



# University of Chester

School of Computer Science  
Faculty of Science & Engineering

## **Virtual and Mixed Reality Support for Activities of Daily Living**

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Thesis submitted in accordance with the requirements of  
the University of Chester for the Degree of  
Doctor of Philosophy  
by

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*Supervisor* Prof. N. W. John

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**Statement of Originality**

The material being presented for examination is my own work and has not been submitted for an award of this or another HEI except in minor particulars which are explicitly noted in the body of the thesis. Where research pertaining to the thesis was undertaken collaboratively, the nature and extent of my individual contribution has been made explicit.

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# Abstract

## **Virtual and Mixed Reality Support for Activities of Daily Living**

**Thomas W. Day**

Rehabilitation and training are extremely important process that help people who have suffered some form of trauma to regain their ability to live independently and successfully complete activities of daily living. VR and MR have been used in rehabilitation and training, with examples in a range of areas such as physical and cognitive rehabilitation, and medical training. However, previous research has mainly used non-immersive VR such as using video games on a computer monitor or television. Immersive VR Head-Mounted Displays were first developed in 1965 but the devices were usually large, bulky and expensive. In 2016, the release of low-cost VR HMDs allowed for wider adoption of VR technology. This thesis investigates the impact of these devices in supporting activities of daily living through three novel applications: training driving skills for a powered wheelchair in both VR and MR; and using VR to help with the cognitive rehabilitation of stroke patients. Results from the acceptability study for VR in cognitive rehabilitation showed that patients would be likely to accept VR as a method of rehabilitation. However, factors such as visual issues need to be taken into consideration. The validation study for the Wheelchair-VR project showed promising results in terms of user improvement after the VR training session but the majority of the users experienced symptoms of cybersickness. Wheelchair-MR didn't show statistically significant results in terms of improvements but did show a mean average improvement compared to the control group. The effects of cybersickness were also greatly reduced compared to VR. We conclude that VR and MR can be used in conjunction with modern games engines to develop virtual environments that can be adapted to accelerate the rehabilitation and training of patients coping with different aspects of daily life.

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# Chapter 1

## Introduction

Activities of Daily Living (ADLs) are a prominent part of a person's normal routine and are completed more or less automatically. When something happens that makes a person unable to perform ADLs, it is important for that person to be able to return to a state where they are able to complete ADLs with little to no assistance. This allows them the freedom to live out their own lives without assistance from others. Supporting patients through their recovery after serious injuries or events, such as physical or cognitive trauma, is important as it helps them to regain their own sense of independence. An important aspect of this is their ability to complete ADLs that allow us to live without the need for someone else there to help us. These activities include a wide range of every day tasks that healthy people take for granted, such as making some toast or cup of tea, brushing your teeth, using a microwave, dishwasher, washing machine, tumble dryer, having a bath or shower, getting dressed, cooking a full meal, or shopping and walking to a destination, just to name a few examples.

Virtual reality (VR) has been used in the past as a way of assisting with rehabilitation and training of patients so they can successfully complete ADLs without assistance. However, as explained by Tieri *et al* [108], the term VR was often misused to refer to "any computer-based device that provides visual stimuli on a monitor, like video games". Previous 'VR' rehabilitation methods have included using equipment like the Nintendo Wii or Xbox Kinect to allow the patients to interact with a virtual environment that is displayed to them via a television or computer monitor. A more accurate definition of VR describes more than just a display, but a wide range of peripherals, such as controllers and audio

output, that provide input for each human sensory and motor channel to create an immersive experience.

There has also been some research in to the use of Mixed Reality (MR) in the context of rehabilitation and training of patients. For example, a mirror therapy system was developed [88] that tested five different hand tracking software development kits (SDKs) and the Xbox Kinect sensor to help the patient recover hand motion by tracking the healthy hand and making the patient believe it is their affected hand. They used this system to play a rhythm based game that is presented to the patient via a computer monitor placed in front of them. But as demonstrated in this example, the term MR often received similar 'misuse' to VR as the MR applications usually displayed a view of the real world overlaid with computer-generated content, or a view of a virtual environment that the user is overlaid on top of, via a non-immersive display like a television or computer monitor.

With the availability of low-cost immersive VR HMDs and the intuitive hand controllers that accompany them, as well as the current generation of MR HMDs that have been released, it is appropriate and timely for research to be conducted into the use and application of these technologies in the areas of rehabilitation and training in the context of activities of daily living.

## **1.1 Hypothesis**

VR and MR can be used to aid in rehabilitation and patient support, in the context of health care, by using bespoke virtual environments that can track patient progress and provide immediate visual feedback. Low-cost VR and MR HMDs can be used in conjunction with modern game engines to create virtual environments that can be adapted to accelerate the rehabilitation and the training of patients in coping with different aspects of daily life.

## 1.2 Contributions

This thesis details the contributions made by the research conducted during the Ph.D. These contributions include (1) the creation of a novel solution for providing powered wheelchair training using low-cost VR hardware and a series of practice scenarios, (2) the creation of a novel solution to overcome the issues found in VR wheelchair training using MR hardware, and (3) the creation of a novel virtual environment for the cognitive rehabilitation of post-stroke patients as an addition to their normal therapy routine and the acceptability of this approach by elderly stroke patients. Validation studies have been carried out to provide evidence of the effectiveness of each of these approaches.

## 1.3 List of Publications

Some of the work presented in this thesis has been published in peer-reviewed literature.

### Journal Publications

- Nigel W. John, Serban R. Pop, **Thomas W. Day**, Panagiotis D. Ritsos, Christopher J. Headleand, 'The Implementation and Validation of a Virtual Environment for Training Powered Wheelchair Manoeuvres'. In: *IEEE Transactions on Visualization and Computer Graphics (2017)*, Vol. 24, No. 5, pp. 1867-1878. Contributions: Development of Virtual Reality application

### Peer Reviewed Conference Publications

- Christopher J Headleand, **Thomas Day**, Serban R Pop, Panagiotis D Ritsos, Nigel W John, 'A Cost-Effective Virtual Environment for Simulating and Training Powered Wheelchairs Manoeuvres'. In: *Medicine Meets Virtual Reality 22: NextMed/MMVR22 220 (2016)*, p. 134. Contributions: Development of Virtual Reality application
- **Thomas W Day**. 'Training Powered Wheelchair Manoeuvres in Virtual Reality'. In: *Posture and Mobility Group Conference, 2016*.

- Long Chen, **Thomas W Day**, Wen Tang, Nigel W John. 'Recent Developments and Future Challenges in Medical Mixed Reality'. In: *2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE. 2017, In Press. Contributions: Research into the applications of MR in Medicine, detailing some of the recent case studies conducted.
- **Thomas W Day**, William Dobson, Christopher J Headleand, Serban R Pop, Nigel W John, 'Using Virtual Reality to Experience Different Powered Wheelchair Configurations'. In: *2017 International Conference on CyberWorlds*. IEEE. 2017 Contributions: Development of Virtual Reality application
- **Thomas W Day**, 'Wheelchair-MR: A Mixed Reality Wheelchair Training Environment'. In: *2017 International Conference on CyberWorlds*

### Poster Publications

- Christopher J Headleand, **Thomas Day**, Serban R Pop, Panagiotis D Ritsos, Nigel W John, 'Challenges and Technologies for Low-Cost Wheelchair Simulation'. In: *EuroGraphics Workshop on Visual Computing for Biology and Medicine, 2015*. Contributions: Development of Virtual Reality application

## 1.4 Thesis Structure

This thesis identifies and outlines the current state of the art for VR and MR technologies, as well as how they have been integrated into rehabilitation and patient support in the context of health care. Several case studies are presented which aim to aid the current practices and introduce new training techniques.

Chapter 2 reviews the developments that have been made surrounding VR and MR over the last few years, and discusses the current research that has been conducted in using VR and MR in rehabilitation and patient support. This chapter is then summarized and potential research opportunities are discussed.

Chapters 3 and 4 cover the work conducted around the use VR and MR for training powered wheelchair manoeuvres. Chapter 3 outlines the design, implementation, and validation of a VR wheelchair training simulator using modern, cost-effective VR HMDs and a games engine. The results of the study are analysed and conclusions are drawn. Limitations of the simulator are identified, with potential solutions and improvements discussed. Chapter 4 describes a continuation of the Wheelchair-VR project described in Chapter 3. This next phase was designed to try and overcome some of the issues that were identified in the original application by using a development version of a MR optical see-through HMD. The design and implementation of a MR wheelchair training environment is detailed. The validation study and results are then discussed and analysed. Conclusions about the project are drawn.

In Chapter 5, our research into cognitive rehabilitation in stroke patients is detailed. Modern, cost-effective VR technology is utilized to create an immersive application that allows patients to practice activities of daily living. The design, implementation, and acceptability study of the StrokeVR simulator are described. The results are then analysed and conclusions from the project are discussed.

A summary of the work detailed in this thesis is discussed in Chapter 6 and any future research that could be considered from this work is outlined.

# Chapter 2

## Background

### **2.1 Chapter Overview**

This chapter explores the different areas of research that are important to the investigations within this thesis, including the concepts of immersion and presence, VR and MR technologies and their limitations, as well as the current methods of support for activities of daily living using VR and MR and the methodologies used to test these methods. The end of this chapter summarizes the advancements in VR, MR, rehabilitation and patient support that have been made, and also highlights areas where new research could be conducted.

### **2.2 Human Perception**

According to the Second, European Edition of *Psychology* [90], perception is stated to be the 'Organization, identification, and interpretation of a sensation in order to form a mental representation', with sensation defined as 'Simple awareness due to the stimulation of a sense organ'. Perception uses sensory information from each of the human sensory inputs, such as vision, sound and touch, to create high-level information that is then connected with a person's own concepts and expectations to help build and influence their perceptions of the environment that they are in.

For virtual reality applications and experiences to be immersive and allow the user to become engrossed in the virtual environment, they need to provide the same, almost lifelike, stimuli for the sensory system that would be present in the real world. This means that they need to draw the user in to the environment, and provide them a sense of



presence, making them perceive that they are really within and can interact with the virtual environment that they are being presented.

### **2.2.1 Immersion**

Immersion can be defined as the objective degree to which a VR system and application projects stimuli onto the sensory receptors of users in a way that is extensive, matching, surrounding, vivid, interactive, and plot informing [53]. There are five factors that affect the quality and immersion of the system:

- Extensiveness - The range of senses presented to the user (visuals, audio, physical forces).
- Matching - The realistic representation of each sensory information (i.e. appropriate visual representation of head movements).
- Surroundness - The extent to which the cues are panoramic (e.g. wide Field of View, Spatial audio, 360° tracking).
- Vividness - The quality of the display technology (resolution, frame rate, audio bitrate).
- Interactibility - The capability to interact with the environment and affect it in real-time.

Each one of these provide a different way of increasing the immersion of VR applications and experiences. However, the immersion of the application is only as good as the worst factor that affects it. For example, the VR system can provide an extensive range of sensory information, a fully surround experience and can match the real world down to minor details, but unless the vividness of the display technology or the interactibility of the system are of the same high standard, the immersion provided by the application could be severely affected and the user may not feel immersed within the environment being presented.

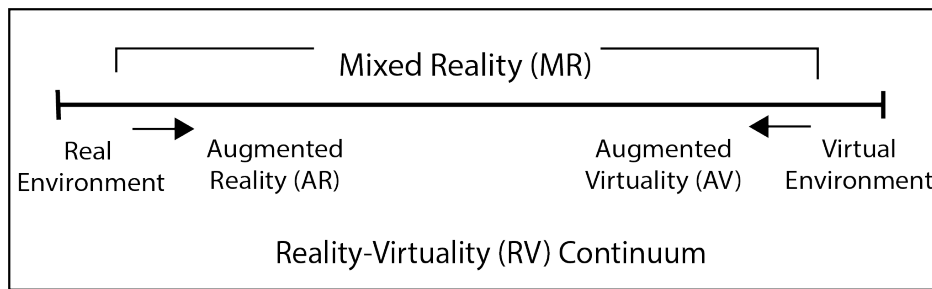
Immersion is an important part of virtual reality experiences as it provides a way of viewing and interacting with the virtual world, but it alone is not enough to create a truly absorbing experience. The user

needs to be able to gain a sense of presence within the virtual world, allowing themselves to become lost within the application.

### **2.2.2 Presence**

Unlike immersion, which is about the characteristics of the technology, presence is an internal psychological state, and is extremely difficult to describe and can only really be understood once it has been experienced. The quality of immersion is an important component for achieving presence, as is proprioception, the internal (unconscious) mental model that a person has regarding the current state and disposition of their body. A necessary condition for presence is that sensory data and proprioception match one another. As presence is an important aspect of virtual and mixed reality applications, the VR community pushed for a definition to be created that would allow them to better design the experiences that they were developing. The International Society for Presence Research provide a 'comprehensive explication of the concept of presence' on their website [51], and starts with this statement:

Presence (a shortened version of the term "telepresence") is a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience. Except in the most extreme cases, the individual can indicate correctly that s/he is using the technology, but at *\*some level\** and to *\*some degree\**, her/his perceptions overlook that knowledge and objects, events, entities, and environments are perceived as if the technology was not involved in the experience. Experience is defined as a person's observation of and/or interaction with objects, entities, and/or events in her/his environment; perception, the result of perceiving, is defined as a meaningful interpretation of experience.



**Figure 2.1:** Milgram's definition of the reality-virtuality continuum [77]

In short, this means that, although the user is aware that they are using VR technology, the VR system and application should almost fool the users senses in to forgetting or ignoring the fact that they viewing the environment using a screen and interacting with it via a controller in their hand.

In terms of virtual and mixed reality experiences, having high quality immersive technologies and realistic virtual environments can aid in providing a user with a sense of presence, allowing them to become lost within the virtual world, however after a certain point, the visual aesthetics of the virtual world can cause the user to reject the experiences and fall in to the uncanny valley and break their sense of presence.

## 2.3 Virtual Reality

According to the Reality-Virtuality continuum, devised by P. Milgram *et. al.* in 1995 (See Fig. 2.1), Virtual Reality (VR) lies at one end of a continuum and Reality lies at the other. The space in-between these two extremes is referred to as MR, which is discussed in more detail in Section 2.4. VR is defined as the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors.

There are multiple types of VR display that have been developed over the years. The most common of these are large-volume displays (LVDs)

and head-mounted displays (HMDs). Both of which include different sub-categories, each with their own advantages and disadvantages.

### **2.3.1 Large-Volume Displays (LVDs)**

This type of display allows multiple users to view the same virtual environment at once. These displays can be split into two sub-categories, monitor-based and projector-based.

#### **Monitor-based**

Modern monitor-based displays normally use one or more stereoscopic monitors, placed side-by-side, and either active or passive stereo glasses to view the 3D environment. Active stereo glasses use an Infra-Red (IR) emitter to synchronize the speed of the shutters built-in to the glasses with the refresh rate of the 3D display. When the image for the right eye is displayed, the shutter on the left lens is closed so only the right eye can see the image. This is then reversed so the left eye image is displayed and the shutter on the right lens is closed. The images and shutters alternate rapidly fooling the brain into perceiving a stereoscopic view. Passive stereo glasses, on the other hand, work by polarizing the lenses in different directions whilst the left and right eye images are projected simultaneously. Either linear or circular polarization can be used to view the 3D imagery so that each eye only sees the image it is meant to. The most common type of polarization is linear, where the lenses are polarized perpendicular to each other, i.e. horizontally and vertically. An issue with this is that the user must keep their head level with the screen, otherwise they will start to lose the 3D effect. Circular polarization overcomes this by polarizing the light in a clockwise or anti-clockwise direction, meaning that user can move and turn their head without losing the 3D effect of the display.

An example of a monitor-based LVD is the z-Space (see Fig. 2.2). A single monitor screen that uses passive stereo glasses to view a 3D environment. Reflective tabs on the glasses also allow the display to track the users position using IR emitters. The view is then adjusted to compensate for their movement, increasing the immersion of the

experience. The display also incorporates a tracked stylus, which is also tracked by the IR emitters, allowing the user to interact with the environment.



**Figure 2.2:** The mock-up of a 3D view on the z-Space display from the vCath project [56]

### **Projector-based**

Large projector-based displays can be split into four different types; Workbench, CAVE Automatic Virtual Environments (CAVE) or Re-configurable Virtual Environments (RAVE), Powerwall, and Dome.

Workbench displays, such as the one seen in Fig. 2.3, are normally self-contained units that use one or more projectors to display the images on diffuser screens. These displays use mirrors to reduce the space required by the projector.

Some projector-based LVDs, such as CAVEs, RAVEs, and Powerwalls, use multiple projectors to create the desired effect. CAVE and RAVE displays, such as the Octave at the University of Salford in Manchester [42], or the CAVE setup at Keele University (see Fig. 2.4), use mirrors to reflect the images from the projectors or short throw lenses to reduce the amount of space required to set up the displays. There are a variety of ways to configure LVDs to fit their intended purpose, for example, powerwalls often have different setups depending on the effect that is being obtained. Some use a single projector that alternates between displaying the left and right eye images, others use multiple projectors to display the images simultaneously or to tile the images so a larger display



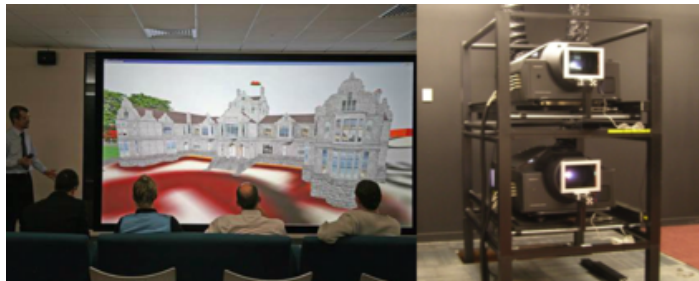
**Figure 2.3:** Fake Space Immersive Workbench N-239 showing skull for reconstructive surgery studies [5]

area could be achieved. For example, in Fig. 2.5, two polarized projectors stacked on top of each-other were used to display the 3d environment using passive stereo glasses. The images from the two projectors were overlaid on top of each-other, with each projector generating a different polarized image to create the stereoscopic effect. Systems that use multiple tiled projectors need to be overlap the images to ensure that 3d environment is displayed seamlessly, i.e. without any gaps between the sections. However, a downside to this kind of setup is that the areas where two or more projectors would overlap would appear brighter than the rest of the image. This had the potential to detract from the experience. To overcome this effect, the projectors modulated the light intensities so the brightness was normalize across the entire display.

