wheelchair might need changing which leads someone to have to re-adapt to a new wheelchair. This experience can be daunting:

"When you are fitted for the chair, so you're physically fine in it, and then once your therapists are all happy and you're physically sat right you're OK, and you let go and you leave your old chair behind and instantly you get thrown into familiarising yourself with a new one, and the capabilities and how different things feel and that's daunting for me as a fairly articulate adult with years of new chair pickups under my belt." (P2)

Throughout the journey of acceptance, personalising the wheelchair can be beneficial, as individuals often use fashion as a means of self-expression. Wearing a preferred clothing style brings comfort, and thus to successfully integrate the wheelchair as an extension of oneself, it could be beneficial to incorporate it into one's fashion choices. In fact, one participant, who customised their own wheelchair to match their outfit, and who seemed most confident, stated:

"Obviously it's a part of me so I've got to make it fit you know, so like you said yea it is my legs essentially isn't it? Let's be honest it is my legs this is how I walk." (P1)

This theme highlighted how using a wheelchair for mobility is a unique experience that varies from person to person, from disability to disability. Nonetheless, acceptance of the disability plays a critical role in the well-being of a person. Finding a solution to improve one's perception of their body image is important as negative body image can lead to mental health problems and reduced social and occupational functioning [118].

3.4.4.2 Fostering Connection: Building a Compassionate Community For Inclusion, Friendship, And Social Integration

The interviews found that challenges are encompassed within social integration limitations. There are three main aspects that can help mitigate these issues in social settings, namely communities for disabled, friendships and a proactive effort for a successful integration in society. The lack of these aspects is a challenge especially in situations that are unavoidable for wheelchair users to be in, as it can lead to them feeling left out. For example, P3 recalls challenges in integration faced when going to school:

"I always I tried to umm participate in especially sports day and stuff like that I tried to find ways to integrate into it, but obviously there wasn't much that I could do because if umm my physical mobility as well." (P3)

In these situations, a multi-layered approach to physical education which includes a collaboration between teachers and students needs to happen [122]. In fact, when appropriately adapted, these spaces can be a positive influence in one's life. P5 positively recalls spaces that were adapted:

"Support for me was really good, my home was adapted for me so I had all the equipment I needed, the same went for school I had lots of support which was amazing." (P5)

Moreover, positive support is often found in friendships.

"I've always had different people to help me, and I've made some good friends over the years that are very understanding and from my limitations." (P3)

Nevertheless, the activities one engages in with friends may need to be tailored according to their varying motor skills.

"I have friends for years that are wheelchair users as well as you know [NAME] but I've also got close friends who are able-bodied as well. I just cater the activities that I do depending on who I'm doing them with." (P3)

Alternative activities like board games and drawing can be a plausible solution, as was mentioned by the participants, that can be enjoyed by individuals with diverse motor abilities simultaneously. Further, online platforms for socialising play a crucial role in connecting people to their friends, particularly for those who are unable to leave the house. Currently, the participants use devices a lot to communicate with friends, by making phone calls, messaging and even joining online community groups. Specifically, one participant, P2, who struggles to engage with others due to having to stay at home, finds online platforms to be useful:

"A lot of my interaction with them is obviously done online so I spend a lot of time in community discords and things like that." (P2)

Though friendships are not limited based on one's disability, participants find it can be nice to speak to people who have gone through similar experiences and who might relate to struggles. In fact, one participant explained how they found comfort in talking to a friend with similar restrictions after being fitted for a new wheelchair:

"My friend [NAME], she was the one I went to and I kind of said to oh that was so frustrating, and she was the only person that kind of understood that on a level because she's got that same experience and she has the same sort of physical limitations as I do." (P2)

Considering the importance of building friendships with people of similar disabilities, community centres might be helpful to bring people together. Further, they can be help with other aspects, beyond emotional support. For example, to play sports it is important to join communities centres as everybody needs to be similarly abled to play fairly, as highlighted by the participants; they can also help with various aspects, like finding an adequate driving instructor and providing support when purchasing an adapted car.

"Without them [company that helps with mobility] I don't think I would have ever been able to drive because this equipment is so advanced and expensive, and they really provide you support." (P4)

However, the importance of mixing with people of all kinds of motor abilities, should not be forgotten.

"I think that just kind of hammers home to me the importance of having wheelchair users and able-bodied people my social spaces." (P2)

Allowing a person to be part of different communities is necessary for a rounded integration in society, and a human right as defined by the United Nations (UN) Human Rights Office [123]. As such, efforts should be made in enabling integration both of infrastructures and communities.

3.4.4.3 Empowering Independence: Navigating Daily Living

The main challenge within everyday life, found in the interviews, is accessibility. This includes accessibility of public places, transport, and of everyday tasks. Though it can be self-explanatory, sometimes when visiting new unknown places, it is hard to find information on their accessibility. Further, as participants explained, just because a place has accessible parking it does not mean the whole location is accessible or that getting there is accessible. This information is necessary for someone in a wheelchair to appropriately plan their outing.

"You can't always be as spontaneous as you would like to be. It takes a lot of planning and preparation to go anywhere when you're in a wheelchair really umm so yeah in terms of struggles I guess it's mainly access." (P4)

This is especially difficult in rural areas, away from big cities, as information is more restricted. This limitation makes it difficult for someone to pursue their hobbies, without doing prior research on access:

"I'm quite social, I love going out with friends for meals or just hanging out with my friends, umm yeah going to theatre shows or comedy shows, umm music I love live events, going to gigs and concerts so all these types of venues I would research in advance for their access." (P4)

Further, certain social spaces do not allow for the inclusion of wheelchair users. Indeed, some recreational spaces and activities exhibit "ableist" tendencies, lacking friendliness towards individuals with disabilities [124]. Issues related to accessibility also arise during travel, particularly in public transportation, with flights being a notable example. The air travel experience can be undignified, as they require wheelchair users to be lifted from their chairs to be seated. Further, wheelchairs are placed in luggage hold often resulting in damage and toilets are inaccessible.

"I mean they are, you can, I have been on aeroplanes in the past ... it's very difficult because I can't physically get in and out of the wheelchair myself; you have to be lifted which is very undignified and uncomfortable, and then once you are lifted obviously your wheelchair is put into the luggage hold umm and the amount of stock times and stories you hear of like wheelchairs get damaged. You get to your location and then your chair has been broken you are completely you know screwed without it." (P4)

Limited accessibility when pursuing hobbies, also affects non-physical activities. Even in gaming, difficulties are found as P3 explained:

"I used to use PlayStation a lot but now I can't oh and PC as well, but I can't use these remotes anymore. The only games I can really play are on mobile applications so I'm quite restricted there as well." (P3)

Thus, to facilitate seamless daily living, assistance from Assistive Technology (AT) and caregivers is essential. In terms of AT, which refers to any piece of technology that assists individuals with a disability [125], ways to get individuals interested in using it are common devices such as smart home technology, which enable home control through smartphones or voice recognition. In fact, P2 describes how mainstream technology has positively influenced their life.

"I do have the more specialist pieces of equipment umm but definitely the more mainstream stuff in a way made me more open to having them all specialist stuff." (P2)

"Just having the independence and the autonomy to make choices like that for myself has been yeah really game changing." (P2)

AT also plays a pivotal role in enhancing education by providing tailored support to individuals with diverse learning needs. Through a variety of tools and resources, AT facilitates improved accessibility and inclusiveness in educational settings. These technologies can encompass a wide range of solutions, such as screen readers, speech-to-text software, graphic organisers, and specialised learning apps. By leveraging AT in the educational environment, students with disabilities can overcome various challenges and participate more actively in academic pursuits. In fact, P2 speaks fondly of it:

"Assistive technology does do wonders I mean from a sort of education standpoint." (P2)

Importantly, AT is able to close the gap between people of differing abilities, as explained by P2:

"It kind of narrows the gap between me and my peers and makes socialisation and common experiences a lot easier." (P2)

AT has an overall positive impact on people's lives, and even though it can be expensive equipment to purchase, people state that the cost of AT in relation to its benefits on their lives is a bargain [126]. However, there are still things that cannot be achieved with AT and that require the assistance of other humans to facilitate; to meet these needs carers play a crucial role. Finding a good trustworthy carer that someone would feel comfortable with is hard, as in some areas resources are limited as explained by P5:

"I do think it could be a lot better. I need more support in terms of care, my mother is still my main carer because there's such limited resources in my area." (P5)

Not being able to receive support from an appropriate carer is an issue. Caregivers play a crucial role in addressing various aspects of life, including physical needs, thereby empowering individuals to lead independent lives. P4, described some examples of assistance carers provide:

> *"All of the initial personal care so washing dressing just support to help live an independent life really so I live in my own bungalow I have my own place, but I've got helpers that come help me maintain that independence to live alone." (P4)*

The relationship between wheelchair users and carers is important and helps different aspects of one's life. Carers can be a great support, not only for their physical needs but also for emotional ones such as confidence [127]. Nonetheless, it must also not be forgotten that being in a wheelchair does not mean a person cannot do a lot of activities, as highlighted by P1.

> *"Just because I can't walk doesn't mean I can't do a lot of other things." (P1)*

3.4.4.4 VR: What Wheelchair Users Really Think

Developing a VR system that caters to the needs of wheelchair users, necessitates an understanding of the wheelchair users' viewpoints on the technology. There are three main aspects that merit particular consideration which are the VR environment design, the type of interaction with VR employed, and the virtual avatar design. The design of a VR environment can significantly vary according to personal preferences, and this holds true for wheelchair users as well. The preferences of the participants in VR design were contingent upon the specific application and their individual opinions. Notably, participants expressed a positive inclination towards two main applications: gaming and immersive activities that are challenging for them to do in real life. Overall, the feedback on VR was favourable, with participants expressing eagerness to explore its possibilities. A noteworthy limitation of current VR technology is the lack of its accessible hardware and limited awareness regarding applications that are accessible, which is the reason why some of the participants have not tried it as P1 explains:

> *"I haven't used VR before because of that reason because I'm not sure if I would be able to use it or not." (P1)*

The limited awareness regarding accessible VR has also been found in other studies, where wheelchair users have expressed a belief that they would be unable to fully experience VR due to control-related challenges [37]. Despite this, wheelchair users acknowledge the increasing popularity of VR and express a desire for applications to be more accessible. In particular, P1 expressed:

> *"I mean I think it's gonna get to a point where people are gonna start, its gonna become a mainstream thing where people learn from VR and stuff so if that happens I 100% wanna be part of it." (P1)*

When asked about the applications they would consider using, participants provided diverse responses. Notably, some expressed a strong desire to simulate activities they cannot do in real life due to their physical abilities. For instance, one participant wished to experience tasks that are often taken for granted by those without physical limitations, such as walking upstairs (P4). Additionally, another participant suggested the potential benefit of an application that facilitates users in adjusting to a new wheelchair, whether due to needing to change the wheelchair or for individuals new to wheelchair use (P2). In particular, participants suggested the following applications:

> *"I think some kind of VR familiarisation with what it is to use a wheelchair whether it's manual, whether it's powered, what the controls are gonna look like, I think that has the potential to be really useful and kind of take the fear out of it because you could get used to how the wheelchair feels, [...]. So I think that would be really powerful for someone younger or someone umm with an acquired disability or yeah someone just changing chairs." (P2)*

> *"Going to somewhere that you couldn't physically do yourself in real life umm I'm trying to think of an example of actually you know you know something easy as in going on an airplane or walking up some stairs or walking on a plank like a diving board type thing. Things that you wouldn't usually be able to do I guess, yea I can see why that would be a fun an interesting experience for someone umm with a disability." (P4)*

Similarly, when considering the Point-of-View (POV) by which the user interacts within a VR application, participants voiced diverse opinions depending on the application. This pertained to whether participants preferred viewing themselves in third person or first person, and also if they desired to engage with VR as themselves or assume the perspective of another character. However, according to one participant (P4), the essence of VR lies in the ability to undergo experiences that are otherwise challenging in real life, all while embodying oneself in the virtual world.

"Okay ya I think I would like to see it as myself, like I would want to like experiencing that as as me more so than a character or anything, umm yea I think for me that's the joy of, that could be the joy of, VR. You can experience it as yourself." (P4)

Despite this, some participants support the idea of embodying a different character; this perspective is consistent with the findings in the literature. In fact, the choice of avatar representation is influenced by factors such as the application type, the task at hand, and personal preferences [38]. Regardless of these VR choices, wheelchair users express enthusiasm to explore the potential of VR applications to help them, with P2 highlighting that their belief in the potential of VR motivated them to partake in this study.

"It was one of the reasons why when I heard that your research I was kind of all down for coming and speaking to you, because that experience and sort of the potential I know VR can do now really stood out for me". (P2)

3.4.5 Summary of Findings: What Are The Main Challenges Identified From The Interviews?

The interviews gave an insight into different aspects of the interviewees' lives, and as such different challenges were identified. Importantly, it was found that self-acceptance can be a difficult journey with it being especially hard during initial wheelchair adaptation. In accordance, extensive literature that highlights the effect a disability has on one's self-esteem was found, which in turn negatively impacts multiple areas of one's life [121]. Struggling to accept oneself has been related to society's stigma on disability [117], which also affects another common challenge, namely integration. Integration within some social spaces is difficult for wheelchair users, as a lot of spaces are inherently "ableist". This is for social communities and infrastructure accessibility. Accessibility is a main limitation, requiring wheelchair users to having to always plan ahead, prior to accessing certain spaces or taking part in certain activities.

3.5 Phase 2: Workshop

The second part of the study consisted in a workshop conducted with researchers. The aim of the workshop was to identify VR solutions that could be developed to help mitigate the challenges, faced by wheelchair users, found in the interviews. The following sections present the methodology used, the findings, and a brief discussion.

3.5.1 Participants

The requirements for the participants of the workshop were: 18 years old or older, can speak, write, and read in English, and be a researcher in an engineering-based subject or related field. The requirement of being an engineer or working in a related field was chosen due to the problem-solving abilities associated with the subject, and expertise with technology. After recruitment, a total of 6 researchers participated in the workshop. The participants were PhD graduates in electronic engineering ($n = 2$), PhD candidates in biomedical engineering ($n = 1$), and PhD candidates in electronic engineering ($n = 3$), with their background being in biomedical engineering ($n = 3$) and electronic engineering ($n = 3$) and having experience in the field of HCI ($n = 1$). Further, all participants had experience with using VR applications.

3.5.2 Workshop Methodology

From *Phase 1* it was found that wheelchair users have a positive outlook on VR and are eager to try applications designed with their needs in mind (section 3.4.4.4). After a discussion amongst the primary collaborators ($n = 3$, CZ, AC and LT), it was concluded that potential solutions to the found challenges should be explored in two groups: to help people with their problems before they face a challenging situation and to support people when they are facing a challenging situation. Consequently, in the workshop, the three main themes from the interviews were presented that discuss the challenges of the interviewees, with quotes, and some videos of other wheelchair users talking about struggling with the same challenges. Afterwards, the participants of the workshop were randomly split into two groups exploring the following topics:

- Indoor training to prepare the user to face the challenges in real life.
- Outdoor assistive system for when the user is facing the challenges.

The workshop agenda was as follows:

1. Step 1: *Introduction.* The participants were first introduced to the study, the study aims, the main themes extracted from the interviews and the workshop aims.

   Study aims: To understand the struggles wheelchair users may face to develop a technological solution that can help new wheelchair users.

   Workshop aims: Generate ideas for how new wheelchair users can be trained to face various challenges.

   How can wheelchair users be trained?

- Wheelchair users can be trained at home in preparation for the challenges.
- Wheelchair users can be supported when they are facing the challenges.

2. Step 2: *Creating empathy.* Some of the interview results were presented and videos were shown of other wheelchair users describing these struggles in more depth.

3. Step 3: *Possible solutions.* Some studies were presented which tried to identify some possible solutions to some of the struggles, as well as videos from wheelchair users discussing other solutions. The interview results of how the interviewees feel about technology, specifically VR, were also presented.

4. Step 4: *Brainstorming.* The participants were asked to individually brainstorm what technological solutions could be developed to address the challenges presented in Step 2. Afterwards, they were split into two groups (indoor solutions and outdoor solutions), where as a group they discussed what VR technologies could be developed for their respective topics, to finalise one big idea per group.

5. Step 5: *Presentation.* Each group presented their ideas with a poster as a visual aid.

The workshop was run by the author of this thesis, with the assistance of the other two primary collaborators (AC and LT) and lasted 2 hours.

3.5.3 Workshop Data Collection And Processing

Data collection occurred during the Step 4 and Step 5. Initially, in Step 4, participants individually brainstormed ideas by jotting them down on notecards (n = 13). This exercise aimed to stimulate participants' creative thinking, preparing them for the subsequent group brainstorming. Though the ideas from this session were not analysed or included in the final outcomes, they are documented in section 3.5.4.1. Following this, participants were split into two groups to brainstorm collectively, with their ideas captured in poster format (n = 2), focusing on developing VR solutions for challenges encountered by wheelchair users. These were presented in Step 5. These collaborative ideas were analysed by group, with findings detailed in section 3.5.4.2 and section 3.5.4.3.

3.5.4 Workshop Findings

The workshop findings are split between overall technological ideas (generated in Step 4), VR indoor solutions group and VR outdoor solution group (generated in Step 4 and presented in Step 5). The results of both VR groups are summarised in Figure 3.5.

3.5.4.1 Overall Technological Ideas

The technological ideas the participants brainstormed individually fall under three categories: Accessibility And Mobility Enhancements, Technological And Interactive Features, Empathy And Experience Sharing. As such, they are narratively presented in Table 3.1.

TABLE 3.1: Outcomes of technological ideas brainstormed by the workshop participants individually.

Accessibility And Mobility Enhancements	**Technological And Interactive Features**	**Empathy And Experience Sharing**
Wheelchair parts/accessories designed to change colour to match the user's outfit.	Extendable robotic arms to grab/collect items, controlled by the joystick.	Wheelchair users' friends/family spend a day in VR wheelchair to understand what it is like.
Incorporate a dark, shield-like screen around the wheelchair, similar to tinted car windows, to provide privacy when needed.	Switch to eye-tracking navigation control when needed.	VR environment with worst-case situations (e.g., people staring) to help wheelchair users face these situations.
Built-in ramp into the wheelchair to assist users in navigating areas with stairs.	Tablet incorporated into the wheelchair to watch something in order to allow users to distract themselves when feeling uncomfortable.	
Adjust wheel configuration or add additional wheels to the wheelchair to facilitate easier navigation over gaps and obstacles.	Tablet integrated into the wheelchair that allows users to monitor their requirements, including the proximity of other wheelchair users.	
Integrate a lifting mechanism to elevate the user to a higher position as required.	A system that monitors emotional state through ECG readings, and upon detecting changes in values, initiates a feedback mechanism, such as playing music.	
A wheelchair that syncs with an app to automatically display accessible locations and routes.		
A wheelchair equipped with an automatic lighting system that activates based on the user's location.		

3.5.4.2 Indoor Solutions Group

The participants came up with a versatile VR training system, as seen in Figure 3.3, designed to address a range of applications. This innovative system incorporates a VR headset seamlessly integrated with a wheelchair, offering assistance in various scenarios. It aims to alleviate anxiety-inducing situations, such as the fear of being scrutinised by creating a virtual world where people gaze at the user while monitoring their anxiety levels through an Electrocardiogram (ECG) monitor, and subsequently adjusting the environment to help users confront and overcome their fears. Additionally, the VR system provides a wheelchair buddy to serve as a guiding and comforting presence during stressful situations. Moreover, the system facilitates practical training for real-world challenges, including parking in public transport and route planning, allowing users to familiarise themselves with these situations, enhancing their confidence and comfort when the time comes to navigate them in reality.

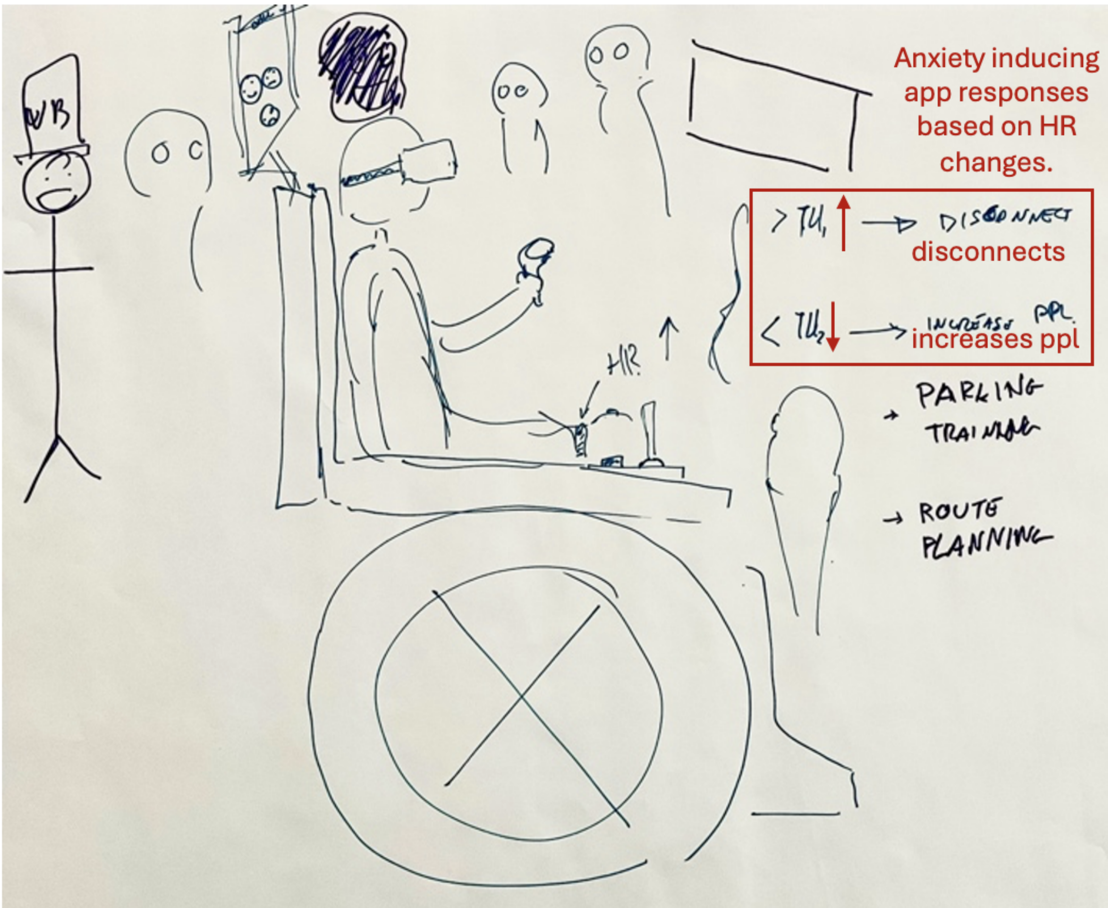

FIGURE 3.3: Sketch of the VR system designed by the indoors solutions group.

3.5.4.3 Outdoor Solutions Group

The participants also came up with a VR training system with a wide array of applications. However, as this system is intended to be used outside and "on-the-go", perhaps Extended Reality (XR) would be a more suitable solution. XR by definition is "an environment containing real or virtual components or a combination thereof, where the variable X serves as a placeholder for any form of new environment" [128], and thus could be used to allow users to be aware of their surroundings while operating the virtual system. This system also integrates a VR headset with a wheelchair, offering invaluable assistance in various ways, as seen in Figure 3.4. Firstly, it includes a mood control activity designed to soothe individuals experiencing anxiety, providing a means to regain emotional equilibrium. Secondly, it boasts an accessibility map, illuminating accessible locations and outlining the routes to reach them via wheelchair-friendly paths. Thirdly, a "hot-spot" map indicates areas of high congestion and spots where fellow wheelchair users gather. Beyond its VR capabilities, the wheelchair itself features customisable design options, allowing users to tailor its appearance to their personal preferences and needs.

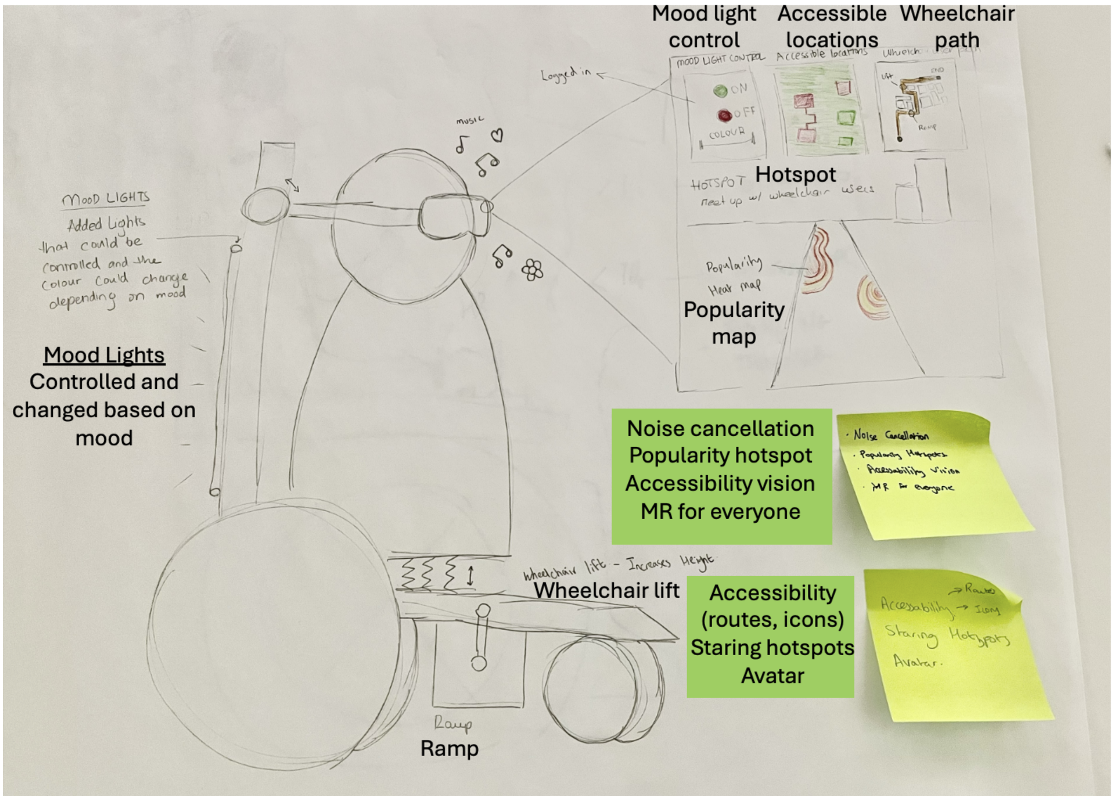

FIGURE 3.4: Sketch of the VR system designed by the outdoor solutions group.

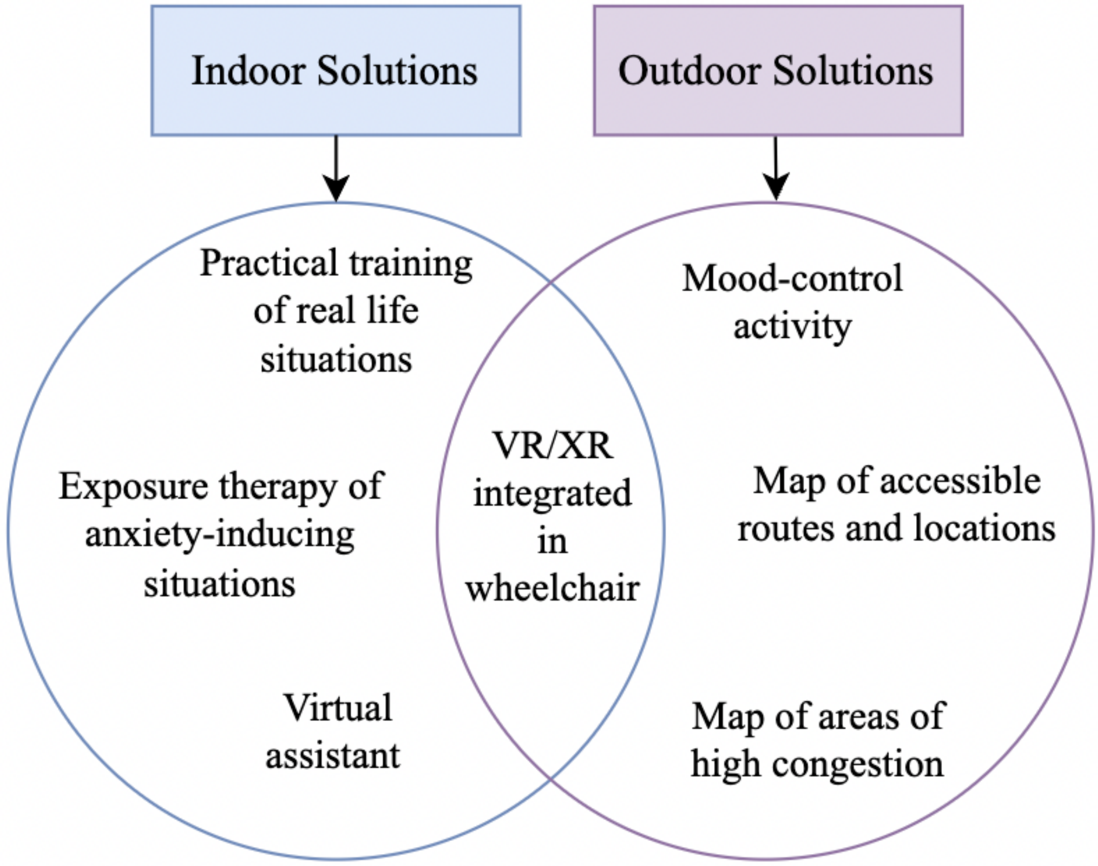

FIGURE 3.5: Main solutions proposed by the two groups of participants.

3.5.5 Summary of Findings: How Can VR be Utilised as an Intervention That Supports New Wheelchair Users in Overcoming Challenges?

The workshop led to fruitful discussions between researchers regarding potential applications of technologies to support someone who is new in a wheelchair to overcome the challenges ahead. Though many struggles were identified in the interviews that are deserving of a solution, not all of them were possible to be discussed. However, the workshop started a conversation that should be continued further.

In the workshop, potential technologies were categorised into two primary categories: indoor training solutions and outdoor assistance solutions. By harnessing the capabilities of VR technology, it is possible to maximise the versatility of a single device, tailored to individual needs and thus use it to address the challenges present in each category. With a VR headset that can be effortlessly attached to and detached from a wheelchair, individuals can conveniently employ it as required. It was discussed how this VR application could be used to address accessibility, by allowing participants to see what places are accessible, how to reach them, and practice skills required to accessing them safely. Current VR technologies do offer navigation skills training [5, 12], with some being specific to certain settings such as navigating through crowded spaces and going grocery shopping [129]. However, personalised routes that mimic real-life settings could be even more beneficial. Another application in which VR could offer support for indoor driving solutions is to train somebody to face anxiety-inducing situations, by mimicking in VR situations which provoke someone to be uncomfortable in real life, as VR exposure therapy for social anxiety disorders has shown positive results [130]. Exposure therapies have also shown to be effective for other conditions such as anorexia nervosa [10]. For someone new in a wheelchair, getting used to the new changes of their physical body, VR could be used to stimulate self-compassion and empathy as compassion interventions lead to positive thoughts towards self and others [11].

In outdoor training scenarios, an accessibility map could serve as a crucial tool. This application would display wheelchair-accessible routes to reach one's destination, while also showing the accessibility status of the location itself. While accessibility maps have been developed for smaller environments like university campuses [131], they do not yet exist for larger-scale settings. Introducing a VR-based version of such a map that can be utilised on the move would enhance the user's immersion in the map, enabling them to gain a more precise understanding of the route and its accessibility.

Though currently VR technologies have been developed for wheelchair users in the fields of wheelchair skills training [5, 12], VR tourism [33, 34], and games even, a lot of applications are not very accessibility friendly as hardware and controls are inaccessible for some people depending on the disability. So far, research lacks a proper understanding on how to incorporate and represent minority bodies in VR [36]. To make devices more adaptable, VR could be incorporated into the wheelchair as an extension and using the wheelchair's existing controls. However, to develop accurate solutions end-users need to be included in the design process of these applications.

3.6 Creative Catalogue of Ideas

Throughout the study, different challenges faced by wheelchair users were identified, for which VR can provide a plausible solution. As such, a creative catalogue of ideas incorporating both theoretical suggestions in Application Software Design and Application Hardware Design can be made, as described below.

3.6.1 Application Software Design

The outcomes of *Phase 1* revealed that addressing the challenges encountered by wheelchair users should be divided into two categories of assistance: indoor solutions and outdoor solutions. Employing VR technology as a solution offers the advantage of consolidating these ideas into a single application. This integrated application allows users to select the specific program they wish to engage with, effectively addressing both indoor and outdoor challenges. Recognising the significance of creating a welcoming environment, it can be proposed to commence the application with a home screen designed to greet the wheelchair user. Drawing insights from *Phase 2*, a notable suggestion is the inclusion of a VR wheelchair buddy to offer support and guidance. This "VR wheelchair buddy" could be envisioned in the form of a virtual assistant. This approach would be particularly advantageous given that research findings indicate a reduction in bias towards wheelchair use when instructions are provided by an avatar in a wheelchair [47]. However, the importance of providing customisation options for the virtual assistant must be emphasised, ensuring users feel the utmost comfort with the application. Similarly, customisable avatars within the application would be beneficial, as the literature suggests that the choice of avatar representation is influenced by the application type, task, and personal preference [38]. Lastly, the home screen could incorporate a feature allowing users to specify the type of assistance required: indoor or outdoor. This comprehensive approach aims to enhance the user experience by tailoring the application to individual preferences and needs. An example of a suggested home screen can be seen in Figure 3.6

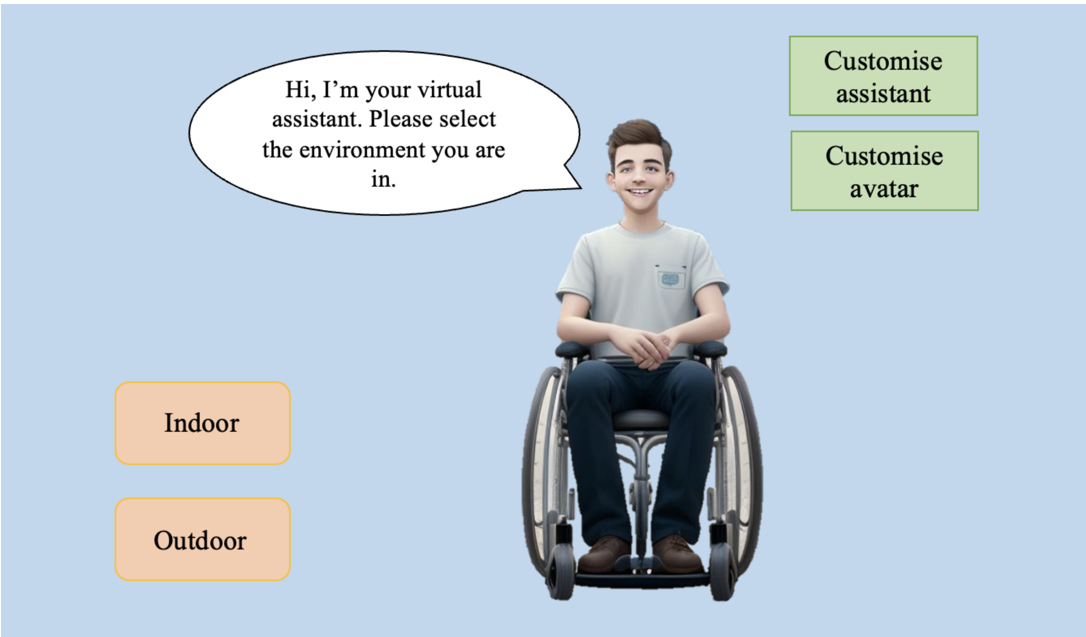

FIGURE 3.6: Example of a home screen for a VR application. The virtual assistant was generated using AI (https://perchance.org/ai-text-to-image-generator).

Once a user selects the kind of help required, the user would be redirected to the appropriate page. The findings of *Phase 2*, propose indoor assistance in three main aspects: navigating social settings, planning outings, and learning wheelchair skills. These aspects would respectively cover the main challenges found from the interviews in *Phase 1*: struggles with acceptance of self-caused by the fear of society's stigma, struggles with accessibility to planning outings and struggles with participating in activities. An example of an indoor assistance page can be seen in Figure 3.7.