Dome displays use three different methods to project onto the dome; projection onto a spherical mirror, projection using a fish-eye lens, or multiple, tiled projectors. Each of these methods have their own benefits and drawbacks. For example, using multiple projectors allows for a higher resolution display but requires light intensity modulation due to overlap, and using a spherical mirror requires less space but doesn't provide a high definition view. All of these displays use the same active stereo or



**Figure 2.4:** The CAVE installation at the University of Keele. Here there are three projection walls but note that CAVES have been built with all four walls, the floor and the ceiling as projection surfaces.



**Figure 2.5:** A Powerwall display (left) that uses two polarized Sony 4K projectors (right) with passive stereo glasses

passive stereo glasses as the monitor-based displays to view the virtual environment correctly.

LVDs have some advantages over HMDs. They don't require any cables to be attached to the user which allows them to move around freely, multiple users can view the same virtual environment collaboratively, and the glasses used are usually lightweight and ergonomic. On the other hand, these displays are often large, bulky and expensive, and can be less immersive than HMDs. This makes them very difficult to transport and they require an open space to set up.

### **Tracking Systems**

Large volume displays employ a variety of different tracking methods to update the images that are displayed to increase the immersiveness of the applications. These methods include the use of optical, ultrasound,

and magnetic tracking. For example, ultrasound and magnetic tracking emit a signal that is reflected back by sensors attached to objects within the tracking area. This reflected signal is received by the tracking system and the position is calculated based on the time it takes to get from the emitter to the object and then back. The position is then used to update the view of the environment so it matches the user's perspective. Optical tracking works in a very similar way to ultrasound magnetic tracking. One drawback to optical and ultrasound tracking is that they require direct line of sight to the sensors for accurate tracking.

### **2.3.2 Head-Mounted Displays (HMDs)**

In 1965, Ivan Sutherland wrote a paper that described "The Ultimate Display" [101]. It discussed the technologies that were available at the time, such as the typewriter keyboard and RAND Tablet, as well as possible future developments into display systems and interactions. He describes the ultimate display as "a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and bullet displayed in such a room would be fatal." A few years later, Sutherland published a paper that described the design and implementation of a head-mounted three dimensional display [102]. Since then, VR HMDs had been used for many different applications, however, the VR HMDs were bulky, uncomfortable, and extremely expensive. An example is the "Virtual Interface Environment Workstation" (VIEW) that was developed by NASA in the early 1990s [106], which consisted of a bulky HMD that they used to view the virtual environment and "DataGloves" for interaction.

Since the emergence of VR technology in 2012, with Oculus' successfully crowd funding campaign for their initial prototype of the Oculus Rift VR HMD, affordable HMDs have become more readily available to the public, with companies such as HTC, Oculus, and Sony developing the first modern VR HMDs. These devices have been primarily used for gaming since their release but they have also been used for a wide range



of other application areas, including civil engineering [26][27], education [10][91], tourism [58] and sports [16]. There are currently two main types of VR HMDs available, desktop and mobile. Each have their own advantages and disadvantages.

### **Tethered HMDs**

HMDs connected to a desktop PC are currently the most popular way of experiencing VR. This is due to the fact that the HMDs, applications and experiences designed for tethered HMDs are more accessible than other VR platforms that are available. Just like LVDs, HMDs are able to take advantage of the increased processing power of modern Central Processing Units (CPU) and Graphics Processing Units (GPUs) , and the sophisticated tracking technologies that the VR systems employ to allow the user to interact within the environment. The two common tethered HMDs available at the moment are the HTC Vive and the Oculus Rift, with others, like the Fove 0, being developed by small VR technology companies, or the Windows VR HMDs designed by Microsoft and built by HP, Lenovo, Asus, and Dell.

The Oculus Rift (see Fig. 2.6b) was the first modern HMD to become available through its two development kits (DKs) that were released in 2013 and 2014 respectively. The DKs initially showed the potential of desktop-based VR and the company was later acquired by Facebook Ltd. in March, 2014. Since then, Oculus VR LLC. have been developing the headset with the backing of Facebook and finally released the first commercial version (CV) in 2016. The Rift uses a constellation based tracking system to track the position and orientation of the headset. This system works by tracking an array of IR emitters built-in to the headset that pulse in a specific sequence, allowing it to accurately track the headset. The rift originally comes with only one sensor which provides up to a 1.5m by 3.3m play-space but with the release of the Rift's hand controllers, Oculus Touch, the system was updated to support multiple sensors to provide a larger tracking area. The controllers use the same tracking system as the headset, with the IR emitters built-in to the

controllers ring. Each touch controller has a range of different control surfaces, such as a trigger, grip button and joystick. Each control surface has the ability to detect whether it is being touched, pressed, or neither. This allows the system to replicate the positioning of the users fingers more accurately and provides the potential for adding gestures and more realistic hand movements, which can increase the immersion of the system and provide the user with a better sense of presence.

Another modern VR HMD to be commercially released was the HTC Vive (See Fig. 2.6a). This HMD was developed and released with the assistance of Valve, owners of an extremely popular and widely used games marketplace, Steam. The Vive HMD is capable of tracking the user within a 4.5m<sup>2</sup> area, as well as two hand controller which allow the users to interact with the virtual environment using their hands. This capability allows the HMD to provide an immersive experience and allows the user to gain a sense of presence within the virtual world they are in. The different control interfaces on the controllers, such as the trigger, touchpad and grip buttons, allow for a range of different interactions within the environment, like navigating menus or grabbing and throwing objects. The system uses two "lighthouse boxes" that produce infra-red light which is picked up by the headset and controllers (See Fig. 2.7). The intensity of the light when it reaches the headset and controllers is used to accurately calculate the users position within the virtual environment, increasing the immersion that is capable within the system.

Another headset that has been developed is the Fove 0 (see Fig. 2.6c). This headset was one of the first headsets to be designed with built-in eye tracking and foveated rendering. This meant that the users gaze could be tracked, allowing objects and menus within the environment to be selected just using their focus, making the experiences more immersive. The foveated rendering also meant that only the content that the user is focussed on is high quality, and the rest of the display is blurred. This reduces the graphical requirements of the system, which meant



**(a)** The HTC Vive and hand controllers [111].



**(b)** The Oculus Rift, Touch Controllers, Clicker, and Xbox One Controller [81].



**(c)** The Fove 0 [41].



**(d)** The HP VR1000-100nn Headset and Hand Controllers [45].

**Figure 2.6:** Desktop-based VR HMDs.

they were able to increase the screen resolution with minimal cost to computing power.

In an effort to make VR HMDs more affordable, Microsoft developed a universal platform that VR and MR HMDs could run on. This platform, called "Windows Mixed Reality (WMR)", was originally referred to as "Windows Holographic" and was designed for their first MR headset, the HoloLens, discussed in the next section (Section 2.4). The technical specifications for the HMD and its hand controllers were sold to companies, like HP, Acer, Lenovo, and Dell, so they could build the



**Figure 2.7:** One of the base stations used by the VIVE's lighthouse system

headsets to run on the platform. An example is the HP VR1000-100nn HMD (see Fig. 2.6d). Unlike other VR HMDs that are currently available, the WMR HMDs use Inside-Out tracking. This tracking system uses an array of cameras and sensors built-in to the headset to map the environment. This means that there is no need for external sensors as they are built-in to the headset itself, potentially allowing the headset to track a larger area, only being limited by the length of the cable that connects it to the PC. A comparison of the technical specifications of the headsets mentioned above is provided in Table 2.1.

All of these headsets are capable of 6 Degrees Of Freedom (DOF) tracking. This means that their positions and orientation within the environment is tracked. Content for these headsets can be developed using Games Engines such as Unity3D and Unreal Engine. Each HMD has their own specific SDK that needs to be included within the projects for the VR experience to function properly on the HMD and to gain full access to the capabilities of the headset, for example, the FOVE's eye tracking.

VR for games consoles also became available at a similar time to Desktop VR. Sony released its PSVR system [85], which was designed to

**Table 2.1:** A comparison of the specifications of four desktop based HMDs

Device Specifications				
	Oculus Rift	HTC Vive	FOVE 0	HP VR1000-100nn
<b>Display Type</b>	OLED	OLED	————	LCD
<b>Resolution</b>	2160 x 1200	2160 x 1200	2560 x 1440	1440 x 1440
<b>Refresh Rate</b>	90 Hz	90 Hz	70 Hz	90 Hz
<b>Field of View</b>	110°	110°	100°	90°
<b>Sensors</b>	Accelerometer Gyroscope Magnetometer	Accelerometer Gyroscope	Accelerometer Gyroscope	Accelerometer Gyroscope
<b>Connections</b>	HDMI USB 2.0 USB 3.0	HDMI USB 2.0 USB 3.0	HDMI USB 2.0 USB 3.0	HDMI USB 3.0
<b>Tracking System</b>	Constellation	Lighthouse	Infrared	Inside-Out
<b>Tracking Area</b>	5 x 11 feet	15 x 15 feet	————	————
<b>Platforms</b>	Oculus Home	SteamVR VivePort	SteamVR OSVR	Windows Mixed Reality

work with the most recent generation of its PS4 Consoles. This system requires the use of the PS4 Camera to enable 6DOF tracking, as well as PlayStation Move controllers for hand interactions, however these accessories are not sold with the PSVR headset. The headset contains a 5.7 inch display capable of displaying at 1080p and a refresh rate of 120Hz.

### Mobile HMDs

Mobile-based VR is a much cheaper, more portable, and more accessible way to experience VR. This is because the VR application is installed and run on the users mobile device, most commonly a smart phone. The device is then placed within a special viewer like the Google Cardboard, Google Daydream, or Samsung Gear VR (See Figure 2.8). A limitation, however, is that mobile phones do not have the same capabilities as desktops so the experiences and interactions are usually more basic. The controls for the applications are also more simplistic. For example, the Google Cardboard only provides a single touch control via a "button" built-in to the viewer. Mobile VR experiences also don't benefit from the same tracking capabilities as desktop VR so they are either static or have simple locomotion like teleportation or flying.

Platforms like Google's Daydream VR and Oculus Mobile, which is used by the Gear VR, have taken some steps towards closing the gap between mobile and desktop VR by providing a lightweight system that the applications can run on to improve their performance when running on mobile. These platforms provide an interface that allow Bluetooth handheld controllers to be connected to applications that are running on the system. This provides a more sophisticated ways of interacting with the environment.



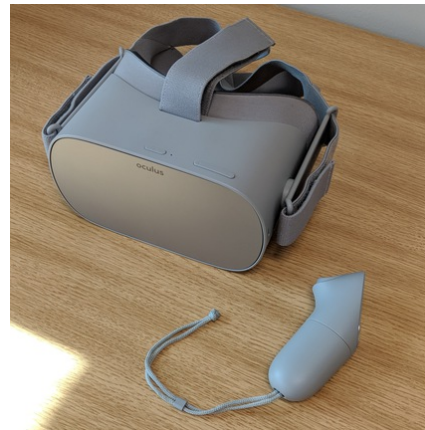
(a) A Google Cardboard [35].



(b) A Google Daydream Viewer with Controller [24].



(c) A Samsung GearVR with Controller [89].



(d) A Oculus Go with Controller [79].

**Figure 2.8:** Mobile-based VR HMDs.

Due to the lack of positional tracking that is currently present in mobile VR systems, they are only capable of 3DOF, allowing the user to look around the environment but not move physically.

As an evolution to mobile VR, Standalone HMDs have been developed that provide the same experience as mobile VR except the whole system is built in to the headset. These devices still lack the same tracking

as desktop and are only capable of 3DOF, an example of which is the Oculus Go [79]. This is a standalone device with the network connectivity capabilities. The initial setup of the device requires the user to have the Oculus App installed on their phone. Once the device is setup, the user is able to download applications directly on to the HMD via the users phone or the built-in store application. Unfortunately, as it lacks a tracking system, the Oculus Go can only be used from a seated or standing position. This means that the user is able to look around in the environment, but it unable to move around unless some form of locomotion is included within the application. This lack of positional tracking does mean that VR experiences may not be as immersive as those running on desktop HMDs. However, developments have been made to add 6DOF to mobile HMDs to enable them to match the tracking capabilities of the desktop-based headsets. An example of this is the Oculus Quest, originally known as project Santa Cruz (See Fig. 2.9). This mobile HMD has Inside-Out tracking built in to the device to allow it to track its position within an environment as well as controllers for the user to interact with.



**Figure 2.9:** The Oculus Quest with controllers [80]

### **2.3.3 VR Content Development**

#### **Desktop VR**

As mentioned before, VR content can be developed for tethered VR HMDs, like the Vive and Rift, and LVDs, like CAVE and Powerwall systems, using commercial, off-the-shelf games engines such as Unity3D engine and Unreal Engine 4. Each VR system has their own SDK to allow applications

to communicate with them. When developing VR content, the developers need to make sure that the SDK for the system they are targeting is present within the application. Originally, when an application was to be developed for multiple VR systems, the code would have to be rewritten to work with the SDK of the systems that they are targeting. Because of this, toolkits have been developed that remove the need to rewrite the application code by creating an interface that can communicate with multiple SDKs. For example, the VRTK [107], which was developed for the Unity Engine, allows developers to create VR experiences that can be used with a range of different HMDs by using an event system that translates the interactions that are triggered in their system to the API that is needed for the HMD that is currently in use, which is detected by determining which VR system is currently running on the machine. Similar packages have been developed for LVDs, like WorldViz [117], that allow for fast development of VR content.

### **Mobile VR**

Much like desktop VR development, Mobile VR can be developed using normal game engines but requires the specific SDK for the platform you are targeting to be present within the application. Toolkits, like VRTK [107], also allow for the development of mobile VR using the same process as desktop VR. The application detects the platform that it is running on and then communicates with the required SDK, assuming that it has been included within the project.

### **Web-based VR**

Web-based VR technologies have also been emerging over the past few years with the release of an API for web-based VR development called WebVR [112]. This API allows websites to detect if they are being viewed on a VR capable device, query their capabilities, get the orientation and position of the VR device, and display the 3d environment on the device at an appropriate frame-rate. Because VR experiences can now be built using the WebVR API, they can be viewed on any device that has a web browser without any configuration changes. Web-based frameworks,



like A-Frame [1], have been built on top of existing technologies to take advantage of the WebVR API and create a faster way of developing and deploying Web-based VR experiences.

#### **2.3.4 Current Issues**

There are currently concerns that using VR can have negative influences on social behaviour of its users. Users who engage in the use of VR games or experiences that include violent or aggressive aspects may become desensitized to these aspects within the real world. This may also lead to them replicating the violent acts that were experienced within the virtual environment in the real world. Another social issue is the potential for the users of VR to abandon the real world, and attempt to live solely within the virtual. This may then lead to that person getting into different kinds of social or economic issues, such as developing social issues due to lack of human contact, or financial troubles because the user may not continue to work in the real world.

Cybersickness [73] is another issue that can cause serious problems for users. It is caused by a disruption to the vestibulo-ocular reflex (VOR) when the user perceives motions but does not experience it. The VOR is an important reflex that stabilizes a persons vision as they move their head. Cybersickness can present with similar symptoms to motion sickness and affects users differently depending on how susceptible they are to the effects of motion sickness. This is an inherent risk with attempting to move around in a virtual environment without appropriate tracking or locomotion [32]. There has been many different attempts at reducing the effects of cybersickness in VR. A few techniques that have been developed have been implemented into games like Eagle Flight [30]. These included speed-based tunnel vision to reduce the number of objects passing by the users peripheral vision, a virtual nose to provide a familiar point of reference within the view, and simulated movement effects such as wind effects. Each of these techniques have helped to reduce the effects of cybersickness but do not remove them completely. Other issues also include the risk of eye strain from prolonged use of VR

HMD due to the proximity of the screens to your eyes. A potential way of removing the effects of cybersickness, and potential issues like eye strain, is to use MR instead of VR, which enables the user to view virtual content within the context of the real world.

## **2.4 Mixed Reality**

Mixed Reality (MR) refers to the space on the Reality-Virtuality continuum that lies between reality and VR (See Fig. 2.1). There are several different sub-categories that fall under the umbrella of MR. These include Augmented-Virtuality (AV), which is where the virtual world is augmented by the real world, and the more commonly known Augmented Reality (AR), which is where the real world is augmented by the virtual world.

AR has been available for a long time, originally using marker-based technology to generate virtual objects when a specific pattern is visible to the camera. Since smartphones have become more powerful, AR applications have seen mainstream adoption in recent years with the release of mobile-based AR games like Pokémon Go [43]. This game overlaid characters from Nintendo's popular game on to the real world. The players would then be able to use PokéBalls to capture Pokémon and use them to fight other Pokémon at gyms. This game also had a location based aspect, requiring the players to move around and visit landmarks to gain more Pokémon, items, and experience.

### **2.4.1 Headsets**

The development of AR and MR headsets has taken a large leap forward over the past few years. In late 2016, Microsoft released their first standalone MR headset called the HoloLens (see Fig. 2.10a). The device has 6 Degrees of Freedom (6DOF) and is capable of tracking the users position and orientation within the real world without the need for external tracking sensors. It does this using an array of sensors built-in to the headset, which are based on the second version of the Xbox Kinect System. Depth, High Definition, and Infra-Red cameras gather information about the environment that the device is in. The information

is then processed and used to reconstruct a 3D model of the environment, allowing the device to spatially map the environment. This spatial map is used, along with information from the sensor array and gyroscope, to place the user and virtual objects within the environment. Processing the data from the sensor array and 3D model also allows the device to "understand" the space, allowing the device to identify different types of surface like walls, floors, and surfaces like tables and chairs. The HoloLens supports several methods of interaction, consisting of gesture recognition, voice commands, and a physical controller. Each one allows the user to interact with the menus and applications running on the device. There are three gestures that are understood by the HoloLens. These are:

- **Air Tap** - Similar to mouse click, allows user to click on objects and menus.
- **Hold** - Allows the user to drag objects and menus around within the environment.
- **Bloom** - System reserved gesture, used to open and close the start menu and close the currently open application.