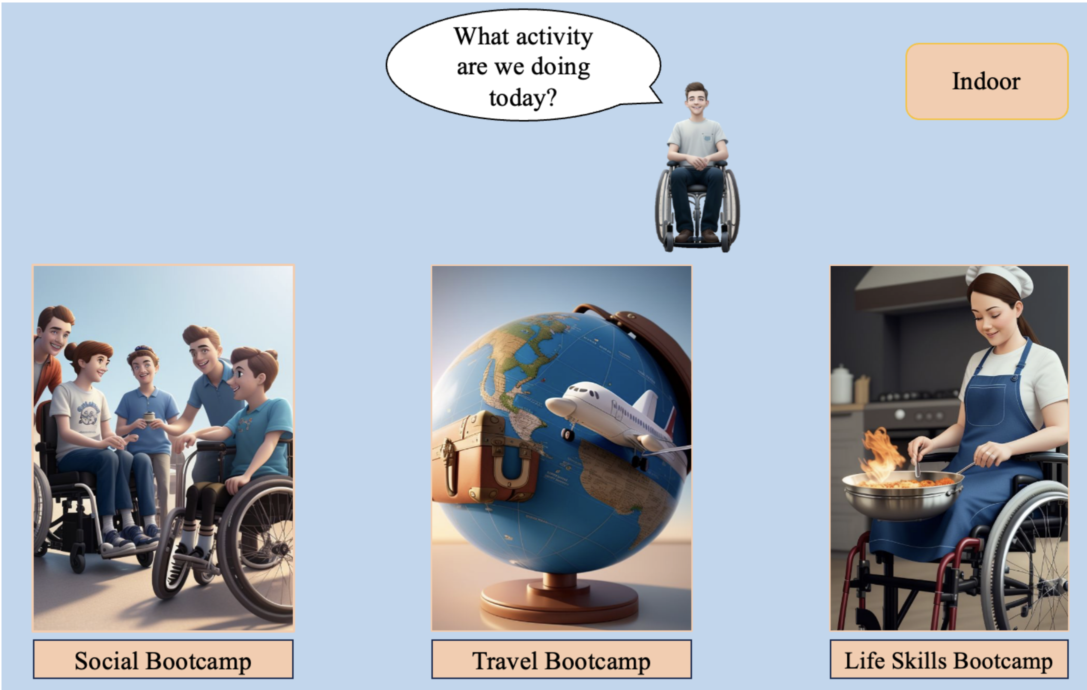

FIGURE 3.7: Example of an indoor menu for a VR application. The images were generated using AI (https://perchance.org/ai-text-to-image-generator).

Similarly, the findings of *Phase 2* propose outdoor assistance in three main other aspects found from the interviews in *Phase 1*: finding accessible routes on the go, spotting crowded location, and help with controlling the mood when perhaps anxious or low. An example of an outdoor assistance page can be seen in Figure 3.8.

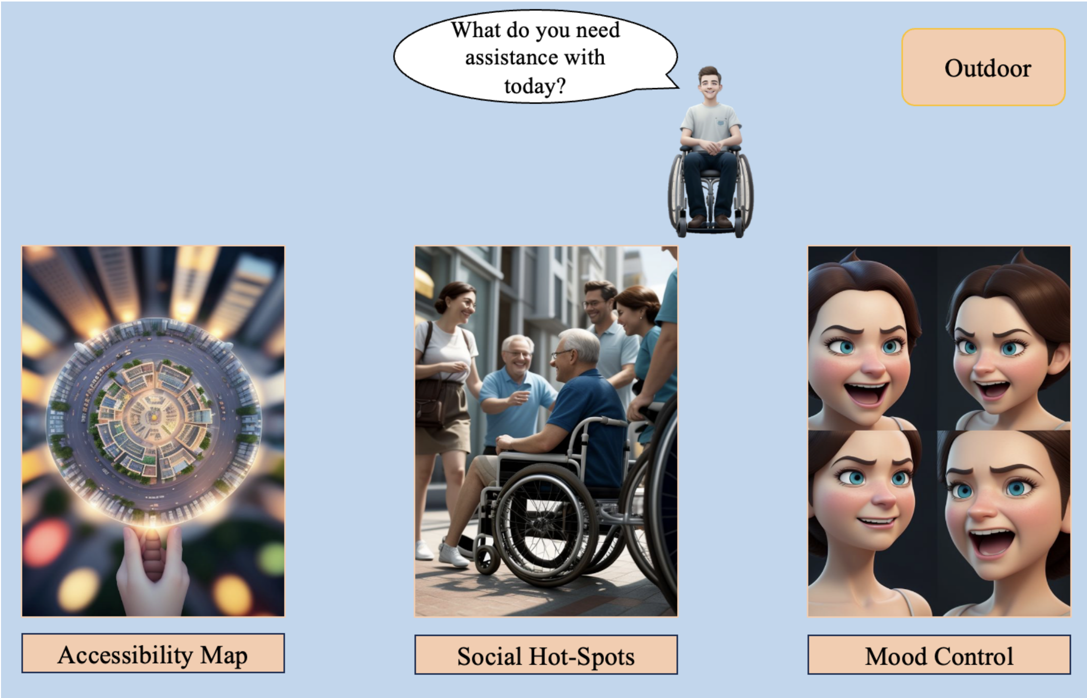

FIGURE 3.8: Example of an outdoor menu for a VR application. The images were generated using AI (https://perchance.org/ai-text-to-image-generator).

3.6.2 Application Hardware Design

Though different application designs were discussed in *Phase 2*, the main limitation to why VR is not popular amongst wheelchair users needs to be considered, which is the inaccessible hardware. Wheelchair users might be unable to perform full-body interactions, and the weight of carrying the VR headset may be uncomfortable [29]. Consequently, when developing interaction hardware, it should not be assumed that a user has one or both hands available, but there should be options adaptable to different motor abilities [38]. For some wheelchair users, VR could be controlled with sensors built-in the headset such as eye-gaze, motion and audio sensors [38]. Thus, it is possible that adapting the wheelchair's built-in driving control, whether that is a joystick or else, to VR could be beneficial, as that way a user would use the same control in VR as in real life. Further, to ease the weight of the headset or the difficulty of putting it on, the headset could be developed as a wheelchair extension, where it is always on the wheelchair and the user can use it when required.

3.7 Overall Conclusion

This chapter aimed to answer R1: *In what ways can the insights and experiences of long-term wheelchair users contribute to the development of solutions tailored for individuals* *new to using wheelchairs?* As such, the aim for the study presented throughout this chapter was to understand how the advances in VR technology can be used to facilitate the transition to wheelchair use, with the goal of helping future generations of wheelchair users get adjusted to their lives more easily. The results show under the point of view of a wheelchair user what life is like and some potential solutions to some challenges that they face were suggested. This approach does not only highlight one aspect of a wheelchair user's life, rather it presents the overall life experiences. Further, the interviewees were a group of diverse people with different disabilities. This allowed for an understanding of varying needs and what barriers are commonly faced by everyone. It was found that an overarching theme is struggling to be confident and to feel included in society due to accessibility issues and the behaviours of strangers.

By conducting a workshop with researchers who are engineers, a fruitful discussion was held about how to best harvest the benefits of technology to develop solutions to assist wheelchair users with their problems. With this, the author of this thesis hopes to start a conversation about the design requirements of inclusive future of technologies. The author of this thesis believes that VR's fast-paced growth and development could provide applications beneficial to wheelchair users. To do so, the special needs and requirements of wheelchair users need to be kept in mind throughout the development phases of the technology, and ideally, wheelchair users are to be included in the development.

In the next chapter, Chapter 4, a more specific field of VR for rehabilitation of wheelchair users is explored, namely VR as a tool for driving skills training. Specifically, an alternative VR navigation controller and a standardised way of assessing skills acquired in VR wheelchair driving training are proposed, and two studies are presented in which these are tested. In the first study, the proposed controller and standardisation are validated; while, in the second study, the effects of gamification on driving skills training are explored.

Chapter 4

Enhancing VR Powered Wheelchair Driving Skills Training

The previous chapter, Chapter 3, outlined the challenges encountered by wheelchair users and proposed VR applications that could address them; this provided an overarching view of VR's potential as a rehabilitation tool for those new to wheelchairs. The current chapter shifts the attention from this broader overview to a specific application where VR has played a significant role in wheelchair rehabilitation: training for driving skills. Specifically, this chapter builds on the literature review conducted in Chapter 2, Section 2.2. In alignment with addressing the gaps identified in current VR training applications for driving skills, the research question investigated throughout this chapter was defined as follows: *How can VR be used to develop an affordable wheelchair driving skill training system, and can a methodology be implemented to assess its effectiveness?* Thus, the current chapter aims to contribute valuable insights into the development of an effective and affordable VR wheelchair driving skills training system.

4.1 Introduction

Learning to drive a wheelchair safely plays a key role in being able to efficiently conduct everyday activities, thus it is important to undergo skills training [2]. Traditionally, training is conducted in real life within controlled environments. Further, a popular and standardised real-life training program, namely the Wheelchair Skills Training Program (WSTP) [17], has been developed. However, real-life training methods can be expensive and require time and resources that are often not available [12, 63]. These methods are described in more detail in Chapter 2 section 2.2.2.

As a result, research has been conducted to investigate how the application of new technologies can mitigate the shortcomings of traditional training, specifically using VR [16]. Though the benefits of VR training are numerous, as described in Chapter 2 section 2.2.3, such as they can be motivating and mitigate the physical risks faced in real-life training [65], there are also some limitations. Firstly, they normally use joysticks specific to a certain wheelchair [12], or gaming joysticks [12]. These joysticks might not accurately represent what a person uses in their day-to-day life, and it is important wheelchair users get acquainted with the joystick of their own chair whilst remaining seated in their own chair. In fact, as found in the interviews described in Chapter 3 section 3.4, it can be challenging to adjust to new chairs for long-term wheelchair users, thus it might be even harder for someone new to a wheelchair. Furthermore, to date, most VR training programs require the help of a clinician [12], and thus they cannot be conducted independently. These factors may restrict the accessibility of VR training. Importantly, due to the heterogeneity of the VR training methods currently available [5, 12], it is unclear what approach best leads to the acquisition of skills in real life. Thus, there is the need for a VR wheelchair training system that is affordable, user-friendly and that can be used in the comfort of one's own chair and crucially, a system that deploys a standardised approach to assess the actual acquisition of skills.

In this chapter, two studies are introduced, detailing our development of a VR-based system designed for the training and evaluation of wheelchair-driving skills. The system utilises affordable equipment, with the aim of extending its applicability beyond a clinical setting and be accessible by the wider public. In particular, the system uses an inertial measurement unit (IMU) sensor to navigate in VR (as described in section 4.2.3). The sensor is retrofitted to the joystick of a wheelchair, allowing the participants to use the same wheelchair for the real-life assessment of driving skills and the VR training.

The first study, Study 1, serves as a validation study of the developed VR system. As such, it investigates two hypotheses:

- *VR training leads to the acquisition of skills in real life.*
- *Low-cost technology can deliver effective VR training.*

  To test these hypotheses, a standardised assessment is proposed based on the improvement in the user's completion time and the number of joystick movements in various tasks performed in real life (see section 4.5.2), both before and after completing the same tasks in VR. In specific, pre- and post-VR training driving performance in terms of completion time per task and total number of joystick movements per task were compared. An adjusted version of the WST Questionnaire [17] (see Appendix B) was also administered, to analyse the users' confidence in their driving skills.

The second study, Study 2, explores how the effectiveness of VR training can be improved by analysing the effects of gamification on the training of wheelchair-driving skills. As such, Study 2 addresses the following hypothesis:

- *Real-life driving performance after VR training will differ based on the environment.*

  To examine potential variations in learning outcomes due to the differences in environment design, post-VR training driving performance was assessed through the number of collisions, the completion time per task, the total number of joystick movements per task and through an adjusted version of the WST Questionnaire [17] (see Appendix B).

The chapter is structured as follows: first, the hardware of the VR system is described, followed by the software utilised for the development the system; then, the two studies are presented, and analysed together at the end in the conclusion section. It must be noted that the studies also monitored how the VR training affected the participants' well-being in terms of the perceived presence, cybersickness, and HR; however, this chapter focuses only on the part of the studies that addresses the effectiveness of VR training, while the well-being results are presented in Chapter 5.

4.2 VR System Hardware

The hardware components used in both studies are the same and are described below. At the end of the section, a system diagram in Figure 4.9 is represented to show the relationship between all hardware components.

4.2.1 VR Headset

The VR headset used in this research is the Oculus Quest 2 (now known as Meta Quest 2 [132]), as seen in Figure 4.1. The headset can be used as a standalone device, or it can also be connected to a PC via the Oculus Link cable (or a third-party cable), or wirelessly through the Oculus Link Air. For this project, it was connected to a Microsoft PC (section 4.2.2) through a third-party cable (from Anker [133]). Further, it does not require an external base station and has a refresh rate of 120 Hz. It has a 1832x1920 per eye resolution and a 97° horizontal Field of View (FoV). Given the versatility of the headset it proves to be a convenient choice for this project.

FIGURE 4.1: VR headset used for the project: Oculus Quest 2. Image taken from: https://www.pcworld.com/article/393503/oculus-quest-2-vr-headset-launches-for-299-with-2k90hz-performance.html

4.2.2 Microsoft PC

The Microsoft PC, as seen in Figure 4.2, used in this project was the ROG [134] Zephyrus M16 running on Windows 11 with Intel i9-12900H processor, GeForce RTX 3080Ti NVIDIA GPU and 32GB DDR5 RAM. It was used for the development of the VR environments, the data collection, the data analysis and the data storage.

FIGURE 4.2: Microsoft PC used for the project: ROG Zephyrus M16. Image taken from: https://nextrift.com/asus-rog-zephyrus-m16-with-almost-bezel-less-screen-now-in-malaysia-from-rm8999/

4.2.3 VR Controller

To control the navigation in VR an IMU sensor-based controller was developed (by CZ). The IMU sensor was chosen as an affordable alternative to current VR driving controllers. This controller can enhance the independence of performing VR driving training by allowing wheelchair users to conduct the training in their own chair. The reliability of using IMU sensors to drive a wheelchair is explained below (section 4.2.3.1), followed by a detailed description of the system in section 4.2.3.2.

4.2.3.1 Reliability of IMU Sensor-Based Adaptive Joysticks

The majority of VR wheelchair training systems are controlled via a joystick, whether that is a real powered wheelchair joystick [12] or a gaming one [12]. Some exceptions use other training systems, such as eye-tracking [40], sensors on the wheels [39], brain-computer interface (BCI) [41] or a mechanical platform in the case of manual wheelchairs [135]. However, the current VR training systems do not accommodate the users' comfort of using their own wheelchair and joystick. Gaming joysticks do not necessarily replicate the mechanisms of a wheelchair joystick, while in cases where a wheelchair joystick is used, it may be a different one than the joystick wheelchair users utilise in their day-to-day life. Further, to use the signals of a real wheelchair joystick as a navigation tool in VR, the joystick has to be "hacked" to send movement signals to the VR system. Thus, a training system could be more effective and convenient if it was adaptable to a variety of joysticks and, if it was made of affordable equipment that can be used "anywhere anytime". For this, IMU sensors could provide a solution.

The use of IMU sensors has been a topic of research when it comes to driving a wheelchair in real life, by attaching the sensor to a person's body parts. Kundu et al. [136] proposed a system that uses the 'SEN10736' IMU sensor, specifically its accelerometer data, to drive a wheelchair with hand gesture recognition. Nirmala et al. [137] also proposed a gesture-controlled wheelchair, to keep it low-cost using the ADXL335 accelerometer. Similarly, Fajrin et al. [138] and Haque at al. [139] used accelerometers (the ADXL335 and ADLX345, respectively), to control the wheelchair with head movements, rather than hand movements.

For VR training of wheelchair users who require a regular joystick for navigation, instead of having the sensor attached to a body part, having it retrofitted to the joystick would be more beneficial. This way the sensor would also be able to monitor the users' joystick's behaviour, and thus allow for an analysis of the users' driving skills based on joystick movements. In fact, determining improvement in driving skill acquisition based on the users' joystick movements is believed to be an efficient assessment measure to determine the effectiveness of VR training. Hernandez-Hossa et al. [40] developed a VR training and validated the effectiveness of its system by looking at the number of joystick movements, for which they used a classifying algorithm for the joystick's analogue signals to determine the direction of navigation (forward, backward, right, left). Similarly, Archambault et al. [77] measured the joystick's amplitudes to determine improvement in the number of joystick signals, however, their joystick interface was not the one of a real powered wheelchair. Measuring improvement in joystick behaviour can indeed be an indicator of the acquisition of skills, as Sorrento et al. [140] found that expert wheelchair users require less manoeuvres in difficult tasks than novice users.

4.2.3.2 VR Controller Description

The developed controller uses an IMU sensor, specifically the MPU-9250 sensor, retrofitted on the wheelchair's joystick (the Dx2-REM550/551) and connected to an ESP-32 microcontroller, see Figure 4.3.

FIGURE 4.3: MPU-9250 sensor attached to the wheelchair's joystick (Dx2-REM550/551) to control the VR System. Inset A shows the MPU-9250 sensor on the joystick. Inset B shows the ESP-32 microcontroller and the battery that powers it (housed in the yellow case), which is wired to the MPU-9250 sensor and wirelessly sends signals to the Microsoft PC. Inset C shows the MPU-9250 sensor on the joystick from the front view.

As seen in Figure 4.3, the controller consists of various components. The IMU sensor's accelerometer values were collected by the ESP microcontroller via an Inter-Integrated Circuit (I2C) interface and sent via a WiFi hotspot to Unity[79]. The I2C interface is a two-wire interface in which devices can act as a master (initiates and controls the communication) or a slave (responds to the commands or requests from the master). In our system, the IMU sensor acts as a slave, listening to the commands of the microcontroller which acts as the master [141]. The accelerometer was also used to measure improvement of driving skills in real life. The ESP-32 microcontroller was fitted on a battery-powered Printed Circuit Board (PCB), thus making the controller system portable. The sections below describe each component in detail.

- IMU sensor:

  The most important part of the controller is the IMU sensor. For this project, the MPU-9250 was chosen and used to retain the joystick signals to control the navigation in VR and to track the users' joystick movements in real life. A close-up image of the sensor can be seen in Figure 4.4.

  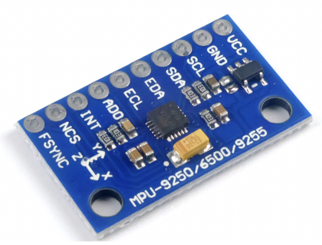

  FIGURE 4.4: IMU sensor utilised for the controller: MPU-9250.

  The sensor was placed vertically on the joystick as seen in Figure 4.3 inset A and inset C. The sensor relies on a supply voltage of 5V and an I2C interface for communication. Being a 9-axis sensor it has a 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer. For this project, only the signals from the accelerometer were used.

  The accelerometer of the MPU-9250, as a MEMS accelerometer, is based on the principle that accelerations correlate to the displacement of a mass attached to a spring; the displacement of the spring is picked by a capacitive sensor [142]. The picked-up signal is then converted to a measurement of acceleration, which is affected by the gravitational force of the earth and is outputted as m/s^2.

  This accelerometer signal differs based on the direction in which the acceleration has occurred, and as such it is possible to derive the direction the sensor is tilted with respect to the ground [143]. Thus, in this project, the accelerometer output was used to determine in which direction the joystick movement has occurred, and therefore this information was used to navigate in VR accordingly. The navigation in VR occurred in four directions: forward, backward, left and right. The sensor was placed vertically and parallel to the joystick (see Figure 4.3 inset A and C 4.4), and the signals on the axes on the horizontal plane were used to navigate in VR.

The accelerometer was also used to determine the total movements of the joystick for each task conducted in the real-life driving sessions. This was done using the signals of the accelerometer (as done to determine the direction of navigation in VR). The accelerometer values of the horizontal plane were recorded for each task, both during the real-life sessions and the VR training, and used to calculate a proxy for the total movements of the joystick, Ljm for each task. Following Farago et al. [144], the Pythagorean Theorem to the accelerometer data to quantify a single movement of the joystick was applied, and then all those values to get a proxy of total movements were summed (done by CZ with guidance from GM).

- Microcontroller: The microcontroller used in this project was the ESP-32, as seen in Figure 4.5. It consumes minimal power, it integrates an antenna switch, RF balun, power amplifier, low noise amplifier, filters, and power management modules, whilst occupying minimal PCB space. It also has Bluetooth (BT) and WiFi properties. It works on a supply voltage of 5V and an interface of I2C, allowing for a smooth communication with the MPU-9250 by acting as the master device. In this project the ESP-32 was programmed using the Arduino Integrated Development Environment (IDE)[145] software platform; the details of the programming are described in section 4.3. The ESP-32 processed the data from the MPU-9250, and its WiFi property was used to create a hotspot to which the Microsoft PC connected to transmit the navigation data to the VR environment.

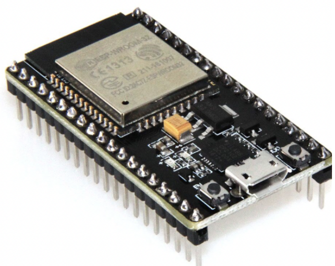

FIGURE 4.5: Microcontroller utilised for the controller: ESP-32.

- Power house: The controller was mainly powered by a lithium-ion battery, seen in Figure 4.6. Lithium is the lightest metal, provides the largest energy density for weight and is small. The chosen battery was charged through a LiPo Charger, seen in Figure 4.7 with Step Booster Converter on the PCB set to 5V to work properly with the other electrical components. The LiPo Charger has an LED to indicate whether the lithium battery is charged or not.

FIGURE 4.6: Lithium-ion battery used to power the controller.

FIGURE 4.7: LiPo battery charger used to recharge the lithium-ion battery.

- <u>Printed Circuit Board:</u> A PCB, as seen in Figure 4.8, connects all the above mentioned electrical components whilst occupying minimal space, through copper tracks on the bottom layer to avoid parallel capacitance. The PCB also includes a power switch to turn the board on or off, and an LED light to show the user when the board is turned on. It also has two ceramic capacitors acting as a dielectric to smoothen the signal and to get rid of noise.

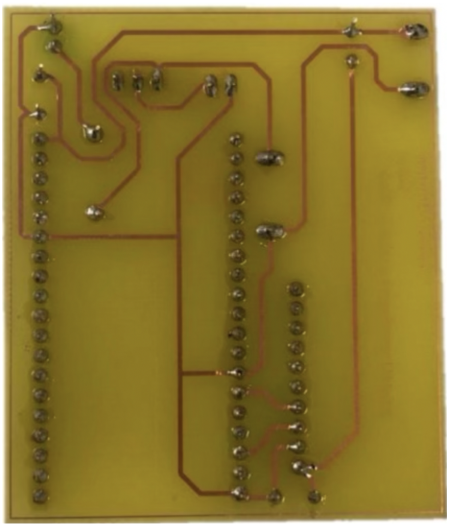

FIGURE 4.8: PCB used to connect all of the electrical components of the controller.

The communication of all the above mentioned components follows the outline of the system diagram in Figure 4.9.

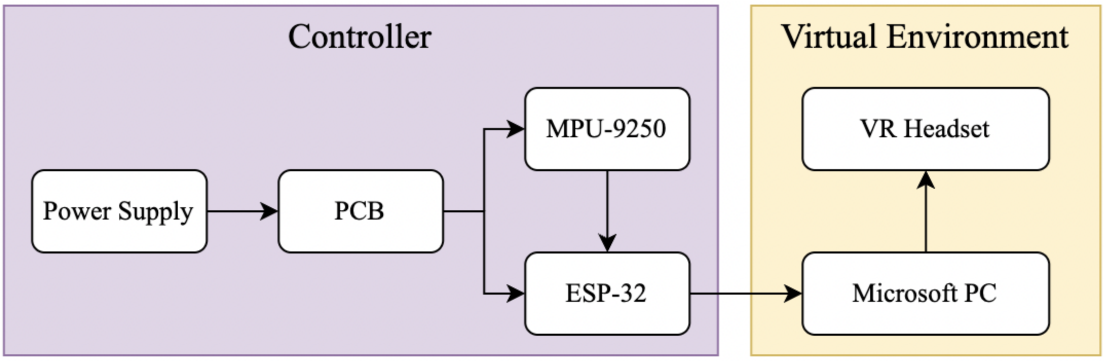

FIGURE 4.9: System diagram of the hardware components.

4.3 VR System Software

This section describes the necessary software platforms, and their respective functions, that allow all the components mentioned in section 4.2 to interact with one another. This section also describes the software used for the data analysis of the studies. The section is divided into the software utilised for the controller, the software dedicated to the development of the VR environment and the software used for the data analysis.

4.3.1 Software For The Controller

To control the navigation in VR, data was collected from the IMU sensor (MPU-9250) on the microcontroller (ESP-32), programmed using the Arduino IDE[145] software platform, and sent to the Unity [79] cross-platform game engine where it was further processed. How the data from the sensor was processed in each software program (i.e. Arduino IDE[145] and Unity[79]) is described below.

4.3.1.1 Arduino Based Code For The Controller

The Arduino IDE[145] cross-platform application was used as the software application to write the code for the data acquisition from the IMU sensor and subsequent data transmission to Unity[79]. It was also used to upload the code onto the ESP-32 microcontroller. The code was written by CZ. The steps executed by the Arduino IDE[145] are as follows:

1. *Establishment of a WiFi hotspot:* The appropriate libraries to create a WiFi connection were accessed ("WiFi.h" and "ESPAsyncWebServerh.h"). Then, a WiFi password-protected hotspot was generated by the microcontroller, the ESP-32 board. This hotspot allowed for the Microsoft PC to wirelessly and safely connect to it.

2. *Data collection from the IMU sensor:* The appropriate libraries to communicate between the ESP-32 and the IMU sensor were accessed ("MPU9250.h" and "Wire.h"). Once a connection with the sensor was established, the accelerometer data was continuously read.

3. *Data transmission via the hotspot:* The collected IMU sensor data was continuously transmitted through the hotspot connection to the Microsoft PC. Importantly, the accelerometer data from each axis was transmitted through discrete data streams, allowing for the separation and identification of data related to the different dimensions (i.e. accelerometer x-axis, y-axis, z-axis).

This comprehensive process facilitated the acquisition of IMU sensor data and wireless transmission of the data from the microcontroller to the VR environment, thereby enabling real-time integration of sensor information into the Unity[79]-based wheelchair driving simulation.

4.3.1.2 Unity Based Code For The Interface With The Controller

The Unity[79] cross-platform game development engine was used for the reading and storing of the IMU sensor data and controlling of the navigation in VR. The code was written in a C# script using the VisualStudio[146] integrated development environment within Unity[79] by CZ. The data was collected wirelessly from the ESP-32, by calling upon the WiFi connection established between the computer and the ESP-32 hotspot. To control the navigation in VR, the data was filtered in real-time within ranges to determine the direction of movement of the virtual wheelchair.

The following steps outline the essential steps of Unity[79] in this process:

1. *Data reception:* Unity[79] acted as the recipient of the data transmitted wirelessly by the ESP-32 microcontroller. After establishing a connection to the ESP-32's hotspot through the PC's WiFi connection, Unity[79] received the IMU sensor data streams.

2. *Data integration:* Unity[79] effectively integrated the received IMU data into its environment. For this integration, the data was parsed into streams from each accelerometer axis and saved as a ".csv" file in the computer's hard drive.

3. *Data filtering:* As the data continued to stream into Unity[79], it underwent a filtration process. This filtration categorised the data into specific ranges that functioned as the determinants of direction of movement of the virtual wheelchair (i.e., forward, backward, left, right).

4. *Real-time navigation control:* Using the filtered data, Unity[79] was able to control the navigation within the VR environment in real-time. The data-driven navigation commands directed the movement and orientation of the virtual wheelchair, providing users with a real-time responsive VR experience.

In summary, Unity[79] served as the central hub for the data reception, integration, storage and processing of the controller system. It effectively managed and interpreted data from IMU sensor which allowed for precise and dynamic control of navigation in the VR environment.

4.3.2 Software For The Virtual Environments

The virtual environments were developed by CZ using the Unity[79] cross-platform game development engine. For Study 1, the assets used within the environment were taken from the Unity Asset Store[147], a repository with a diverse assortment of pre-designed digital assets conducive to interactive 3D content creation, and external repositories including Sketchfab[148] and Turbosquid[149]. A total of one VR training environment, and one real-life training interface (to collect the real-life driving performance data) were developed for Study 1. For Study 2, the assets were developed using Autodesk Maya[150] as the 3D computer graphics application by TS. A total of two VR training environments (one with gamification elements and one without) and one real-life training interface (to collect the real-life driving performance data) were developed for Study 2. The following subsection describes the interactions between the different scenes and scripts (with the code written in C# using VisualStudio[146]) within Unity[79], as used in both studies. Details about the specific environment designs for each study are found in section 4.5 for Study 1, and section 4.6 for Study 2.

4.3.2.1 Unity Based Code For VR Development

The interactions within the Unity[79] environment were coded in a C# script using VisualStudio[146] by CZ. When a training session was started, a login page first appeared as seen in Figure 4.10.

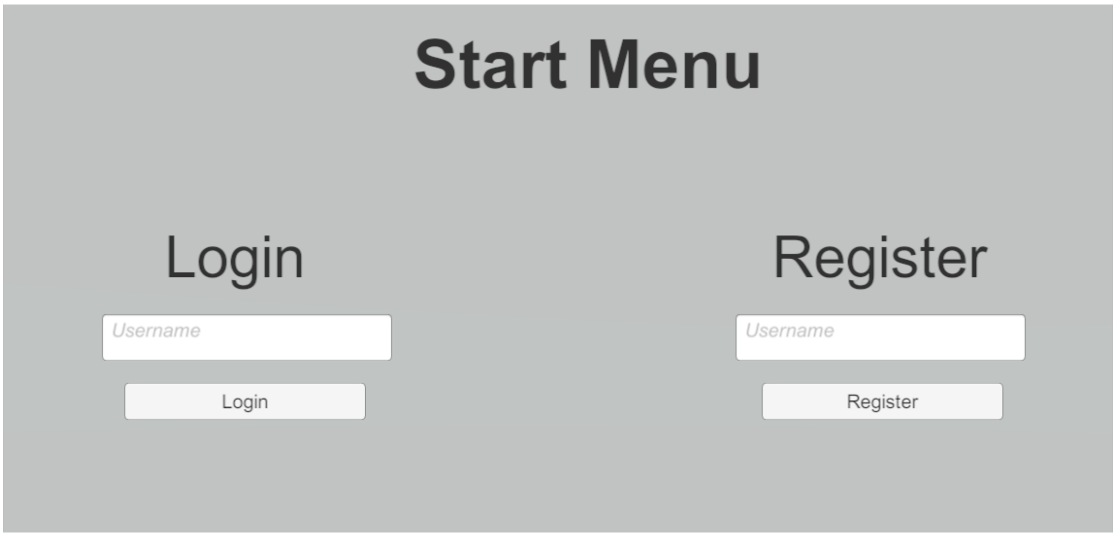

FIGURE 4.10: VR environment login screen for both Study 1 and Study 2.

Any new user was first registered on the login page. Upon the user registration, a dedicated directory was automatically created on the Microsoft PC's local C-drive. This directory was designated for housing and organising all data associated with the registered user. Once the users were registered, to start the training, the users were logged into their profile and the type of training (i.e. for Study 1: real life or VR; for Study 2: real life, gamified VR or non-gamified/realistic VR) was selected, as can be seen in Figure 4.17 and Figure 4.26 respectively. Once the type of training was selected, the users' data was saved in the form of ".csv" files, a data file format renowned for its structured representation, as it was being collected. Each ".csv" file, included data relevant to the users' training activities, more specifically IMU sensor accelerometer x-axis, y-axis and z-axis signals, timer for the whole VR experience, start and end of each task, and for Study 2 also collision events.

The way this data was saved depended on the selected training. For the real-life training, a page appeared with buttons to indicate the start and end of each task as seen in Figure 4.15 for Study 1, as well as collision as seen Figure 4.25 for Study 2. As such, while the IMU sensor signals and the timer data were automatically saved, the start and end of a task, as well as collisions, had to be manually selected by the researcher (CZ) on the Microsoft PC's monitor screen. It has to be noted that for the real-life training, the users did not wear the HMD.

For the VR training, the user was immediately immersed in the training environment where tasks had to be completed in VR seen through the HMD. The tasks, and layout of the training depended on the study and as such are described in more detail in their respective sections (see section 4.5.1 for Study 1 and section 4.6.2 for Study 2). However, the data-saving process was similar. The IMU sensor signals and timer began saving automatically at the commencement of the training (as for the real-life training), while the start and end of each task were logged as users drove through invisible colliders positioned at the task's beginning and finish lines. These collision events triggered the automatic saving of start and end times. Additionally, occurrences of collisions with any object within the environments were also logged automatically for Study 2.

Further, within the VR training, the users assumed a first-person POV, thus creating a heightened sense of presence within the digital realm. Within this immersive VR landscape, the users found themselves seated in a virtual wheelchair. Looking downwards, the users saw a virtual body, thereby fostering a connection between the physical self and the digital representation. The users' real-world actions were synchronized with the corresponding movements of the virtual wheelchair. Thus, as users physically manoeuvred the joystick, the virtual wheelchair mirrored these actions in real time, creating a correspondence between physical inputs and virtual outputs. Physics properties were also integrated into the simulations, which led to a high degree of realism within the VR environment. When users navigated the virtual wheelchair into a virtual object, a simulated collision occurred.

4.3.3 Communication Between The Controller And The Virtual Environment

Section 4.3.1 describes the software used for the programming of the developed controller, while section 4.3.2 describes the software used for the programming of the developed virtual environments. For the training sessions to be carried out, both the controller and the virtual environments have to work correctly and seamlessly communicate with one another. Figure 4.11 presents a graphical summary of their communication (which is described in detail in the sections above).

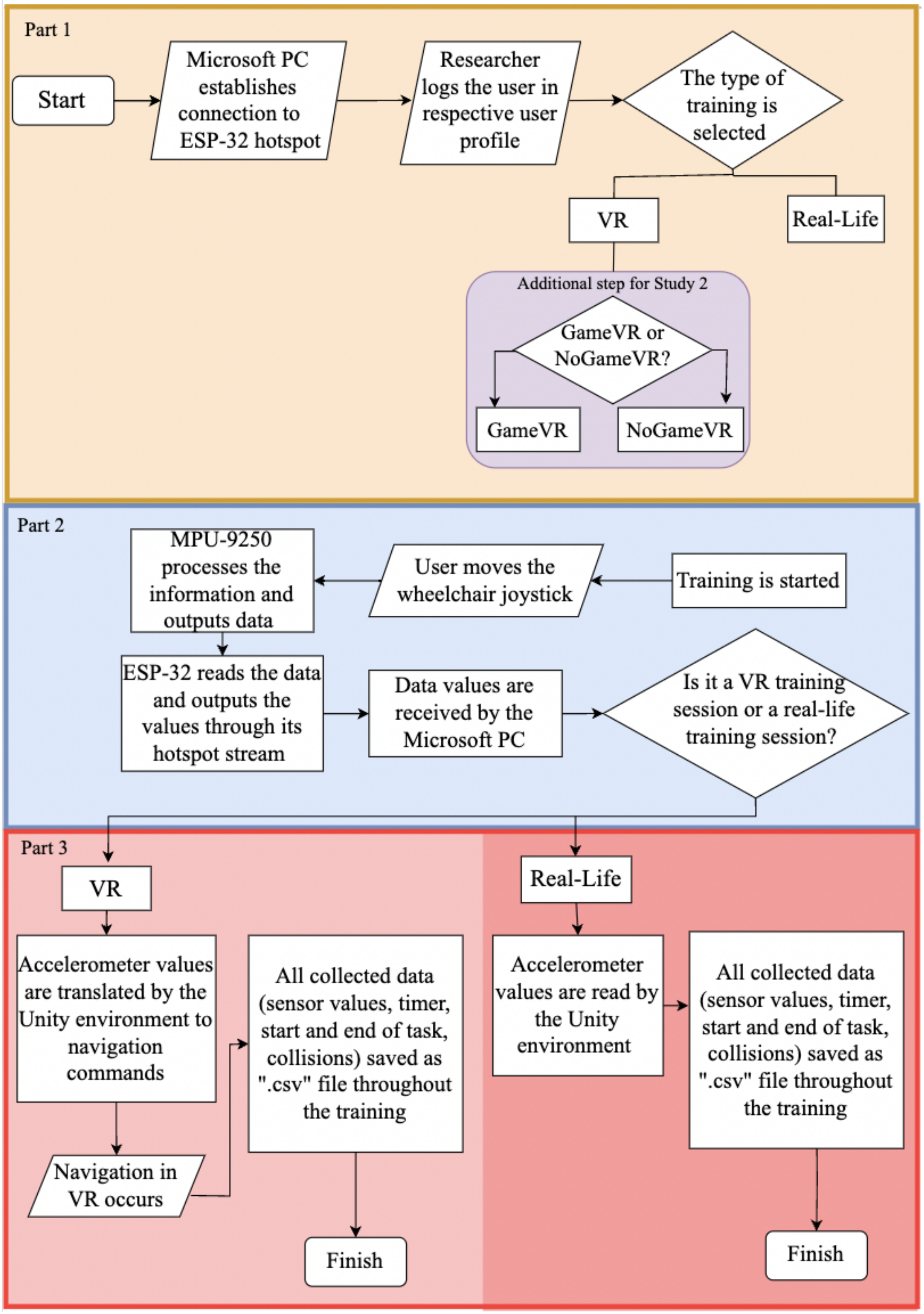

FIGURE 4.11: System flowchart of the communication between the controller and the VR environment.

4.3.4 Processing of The Collected Data

For Study 1 and Study 2, the processing of the data (conducted by CZ) followed a similar process. The data derived from the Unity[79] environment (both for VR training and real-life training) was systematically saved in a structured format within an Excel[151] spreadsheet, represented by the ".csv" file extension. The data within the spreadsheet was arranged as follows: chronological timer values, accelerometer readings along the x, y, and z axes, task initiation and completion timestamps, and collision events (where applicable). The dataset was subsequently imported into the MATLAB[152] numerical computing environment for further analytical processing. The data were finally re-organised into Excel[151], and statistically analysed using the IBM SPSS[153] software platform. The function of each software platform is described below.

- Microsoft Excel: In both Study 1 and Study 2, Microsoft Excel[151] assumed an important role in the data management and analysis processes. It functioned as a repository for the initial organisation of the datasets collected during these studies, both for the VR training and for the real-life performance. Primarily, Microsoft Excel[151] housed the data belonging to participants' performance metrics and analysed it. To facilitate analyses, once saved into Excel[151], the data of the real-life performance of each participant was imported into MATLAB[152] , which extracted specific subsets (the total joystick movements for each task, the total time required for each task completion, and the total count of collision events). Upon the completion of data processing within MATLAB, the resultant datasets were re-imported into Excel[151]. In Excel[151], this data was organised into a control group (who underwent no VR training) and a VR group for Study 1; while for Study 2, into a gamified VR group and an ungamified VR group. This data was graphed to visually convey performance trends and differences among the groups of participants. Furthermore, the organised datasets were systematically imported into IBM SPSS[153] for statistical analyses between the groups.
- MATLAB: The use of MATLAB[152] in Study 1 and Study 2 played an instrumental role in the extraction of specific data subsets from the Excel[151] files associated with each participant. The MATLAB[152] programming code (written by CZ) navigated through individual participant directories, to parse and analyse the performance metrics data from the Excel[151] files therein contained. Primarily, the MATLAB[152] code calculated the total number of joystick movements for each task. This calculation was achieved through a multi-step process that began with the identification of task start and end timestamps, manifesting as log entries within the Excel[151] files. The total joystick movements were calculated by processing the accelerometer data encompassed within the range defined by the start

and end log entries, as explained in section 4.2.3.2. In tandem with the computation of joystick movements, MATLAB[152] determined the task completion times. This process entailed identifying task start and end timestamps, as for the joystick movements computation methodology. The time taken to complete each task was computed by calculating the time difference between the end log timestamp and the start log timestamp. Furthermore, MATLAB[152] counted the recorded collisions for Study 2 and compiled a record of collision occurrences. The computed data, inclusive of joystick movements, task completion times, and collision counts, was output as ".xlsx" (Excel[151]) files. These output files were imported into Excel[151], where they underwent further processing.

- IBM SPSS: The IBM SPSS[153] software was used to perform statistical analyses for both Study 1 and Study 2. The data designated for analysis was imported into the application as a ".csv" Excel[151] format. Subsequently, distinct statistical tests were executed as outlined in the respective sections below of the data analysis of the studies. All the statistical tests performed were chosen based on what tests would most appropriately test the hypotheses of each study, and what tests would be most appropriate to use on the type of data collected, after a consultation with the statistics clinic of the University of Kent (specifically with the guidance of BS).

4.4 Ethical Approval

The research was ethically approved by the Central Ethics Advisory Research Group of the University of Kent. All participants read and signed a consent form prior to starting any data collection. Participants were recruited through the University of Kent body of students and staff. The studies were advertised through word of mouth and an email to all the divisions of the university, and interested participants were screened according to the following eligibility requirements: be over 18 years of age, speak and write fluent English, have little to no wheelchair driving experience, have no known cognitive disability and no history of serious motion sickness. Participants of Study 1 were not allowed to participate in Study 2 due to the acquired wheelchair driving experience.

4.5 Study 1: Validation of The Developed System

This study functioned as a validation study for the developed VR system, specifically the controller. In this context, it aimed to investigate two key hypotheses:

- *VR training leads to the acquisition of skills in real life.*
- *Low-cost technology can deliver effective VR training.*

To test these hypotheses, a standardised way to assess any acquired skills was proposed (section 4.5.2), based on improvements in participants' completion times and the total joystick movements during various real-life tasks. Evaluations were conducted both before and after participants engaged in the VR training. Additionally, an adapted version of the Wheelchair Skills Training (WST) Questionnaire (see Appendix B) was administered to assess participants' confidence in their acquired skills. The study also analysed participants' well-being in terms of HR, SSQ[20] scores and IPQ[19] scores, however, these measures are described in Chapter 5.

4.5.1 Set-up of Study 1

In this study, a total of 16 non-disabled participants were recruited. One of the participants dropped out, while one could not complete the study due to severe nausea, thus, 14 participants took part in the study. Of the 14 participants that took part, 5 were allocated to the control group, while the remaining 9 were allocated to the VR group. The sample size was chosen to include twice as many participants in the test group in order to have more test results, for a better understanding of the effectiveness of the VR system. However, with one participant of the VR group unable to complete the training, only 9 participants took part in the VR group. The allocation of VR group and control group was random. After completing the study, participants were given a £5 Amazon Voucher as a token of appreciation for taking the time to participate in the study. The participants identified as male (n = 10) and female (n = 4), and were between the ages of 18-23 (n = 2), 24 - 28 (n = 9), 29 - 33 (n = 2), 34 - 38 (n = 1).

Individual participants, from both groups, came in for two sessions, on two different dates (between 2 to 5 days apart). In the first session, which was the same for both groups, participants were first introduced to the project aims, had the opportunity to ask questions, and then signed a consent form. Afterwards, participants were allowed to get acquainted with driving the real-life wheelchair, after which they completed a set of real-life driving tasks based on the WSTP [17] (see the following sections for details), where the accelerometer data and the completion time were collected. Following the completion of the driving tasks, the participants filled out the WST-style questionnaire (see Appendix B).

After 2 to 5 days, according to their availability, participants returned for the second session. Participants were randomly allocated to either the control group or the VR group. Participants from the control group performed the real-life WSTP [17] tasks and completed the WST-style questionnaire again; importantly, this was done to check whether some of the skills learned from the first session were retained. Participants from the VR group performed the VR training, where the following parameters were collected: accelerometer data and completion time. During the VR training, the participants were seated in the same wheelchair used in the first session, with the motors disabled and with the joystick retrofitted with the IMU sensor to control navigation in the VR environment. The VR training was conducted up to four times (contingent upon the participants' desire and experience of cybersickness), with a 5-to-10-minute break in between. Where participants reported feeling unwell, the training was ceased immediately. At the end of the second session, participants repeated the same set of real-life driving WSTP [17] tasks as in their first session, followed by completing the WST-style questionnaire. The flowchart in Figure 4.12 shows the set-up of the study.

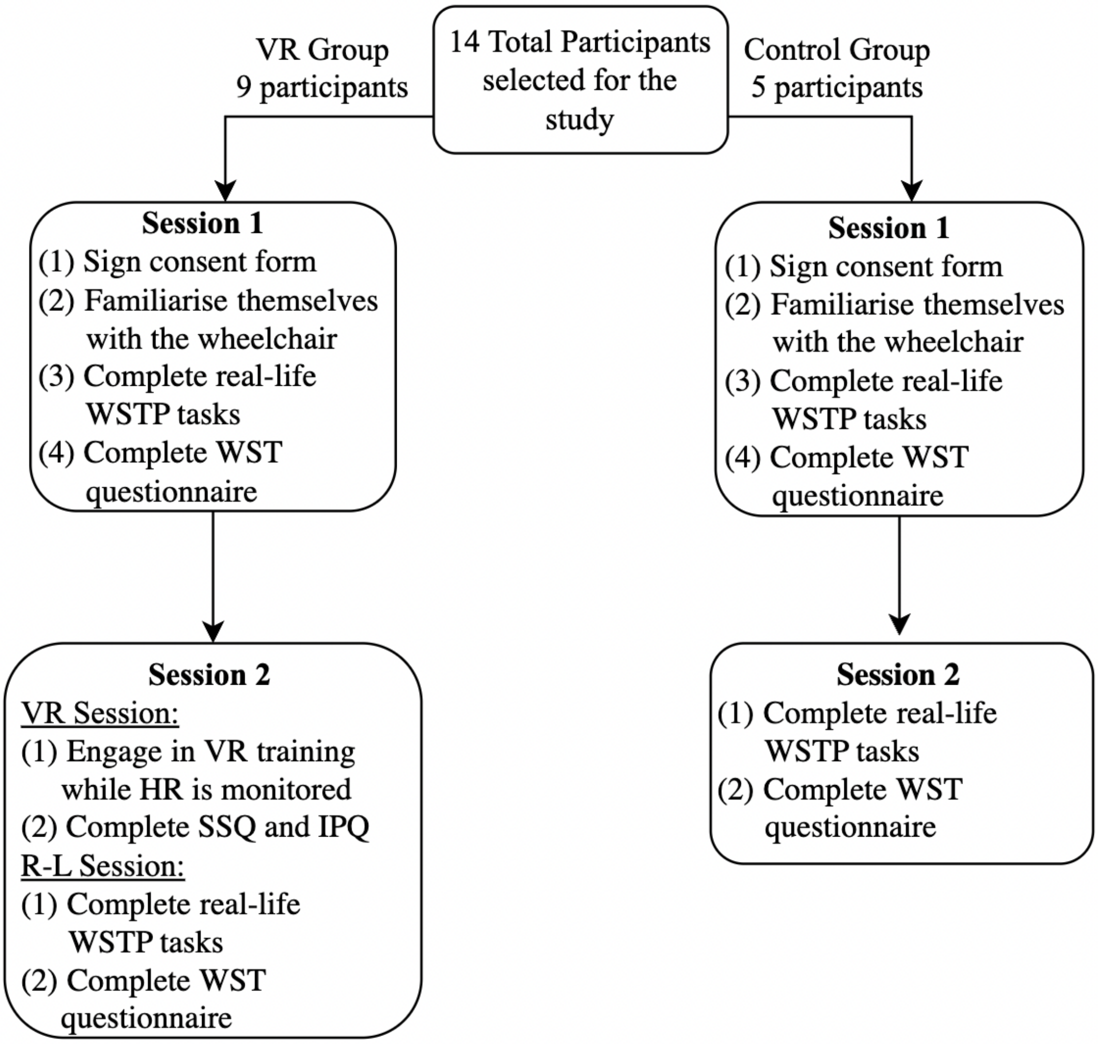

FIGURE 4.12: Flowchart of the set-up of Study 1.

4.5.1.1 Real-Life Set-up of Study 1

The real-life set-up is important in validating the standardisation framework proposed in section 4.5.2 as it consisted in performing specific tasks to assess the acquisition of driving skills. It was completed by both groups of participants, in both of their sessions, and consisted of the following tasks: following a straight line forward for 5m and backward for 5m (see Figure 4.13 inset C); then, going through a slalom course with 3 obstacles (on a 5m line, 1.5m apart, see 4.13 inset B) both forwards and backward; finally, going through a maze (with path with alternating width of 1m, 1.5m, 2m, see Figure 4.13 inset A and Figure 4.14 for the floor plan).

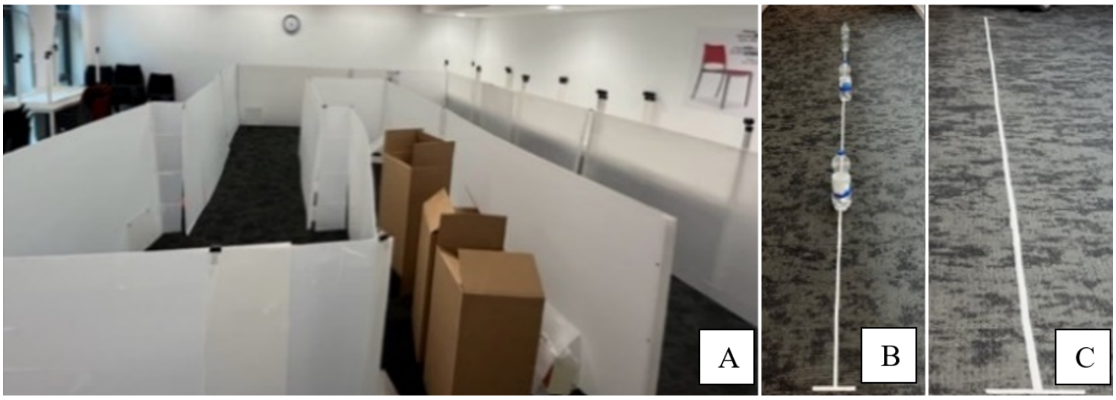

FIGURE 4.13: Set-up to perform the tasks in real life for Study 1. Inset A represents the room where the maze task was performed. Inset B represents where the forward slalom and backward slalom tasks were performed. Inset C represents where the forward and backward tasks were performed.

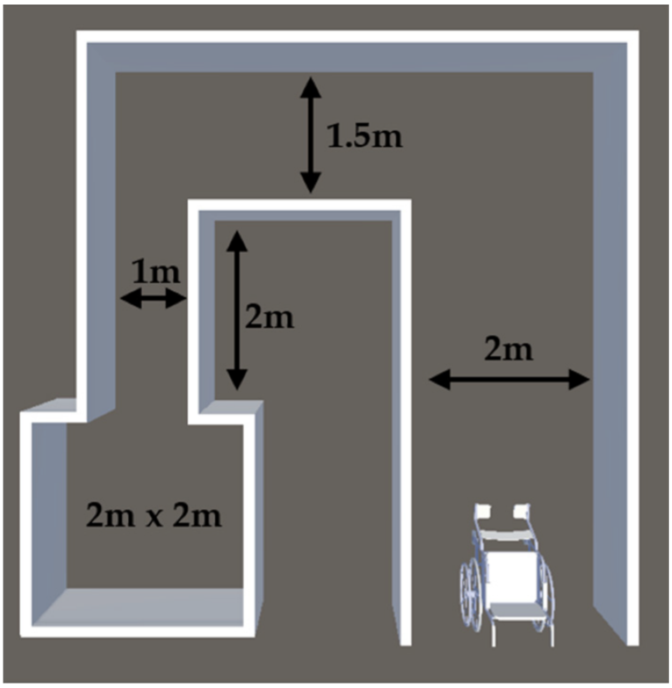

FIGURE 4.14: Floor plan of the real-life maze task.

The times when the participants started and finished each task in Unity[79] (see Figure 4.15) were logged by the researcher who conducted the study (CZ). The measures collected when performing these tasks were completion time and accelerometer data to record the real-life joystick's movements (through the IMU sensor signals). The participants drove the wheelchair at a speed of 1km/h (the lowest speed setting available for safety reasons). Figure 4.16 shows a participant completing the real-life tasks.

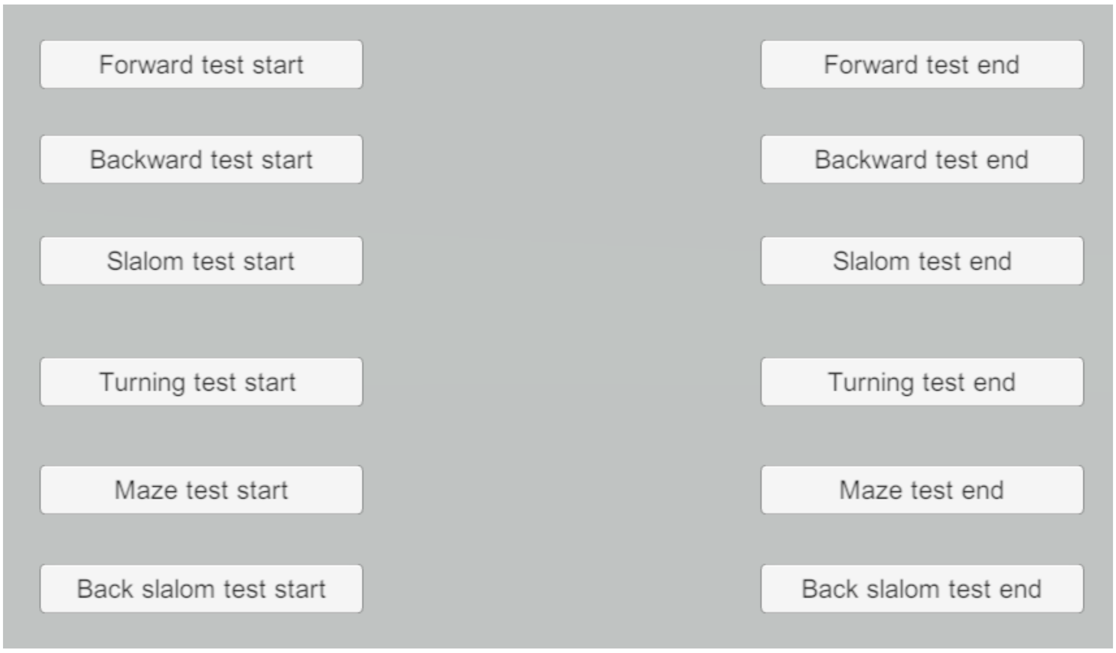

FIGURE 4.15: Virtual environment log screen for the tasks conducted in real life for Study 1.

FIGURE 4.16: Participant performing tasks in real life in Study 1.

4.5.1.2 Virtual Environment Design For Study 1

The virtual environment was developed using Unity[79], a description of this can be found in section 4.3.2.1. At the beginning of the training session, the type of training was selected as seen in Figure 4.17. The environment developed for the VR training in this study mimicked a simple training room and is loosely based on the WSTP [17]. It consists of five tasks (replicas of the tests conducted in real life): forward driving on a straight line for 10m, backward driving on a straight line for 10m, forward slalom course through 3 obstacles placed 1.5m apart, backward slalom course through 3 obstacles placed 1.5m apart, and a maze with corridors varying in width as the real life one (see Figure 4.18). When the user began or finished a task, the user drove through an invisible collider (placed at the start and finish lines of each task) which automatically logged the start and end of each task.

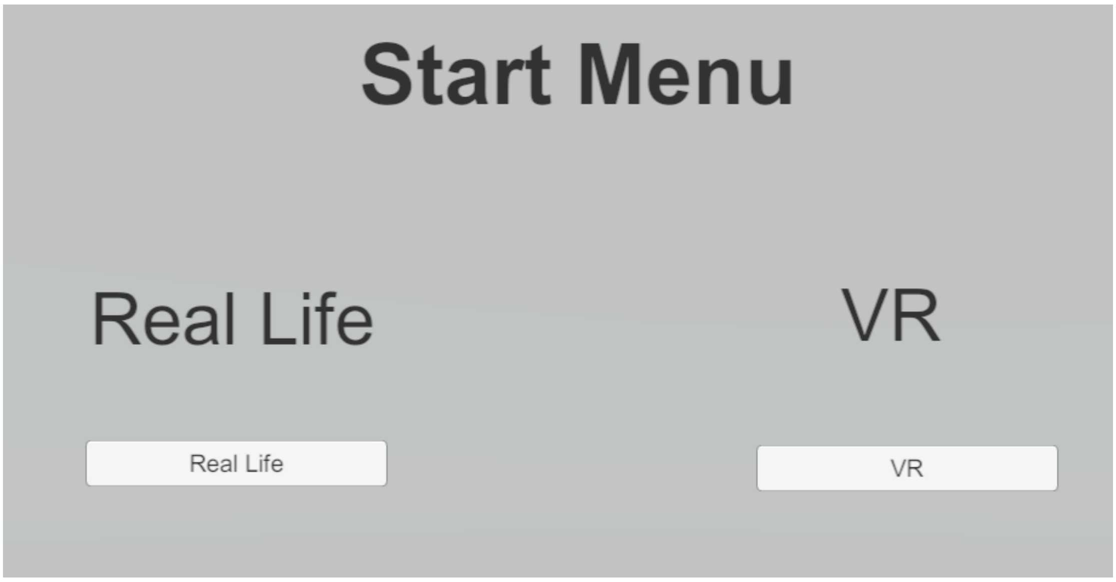

FIGURE 4.17: Start menu for Study 1.

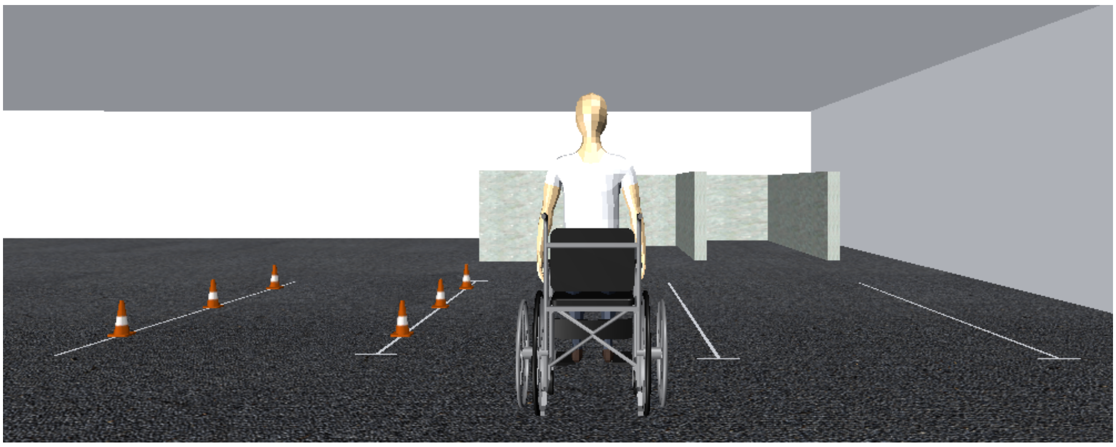

FIGURE 4.18: VR training environment for Study 1.

A VR training session consisted in completing all the tasks the participants felt comfortable with in one go. Participants were given the option to train in VR as many times as they felt comfortable in the span of an hour (the minimum time was one and the maximum was four). The reason why participants were given a choice of how many times to train in VR is because each person perceives cybersickness to a different extent and thus can use VR for different lengths of time. The system was designed so that while the participants performed the VR training wearing the HMD, the researcher (CZ) could see the simulation on the Microsoft PC and guide the participants when needed.

4.5.2 Standardisation Framework

In this study, a framework for the standardisation of VR-based wheelchair driving skills training is proposed. This framework is rooted in the WSTP [17], which is a well-established program that has been validated against other training approaches [68, 69]. The framework proposed methods for the assessment of acquired skills in VR training, and suggestions about the design of the VR environment.

- *Assessment of skills acquisition:* The guidelines of the WSTP [17] outline three assessment methods: one involves an external evaluator who rates a wheelchair user's competency in executing various tasks, while the other two entail self-assessments by wheelchair users regarding their own task completion capabilities. In the event of VR training being administered within a clinical setting under the supervision of qualified caregivers, these assessment methods can be applied effectively. However, in research settings, the absence of trained caregivers necessitates a different approach to evaluating skill acquisition. To gauge the effectiveness of VR-based training, participants should perform a set of tasks chosen from the WSTP [17] before and after the VR training. During this process, metrics used to assess VR wheelchair training applications should be examined, specifically completion time and the number of joystick movements. These metrics should be taken before and after VR training has occurred. The resulting data from these metrics should then be compared between pre-VR training and post-VR training through statistical analysis to assess if acquisition of skills has occurred. It is worth noting that in a clinical context, these metrics may serve as an objective means of quantifying skill improvement, and thus as additional metrics to the clinician's observations. Further, to maintain an assessment as similar as possible to the one used by the WSTP [17], and to assure its reliability, self-assessment questionnaires should be given to the wheelchair users to judge their own task completion capabilities in both these real-life sessions. Statistical improvement from the initial session would thereby indicate skill acquisition. Having the researcher also rate the user's competency in driving a wheelchair, as suggested in the WSTP [17] guidelines for clinical uses of the program, may however not be appropriate when it comes to VR training in an experimental setting unless a researcher has previous knowledge and experience in the assessment of skills, as it might wrongfully suggest skills have been acquired.

- *Design of the VR environment:* Given that the WSTP [17] operates in real life scenarios, definitive recommendations regarding VR environment design cannot be firmly asserted. While having guidelines would be beneficial, the absence of tested designs and their comparative effectiveness, as found in the literature review in Chapter 2 section 2.2.3, does not allow for the suggestion of specific guidelines for VR environments. Nevertheless, adopting a strategy in VR that mirrors the skills to be tested in real life could prove efficient, offering continuous practice of specific skills. Importantly, this emulation need not be a realistic replica; it can be as creative as possible to harness the full advantages of VR, providing researchers with the flexibility to optimise the training experience based on the needs of the patients as some may benefit from specifically a non-realistic environment [74].

This standardisation framework combines the benefits of the WSTP [17] with the benefits of VR-based programmes and proposes a guideline for the training in VR and its assessment of teaching driving skills transferable to real life. The aim of this framework is to decrease the heterogeneity of VR wheelchair driving skills training in a way that allows for a universal validation of their effectiveness, while still allowing researchers to be creative in their designs of the VR worlds.

4.5.3 Collected Data For Study 1

The completion time and length of movement of the joystick were collected using Unity[79]. The WST-style questionnaire was filled out by the participants on paper. All this data was stored, organised and plotted with Microsoft Excel[151]; the completion time and total joystick movements were processed with MATLAB[152]; the statistical analysis was performed using IBM SPSS[153]. The statistical tests were chosen based on what tests would most appropriately test the hypotheses of this study, as well as based on the type of data to be tested (to ensure it complies with the specific assumptions of the chosen statistical tests), after a consultation with the statistics clinic of the University of Kent (specifically with the guidance of BS). For all statistical tests, $p = 0.05$ was used as a standard of significance. The different data collected in this study are described in detail in the following subsections. Details on the data processing can be found in section 4.3.4. This study also measured participants' well-being through the HR, the SSQ [20] and the IPQ [19], however, these are described in Chapter 5.

- Proxy of the total joystick movements: The IMU sensor was placed on the joystick in the vertical direction (see Figure 4.3 inset A). The accelerometer values were recorded for each task, both during the real-life sessions and the VR training, and used to calculate a proxy for the total sum of the movements of the joystick, Ljm. The joystick data for both the real-life sessions and VR training was collected using Unity[79]. The sum of the movements, Ljm, for each task and in each of the two real-life sessions, were calculated as outlined in section 4.2.3.2 and compared for both groups (VR group and control group) between session 1 and session 2 respectively; as the statistical tests were performed on the same groups of participants, paired t-tests were conducted to see if there were any statistical differences within each task. The Ljm for each task was also collected and processed during the VR training.

- Completion time: The completion time, Ct, for each task, was recorded both in VR and in real life using Unity[79]. Upon starting the training, a timer automatically started in the VR experience. The time completion for the individual tasks was then calculated in Excel[151] (see section 4.3.4). The real-life Ct for each task and for both VR group and control group were compared between session 1 and session 2 using paired t-tests to see if there were any statistical differences within each task. Paired t-tests were chosen as the statistical tests were performed on the same groups of participants. The Ct for each task was also collected and processed during the VR training.

- WST-style questionnaire: The WST-style questionnaire was adapted to the tasks performed in the study; the original questionnaire has 27 questions while the adapted one consisted of 6 questions (see Appendix B). The adapted questionnaire was completed by the participants after each real-life session and allowed them to do a self-assessment of their driving skills. The results were statistically analysed by comparing the results of the first and second real life sessions using paired t-tests, as the statistical tests were performed on the same groups of participants.

4.5.4 Results of Study 1

The collected data were processed using MATLAB[152], and then analysed for statistical testing using IBM SPSS[153]. In this study, it was proposed that the total joystick movements, Ljm, and the completion time, Ct, (for the real-life tasks), can be used as a proxy of the improvement in skills. Paired t-tests were conducted for these two measures from each real-life task, as the difference in performance between the two sessions was compared for each group individually. Values of Ljm and Ct and the results of the t-tests are reported in the following sections. Each section includes the hypotheses tested in the statistical analysis. These hypotheses are specific and so a one-sided p-value (with p <0.05) was used. Regarding the questionnaires, paired t-tests were conducted for the WSTP-style questionnaire.

- <u>Proxy of the total joystick movement:</u> Paired t-tests were conducted for both groups (VR and control), after ensuring no major outliers were present and that the difference between the pairs was approximately normally distributed, to test for the following statistical null hypothesis and alternate hypothesis:

  – H0: (mean-over group of Ljm in session 1) - (mean-over group of Ljm in session 2) = 0

  – Ha: (mean-over group of Ljm in session 1) - (mean-over group of Ljm in session 2) >0

  For the VR group, the total joystick movements for each participant in a given real life task was measured, and then the average for that task across all the participants was calculated, Ljm-task. Figure 4.19 shows the total Ljm-task for each of the five tasks; the blue bars represent the Ljm-task pre-VR training, while the orange bars represent the Ljm-task post-VR training. A shorter orange bar indicates improvement within that task. This is the case of task 4 with a percentage improvement of 27% and a significant difference between pre-VR training and post-VR training (t8= 2.047, p=0.037). For task 4, on average, the sum of post-VR training was 134.511 points shorter than pre-VR training (95 CI[-17.022, 286.04]).

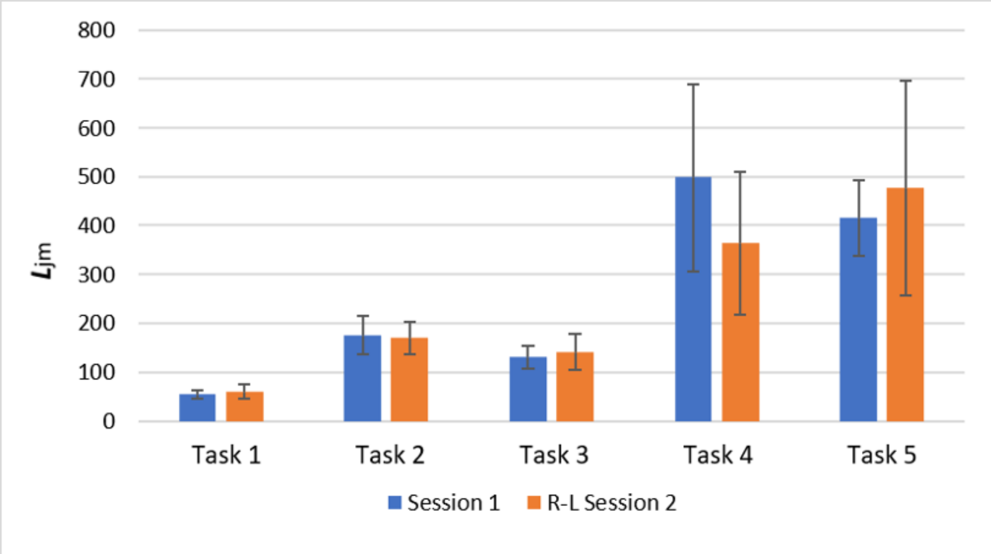

FIGURE 4.19: VR group total length of joystick movements for each real-life task, before and after VR training (sessions 1 and R-L session 2). Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze. The error bars represent the standard deviation.

For the control group, the same calculations were performed. Figure 4.20 shows the Ljm-task for each of the five tasks. An improvement can be seen in the backward task (with a percentage improvement 26.37%) and the backward slalom task (with percentage improvement of 16.63%). However, neither task shows significant statistical improvement according to the p-value.

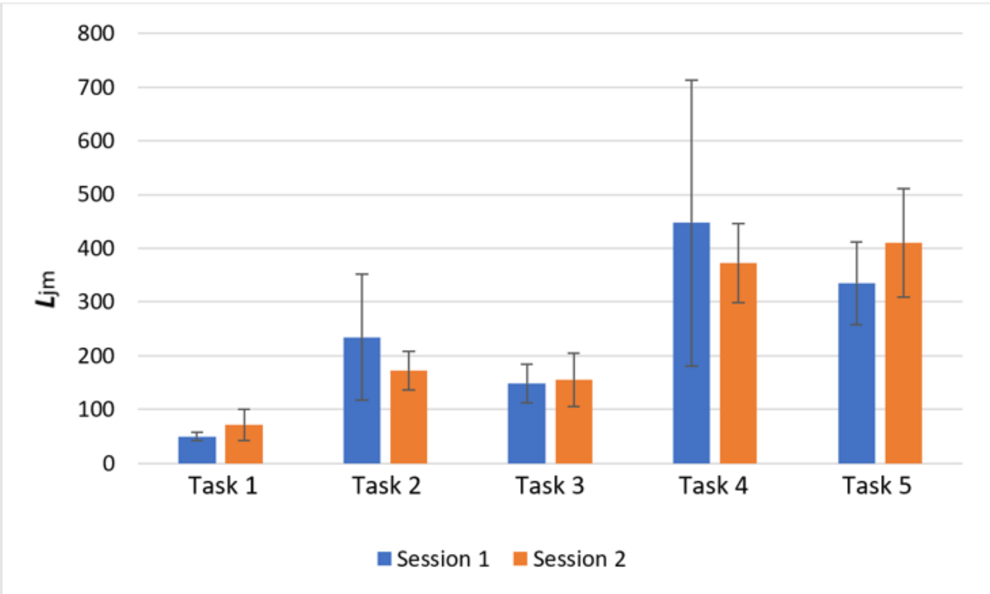

FIGURE 4.20: Control group total sum of joystick movements for each real-life task (sessions 1 and 2, no VR training). Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze. The error bars represent the standard deviation.

- Completion time: Paired t-tests were conducted for both groups (VR and control), after ensuring no major outliers were present and that the difference between the pairs was approximately normally distributed, to test for the following statistical null hypothesis and alternative hypothesis:
  - H0: (mean-over group of Ct in session 1) - (mean-over group of Ct in session 2) = 0
  - Ha: (mean-over group of Ct in session 1) - (mean-over group of Ct in session 2) >0

  For the VR group, the completion time for each participant was measured for the tasks performed in real life, and then the average was calculated for that task across all the participants Ct. Then, differences between the performances of session 1 and the real-life tasks performed in session 2 were analysed. Figure 4.21 follows a similar pattern as 4.19. It shows a decrease in Ct for task 4 with a percentage improvement of 22% and a significant difference between pre-VR training and post-VR training (t8= 2.163, p=0.031). For task 4, on average, the Ct of post-VR training was 24.67 seconds shorter than pre-VR training (95 CI[-1.63, 50.97]).

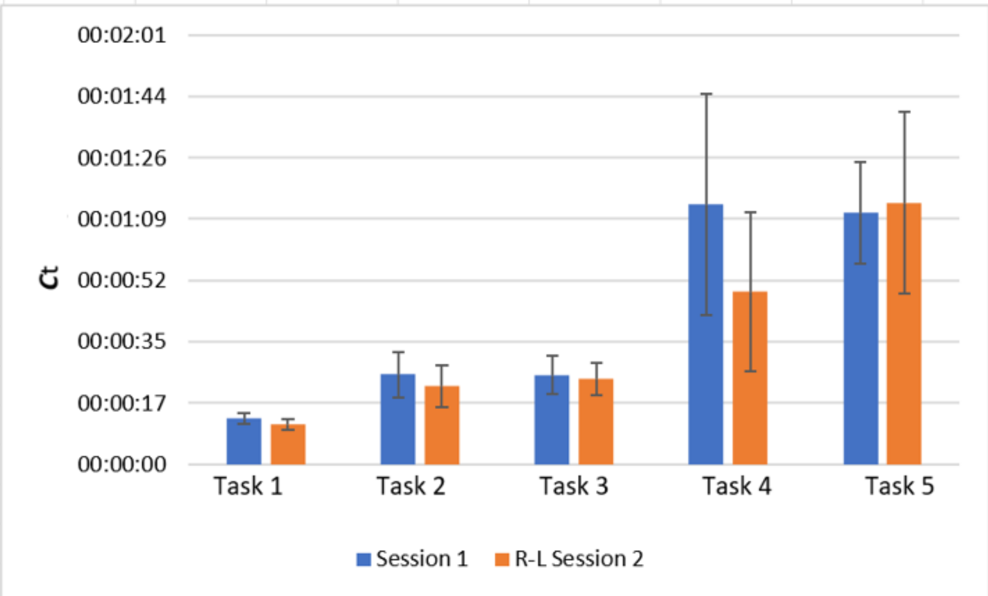

FIGURE 4.21: VR group completion time for each real-life task, before and after VR training (session 1 and R-L session 2). Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze. The error bars represent the standard deviation.

For the control group, the same calculations were performed. Figure 4.22 follows a similar pattern as Figure 4.21. It shows a decrease in Ct for the backward task (with a percentage improvement of 23.33%) and the backward slalom task (with a percentage improvement of 13.79%), as well as a slight one for task 5. However, the t-test shows no statistical difference for any of the tasks.

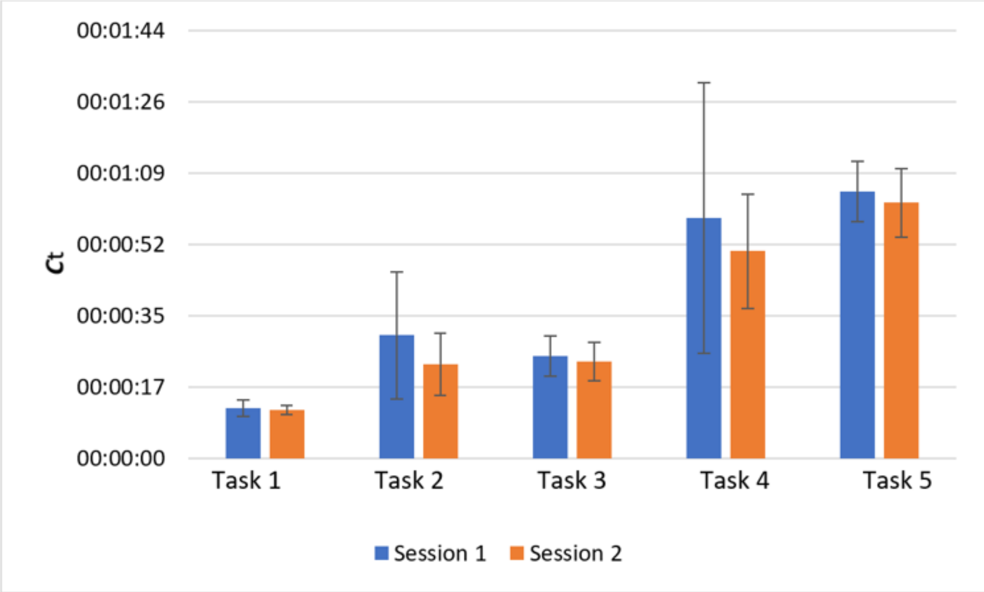

FIGURE 4.22: Control Group completion time for each real-life task (sessions 1 and 2, no VR session). Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze. The error bars represent the standard deviation.