Due to the technological limitations of the display used in the device, the HoloLens only has a small viewport or field of view (FOV) of only 35°. This means that the user can only see the objects that they are looking at directly, with no rendering of any objects in the users peripheral vision.

Other MR headsets have also been developed, such as the Meta2 (See Fig. 2.10b) or Magic Leap One headset (See Fig. 2.10d). The Magic Leap One device is designed to look more like a pair of glasses and uses light field displays and inside-out tracking to superimpose virtual content on to the real world. The device is a standalone headset, similar to the HoloLens, except the computer components are in a separate device that is connected to the headset via cables and can be place in a pocket or hooked on to a belt. The Magic Leap also comes with a controller that allows you to interact with the virtual content in a similar way to the

controllers used in VR. The FOV for the device is 40° by 30° which is 45% larger than that of the HoloLens.

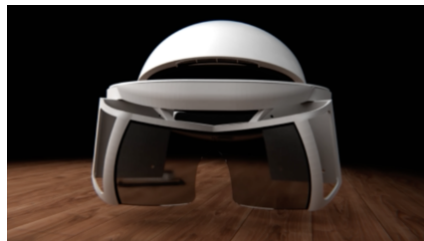
The Meta2 glasses has a similar design to the HoloLens. It has a completely transparent front face and uses half-silver mirrors to reflect the images from LCD screens towards the users eyes. The device also has a larger FOV of 90° potentially allowing users to see more within the environment and feel more immersed. An array of cameras and other sensors are built into the device, meaning that it is also capable of inside-out style tracking. However, this devices is not standalone and needs to be connected to a computer to function, reducing the amount of space the device can use.



(a) The Microsoft HoloLens [75].



(b) Meta2 Augmented Reality Glasses [74].



(c) Concept Image of Project Northstar [109].



(d) Magic Leap One promotional Image [113].

**Figure 2.10:** Mixed Reality Headsets

Another Open-source AR device is currently under development by Leap Motion. This device, codenamed Project North Star, combines AR technology with Leap Motion’s hand tracking system to enable more seamless interactions with the virtual world. The device uses two

displays, each with a resolution of 1600x1440 and refresh rate of 120 frames per second (FPS). These displays provide a combined FOV of over 200° which is much larger than the HoloLens, Magic Leap, and Meta 2 AR glasses.

**Table 2.2:** A comparison of the Specifications of four MR HMDs

Device Specifications				
	<b>Microsoft HoloLens</b>	<b>Magic Leap One</b>	<b>Meta 2</b>	<b>Project NorthStar</b>
<b>Display Type</b>	Waveguide	Light field	LCD	LCD
<b>Field of View</b>	35°	50°	90°	200°
<b>Standalone</b>	✓	✓	✗	✗
<b>Tracking</b>	Inside-Out	Inside-Out	SLAM	Infra-red

## Mobile

As mobile phones have grown more and more powerful, their capabilities have also greatly improved. As mentioned in Section 2.3.2, mobile phone has already been used to view VR experiences using special viewers like the daydream or GearVR. Multiple mobile-based AR software development kits (SDKs) have been developed.

Vuforia is a marker-based AR SDK. It uses the built-in camera and computer vision techniques to detect and track markers and simple 3D objects placed within an environment. The targets can then be used to place objects within the environment. The objects are orientated to the targets so the users perspective changes as they move around the object.

Google released an AR SDK called ARCore [6]. This SDK was based on Project Tango, one of their previous research projects [103]. Project Tango was initially designed to use phones that contained a depth camera as well as the standard HD camera. The device utilizes SLAM (Simultaneous Localization and Mapping) [11], [29] techniques to capture the environment and triangulate the devices position using data from the depth camera. ARCore uses very similar design principles to Project Tango. The main difference is that ARCore will work with just the standard camera. It does this by using SLAM and computer vision techniques to identify flat open spaces, such as floors and walls, and combines the

data with the devices gyroscope and accelerometer data to calculate its position within the environment. The SDK was designed to run on Google's Pixel 2 Smartphone, as well as some of the newer Samsung Galaxy devices. It allows the application to overlay virtual objects and information in a way that makes them appear as if they are actually within the environment, not just superimposed.

ARKit [7] is Apple's in-house AR Application Programming Interface. The API is built-in to iOS 11 and is only available for devices that hold their A9 processor or later due to the processing requirements needed to create a seamless experience. Similar to ARCore, ARKit relies on multiple sensors to create an AR scene. These include Apple's TrueDepth Camera built-in to their modern devices, Visual Inertial Odometry (VIO), which fuses the data from the camera and Core Motion sensors to "understand" its position within the environment, Scene Understanding, which uses data from the camera to detect planes and surfaces within the environment which are used to place virtual objects, and Light Estimation which allows the device to apply realistic lighting to the virtual objects.

These APIs allow for easier development of AR experiences on mobile platform.

#### **2.4.2 XR**

With the development of VR and MR devices over the last few years, the technologies and techniques required to run and develop experiences have started to become very similar. Toolkits have been developed that are designed to allow VR and MR experiences to be created with little to no configuration changes. An example of this is the Mixed Reality Toolkit (MRTK) [34], originally known as the HoloToolkit. This toolkit was initially developed by Microsoft for the HoloLens, but as the WMR devices were released, the toolkit was expanded to incorporate Immersive VR development.

Standards and Toolkits that are designed to incorporate VR and MR development are known under an umbrella term called XR. There is some debate around the meaning of the X in XR. Some suggestions have been

Extended Reality, Cross Reality, or just simply X Reality, where the X can be replaced with Virtual, Augmented, or Mixed. One example of a XR Standard is WebXR. This web-based standard was created to outline a single API that can be used by both VR and AR applications, replacing plans for a new version of the WebVR Standard. Some game engines have also updated to include the XR namespace. Since the release of version 2017.3.1f1 of the Unity game engine, the `UnityEngine.VR` namespace was changed to `UnityEngine.XR` as the namespace was all-encompassing due to it being used when developing VR, AR, and MR experiences.

## **2.5 Patient support using Virtual Reality and Mixed Reality**

VR and MR have the potential to increase the impact of rehabilitation and training as it allows scenarios and challenges to be created that would otherwise be more difficult to create safely in a real-world situation. It also allows for a task to be repeated multiple times in the same conditions and with the same parameters and can help patients to improve by tracking their progress using different metrics within the environment and displaying them to provide them with immediate visual feedback. An overview of the research into using VR and MR in rehabilitation and training is given below.

### **2.5.1 Rehabilitation**

Rehabilitation is an important part of a patients recovery process. It allows the individual to slowly regain control over different parts of their life, depending on the type of rehabilitation therapy that they are undertaking. In 2005, Rizzo *et al* [87] did a SWOT analysis of VR in rehabilitation and therapy. They stated that, at the time, the field of VR was still in the early stages of its development as many of the systems that had been developed were "proof of concept", although they did show some encouraging initial results.

VR has been used to aid in supporting patients through their recovery in many different areas of medicine. For example, a study indicated that VR could be used to aid in the reduction of phantom limb pain in lower limb amputees [3]. There has also been examples of the commercial application of using VR in rehabilitation. One example is the CAREN system, developed by the BASIC (Brain and Spinal Injury Centre) Charity [15]. It is a rehabilitation tool that uses a LVD and omni-directional treadmill to allow users to move within a video game style environment. The users are "forced" to use atrophied muscles and are taught the necessary skills needed to recover quickly from brain or spinal injuries and other disorders. Another is ImmersiCare [47], which is an immersive VR healthcare application designed to improve the mood and wellbeing of residents in elderly care homes. This system uses the Oculus Rift headset and Touch controllers with a VR-Ready laptop so it can be moved around within the care-home and taken to the users.

### **Stroke**

A specific example of when rehabilitation is necessary is helping with the recovery process of people who have suffered a stroke. According to statistics provided by the Stroke Association, more than 100,000 strokes occur every year, and 1.2 million survivors currently live within the UK [98]. There are currently two known types of stroke, the most common of which is ischemic, which is caused by a blood clot that either forms in one of the blood vessels that supplies the brain (Thrombotic Stroke), or forms somewhere else in the body, most commonly in the heart, and travels in to the brain and gets lodged in a blood vessel (Embolic Stroke). The other type is haemorrhagic, which are caused by either a brain aneurysm that has burst (Subarachnoid Haemorrhage) or weakened blood vessel that has broken and started leaking (Intracerebral Haemorrhage).

How someone is affected by a stroke is entirely dependent on which parts of brain have been affected. Common conditions that can develop post-stroke include paralysis of one or more parts of their body, hemiparesis which is weakness of one entire side of the body, fatigue,



seizures, visual impairment, an inability to speak, read or write (Aphasia), and issues with problem solving, memory and task sequencing (Vascular Dementia). The brain has the ability to form and reorganize synaptic connections, called neuroplasticity, and is done in response to different events such as experiences, learning, or following injury.

VR has been applied to stroke rehabilitation, but it has mainly been used for physical rehabilitation. Over the years, there has been a range of studies conducted to determine the feasibility [96], [99], [116], usability [19], effectiveness [13] and efficacy [23], [68], [104] of VR in stroke rehabilitation. In 2017, A review of VR for stroke rehabilitation was published in the Cochrane Journal by Laver *et al.* [65]. This review was an update to the two papers that they had published previously [63], [64]. In this update, they analysed the data from 72 studies, which included the studies from the other papers as well as an additional 35 new studies, all of which included a total of 2470 participants. The sample sizes that were used in these studies were generally small, and the interventions varied in terms of the goal of the study and the VR equipment that was used. The authors summarize by saying that VR in upper-limb rehabilitation provided no additional benefit. However, it does provide benefit in upper-limb and ADLs if used in conjunction with the normal care process, effectively increasing overall therapy time. There is insufficient evidence from these studies to make conclusions about VR in terms of gait speed, balance, participation, and quality of life. Increased therapy hours and customizable VR applications were preferable in the studies analysed, however, no statistically significant findings were present. Many different studies have been conducted that use VR in stroke rehabilitation to aid in parts of the recovery process. Five different factors that affect the experiences of acute stroke patients using VR for rehabilitation were identified by Lee *et al.* [67]. The factors stated were (1) Ease of following directions, (2) Experience of pain, (3) Scores achieved, (4) Novelty and Immediate Feedback, and (5) Self-perceived effectiveness. They stated that the patient perceived difficulty of the rehabilitation depended on the mode of training and the phase of recovery that the patient was

in. They summarize that any VR training would need to be "levelled" or "graded" to account for the difference between patients to decrease the perceived difficulty of the rehabilitation. A study by Lledó *et al.* [70] showed that when doing rehabilitation tasks using a robotic arm and standard monitor, there is very little difference between using 2D and 3D imagery in upper-limb rehabilitation. Other research has also been conducted around using VR for upper-limb rehabilitation [12] and sitting balance [20], [94].

In the context of ADLs, the use of VR to help with cognitive rehabilitation has been researched, although not to the same extent as physical rehabilitation. There has been research conducted in this area to test the efficacy of using VR for cognitive and motor rehabilitation [14]. Faria *et al.* [31] conducted a study that compared a virtual rehabilitation city, called Reh@City, with the traditional pen-and-paper based methods. Within the virtual city, the participants were able to complete tasks that incorporated different cognitive challenges that would test their memory, attention, visuo-spatial abilities and executive functions. Each of the task also incorporated levels of difficulty, through the use of disappearing prompts, to increase the value of training. Eighteen participants took part in the study, randomly split into two groups of nine each. Both groups undertook four to six weeks of intervention, each session lasting twenty minutes, with one group having sessions using the VR city, and the other using traditional methods. Results from the study showed that the group that used the VR system show significant improvement in their overall recovery, as well as in memory, attention, executive function, and other areas, compared to the control group who only showed a small amount of improvement in memory and social-participation. Another study [60] looked at the effect of VR training combined with computer-based cognitive rehabilitation on the recovery of the cognitive impairment of stroke patients compared to just computer-based rehabilitation on its own. Twenty-eight patients with cognitive impairment took part in the study. The participants were split into two groups, fifteen received VR and Computer-based rehabilitation, while the other thirteen received only

the latter. Each of the participants were evaluated before rehabilitation, and four weeks after the study rehabilitation. Several tools were used to conduct the evaluations, including the Tower of London (TOL) test for cognitive function [93], which requires patients to solve problems using pegs and beads, Korean-Modified Barthel Index (K-MBI) for functional status [57], and Motricity Index (MI) for motor function. The results from the study did show that using VR along side computer-based cognitive rehabilitation did provide some additional benefits for treating cognitive impairment. A study conducted by Kyoung-Hee Lee [66] tested the effects of VR rehabilitation on cognitive function and patients ability to complete ADLs. Ten patients had their abilities assessed before training, then received thirty minute VR therapy sessions, three times a week for four weeks and were assessed again after the four week period. The results from the study showed significant improvement after the four week training period.

The studies that have been conducted in both physical and cognitive rehabilitation often do not use immersive VR HMDs to view the virtual content. They refer to VR as the use of a standard PC monitor or a television to view a virtual environment, and the participants interact with it using a joystick, controller, or other body tracking technology, providing a non-immersive experience. Cognitive rehabilitation using immersive VR HMDs is a relatively unknown area, mainly due to the fact that modern VR HMDs have only been commercially available since 2016.

Research has also been conducted around using MR in stroke rehabilitation. Colomer *et al* [21] created a portable, table-top application that transformed a conventional table into a virtual environment and allowed for a wide range of custom arm, hand, and finger exercises. The system allowed users to interact with tangible objects while providing audio-visual feedback. Results from their effectiveness study showed significant improvement after the MR-based intervention. Participants also reported that the application was enjoyable and motivating. Duff *et*

*al* [28] also created an MR application that was designed to improve the reaching movements of stroke patients with hemiparesis. The system provided real-time, multimodal, customizable and adaptive feedback to the user while they are doing the reaching exercises. A study was conducted to test the feasibility of the system and the results showed that the system was widely accepted and had the potential to be a useful tool for enhancing stroke rehabilitation. Another MR application was created by Aung *et al* [8] for upper limb rehabilitation using a virtual arm illusion. The system combined AR, computer vision, 3d modelling and signal processing to create a serious game for practicing upper limb exercise. A validation study was conducted that showed positive results and indicated that this approach could be effective for upper-limb rehabilitation.

Some studies also tested the effect of using AR systems on patient motivation to take part in the therapy sessions. The work done by Vidrios *et al* [110] is an example of this. They created a robot-assisted motor rehabilitation system that combined AR and a haptic interface to improve the fine movement of patients with upper-limb motor deficits. The system used visual and tactile stimulants to improve the motivation of the patients as well as monitoring their performance. A pilot study showed that users were very pleased with the system. Another is an AR-based serious game framework was developed by Hossain *et al* [44] that was designed to aid in the rehabilitation of post-stroke patients by improving their motivation to take part in the therapy sessions. A validation study was conducted to assess the suitability and utility of the framework by comparing the performance of stroke patients against healthy volunteers. Results from the study showed that the serious games framework was well accepted by the patients.

### **2.5.2 Training**

Training is another important part of the recovery process as it helps patients relearn skills that they may no longer be able to do, or learn new skills that can help them regain their independence. Training and skills

transfer can also help with tasks that the patients haven't practiced by teaching them necessary underlying skills like logical reasoning, problem solving and task sequencing.

In terms of Skills transfer, there has been research conducted that demonstrated positive results. Seymour *et al* [92] looked at using VR training to improve the accuracy of surgeons in the operating theatre. Their results showed that there was significant increase in the performance of residents during laparoscopic cholecystectomy.

Many researchers have investigated the potential of using VR for training and the potential transfer of motor skills. A comprehensive review was conducted by Molina *et al* [78] on the use of VR-based gaming for rehabilitating physical exercises for older adults. They highlight the need for further investigation in to the potential benefits of VR training compared to the traditional methods. Another review was done by Adamovich *et al* [2] who looked at studies that used VR in sensorimotor training for neurorehabilitation up to 2009. They argue that VR may be an optimal tool for designing and creating environments that would be otherwise difficult to recreate in real life. They state that VR can provide a way of automatically modulating the difficulty of the tasks that are used in the training scenarios, as well as high levels of engagement and motivation. De Bruin *et al* [17] explored how VR could be used to train motor skills through dancing for older adults. They found that VR offered a safe environment for the training to occur, with the opportunity for independent exploration and consistent delivery of therapeutic protocols. In terms of sports training, Miles *et al* [76] tested the efficacy of using a virtual environment for training ball passing skills needed to play rugby. A system was developed that used a LVD and tracked rugby ball to enable the system to simulate the projected path and distance covered by the ball based on the user's throw. Two studies were conducted to test their system, one of which compared different combinations of the physical position of the user, the stereoscopic presentation of the application, and the use of a floor screen to extend the FoV of the virtual screen to see

if they had an effect on the training. Results from the studies showed that only the physical position of the user affected the distance that they threw the ball, not the simulated distance of the targets.

### **Medical Training**

VR has also been used in training for different areas of medicine. A review was conducted in 2005 by Gallagher *et al* [33] looked at surgical education, human-factors and psychological literature that could have an effect on the adoption and integration of VR training in surgical training programs for minimally invasive surgeries. The outcome of the review stated that VR would be more likely to be integrated if it was systematically incorporated into training programs that assess the improvement of the technical skills of surgeons in relation to their learning experience. The VR training programs would also have to occur over multiple sessions during an extended period of time. Any metrics should also be relevant for the surgical task that is being practiced and will require the trainees to achieve a pre-determined level of proficiency. They also state that high-fidelity VR simulations would provide the greatest skills transfer for the surgical task, however less expensive VR would still lead to improved skill generalization.