- Improvement in VR: The real-life task that showed statistical improvement was the backward slalom task, thus it was also looked if improvement occurred when completing this task in VR more than once. Five participants repeated the VR training more than once, and the average percentage improvement from the first time they did that task in VR to the last was 9.9% for Ljm and 9.16% for Ct. This percentage improvement indicates that repetitive training may lead to improvement of skills in VR, which may be associated to real life skills acquisition.

- WST-style questionnaire: Paired t-tests were conducted for both groups (VR and control) as the limited number of participants allowed for this to be the most appropriate statistical test [154], to test for the following statistical null hypothesis and alternative hypothesis:
  - H0: (mean-over group of *WST-style questionnaire* answer in session 1) - (mean-over group of *WST-style questionnaire* answer in session 2) = 0
  - Ha: (mean-over group of *WST-style questionnaire* in session 1) - (mean-over group of *WST-style questionnaire* in session 2) >0

For the VR group, the participants' perception of improvement was analysed from the answers of the WST-style questionnaires. The results were statistically significant compared between the first and second real life sessions using paired t-tests. For the following two questions:

- Moving the wheelchair forward, for example along a hallway. How confident are you?
- Moving the wheelchair backward, for example, to back away from a table. How confident are you?

The paired t-test analysis showed a statistically significant improvement. The analysis reported (t8=-2.530 , p=0.018) and (t8=-2.401 , p=0.022) respectively, implying the participant's confidence increased in moving forward and backward. Paired t-tests were also performed to the questionnaire answers of the control group; however, no statistical difference was seen.

4.5.5 Discussion of Study 1

In this study, two hypotheses were tested. The first hypothesis, *H1: VR training leads to the acquisition of skills in real life*, was accepted. The results show that this was the case for the backward slalom task where statistical significance is observed, in which the Ljm and Ct improved by 27% and 22% respectively, between the real-life sessions 1 and 2 completed by the VR group. Further, the highest improvement in Ljm of an individual participant was 58%. It must be pointed out that the statistical tests for the control group results, when no VR training was undertaken, indicate that there is no significant improvement on average between real-life sessions 1 and 2. However, the variance of the results was large and limited participants took part in the study, thus bigger trials should be conducted in the future for more accurate results. Comparing a user's performance in real life before and after VR training is essential to see if a person has indeed acquired any skills with VR, yet this is not often done [12]. In this study, the backward slalom task is where the participants improved the most. This was perhaps the most difficult task for the participants to do as it required the most manoeuvres to complete (see Figure 4.19 and Figure 4.20).

The second hypothesis *H2: Low-cost technology can deliver effective VR training*, is also accepted by the results. An IMU sensor retrofitted to a powered wheelchair joystick to control the navigation in VR was used in this study. The same sensor was also used to record the Ljm in real life sessions to measure skill improvement. Using an IMU sensor attached to the joystick would enable new wheelchair users to remain seated on their own wheelchair and use their own joystick to conduct their training in VR, without 'hacking' into the electronics of the joystick. In this study, it was assumed that the more proficient in driving a person becomes, the fewer manoeuvres they will require to achieve a task. In this regard, Sorrento et al. [140] compared joystick movements and strategies between novice wheelchair users and expert ones and found that in more difficult tasks the expert group required fewer joystick manoeuvres than the novice group. The reliability of using this metric as a measure of improvement is justified in this study by looking at its relationship with a commonly used measure, namely completion time Ct [12, 16]. It was noticed that the results of the Ljm show a similar pattern with the Ct ones for both the VR group and the control group analysis. Similar findings were reported by Archambault et al. [77]. The participants were also asked to fill out an adjusted version of the WST questionnaire after each of the two real life sessions, to see if they perceived they had improved their skills. The results were compared for both the control group and the VR group using paired t-tests. Though paired t-tests are best suited for continuous data points, rather than discrete ones like the questionnaire, due to the limited number of participants this is the most appropriate statistical test [154]. The results of this analysis indicate the VR group perceived improvement for tasks 1 and 2 (going forward and backward), while the control group did not.

4.6 Study 2: Enhancing The Developed System Through Gamification

In the previous study, Study 1, the developed VR system was validated by testing the efficacy of the controller and the reliability of using VR to teach driving skills training. As the results of the study were positive, this study expands on Study 1 by focusing on how the design of the VR environment itself can be improved to provide more effective training. Currently, there is a heterogeneity amongst VR training designs. The variety of systems is immense with three main aspects that vary: the ways the VR environment is displayed to the user, the ways navigation is controlled, and the design of the VR environment itself. As such, each of these aspects needs to be considered to determine what approach to VR training is most effective to teach driving skills transferable to real life.

Firstly, VR environments can be viewed by a user through HMDs, monitor screens, and CAVE systems (semi-immersive rooms in which all the walls are a projection of the virtual environment). All these methods have been used in the field of wheelchair skills training. John et al. [72] carried out a VR training study for powered wheelchair users with participants split between a control group (who did not undergo training), a HMD group and a monitor screen group. They found overall better improvement in skills for the group using the HMD over the other groups. In terms of the user's point of view, Débora et al. [155] found that HMDs elicit higher levels of presence, and pleasant and exciting emotions. Increased presence was also found by Alshaer et al. [45], whose results demonstrate that HMDs lead to better involvement and ability to recognise passable gaps and door frames. These findings indicate HMDs may be a better option than monitor screens for wheelchair skills training.

Secondly, the ways navigation is controlled may depend on the mobility needs of the wheelchair users, and how they drive their own wheelchair in their day-to-day life. As such, VR can be controlled using gaming joysticks, powered wheelchair joysticks, sensors on the wheels, and eye-tracking devices, to name a few. Please see Chapter 2 section 2.2.4 for more detail. For powered wheelchair users who use a regular joystick for navigation, there is more flexibility when it comes to choosing the controller in VR. However, the flexibility may lead to using a joystick which is not necessarily the one someone uses in their day-to-day life. Undergoing training using a different joystick than the one someone needs, may result in the user having to get adjusted to multiple controllers and further, it may require wheelchair users to have to attend in-person training sessions which may not always be feasible. To provide a solution, Study 1 presents the validation of a method of navigation using an IMU sensor that can be retrofitted to various joysticks. This method has the potential to allow users to train independently and in the comfort of their own chair, making it an efficient alternative to other controllers.

Thirdly, VR environments for training also vary regarding design choices. Some are realistic, recreating a virtual replica of laboratory rooms [40] or rehabilitation centres [64]. Some are more abstract and contain elements of gamification, such as having the user collect balls of a specific colour while avoiding collision with other coloured balls [72]. Completing different tasks in VR environments, results in the training of different skills. In real-life training, the tasks are standardised using the WSTP [17]. In Study 1, it was proposed to replicate some of the tasks of the WSTP [17] in VR and to assess the same tasks in real life before and after the VR training; it was found that training with a replica of the harder tasks leads to the acquisition of skills in real life. However, the environment was very realistic, lacking any aspects of gamification. Adding elements of gamification could improve the effectiveness of VR-based training for wheelchair skills. In the context of training assembly tasks, Palmas et al. [156] compared a gamified VR environment to a non-gamified one and found that the use of gamification can enhance the efficacy of VR training applications. Despite the potential of gamification in enhancing trainees' outcomes in other disciplines, it is unclear whether such effects could be replicated in the context of wheelchair skills training. As such, further research work is needed to investigate whether the gamification of VR training can enhance the wheelchair skills training outcomes. As a result, this study investigates whether elements of gamification enhance the VR-based wheelchair training effectiveness.

To do so, this study compares user performance undergoing wheelchair skills training in a "non-gamified" VR environment versus a "gamified" one. The following hypothesis is investigated:

- *Real-life driving performance after VR training will differ based on the environment.*

To examine potential variations in learning outcomes due to the differences in environment design, post-VR training driving performance is assessed. This was measured with the number of collisions, the completion time per task, the total joystick movements per task and through a modified version of the WST questionnaire (see Appendix B). The study also analysed participants' HR, SSQ [20] scores and IPQ [19] scores, however, these being aspects of the participants' well-being are described in Chapter 5.

4.6.1 Gamification in Training

The term gamification refers to the use of game aspects in non-gaming contexts [157]. Aparicio et al. [158] defined a framework for gamification, which can help improve the participation and motivation of carrying out certain tasks. The authors suggested ways to motivate people using game mechanics (e.g., points, levels, and leaderboards) that favour autonomy, competence and relatedness. When examining if game mechanics are effective in VR rehabilitation systems, Winter et al. [159] developed an application to increase motivation by promoting relatedness, autonomy, and competence during gait rehabilitation. In their system, they used elements of gamification, including an engaging storyline, a gamified reward system, and a social companion. Compared to traditional rehabilitation, their system allowed for increased decision freedom, increased perceived task meaningfulness, lower anxiety, lower frustration, and lower physical demand. Gamification was also found useful by Škola et al. [160], who developed a gamified training for Motor Imagery BCI (MI-BCI). The elements of gamification included in their study were a themed environment, score points, progressive increase in speed across several training runs, and levels. The results showed that gamification improves MI-BCI skills for beginner users and stimulates low levels of fatigue.

The use of game mechanics in VR training has also been found effective in the improvement of skills in real life by Ulmer et al. [161] in the training for assembly tasks. The authors suggested that even though gamified VR could provide support for the completion of the tasks at the beginning of training, this positive effect can decrease gradually.

Furthermore, both positive and negative feedback should be provided throughout the training to balance the participants' feeling of competence without adding pressure. The authors suggested that effective gamified VR training should motivate the participants to build, retain, and recall their knowledge of the performed tasks. As for how the users feel about gamified VR training, Yan et al. [162] investigated the acceptance of gamification by older adults. They used a total of 6 games designed for life-skills training, for leisure (e.g., hobbies) and motor exercise development. The findings revealed that after exposure to the VR games participants felt it was useful and easy to use.

However, the studies directly comparing the effects of gamified VR training to non-gamified ones are very limited. Palmas et al. [156] investigated gamification's benefits over non-gamification in the context of training assembly tasks and found that it enhanced the efficacy of the VR training application. Despite the existing body of research exploring the benefits of gamification in various contexts, there remains a gap in understanding the specific advantages of using a gamified approach versus a non-gamified one in the domain of rehabilitation, specifically wheelchair-driving skills training. The unique challenges and goals of wheelchair skills training, necessitate a tailored investigation into the potential benefits of incorporating gamification in VR training systems.

4.6.2 Set-up of Study 2

In this study, a total of 22 non-disabled participants were recruited. After completing the study, participants were entered into a draw to win one of three Amazon vouchers (£25, £15, or £10) as a token of appreciation for taking the time to participate in the study. Out of the 22 participants, 11 were allocated to the gamified VR training (Game VR) and 11 to the non-gamified VR training (NoGame VR). The allocation of the groups was random. The participants identified as male (n = 13) and female (n = 9), and were between the ages of 18-23 (n = 12), 24 - 28 (n = 6), 29 - 33 (n = 2), 34 - 38 (n = 1), 39 - 43 (n = 1).

Individual participants, from both groups, came in for two sessions, on two different dates (between 2 to 5 days apart). In the first session, which was the same for both groups, participants were first introduced to the project aims, had the opportunity to ask questions, and then were asked to sign a consent form. Afterwards, participants were given the opportunity to get acquainted with the real-life wheelchair used for the study, after which they completed a set of real-life driving tasks based on the WSTP [17] (see the following sections for details). During this session, the following parameters were collected: number of collisions, accelerometer data, and completion time. Following the completion of the driving tasks, the participants filled out the WST-style questionnaire.

After at least two days, participants came back for their second session, based on their availability. Participants were randomly allocated to either NoGame VR or Game VR training. During the VR training number of collisions, accelerometer data, and completion time, were collected. During the VR training, the participants were seated in the same wheelchair used in the first session, with the motors disabled and using the same joystick retrofitted with an IMU sensor to control navigation in the VR environment.

The VR training was conducted up to three times (contingent upon the participants' desire and experience of cybersickness), with a 5-to-10-minute break in between. Where participants reported feeling unwell, the training was ceased immediately. After completing the VR training, participants repeated the same set of real-life driving tasks as in their first session, followed by completing the WST-style questionnaire (Appendix B). Figure 4.23 shows a flowchart of the setup of the study.

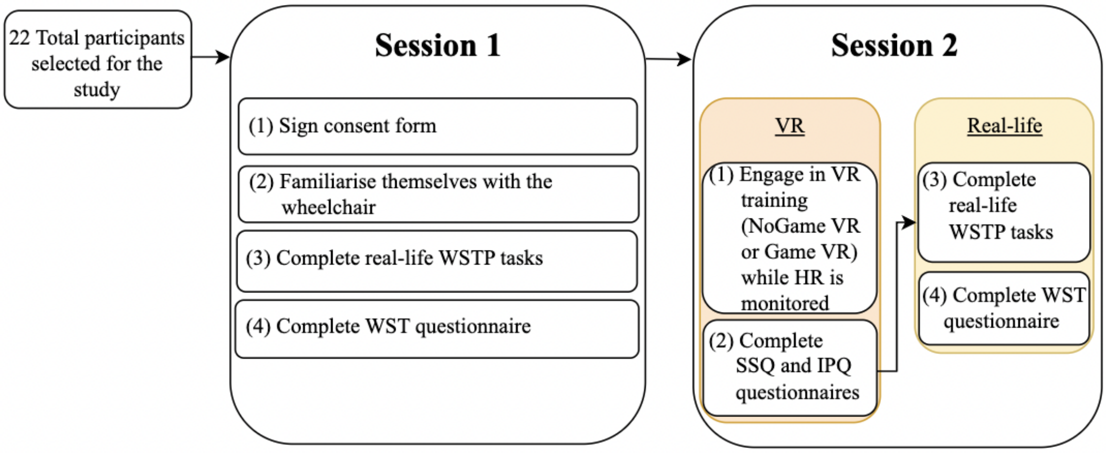

Figure 4.23: Flowchart of the set-up of Study 2.

4.6.2.1 Real-Life Set-up of Study 2

The real-life set-up, which was used by both groups of participants in both of their sessions, was the same as for Study 1. It consisted of the participants performing the following tasks: following a straight line forward for 5m and backward for 5m (see Figure 4.24 inset C); then, going through a slalom course with 3 obstacles (on a 5m line, 1.5m apart, see inset B) both forwards and backward; finally, going through a maze (with corridors of alternating width of 1m, 1.5m, 2m, see Figure 4.24 inset A).

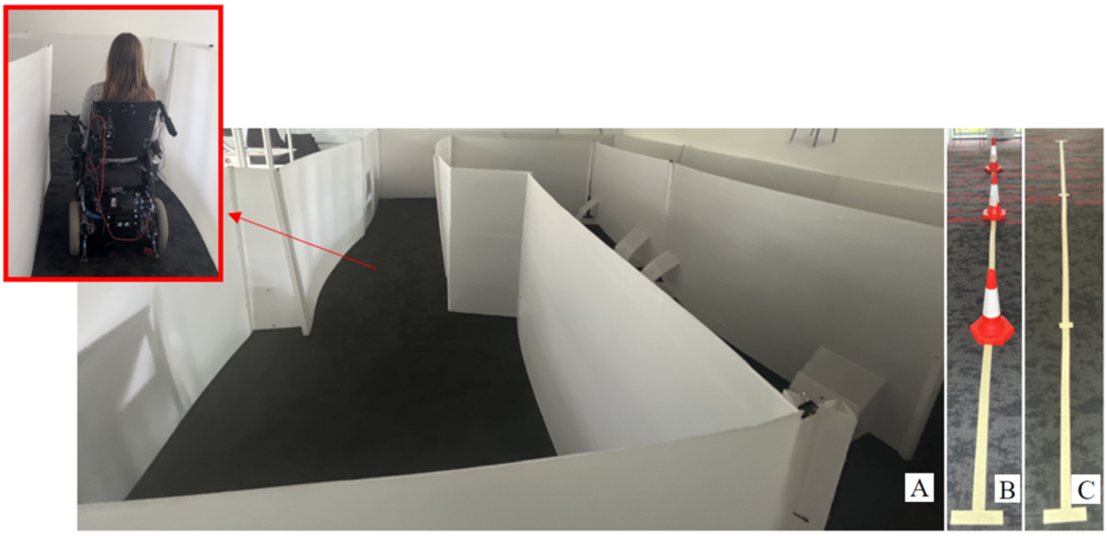

FIGURE 4.24: Set-up to perform the tasks in real life for Study 2. Inset A represents the room where the maze task was performed. Inset B represents where the forward slalom and backward slalom tasks were performed. Inset C represents where the forward and backward tasks were performed.

The researcher (CZ) logged the times when the user started and finished each task, and when collisions occurred, into Unity[79] (see Figure 4.25). The measures collected when performing these tasks were completion time and IMU signals (the wheelchair's joystick (Dx2-REM550/551 was retrofitted with the MPU-9250 IMU sensor to record the real-life joystick's movements). The participants drove the wheelchair at a speed of 1km/h (the lowest speed setting available for safety reasons). The floor plan and size of the maze are the same as in Study 1 and can be seen in Figure 4.14.

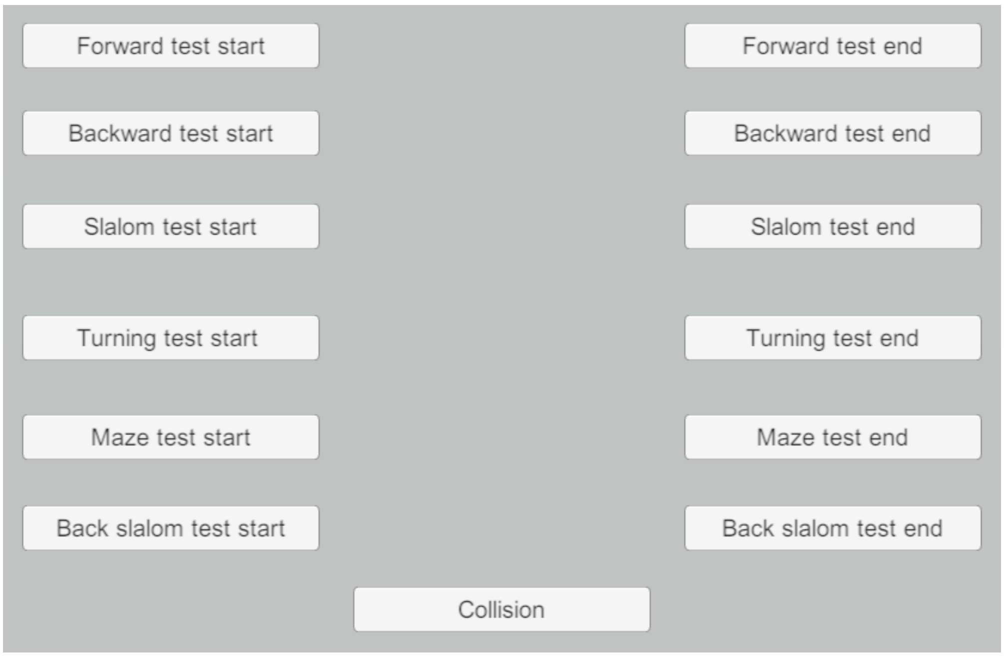

FIGURE 4.25: Unity[79] real life task log screen for Study 2.

4.6.2.2 Virtual Environment Design For Study 2

For this study, two VR environments were developed to conduct wheelchair skills training using Autodesk Maya[150] to produce all 3D elements (by TS), and Unity[79] to develop the training system. One environment was designed to be non-gamified, and one environment was designed to be gamified. A VR training session consisted of completing all the tasks the participants felt comfortable with in one go. Participants were given the option to train in VR as many times as they felt comfortable in the span of an hour (the minimum time was one and the maximum was three). The reason why participants were given a choice of how many times to train in VR is because each person perceives cybersickness to a different extent and thus can use VR for different lengths of time. The system was designed so that while the participant performed the VR training wearing the HMD, the simulation could be seen on the Microsoft PC which allowed the researcher (CZ) to guide the participants when needed.

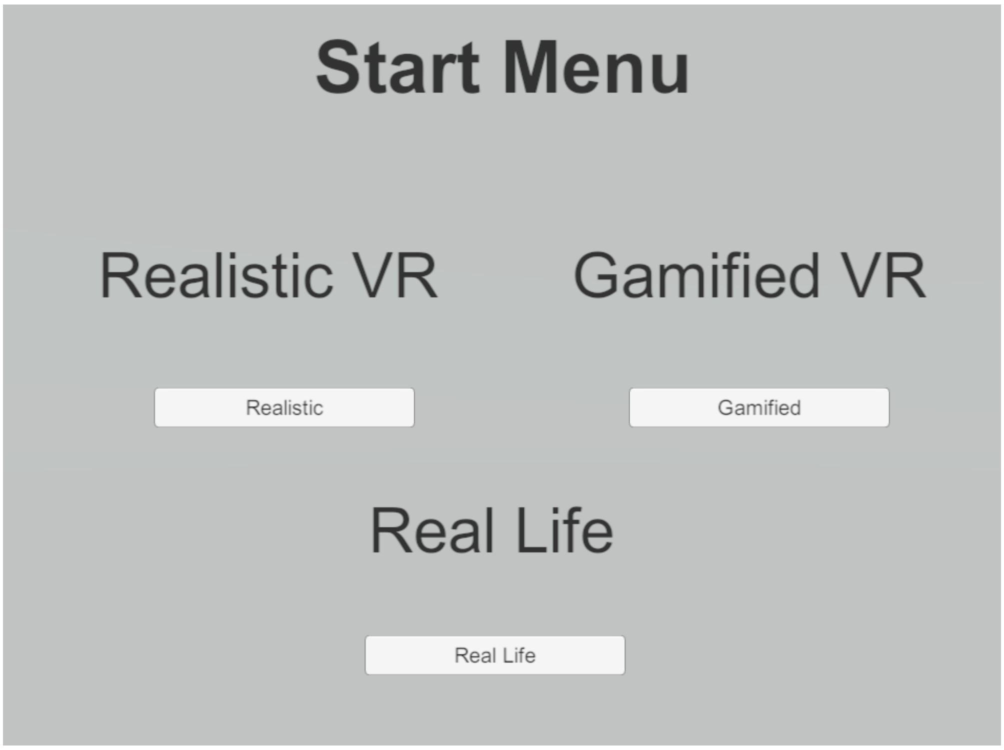

FIGURE 4.26: Start menu for Study 2.

- NoGame VR: The non-gamified (realistic) VR environment was developed using Maya[150] (by TS) and Unity[79] and is a replica of part of the Jennison Building of the University of Kent (see Figure 4.27); in this scenario, participants performed the following 5 tasks loosely based on the WSTP [17] (the same for Game VR): driving forward 10m, driving backward 10m, driving through 3 obstacles placed 1.5m apart (both forward and backward) and driving through a maze.

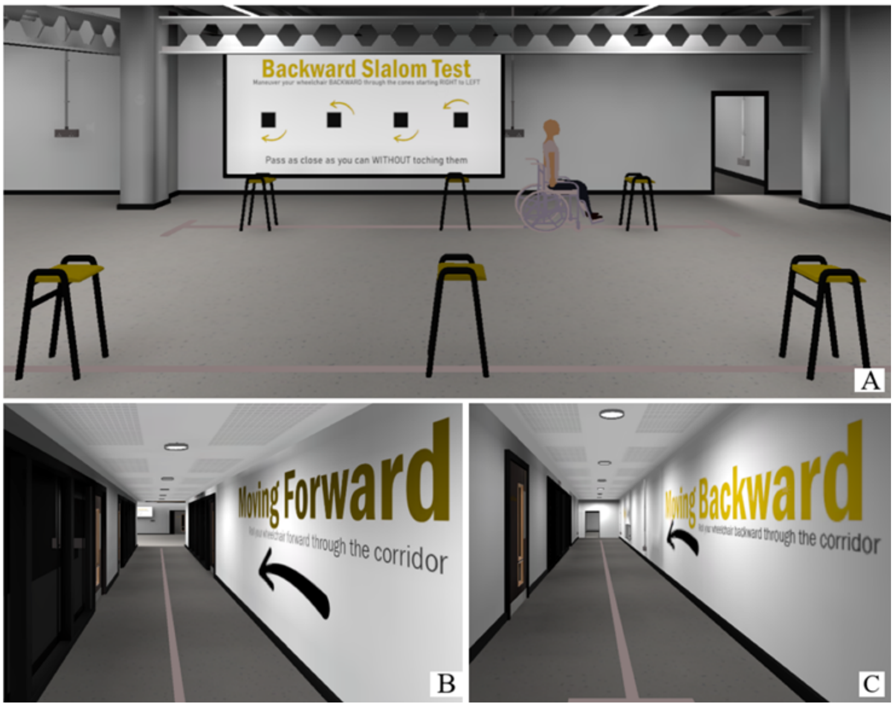

FIGURE 4.27: NoGame VR training. Image A represents the room where the forward slalom test and backward slalom test were performed. Image B represents the room where the forward test was performed. Image C represents the room where the backward test was performed.

- Game VR: The gamified VR environment, developed using Maya[150] (by TS) and Unity[79], as seen in Figure 4.28, is a non-realistic environment and contains the following 5 tasks (the same as for NoGame VR): driving forward 10m, driving backward 10m, driving through 3 obstacles placed 1.5m apart (both forward and backward), and driving through a maze. Both environments have the same floor plan and layout as seen in Figure 4.29.

  The elements of gamification derive from the framework based on the self- determination theory of human motivation defined by Aparicio et al. [158]. This framework analyses tasks for gamification, considering the psychological and social needs of the participants. It incorporates appropriate game mechanics and evaluates the effectiveness of gamification based on fun, playability, and improved results using a quality service model (which outlines three main needs to be addressed: autonomy, competence and relatedness). For this environment, the focus was on competence. Examples of competence are positive feedback, optimal challenge, progressive information, intuitive controls, points, levels and leaderboards. Positive feedback, optimal challenge and points were incorporated. As such, the design of Game VR training is based on a space shuttle and has the following elements of gamification: a target collection system (where the user follows the aliens to complete the tasks and to get points), positive visual feedback upon task completion, space shuttle background sound and audio feedback upon collision.

Figure 4.28: Game VR training. Image A represents the room where the forward slalom test and backward slalom test were performed. Image B represents the room where the forward test was performed. Image C represents the room where the backward test was performed.

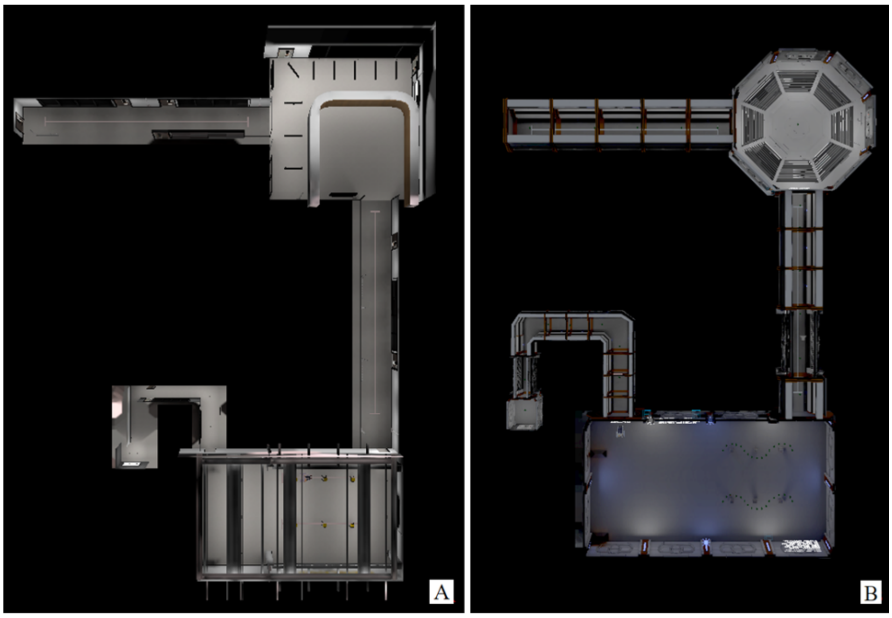

Figure 4.29: NoGame VR and Game VR training floorplans. Image A represents the floorplan view of the NoGame VR training and Image B represents the floorplan view of the Game VR training. The images are not to scale.

4.6.3 Collected Data For Study 2

The same data as for Study 1 was collected, namely the completion time and the total joystick movements, but this time also the number of collisions was collected using Unity[79], for both the real-life evaluation and the VR training. The WST-style questionnaire (Appendix B) was filled out on paper by the participants. All this data was stored, organised and plotted via Microsoft Excel[151]; further processing of the number of collisions, completion time and sum of movement of the joystick was done in MATLAB[152]. Statistical analysis was performed using IBM SPSS[153]. The statistical tests were chosen based on what tests would most appropriately test the hypothesis of this study, as well as based on the type of data to be tested (to ensure it complies with the specific assumptions of the chosen statistical tests), after a consultation with the statistics clinic of the University of Kent (specifically with the guidance of BS). For all statistical tests, $p = 0.05$ was used as a standard of significance. The details for the data processing can be found in section 4.3.4. The different data collected in this study are described in detail in the following subsections.

- Proxy of the total joystick movements: The IMU sensor was placed on the joystick in the vertical direction (see Figure 4.3 extension A). The accelerometer values were recorded for each task and used to calculate a proxy for the total movements of the joystick, Ljm. The joystick data for both the real-life sessions and VR training was collected using Unity[79]. The real-life Ljm (from session 2 and for each task) from NoGame VR was compared with the one from Game VR through a Mann-Whitney U test; the same test was conducted for the Ljm from session 1 for those tasks which showed statistical significance, to check if the significant difference was truly the result of VR training. The Mann-Whitney U test was chosen as the data of two small and not normally distributed independent samples was compared.

- Completion time: The completion time, Ct, for each task, was recorded both in VR and in real life using Unity[79]. The real-life Ct (from session 2 and for each task) from NoGame VR was compared with the one from Game VR through a Mann-Whitney U test; the same test was conducted for the Ct from session 1 for those tasks which showed statistical significance, to check if the significant difference was truly the result of VR training. The Mann-Whitney U test was chosen as the data of two small and not normally distributed independent samples was compared.

- Number of collisions: The number of collisions, Nc, with obstacles and the walls, was recorded both in VR and in real life using Unity[79]. The real-life Nc from session 2 of the two groups was compared through independent t-tests, as the data of two small and normally distributed independent samples was compared. If the

Nc showed statistical significance, then the real-life Nc from session 1 was also tested to see whether the significant difference was a result of VR training.

- WST-style questionnaires: The WST questionnaire was adapted to the tasks performed in the study; the original questionnaire has 27 questions while the adapted one consisted of 6 questions (see Appendix B) as for Study 1. The adapted questionnaire was completed by the participants after each real-life session and allowed them to do a self-assessment of their driving skills. The scores from session 2 of the two groups were compared through independent t-tests, as the data of two independent samples was compared. If any score showed statistical significance for any question, then the scores from session 1 of that question were also tested to see whether significant difference was a result of VR training.

4.6.4 Results of Study 2

The collected data were processed using MATLAB[152], and then analysed for statistical testing using IBM SPSS[153]. The proxy of the total of joystick movements, Ljm, and the completion time, Ct, for each real-life task from session 2, were used to assess differences in driving performances following VR training between NoGame VR and Game VR, using independent sample Mann-Whitney U tests. For any task where a statistical difference was observed, independent sample Mann-Whitney U tests for each corresponding real-life task from session 1 were conducted, to check whether the statistical difference was the consequence of going through the VR training. Independent t-tests were also carried out to analyse if there was any difference in the number of collisions, Nc and the answers of the WST-style questionnaire (Appendix B). These tests were chosen as the difference in results between two independent samples was compared.

- Proxy of the total joystick movements: Ljm was used to test for statistical significance between the two groups for the tasks conducted in real life in session 2 (after the VR training). An independent Mann-Whitney U test was used, after testing for normality and noticing the two populations were not normally distributed, for the following statistical null hypothesis and alternative hypothesis:

  - H0: the distribution of both populations is identical.
  - Ha: the distribution of both populations is not identical.

  The null hypothesis was retained for all tasks except for the forward task, where the null hypothesis was rejected (U = 81, $p = 0.016$) with the Ljm for Game VR being statistically lower than the Ljm for NoGame VR. Therefore, a Mann-Whitney U test was conducted for Ljm for the forward task but this time from session 1, where the null hypothesis as U = 61, $p = 0.436$ was retained. These findings suggest that, while participants from NoGame VR and Game VR exhibited similar performance for the forward task in session 1, a significant difference was present following the VR training, with Game VR demonstrating better performance. However, the difference in performance in Ljm between the groups is minimal as seen in Figure 4.30.

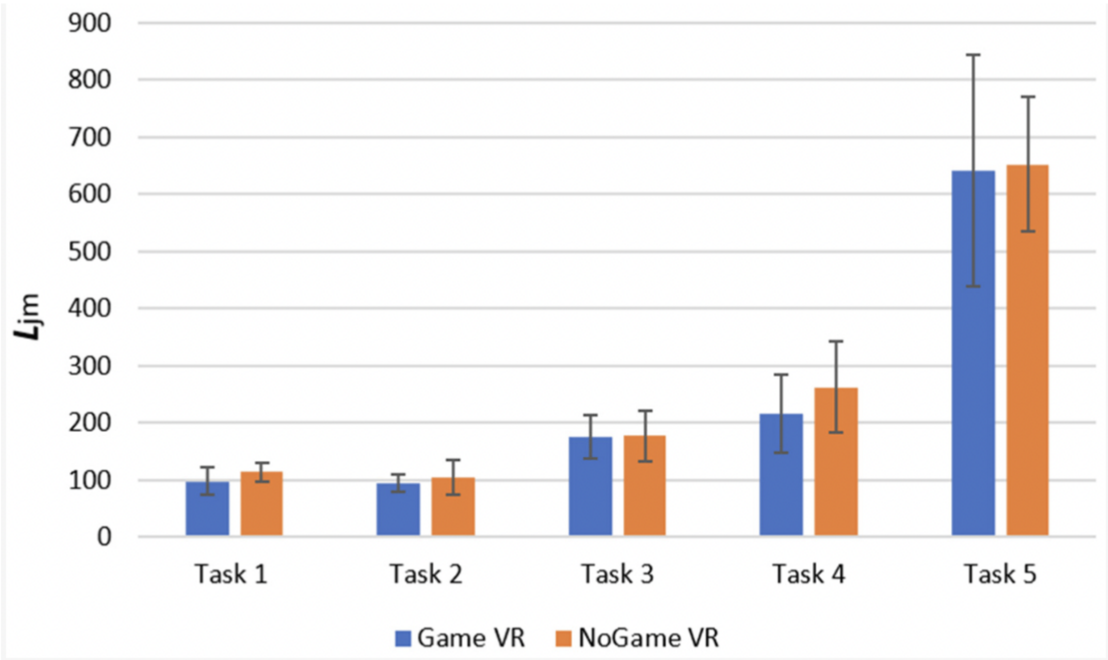

FIGURE 4.30: Session 2 real-life Ljm (proxy of sum of joystick movement) for the different tasks and groups. Task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze. The error bars represent the standard deviation.

- Completion time: Ct was used to test for statistical significance between the two groups for the tasks conducted in real life in session 2 (after the VR training). This was used as an additional measure of difference in performance between groups, in conjunction with Ljm. An independent Mann-Whitney U was used, after testing for normality and noticing the two populations were not normally distributed, to test for the following null hypothesis:

  – H0: the distribution of both populations is identical.

  – Ha: the distribution of both populations is not identical.

The null hypothesis was retained for all tasks except for the forward task, where the null hypothesis was rejected (U = 90.5, $p = 0.010$) with the Ct for Game VR being statistically lower than the Ct for NoGame VR. As such, a Mann-Whitney U test is conducted for Ct for the forward task in session 1, where the null hypothesis was retained as U = 66, $p = 0.230$. These findings indicate the reliability of the results obtained from the Ljm, affirming that gamified VR training leads to improvement in the forward task compared to non-gamified VR training. Furthermore, the performance in the completion time of most tasks is very similar between the two groups as seen in Figure 4.31.

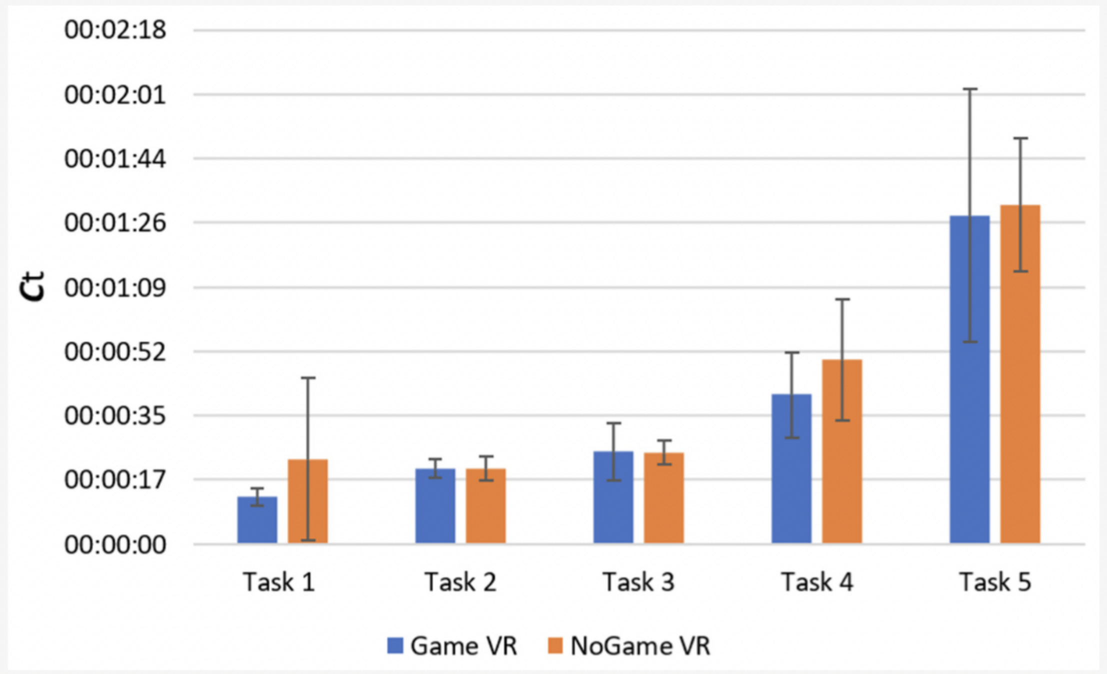

FIGURE 4.31: Session 2 real-life Ct (completion time). Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze. The error bars represent the standard deviation.

- Number of collisions: The number of collisions, Nc, was compared from session 2 between the two groups. An independent t-test was performed, after testing for normality and ensuring the two populations were normally distributed, to test the following statistical null hypothesis and alternative hypothesis:

  - H0: (Nc mean over Game VR) - (Nc mean over NoGame VR) = 0
  - Ha: (Nc mean over Game VR) - (Nc mean over NoGame VR) >0 or <0

  The result of the test, $p = 0.754$, retained the null hypothesis, therefore there is no significant difference between the two groups.

- WST-style questionnaire: An adaption of the WST questionnaire was used as a further measure to determine the difference in performance between the two groups in session 2. Independent t-tests were performed for each question between the two groups, as the limited number of participants allowed for this to be the most appropriate statistical test [154], and no statistical difference was found. The independent t-tests were performed for the following statistical null hypothesis and alternative hypothesis:

- H0: (*WST-style questionnaire* mean over Game VR) - (*WST-style questionnaire* mean over NoGame VR) = 0
- Ha: (*WST-style questionnaire* mean over Game VR) - (*WST-style questionnaire* mean over NoGame VR) >0 or <0

4.6.5 Discussion of Study 2

This study aimed to research whether elements of gamification can enhance the VR-based wheelchair training effectiveness. This aim was addressed through the following hypothesis: *Real-life driving performance after VR training will differ based on the environment.* As such, this study examined the different effects of non-gamified versus gamified VR environments on the experience of wheelchair driving skills training

The hypothesis is not supported by the findings. The results indicate that the only task in which a significant difference in performance is observed after training, both in terms of Ljm and Ct, is the forward task. However, considering that this task does not require advanced skills to be completed and no significant differences are observed in other tasks, the statistical disparity may be attributed to chance. It is important to note that VR training was conducted during a single session/day and with the majority of participants undergoing VR training only once; the results may suggest that to observe a significant difference, more training sessions might be necessary. Based on how this study was conducted, the results do however indicate that training in either environment gives the same retention of skills in real life, and thus the environment participants prefer can be used for training.

4.7 Overall Conclusion

This chapter aimed to answer R2: *How can VR be used to develop an affordable wheelchair driving skill training system, and can a methodology be implemented to assess its effectiveness?* In this regard, a low-cost controller system that depended on an IMU sensor which can be used on different powered wheelchairs controlled by joysticks was developed, along with different VR environments. Two studies were conducted for the evaluation and improvement of the developed system. In Study 1 the system was validated and it was found that: 1) affordable technology can be used to train driving skills in VR which leads to improvement of driving skills in real life; 2) acquisition of wheelchair driving skills can be accelerated using VR; in fact, the results of section 4.5.4 show that the VR training system supports the immediate to short term acquisition of skills for more challenging tasks. In Study 2, it was explored how to improve the design of the VR environment through gamification. Notably, no prior research has examined the impact of gamification on VR wheelchair-driving skills training. The findings do not provide conclusive evidence regarding the influence of gamification on acquired real-life driving skills, meaning participants may choose the environment design they prefer without being penalised when it comes to acquiring skills. It must also be noted, that in this study, participants undertook only one VR training session; therefore, multiple sessions (with more participants and different VR environments) are warranted in future investigations to test the long-term effect of gamification on wheelchair driving skills.

In the next chapter, Chapter 5, the two studies presented in this chapter are explored in terms of the VR training's effects on the participants' well-being. Specifically, the results of the participants to two questionnaires, namely the SSQ[20] scores and IPQ[19] scores, are analysed. Further, the measures of the participants' HR are also analysed.

Chapter 5

Well-Being Monitoring in VR Training

The previous chapter, Chapter 4, presented the developed VR system for wheelchair driving skills training and evaluated its performance and effectiveness through two studies. The current chapter further explores the developed VR system, through the same two studies, however, by investigating how VR affects the well-being of its users by measuring the HR, the experienced cybersickness and the perceived presence. Notably, this chapter builds on the literature review conducted in Chapter 2 section 2.3, where it was found that HR can effectively be used as an objective measure of physiological signals in VR. As a result, the research question investigated throughout this chapter was defined as follows: *How can the impact of the VR training be implicitly assessed in relation to participant's well-being?* Thus, the current chapter explores what changes in HR throughout a VR experience can indicate while also monitoring the subjective experience of VR through questionnaires about the perceived cybersickness and presence.

5.1 Introduction

During a VR experience, it is important to monitor a user's well-being to ensure a positive overall user experience. In fact, the QoE [84] during a VR simulation has the potential to either positively or negatively impact the user's well-being. Assessment of the QoE can be conducted explicitly through self-assessed questionnaires or implicitly through physiological measurements.

The QoE is typically measured explicitly in terms of two key factors: Sense of Presence (SoP) and cybersickness. SoP, defined as the feeling of "being" in the computer-generated environment rather than the physical surroundings, strongly correlates with the effectiveness of VR-based training. It is influenced by the level of immersion and involvement in the VR experience, ultimately contributing to a more positive user experience [5, 66]. Conversely, cybersickness, which manifests as discomfort, visual fatigue, nausea, disorientation, and headaches, has a negative impact on the VR experience. It is known to reduce enjoyment [51] and, consequently, can adversely affect the user's well-being during VR interactions. Cybersickness is often measured immediately after a VR experience using the SSQ [70, 72, 76], even though it can lead to prolonged side effects [163].

Alongside explicit measurements of the QoE, it is also valuable to explore implicit measurements, such as monitoring the users' HR. The HR can be an important indicator of different physiological reactions resulting from a VR environment. In fact, the HR has been shown to have a positive correlation with cybersickness and can be used alongside questionnaires to determine the presence of cybersickness [49]. Furthermore, the HR has been shown to differ based on the tasks a participant performs in VR. It has been found that different tasks have different psychophysical loads, which result in HR changes based on task [164, 165]. Considering that different tasks in VR, such as those involving different interaction or locomotion techniques, affect the users' QoE [166] they are another important aspect to consider when evaluating a VR system.

In this chapter, the two studies described in Chapter 4 are analysed under the aspect of the participants' well-being during the VR experiences. The first study, Study 1, was used to validate the developed VR system, and as such the well-being factors measured served to ensure that the system did not provoke the user any discomfort. As a result, the SoP was evaluated using the IPQ [19], and cybersickness was evaluated using the SSQ [20]; both questionnaires were administered after VR training (to the VR group only) in accordance to the literature [70, 72, 76]. Furthermore, changes in HR (during the VR training) based on the task were monitored, and the following hypothesis was tested:

- *Changes in HR during VR training are related to performance improvement in real-life.*

To test this hypothesis, the HR was measured throughout the entire VR experience and then divided between tasks to compare the HR differences between the different tasks. This allowed to analyse whether different tasks stimulate a higher psychophysical load.

Any HR differences were then compared to the participants' real life driving performance differences between each task.

The second study, Study 2, explored whether the effectiveness of VR training of wheelchair driving skills can be improved through gamification. In Study 2, the performance outcomes of two different VR environments, namely a gamified VR one and a non-gamified VR one, were compared. As such, the results of the IPQ [19], the SSQ [20] and the HR (in this study used as an additional measure of cybersickness) were compared between the two groups. The following two hypotheses were addressed:

- *The levels of involvement and presence will vary based on the environment.*
- *The perceived cybersickness will vary based on the environment.*

To test these hypotheses, the HR of the participants of both groups was measured throughout the entire VR experience, broken down by tasks, and then compared between the two groups. The IPQ [19] and the SSQ [20] were administered after the VR experience, in accordance to the literature [70, 72, 76], and compared between the two groups.

5.2 Heart Rate Monitor

The VR hardware used to conduct the studies is described in Chapter 4. However, as this chapter analyses the studies in terms of well-being and one of the measures analysed is HR, the hardware used to capture the HR data is described below.

The Polar H10[104] chest strap, shown in Figure 5.1 was used as the HR monitor. The Polar H10[104] uses ECG sensors and outputs HR in beats per minute (bpm) at a sampling rate of 1Hz. The technical specifications of the sensor are given in Table 5.1. The Polar H10[104] with the Pro Strap (as chest strap) has been validated for its accuracy by Schaffarczyk et al. [106] against a 12-channel ECG, where it was found that in terms of R-R intervals and HR the Polar H10[104] gives similar results to an ECG. It must also be noted that the Polar H10[104] has been proven to be as accurate as the gold standard ECG monitor for ambulatory setting, the ECG Holter device, during low and moderate intensity activities [107]. Thus, the Polar H10[104] with the Pro Strap (as chest strap) was deemed to be an appropriate sensor for the study. By being an affordable sensor renowned for its accuracy, it also meets the goal of this project to create an affordable system for wheelchair users.

FIGURE 5.1: Polar H10 HR monitor (with chest strap).

TABLE 5.1: Polar H10 HR monitor specifications.

Polar H10 Specifications	
Battery Type	CR 2025
Battery Sealing Ring	O-ring 20.0 x 0.90 Material Silicone
Battery Lifetime	400 h
Sampling Rate	1 Hz
Operating Temperature	-10 °C to +50 °C / 14 °F to 122 °F
Connector Material	ABS, ABS + GF, PC, Stainless steel
Strap Material	38%Polyamide, 29%Polyurethane, 20%Elastane, 13%Polyester, Silicone prints

5.3 Software Used For Well-Being Data Processing And Analysis

This section outlines the necessary software used for the capturing of the HR data and for the analysis of both the explicit and implicit well-being data collected throughout the two studies.

5.3.1 Polar Beat App

To collect the HR data, the Polar Beat[167] app (the recommended app by Polar [168]) was used. The app was accessed from a mobile phone, which connected to the monitor through Bluetooth (BT). The data saved in the app graphically represents the change of HR over time and indicates the duration of the data collection, the maximum HR and the average HR. The data saved on the app can also be accessed from the Polar[168] website, where the change in collected HR per second can be seen. For the data analysis, the data was accessed from the website, and downloaded in the form of a ".csv" file. As such, after downloading the data it was processed in Microsoft Excel[151] (by CZ) and statistical analysis using IBM SPSS[153] was performed (by CZ with guidance from GM, following consultation with BS).

5.3.2 Processing of The Collected Well-being Data

For both Study 1 and Study 2, the processing of the data followed a similar process. The HR data was collected with the Polar Beat[167] App, processed using Excel[151] and statistically analysed using IBM SPSS[153]. The questionnaire data, for both the IPQ [19] and the SSQ [20] was collected through conventional printed survey sheets by CZ. These hard-copy records were subsequently digitised by CZ into an Excel[151] spreadsheet for organisation and graphical analysis. For Study 2, these datasets were subsequently statistically analysed using IBM SPSS[153] by comparing the results of the two groups. The following software was used to analyse the collected data:

- Microsoft Excel: Excel[151] played an important role as a data management and processing tool for handling all the collected data. Specifically, for the HR data, the collected data was downloaded as a ".csv" file from the Polar Flow[169] website. Subsequently, the HR data of each participant was imported into the participant's individual folder that was created upon registering the participant (see Chapter 4 section 4.3.2.1). Following this, the HR data was merged with the data obtained from the Unity[79] environment (described in Chapter 4 section 4.5.3 for Study 1 and 4.6.3 for Study 2), enabling the alignment of HR data with the corresponding events in the Unity[79] environment.

  For the SSQ [20], the data was collected on paper first and afterwards it was transcribed into Excel[151]. The SSQ [20] investigates perceived cybersickness by asking the user to score 16 symptoms from 0 to 3 (0 - none, 1 - slight, 2 - moderate, 3 - severe). This test was administered to the participants at the end of the VR training. Each of the symptoms corresponds to one or more of three categories:

nausea (N), oculomotor (O) and disorientation (D). The score for each category (N, O, D) and the total score (TS) were calculated using the following formulas [20].

$$N = [a] * 9.54$$

$$O = [b] * 7.58$$

$$D = [c] * 13.92$$

$$TS = ([a] + [b] + [c]) * 3.74$$

The average, standard deviation (SD), min and max of each category (N, O, D) and the total score (TS) were also calculated. The scores for the N, O, D and TS were then compared to reference scores [72], to quantify the level of cybersickness (i.e., none, slight, moderate, severe) caused by the system. In Study 2, the scores were also statistically compared between the two groups that trained in VR.

A similar process was followed for the IPQ [19] where the data was collected on paper first and afterwards it was transcribed into Excel[151]. The IPQ [19] asks the participants to assign a score from 0 to 6 to 14 questions. Each question falls within one of the following categories: involvement, experienced realism, spatial presence, and general presence. Participants were given the questionnaire after the VR training to measure the sense of presence elicited by the virtual environment and simply assigned a score to each question. The data was then imported in Excel[151]. In Excel[151], the data was split into their corresponding categories. The data was analysed in terms of the extent to which each symptom was perceived, for both studies. In Study 2, the scores of each category were also statistically compared between the two groups of participants (Game VR and NoGame VR) using IBM SPSS[153].

- IBM SPSS: IBM SPSS[153] was used to statistically analyse the collected data. All the statistical tests performed were chosen based on what tests would most appropriately test the hypotheses of the studies and based on the type of data to be tested (to ensure it complies with the specific assumptions of the chosen statistical tests), after a consultation with the statistics clinic of the University of Kent (specifically BS). In Study 1, the only statistical analysis performed was for the HR using a Welch one-way ANOVA test to see if there were any statistical differences between the HR from different tasks. This test was chosen as the HR of five tasks with unequal variances was compared. A Games-Howell post-hoc test was then performed to find significant differences between tasks; this specific test was chosen as the HR measured for the different tasks have unequal variance [154]. For all statistical tests, $p= 0.05$ was used as a standard of significance.

In Study 2, the HR measured throughout the whole VR training for each participant was batched with the HR of the other participants from the same group; the two batches of HR data were compared using an independent t-test given the results of two independent participant samples with normal distribution were compared. As the test showed statistical significance, batches for each task from the two groups were compared with independent t-tests. Independent t-tests were also performed to test the statistical significance between the results of the SSQ [20] and the IPQ [19] of the two groups.

5.4 Study 1: Validation of The Developed System Through Well-Being Measures

This study served as a validation of the developed VR system, with comprehensive details about the study set-up and VR development provided in Chapter 4 section 4.5. In addition to validating the system's functionality, the study also focused on evaluating the overall user experience to ensure it remained positive without negatively impacting the user's well-being.

Specifically, the study assessed the level of presence, immersion, and involvement induced by the system by analysing responses of the IPQ [19]. Furthermore, it gauged the degree of cybersickness induced by the system by comparing the results from the SSQ [20] against reference scores, thus categorising cybersickness as none, slight, moderate, or severe. Most notably, the study delved into whether the various tasks conducted within the VR environment prompted varying levels of psychophysical load; this was based on differences in the HR during the multiple tasks, and whether they resulted in real-life performance outcome differences. In particular, the following hypothesis was investigated:

- *Changes in HR during training are related to performance improvement in real life.*

To investigate this hypothesis, the HR throughout the whole VR experience was measured for each participant. The HR was then batched between the HR of each task (for each participant), and the results of the different tasks from all participants were added. These batched HR by task were statistically analysed between one another. It must be noted that in this study two groups of participants took part, but only one underwent VR training and as such only that group had the HR of participants taken.

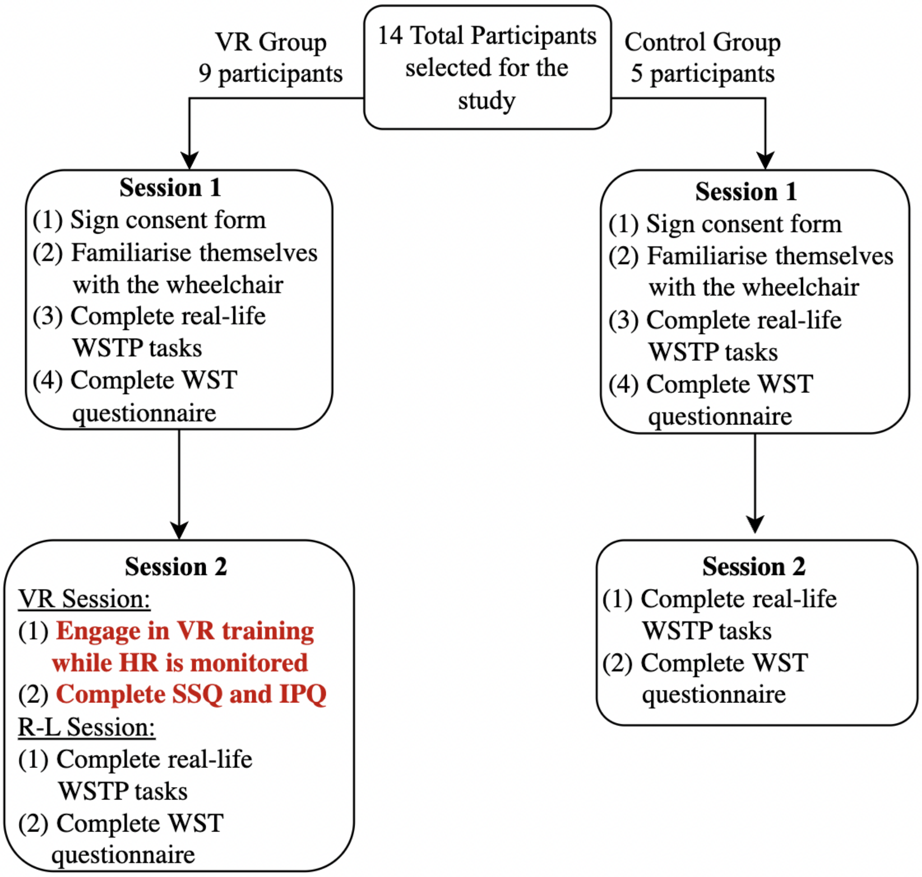

FIGURE 5.2: Set-up of Study 1 with well-being steps highlighted in red.

5.4.1 Results of Study 1 Well-Being Measures

In this section, the results of the well-being measures taken for Study 1 are described. First, the IPQ [19] results are presented. Second, the SSQ [20] results are presented and compared to the reference scores. Third, the HR results are presented and statistically analysed between each task.

- Igroup presence questionnaire: The results of the IPQ [19] are found in Table 5.2 and Figure 5.3. These show that the system elicits presence as spatial presence with an average score of 4.1, while general presence with an average score of 4.2 (both above the median score of 2.5). However, regarding realism, the scores indicate the participants did not feel that the simulated environment was real. Further, the involvement score was just above the median score; this can be due to the lack of interactive activities in the simulated environment.

TABLE 5.2: Average IPQ results for Study 1.

IPQ Results		
	Mean	SD
Involvement	2.93	2.08
Experience Realism	1.93	1.86
Spatial Presence	4.1	1.63
General Presence	4.2	1.33

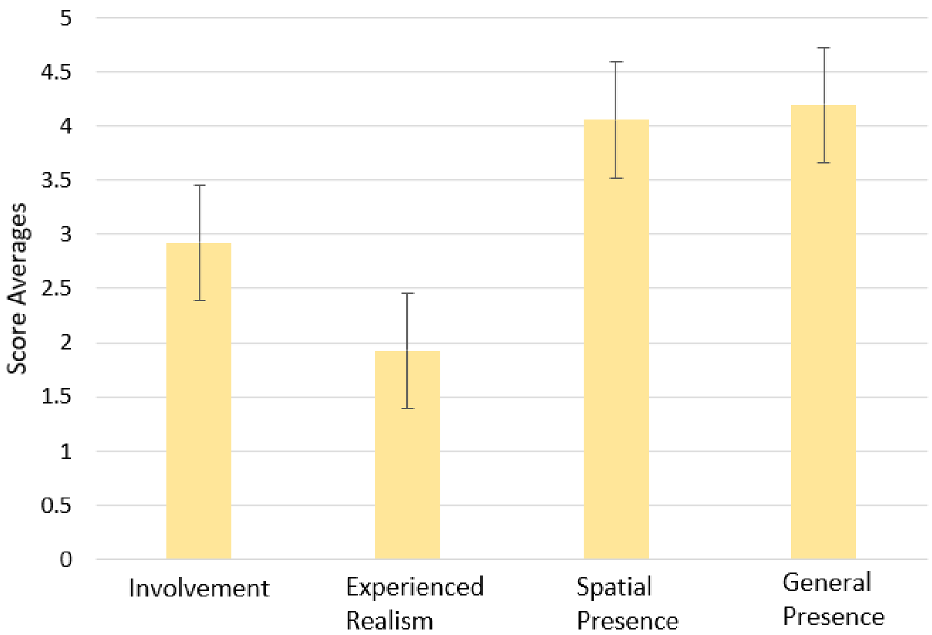

FIGURE 5.3: Average IPQ results for Study 1. Error bars indicate standard deviation.

- Simulator sickness questionnaire: The extent of perceived cybersickness was assessed through the SSQ [20], and the corresponding results are shown in Table 5.3. These results were compared to reference scores, as presented in Table 5.4, which delineate a spectrum of values corresponding to symptom severity levels. On average, the individual symptoms induced by the training system were rated between *slight* and *moderate*, with the overall total symptom score (TS) falling between *moderate* and *severe*. It's worth noting that the scores are subjective, and when looking at the minimum and maximum scores, participants assigned scores ranging from not feeling any symptoms to feeling symptoms between moderate and severe.

TABLE 5.3: SSQ results for Study 1.

SSQ Results Study 1				
	Nausea	Oculomotor	Disorientation	Total
Mean	74.2	59.3	106.7	84.4
SD	41.8	41.6	69.6	49.6
Min	0	0	0	0
Max	133.6	144.0	208.8	175.8

TABLE 5.4: SSQ reference scores.

SSQ Reference Scores				
	Nausea	Oculomotor	Disorientation	Total
None	0	0	0	0
Slight	66.8	53.1	97.4	40.2
Moderate	133.6	106.1	194.9	80.4
Severe	200.3	159.2	292.3	120.5

- Heart rate: A Welch one-way ANOVA test was performed to investigate if any statistical difference was present between the HR from different tasks. This test was chosen as the HR of five tasks with unequal variances were compared. Thus, the following statistical null hypothesis and alternative hypothesis were investigated:
  - H0: Task 1 mean bpm = Task 2 mean bpm = Task 3 mean bpm = Task 4 mean bpm = Task 5 mean bpm
  - Ha: the means of each task are unequal

  Overall, there was a statistically significant difference in the HR between the tasks (F(5,9169) = 206.385, p <0.001). Given that the results from Chapter 4 section 4.5.4 reported the biggest improvement in task 4, a Games-Howell post-hoc test between task 4 and each of the other tasks was performed, as the variances of the groups was unequal. This revealed a statistical difference in the level $p = 0.05$ in the HR between task 4 and every other task. Figure 5.4 represents a plot of the HR data of all participants grouped by task, while Table 5.5 lists all the tasks with the corresponding mean HR, SD and standard error. An increase in mean, median and minimum HR values is seen for the backward slalom task, which may suggest that task 4 has a higher psychophysical load compared to the other tasks.

TABLE 5.5: HR results batched by task of Study 1.

HR Results			
	Mean	SD	Std. Error
Forward Task	75.39	9.05	0.45
Backward Task	76.97	10.04	0.38
Forward Slalom Task	78.30	7.90	0.23
Backward Slalom Task	79.27	9.04	0.25
Maze Task	75.95	8.86	0.17

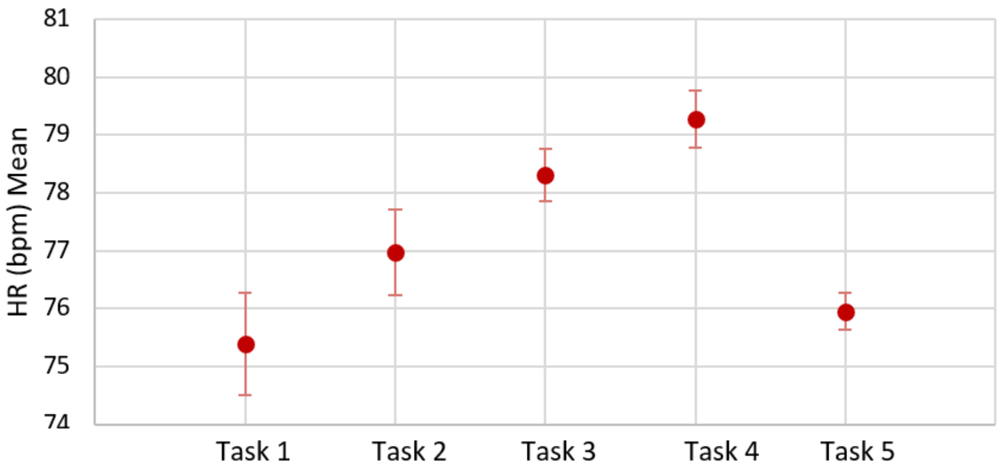

FIGURE 5.4: HR batched by task. Error bars represent the confidence interval.

5.4.1.1 Summary of Results of Study 1

The IPQ results indicated that the VR system successfully elicited a sense of presence, with spatial presence and general presence scoring above the median score of the assessment scale. However, the system was less effective in creating a sense of realism and involvement, likely due to the lack of interactive activities in the simulated environment. The SSQ results showed that the training system induced cybersickness symptoms ranging from slight to moderate for nausea, oculomotor issues, disorientation, and from moderate to severe for the total SSQ score compared to reference scores. HR monitoring revealed statistically significant differences between the HR of different tasks, specifically the HR of participants during task 4, which was the task with improvements in driving skills in real life, was statically higher than the HR of all other tasks.

5.4.2 Discussion of Study 1

In Chapter 4 it was found that the task which showed the most significant improvement was the backward slalom task. Notably, the HR data analysis revealed that participants recorded their highest HR values while engaged in the VR backward slalom task (refer to Figure 5.4 and Table 5.5). These findings corroborate the hypothesis: *Changes in HR during VR training are related to performance improvement in real life.* The elevated HR during more challenging tasks in VR suggests that the technology may offer greater benefits for acquiring those skills, particularly in the short term. This aligns with the observations of Bassano et al. [98], who noted slightly increased HR during faster tasks in ship-handling simulations, attributing this to task difficulty. Furthermore, as suggested by Berntson et al. [164, 165], variations in HR based on tasks may reflect differences in psychophysiological demands. Consequently, HR data can serve as an indicator to identify specific tasks that may warrant closer attention for improved training outcomes tailored to individual participants.

The degree of presence and realism engendered by the system was also evaluated by tasking the participants with completing the IPQ [19]. The results indicate that the system successfully evokes a sense of presence, as evidenced by above-average scores (refer to Figure 5.3). This is particularly significant because higher levels of presence have been linked to enhanced effectiveness in VR-based learning [5]. However, the system was not as effective in eliciting a strong sense of realism and involvement. This outcome may be attributed to the absence of engaging tasks within the VR environment.

Given that cybersickness is one of the limitations of VR, the SSQ [20] was administered as well. The results reveal that, on average, the system induces moderate cybersickness. Notably, when examining the range of scores provided by the participants, it becomes evident that cybersickness is a highly subjective experience, with individuals reporting symptoms ranging from slight to moderate to severe (refer to Table 5.3). Cybersickness typically arises due to the discord between visual stimuli and the absence of corresponding vestibular stimuli during VR use [170]. Consequently, it is expected to be present to some degree when employing VR technology; indeed, research suggests that 40%-70% of users may experience cybersickness after just 15 minutes of use [170]. To mitigate this effect, alternative training methods like desktop monitors have been explored. However, studies comparing HMDs and monitors have demonstrated that HMDs are more effective in teaching skills such as wheelchair mobility than desktop monitors [73].

5.5 Study 2: Assessing How Gamification Effects The Well-Being of Participants Training in VR

While Study 1 served as a validation for the developed VR system, this study, Study 2, aimed to enhance the VR training through different design elements. Specifically, it explored the potential impact of gamification on the effectiveness of VR-based training. For an in-depth understanding of the design processes of Study 2, please refer to Chapter 4 section 4.6.

In this study, participants were randomly divided into two groups: one undergoing wheelchair driving skills training in a gamified VR (Game VR) environment and the other in a non-gamified VR (NoGame VR) environment. Consequently, data collected from these two groups of participants were compared across multiple aspects, including well-being measures specifically through the IPQ [19], the SSQ [20], and HR. As such, this investigation aims to test whether differences in environmental design influence the SoP and cybersickness experienced during VR training. As a result, the following two hypotheses were investigated.

- *The levels of involvement and presence will vary based on the environment.*
- *The perceived cybersickness will vary based on the environment.*

The first hypothesis was assessed using the IPQ [19], while the second was assessed by using the SSQ [20] and by measuring the HR of the participants.

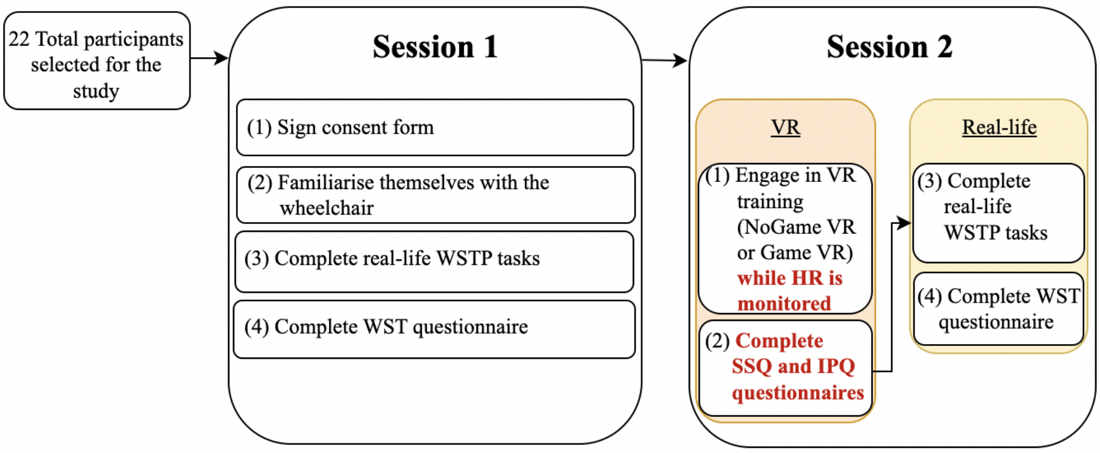

FIGURE 5.5: Set-up of Study 2 with well-being steps highlighted in red.

5.5.1 Results of Study 2 Well-Being Measures

In this section, the results of the well-being measures taken for Study 2 are described. First, the IPQ [19] results of the two groups are presented and statistically analysed between the groups. Second, the SSQ [20] results of the two groups are presented, statistically analysed between the groups and compared to the reference scores. Third, the HR results of the two groups are presented and statistically analysed between the groups as a whole, and for each task.

- Igroup presence questionnaires: The IPQ was administered after the VR training. Table 5.5.1 represents the results of the IPQ for NoGame VR, while Table 5.5.1 represents the results of the IPQ for Game VR. Figure 5.6 shows the results of both groups.

Table 5.6: IPQ results for Study 2 - NoGame VR.

IPQ Results For NoGame VR		
	Mean	SD
Involvement	3.32	1.36
Experience Realism	2.93	1.63
Spatial Presence	4	1.27
General Presence	4.55	0.85

Table 5.7: IPQ results for Study 2 - Game VR.

IPQ Results For Game VR		
	Mean	SD
Involvement	3.2	1.50
Experience Realism	2.5	1.66
Spatial Presence	3.56	1.58
General Presence	3.91	1.58

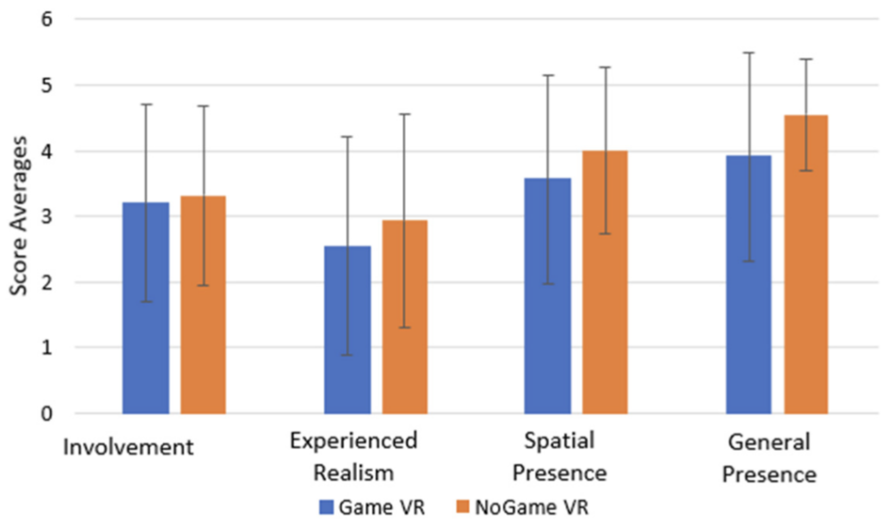

FIGURE 5.6: IPQ results of both groups for Study 2.

Surprisingly, NoGame VR demonstrated a higher overall perception of the different categories; although higher realism was to be expected for the non-gamified environment, the greater involvement and presence were unexpected. However, it is important to note that the SD indicates a high variance in the results. Given the results of two independent groups of participants were compared, independent t-tests were conducted between NoGame VR and Game VR to analyse further these findings. As such, the following statistical null hypothesis and alternative hypothesis were tested:

- H0: (IPQ mean over Game VR) - (IPQ mean over NoGame VR) = 0
- Ha: (IPQ mean over Game VR) - (IPQ mean over NoGame VR) >0 or <0

The t-tests revealed no statistically significant difference. Consequently, while differences exist, they lack statistical significance.

- Simulator sickness questionnaire: The SSQ [20] was administered after the VR training for both groups. The results of NoGame VR are presented in Table 5.8, while the results of Game VR are presented in Table 5.9. The results were first compared to the reference scores in Table 5.10, and then they were statistically compared between groups through an independent t-test, given the results of two independent groups of participants were compared.

TABLE 5.8: SSQ results for Study 2 - NoGame VR.

SSQ Results For NoGame VR				
	Nausea	Oculomotor	Disorientation	Total
Mean	82.39	58.57	112.63	91.46
SD	24.24	35.24	56.18	37.45
Min	38.16	0	27.84	22.44
Max	114.48	113.7	208.8	145.86

TABLE 5.9: SSQ results for Study 2 - Game VR.

SSQ Results For Game VR				
	Nausea	Oculomotor	Disorientation	Total
Mean	42.5	33.08	67.07	51
SD	31.46	28.82	52.02	36.23
Min	0	0	0	0
Max	95.4	83.38	139.2	97.24

TABLE 5.10: SSQ reference scores.

SSQ Reference Scores				
	Nausea	Oculomotor	Disorientation	Total
None	0	0	0	0
Slight	66.8	53.1	97.4	40.2
Moderate	133.6	106.1	194.9	80.4
Severe	200.3	159.2	292.3	120.5

Comparing the reference scores in Table 5.10 with the scores in Table 5.8 (NoGame VR), the non-gamified environment seems to provoke, on average, symptoms ranging between *slight* and *moderate*, with the total ranging between *moderate* and *severe*. The gamified environment, on the other hand, provokes on average symptoms ranging between *none* and *slight*, with the total ranging between *slight* and *moderate*, as seen in Table 5.9. Because of these differences, a one-sided independent *t*-test was performed for the following statistical null hypothesis and alternative hypothesis:

– H0: (SSQ mean over Game VR) - (SSQ mean over NoGame VR) = 0

– Ha: (SSQ mean over Game VR) - SSQ mean over NoGame VR) >0 or <0

The results show that the non-gamified environment seems to provoke significantly higher sickness symptoms for nausea (t20 = 3.332, p = 0.002), oculomotor (t20 =

1.857, p = 0.039), disorientation (t20 = 1.973, p = 0.031), and total (t20 = 2.575, p = 0.009).

- Heart rate: The HR measured throughout the whole VR training (and all tasks) for each participant was batched with the HR of the other participants from the same group; the two batches of HR data were compared using an independent *t*-test, given the results of two independent groups of participants with normally distributed data were compared. As the test showed statistical significance, batches for each task from the two groups were compared with independent *t*-tests. The overall batched HR data was compared between the two groups to test the following statistical null hypothesis and alternative hypothesis:

  – H0: (HR mean over Game VR) - (HR mean over NoGame VR) = 0

  – Ha: (HR mean over Game VR) - (HR mean over NoGame VR) >0 or <0

  The results for the overall HR rejected the null hypothesis, with the HR being statistically higher for the NoGame VR group with p <0.001. As such, the batched HR for each task between the two groups was also statistically compared by performing independent *t*-tests. In the *t*-tests for the individual tasks, the null hypothesis was retained for task 1 - forward task, task 2 - backward task, and task 5 - maze task; therefore, there is no significant difference between the two groups for those tasks. However, for task 3 - slalom task, and task 4 - backward slalom task, the results of the tests rejected the null hypothesis with p <0.001 and p <0.001, respectively; in these tests, the HR was higher for the NoGame VR group. The HR mean values and confidence intervals of both studies can be seen in Figure 5.7, while the mean, SD and standard error can be seen in Table 5.11 for Game VR and in Table 5.12 for NoGame VR.