John *et al* [55] developed a tablet-based training application called VCath to help neurosurgical residents learn how to perform the ventriculostomy procedure. A study was conducted at a boot camp for all of the first year trainees in neurosurgery in the UK to test the effectiveness of this application. The attendees were randomly allocated between a control group, and a group that received some training with the application. The performance of each trainee completing the procedure was tested before and after their training sessions and the difference between their performance on both tests was analysed. The results showed that there was significant improvements in the trainees performance when performing the procedure after they used the VCath application compared to the control group. They conclude by saying that cognitive task based education for straight-line trajectory procedures

is a useful addition to traditional training methods and may reduce the learning curve of learning procedures like ventriculostomy. Luboz *et al* [71] created a VR training application for practicing the Seldinger technique, the first step of many interventional radiology procedures. The system consisted of two workstations, one simulated a pulse for practicing the needle guidance using palpation in a virtual environment, and the other used two haptic devices provide an interface for using a needle to guide a guidewire and catheter within the vessel using virtual fluoroscopy. A validation study conducted using this system showed effective training and skills transfer. Larsen *et al* [62] conducted a study to test the effect of VR training on learning laparoscopic operations. Results from the study showed that participants who received VR training achieved a median score of 33, which was the equivalent experience of 20-50 laparoscopic procedures, which is much higher than that of the control who only obtained a median score of 23 (less than five procedures). They state that these results do show that VR training can increase the skill required for laparoscopic procedures, with the performance level of the novices increased to that of an intermediately experienced surgeon and halved the time needed to complete the procedure.

MR trainers for medical procedures have also been developed. Sielhorst *et al* [95] presented an AR extension to their previous birth training simulator. The original simulator comprised direct haptic and auditory feedback, and provided important physiological data that was necessary for training physicians. The extension addresses issues with the in-direct viewing of the virtual content used in the original by converting it into an *in-situ* visualization. They state that the addition of the *in-situ* AR visualization increased the efficiency of the training simulation because the physician can focus directly on the vaginal delivery rather than a remote computer screen.

## Powered Wheelchair Manoeuvres

A specific training example investigated in this thesis is how to learn to manoeuvre a powered wheelchair. The ability to use a wheelchair is very important to those who have either a physical or cognitive impairment that makes it difficult for them to walk. It enables them to get around with little to no assistance from others, allowing them to return to a state similar to before impairment.

In 2004, Grant *et al* [36] reviewed the current state of wheelchair simulation technologies, looking particularly at the strengths of the idea and any potential future developments and opportunities that could be undertaken. The applications that they covered included manual and powered wheelchair simulation, assistive technologies, wheelchair control interface designs, cognitive development, and virtual environment design.

In 2009, a comprehensive review was conducted by Pithon *et al* [84]. The studies that were reviewed focussed on wheelchair simulator characteristics according to a user centered view, driven by perception and interaction, and wheelchair behaviour simulation. All of the studies showed some evidence that the use of VR in training could be effective and increase the motivation of the users but there was evidence to suggest that the behaviour of the wheelchairs within the virtual environment needed to be improved. VR wheelchair training has been taking place since the late 1990s but the limitations of the technology were hampering the capabilities of the environment. Inman *et al* [48] developed environments that were entertaining for children to use to improve their motivation. They demonstrated that some aspects of the driving skill of the children was improved through the use of the VR wheelchair training system. It was also noted that the children preferred to view the environment via a large monitor rather than a HMD, although this could have been due to the inferior resolution of the HMD compared to the large monitor at the time. Studies by Desbonnet *et al* [25] and



Linden *et al* [69] both show evidence of the efficacy and value of VR-based wheelchair training for children.

A recent review into using virtual technologies for wheelchair training was conducted by Lam *et al* [61]. The review included ten studies that met their inclusion criteria, out of 4994 that were initially identified from a range of sources. They state that given the positive outcomes from the most of the studies that they reviewed, VT could be a solution to help alleviate the barriers that are present around wheelchair skills training and could subsequently improve wheelchair users skills.

A study carried out by Harrison *et al* [38] explored the use of VR in the assessment and training of powered wheelchair users. The system they developed used a standard monitor to display a virtual environment, that consisted of a large room filled with several tables and chairs that the user would navigate around using a game joystick or a wheelchair joystick. The study used able-bodied participants and included experienced and inexperienced wheelchair users. During the study, the participants were required to complete several different challenges within the environment. These challenges included (1) driving the chair forward in a straight line for 10 meters, (2) reversing the chair into and out of an enclosed space, (3) completing a 180° turn around a stationary object, (4) navigating a slalom, and (5) stopping the chair suddenly on command. All of the participants were allowed to familiarize themselves with the controls for the VR trainer, but only the experienced participants were allowed to explore a real world environment before using the VR environment. The results from the study showed that the participants completed the real world course faster than the VR course. They also reported that the participants performed the best on the straight line task, and worst on the slalom, due to the need for fine control of the wheelchair. They concluded that for VR wheelchair training to be effective, the environment needs to be less challenging than the real-world equivalent. A simulator called WheelchairNET was created by Inman *et al* [49] that was designed to help orthopedically challenged individuals learn how to use a powered

wheelchair in a safe and effective manor. This was achieved by allowing the users to practice powered wheelchair manoeuvres in three different virtual environments. The simulation was mainly controlled using the arrow keys and was viewed using a computer monitor with a first person perspective of the environment. The user also had the ability to pan their perspective up and down so they can bring the virtual legs into view. Results from the study suggested that the skills of the participants improved over the training time and all of the participants who completed the study showed gains in driving skills, as indexed in the real world. They stated the results were significant and supported their hypothesis that children with severe orthopaedic disabilities can acquire important functional skills in VR without the risks associated with learning in the real world. A wheelchair training application was designed by Stredney *et al* for use by (1) Architects and designers to help them visualize structures to help improve the accessibility of their building designs, (2) wheelchair users to provide a more appropriate device fitting and training method, and (3) health-care professionals to provide a way to evaluate wheelchair skill [100]. The system used a 3D-capable monitor and stereo glasses to view the environment, with a powered wheelchair connected to the graphics workstation to pass accurate, real-time data to the simulator so the user could move within the virtual environment. The authors had the option to use a VR HMD at the time, but chose not to as they were too expensive and cumbersome, while stereo glasses were easily available and cheap in comparison.

## **2.6 Methodology for VR Human Factors Studies**

According to Stanney *et al.* [97], there are three areas of human factors that affect the use of VR. These are Health and Safety, Social Implications and Human performance efficiency. Human factors studies follow a particular structure:

1. Develop the Focus of the Study
2. Develop the Experimental Protocol

3. Subject Recruitment
4. Data Collection
5. Data Analysis

This structure helps in the process of designing and running Human Factors studies, as well as the data capture and analysis of the study data, by providing a possible outline for the study that researchers can use throughout the process. Each phase of the structure helps with important parts of the studies.

### **2.6.1 Develop the Focus of the Study**

In the "Develop Focus" phase, the purpose and type of the study are outlined. This is whether the study will be a qualitative, semi-quantitative or quantitative studies. At this stage, the hypothesis for the study is also devised.

### **2.6.2 Develop the Experimental Protocol**

Once the hypothesis of the study has been determined, the study is then designed to try and provide an answer to the hypothesis. This includes how long the study will take, how many sessions there will be over the study period, either overall or per day. The data that will be captured during the study, how the data will be collected, and how the data will be stored during and after the study is also outlined at this stage.

### **2.6.3 Subject Recruitment**

During subject recruitment, the minimum number of participants needed to obtain a statistically significant result is calculated, usually by means of a power calculation. Once the number of participants required has been calculated, the method with which the population will be sampled to obtain the participants is chosen.

### **Sampling Techniques**

There are different techniques that can be used to select the participants to include in a study. These can be split into two different categories, probability and non probability sampling techniques.

Probability sampling techniques employ randomization to allow each member of a population to have an equal chance of being selected. This method of sampling includes simple random sampling, every participant in a population has an even chance of being selected, stratified sampling, population is split into groups and participants are proportionately selected from all groups, systematic sampling, a random member of the population is chosen and any subsequent participants are selected based on a sampling interval from the initial participant, and cluster sampling, the population is split into clusters and a random sample of the clusters are chosen.

Non-probability sampling techniques do not rely on randomization of the population before selecting a sample. This can have the benefit of increasing the sampling speed and reducing cost in terms of time or effort, but does rely on the researchers ability to select members from a population equally and may cause a bias in the data. There are several different techniques that come under non-probability based sampling. These include Convenience Sampling, sampling based on the availability of participants, Purposive Sampling, sampling based on characteristics, and Referral or Snowball Sampling, sampling by participants referring others to the researchers.

After the population has been sampled, and the participants have been selected and invited to participate in the study, they go through a screening process to determine their suitability for the study, they are asked to sign any consent forms and other forms associated with the study, as well as being assigned a unique identifier and exposed to the technology that is being used for the study.

#### **2.6.4 Data Collection**

The method for data collection is specific to each study. VR can sample much larger quantities of data and at higher temporal density than classical paper-and-pencil methods. The data and measurements that are collected during the study need to follow several rules. The measurements needs to be sensitive (results can be distinguished

between a novice and expert), reliable (data is repeatable and consistent), and valid (data is representative of the real world). Data that has been recorded online can also be played back during task debriefing and researchers do not have to be co-located with the subjects (remote measurements). Once the data collection has been finished and the study concluded, the data needs to be analysed. Human factors studies store different variables, depending on the type of test:

- task completion time: time needed to finish the task (system time, sequence of actions, or stopwatch)
- task error rate: number or percentage of errors done during a trial
- task learning: a decrease in error rate, or completion time over a series of trials

### **2.6.5 Data Analysis**

Data analysis typically requires appropriate statistical techniques to be applied to the collected data. There are two main subsets of statistical tests, parametric and non-parametric. The difference between these two is that a parametric test assumes that the data follows a probability distribution based on a set of parameters, where as non-parametric testing does not.

Parametric tests are used to analyse group means. Examples of parametric analysis methods include t-tests and ANOVAs. t-tests are defined as a type of inferential statistics that is used to determine significance between two group means that may be related in some way. These tests are used as a hypothesis testing tools and is normally used with data that follows a normal distribution and may have unknown variances in the data. t-tests can be split into three different types, Correlated (Paired), Equal Variance (Pooled), and Unequal Variance. The Correlated (Paired) t-test is performed when the samples typically consist of matching pairs, such as data from a single patient before and after treatment, or when the samples are related or have matching characteristics, such as a comparative analysis of children, siblings or

parents. This test is categorized as a dependent test as it is used for related datasets. Equal and Unequal Variance t-tests are categorized as Independent tests. These tests are used when the data is unrelated from each other, such as two groups who have undergone different treatments, e.g. a control group and group who used a new form of therapy. The main difference between these tests is that unequal variance test is used when the number of patients and the amount of variance is different between the groups.

Analysis of Variance (ANOVA) is a collection of statistical models designed to analyze differences among group means in a sample. ANOVA is very similar to two sample t-tests but is designed to analyse the results from three or more groups, and produces fewer type I errors. A Type I error is defined as the rejection of a true null hypothesis and is more commonly known as a "False Positive" finding. ANOVAs allow for one (One-way) or multiple (Two-way) Independent variables to be taken in to account when analysing data from an experiment. In a One-way ANOVA, the Independent variable (IV) can have two levels that affect the dependent variable. For example, the IV could be group, and the levels would be the different groups in the experiment. In Two-way, there can be multiple IVs, each with their own different levels, allowing for a wider range of variables and comparisons on the same dataset. Two-way can also be defined as with replication, as in members of the groups doing multiple tests, or without replication, where you are double-testing a single group such as before and after.

Non-parametric tests analyse group medians. Mann-Whitney and Friedman are examples of non-parametric tests. The Mann-Whitney U test is the non-parametric equivalent of an Independent t-test. This test is used to test whether two sample means from the same population are equal or not, and is used when the data is either ordinal or the assumptions of a t-test are not met. There are several assumptions to take note of when using Mann-Whitney, the sample that is drawn from the population is random, independence within the samples and mutual

independence is assumed and an ordinal measurement scale is also assumed.

Spearman's Rank Correlation Coefficient is another non-parametric statistical test. It is a statistical measure of the strength of a monotonic relationship between paired data. A monotonic relationship or function is one that either never increases or never decreases as its independent variable increases. This means that when the independent variable increases, the paired variable either increases with the independent variable or decreases, but never both increases and decreases. The test is commonly used when the data is ordinal, interval or ratio, and there is no linear relationship between the data.

### **2.6.6 Examples of Data Analysis in VR Studies**

A study to test the efficacy of a Ventricular Catheterisation Tablet application called VCath, conducted by John *et al.* [55], demonstrated a similar design strategy to the Human Factors strategy mentioned previously. After the study was designed and the hypothesis was set, the study used the Convenience sampling technique to recruit participants at a Neurosurgical boot camp that was attended by all year one trainees in neurosurgery in the UK. The participants were screened, with four being excluded due to previous exposure to the application, provided with a consent form and randomly split into two groups. The performance of the participants was tested before and after the study to determine their improvement. Once they collected the data, they analysed it using several different statistical tests. Probability plots were used to determine if the data followed a normal distribution, if they did, then the researchers used two tailed t-tests to analyse the data, otherwise the Mann-Whitney test was used.

A study conducted by Larsen *et al.* [62] looked at the effect of VR on laparoscopic surgery. The researchers used the convenience sampling technique, taking from a population of gynaecological trainees (Years 1 and 2) that have had no prior advanced laparoscopic training or experience in the Zeeland region of Denmark. The participants

were randomized using a stratified randomization strategy based on their previous experience with laparoscopic procedures using a single instrument. The researchers used a non-parametric statistical method, Mann-Whitney U test, to analyse the cumulative median scores, the average score of two observers, obtained from the study data.

Once Linden *et al* [69] had decided on a randomized control trial, they used a convenience sampling technique to obtain participant from a population of local school children who were aged 5 to 7 and had no physical or cognitive impairment. The participants were randomly assigned to one of two groups, maintaining an even distribution between the groups. The baseline performance of the participants was analysed using a chi-square test. An ANOVA was then used to analyse the within and between differences between the groups. Spearman's Rank Correlation Coefficient was also used to analyse difference between gender, vision and pre-training scores due to the non-parametric nature of some of the data.

Mahajan *et al*. [72] used a convenience sampling technique in a study to recruit from a population of 18 to 80 year olds who use powered or attendant-propelled wheelchairs, and had the basic cognitive, visual, and motor-skills needed to interact with an interface. Participants were screened based on having sufficient short-term memory, an ability to perceive the motion in the virtual world, and ability to tap or hit the joystick. An two-way, repeated measures ANOVA was used to analyse the data from the study.

A study to test whether a virtual reality laparoscopic training improved students performance in an operating theatre was conducted by Seymour *et al* [92]. They used a convenience sampling technique to select postgraduate surgical residents, in years 1 to 4, at the Medical Department of Yale University. They used a stratified randomization method, separating them by their year group before randomly assigning them to one of the two groups. All participants were tested before the study to determine their baseline fundamental abilities and then after the



training to . The researchers used both the chi-square and Mann-Whitney tests to analyse the data. The chi-square test was used to compare the error rate between the two groups, with the Mann-Whitney used to analyse the mean lack of progress and the mean number of scored errors per procedure between the two groups.

There have been many studies that have taken place in VR. The techniques listed above are by far the most common statistical approaches taken when analysing the data collected.

## **2.7 Summary**

Being able to complete activities of daily living is extremely important as it allows people to live independently. There has been a lot of research into using VR and MR in different areas of rehabilitation and training to support activities of daily living, such as physical and cognitive rehabilitation and training after physical trauma or stroke, but these applications tended to use normal computer monitors or a television to display a virtual environment. VR HMDs were first developed in 1968 by Ivan Sutherland [102] with the "Sword of Damocles" project [105], however, up until recently VR HMDs were very large and expensive. With the release of commercially available and affordable immersive, VR HMDs, as well as MR HMDs, in 2016 and the continued increase in the graphical power and hardware in modern computers, the possibilities of VR and MR have expanded. These new VR HMDs can provide highly immersive experiences and allow the user to gain a sense of presence, which is important for it to be effective in rehabilitation and training.

The use of immersive VR technologies in rehabilitation and training is a growing area of interest with the release of commercially available and affordable VR devices. Cognitive rehabilitation is one area that is of particular interest because the use of non-immersive VR has seen some very promising results but it could be argued that it has suffered due to a lack of immersion, which could increase the rehabilitation value. Using VR to train powered wheelchair manoeuvres is another area of

interest because, at the moment, there is no formal training methods for learning how to manoeuvre a powered wheelchair, with the only training that patients receive is during their assessment at their local wheelchair centre. A potential side-effect of wheelchair training in VR however is cybersickness, as mentioned in Section 2.3.4. This could detract from the training value as it would limit how long someone could use it before feeling ill, breaking their immersion within the application and their sense of presence, and discourage them from using it again. There are different solutions for this issue, but one potentially effective solution would be to use MR, which could negate the effects of cybersickness by moving the virtual world into the real.

The following chapters detail a series of investigations that are aimed to answer the questions related to the use of VR and MR for cognitive rehabilitation and the training of powered wheelchair manoeuvres that are posed within this chapter.

## Chapter 3

# Wheelchair-VR

### **3.1 Chapter Overview**

In this chapter, the design, development, and validation of a VR powered wheelchair training simulator is outlined and the conclusions are discussed.

### **3.2 Motivation**

The first time someone starts using a powered wheelchair, they initially attend an assessment at a specialist centre where they are given an opportunity to try out a range of different wheelchair configurations to see which one fits their needs the most. The amount of time that they get to "train" in the chair is limited, and most of the users are inexperienced and not fully competent when they first take the chair home. In 2015, research conducted by Fleur Perry showed that data from the 2011 census and the 2012-13 Family Resources Survey showed that 1.9% of the population in England and Wales used wheelchairs [83]. On top of this, the demand for wheelchairs, powered wheelchairs in particular, has been growing year on year. The global market for powered wheelchairs is expected to grow up to \$6.1 billion by 2022 [37].

Learning the skills that are necessary for driving and manoeuvring a powered wheelchair can be a daunting task for people who are new to living with a wheelchair, especially those who suffer from severe, or multiple, motor limitations. There are significant challenges that are evident in the training, including the need for the users to improve their spatial awareness, reaction time, and general confidence while in the wheelchair.

Unfortunately, there is currently no common standard for training and assessment of a person's ability when manoeuvring a powered wheelchair. Most wheelchair services and centres have developed their own protocols, typically involving a driving assessment in both interior and exterior surroundings. This investigation, which is part of our overarching hypothesis, was designed to evaluate whether low-cost VR technologies can be used to supplement the current training experience of new wheelchair users, as well as providing some effective home-based training that the users can do when they are not at the assessment centre.