TABLE 5.11: HR results batched by task for Game VR of Study 2.

HR Results			
	Mean	SD	Std. Error
Forward Task	79.09	11.67	0.56
Backward Task	79.46	11.74	0.58
Forward Slalom Task	83.28	12.56	0.60
Backward Slalom Task	82.65	11.47	0.53
Maze Task	80.35	11.83	0.38

TABLE 5.12: HR results batched by task for NoGame VR of Study 2.

HR Results			
	Mean	SD	Std. Error
Forward Task	78.67	13.03	0.45
Backward Task	79.01	12.65	0.40
Forward Slalom Task	78.99	12.43	0.49
Backward Slalom Task	80.60	13.23	0.42
Maze Task	76.56	11.32	0.23

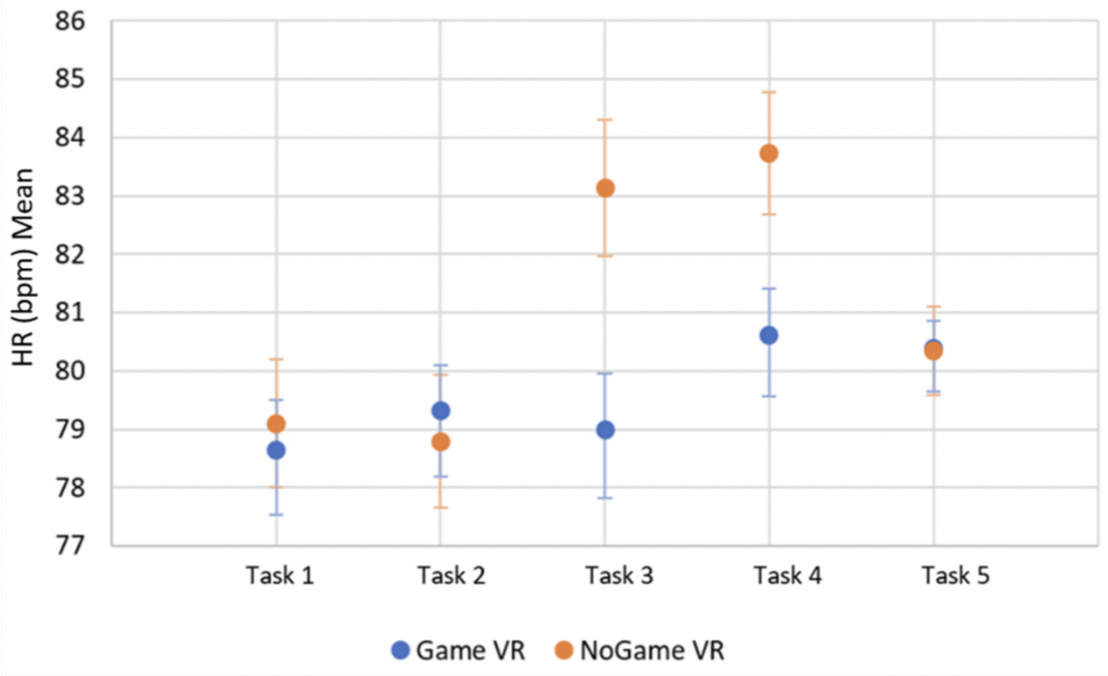

FIGURE 5.7: HR batched by task. The error bars represent the confidence interval.

5.5.1.1 Summary of Results of Study 2

The IPQ results indicate that the NoGame VR group had higher mean IPQ scores across categories such as involvement, experienced realism, spatial presence, and general presence compared to the Game VR group. However, these differences were not statistically significant. In terms of cybersickness, participants in the Game VR group reported lower mean scores for nausea, oculomotor issues, disorientation, and overall SSQ scores compared to those in the NoGame VR group, suggesting that gamification can effectively reduce cybersickness symptoms. HR monitoring revealed higher HR in the NoGame VR group, correlating with higher SSQ scores. Specific tasks, such as the slalom and backward slalom, showed significant higher HR increases for the NoGame VR group. Additionally, participants in the Game VR were more likely to engage in repeated training sessions, likely due to reduced cybersickness and increased enjoyment. In contrast, as participants in the NoGame VR group experienced higher cybersickness, it may have limited their ability to continue training.

5.5.2 Discussion of Study 2

In this study, it was tested whether elements of gamification can enhance the VR-based wheelchair training effectiveness. This was addressed through two distinct hypotheses related to the user's well-being.

The first hypothesis, *H1: The levels of immersion and presence will vary based on the environment* is unsupported by the findings. Interestingly, participants in NoGame VR exhibited slightly higher average results in terms of the IPQ [19]. However, the difference in results between the two groups is not statistically significant, and therefore, it cannot be concluded that the non-gamified environment significantly elicits higher levels of presence. It is important to point out that Schwind et al. [171] also reported slightly higher scores in the IPQ [19] for the non-gamified environment over the gamified one but with no significant difference. As the IPQ [19] is administered after the training, for more accurate IPQ [19] results Schwind et al. [171] suggested to administer the IPQ [19] during the VR experience rather than after it. Presence can be enhanced, instead, by adding more sophisticated haptic and visual feedback [172], as well as sound for directional cues to complete tasks [173].

The second hypothesis, *H2: The perceived cybersickness will vary based on the environment* is supported by the findings, which show a significant difference, as participants in NoGame VR experienced statistically higher symptoms of cybersickness compared to Game VR (according to the SSQ [20]). Several studies suggested that reducing the Field of View (FOV) can help alleviate cybersickness symptoms [174–176]. Although both groups had the same FOV, participants in Game VR had to collect targets (aliens), resulting in focusing their attention on a single object in their central vision. The findings align with the study conducted by Yip and Saunders [177], who showed that directing the user's attention to the central vision rather than peripheral vision has a positive impact on cybersickness. It is also possible that the presence of background noise contributed to the reduction of cybersickness symptoms, as found by Keshavarz and Hecht [178] who showed that pleasing sounds reduced cybersickness. Other studies [179] however, argue that sound has no effect on the level of perceived cybersickness.

Consistent with these findings, Nalivaiko et al. [50] found that participants with higher perceived cybersickness scores also showed an increase in HR. In this study, a statistically higher HR was found in participants of NoGame VR, which is the group with the higher SSQ [20] scores. In terms of HR difference for specific tasks, NoGame VR had statistically higher HR values for the slalom task and backward slalom task, which may be the tasks in which participants experienced symptoms of sickness. Similarly, Salgado et al. [76] observed a correlation between increased HR and cybersickness, suggesting that HR increases as a result cybersickness. Another physiological measure that is worthy of investigation in relation to cybersickness is Electrodermal Activity (EDA), as other studies believe changes in EDA are a result of cybersickness [180, 181]. It must be noted that the cybersickness was measured immediately after a VR experience following examples from the literature [70, 72, 76]. However, it has been found that sometimes it can lead to prolonged side effects [163]. There is, however, a lack of literature measuring these prolonged side effects as well as whether any symptoms have an onset after using a VR application. To measure the true effects of cybersickness and the extent to which it can affect a person, it would be interesting to conduct longitudinal studies in which the symptoms are monitored over a period of time after using a VR application.

Finally, it was found that the Game VR participants, who experienced less cybersickness, were more inclined to engage in repeated sessions of VR training. In fact, in Game VR, three participants repeated the VR training twice and three repeated it three times. This could be attributed to the reduced incidence of cybersickness due to gamification, which consequently enhances the overall enjoyment and long-term sustainability of the VR experience. In contrast, only two participants in NoGame VR attempted the training twice, and both had to stop the second attempt halfway due to severe nausea. These findings align with prior research conducted by Yildirim [182], who stated that feeling cybersickness decreases enjoyment. Garrido et al. [51] also found cybersickness to have a negative impact on enjoyment and future use of VR. In fact, one participant of NoGame VR stated "Tasks in the reversed direction caused nausea. I had to stop working halfway.". Therefore, the implementation of a gamified environment in VR training holds the potential for a broader adoption of the system, due to the lower incidence of cybersickness, and thus a more enjoyable VR training experience.

5.6 Study 1 And Study 2 Relation For Well-Being Results

In this chapter, the well-being of the participants who trained using the developed VR system described in Chapter 4 is studied. This is to assess the system does not negatively affect the well-being of the participants. In this respect, it assesses the presence through the IPQ [19], the cybersickness through the SSQ [20] and the HR, and psychophysical load of task through the HR. Importantly, this chapter aims to see if the well-being of the participants can be measured implicitly. Through analysing the results of these well-being measures, some similarities were noticed and as such the relation between Study 1 and Study 2 in terms of IPQ [19], SSQ [20] and HR is analysed below.

5.6.1 IPQ Relation Between Study 1 And Study 2

In this section the IPQ [19] scores of Study 1 and Study 2 are compared (by CZ), because they show similar pattern across the four different categories. Specifically, the overall presence score consistently ranked highest in all environments, followed by spatial presence, involvement, and experienced realism. To ascertain if any statistically significant differences occurred between Study 1 and Study 2, a closer examination was conducted by performing independent$t$-test between the two studies using IBM SPSS[153]. The results of the t-tests show that no statistical difference is present between the environment of Study 1 and either environment of Study 2 in any of the IPQ categories, except for the experienced realism between NoGame VR (Study 2) and Study 1, with a $p = 0.034$. However, all experienced realism scores were below 3 on a scale from 0 to 6. Thus, it can be concluded that the IPQ scores of all the environments are not significantly different.

5.6.2 SSQ Relation Between Study 1 and Study 2

In this section the occurrence of cybersickness in Study 1 and Study 2 induced by the VR environments using the SSQ [20] results are compared (by CZ). Specifically, similar trends can be observed between the results of NoGame VR (Study 2) with those of Study 1. In both studies, symptoms of nausea, oculomotor, and disorientation ranged from *slight* to *moderate*, with the total score falling between *moderate* and *severe*. Notably, the only environment where symptoms were consistently lower was the Game VR environment, with lower scores for all symptoms compared to both NoGame VR and Study 1. These reduced scores fall between *none* and *slight* for symptoms of nausea, oculomotor, and disorientation, and between *slight* and *moderate* for the total score. This highlights the potential of gamification in mitigating cybersickness symptoms. Table 5.13 and Figure 5.8 show the mean SSQ [20] scores provoked by all the environments, and it can be seen that the mean scores for the Game VR group of each category is significantly lower than the one for the other groups (NoGame VR and Study 1).

SSQ Results				
	Nausea	Oculomotor	Disorientation	Total
Mean S2 GVR	42.5	33.08	67.07	51
Mean S2 NoGVR	82.39	58.57	112.63	91.46
Mean S1	74.2	59.3	106.7	84.4

TABLE 5.13: Mean SSQ results for all studies.

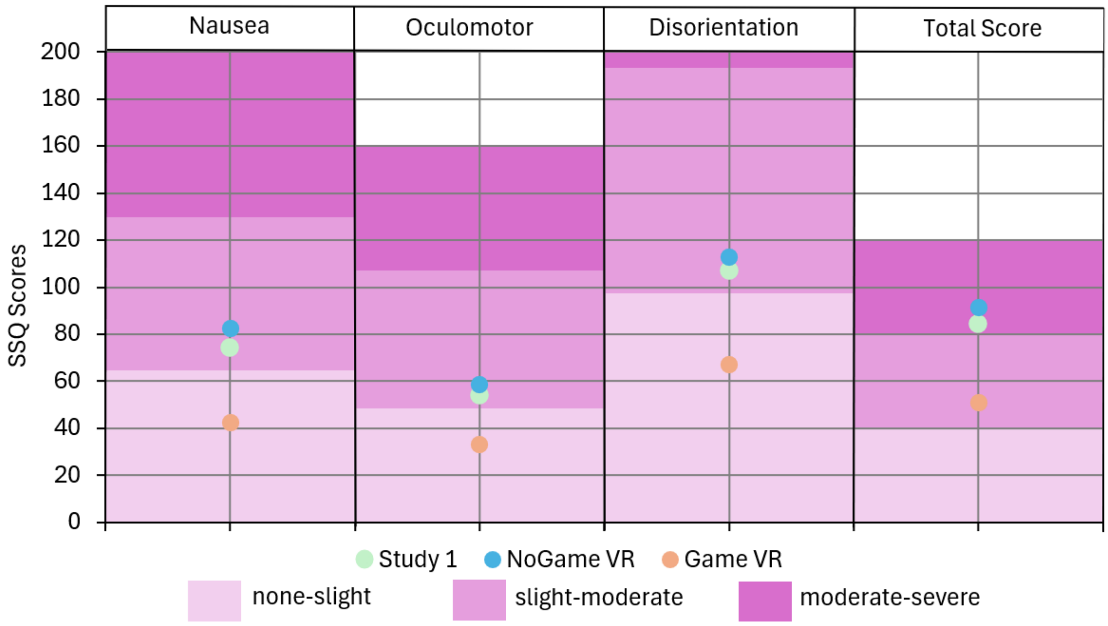

FIGURE 5.8: Mean SSQ Scores of all three groups of participants.

5.6.3 Heart Rate

In this section the fluctuations of HR in Study 1 and Study 2 as a response to the VR environments are compared (by CZ). In Study 1, the HR was measured to determine psychophysical load of task and in Study 2 the HR was measured to determine cybersickness. Interestingly, the HR patterns exhibited in both studies by each participant group followed a similar trajectory. Specifically, task 4 consistently yielded the highest HR across all VR environments. Given the resemblance in HR patterns, a Welch one-way ANOVA test was performed (by CZ) followed by a Games Howell post-hoc test for Study 2, mirroring the approach used in Study 1. These tests yielded intriguing results. For both groups in Study 2, there was an overall significant difference between the different tasks p <0.001. However, the Games Howell post-hoc tests showed that within the Game VR group, task 4 displayed a statistically significant difference only when compared to task 1 (p = 0.016), while also task 5 exhibited a significant difference compared to task 1 (p = 0.006). Conversely, within the NoGame VR group, the Games

Howell post-hoc tests demonstrated a significant difference between task 4 and all other tasks (p <0.001), except for task 3, where no statistical difference was discerned with task 4. Notably, these results from the NoGame VR group closely resemble those obtained in Study 1, where task 4 likewise displayed a significant difference from all other tasks.

5.7 Overall Conclusion

This chapter aimed to answer R3: *How can the impact of the VR training be implicitly assessed in relation to participant's well-being?* To do so, the HR was used as an implicit assessment measure of well-being of the participants during the two studies described in Chapter 4, and it was analysed under two aspects: psychophysical load of task and cybersickness. Furthermore, the studies were also assessed in terms of well-being through two commonly used questionnaires, the IPQ [19] and the SSQ [20] to have a reliable and validated assessment measure.

In Study 1, being a validation study, the aspect of HR as an indicator of psychophysical load of task was looked at. In this regard, it was found that more difficult tasks have the highest improvement and elicit the highest psychophysical load (as evidenced by the HR measurements). The study also shows the system does not elicit high levels of cybersickness and evokes a moderate sense of presence. Following this validation, Study 2 was conducted in which the VR training effectiveness of two distinct environments was compared; in this latter study, the HR was used to measure cybersickness. In terms of perceived presence and involvement, no statistically significant differences were observed between the two environments of Study 2. However, interesting results emerged in regard to cybersickness. Gamification was found to significantly reduce levels of perceived cybersickness and HR. Consequently, while users can obtain the appropriate wheelchair driving skills in VR training regardless of whether the environments are gamified or not (as found in Chapter 4), reducing cybersickness through gamification may enhance the usability and sustainability of the VR training by enabling users to repeat and enjoy the training as long as they need.

The well-being results of Study 2 can also be compared to the results of Study 1, where similarities are found. Regarding the SoP, in both studies the overall presence score ranked highest, followed by spatial presence, involvement, and experienced realism. However, experienced realism consistently scored below the median value in both studies, indicating room for improvement. Regarding cybersickness, the SSQ [20] scores for NoGame VR show symptoms were perceived to a similar extent to the SSQ [20] scores from Study 1, while the results of Game VR demonstrate the environment provoked lower symptoms. Further, the HR results also showed a similar pattern, with the HR of NoGame VR also having a similar statistical difference between task 4 and other tasks like the HR for Study 1, while these statistical differences are not observed for Study 2 GameVR. Through these similar relationships of the perceived cybersickness and HR, it can be assumed that HR changes in tasks are correlated with perceived cybersickness, and as a participant in Study 2 stated they started to experience symptoms of cybersickness in task 4, that this in turn is also related to different psychophysical load. This proves that HR is consistent and can be used as a metric to implicitly assess the well-being of the user in a VR experience.

In the next chapter, Chapter 6, the results of this chapter, along with the results of the previous chapters, are discussed in terms of how each chapter contributes to answer the research question it was meant to address. Further, the contribution to knowledge provided by the chapters is explained, along with the limitations of the research and avenues of future work. Finally, all the research conducted is tied together in a conclusion.

Chapter 6

Discussion And Conclusion

The previous chapters introduced the thesis, outlined the research questions, presented background literature and the experimental studies conducted throughout the PhD. Thus, this chapter ties everything together through discussions and conclusions. First, each research question is answered. This is followed by an overall discussion, and the thesis's contributions to knowledge. Afterwards, the limitations are discussed and directions for future work are proposed. The chapter ends with a conclusion.

6.1 Research Questions Addressed

The purpose of this research was to explore the viability of VR as a rehabilitation tool for individuals new to using wheelchairs. To meet this goal, three studies were undertaken. The study presented in Chapter 3 involved interviewing experienced wheelchair users to comprehend their challenges, which allows for an increased understanding of them and for the identification of how to develop mindful VR systems that could address these issues. The other two studies, presented in Chapter 4, were dedicated to evaluating the effectiveness of a VR system, made of a controller and VR environments developed by the author of this thesis with the assistance of the research team, and examining the impact of various environment designs on it, by assessing whether this system could teach practical driving skills (see Chapter 4) and how it affects the well-being of its users (see Chapter 5).

6.1.1 In What Ways Can The Insights And Experiences of Long-Term Wheelchair Users Contribute To The Development of Solutions Tailored For Individuals New to Using Wheelchairs?

To address this research question, a study of semi-structured interviews with wheelchair users, followed by a workshop with researchers, was conducted. This study is presented in Chapter 3, and it investigates and addresses the requirements of wheelchair users.

The semi-structured interviews explored and documented the daily experiences of five wheelchair users with diverse motor abilities and backgrounds, to identify specific challenges that can be addressed through VR solutions. In their analysis, it was found that regardless of the interviewees' motor abilities there is an inherent issue of ableism within our society which causes a lot of the challenges for disabled people. Ableism refers to the systemic discrimination and prejudice against individuals with disabilities, which often results in barriers to inclusion and full participation in various aspects of life [124]. In fact, lots of issues stem from the lack of awareness about disabilities. This leads to both negative attitudes towards people in a wheelchair and overly helpful attitudes (see Chapter 3), both of which make it harder to self-accept the disability. Struggles with self-acceptance, which are due to the beauty standards of a society one lives in [117], lead to a lack of confidence. Supportive family members and friends can help with self-confidence, as positive attitudes of others influence how one sees oneself [117]. However, for more complex emotional needs, where the support and expertise of a qualified mental health professional is needed, difficulties arise. The accessibility of mental health services specialised in the unique requirements of wheelchair users is limited, with professionals who have a deep understanding of the needs and challenges faced by wheelchair users often being scarce.

Accessibility is used as the umbrella term for wheelchair-friendly locations, pathways, restrooms, and all related aspects. Restricted accessibility of certain locations make planning an outing a very important aspect. Wheelchair users are concerned of finding themselves in locations that are not accessible to them. To address this concern, and make planning easier, it is crucial to have access to accurate and readily available information about the accessibility status of various places. Unfortunately, in many instances, especially in rural areas, accessibility is often an overlooked aspect of the infrastructure and service provision such as public transport.

Following an examination of the interviews, a workshop was convened (as described in Chapter 3). Specifically, the workshop centred around VR technology as a versatile solution. It was discussed whether VR could be used as a "one-fits-all" solution, as it can offer a spectrum of applications that can address both physical and psychological challenges faced by wheelchair users. For the successful implementation of VR technology as a solution, various technical, affordability, and accessibility considerations need to be addressed (see Chapter 3).

Despite the variety of VR applications, the hardware and controls are often inaccessible to certain individuals. Currently, VR technologies need to be purchased separately from a wheelchair; are high in costs and cannot always be used by wheelchair users due to hardware accessibility issues. The need for adaptable control hardware suitable for diverse motor abilities should be emphasised. Thus, the author of this thesis suggests control options such as eye-gaze, motion and audio sensors, and proposes integrating VR controls with the wheelchair's existing driving controls for consistency. Additionally, the author of this thesis suggests developing the VR headset as a wheelchair extension to alleviate the weight [29] of the headset and to address hardware accessibility issues. The conceptualisation of an integrated VR headset designed as an adjunct to a wheelchair and controlled through the wheelchair interface, could be a solution to the different challenges faced by wheelchair user. This integrated headset could address the multiple issues identified from the interviews, including serving as an educational tool for diverse aspects, such as driving proficiencies, identifying the accessibility of locations, and psychological support. This solution could also be used as a leisure device for people who enjoy gaming, or to watch movies. This would give the opportunity to help with different problems in one combined solution, rather than having a lot of different devices. While a solution like this could result to be expensive, if it serves as an important Assistive Technology (AT) device that could have a positive impact on people's lives, the high cost would not be a concern, as research indicates that the cost of AT in relation to its benefits is often considered a worthwhile investment [126].

In terms of VR software, the author of the thesis suggests a comprehensive VR application that combines indoor and outdoor assistance, as a result of the findings on the interviews and the workshop. The software could have a customisable virtual assistant and avatar to cater to individual preferences, with a home screen allowing users to select the type of assistance needed. Indoor assistance could focus on navigating social settings, planning outings, and learning wheelchair skills, addressing challenges related to self-acceptance, accessibility, and participation. In fact, VR has also been shown to have positive results in simulating anxiety-inducing situations to help individuals cope and enhance self-esteem [130, 183]. Outdoor assistance could focus on finding accessible routes, identifying crowded locations, and managing mood. Indeed, while accessibility maps exist for small-scale settings [131], there is a need for larger-scale settings.

Though the design possibilities for VR are many, end-users need to be included in the design process. These co-design approaches are important to develop solutions that would actually benefit the target populations, as it has been found that they can benefit researchers, practitioners, research processes and research outcomes [111]. Chapter 3 shows the significance of learning from wheelchair users when developing solutions for them, to be able to better understand their everyday challenges. Though the lifestyles vary amongst different users, and how they would use the VR devices vary, the author of this thesis believes that customisation is important for effective AT. VR has the potential to close the gap between disability and non-disability if developed with inclusiveness and accessibility as a priority.

6.1.2 How Can VR be Used to Develop an Affordable Wheelchair Driving Skill Training System, And Can a Methodology be Implemented to Assess Its Effectiveness?

To address this research question, a VR wheelchair driving training system with a low-cost VR navigation controller based on an IMU sensor that was retrofitted to a wheelchair's joystick was developed. Additionally, a standardisation framework to evaluate the system's effectiveness was proposed. Two studies were conducted as described in Chapter 4 to test the developed system. In Study 1, the system was validated by evaluating its ability to train skills in VR that can be transferred to real life. In Study 2, the potential enhancement of the system through adding gamification elements to the VR environment was investigated.

Given that IMU sensors have been validated as an alternative wheelchair controller in real life settings [136–139], an IMU sensor was used in this project to conduct training in VR to mitigate the high costs associated with VR equipment. This would also allow for wheelchair users to control the movement in a VR environment in their own chair, as the sensor could be retrofitted to any joystick. Giving wheelchair users the opportunity to conduct skills training in their wheelchair, would mean that they do not have to get acquainted to multiple wheelchairs, and would ultimately allow them to be more comfortable. This is important as in Chapter 3 it was found that getting acquainted to a new wheelchair can be daunting for experienced wheelchair users who are familiar with needing to switch between chairs; thus, it might be even more difficult for someone who is new to driving a wheelchair and who is just learning to be comfortable with the transition to wheelchair use. Using one's own wheelchair joystick to navigate in VR is also a more appropriate controller than common VR joysticks, especially for those who find it difficult to use VR controllers due to their mobility restrictions. Taking various mobility restrictions into consideration when developing VR hardware is important, as currently VR technology is believed to be "ableist" [36], which limits the wheelchair users' engagement with it, as it was found in Chapter 3.

Further, the IMU sensor can provide benefits beyond being an economic and user-friendly controller. In fact, as part of the standardisation framework the author of this thesis proposes utilising the sensor as a measure to test if driving skills have been acquired by using it to measure the total joystick movements. This method was validated in both studies by looking at the relationship between total joystick movements and the completion time of the tasks, and in both studies the two measures showed the same pattern (i.e. tasks that took longer to perform had more movements, while tasks that took shorter to perform had less movements).

One of the main limitations found in current VR training programs is the heterogeneity of the VR designs and of the methods to assess the acquired real life skills from them [12]. For these reasons, the standardisation framework in Chapter 4 section 4.5.2 is proposed. In real-life training the heterogeneity amongst methods has been minimised with the standardised WSTP [17] which has been validated against other training methods where it was found to be the more effective method [68, 69]. In fact, this program has consistently shown positive results for adults to the extent that it is in the process of being validated as a reliable program to teach and assess wheelchair driving skills to children [184]. Therefore, the standardisation framework proposes evaluating wheelchair driving skills acquired from VR training in real life situations through the WSTP [17]. This involves conducting assessments both before and after VR training through WSTP [17] tasks. Additionally, it suggests that employing a VR replica of the WSTP [17] could facilitate the training of wheelchair driving skills.

In Study 1 the following WSTP [17] tasks were performed in VR: forward and backward driving, turns while moving forward and backward (through a slalom course) and getting through a hinged door (by driving through a maze with varying widths between the walls). The acquisition of skills was tested by performing the same tasks in real life before and after VR training; while performing these tasks, the joystick movements and completion time (both serving as objective assessments of skills acquisition) were measured, and an adjusted version of the WST self-assessment questionnaire after each real-life performance was administered. The acquisition of skills was determined by testing for differences in each of these collected measures before and after VR training. In Study 1, acquired skills were found for the backward slalom task. The standardisation framework suggests that these objective assessment measures can be used in experimental settings for an unbiased assessment of acquired skills; and in a professional rehabilitation setting with a qualified clinician performing the assessment, as an addition to the assessment methods of the WSTP [17] guidelines, to provide stronger evidence of whether skills have been acquired.

The standardisation framework proposes a way to give a clearer understanding of what skills have been acquired as a result of VR training, allowing researchers and clinicians to more easily find effective training solutions. It could also allow researchers to identify the gaps and limitations of training programs, which is important as currently these aspects are unclear due to the heterogeneity amongst VR training programs. Importantly, the framework outlines that the skills acquired in VR need to be validated in real life, which is currently not always done [12].

To allow research in VR for wheelchair skills training to take advantage of the benefits of VR, the standardisation framework does not limit the design choices of a VR environment. In fact, in Study 2, two different styles of VR environments were explored, one gamified and one non-gamified, to test whether they lead to a different training outcome. In Study 2, for gamification the principle of competence was applied to the VR environment. Examples of competence are: positive feedback, optimal challenge, progressive information, intuitive controls, points, levels and leaderboards [158]. Positive feedback, optimal challenge and points were incorporated in the environment design. Though research exists in studying the effects of gamification vs non-gamification in training [156, 161], it is limited when it comes to wheelchair skills training.

The results of Study 2 demonstrate that though the participants of the two environments did not show a different driving performance in real life after training, applying the principles of gamification can be an important tool in improving the overall VR experience. The results presented in Chapter 5 show that gamification reduced the amount of perceived cybersickness, which in turn positively impacts the VR experience making it more enjoyable and more sustainable as a training option. Thus, elements of gamification can be assets to wheelchair skills training. To explore further ways in which gamification might improve the VR training experience for wheelchair users, the standardisation protocol could be used as guide as it would provide a structure for testing what gamification methods help acquire driving skills efficiently.

In essence, VR can be used to develop affordable wheelchair training programs using an IMU sensor retrofitted to a joystick for navigation. This method also gives new wheelchair users the opportunity to train independently and in the comfort of their own chair. Further, it allows for an objective way to monitor one's improvement in driving skills both in VR and in real life. This objective way of assessing driving skills can be a part of a standardisation framework based on the renowned WSTP [17], to assess the effectiveness of VR systems to teach skills transferable to real life. The standardisation framework would allow for a clearer understanding of effective VR systems and allow clinicians and wheelchair users themselves to have an objective and efficient way to monitor their improvement in skills.

6.1.3 How Can The Impact of The VR Training be Implicitly Assessed in Relation to Participant's Well-Being?

To address this research question, a literature review was performed by the author of this thesis in which it was found that most commonly the HR is measured during VR experiences as an implicit assessment of the well-being of users, compared to other signals. The HR has been used to study VR-induced cognitive load, emotional stress, and cybersickness as found in Chapter 2 section 2.3. Thus, in this research the HR was used as an implicit assessment of the well-being of the participants who tested the developed VR system described in Chapter 4. The HR of the participants was measured throughout the two studies as described in Chapter 5. In each of these studies, the well-being of the participants was also monitored explicitly through two validated questionnaires, namely the IPQ [19] and the SSQ [20]. In each study, however, the HR was used to explore a different aspect of well-being, namely psychophysical load of a VR task in Study 1 and cybersickness in Study 2. In Study 1, HR as an indicator of psychophysical load of task was chosen to be analysed as the effects of only one VR environment consisting of different tasks was explored. In Study 2, HR as an indicator of cybersickness was chosen to be analysed as the effects of two different VR environments were explored.

The Polar H10[104] chest strap monitor was used to measure the HR in this research, due to it being a low-cost device and having been validated against medical equipment for its reliability [106, 107]. Another advantage of the Polar H10[104] is that it can be paired to any smartphone for data collection, and the data can be accessed online and downloaded as a ".csv" format which allows for easy access and processing. These characteristics meet the requirements of the thesis of using affordable technology so that the conducted research could be applied in real life situations with ease.

The HR was used in Study 1 as indicator for psychophysical activity of task; it was found that task 4, the hardest to perform and the one that showed the highest improvement in real life skill acquisition, was the task in which participants had the highest HR when performing the training in VR. A correlation between higher HR and harder tasks has also been found by other research [98], and is believed to be attributed to the higher psychophysical load of the task [164, 165]. As a result, the author of this thesis proposes using HR data as a signal for pinpointing particular tasks that may require more focused attention by the trainee and by the designers of the system, in order to enhance training outcomes. Similar results were found in Study 2, which showed a similar pattern for the HR results. The tasks performed in Study 2 were the same as in Study 1. In Study 2, two different environments were tested, a gamified one and non-gamified one. Yet, regardless of the environment, the mean HR of participants per task followed a pattern similar to Study 1; specifically, the HR was highest during task 4, the hardest one to perform.

Furthermore, in Study 2, differences between the mean HR of the two groups (gamified and non-gamified) of participants were analysed and used as an indicator of cybersickness. The results show that there is a statistically significant difference between the overall HR of the two groups, and between the mean HR of task 4 and of task 3 of the two groups, with the group who completed the non-gamified environment having the higher HR. To determine whether these differences are related to cybersickness, the SSQ [20] scores of the two groups were compared. The SSQ [20] scores reported a significant difference in perceived cybersickness between the two groups, as found in the HR results, with the non-gamified group reporting higher symptoms.

The SSQ [20] assesses the experienced cybersickness through four categories: nausea, oculomotor, disorientation, and total symptoms. The lower the score, the lower the perceived cybersickness. To test the extent of cybersickness experienced by the participants, the SSQ [20] scores can be compared to reference scores which determine the range (*none-slight*; *slight-moderate*; *moderate-severe*) of symptom severity. In Study 1, the individual symptoms provoked by the system were between *slight* and *moderate*, with the total being between *moderate* and *severe*. However, the scores had a high variance with some participants perceiving severe cybersickness and others none at all. Commonly, cybersickness is experienced by 40%-70% of people using VR [170], but ideally the system should be designed so to provoke minimal symptoms for everyone. In Study 2, the non-gamified environment provoked on average similar symptoms to Study 1, with individual symptoms ranging between *slight* and *moderate*, and the total ranging between *moderate* and *severe*. The gamified environment, on the other hand, provoked on average individual symptoms ranging between *none* and *slight*, with the total ranging between *slight* and *moderate*. Thus, and importantly, gamification greatly reduced perceived cybersickness symptoms (and HR). Similar to these findings, Nalivaiko et al. [50] reported a correlation between higher perceived cybersickness scores and an elevated HR in participants. Salgado et al. [76] also noted a correlation between increased HR and cybersickness, suggesting that HR elevation may be a consequence of cybersickness.

The results of the two studies show that HR can be used as an indicator of different well-being aspects during a VR experience. The results of both studies indicate that the difficulty of tasks increases both HR and cybersickness. Participants started feeling symptoms of cybersickness, as task difficulty increased, as reported in Study 2, and in these tasks their HR increased as well. The results of both studies show promising applications for the HR in the understanding of the well-being of participants of VR training. HR, being the most commonly measured physiological signal with at home devices and smart watches, can be considered as a viable candidate for monitoring well-being of participants during VR experiences.

6.2 Overall Discussion

In recent years, research in VR within the healthcare field, and its sub-field of rehabilitation, has expanded exponentially including its use as a device for wheelchair users. In this field, VR applications have mainly been developed for the training of wheelchair driving skills. However, some gaps are still present such as ergonomic and accessible VR hardware for those with limited mobility, a training guideline that effectively teaches skills transferable to real life and limiting the side effects present in VR driving experiences. Further, for an effective rehabilitation intervention using VR, other challenges people face during the transition need to be considered such as the social, physiological and emotional struggles. Thorough research on how to mitigate each of these gaps is required, however, this lies beyond the scope of a single PhD.

Acknowledging the importance of all these gaps, while considering the time frame and resource restrictions available to conduct one PhD, three distinct topics were chosen to be investigated following a review of their literature. In Chapter 2, it was found that research often fails to consider the challenges wheelchair users face beyond getting acquainted with driving their chair and that limited research includes their lived experiences in the design of VR applications. As such, the study presented in Chapter 3 focuses on understanding life in a wheelchair and how VR can help the process of getting used to it. Further, though wheelchair skills training is the most researched field, some limitations were identified in Chapter 2, and addressed in Chapter 4, namely the lack of standardisation within assessing the effectiveness of the training and the use of efficient hardware. Lastly, in Chapter 2 it was found that VR leads to various physiological responses, especially changes in HR, and as such this is analysed in Chapter 5. Thus, the results address the following research gaps:

- *Enhancing the understanding of how VR can mitigate the challenges faced by wheelchair users.* The key findings of Chapter 3 underscore the importance of incorporating wheelchair user experiences in developing VR solutions, highlighting how understanding and integrating end-user perspectives are fundamental to creating useful and effective VR systems. In particular, it was found that common challenges faced are related to accessibility, inclusion and confidence. These challenges could be supported through VR applications which provide assistance when someone is facing them, or even training to prepare someone to face them. A creative catalogue of ideas for various VR solutions was proposed in Chapter 3 section

3.6. This could inspire future research to consider wheelchair users throughout the developmental phases of VR applications to create more user-centred designs, as there is a need for further development of VR applications tailored to the unique needs of minority groups, including wheelchair users. In particular, future research could implement and refine the general suggestions made in Chapter 3 section 3.6, e.g., to create diverse VR applications that cater to the specific challenges faced by individuals transitioning to wheelchair use.

- *Maximising the efficiency and effectiveness of VR wheelchair training systems.* The key findings of Chapter 4 demonstrate that affordable VR applications, by using an IMU sensor attached to a wheelchair joystick as the controller, can be effective in training wheelchair driving skills, thus offering a viable alternative to traditional methods. The controller was effective in terms of VR navigation and data capture to assess driving performance. Future research could expand on this concept to enhance the effectiveness of IMU sensors as VR-wheelchair driving controllers, while also improving the ergonomic design of these controllers. Further contributions of the chapter are the proposal of a standardisation framework (section 4.5.2) for the assessment of the effectiveness of a VR wheelchair driving skills training application, and the effects of gamification on such applications (section 4.6). The recommendations for the assessment could be used in future research, even with the development of more personalised environments, to reduce heterogeneity among VR training programs and their assessment methods. In fact, future studies could focus on improving VR-based wheelchair training programs by considering outdoor training simulations and artificial intelligence (AI) for personalised training, while utilising the standardised framework for assessment of acquired skills.

- *Exploring the effect VR can have on someone's physiological well-being during wheelchair skills training.* The key findings of Chapter 5 show how HR can be used as an implicit measure of user well-being during VR interactions. Importantly, it was found that HR could be used as an indicator of psychophysical load of task in VR as well as for the onset of cybersickness. Future research could explore additional physiological signals adjunct to HR, such as electrodermal activity (EDA), to assess user well-being more comprehensively. Further findings of Chapter 5 are related to self-reported measures of presence and cybersickness where it was interestingly found that elements of gamification lead to lower self-reported cybersickness symptoms. The relationship between gamification and cybersickness in wheelchair skills training applications is unexplored, and thus it would be interesting in future research to investigate it further.

The work done in this thesis covers a variety of aspects related to increasing the effectiveness of VR rehabilitation programs for wheelchair users and addresses all the research questions set in the introduction (Chapter 1). In particular, the thesis provides a foundation for developing VR applications that are cost-effective, user-friendly, and aligned with the needs of wheelchair users. It also offers insights into using HR as a reliable physiological indicator of user well-being, highlighting the balance needed between technological advancements and the physiological comfort of users. As a result, this thesis provides both general and technological contributions to the knowledge in the field.