### **3.3 Methods and Tools**

The virtual wheelchair is modelled based on the specification of a real powered wheelchair. This section provides an overview of possible wheelchair configurations and the hardware and software used to implement Wheelchair-VR.

#### **3.3.1 Powered Wheelchair Specifications**

The simulated wheelchair within the trainer is restricted to Class 2 Wheelchairs. This class of chair is limited to a maximum speed of 4mph and can only be used on pavements when used outdoors. Class 3 Wheelchairs are classed as road legal and are capable of travelling at 8mph. However, due to this they tend to be much larger than Class 2 chairs and have extra safety features built in. The controls for a power wheelchair commonly consist of a single, proportional control joystick to control the speed and direction of the chair, as well as several buttons to control the top speed, horn, lights (if installed), etc. The control panel can be fixed to either side of the chair, depending on the requirements of the user. Other forms of controller, such as head, chin, tongue, or sip and puff, are also available depending on the needs of the wheelchair user, however these types of input were not included in this investigation.

The drive system of the wheelchair depends on which set of wheels are being powered by the motor. There are several configurations available for this class of chair:

- **Mid wheel drive** - The drive wheels sit in the middle of a set of six. This makes the chair more manoeuvrable and minimizing the turning circle. Six wheels also helps maintain the stability of the chair on slopes but performs better on solid and even ground. Not commonly used outdoors.
- **Front wheel drive** - The drive wheels are at the front of the wheelchair. This system is best for steering around tight corners and for use on uneven terrain (as the large front wheels can 'climb' over bumps and obstacles). It is more stable on slopes but can also be more difficult to steer at high speed.
- **Rear wheel drive** - The drive wheels are at the rear of the wheelchair with free motion of pivoting front caster wheels. This is the most common system. The turning circle is larger than other systems, but many people find it easier to drive in a straight line. This system also helps maintain smoothness on rough terrain. Often used with anti-tippers to keep the wheelchair from tipping backwards, as the majority of the wheelchair's weight is at the back.
- **Dual Configuration** - Wheelchairs that can switch between front and rear wheel drive.
- **Four wheel drive** - Driving force is applied to all four wheels. This configuration is the best for rough terrain and steps.

The virtual wheelchair that is used in this system can be configured to behave according to any of the above configurations. However, for the initial validation study the chair was modelled on the Spectra XTR2 rear wheel drive wheelchair (see Figure 3.6).

### 3.3.2 Hardware Components

As previously mentioned in Section 2.3, several cost-effective VR HMDs became commercially available over the last few years. At the time that this project was being developed, the Oculus Rift DK2 was the most recent VR HMD to become available and was used for the prototype. This HMD provided a low persistence OLED display, which helped reduce motion blur, with 960 x 1080 pixels per eye, up to 75Hz refresh rate, 100° field of view, and 6DOF infrared tracking system. Figure 3.1 shows the Wheelchair-VR setup in use with a participant wearing the Oculus Rift DK2.



**Figure 3.1:** The Wheelchair-VR Hardware components consist of the PC, an Oculus Rift DK2 HMD, and an Xbox controller. Insert shows the adapted joystick on the Xbox controller.

To replicate the controls on a powered wheelchair, a convenient, off-the-shelf solution was to use a PC gamepad device like an Xbox One Controller from Microsoft. One of the thumbsticks on the gamepad can be used as the control joystick for the wheelchair. To increase the face validity of this solution, a joystick grip from a real wheelchair was attached to the gamepad joystick (See Fig. 3.1). A replica of a standard joystick which was able to snap on to the joystick was also fabricated using a 3D printer. When the simulator is in use, the controller is placed on either side of the user depending on which hand is dominant.

The Wheelchair-VR application also supports the Leap Motion device (Leap Motion Inc., CA, USA) for hand tracking. This allows the user to

interact with the environment using their own hands, such as pressing buttons to activate an elevator or pushing doors open. This can help to increase the potential immersion of the simulator.

A standard 'gaming' PC or laptop is needed to run Wheelchair-VR. A powerful graphics card is also required to run the VR HMD and application.

### **3.3.3 Software Implementation**

Wheelchair-VR has been developed using the Unity 3D game development platform (Unity Technologies, San Francisco, CA). At the time that this application was developed, the Unity3D engine was one of the only engines that natively supported VR content development, as well as development for peripheral devices like the Leap Motion. The system can be run on a computer capable of supporting the Oculus Rift Headset and Gamepad Controller, such as Xbox One Controller.

#### **Wheelchair Model**

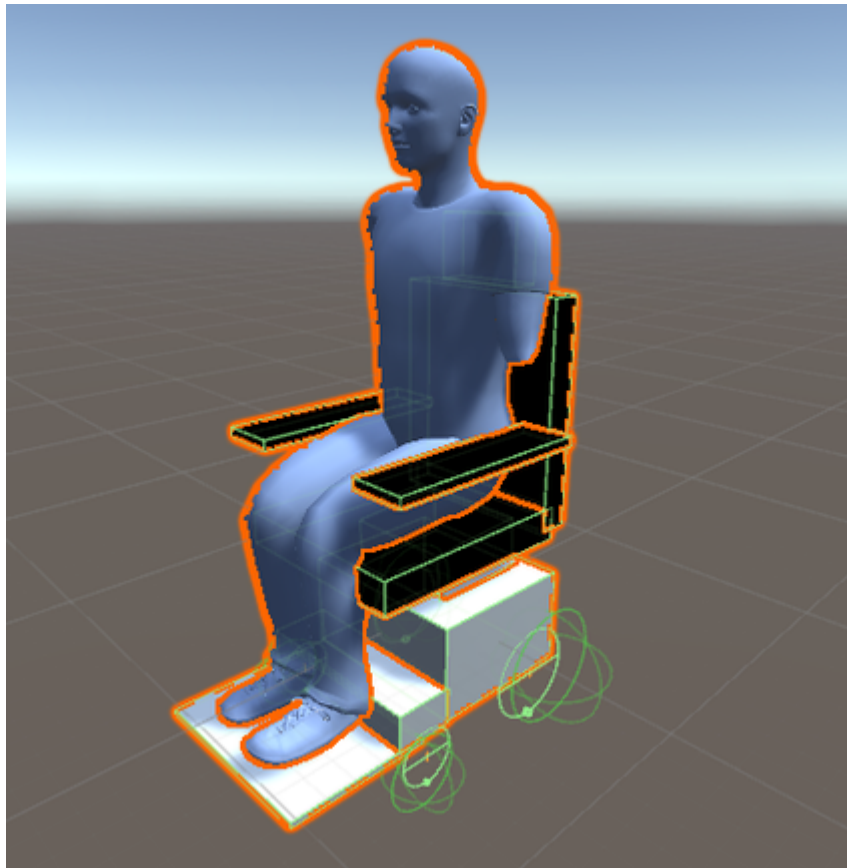
During the initial development of the chair model that was used in Wheelchair-VR, two different versions of the virtual chair were created. A physics based model and a kinematic model, each of which have their own advantages and disadvantages. Both of these virtual designs were developed by one of our collaborators and were capable of being configured to support any of the configurations mentioned in Section 3.3.1.

The initial design for the chair that was a physics-based approach. This version used a combination of different physics colliders, with the wheels being represented with tune-able wheel colliders (see Fig. 3.2). It was able to closely replicate the behaviour of a real powered wheelchair. The behaviour of the chair could be adjusted using several different parameters such as:

- **Axle Information:** Information on how many axels the chair has, which wheels are powered, etc.
- **Max Motor Torque:** Maximum amount of torque applied to wheels
- **Max Turning Speed:** Max speed while turning

- **Max Braking Force:** Maximum force applied while braking

However, the collider physics used for this approach made the chair difficult to configure correctly, and the settings for each individual component needed to be modified for each different wheelchair configuration. Doing this ensured that the different characteristics of the wheelchair, like weight distribution, friction curves, torque, and drag, were correctly allocated. If there is any disparity in any of the settings, the wheelchair would not behave in a realistic manner. It was also difficult to simulate certain aspects of commercial wheelchairs such as free-rotating caster wheels.



**Figure 3.2:** Physics based wheelchair model with wheel colliders

Due to issues that can occur when using the physics based model, a kinematic version was created that used a character controller instead of physics colliders (See Fig. 3.3). The character controller is designed to provide similar behaviour and interactions to the physics model without the use of rigid bodies. This means that the issues that occur when using



the physics collider, such as improper collisions with an object causing the user to propel away from the object unexpectedly, were removed. This approach allows for significant configuration with minimal, logical parameters such as:

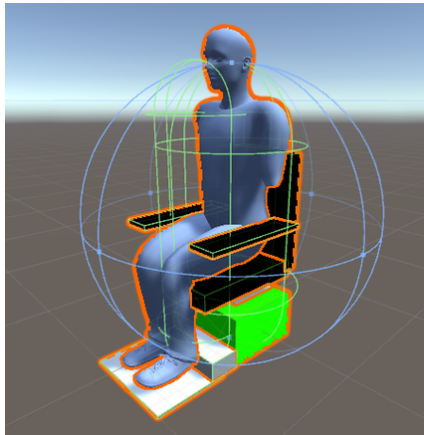
- **Slope Limit:** The maximum incline that the chair can successfully navigate
- **Pivot Centre:** The centre of pivot for the chair during a turn, allowing the simulation of rear, and centre wheel drive chairs
- **Acceleration:** The acceleration curve from zero to maximum speed
- **Turn Speed:** The rotational speed of the chair while turning
- **Stopping Speed:** How quickly the chair stops when power is no longer being applied

Changing these parameters allows different commercially available chairs and configurations to be simulated within an acceptable error margin. Fig. 3.3c shows the configuration that was initially developed for this project, Figs. 3.3a and 3.3b show configurations integrated into the simulator at a later stage which are discussed in Section 3.5. The dual configuration and four-wheel drive wheelchairs were not implemented into the environment as they are not commonly compared to the other configurations.

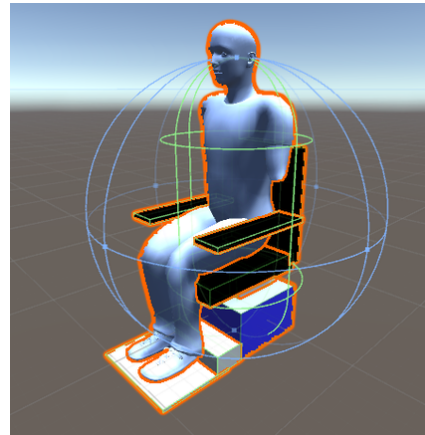
When the user is immersed in the simulator, the trainee is given a first person view of the scene from the perspective of sitting in the virtual wheelchair model (see Fig. 3.4). If the trainee looked down, they would see virtual legs in the position where their real legs would be. This helps increase the immersion of the simulator and provides the user with familiar point of reference.

### **Training Tasks**

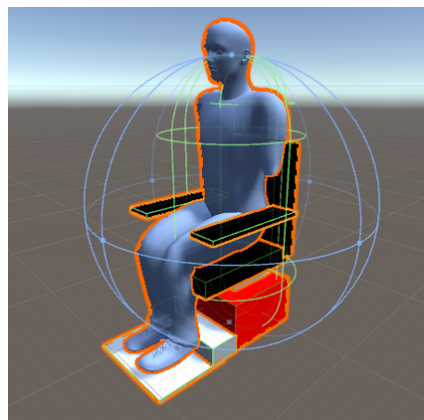
A series of different tasks and scenarios are available within the virtual environment. Each of these tasks are based on skills that are needed when manoeuvring a powered wheelchair. Peter Axelson *et al* wrote a



**(a)** Front wheel drive configuration.

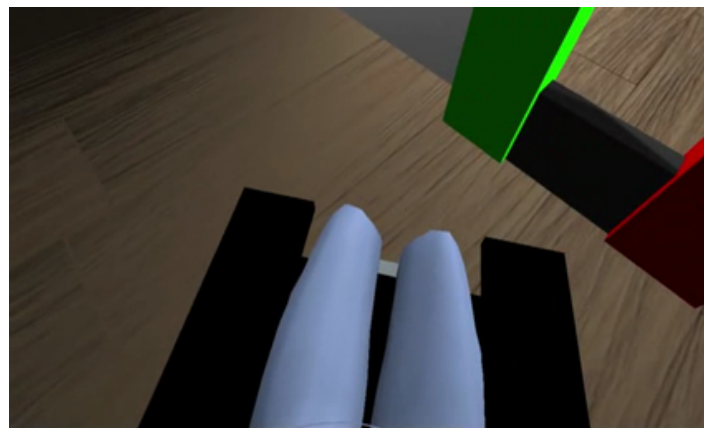


**(b)** Centre wheel drive configuration.



**(c)** Rear wheel drive configuration.

**Figure 3.3:** Kinematic Virtual Wheelchair Models



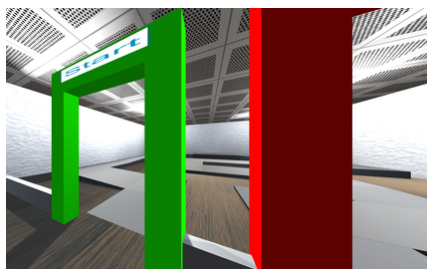
**Figure 3.4:** Wheelchair-VR provides a first person view of the scene from the perspective of sitting in a wheelchair.

guide [9] based around personal wheelchair training. All the scenarios were built in using the game engine, allowing more scenarios to be added

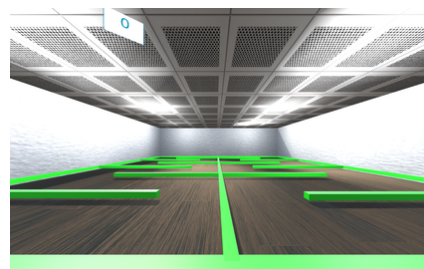
as desired. The current scenarios have been designed in collaborations with professionals from local wheelchair centres and consists of:

- Navigating through a simple maze, requiring the user to make several turns, open doors, and manoeuvre through doorways.
- Navigating through a room filled with floating red and blue balls. The trainee has to collect all of the blue balls by driving in to them (or reaching out to grab them if the LEAP Motion is being used). Collisions with the red balls must be avoided.
- Traverse a room that contains a random number of human size capsules that move around the room. This represents driving the wheelchair through a crowded room.
- Navigate through a track made up of kerbstones as quickly as possible, avoiding collisions with a kerbstone.
- A room full of ramps that must be ascended and descended. Time taken is recorded

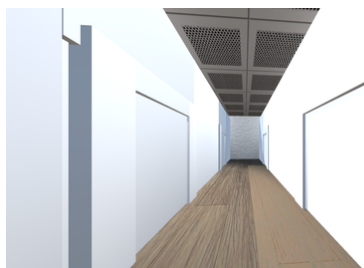
Figure 3.5 provides four example snapshots from these different scenarios.



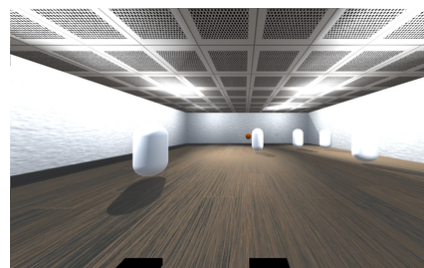
**(a)** Ramp Challenge.



**(b)** Maze of low curbs.



**(c)** Doorway Maze.



**(d)** Moving obstacles.

**Figure 3.5:** Snapshots taken from different rooms in Wheelchair-VR

Snippet 3.1 shows an example of one of the control scripts that used within the application. This script, used in the Kerbstones level, updates the colour of the kerbs when they are triggered by the user, and increases the counter on the user interface for every second they trigger the kerbs.

### **3.3.4 Testing**

A basic prototype version of Wheelchair-VR was developed during the initial stages of the project. This version was tested with subject matter experts from different regional Wheelchair centres from across the United Kingdom. The experts provided some initial face validation on the usability and functionality of the application and made some suggestions about improvements that could be made. Each expert was asked to use the application with the HMD for up to 15 minutes, in which time, they were asked to complete the different training tasks that were available. Qualitative feedback was collected from the experts. This feedback was then used to modify and improve the system.

The overall feedback that was given suggested that the certain aspects of the simulation was accurate in its operation, with the feeling of immersion, the interactions within the environment and the quality of the environment and scenarios being strong points. A series of parameters were identified that needed to be adjusted to increase the accuracy of the simulation. These included the turning and braking speeds of the wheelchair. Additional scenarios were suggested by the experts. These involved navigating tight spaces, outdoor paths with kerbs, and manoeuvring over ramps. These suggestions were considered and subsequently implemented into the application.

## **3.4 Validation Study**

A validation study was conducted to determine whether using the VR simulator had any effect on learning the skills required to safely operate a real powered wheelchair. The current way of learning how to use a powered wheelchair is a trial-and-error process of attending sessions at a wheelchair centre and reading an informational leaflet [82]. Ethical

```

public class level6Script : MonoBehaviour {
    public GameObject[] curbs; // Curb objects within the
    ↪ environment
    private TriggerScript[] scripts; // Curb Triggers
    public GameObject gui, wheelchair, tObj;
    public float count = 0, timer = 0;
    private Vector3 rot;
    void Start () {
        wheelchair = MasterControl.MC.getActiveChair();
        curbs = GameObject.FindGameObjectsWithTag ("Curb");
        scripts = new TriggerScript[curbs.Length];
        for (int i = 0; i < curbs.Length; i++) {
            scripts [i] = (TriggerScript)curbs
            ↪ [i].GetComponent<TriggerScript> ();
        }
    }
    void Update () {
        tObj.GetComponent<Text> ().text = "" + count;
        // For each curbs
        for (int i = 0; i < curbs.Length; i++) {
            if (scripts[i].getTriggered() && (timer == 0)) { // If
            ↪ wheelchair triggers the curb
                foreach (GameObject curb in curbs){
                    curb.GetComponent<MeshRenderer>().material.color =
                    ↪ Color.red; // Turn curbs red
                }
                timer = 1; // Start timer
                if (timer < 0) {
                    count++; // Increment hit counter after 1 second
                    timer = 0;
                }
            }
        }
        if (timer > 0) {
            timer -= Time.deltaTime; // Decrement the timer
        }
        if (timer <= 0) { // Reset curbs
            timer = 0;
            foreach (GameObject curb in curbs) {
                curb.GetComponent<MeshRenderer>().material.color =
                ↪ Color.green;
            }
        }
    }
}

```

**Code Snippet 3.1:** Script for controlling the curbs level and updating the environment if the user has hit the curbs

approval for the study was obtained from the University of Chester's Research Ethics Committee.

### **3.4.1 Experimental Design**

Thirty three able-bodied volunteers participated in the validation study, Seven female and twenty-six male. The participants were selected using a convenience sampling method, where the study was advertised within the Faculty of Science and Engineering and were from the current pool of students and members of staff. The age range of the participants was from 20 years old to over 60 with the majority of the participants (19) being under 29. All of the participants were beginners in the use of a powered wheelchair and had not driven one before. To ensure that all of the participants met our requirements, each were screened before taking part in the study. The iPhone app, Reaction Test Pro, created by Freedom Apps, was used to test the reaction time of each participant. Everyone managed to achieve a time of under 0.6 seconds, with the average of  $0.36 \pm 0.08$  seconds. The reaction times obtained were well within the acceptable range that was recommended to us by our collaborators at the local wheelchair centre. The participants for the study were randomly allocated to three groups of eleven. The groups consisted of:

- **Control**
- **Desktop** - Trained using the Wheelchair-VR simulator with a standard monitor
- **HMD** - Trained using the Wheelchair-VR simulator with the Oculus Rift DK2 HMD

Table 3.1 details the allocation of training for each of the groups. Both the HMD and Desktop groups used the gamepad to control the movement of the virtual wheelchair. The HMD group were able to freely look around the environment by moving their head. The desktop group were restricted to looking straight ahead, but always had a good view of the obstacles within the environment that they were navigating.

**Table 3.1:** Wheelchair-VR: Group-per-session allocation

	HMD	Desktop	Control
Obstacle Course (control)	✓	✓	✓
Training Session VR	✓		
Training Session Desktop		✓	
Obstacle Course	✓	✓	✓

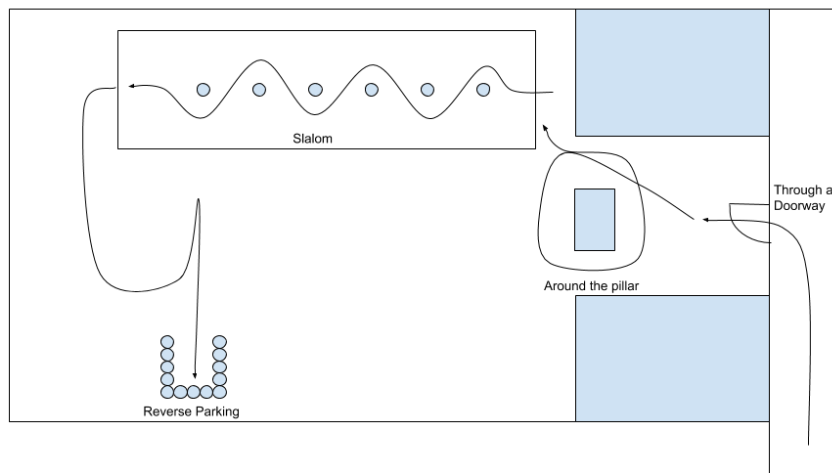


**Figure 3.6:** The Spectra XTR2 Rear Wheel Drive Wheelchair used in the Validation Study

A Spectra XTR2 rear wheel drive wheelchair was used during the study (see Fig. 3.6). The participants were asked to complete an initial run of the obstacle course to determine their baseline skill. Each section of the course was timed, with each time being combined to calculate the time over the full course. Figure 3.7 shows a design of the obstacle course and how it would be laid out within the testing area. The course consisted of four stages (see Fig. 3.8), each stage testing a particular skill needed for wheelchair usage.

1. Manoeuvring through an open door.

2. Drive the chair around a circular path, pausing to reach out and flick a wall mounted light switch.
3. A slalom course through six cones, placed 1m apart.
4. Reverse parking the wheelchair into a tight area marked out by cones.



**Figure 3.7:** Layout of the obstacle Course used

A time penalty of one second was added for any cone that was hit by the wheelchair. To ensure that the chair was configured correctly for the user, the control module was mounted on the left or right arm of the wheelchair depending on the handedness of the participant.

After the participants completed their initial timed run of the obstacle course, those in the HMD and Desktop groups received their respective training sessions. They were required to complete four of the different training scenarios described in Section 3.3.3. The Xbox controller used for the simulator was placed in the appropriate position based on the handedness of the participant. They were allowed to complete the four scenarios in their own time but nobody required more than 10 minutes to complete the training. The HMD group also completed a Simulator





**Figure 3.8:** The four sections of the timed obstacle course. Top Left - Navigating a doorway. Top Right - Traversing a circular path and using a light switch. Bottom Left - Slalom Course. Bottom Right - Reverse Parking

Sickness Questionnaire (SSQ) before and after the training session so that any occurrence of cybersickness could be recorded and analysed [59]. The participants in the HMD group were also told that they could remove the HMD at any point if their levels of discomfort from using the simulator became too much to continue with the training. The control group were not given any training. Instead, they were asked to read through a guide

to using an electric wheelchair safely [82]. The group were given ten minutes to read through the guide. None of the participants in any of the groups were allowed any extra time in the wheelchair between their two attempts of the obstacles.

Once their training was finished, all of the participants completed the obstacle course in the Spectra a second time, with the time taken and number of cones hit recorded again.

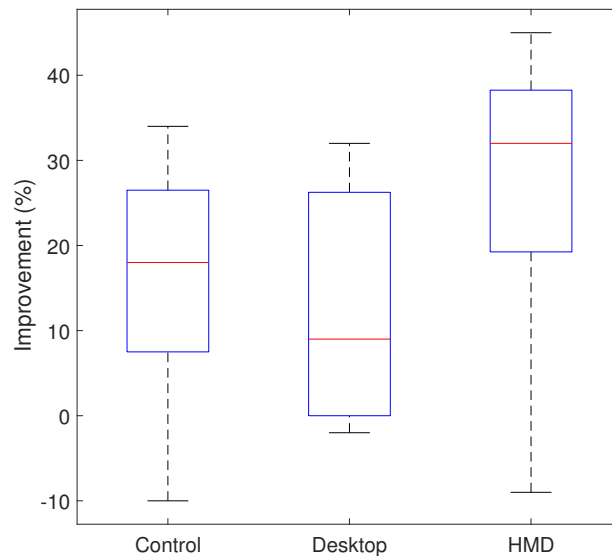
### **3.4.2 Results**

The overall timings from the first run of the course were analysed using a one-way analysis of variance (ANOVA) statistical model to confirm that there were no significant difference between the three groups (group  $p = 0.285$ ). Probability plots also confirmed that the data values did follow a normal distribution.

To determine any improvement in the driving ability of the individual participants, i.e. less time taken to complete the course and less obstacles hit during their run, an *improvement parameter* was defined. This parameter was the difference between the recorded time of each run of the course, both per stage and overall, divided by the absolute maximum value of the two runs. This normalized parameter was expressed as a percentage, with the sign denoting whether the participants was better or worse on the second run of the course. The data was initially visualized in a box plot (see Fig. 3.9) to indicate whether any difference could be found between the groups over the entire course. The plot did show that the HMD group improved more on their second run when compared to the other two groups. Because of this, a one-way ANOVA was performed on the data to retrieve any significant differences between the groups. A one-way ANOVA was carried out to determine the statistical significance of the data. A contrast analysis was also performed to determine the difference between the HMD and other two groups both separately and combined.

The ANOVA for the improvement across the entire course produced a  $p$ -value of 0.083 for the comparison between the three groups. The

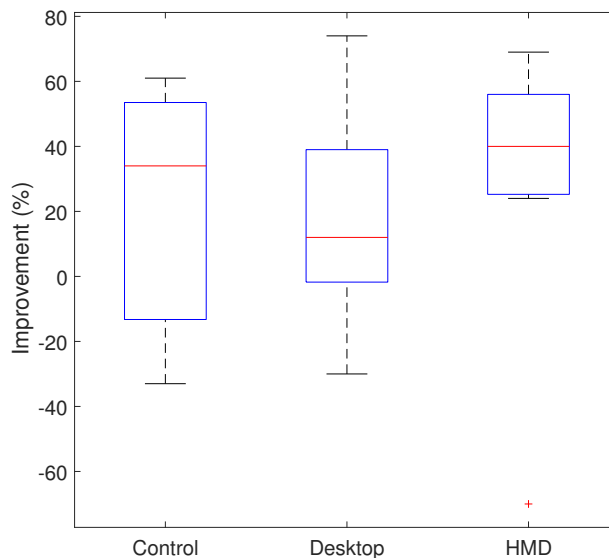
contrast analysis produced two significant results at the 5% level: HMD vs Desktop ( $p = 0.034$ ), and HMD vs Combined (Desktop and Control) ( $p = 0.030$ ).



**Figure 3.9:** The improvement across the whole obstacle course. The median is indicated by the red horizontal line.

The data from each of the stages were also visualized in box-plots to indicate any possible difference between the groups. If the plot indicated any difference, a one-way ANOVA was carried out to determine the significance of the data for each individual section of the obstacle course. The results of the ANOVA was also used to determine which were more challenging and where performance was gained the most. At the first stage of the course, each group showed a similar improvement between the runs when navigating the doorway. The initial box-plot showed that the performance of the participants largely varied between the groups (see Fig. 3.10). The ANOVA produced a group  $p$ -value of 0.496. Some of the participants improved significantly when completing the task a second time (60-70%), whereas one participant had difficulty and were stuck in the doorway (-70%). This made the standard deviation of this task quite large. With the worst performing participant removed from the analysis, the group  $p$ -value becomes 0.084, with a contrast analysis

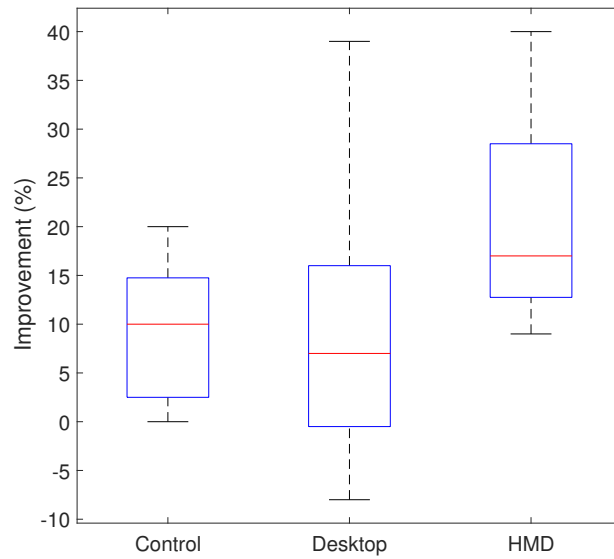
giving two significant results at the 5% level: HMD vs Desktop ( $p = 0.031$ ), and HMD vs Combined ( $p = 0.034$ ).



**Figure 3.10:** The improvement for navigating through the narrow door. Outlier with negative improvement is marked with a cross.

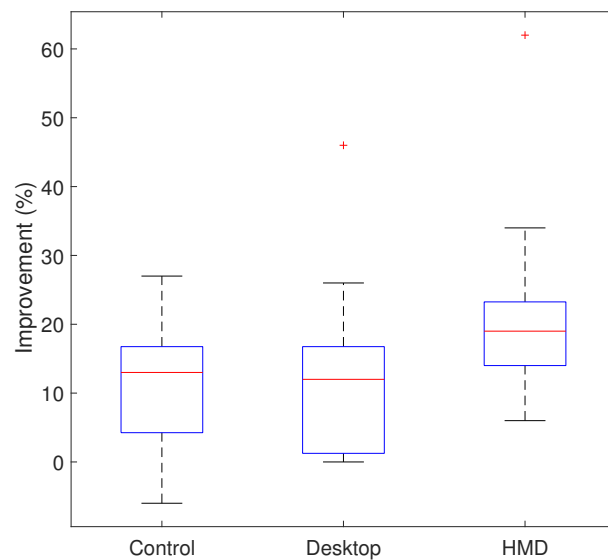
The visualization of the data from the second task can be seen in Fig. 3.11. The HMD group showed mean improvement of 20% compared to the other groups, who both improved by only 9%, when navigating around a pillar and reaching out to use a light switch. An ANOVA gives a group  $p$ -value of 0.032 and results from the contrast analysis show significance below 5%: HMD vs Control ( $p = 0.02$ ), HMD vs Desktop ( $p = 0.024$ ), and HMD vs Combined ( $p = 0.009$ ).

An initial visualization of the third stage, the slalom, can be seen in Fig. 3.12, and did indicate differences between the groups. The ANOVA of the data from the slalom shows the HMD group improved more (22%) compared to the other groups (12-13%). The  $p$ -value of the group from the analysis was 0.127. Results from a contrast analysis of the groups gave one significant value at the 5% level, HMD vs Combined which had a  $p$  of 0.046. There are two potential outliers, one in the Desktop group and one in the HMD group, who showed very large improvements for this task. If these outliers are removed from the respective groups, the



**Figure 3.11:** The improvement for the circular path with light switch

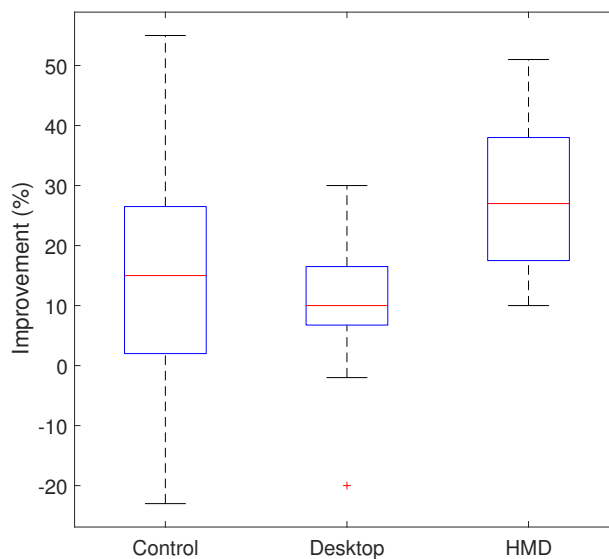
$p$ -value from the ANOVA becomes 0.061. A contrast analysis shows two significant values, HMD vs Desktop ( $p = 0.025$ ) and HMD vs Combined ( $p = 0.022$ ). This indicates that the HMD group's increased improvement compared to the other groups is a significant result below the 5% level.



**Figure 3.12:** The improvement for the slalom. Outliers are marked with a cross.

The final stage of the course was to reverse park the wheelchair in an area marked out with cones. The visualization of the data (see box plots in Fig. 3.13) indicated that differences were present between the groups. An ANOVA shows that the HMD group improved by a mean of 29% compared to the other two groups who improved by 10% and 12%. The group  $p$ -value from the analysis is 0.026 and was significant at the 5% level. The contrast analysis for this task showed several results at the 5% level: HMD vs Control ( $p = 0.027$ ), HMD vs. Desktop ( $p = 0.013$ ), and HMD vs Combined ( $p = 0.008$ ). These values indicate that the HMD group performed significantly better than the others.

Finally, with the same three outliers referred to above removed from the ANOVA, then the group  $p$ -value for the improvement across the complete obstacle course becomes 0.010.



**Figure 3.13:** The improvement for reverse parking. Outlier with negative improvement is marked with a cross.

### Simulator Sickness Questionnaire

The HMD group completed a SSQ devised by Kennedy *et. al.* [59] before and after their training sessions. This questionnaire asks the participant to rate a series of symptoms, including nausea, light-headedness, dizziness, difficulty focussing, etc. The questionnaire used a Likert

scale and used four different levels; *none* (lowest), *slight*, *moderate*, and *severe* (highest). Each of the symptoms on the questionnaire can be grouped in different symptom clusters; Nausea (N), Oculomotor (O), and Disorientation (D), along with the Total Severity (TS). The scores for each of these symptom clusters were calculated. The results are summarized in Table 3.2 for the pre-training symptoms and Table 3.3 for the post-training symptoms. Table 3.4 shows the scores ranges for each of the symptom levels (*none*, *slight*, *moderate*, *severe*).

On average, the participants reported only slight levels discomfort, with one participant in particular reporting moderate levels, in all three clusters after their training session. All of the participants in the group reported a slight increase in discomfort in at least one of the symptoms. None of the participants reported severe levels. Burping was the only symptom that was not reported by any of the participants, all 15 of the other symptoms had some increase from at least one participant after training.

Out of the symptoms that are included in the SSQ, general discomfort was the most common felt by the participants, with eight participants reporting slight or moderate increases following the training session. Six of the participants also reported that they felt a slight or moderate increase in the feeling of nausea whilst none was felt before the training. Sweating and stomach awareness were also common symptoms that were reported after the participants completed their training session. Only one participant reported an increased feelings of vertigo or salivation after the training, and two reported slight headaches.