6.3 Contributions to Knowledge

The body of literature on VR as a rehabilitation tool shows promising findings, with VR having the potential to be used as an effective tool to help the transition to wheelchair use. To contribute to the body of literature, the author of this thesis investigated how VR could be used to mitigate challenges faced by wheelchair users, how the efficiency of VR as a wheelchair driving skills application could be improved, and how the developed VR wheelchair driving skills application affects the users' HR. Thus, the work of this thesis generated both general and technological contributions to knowledge. These contributions are described in detail in the following subsections.

6.3.1 General Contributions

Current literature in this field focuses mainly on using VR to train wheelchair driving skills, neglecting the other areas of one's life the transitioning process affects. Thus, one of the contributions of this thesis is to raise awareness of these other areas and how VR could be used to mitigate the challenges faced in them. Further, as VR driving skills programs vary a lot in heterogeneity, the work done throughout this PhD proposed ways to standardise the assessment of wheelchair driving skills training systems. Finally, the work done throughout this PhD demonstrated how HR can be used as a physiological measure of the well-being of the participants during the developed VR training. Specifically, this thesis contributes to the general knowledge of the field as follows:

- *Awareness of the potential of VR applications to address wheelchair users' needs.* Chapter 3 delves into an exploration of a day in the life of a wheelchair user, shedding light on the various challenges encountered in different daily scenarios and capturing the perspectives of wheelchair users regarding VR. Given the limited opportunities for co-design with wheelchair users in the development of VR applications, this chapter makes a contribution to the understanding of how end-users perceive VR. The chapter suggests potential VR applications to address the challenges faced by wheelchair users by proposing new ideas for software and hardware solutions (e.g. using VR as an every-day AT device incorporated within the wheelchair). These recommendations are grounded in the insights provided by wheelchair users and are further informed by successful approaches in other research. This chapter places a high value on how to address the needs of wheelchair users through VR technology.

- *Standardising VR wheelchair driving skills training.* In Chapter 2, an examination of VR wheelchair driving skills training applications reveals a notable heterogeneity amongst them and amongst their assessment of acquired skills, posing a limitation in the objective understanding of the effectiveness of one application over another. Consequently, in Chapter 4 a standardised framework is proposed designed for instructing and evaluating driving skills in VR with direct applicability to real life scenarios, based on the well-established WSTP [17]. The findings from Chapter 4 demonstrate that this proposed standardisation can effectively gauge the acquisition of skills in an unbiased manner, providing insights into the specific skills acquired. By integrating the evaluation methods of the WSTP [17] with those commonly used for assessing VR systems, this framework enhances the reliability of skill assessment. This framework represents an initial stride towards addressing the diversity gap among VR wheelchair driving skills applications, marking a significant and valuable contribution to the thesis.

- *Improving the experience of VR wheelchair driving skills training.* In Chapter 4 and Chapter 5, the effects of gamification in VR wheelchair skills training was explored. Although the results indicate no significant difference in the performance of acquired skills between gamified and non-gamified environments, it was found that gamification could enhance the sustainability and usability of training applications (see Chapter 5). Notably, the use of gamification leads to a reduction in experienced cybersickness and lower HR, contributing to an overall more enjoyable experience. Given that cybersickness is a primary limitation of VR applications, these findings hold significant importance by demonstrating an effective way to mitigate this issue. Furthermore, as there is a correlation between reduced cybersickness and heightened overall enjoyment of the VR experience [182], the results of Chapter 5 emphasise the positive impact of incorporating gamification into the VR experience.

- *Studying the relation between VR and HR.* In Chapter 5, an analysis was conducted on the impact of VR on a user's physiological activity, particularly focusing on HR.

The findings reveal that HR fluctuations in VR are related to the task difficulty, aligning with existing literature suggesting a heightened psychophysical load during more challenging tasks. Moreover, Chapter 5 establishes a correlation between HR and experienced cybersickness (which was assessed through the SSQ [20]).

6.3.2 Technological Contributions

Current literature about VR for wheelchair skills training shows a variety of training systems that use either a real wheelchair joystick, or a gaming joystick, which may be inconvenient for some users due to their limited motor abilities. As such, through the work of this thesis an alternative controller was developed which aims to prioritise the user's comfort. Further, though literature exists which measures physiological signals in a variety of VR scenarios using medical equipment, limited research is available on how to efficiently measure physiological signals in VR wheelchair driving skills scenarios. Specifically, this thesis contributes to the technological knowledge of the field as follows:

- *Cost-effective VR wheelchair driving skills training.* In Chapter 4 the development of the cost-effective VR controller is presented, which was designed to facilitate navigation in VR using an IMU sensor retrofitted to the wheelchair's joystick. This innovative controller serves not only as a technological means of navigating VR environments but also as an additional tool for evaluating the effectiveness of driving skills training, emphasising the transferability of skills to real-life scenarios. Given the current high costs associated with rehabilitation programs and the expense of VR technology, this controller offers a potentially economical solution. Moreover, its standalone usability allows users to benefit from it in the comfort of their homes, aligning with the recent trend of doing tasks remotely. Finally, as it could be retrofitted to the joystick a wheelchair user employs for daily navigation, it allows for the VR system to be accessible by wheelchair users who might find it uncomfortable to use another joystick due to their mobility restrictions. As such, this development stands as a noteworthy and valuable contribution within the context of the thesis.

- *Implementation of HR monitor in VR applications.* In Chapter 5, the user's HR during the two VR studies presented in Chapter 4 was measured using the Polar H10[104] HR sensor. This sensor was validated for accuracy against medical devices in the literature, thus making it a reliable and accurate measure of one's HR. Moreover, it is convenient as it can be connected to one's mobile phone, making the data easily accessible. Even though the HR monitor was not developed, the chosen sensor was effectively used as an assessment method of the users well-being in VR. This highlights the reliability of HR as a physiological indicator of user well-being, which is important as VR can elicit a lot of emotions and as an implicit way to assess them is necessary, to reduce any potential biases which are often found in explicit assessment methods.

6.4 Limitations And Lessons Learnt

The work carried out in this thesis has limitations that merit consideration. Importantly, the aim of the thesis is to contribute to the knowledge of using VR as a tool for the rehabilitation of wheelchair users, however, only limited wheelchair users contributed to the results of the thesis and by only taking part in one study. Efforts were made to recruit more wheelchair participants and to collaborate with clinicians, however due to resource and ethics constraints an effective inclusion of these user groups was not possible. As a result, only one study with wheelchair user participants was undertaken in the form of interviews. This study, though important for the understanding of the needs of the end-users, also presents some limitations, particularly the resulting ideas of VR applications were not developed. Given more time, a development and assessment of a prototype following the suggestions proposed in Chapter 3 would have been able to greatly contribute to the thesis. In particular, how VR could support some of the main challenges encountered by wheelchair users could be interesting, such as accessibility.

Further, testing of the system developed in Chapter 4 with wheelchair participants was planned, but unfortunately, due to the recurring isolation rules as a result of the COVID-19 pandemic, it did not go through. The system was nonetheless tested with non-disabled participants in two studies. Further, the participant sample size in the two studies which tested the VR system was small. The sample size was chosen based on what sample size similar research included. However, a larger sample size could have yielded more accurate results and given a better representation of the effectiveness of VR. Though the results do provide an assessment of the system, a more accurate evaluation could have been conducted if more participants took part in the studies, and if more VR sessions over multiple days were performed. In fact, longitudinal studies could present a useful tool, especially comparing the effectiveness of VR training and no-VR training, in determining the extent to which VR could be useful. Unfortunately, due to the experiments requiring a large room for testing, limited time was available to perform the studies and limited resources were available to incentivise participants to take part in them. A further limitation of those two studies is that though the participants were allowed to practice VR as many times as they felt comfortable, the relationship between length of VR usage and skill acquisition was not tested. In Study

1, the relationship between number of times practiced in VR and skill acquisition in VR was assessed by looking at the percentage of improvement, however this relationship was not tested to see if it was related with improvements in real life driving performance. It might be interesting in future investigations to assess how the amount of VR training can affect the real-life skill acquisition. Further, the literature highlights the benefits of having an avatar of a wheelchair user, thus the avatar in the developed application was someone in a wheelchair. Nonetheless, the benefits of it over another type of avatar were not investigated in the study, and may be worthy of future investigations.

The VR driving controller developed and tested in Chapter 4, also presents some limitations. To increase the comfort of the controller it could be designed to be more ergonomic with a smaller sensor as to not affect the tactile experience of using the joystick. This was initially attempted by developing a smaller PCB and soldering the current sensor on, however that attempt was unsuccessful. Another smaller sensor was planned to be purchased, however due to the shortage and delays of electronic equipment arriving from abroad the sensor would not have arrived within the required time frame. Thus, the developed controller is an initial prototype, with room for improvement.

To enhance the precision of evaluating the impact of VR on a participant's well-being, it would have been beneficial to collect additional signals beyond the HR. Furthermore, using medical-grade equipment to measure HR could have provided more accurate results in identifying tasks which yield a higher psychophysical load and onset of cybersickness. An even more comprehensive analysis could have incorporated heart rate variability (HRV). Unfortunately, due to constraints in both budget and time, the inclusion of these additional measures was not feasible. Despite these limitations, acknowledging the importance of these factors highlights avenues for future research to delve deeper into the effects of VR experiences on participants' physiological responses. Furthermore, cybersickness was assessed immediately after the training, thus neglecting long-term side effects. In the future, it would be interesting to investigate the long-term effects cybersickness may have on the participants, through longitudinal studies.

Despite encountering various challenges, the project was ultimately brought to a successful completion. The limitations encountered along the journey of completing the PhD served as invaluable learning experiences. These hurdles challenged the initial plans but inspired the generation of fresh ideas and alternative approaches to navigate the difficulties inherent in completing the PhD. While these limitations should be considered in the evaluation of the work and the planning of future projects, they should also be appreciated for the substantial learning curve they provided to the overall PhD experience. These challenges, rather than hindrances, were valuable lessons that improved my approach and how I handle things in my academic journey.

6.5 Future Work

The work carried out in this thesis aimed to expand the knowledge of VR as a tool for rehabilitation for wheelchair users. Throughout the PhD journey, many areas of weakness were identified in the field; however, not all were possible to be addressed through a single PhD thesis. The thesis provided insights on the type of VR applications that could contribute to the effectiveness of rehabilitation programs, and it suggested how to improve VR wheelchair-driving skills programs. It also proposed how the HR can be used as an implicit assessment of a participant's well-being during a VR experience. As such, this thesis provides a foundation for future developments of these applications. Consequently, there is a lot of opportunity for expanding this thesis in future work. Below, are some proposed topics.

6.5.1 Guidelines on The Improvement of VR-Based Wheelchair Training Applications

In Chapter 4, how to improve VR-based wheelchair skills training programs was explored by proposing a standardisation framework and minimising the VR-related costs through an affordable controller. Nonetheless, as this field is still in its early stages with limited research conducted, there are numerous aspects that could be enhanced. In fact, two main ideas were considered throughout the PhD that are worthy of being explored further: outdoor training simulations and using AI for personalised training.

During the course of the PhD, regular meetings were conducted with clinicians actively involved in wheelchair training programs. Insights from these interactions revealed a notable distinction between training outdoors and indoors, with training outdoors posing more challenges due to the heightened environmental risks. Recognising this, the idea emerged that VR could serve as a viable solution, creating a controlled and safe space for training. The concept involves leveraging VR technology to simulate outdoor environments, offering a realistic yet secure platform for wheelchair training programs. This approach would address the inherent challenges associated with outdoor training, providing a practical and risk-free alternative for individuals undergoing wheelchair training.

Moreover, AI has the potential to improve the creation of training applications by engaging users in a personalised and adaptive manner. By employing AI-driven algorithms, a training application could tailor its content based on user responses to specific questions, crafting an environment uniquely suited to individual needs. For example, the VR environment could mimic a room or space familiar to the individual. This personalised approach could enhance the overall effectiveness of the VR training, as it would cater specifically to the user's requirements, preferences, and skills level. Thus, exploring AI in VR-based wheelchair training applications merits consideration.

6.5.2 Possibilities of Implicitly Measuring The Users' Well-Being During VR Experiences

Chapter 5 revealed that HR varies in response to stimuli induced by VR. This observation was made by tracking the HR during VR experiences utilising a commercially available HR sensor. Given the aim of this PhD was to employ affordable equipment accessible to the general public, the choice of the sensor was deemed appropriate. Nevertheless, the use of medical grade equipment could have yielded more precise results, offering insights into HRV and other cardiovascular responses. Future research might consider using medical-grade equipment, with the aim of pinpointing instances of significant HR fluctuations linked to events occurring within the VR environment.

Moreover, there is merit in exploring the responses of additional physiological signals beyond HR. In Chapter 5, specifically during Study 2, an interesting observation was made: participants exhibited signs of sweating when they began to feel uneasy. Literature indicates that electrodermal activity (EDA), associated with sweating, can indeed vary in response to stress or cybersickness [180, 181]. Delving deeper into this aspect is worthy for future research. Investigating the correlation between EDA, or other physiological signals, to the onset of stress or cybersickness can contribute valuable insights, further enhancing the understanding of the physiological reactions induced by virtual reality experiences.

6.5.3 Need For Further Development of VR Applications For Minority Groups

In Chapter 3, a comprehensive exploration was undertaken through interviews with wheelchair users, aiming to pinpoint challenges that could potentially be alleviated through the integration of VR solutions. The findings shed light on the multifaceted adjustments that individuals undergoing the transition to wheelchair use encounter in various aspects of their lives, beyond addressing merely physical needs. While Chapter 3 lays down general suggestions for potential VR applications catering to these challenges, the constraints within the time frame of the PhD project prevented the actual development of these applications.

The general suggestions in Chapter 3 encompass a wide range of applications that could be explored in the future. These include, but are not limited to, VR gaming experiences inclusive for wheelchair users, psychological VR interventions specifically for wheelchair users, VR travel-related applications to ease navigation of certain environments, and innovations in hardware design. Although these applications were not developed during the current project, they serve as valuable blueprints for future research. Subsequent works should consider implementing and refining these general suggestions to create a diverse array of VR applications that cater to the unique needs and challenges faced by individuals transitioning to wheelchair use. Importantly, subsequent works should include wheelchair users throughout the developmental phases of their VR applications.

6.6 Conclusion

The work carried out in this thesis explored the application of VR technology to enhance the rehabilitation process and training for new wheelchair users. Through an examination of VR's potential to mitigate the challenges faced by wheelchair users, the development of an affordable VR driving skills training system, and the assessment of VR's impact on users' physiological responses, this research contributes to the field of biomedical engineering.

The findings underscore the importance of incorporating wheelchair user experiences in developing VR solutions for them; this is because understanding and integrating the perspectives, needs, and feedback of end-users are foundational to creating useful VR systems. This approach would ensure that VR technologies are not only technologically advanced but are also aligned with the requirements and preferences of the people they are designed to serve. By prioritising user experience in VR development, the usability, accessibility, and overall impact of VR applications, can be enhanced.

The findings also highlight the effectiveness of affordable VR in training wheelchair driving skills, by offering a compelling alternative to traditional wheelchair training methods for powered wheelchair users. In particular, the thesis proposed a VR system which uses an IMU sensor retrofitted to a wheelchair's joystick, for affordable training that can take place in one's own wheelchair. Further, it proposed a standardisation framework for the assessment of driving skills based on the methods renowned for real-life training in conjunction to the methods known to be effective for VR training.

Finally, the findings provide insights into the physiological implications of VR usage showcasing how HR can be used as an assessor of the well-being of users during VR interactions. It can indicate psychophysical load of task and cybersickness, offering a direct link between VR experiences and users' physiological responses. Such insights help emphasise the necessity of designing VR experiences that are mindful of their users' health, highlighting the balance needed between technological advancements and the physiological comfort of users.

The research conducted in this thesis could benefit a range of key stakeholders. For researchers, particularly in the fields of biomedical engineering and rehabilitation, the findings offer a foundation for further exploration and enhancement of VR applications for various rehabilitation purposes. Moreover, companies developing assistive technologies could find this research valuable, as the insights can aid in designing and improving VR-based rehabilitation tools. The focus on cost-effective and user-friendly designs can guide future product development. Hospitals, rehabilitation centres, clinics and health professionals (e.g. nurses, medical personnel, physiotherapists) aiming to provide innovative treatment options can also benefit from implementing the VR applications discussed in the thesis. Most importantly, individuals transitioning to wheelchair use can greatly benefit from VR-based training programmes, which offer a safe and controlled environment to practice and improve their wheelchair driving skills, facilitating their adaptation to new mobility needs.

Future research should focus on further refining VR training programs, exploring long-term effects of VR on rehabilitation, and expanding VR applications to address a wider range of needs of wheelchair users. This work not only advances the understanding of VR's role in rehabilitation but also opens new avenues for enhancing the quality of life for individuals adapting to wheelchair use.

References

[1] Wheelchair needs in the world, Sep 2019. URL `https://www.wheelchairfoundation.org/fth/analysis-of-wheelchair-need/`.

[2] Physiopedia. Wheelchair users — physiopedia, 2022. URL `https://www.physio-pedia.com/index.php?title=Wheelchair_Users&oldid=314687`. [Online; accessed 27-April-2023].

[3] Ian M. Rice, Alex W. K. Wong, Benjamin A. Salentine, and Laura A. Rice. Differences in participation based on self-esteem in power and manual wheelchair users on a university campus: a pilot study. *Disability and Rehabilitation: Assistive Technology*, 10(2):102–107, Mar 2015. doi: 10.3109/17483107.2013.840864. PMID: 24088039.

[4] Jennifer Hastings, Hillary Robins, Yvette Griffiths, and Christina Hamilton. The differences in self-esteem, function, and participation between adults with low cervical motor tetraplegia who use power or manual wheelchairs. *Archives of Physical Medicine and Rehabilitation*, 92(11):1785–1788, Nov 2011. ISSN 0003-9993. doi: https://doi.org/10.1016/j.apmr.2011.03.023.

[5] Sara Arlati, Vera Colombo, Giancarlo Ferrigno, Rinaldo Sacchetti, and Marco Sacco. Virtual reality-based wheelchair simulators: A scoping review. *Assistive Technology*, 32(6):294–305, Nov 2020. doi: 10.1080/10400435.2018.1553079. PMID: 30615571.

[6] Leif P. Berg and Judy M. Vance. Industry use of virtual reality in product design and manufacturing: A survey - virtual reality. *SpringerLink*, Sep 2016. doi: https://doi.org/10.1007/s10055-016-0293-9.

[7] Isabell Wohlgenannt, Alexander Simons, and Stefan Stieglitz. Virtual reality - business amp; information systems engineering. *SpringerLink*, Jul 2020. doi: https://doi.org/10.1007/s12599-020-00658-9.

[8] Christoph Anthes, Rubén Jesús García-Hernández, Markus Wiedemann, and Dieter Kranzlmüller. State of the art of virtual reality technology. pages 1–19, Mar 2016. doi: 10.1109/AERO.2016.7500674.

[9] Shi Cao. Virtual reality applications in rehabilitation. In Masaaki Kurosu, editor, *Human-Computer Interaction. Theory, Design, Development and Practice*, pages 3–10, Cham, Jun 2016. Springer International Publishing. doi: https://doi.org/10.1007/978-3-319-39510-4_1.

[10] Bruno Porras-Garcia, Eduardo Serrano-Troncoso, Marta Carulla-Roig, Pau Soto-Usera, Marta Ferrer-Garcia, Natàlia Figueras-Puigderrajols, Lena Yilmaz, Yigit Onur Sen, Nazila Shojaeian, and José Gutiérrez-Maldonado. Virtual reality body exposure therapy for anorexia nervosa. a case report with follow-up results. *Frontiers in Psychology*, 11, May 2020. doi: 10.3389/fpsyg.2020.00956.

[11] Ausiàs Cebolla, Rocío Herrero, Sara Ventura, Marta Miragall, Miguel Bellosta-Batalla, Roberto Llorens, and Rosa Ma Baños. Putting oneself in the body of others: A pilot study on the efficacy of an embodied virtual reality system to generate self-compassion. *Frontiers in Psychology*, 10, Jul 2019. doi: 10.3389/fpsyg.2019.01521.

[12] Jean-François Lam, Laurent Gosselin, and Paula W. Rushton. Use of virtual technology as an intervention for wheelchair skills training: A systematic review. *Archives of Physical Medicine and Rehabilitation*, 99(11):2313–2341, Mar 2018. ISSN 0003-9993. doi: https://doi.org/10.1016/j.apmr.2018.02.007.

[13] NHS. Nhs choices, Jun 2022. URL `https://www.nhs.uk/conditions/social-care-and-support-guide/care-services-equipment-and-care-homes/walking-aids-wheelchairs-and-mobility-scooters/`.

[14] Sara Spary. How to choose the right wheelchair: Nhs, hire or buy your own?, Aug 2023. URL `https://www.which.co.uk/reviews/mobility-equipment/article/choosing-the-best-wheelchair-aAfTd2J7ji39#types-of-wheelchairs`.

[15] Anneke Hertig-Godeschalk, Armin Gemperli, Ursina Arnet, and Timo Hinrichs. Availability and need of home adaptations for personal mobility among individuals with spinal cord injury. *The Journal of Spinal Cord Medicine*, 41(1):91–101, Jan 2018. doi: 10.1080/10790268.2017.1308995. PMID: 28359190.

[16] Catherine Bigras, Dolapo D. Owonuwa, William C. Miller, and Philippe S. Archambault. A scoping review of powered wheelchair driving tasks and performance-based outcomes. *Disability and Rehabilitation: Assistive Technology*, 15(1):76–91, Jan 2020. doi: 10.1080/17483107.2018.1527957. PMID: 30729829.

[17] Dalhousie University Faculty of Medicine Wheelchair skills program. Wheelchair skills program. URL `https://wheelchairskillsprogram.ca/en/`.

[18] Kay Stanney, Ben D. Lawson, Bas Rokers, Mark Dennison, Cali Fidopiastis, Thomas Stoffregen, Séamas Weech, and Jacqueline M. Fulvio. Identifying causes of and solutions for cybersickness in immersive technology: Reformulation of a research and development agenda. *International Journal of Human–Computer Interaction*, 36(19):1783–1803, Nov 2020. doi: 10.1080/10447318.2020.1828535.

[19] Igroup presence questionnaire (ipq) overview — igroup.org – project consortium. URL `https://igroup.org/pq/ipq/index.php`.

[20] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. Simulator sickness questionnaire. *PsycTESTS Dataset*, 1993. doi: 10.1037/t04669-000.

[21] Christina Papadimitriou. Becoming en-wheeled: the situated accomplishment of re-embodiment as a wheelchair user after spinal cord injury. *Disability & Society*, 23(7):691–704, Mar 2008. doi: 10.1080/09687590802469420.

[22] Anna Carin Aho, Sally Hultsjö, and Katarina Hjelm. Perceptions of the transition from receiving the diagnosis recessive limb-girdle muscular dystrophy to becoming in need of human support and using a wheelchair: an interview study. *Disability and Rehabilitation*, 41(19):2289–2298, Sep 2019. doi: 10.1080/09638288.2018.1464602. PMID: 29688081.

[23] Myriam Winance. Trying out the wheelchair: The mutual shaping of people and devices through adjustment. *Science, Technology, & Human Values*, 31(1):52–72, Jan 2006. doi: 10.1177/0162243905280023.

[24] Richard Levi Gunilla Stenberg, Catharina Henje and Maria Lindström. Living with an electric wheelchair – the user perspective. *Disability and Rehabilitation: Assistive Technology*, 11(5):385–394, Oct 2016. doi: 10.3109/17483107.2014.968811. PMID: 25270614.

[25] Edward M. Giesbrecht, William C. Miller, and Roberta L. Woodgate. Navigating uncharted territory: A qualitative study of the experience of transitioning to wheelchair use among older adults and their care providers. *BMC Geriatrics*, 15 (1), Jul 2015. doi: 10.1186/s12877-015-0092-2.

[26] Maria Lindström, Ann-Charlotte Bäckström, Catharina Henje, and Gunilla Stenberg. 'when i use the electric wheelchair, i can be myself' – real-life stories about occupational identity construction. *Scandinavian Journal of Occupational Therapy*, 0(0):1–15, Oct 2022. doi: 10.1080/11038128.2022.2093268. PMID: 35786150.

[27] Thais Pousada García, Betania Groba González, Laura Nieto Rivero, Javier Pereira Loureiro, Emiliano Díez Villoria, and Alejandro Pazos Sierra. Exploring the psychosocial impact of wheelchair and contextual factors on quality of life of people with neuromuscular disorders. *Assistive Technology*, 27(4):246–256, Dec 2015. doi: 10.1080/10400435.2015.1045996. PMID: 26186427.

[28] Sarah-Grace Paguinto, Nadine A. Kasparian, Paula Bray, and Michelle Farrar. Multidisciplinary perspectives and practices of wheelchair prescription for children with neuromuscular conditions. *Disability and Rehabilitation: Assistive Technology*, 18(2):166–174, Feb 2023. doi: 10.1080/17483107.2020.1839793. PMID: 33147417.

[29] Kathrin Gerling, Patrick Dickinson, Kieran Hicks, Liam Mason, Adalberto L. Simeone, and Katta Spiel. Virtual reality games for people using wheelchairs. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, page 1–11, New York, NY, USA, Apr 2020. Association for Computing Machinery. ISBN 9781450367080. doi: 10.1145/3313831.3376265.

[30] Gabriel Augusto Ginja. Applications of virtual reality in the practice of para-badminton. In *2018 20th Symposium on Virtual and Augmented Reality (SVR)*, pages 230–232, Oct 2018. doi: 10.1109/SVR.2018.00042.

[31] Raquel Macedo, Nuno Correia, and Teresa Romão. Paralympic vr game: Immersive game using virtual reality and video. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI EA '19, page 1–6, New York, NY, USA, May 2019. Association for Computing Machinery. ISBN 9781450359719. doi: 10.1145/3290607.3312938.

[32] Epuran Gheorghe, Tecau Alina Simona, Constantin Cristinel, Bianca Tescasiu, and Chitu Iona B. Opportunities of using new technologies (vr/ar) in order to facilitate the access of persons with disabilities to tourism products. *Bulletin of the Transilvania University of Brasov. Series V: Economic Sciences*, Dec 2020. doi: https://doi.org/10.31926/but.es.2020.13.62.2.6.

[33] Emiliano Pérez, María José Merchán, Santiago Salamanca, and Pilar Merchán. Virtual reality to allow wheelchair users touring complex archaeological sites in a realistic manner. towards their actual social integration. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W9:597–604, Jan 2019. doi: 10.5194/isprs-archives-XLII-2-W9-597-2019.

[34] Emiliano Pérez, Pilar Merchán, María José Merchán, and Santiago Salamanca. Virtual reality to foster social integration by allowing wheelchair users to tour

complex archaeological sites realistically. *Remote Sensing*, 12(3), Jan 2020. ISSN 2072-4292. doi: 10.3390/rs12030419.

[35] Alexandra J. Fiocco, Geneva Millett, Danielle D'Amico, Laura Krieger, Yadurshana Sivashankar, Seung Hwan Lee, and Richard Lachman. Virtual tourism for older adults living in residential care: A mixed-methods study. *PLOS ONE*, 16 (5), May 2021. doi: 10.1371/journal.pone.0250761.

[36] Kathrin Gerling and Katta Spiel. A critical examination of virtual reality technology in the context of the minority body. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, CHI '21, New York, NY, USA, May 2021. Association for Computing Machinery. ISBN 9781450380966. doi: 10.1145/3411764.3445196.

[37] Martez Mott, John Tang, Shaun Kane, Edward Cutrell, and Meredith Ringel Morris. "i just went into it assuming that i wouldn't be able to have the full experience": Understanding the accessibility of virtual reality for people with limited mobility. In *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '20, New York, NY, USA, Oct 2020. Association for Computing Machinery. ISBN 9781450371032. doi: 10.1145/3373625.3416998.

[38] Martez Mott, Edward Cutrell, Mar Gonzalez Franco, Christian Holz, Eyal Ofek, Richard Stoakley, and Meredith Ringel Morris. Accessible by design: An opportunity for virtual reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pages 451–454, Oct 2019. doi: 10.1109/ISMAR-Adjunct.2019.00122.

[39] Wanwan Li, Javier Talavera, Amilcar Gomez Samayoa, Jyh-Ming Lien, and Lap-Fai Yu. Automatic synthesis of virtual wheelchair training scenarios. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 539–547, Mar 2020. doi: 10.1109/VR46266.2020.00075.

[40] Kevin A. Hernandez-Ossa, Eduardo Montenegro-Couto, Berthil Longo, Alexandre Luís Cardoso Bissoli, Mariana Midori Sime, Hilton M Lessa, Ivan Enriquez, Anselmo Frizera-Neto, and Teodiano Freire Bastos Filho. Simulation system of electric-powered wheelchairs for training purposes. *Sensors (Basel, Switzerland)*, 20, Jun 2020. doi: https://doi.org/10.3390/s20123565.

[41] Haseeb Younis, Farheen Ramzan, Javeria Khan, and Muhammad Usman Ghani Khan. Wheelchair training virtual environment for people with physical and cognitive disabilities. In *2019 15th International Conference on Emerging Technologies (ICET)*, pages 1–6, Dec 2019. doi: 10.1109/ICET48972.2019.8994550.

[42] Guo Freeman, Samaneh Zamanifard, Divine Maloney, and Alexandra Adkins. My body, my avatar: How people perceive their avatars in social virtual reality. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI EA '20, page 1–8, New York, NY, USA, 2020 2020. Association for Computing Machinery. ISBN 9781450368193. doi: 10.1145/3334480.3382923.

[43] Emmanuel Fokides. My avatar and i. a study on avatars, personality traits, self-attributes, and their perceived importance - journal of ambient intelligence and humanized computing, Apr 2020.

[44] Kexin Zhang, Elmira Deldari, Zhicong Lu, Yaxing Yao, and Yuhang Zhao. "it's just part of me:" understanding avatar diversity and self-presentation of people with disabilities in social virtual reality. In *Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '22, New York, NY, USA, Oct 2022. Association for Computing Machinery. ISBN 9781450392587. doi: 10.1145/3517428.3544829.

[45] Abdulaziz Alshaer, Holger Regenbrecht, and David O'Hare. Immersion factors affecting perception and behaviour in a virtual reality power wheelchair simulator. *Applied Ergonomics*, 58:1–12, Jan 2017. ISSN 0003-6870. doi: https://doi.org/10.1016/j.apergo.2016.05.003.

[46] Elaine Hoter and Ilan Nagar. The effects of a wheelchair simulation in a virtual world - virtual reality. *SpringerLink*, Feb 2022. doi: https://doi.org/10.1007/s10055-022-00625-7.

[47] Tanvir Irfan Chowdhury and John Quarles. A wheelchair locomotion interface in a vr disability simulation reduces implicit bias. *IEEE Transactions on Visualization and Computer Graphics*, 28(12):4658–4670, Jul 2021. doi: 10.1109/TVCG.2021.3099115.

[48] Marieke AG Martens, Angus Antley, Daniel Freeman, Mel Slater, Paul J Harrison, and Elizabeth M Tunbridge. It feels real: physiological responses to a stressful virtual reality environment and its impact on working memory. *Journal of Psychopharmacology*, 33(10):1264–1273, Oct 2019. doi: 10.1177/0269881119860156. PMID: 31294651.

[49] Yoon Sang Kim, JuHye Won, Seong-Wook Jang, and Junho Ko. Effects of cybersickness caused by head-mounted display–based virtual reality on physiological responses: Cross-sectional study. *JMIR Serious Games*, 10(4):e37938, Oct 2022. ISSN 2291-9279. doi: https://doi.org/10.2196/37938.

[50] Eugene Nalivaiko, Simon L. Davis, Karen L. Blackmore, Andrew Vakulin, and Keith V. Nesbitt. Cybersickness provoked by head-mounted display affects cutaneous vascular tone, heart rate and reaction time. *Physiology Behavior*, 151:583–590, Sep 2015. ISSN 0031-9384. doi: https://doi.org/10.1016/j.physbeh.2015.08.043.

[51] Luis Eduardo Garrido, Maite Frías-Hiciano, Mariano Moreno-Jiménez, Gabriella Nicole Cruz, Zoilo Emilio García-Batista, Kiero Guerra-Peña, and Leonardo Adrián Medrano. Focusing on cybersickness: Pervasiveness, latent trajectories, susceptibility, and effects on the virtual reality experience. *Virtual Reality*, 26(4):1347–1371, Mar 2022. doi: 10.1007/s10055-022-00636-4.

[52] Kerri A. Morgan, Jack R. Engsberg, and David B. Gray. Important wheelchair skills for new manual wheelchair users: health care professional and wheelchair user perspectives. *Disability and Rehabilitation: Assistive Technology*, 12(1):28–38, Jan 2017. doi: 10.3109/17483107.2015.1063015. PMID: 26138222.

[53] R. Lee Kirby and Steve P. Doucette. Relationships between wheelchair services received and wheelchair user outcomes in less-resourced settings: A cross-sectional survey in kenya and the philippines. *Archives of Physical Medicine and Rehabilitation*, 100(9):1648–1654.e9, Sep 2019. ISSN 0003-9993. doi: https://doi.org/10.1016/j.apmr.2019.02.002.

[54] O.J.E. Kilkens, Marcel W. M. Post, Annet J. Dallmeijer, Floris W. A. van Asbeck, and Lucas H. V. van der Woude. Relationship between manual wheelchair skill performance and participation of persons with spinal cord injuries 1 year after discharge from inpatient rehabilitation. *Journal of rehabilitation research and development*, 42 3 Suppl 1:65–73, Jun 2005. doi: 10.1682/jrrd.2004.08.0093.

[55] Melissa S. Riggins, Padmaja Kankipati, Michelle L. Oyster, Rory A. Cooper, and Michael L. Boninger. The relationship between quality of life and change in mobility 1 year postinjury in individuals with spinal cord injury, Jul 2011.

[56] Asuman Öztürk and Ferda Dokuztug Ucsular. Effectiveness of a wheelchair skills training programme for community-living users of manual wheelchairs in turkey: a randomized controlled trial. *Clinical Rehabilitation*, 25(5):416–424, May 2011. doi: 10.1177/0269215510386979. PMID: 21059666.

[57] Jill Dawson and Heather Thornton. Can patients with unilateral neglect following stroke drive electrically powered wheelchairs? *British Journal of Occupational Therapy*, 66(11):496–504, Nov 2003. doi: 10.1177/030802260306601102.

[58] Meike Jipp. Individual differences and their impact on the safety and the efficiency of human-wheelchair systems. *Human Factors*, 54(6):1075–1086, Dec 2012. doi: 10.1177/0018720812443826. PMID: 23397815.

[59] Rory A. Cooper, D.K. Jones, Shirley Fitzgerald, Micheal L. Boninger, and S.J. Albright. Analysis of position and isometric joysticks for powered wheelchair driving. *IEEE Transactions on Biomedical Engineering*, 47(7):902–910, Jul 2000. doi: 10.1109/10.846684.

[60] Wei Pin Huang, Chia Cheng Wang, Jo Hua Hung, Kai Chun Chien, Wen-Yu Liu, Chih-Hsiu Cheng, How-Hing Ng, and Yang-Hua Lin. Joystick-controlled video console game practice for developing power wheelchairs users' indoor driving skills. *Journal of physical therapy science*, Feb 2015. doi: 10.1589/jpts.27.495.

[61] Helen Hoenig, Michelle Morgan, Christy Montgomery, Lawrence R. Landerman, and Kevin Caves. One size does not fit all—mobility device type affects speed, collisions, fatigue, and pain. *Archives of Physical Medicine and Rehabilitation*, 96 (3):489–497, Mar 2015. doi: 10.1016/j.apmr.2014.07.420.

[62] Heikki Uustal and Jean L. Minkel. Study of the independence ibot 3000 mobility system: An innovative power mobility device, during use in community environments. *Archives of Physical Medicine and Rehabilitation*, 85(12):2002–2010, Dec 2004. doi: 10.1016/j.apmr.2004.04.044.

[63] Krista L. Best, François Routhier, and William C. Miller. A description of manual wheelchair skills training: current practices in canadian rehabilitation centers. *Disability and Rehabilitation: Assistive Technology*, 10(5):393–400, Apr 2014. doi: 10.3109/17483107.2014.907367. PMID: 24702608.

[64] Joanne Nunnerley, Swati Gupta, Deborah Snell, and Marcus King. Training wheelchair navigation in immersive virtual environments for patients with spinal cord injury – end-user input to design an effective system. *Disability and Rehabilitation: Assistive Technology*, 12(4):417–423, May 2017. doi: 10.1080/17483107.2016.1176259. PMID: 27376716.

[65] A. Harrison, G. Derwent, A. Enticknap, F. D. Rose, and E. A. Attree. The role of virtual reality technology in the assessment and training of inexperienced powered wheelchair users. *Disability and Rehabilitation*, 24(11-12):599–606, Jul 2009. doi: 10.1080/09638280110111360. PMID: 12182799.

[66] Bob G. Witmer and Michael J. Singer. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, 7(3):225–240, Jun 1998. doi: 10.1162/105474698565686.

[67] Lynn S. Wolf, Teresa L. Massagli, Kenneth M. Jaffe, and Jean Deitz. Functional assessment of the joncare hi-lo master power wheelchair for children. *Physical & Occupational Therapy In Pediatrics*, 11(3):57–72, Jan 1991. doi: 10.1080/J006v11n03_04.