**Table 3.2:** SSQ - Pre-training Scores

	<i>Nausea</i>	<i>Oculomotor</i>	<i>Disorientation</i>	<i>TS</i>
<b>Mean</b>	3.47	2.76	2.53	3.40
<b>SD</b>	6.43	7.01	5.63	6.78
<b>Min</b>	0.00	0.00	0.00	0.00
<b>Max</b>	19.08	22.74	13.92	22.44

**Table 3.3:** SSQ - Post-training Scores

	<i>Nausea</i>	<i>Oculomotor</i>	<i>Disorientation</i>	<i>TS</i>
<b>Mean</b>	32.96	22.74	41.76	35.36
<b>SD</b>	23.12	18.57	40.34	26.56
<b>Min</b>	9.54	0.00	0.00	3.74
<b>Max</b>	76.32	68.22	139.20	100.98

**Table 3.4:** SSQ - Reference Scores

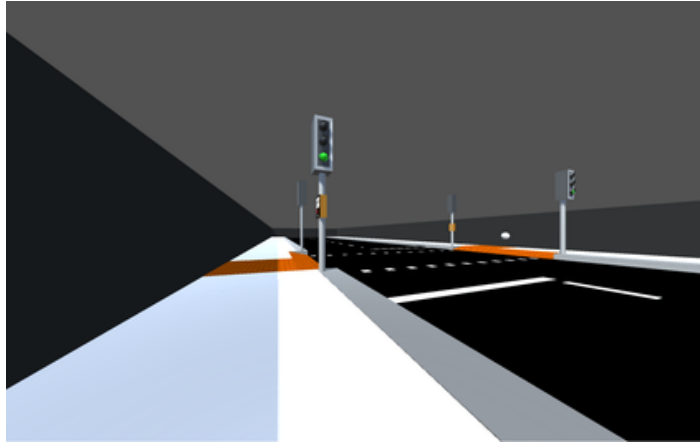
	<i>Nausea</i>	<i>Oculomotor</i>	<i>Disorientation</i>	<i>TS</i>
<b>none</b>	0	0	0	0
<b>slight</b>	66.8	53.1	97.4	78.5
<b>moderate</b>	133.6	106.1	194.9	157.1
<b>severe</b>	200.3	159.2	292.3	235.6

### 3.5 Configurations Study

As mentioned in Section 3.3, the functionality of the simulator can be extended to include multiple drive configurations for the virtual wheelchair. Two additional virtual chairs, one configured for front-wheel drive and another for centre-wheel drive, were implemented and included in the simulator to accompany the rear-wheel drive configuration that was already present (See Fig. 3.3). To increase the immersion of the simulator, sound recordings were taken from a real powered wheelchair, processed to remove excess noise, and then integrated into the virtual chair to increase the realism of the simulator. An outdoor area was also implemented to extend the simulator to include different types of scenario (See Fig. 3.14). The scenario created for this area consists of the user driving down the pavement to a puffin style crossing, interacting with the control, and then crossing at the appropriate time. Sound clips were also included for the traffic light system so the user would get a visual and audible cue as to when they are able to cross safely.

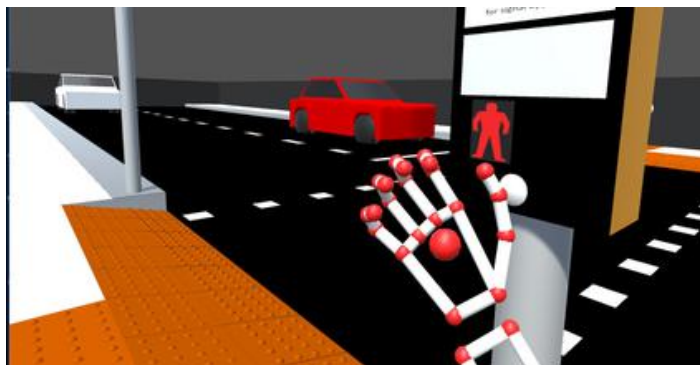
To allow the user to interact with the traffic lights, the Leap Motion hand tracking device was integrated into the simulator. This let the user use their own hand to interact with the virtual environment more naturally (See Fig. 3.15). Including hand tracking meant that the user





**Figure 3.14:** A road scene including traffic lights and moving vehicles. This scene was developed by William Dobson as part of an undergraduate project at the University of Chester.

would have to be conscious about how far they are from the controls, and how much time they have to reposition to allow them to cross the road safely.



**Figure 3.15:** The Leap Motion allowing a user to interact with the traffic lights using their own hand

A study was conducted to test whether or not a user could determine which configuration they were using, as well as whether they perform the same as the real world equivalent.

### **3.5.1 Experimental Design**

Ten able-bodied volunteers took part in this study, none of whom were experienced with using a powered wheelchair. They were asked to complete two scenarios, crossing the road (Fig. 3.14) and navigating low curbs (Fig. 3.5b), once per chair configuration. To ensure that no training bias was present, each participant used the different configurations in a

randomized order. During each run of the tasks, the time the participant took to complete the task was recorded. Once they completed all six of the runs, they were asked to complete a questionnaire which asked them to rate each wheelchair, referred to as *A*, *B*, and *C*, based on which was the best for each task, which was best at turning, and then any other comments they had about the different configurations.

### 3.5.2 Results

The average time that was taken for the participants to complete each task are shown in Table 3.5.

**Table 3.5:** Average Time per Configuration per Task (In Seconds)

	<i>Centre-wheel Drive</i>	<i>Front-wheel Drive</i>	<i>Rear-wheel drive</i>
<b>Indoor</b>	1.21	1.17	1.31
<b>Outdoor</b>	0.48	0.44	0.41

The preferred choice of wheelchair configuration was mixed, however the centre-wheel drive configuration did gain a slight majority over the other two configurations in the indoor scenario. On the other hand, the preference for the outdoor scenario was equal between the front and centre-wheel drive configurations. The centre-wheel drive configuration was also selected by the majority of participants as the best for turning. Similar to our validation study, some participants during this study did experience some discomfort and had reported some of the typical symptoms related to cybersickness.

## 3.6 Conclusions

A VR based wheelchair training simulator was created. This simulator demonstrated the utility of a cost-effective virtual environment for powered wheelchair training built from commercial off-the-shelf components. A prediction was made that most of the participants in the validation study would likely improve between the first and second run after just the experience of completing the course. This was indeed the case, however, the overall improvement of the HMD group was far better than that of the other two groups. Their improvements often showed

significant results at the 5% level for particular manoeuvres. These results supports our hypothesis that low-cost VR HMDs can be used in conjunction with modern games engines to create virtual environments that can help with the training of powered wheelchair manoeuvres and support of patients in different aspects of daily life. The improvement shown by the participants was interesting as they only had a single, short training session between the attempts at the course. It could be argued that the presence that the participants experienced allowed them to believe that any consequences from the simulator would affect them in the real world. Without presence, the training benefit from the simulator is dramatically reduced, as shown by the participants who just used a standard monitor from just a single use. If the participants were exposed to the desktop training over an extended period of time, then the training can be effective as demonstrated by Inman *et al.* [49]. The desktop having a more restricted view than that of the HMD could have possibly had a negative effect on the simulator, because of its reduced immersion and sense of presence compared the VR HMDs, however the obstacles were always clearly visible from the participant's perspective and this issue never came up in the feedback. The Control group didn't receive any training during the study and could be expected to not show as much improvement as the other groups. They did however show the same amount of improvement as the Desktop group.

Across the four tasks used in the initial study, the improvement from the groups varied. For the traversal of a circular path with light switch task, and the reverse parking task, it is clear that the HMD group significantly improved at the 5% level compared with other groups. One possible reason for this is the added spatial awareness obtained from the ability to look around the environment when using the VR HMD. Less evidence is available to suggest that any of the groups did significantly better when learning how to navigate through a doorway. If the outliers are removed from the HMD group, then the remaining participants in the group show significant improvement in the doorway task. This is the same with the Slalom task if the two outliers are removed.

The results from the SSQ indicate that the mismatch between the physical and virtual motion when using the Wheelchair-VR with a HMD is a problem, even when the period of exposure is short. As the user remains stationary in a seated position, they move around within the environment. This causes a neuro-conflict and disrupts the vestibulo-ocular reflex, which in turn causes the user to experience cybersickness. The simulator was later used with the commercial version of the Oculus Rift HMD. Initial feedback did show that symptoms of cybersickness were slightly reduced, which was potentially due to the higher immersion, increased resolution, refresh rate, and positional tracking accuracy, however the effects of cybersickness were not completely removed. It was noted that those who experienced minimal symptoms of cybersickness tended to look downwards when driving the virtual wheelchair, keeping the virtual knees in view. It is believed that having a familiar point of reference may help reduce the effects of cybersickness. A recent study showed that including an image of a virtual nose while using an Oculus Rift HMD, providing a familiar point of reference for the users, supports this theory [114].

A secondary study was conducted to assess whether it is possible to determine which drive configuration is being used within the virtual environment while using the simulator, and whether they match to the expected performance of their real life counterparts. Although the average times for each task and configuration were very similar, the participants did feel that you could tell the difference between the three configurations

As cybersickness is caused by a neuro-conflict between the eyes and the inner-ear, one possible solution is to introduce real world in to the virtual. Doing so could potentially remove the effects of cybersickness by allowing the user to view the real world while also being able to see the virtual obstacles. Because of this, and the release of the Microsoft HoloLens, a MR version of the wheelchair training application was chosen as the next phase of research for the project.

## Chapter 4

# Wheelchair-MR

### **4.1 Chapter Overview**

In this chapter, the design, development, and validation of a MR wheelchair training environment is outlined and the conclusions are discussed.

### **4.2 Motivation**

In Chapter 3, The development and validation of a VR wheelchair training simulator was discussed. The results of the validation study that was conducted showed some benefit to the training of powered wheelchair usage when using the VR simulator. However, one major issue that was highlighted during the study was that the participants experienced varying degrees of cybersickness. There has been research conducted around the reduction of the effects of cybersickness in VR, which included added in effects such as tunnel vision, or a perception of speed in to the environment, with varying degrees of success. Another potential solution is to introduce the virtual environment into the real world using MR.

As discussed in Section 2.4, MR allows the real world and the virtual world to be seen at the same time. This means that the user could use the device to view virtual objects while moving around in the real world. At moment, the only other paper that was found that used a MR environment in the context of wheelchair training was related to tele-rehabilitation [18]. In this paper, a small electronic vehicle with a camera attached was used to simulate the movements of a wheelchair. This vehicle moved within an environment that contained markers that would have virtual objects "placed" on them when in view of the camera.

Commands could be issued to the vehicle remotely by the patient or healthcare professional.

There has been no evidence yet that the new generations of MR HMDs such as the Microsoft HoloLens or Meta 2 (see Section 2.4) have been used to provide a more intuitive and markerless MR interface for wheelchair users.

### 4.3 Method and Tools

A MR environment was developed that a wheelchair user could use to practice manoeuvring within. The system uses an empty space in the real world, which then has virtual obstacles superimposed on to it in a way that makes them appear as if they are real. Visual and audible cues are given if the user collides with an object within the environment but no physical damage is done to them. As this system uses MR to allow the user to see the virtual obstacles, it can be used with any class or configuration of wheelchair, including both powered and manual chairs, without any software changes. Figure 4.1 shows a mock-up of how the environment looks from the users perspective while they are using the application.



**Figure 4.1:** The Wheelchair-MR System in use. The user is wearing a Microsoft HoloLens and is driving a powered wheelchair through an empty space in the real world. However, virtual objects (tables and chairs) are present and the user must manoeuvre around them.

### **4.3.1 Hardware Components**

As mentioned in Section 3.6, cybersickness is an inherent issue with attempting to moving in VR without appropriate tracking methods. MR HMDs offer a way to overcome the effects of cybersickness by allowing the user to view and interact with the virtual world and the real world at the same time. This means that they are able to physically walk around the environment without worrying about knocking into any real objects or the display lagging.

The Microsoft HoloLens was used to create this system as it was one of the first available MR development kits. The device is tetherless and does not need to be connected to any external devices like computers or tracking sensors, allowing the device to be used easily while sat in a wheelchair. Its gesture recognition system also provides a way to interact with menus and objects within the application

### **4.3.2 Software Implementation**

Wheelchair-MR was developing using the Unity3D games engine (Unity Technologies, San Francisco, CA) and the Mixed Reality Toolkit (MRTK), developed by Microsoft, which was designed to enable the development of content for their VR and MR HMDs. The system runs directly on the Microsoft HoloLens and doesn't require any peripheral devices.

#### **User Interface**

As the application is started, the user interface can be placed by the user at a location within the environment that is convenient for them in the real world. This interface gives them access to a range of controls for the environment. Fig. 4.2 shows the original design for the user interface. It consisted of two buttons that starts and stops the scanning process for the application, which is discussed more in Section 4.3.2. It also displays some debugging information and the metrics for the players performance, mainly the number of hits they have incurred on specific parts of the wheelchair.



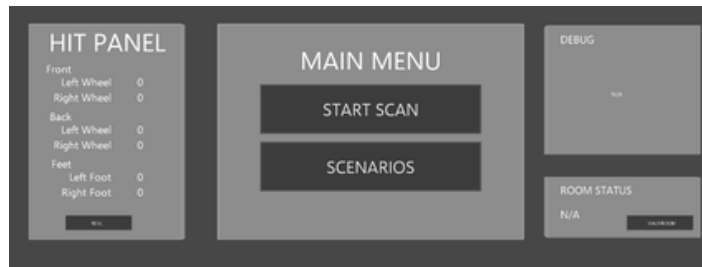
**Figure 4.2:** The initial user interface that was developed for the system.

The user interface was updated to make it more readable. The metrics panel has been retained and the information has been made more readable as well. A button was also added to the metrics panel to allow the user to reset the metrics between each attempt. Fig. 4.3a shows the main menu for the updated interface. This includes a single button used for starting and stopping the scanning process, and a button used to open the Scenarios menu that is visible in Fig. 4.3b. The top right panel is currently unused. Below that is a panel that shows the current state of the room mesh. This will inform the user whether the currently available room has been loaded, or whether the newly scanned environment has been saved (See snippets 4.1 and 4.2). A loading animation, which is not visible in Fig. 4.3, is also present in the user interface to indicate that a task is currently running. This includes loading and saving the room mesh, or a scenario that is currently running. The Scenario menu (Fig. 4.3b), gives the user the ability to load one of the currently implemented scenarios, which includes living room, kitchen, and café scenarios.

### **Spatial Understanding**

The HoloLens' spatial mapping and understanding capabilities allow the device to scan and utilize the current environment that the user is in. Once the scanning process is initiated by the user via the user interface, data from the camera array within the device is converted in to blocks of mesh data and stored as 8cm voxel cubes. The environment is built using a combination of the voxels obtained from the camera array, the





(a) Main Menu.



(b) Scenarios Menu.

**Figure 4.3:** User interface for the Wheelchair-MR Application.

initial orientation of the devices, and the current view from the devices HD camera. This process builds a seamless representation of the real world environment that is used within the application. When the scanning process is completed and the mesh data is finalized, any areas of mesh that haven't been completed, for example gaps in the walls, floor, or ceiling, are filled in automatically to stop the system from placing beyond the bounds of the environment. Fig. 4.4 shows the mesh created from the scanning stage overlaid on to the real world view.



**Figure 4.4:** A view of the mesh generated by the HoloLens' spatial understanding system, overlaid on to the real world.

```

public class RoomLoader : SpatialMappingSource {
    // Name of room save file
    public string fileName, anchorStoreName;
    // List that will hold the retrieved room meshes
    List<Mesh> roomMeshes;
    UnityEngine.XR.WSA.Persistence.WorldAnchorStore anchorStore;
    void Start() { Instance = this; }
    public void Unload() { // Reset the current mapping source
        SpatialMappingManager.Instance.SetSpatialMappingSource(null);
    }
    public void Load() { // Start loading room
        UnityEngine.XR.WSA.Persistence.WorldAnchorStore.GetAsync(AnchorStoreReady);
    }
    void
    ↪ AnchorStoreReady(UnityEngine.XR.WSA.Persistence.WorldAnchorStore
    ↪ store) {
        RoomManager.Instance.SetState(RoomManager.State.Loading);
        ↪ // Change to loading state
        anchorStore = store;
        if (File.Exists(Path.Combine(MeshSaver.MeshFolderName,
        ↪ fileName + ".room"))){
            SpatialMappingManager.Instance.SetSpatialMappingSource(this);
            // Load meshes from file
            roomMeshes = MeshSaver.Load(fileName) as List<Mesh>;
            foreach (Mesh surface in roomMeshes) { // Create surface
            ↪ object from loaded meshes
                int meshID = roomMeshes.IndexOf(surface);
                AddSurfaceObject(CreateSurfaceObject(
                    mesh: surface,
                    objectName: surface.name,
                    parentObject: transform.root,
                    meshID: meshID
                ));
            }
            RoomManager.Instance.RoomLoaded();
        }
    }
}

```

**Code Snippet 4.1:** Room Loading Class

The mesh environment is used by the system to "understand" the semantics of the environment that the device is within. To do this, the system steps through each voxel generated during the scanning process, processes the data in each, and tags them, based on specific criteria, to denote which type of surface that the voxel contains. The surface types that are currently known by the HoloLens are:

```

public void SaveRoom() {
    if (anchorStore == null) return;
    // Set state to saving
    RoomManager.Instance.SetState(RoomManager.State.Saving);
    string[] anchorIds = anchorStore.GetAllIds();
    for (int i = 0; i < anchorIds.Length; i++) {
        if (anchorIds[i].Contains(anchorStoreName)) {
            anchorStore.Delete(anchorIds[i]);
        }
    }
    roomMeshFilters =
    ↪ SpatialUnderstanding.Instance.UnderstandingCustomMesh.GetMeshFilters()
    ↪ as List<MeshFilter>;
    List<Mesh> roomMeshes = new List<Mesh>();
    // For each mesh in room, process and save to file
    foreach (MeshFilter filter in roomMeshFilters) {
        meshCount++; // Increment mesh counter
        string meshName = anchorStoreName + meshCount.ToString();
        filter.mesh.name = meshName;
        roomMeshes.Add(filter.mesh);
        UnityEngine.XR.WSA.WorldAnchor attachingAnchor =
        ↪ filter.gameObject.GetComponent<UnityEngine.XR.WSA.WorldAnchor>();
        if (attachingAnchor == null){ // Get anchor that holds
            ↪ current room
            attachingAnchor =
            ↪ filter.gameObject.AddComponent<UnityEngine.XR.WSA.WorldAnchor>();
        } else {
            DestroyImmediate(attachingAnchor);
            attachingAnchor =
            ↪ filter.gameObject.AddComponent<UnityEngine.XR.WSA.WorldAnchor>();
        }
        if (attachingAnchor.isLocated) {
            if (!anchorStore.Save(meshName, attachingAnchor)){
                // Loading Failed
            }
        } else {
            attachingAnchor.OnTrackingChanged +=
            ↪ AttachingAnchor_OnTrackingChanged;
        }
    }
    string fileLocation = MeshSaver.Save(fileName, roomMeshes);
    if (fileLocation != "" || fileLocation != null){
        // Room Saved to file
        RoomManager.Instance.SetState(RoomManager.State.Saved);
    }
}

```

**Code Snippet 4.2:** Room Saving Method

- **Invalid** - No intersection with other mesh data
- **Other** - Doesn't match with other surface types
- **Floor** - Flat surface at the base of the mesh environment
- **FloorLike** - Not part of the floor topology, but close to the floor and looks like the floor
- **Platform** - Horizontal platform between the ground and the ceiling, e.g. chair seat or table top
- **Ceiling** - Flat surface at the top of the mesh environment
- **WallExternal** - Flat surface at the edges of the mesh environment
- **WallLike** - Not part of wall topology, but close to a wall and looks like a wall

These tags allow the system to place objects based on a placement definition that describes the initial placement of the object, for example on or under a platform, and a series of rules and constraints that further refine the placement by defining how far the object should be away from walls and other objects. This process of placement and refinement allows the HoloLens to place the objects in a way that would make them fit better within the real world context.