[68] Chun-Jing Tu, Lin Liu, Wei Wang, He-Ping Du, Yu-Ming Wang, Yan-Bing Xu, and Ping Li. Effectiveness and safety of wheelchair skills training program in improving the wheelchair skills capacity: a systematic review. *Clinical Rehabilitation*, 31(12): 1573–1582, Dec 2017. doi: 10.1177/0269215517712043. PMID: 28580801.

[69] Laura Keeler, R. Lee Kirby, Kim Parker, Katie D. McLean, and Jill A. Hayden. Effectiveness of the wheelchair skills training program: a systematic review and meta-analysis. *Disability and Rehabilitation: Assistive Technology*, 14(4):391–409, May 2019. doi: 10.1080/17483107.2018.1456566. PMID: 29616832.

[70] Thomas W. Day and Nigel W. John. Training powered wheelchair manoeuvres in mixed reality. In *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*, pages 1–7, Sep 2019. doi: 10.1109/VS-Games.2019.8864515.

[71] Caryne Torkia, Stephen E. Ryan, Denise Reid, Patrick Boissy, Martin Lemay, François Routhier, Resi Contardo, Janet Woodhouse, and Phillipe S. Archambault. Virtual community centre for power wheelchair training: Experience of children and clinicians. *Disability and Rehabilitation: Assistive Technology*, 14(1):46–55, Nov 2017. doi: 10.1080/17483107.2017.1392622.

[72] Nigel W. John, Serban R. Pop, Thomas W. Day, Panagiotis D. Ritsos, and Christopher J. Headleand. The implementation and validation of a virtual environment for training powered wheelchair manoeuvres. *IEEE Transactions on Visualization and Computer Graphics*, 24(5):1867–1878, May 2018. doi: 10.1109/TVCG.2017.2700273.

[73] Louise Devigne, Marie Babel, Florian Nouviale, Vishnu K. Narayanan, François Pasteau, and Philippe Gallien. Design of an immersive simulator for assisted power wheelchair driving. In *2017 International Conference on Rehabilitation Robotics (ICORR)*, pages 995–1000, Jul 2017. doi: 10.1109/ICORR.2017.8009379.

[74] Nancy Rodriguez. Identifying accessibility conditions for children with multiple disabilities: A virtual reality wheelchair simulator. In *2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pages 370–372, Oct 2018. doi: 10.1109/ISMAR-Adjunct.2018.00107.

[75] Catherine Bigras, Dahlia Kairy, and Philippe S. Archambault. Augmented feedback for powered wheelchair training in a virtual environment. *J NeuroEngineering Rehabil*, Jan 2019. doi: 10.1186/s12984-019-0482-3.

[76] Débora Pereira Salgado, Ronan Flynn, Eduardo Lázaro Martins Naves, and Niall Murray. The impact of jerk on quality of experience and cybersickness in an immersive wheelchair application. In *2020 Twelfth International Conference on Quality of Multimedia Experience (QoMEX)*, pages 1–6, May 2020. doi: 10.1109/QoMEX48832.2020.9123086.

[77] Philippe S. Archambault, Stéphanie Tremblay, Sarah Cachecho, François Routhier, and Patrick Boissy. Driving performance in a power wheelchair simulator. *Disability and Rehabilitation: Assistive Technology*, 7(3):226–233, Oct 2011. doi: 10.3109/17483107.2011.625072.

[78] Bastien Fraudet, Emilie Leblong, Patrice Piette, Benoit Nicolas, Marie Babel, Valerie Gouranton, francois Pasteau, Louise Devigne, Guillaume Vailland, and Philippe Gallien. *Evaluation of powered wheelchair driving performance in simulator compared to driving in real-life situations. the SIMADAPT (simulator ADAPT) project: A pilot study*, May 2022. doi: 10.21203/rs.3.rs-1711205/v1.

[79] Real-time development platform — 3d, 2d, vr ar engine. URL `https://unity.com/`.

[80] Takashi Ota, Takuto Nakamura, and Hideaki Kuzuoka. Effects of gamification and communication in virtual reality frozen shoulder rehabilitation for enhanced rehabilitation continuity. *IEEE Access*, 11:50841–50850, May 2023. doi: 10.1109/ACCESS.2023.3279269.

[81] Mrityunjaya A Alapakkam Govindarajan, Philippe S Archambault, and Youri Laplante-El Haili. Comparing the usability of a virtual reality manual wheelchair simulator in two display conditions. *Journal of Rehabilitation and Assistive Technologies Engineering*, 9:20556683211067174, Feb 2022. doi: 10.1177/20556683211067174. PMID: 35237445.

[82] Stacy A Balk, Mary Anne Bertola, and Vaughan W Inman. Simulator sickness questionnaire: Twenty years later. *Proceedings of the 7th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design: driving assessment 2013*, Oct 2013. doi: 10.17077/drivingassessment.1498.

[83] Alireza Mazloumi Gavgani, Frederick R. Walker, Deborah M. Hodgson, and Eugene Nalivaiko. A comparative study of cybersickness during exposure to virtual

reality and “classic” motion sickness: Are they different? *Journal of Applied Physiology*, 125(6):1670–1680, Dec 2018. doi: 10.1152/japplphysiol.00338.2018.

[84] Kjell Brunnström, Sergio Ariel Beker, Katrien de Moor, Ann Dooms, Sebastian Egger, Marie-Neige Garcia, Tobias Hossfeld, Satu Jumisko-Pyykkö, Christian Keimel, Mohamed-Chaker Larabi, Bob Lawlor, Patrick Le Callet, Sebastian Möller, Fernando Pereira, Manuela Pereira, Andrew Perkis, Jesenka Pibernik, Antonio Pinheiro, Alexander Raake, Peter Reichl, Ulrich Reiter, Raimund Schatz, Peter Schelkens, Lea Skorin-Kapov, Dominik Strohmeier, Christian Timmerer, Martin Varela, Ina Wechsung, Junyong You, and Andrej Zgank. Qualinet white paper on definitions of quality of experience, Mar 2013.

[85] Eleni Kroupi, Philippe Hanhart, Jong-Seok Lee, Martin Rerabek, and Touradj Ebrahimi. Modeling immersive media experiences by sensing impact on subjects. *Multimedia Tools Appl.*, 75(20):12409–12429, Oct 2016. ISSN 1380-7501. doi: 10.1007/s11042-015-2980-z.

[86] Eun-Hye Jang, Byoung-Jun Park, Mi-Sook Park, Sang-Hyeob Kim, and Jin-Hun Sohn. Analysis of physiological signals for recognition of boredom, pain, and surprise emotions. *Journal of Physiological Anthropology*, 34(1), Jun 2015. doi: 10.1186/s40101-015-0063-5.

[87] Martine J. van Bennekom, Pelle P. de Koning, Martin J. Gevonden, M. Soemiati Kasanmoentalib, and Damiaan Denys. A virtual reality game to assess ocd symptoms. *Frontiers in Psychiatry*, 11, Jan 2021. doi: 10.3389/fpsyt.2020.550165.

[88] Adina E. Draghici and J. Andrew Taylor. The physiological basis and measurement of heart rate variability in humans. *Journal of Physiological Anthropology*, 35(1), Sep 2016. doi: 10.1186/s40101-016-0113-7.

[89] Harvard Health Publishing Staff. Heart rate variability: How it might indicate well-being, Dec 2021. URL `https://www.health.harvard.edu/blog/heart-rate-variability-new-way-track-well-2017112212789`.

[90] Haipeng Liu, John Allen, Dingchang Zheng, and Fei Chen. Recent development of respiratory rate measurement technologies. *Physiological Measurement*, 40(7), Aug 2019. doi: 10.1088/1361-6579/ab299e.

[91] Andrea Nicolò, Carlo Massaroni, Emiliano Schena, and Massimo Sacchetti. The importance of respiratory rate monitoring: From healthcare to sport and exercise. *Sensors*, 20(21), Nov 2020. ISSN 1424-8220. doi: 10.3390/s20216396.

[92] Yuri Masaoka and Ikuo Homma. Anxiety and respiratory patterns: their relationship during mental stress and physical load. *International Journal of Psychophysiology*, 27(2):153–159, Sep 1997. ISSN 0167-8760. doi: https://doi.org/10.1016/S0167-8760(97)00052-4.

[93] Elvira Salazar-López, E. Domínguez, Veronic Juárez Ramos, Juanma de la Fuente, A. Meins, Oscar Iborra, G. Gálvez, Miguel A. Rodríguez-Artacho, and Emilio Gómez-Milán. The mental and subjective skin: Emotion, empathy, feelings and thermography. *Consciousness and Cognition*, 34:149–162, Jul 2015. ISSN 1053-8100. doi: https://doi.org/10.1016/j.concog.2015.04.003.

[94] Katherine A. Herborn, James L. Graves, Paul Jerem, Neil P. Evans, Ruedi Nager, Dominic J. McCafferty, and Dorothy E.F. McKeegan. Skin temperature reveals the intensity of acute stress. *Physiology Behavior*, 152:225–230, Dec 2015. ISSN 0031-9384. doi: https://doi.org/10.1016/j.physbeh.2015.09.032.

[95] Yoko Nagai, Hugo D. Critchley, Eric Featherstone, Micheal R. Trimble, and Ray J. Dolan. Activity in ventromedial prefrontal cortex covaries with sympathetic skin conductance level: a physiological account of a "default mode" of brain function. *NeuroImage*, 22(1):243–251, May 2004. ISSN 1053-8119. doi: https://doi.org/10.1016/j.neuroimage.2004.01.019.

[96] Dong P. Jang, In Y. Kim, Sang W. Nam, Brenda K. Wiederhold, Mark D. Wiederhold, and Sun I. Kim. Analysis of physiological response to two virtual environments: Driving and flying simulation. *CyberPsychology amp;amp; Behavior*, 5(1): 11–18, Feb 2002. doi: 10.1089/109493102753685845.

[97] Marcel Delahaye, Patrick Lemoine, Shanique Cartwright, Gunnar Deuring, Johannes Beck, Marlon Pflueger, Marc Graf, and Henning Hachtel. Learning aptitude, spatial orientation and cognitive flexibility tested in a virtual labyrinth after virtual stress induction. *BMC Psychology*, 3(1), Jul 2015. doi: 10.1186/s40359-015-0080-5.

[98] Chiara Bassano, Manuela Chessa, Luca Fengone, Luca Isgrò, Fabio Solari, Giovanni Spallarossa, Davide Tozzi, and Aldo Zini. Virtual reality system for ship handling simulations: A case study on nautical personnel performance, observed behaviour, sense of presence and sickness. In Ana Paula Cláudio, Kadi Bouatouch, Manuela Chessa, Alexis Paljic, Andreas Kerren, Christophe Hurter, Alain Tremeau, and Giovanni Maria Farinella, editors, *Computer Vision, Imaging and Computer Graphics Theory and Applications*, pages 101–127, Cham, Feb 2020. Springer International Publishing. ISBN 978-3-030-41590-7.

[99] Jože Guna, Gregor Geršak, Iztok Humar, Jeungeun Song, Janko Drnovšek, and Matevž Pogačnik. Influence of video content type on users' virtual reality sickness perception and physiological response. *Future Gener. Comput. Syst.*, 91(C): 263–276, Feb 2019. ISSN 0167-739X. doi: 10.1016/j.future.2018.08.049.

[100] Jan-Philipp Stauffert, Florian Niebling, and Marc Erich Latoschik. Effects of latency jitter on simulator sickness in a search task. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 121–127, Mar 2018. doi: 10.1109/VR.2018.8446195.

[101] Conor Keighrey, Ronan Flynn, Siobhan Murray, Sean Brennan, and Niall Murray. Comparing user qoe via physiological and interaction measurements of immersive ar and vr speech and language therapy applications. In *Proceedings of the on Thematic Workshops of ACM Multimedia 2017*, Thematic Workshops '17, page 485–492, New York, NY, USA, Oct 2017. Association for Computing Machinery. ISBN 9781450354165. doi: 10.1145/3126686.3126747.

[102] Mark D. Wiederhold, Kenneth Gao, and Brenda K. Wiederhold. Clinical use of virtual reality distraction system to reduce anxiety and pain in dental procedures. *Cyberpsychology, Behavior, and Social Networking*, 17(6):359–365, Jun 2014. doi: 10.1089/cyber.2014.0203.

[103] Angela M. Salva, Antonio J. Alban, Mark D. Wiederhold, Brenda K. Wiederhold, and Lingjun Kong. Physiologically driven rehabilitation using virtual reality. In Dylan D. Schmorrow, Ivy V. Estabrooke, and Marc Grootjen, editors, *Foundations of Augmented Cognition. Neuroergonomics and Operational Neuroscience*, pages 836–845, Berlin, Heidelberg, Jul 2009. Springer Berlin Heidelberg. ISBN 978-3-642-02812-0.

[104] Polar h10 — polar uk, . URL `https://www.polar.com/uk-en/sensors/h10-heart-rate-sensor/`.

[105] Polar h10 heart rate sensor system, Nov 2019. URL `https://www.polar.com/sites/default/files/static/science/white-papers/polar-h10-heart-rate-sensor-white-paper.pdf`.

[106] Marcelle Schaffarczyk, Bruce Rogers, Rüdiger Reer, and Thomas Gronwald. Validity of the polar h10 sensor for heart rate variability analysis during resting state and incremental exercise in recreational men and women. *Sensors*, 22(17):6536, Aug 2022. doi: 10.3390/s22176536.

[107] Rahel Gilgen-Ammann, Theresa Schweizer, and Thomas Wyss. Rr interval signal quality of a heart rate monitor and an ecg holter at rest and during exercise.

European Journal of Applied Physiology, 119(7):1525–1532, Jul 2019. doi: 10.1007/s00421-019-04142-5.

[108] Seiya Otsuka, Kanami Kurosaki, and Mitsuhiro Ogawa. Physiological measurements on a gaming virtual reality headset using photoplethysmography: A preliminary attempt at incorporating physiological measurement with gaming. In *TENCON 2017 - 2017 IEEE Region 10 Conference*, pages 1251–1256, Nov 2017. doi: 10.1109/TENCON.2017.8228049.

[109] Shigeo Tanabe, Eiichi Saitoh, Soichiro Koyama, Kei Kiyono, Tsuyoshi Tatemoto, Nobuhiro Kumazawa, Hitoshi Kagaya, Yohei Otaka, Masahiko Mukaino, Akira Tsuzuki, Hirofumi Ota, Satoshi Hirano, and Yoshikiyo Kanada. Designing a robotic smart home for everyone, especially the elderly and people with disabilities. *Fujita Medical Journal*, 5(2):31–35, Feb 2019. doi: 10.20407/fmj.2018-009.

[110] Alisha Pradhan, Kanika Mehta, and Leah Findlater. "accessibility came by accident": Use of voice-controlled intelligent personal assistants by people with disabilities. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, page 1–13, New York, NY, USA, Apr 2018. Association for Computing Machinery. ISBN 9781450356206. doi: 10.1145/3173574.3174033.

[111] Peter Slattery, Alexander K. Saeri, and Peter Bragge. Research co-design in health: A rapid overview of reviews. *Health Research Policy and Systems*, 18(1), Feb 2020. doi: 10.1186/s12961-020-0528-9.

[112] Zoom. URL `https://zoom.us/`.

[113] Sign in — microsoft teams. URL `https://www.microsoft.com/en-ca/microsoft-teams/log-in`.

[114] Virginia Braun and Victoria Clarke. Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2):77–101, Jan 2006. doi: 10.1191/1478088706qp063oa.

[115] Nvivo, Oct 2023. URL `https://lumivero.com/products/nvivo/`.

[116] Microsoft word — microsoft 365. URL `https://www.microsoft.com/en-us/microsoft-365/word`.

[117] George Taleporos and Marita P McCabe. Body image and physical disability—personal perspectives. *Social Science amp; Medicine*, 54(6):971–980, Mar 2002. doi: 10.1016/s0277-9536(01)00069-7.

[118] Viviana Lo Buono, Lilla Bonanno, Francesco Corallo, Davide Cardile, Giangaetano D'Aleo, Carmela Rifici, Edoardo Sessa, Angelo Quartarone, and Maria Cristina De Cola. The relationship between body image, disability and mental health in patients with multiple sclerosis. *Journal of Clinical Medicine*, 12(10):3606, May 2023. doi: 10.3390/jcm12103606.

[119] Giulia Barbareschi, Mark T. Carew, Elizabeth Aderonke Johnson, Norah Kopi, and Catherine Holloway. "when they see a wheelchair, they've not even seen me"—factors shaping the experience of disability stigma and discrimination in kenya. *International Journal of Environmental Research and Public Health*, 18(8): 4272, Apr 2021. doi: 10.3390/ijerph18084272.

[120] Rosemary D F Bromley, David L Matthews, and Colin J Thomas. City centre accessibility for wheelchair users: The consumer perspective and the planning implications. *Cities*, 24(3):229–241, Jun 2007. ISSN 0264-2751. doi: https://doi.org/10.1016/j.cities.2007.01.009.

[121] Hannah Tough, Johannes Siegrist, and Christine Fekete. Social relationships, mental health and wellbeing in physical disability: A systematic review. *BMC Public Health*, 17(1), May 2017. doi: 10.1186/s12889-017-4308-6.

[122] Joel Devcich Kirsten Petrie and Hayley Fitzgerald. Working towards inclusive physical education in a primary school: 'some days i just don't get it right'. *Physical Education and Sport Pedagogy*, 23(4):345–357, Feb 2018. doi: 10.1080/17408989.2018.1441391.

[123] United Nations Human Rights. Empowerment, inclusion, equality: Accelerating sustainable development with human rights. URL `https://www.ohchr.org/sites/default/files/Documents/Issues/MDGs/Post2015/EIEPamphlet.pdf`.

[124] Nick Hodge and Katherine Runswick-Cole. 'they never pass me the ball': exposing ableism through the leisure experiences of disabled children, young people and their families. *Children's Geographies*, 11(3):311–325, Jul 2013. doi: 10.1080/14733285.2013.812275.

[125] Matteo Zallio and Takumi Ohashi. The evolution of assistive technology: A literature review of technology developments and applications. *Human Factors in Accessibility and Assistive Technology*, 37, Jul 2022. doi: 10.54941/ahfe1001646.

[126] James A. Lenker, Frances Harris, Mary Taugher, and Roger O. Smith. Consumer perspectives on assistive technology outcomes. *Disability and Rehabilitation: Assistive Technology*, 8(5):373–380, Jan 2013. doi: 10.3109/17483107.2012.749429.

[127] R. Lee Kirby, Paula W. Rushton, Francois Routhier, Louise Demers, Laura Titus, Jan Miller-Polgar, Cher Smith, Mike McAllister, Chris Theriault, Kara Matheson, Kim Parker, Bonita Sawatzky, Delphine Labbé, and William C. Miller. Extent to which caregivers enhance the wheelchair skills capacity and confidence of power wheelchair users: A cross-sectional study. *Archives of Physical Medicine and Rehabilitation*, 99(7):1295–1302.e9, Jan 2018. ISSN 0003-9993. doi: https://doi.org/10.1016/j.apmr.2017.11.014.

[128] Gillian Makamara and Martin Adolph. A survey of extended reality (xr) standards. In *2022 ITU Kaleidoscope- Extended reality – How to boost quality of experience and interoperability*, pages 1–11, Dec 2022. doi: 10.23919/ITUK56368.2022.10003040.

[129] Philippe S. Archambault, Émilie Blackburn, Denise Reid, François Routhier, and William C. Miller. Development and user validation of driving tasks for a power wheelchair simulator. *Disability and Rehabilitation*, 39(15):1549–1556, Sep 2016. doi: 10.1080/09638288.2016.1226423. PMID: 27669905.

[130] Paul M. Emmelkamp, Katharina Meyerbröker, and Nexhmedin Morina. Virtual reality therapy in social anxiety disorder. *Current Psychiatry Reports*, 22(7), May 2020. doi: 10.1007/s11920-020-01156-1.

[131] Hassan A. Karimi, Lei Zhang, and Jessica G. Benner. Personalized accessibility map (pam): A novel assisted wayfinding approach for people with disabilities. *Annals of GIS*, 20(2):99–108, Apr 2014. doi: 10.1080/19475683.2014.904438.

[132] Meta quest 2: Immersive all-in-one vr headset. URL `https://www.meta.com/ca/quest/products/quest-2`.

[133] Anker. URL `https://www.anker.com/`.

[134] @rog. URL `https://rog.asus.com/`.

[135] Guillaume Vailland, Fabien Grzeskowiak, Louise Devigne, Yoren Gaffary, Bastien Fraudet, Émilie Leblong, Florian Nouviale, François Pasteau, Ronan Le Breton, Sylvain Guégan, Valérie Gouranton, Bruno Arnaldi, and Marie Babel. User-centered design of a multisensory power wheelchair simulator: Towards training and rehabilitation applications. In *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, page 77–82. IEEE Press, Jun 2019. doi: 10.1109/ICORR.2019.8779496.

[136] Ananda Sankar Kundu, Oishee Mazumder, Prasanna Kumar Lenka, and Subhasis Bhaumik. Hand gesture recognition based omnidirectional wheelchair control

using imu and emg sensors. *Journal of Intelligent amp; Robotic Systems*, 91(3–4): 529–541, Oct 2017. doi: 10.1007/s10846-017-0725-0.

[137] M. Nirmala, S Pranesh, T Kavin, and Raja V Kavin. Gesture control integrated wheelchair. In *2022 International Virtual Conference on Power Engineering Computing and Control: Developments in Electric Vehicles and Energy Sector for Sustainable Future (PECCON)*, pages 1–6, May 2022. doi: 10.1109/PECCON55017.2022.9851174.

[138] Hanifah Rahmi Fajrin, Subhan Bariton, Muhammad Irfan, and Putri Rachmawati. Accelerometer based electric wheelchair. In *2020 1st International Conference on Information Technology, Advanced Mechanical and Electrical Engineering (ICITAMEE)*, pages 199–203, Oct 2020. doi: 10.1109/ICITAMEE50454.2020.9398415.

[139] Farah Binte Haque, Tawhid Hossain Shuvo, and Riasat Khan. Head motion controlled wheelchair for physically disabled people. In *2021 Second International Conference on Smart Technologies in Computing, Electrical and Electronics (ICSTCEE)*, pages 1–6, Dec 2021. doi: 10.1109/ICSTCEE54422.2021.9708577.

[140] Gianluca U Sorrento, Philippe S Archambault, François Routhier, Danielle Dessureault, and Patrick Boissy. Assessment of joystick control during the performance of powered wheelchair driving tasks. *Journal of NeuroEngineering and Rehabilitation*, 8(1):31, May 2011. doi: 10.1186/1743-0003-8-31.

[141] Tdkinvensense, Jun 2016. URL `https://invensense.tdk.com/wp-content/uploads/2015/02/PS-MPU-9250A-01-v1.1.pdf`.

[142] Matej Andrejašic. Mems accelerometers, Mar 2008. URL `http://www-personal.umich.edu/~bkerkez/courses/cee575/Handouts/5`$_{\mathrm{a}}$`dxl`$_{\mathrm{t}}$`heory.pdf`.

[143] Mark Pedley. Tilt sensing using linear accelerometers - nxp semiconductors, Mar 2013. URL `https://www.nxp.com/docs/en/application-note/AN3461.pdf`.

[144] Paul Farag, Robert Groza, and Sorin Hintea. High precision activity tracker based on the correlation of accelerometer and emg data. In *2019 42nd International Conference on Telecommunications and Signal Processing (TSP)*, pages 428–431, Jul 2019. doi: 10.1109/TSP.2019.8768874.

[145] The Arduino Team. Arduino ide. URL `https://www.arduino.cc/en/software`.

[146] Visual studio. URL `https://visualstudio.microsoft.com/vs/unity-tools/`.

[147] Unity asset store. URL `https://assetstore.unity.com/`.

[148] Sketchfab. URL `https://sketchfab.com/feed`.

[149] Turbosquid. URL `https://www.turbosquid.com/`.

[150] Autodesk maya: Create expansive worlds, complex characters, and dazzling effects. URL `https://www.autodesk.com/products/maya`.

[151] URL `https://www.microsoft.com/en-us/microsoft-365/excel/`.

[152] Matlab. URL `https://www.mathworks.com/products/matlab.html`.

[153] Spss software. URL `https://www.ibm.com/spss`.

[154] Andy P. Field. *Discovering statistics using IBM SPSS statistics: And sex and drugs and rock "n" roll.* SAGE, 2017.

[155] Débora Pereira Salgado, Ronan Flynn, Eduardo Lázaro Martins Naves, and Niall Murray. A questionnaire-based and physiology-inspired quality of experience evaluation of an immersive multisensory wheelchair simulator. In *Proceedings of the 13th ACM Multimedia Systems Conference*, MMSys '22, page 1–11, New York, NY, USA, Jun 2022. Association for Computing Machinery. ISBN 9781450392839. doi: 10.1145/3524273.3528175.

[156] Fabrizio Palmas, David Labode, David A. Plecher, and Gudrun Klinker. Comparison of a gamified and non-gamified virtual reality training assembly task. In *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*, pages 1–8, Sep 2019. doi: 10.1109/VS-Games.2019.8864583.

[157] Sebastian Deterding, Dan Dixon, Rilla Khaled, and Lennart Nacke. From game design elements to gamefulness: Defining "gamification". In *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments*, MindTrek '11, page 9–15, New York, NY, USA, Sep 2011. Association for Computing Machinery. ISBN 9781450308168. doi: 10.1145/2181037.2181040.

[158] Andrés Francisco-Aparicio, Francisco Luis Gutiérrez-Vela, José-Luis Isla-Montes, and José Luís González Sánchez. Gamification: Analysis and application. Jan 2013. doi: doi.org/10.1007/978-1-4471-5445-7_9.

[159] Carla Winter, Florian Kern, Dominik Gall, Marc Erich Latoschik, Paul Pauli, and Ivo Käthner. Immersive virtual reality during gait rehabilitation increases walking speed and motivation: A usability evaluation with healthy participants and patients with multiple sclerosis and stroke. *Journal of NeuroEngineering and Rehabilitation*, 18(1), Apr 2021. doi: 10.1186/s12984-021-00848-w.

[160] Filip Škola, Simona Tinková, and Fotis Liarokapis. Progressive training for motor imagery brain-computer interfaces using gamification and virtual reality embodiment. *Frontiers in human neuroscience*, 13:329, Sep 2019. ISSN 1662-5161. doi: 10.3389/fnhum.2019.00329.

[161] Jessica Ulmer, Sebastian Braun, Chi-Tsun Cheng, Steve Dowey, and Jörg Wollert. Gamification of virtual reality assembly training: Effects of a combined point and level system on motivation and training results. *International Journal of Human-Computer Studies*, 165:102854, Sep 2022. ISSN 1071-5819. doi: https://doi.org/10.1016/j.ijhcs.2022.102854.

[162] Wing Yan Jasman Pang and Lee Cheng. Acceptance of gamified virtual reality environments by older adults. *Educational Gerontology*, 49(9):830–841, Jan 2023. doi: 10.1080/03601277.2023.2166262.

[163] Nana Tian, Phil Lopes, and Ronan Boulic. A review of cybersickness in head-mounted displays: raising attention to individual susceptibility. *Virtual Real.*, 26 (4):1409–1441, dec 2022. ISSN 1359-4338. doi: 10.1007/s10055-022-00638-2. URL `https://doi.org/10.1007/s10055-022-00638-2`.

[164] Marzena Malińska, Krystyna Zużewicz, Joanna Bugajska, and Andrzej Grabowski. Heart rate variability (hrv) during virtual reality immersion. *International Journal of Occupational Safety and Ergonomics*, 21(1):47–54, Jan 2015. doi: 10.1080/10803548.2015.1017964.

[165] Gary G. Berntson, John T. Cacioppo, and Karen S. Quigley. Autonomic determinism: The modes of autonomic control, the doctrine of autonomic space, and the laws of autonomic constraint. *Psychological Review*, 98(4):459–487, 1991. doi: 10.1037/0033-295x.98.4.459.

[166] Sara Vlahovic, Mirko Suznjevic, and Lea Skorin-Kapov. A survey of challenges and methods for quality of experience assessment of interactive vr applications. *Journal on Multimodal User Interfaces*, 16(3):257–291, Apr 2022. doi: 10.1007/s12193-022-00388-0.

[167] Polar beat — polar usa. URL `https://support.polar.com/us-en/beat`.

[168] Heart rate monitors, activity trackers and bike computers — polar uk, . URL `https://www.polar.com/uk-en/`.

[169] Polar flow, . URL `https://flow.polar.com/`.

[170] Sungchul Jung, Richard Li, Ryan McKee, Mary C. Whitton, and Robert W. Lindeman. Floor-vibration vr: Mitigating cybersickness using whole-body tactile stimuli in highly realistic vehicle driving experiences. *IEEE Transactions*

on Visualization and Computer Graphics, 27(5):2669–2680, Mar 2021. doi: 10.1109/tvcg.2021.3067773.

[171] Valentin Schwind, Pascal Knierim, Nico Haas, and Niels Henze. Using presence questionnaires in virtual reality. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, May 2019. doi: 10.1145/3290605.3300590.

[172] Janet K. Gibbs, Marco Gillies, and Xueni Pan. A comparison of the effects of haptic and visual feedback on presence in virtual reality. *International Journal of Human-Computer Studies*, 157:102717, Jan 2022. ISSN 1071-5819. doi: https://doi.org/10.1016/j.ijhcs.2021.102717.

[173] Bernhard E. Riecke, Aleksander Väljamäe, and Jörg Schulte-Pelkum. Moving sounds enhance the visually-induced self-motion illusion (circular vection) in virtual reality. *ACM Transactions on Applied Perception*, 6(2):1–27, Mar 2009. doi: 10.1145/1498700.1498701.

[174] Isayas Berhe Adhanom, Majed Al-Zayer, Paul Macneilage, and Eelke Folmer. Field-of-view restriction to reduce vr sickness does not impede spatial learning in women. *ACM Transactions on Applied Perception*, 18(2):1–17, May 2021. doi: 10.1145/3448304.

[175] Colin Groth, Jan-Philipp Tauscher, Nikkel Heesen, Susana Castillo, and Marcus Magnor. Visual techniques to reduce cybersickness in virtual reality. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 486–487, Apr 2021. doi: 10.1109/VRW52623.2021.00125.

[176] Joel Teixeira and Stephen Palmisano. Effects of dynamic field-of-view restriction on cybersickness and presence in hmd-based virtual reality. *Virtual Reality*, 25(2): 433–445, Aug 2020. doi: 10.1007/s10055-020-00466-2.

[177] Sai Ho Yip and Jeffrey Allen Saunders. Restricting the distribution of visual attention reduces cybersickness. *Cognitive Research: Principles and Implications*, 8(1), Mar 2023. doi: 10.1186/s41235-023-00466-1.

[178] Behrang Keshavarz and Heiko Hecht. Pleasant music as a countermeasure against visually induced motion sickness. *Applied Ergonomics*, 45(3):521–527, May 2014. ISSN 0003-6870. doi: https://doi.org/10.1016/j.apergo.2013.07.009.

[179] Ari Widyanti and Hana Nadhilah Hafizhah. The influence of personality, sound, and content difficulty on virtual reality sickness. *Virtual Reality*, 26(2):631–637, Jun 2021. doi: 10.1007/s10055-021-00525-2.

[180] Takurou Magaki and Michael Vallance. Seeking accessible physiological metrics to detect cybersickness in vr. *International Journal of Virtual and Augmented Reality*, 4(1):1–18, Sep 2020. doi: 10.4018/ijvar.2020010101.

[181] Jean-Rémy Chardonnet, Mohammad Ali Mirzaei, and Frédéric Mérienne. Features of the postural sway signal as indicators to estimate and predict visually induced motion sickness in virtual reality. *International Journal of Human–Computer Interaction*, 33(10):771–785, Feb 2017. doi: 10.1080/10447318.2017.1286767.

[182] Caglar Yildirim. Cybersickness during vr gaming undermines game enjoyment: A mediation model. *Displays*, 59:35–43, Sep 2019. ISSN 0141-9382. doi: https://doi.org/10.1016/j.displa.2019.07.002.

[183] Bruno Porras-Garcia, Eduardo Serrano-Troncoso, Marta Carulla-Roig, Pau Soto-Usera, Marta Ferrer-Garcia, Natàlia Figueras-Puigderrajols, Lena Yilmaz, Yigit Onur Sen, Nazila Shojaeian, and José Gutiérrez-Maldonado. Virtual reality body exposure therapy for anorexia nervosa. a case report with follow-up results. *Frontiers in Psychology*, 11, May 2020. doi: 10.3389/fpsyg.2020.00956.

[184] Béatrice Ouellet, Paula W. Rushton, Andrée-Anne Côté, Laurence Fortin-Haines, Emma Lafleur, Isabelle Paré, Melanie Barwick, R. Lee Kirby, Maxime T. Robert, François Routhier, and et al. Evaluation of pediatric-specific resources to support utilization of the wheelchair skills training program by the users of the resources: A descriptive qualitative study. *BMC Pediatrics*, 22(1), Aug 2022. doi: 10.1186/s12887-022-03539-0.

Appendix A

Open-Ended Questionnaire

<u>Theme 1:</u> *Initial Wheelchair Struggles*

- How long have you been in a wheelchair?
- What were your biggest struggles when you first started using a wheelchair?
- How was the support available to you?
- Do you think you could have received more support?

<u>Theme 2:</u> *Wheelchair Struggles Now*

- What are the difficulties you face now?
- How is the support available to you now? Do you think it could be better?

<u>Theme 3:</u> *User's knowledge of technology*

- What technology do you use most in your day-to-day life?
- Is there a piece of technology that you think you have particularly benefitted from being a wheelchair user? If so, what is it?
- Do you think there is another piece of technology that has the potential of supporting someone with a disability?

<u>Theme 4:</u> *Users and VR*

- Have you ever used virtual reality?

- Thinking back on when you first started using a wheelchair, if there was a virtual reality application to help you overcome your struggles, what would you like it to be? What struggles do you wish it could have helped you with?
- In this moment in time, do you think you could benefit from any virtual reality applications? If so, what?

Theme 5: *VR themes*

- Would you prefer a realistic or abstract VR application?
- Would you prefer a gamified application or more of a video/passive application?
- What sort of interactions would you like to see in VR?

Theme 6: *Ease of interacting with VR for users with multiple disabilities*

- In what ways would you like to interact with VR?
- What controllers would you like to use to interact with VR (classic VR joystick, sensors on the body, other gaming joysticks, hands, etc)? Why?

Theme 7: *Integrating VR in the day-to-day life of a wheelchair user*

- What VR applications, if any, would you consider using on a regular basis? Why?
- Different forms of skills training
- Confidence building applications
- General gaming

Appendix B

Adjusted WST Questionnaire

User ID:

Adapted version of the Wheelchair Skills Test Questionnaire (WST-Q) Version 5.2 for Powered Wheelchairs

Question	**Answer**
How experienced are you in driving a wheelchair?	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
How experienced are you with gaming?	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
How experienced are you with VR?	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
How realistic did the VR joystick feel?	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
What is your age range?	☐ 18-23 ☐ 24-28 ☐ 29-33 ☐ 34-38 ☐ 39-43 ☐ 44-48 ☐ 49-53 ☐ 54-58 ☐ 59-63 ☐ 63+
To which gender do you most identify?	☐ Male ☐ Female ☐ Other:..... . . .. ☐ Prefer not say

Introduction to the questionnaire

- Copies of this questionnaire can be downloaded from

  www.wheelchairskillsprogram.ca/eng/wstq.php.

- More details about the questionnaire can be found there in the WSP Manual.

- In this questionnaire, you will be asked questions about different skills that you might do in your wheelchair. These skills range from ones that are more basic at the beginning to those that are more advanced at the end.

- There are no "right" or "wrong" answers. The purpose of the questionnaire is simply to help us understand how you use your wheelchair.

- It will probably take about 10 minutes to complete the questionnaire, but please take as much time as you need.

- If you have any comments, you will be able to record them at the end of the questionnaire.

- For each specific skill, beginning on page 3. The questions and the possible answers are shown below.

	Skill Description	Can you do it?	How confident are you?
1	Moving the wheelchair forward, for example along a hallway.	☐Yes, very well ☐Yes, but not well ☐Yes, with help ☐No	☐Very confident ☐Somewhat confident ☐Somewhat unconfident ☐Very unconfident
2	Moving the wheelchair backward, for example to back away from a table.	☐Yes, very well ☐Yes, but not well ☐Yes, with help ☐No	☐Very confident ☐Somewhat confident ☐Somewhat unconfident ☐Very unconfident
3	Turning the wheelchair around in a small space so that it is facing in the opposite direction.	☐Yes, very well ☐Yes, but not well ☐Yes, with help ☐No	☐Very confident ☐Somewhat confident ☐Somewhat unconfident ☐Very unconfident
4	Turning the wheelchair around obstacles while moving forward.	☐Yes, very well ☐Yes, but not well ☐Yes, with help ☐No	☐Very confident ☐Somewhat confident ☐Somewhat unconfident ☐Very unconfident
5	Turning the wheelchair around obstacles while moving backward.	☐Yes, very well ☐Yes, but not well ☐Yes, with help ☐No	☐Very confident ☐Somewhat confident ☐Somewhat unconfident ☐Very unconfident
6	Moving the wheelchair sideways in a small space, for example to get the side of your wheelchair next to a kitchen counter, and then back to where you started.	☐Yes, very well ☐Yes, but not well ☐Yes, with help ☐No	☐Very confident ☐Somewhat confident ☐Somewhat unconfident ☐Very unconfident

If you have any general comments about the questions that you have answered above, please record them in the space available below.

This is the end of the questionnaire. Thank you for completing it.