Snippet 4.5 shows a `LoadObjects` method that retrieves objects from a manager script, stores them in a `ObjectData` structure (see snippet 4.3), and generates queries using placement definitions, rules, and constraints which are then stored in a query structure (see snippets 4.4 and 4.6). The generated queries are then passed to the `PlaceObjectAsync` method (see snippet 4.7), which passes each query and the corresponding object to pipeline that processes and validates the query and passes it on to be created within the environment. The first step of the pipeline validates the query and checks that the placement of the object is possible within the environment (See snippet 4.8). If it is, then the result of the validation is stored in a list, and used to create the objects within the environment at their specific locations.

```

public struct ObjectData{
    public ObjectData (int _index, String _name, Vector3 _size,
        ↪ int _count){
        index = _index; // Object index
        name = _name; // Name of the Object
        size = _size; // Size of the Object (X, Y, Z)
    }
    public int index;
    public String name;
    public Vector3 size;
}

```

**Code Snippet 4.3:** Object Data Structure

```

private struct PlacementQuery {
    public PlacementQuery(
        SpatialUnderstandingDllObjectPlacement.ObjectPlacementDefinition
        ↪ _definition,
        List<SpatialUnderstandingDllObjectPlacement.ObjectPlacementRule>
        ↪ _rules = null,
        List<SpatialUnderstandingDllObjectPlacement.ObjectPlacementConstraint>
        ↪ _constraints = null
    ){
        definition = _definition; // Placement Definition
        rules = _rules; // Placement Rules
        constraints = _constraints; // Placement Constraints
    }

    public
    ↪ SpatialUnderstandingDllObjectPlacement.ObjectPlacementDefinition
    ↪ definition;
    public
    ↪ List<SpatialUnderstandingDllObjectPlacement.ObjectPlacementRule>
    ↪ rules;
    public
    ↪ List<SpatialUnderstandingDllObjectPlacement.ObjectPlacementConstraint>
    ↪ constraints;
}

```

**Code Snippet 4.4:** Placement Query Structure

### Chair Simulation

The wheelchair is not rendered into the virtual environment as this system is designed to be used with a real chair in the real world. Because of this, a series of physics colliders that represent the generic shape of a wheelchair have been included within the environment to allow the real wheelchair to interact within the virtual world (see Fig. 4.5). This

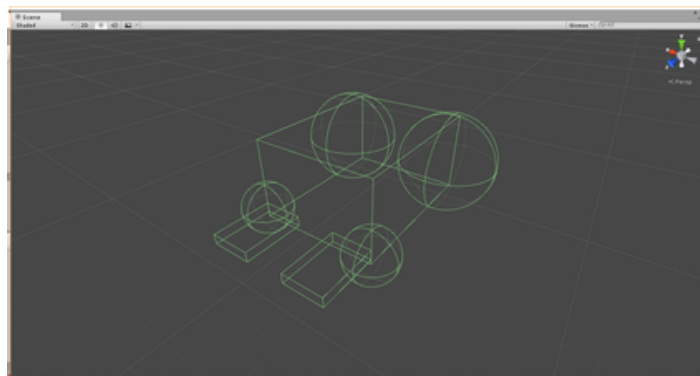
```

obstacles = RoomManager.Instance.GetObjects(scenario);
List<ObjectData> objData = new List<ObjectData>();
foreach(ObstacleData obstacle in obstacles){
    GameObject obj = obstacle.obj;
    if (obj.GetComponent<Renderer>() != null){ // Get object
        ↪ size from object
        objData.Add(new ObjectData(obstacles.IndexOf(obstacle),
            ↪ obj.name, obj.GetComponent<Renderer>().bounds.size));
    } else { // Get object size from bounds of children
        Vector3 objSize = new Vector3();
        for (int i = 0; i < obj.transform.childCount; i++){
            if (obj.transform.GetChild(i).tag == "Obstacle"){
                if (obj.transform.GetChild(i).GetComponent<Renderer>()
                    .bounds.size.sqrMagnitude > objSize.sqrMagnitude){
                    objSize = obj.transform.GetChild(i)
                        .GetComponent<Renderer>().bounds.size;
                }
            }
        }
        objData.Add(new ObjectData(obstacles.IndexOf(obstacle),
            ↪ obj.name, objSize));
    }
}
}

```

**Code Snippet 4.5:** Loading objects from the Room Manager and retrieving relevant data

allows the application to track which parts of the wheelchair have collided with the virtual environment, which can then be fed back to the user via the user interface so they can see where they need to improve with manoeuvring a wheelchair. Visual and audio cues were also included to provide the user with a way to indicate whether the user has hit an object or not (See snippet 4.9).



**Figure 4.5:** The physics colliders used to represent the chair

```

// If Spatial Understanding is ready and room is loaded
if (RoomManager.Instance.state == RoomManager.State.Loaded ||
    ↪ SpatialUnderstanding.Instance.ScanState ==
    ↪ SpatialUnderstanding.ScanStates.Done)
{
    List<PlacementQuery> placementList = new
    ↪ List<PlacementQuery>();
    // For each object, generate placement query and process
    ↪ them
    foreach (ObjectData data in objData) {
        for (int i = 0; i < data.count; i++) {
            placementList.Add(new PlacementQuery(
                SpatialUnderstandingDllObjectPlacement
                    .ObjectPlacementDefinition
                    .Create_OnFloor(data.size),
                new
                ↪ List<SpatialUnderstandingDllObjectPlacement.ObjectPlacementRule>(){
                    SpatialUnderstandingDllObjectPlacement
                        .ObjectPlacementRule
                        .Create_AwayFromOtherObjects(1.5f)
                }, new List<SpatialUnderstandingDllObjectPlacement
                    .ObjectPlacementConstraint>(){
                    // No Constraints
                }
            ));
        }
    }
    PlaceObjectAsync(scenario.ToString(), objData,
    ↪ placementList);
}

```

**Code Snippet 4.6:** Processing placement queries based on the object data

## Training Tasks

The tasks implemented in the Wheelchair-MR application are designed to allow the user to practice manoeuvring a wheelchair and navigating environments that would be familiar to them. Three scenarios are included; a living room, a kitchen, and a café. Each task is accessible from the user interface as mentioned in Section 4.3.2. Each task has different objects, such as sofas and chairs for the living room scenario, or table and chairs for the café, associated with them. These objects are placed within the environment based on predefined rules and constraints defined within the tasks. As suggested during our pilot study, discussed in Section 4.4, all of the objects within each scenario can be manually

```

private bool PlaceObjectAsync(String placementName,
↪ List<ObjectData> objData, List<PlacementQuery>
↪ placementList, bool clearObjectsFirst = true){
    if (queryStatus.State != QueryStates.None){
        return false;
    }
    if (clearObjectsFirst){
        ClearGeometry();
    }
    // Reset state of query processing
    queryStatus.Reset();
    queryStatus.State = QueryStates.Processing;
    queryStatus.Name = placementName;

    // Start separate thread to process and place the objects
    System.Threading.Tasks.Task.Run(() => {
        threadStarted = true;
        for (int i = 0; i < placementList.Count; i++){
            bool success = PlaceObject(
                objData[i].name,
                placementList[i],
                objData[i].index,
                clearObjectsFirst,
                true
            );
            queryStatus.CountSuccess = success ?
                ↪ (queryStatus.CountSuccess + 1) :
                ↪ queryStatus.CountSuccess;
            queryStatus.CountFail = !success ?
                ↪ (queryStatus.CountFail + 1) : queryStatus.CountFail;
        }
        queryStatus.State = QueryStates.Finished;
    });
}

```

**Code Snippet 4.7:** Thread Worker for processing the queries generated by the system

repositioned and rotated using the HoloLens' gesture system. Future tasks could include the users being able to recreate rooms within their own homes.

## 4.4 Initial User Testing

To gain feedback about the initial version of the system, three able-bodied participants drove a powered wheelchair in a small empty area



```

private bool PlaceObject(String name, PlacementQuery query,
↳ int index, bool clearObjectsFirst = true, bool isAsync =
↳ false) {
    // Process placement query
    if
↳ (SpatialUnderstandingDllObjectPlacement.Solver_PlaceObject(
↳ name,
    SpatialUnderstanding.Instance.UnderstandingDLL.PinObject(query.definition),
    (query.rules != null) ? query.rules.Count : 0,
    ((query.rules != null) && (query.rules.Count > 0)) ?
↳ SpatialUnderstanding.Instance.UnderstandingDLL.PinObject(
    query.rules.ToArray()
    ): IntPtr.Zero,
    (query.constraints != null) ? query.constraints.Count : 0,
    ((query.constraints != null) && (query.constraints.Count >
↳ 0)) ?
↳ SpatialUnderstanding.Instance.UnderstandingDLL.PinObject(
    query.constraints.ToArray()
    ): IntPtr.Zero,
    SpatialUnderstanding.Instance.UnderstandingDLL
    .GetStaticObjectPlacementResultPtr()) > 0){
    // If successful, start object placement
    SpatialUnderstandingDllObjectPlacement.ObjectPlacementResult
↳ placementResult = SpatialUnderstanding.Instance
    .UnderstandingDLL.GetStaticObjectPlacementResult();
    name += " " + index;

    if (!isAsync) { // Add delay if asynchronous
        float timeDelay = 0;
        placementResults.Add(new PlacementResult(timeDelay,
↳ placementResult.Clone() as
↳ SpatialUnderstandingDllObjectPlacement.ObjectPlacementResult,
↳ name));
    } else { // Create immediately
        ObjectResult or = new ObjectResult(name,
↳ placementResult.Clone() as
        SpatialUnderstandingDllObjectPlacement.ObjectPlacementResult);
        queryStatus.ObjectResults.Add(or);
    }
    return true;
}
return false;
}

```

**Code Snippet 4.8:** Method to validate a placement query and add result to list

while using the Wheelchair-MR system via the HoloLens (See Fig. 4.6). The purpose of the user test was to find any problems that were present

within the system and what need to be fixed before a validation study could be carried out. The participants of this user test were asked to provide verbal feedback about the system during and after they have used the application.



**Figure 4.6:** A small pilot study to identify features and issues

An issue that was identified with the application was that the objects that were placed within the environment appeared as if they were floating above the floor which reduced the realism of the virtual obstacles. Other improvements that were suggested during the study included the addition of realistic shadows which would increase the realism of the virtual objects within the real world, and the ability to move, rotate, and scale the virtual objects so that can be positioned to fit better within the environment.

## 4.5 Validation Study

### 4.5.1 Experimental Design

A validation study was designed to provide feedback on whether using Wheelchair-MR had any impact on training when compared with our VR system, and a control group. Thirty-five able-bodied volunteers took part in the validation study, consisting of 9 Females and 26 males. The participants were selected from the same pool as the original VR validation study, with the same convenience sampling technique used. This had the potential to negatively skew the data as the participants could potential have participated in the original study, but because of the time that had lapsed between the two studies, it was believed that it would not affect the results. The ages of the participants ranged between 18 to 70 years old with the majority (16) aged under 29. All of the participants had their average reaction times recorded using an online tool called Human Benchmark [46]. The average reaction time of the participants were around  $0.4 \pm 0.04$  seconds, which was well within the acceptable range recommended for the safe usage of a powered wheelchair. All of the participants were randomly assigned to one of three groups (see Table 4.1). The group allocation was done by drawing lots out of a bag to ensure randomization amongst the participants. The groups were:

- **Control** - No formal training. Only provided with a pamphlet [82] and book about safely using a powered wheelchair [9]
- **VR** - Trained using the Wheelchair-VR application
- **MR** - Trained using the Wheelchair-MR application

To gauge the baseline ability of the participants when manoeuvring a powered wheelchair, each one was asked to completed an initial run of an obstacle course using a wheelchair. The Spectra XTR2 was used to navigate the obstacle course during the study. The time for each participant to complete the obstacle course was recorded, alongside the number of times each participant hit a cone or left the bounds of the

**Table 4.1:** Wheelchair-MR: Group-per-session Allocation

	Control	VR	MR
Obstacle Course	✓	✓	✓
Training (VR)		✓	
Training (MR)			✓
Obstacle Course	✓	✓	✓

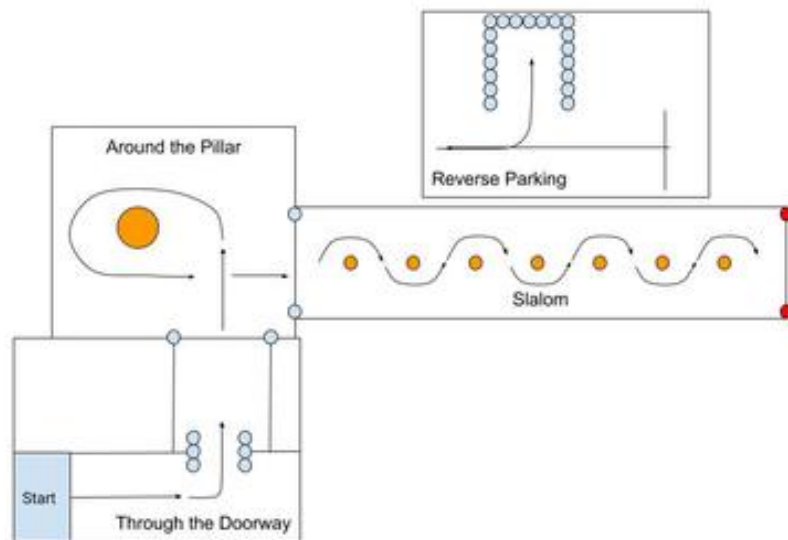
course. The obstacle course consisted of four different stages based on real-world situations (see Figures 4.7 and 4.8):

1. To manoeuvre through a narrow doorway - represented by a set of cones - and stop on the other side.
2. To drive in a circular path, stopping at a specified point
3. To complete a slalom course through seven cones, placed 1.5m apart.
4. To reverse park the chair in a small area marked out by cones.

A time penalty of one second was incurred every time the participant hit a cone or left the bound of the course. This penalty was added on to the participants time for the section of the course that the penalty occurred.

After their initial run of the obstacle course, the participants were asked to complete a specific training activity, depending on the group that they were placed within:

1. The VR group trained using Wheelchair-VR [54] using the Oculus Rift HMD. They were required to complete two different scenarios that involved driving the virtual wheelchair through a maze and through doorways. Participants were allowed to complete the training in their own time, but no-one took more than 10 minutes to complete the scenarios.
2. The MR group were taken to a nearby empty area where they used the Wheelchair-MR system with the café scenario pre-loaded. The Scandinavian Mobility rear-wheel chair was used during the Wheelchair-MR training. They were asked to navigate their way



**Figure 4.7:** Design view of the Layout of the Obstacle Course



**Figure 4.8:** The Slalom Section of the Obstacle Course

through the area, making their way from one end to the other whilst avoiding the virtual tables and chairs that were placed within the environment. Participants were allowed a short period to adjust to the MR headset before given 5 minutes to carry out their training.

3. The control group were asked to read through two separate guides about using a powered wheelchair safely [9], [82].

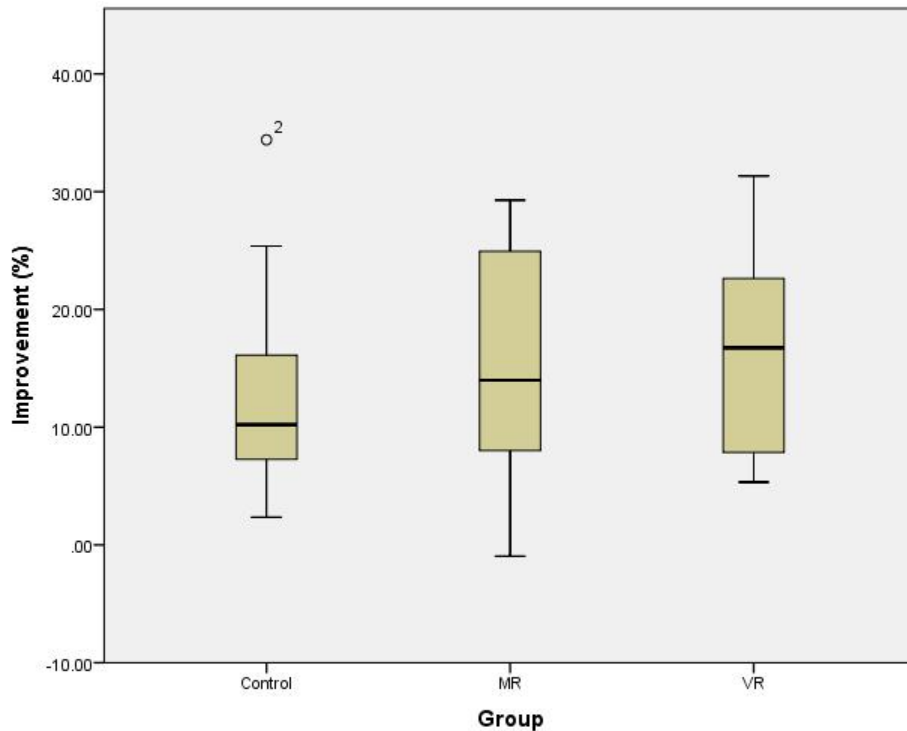
The participants in the VR and MR groups were also asked to completed a simulator sickness questionnaire before and after their training session. This was so any occurrence of cybersickness could be recorded. If the participants from either group felt ill at any stage during their training session, they were told to remove the headset immediately.

Once the training was completed, each participant completed a second run of the obstacle course. The majority of participants showed some improvement after their training session. We were interested in any difference in the rate of improvement between the three groups.

#### **4.5.2 Results**

A one-way analysis of variance (ANOVA) was carried out on the times to complete each task from the initial run of the course. No significant difference was found for the circular path, slalom, and reverse parking tasks. However, a significant difference ( $p = 0.043$ ) was found for the doorway task. This task was therefore excluded from the improvement analysis that follows.

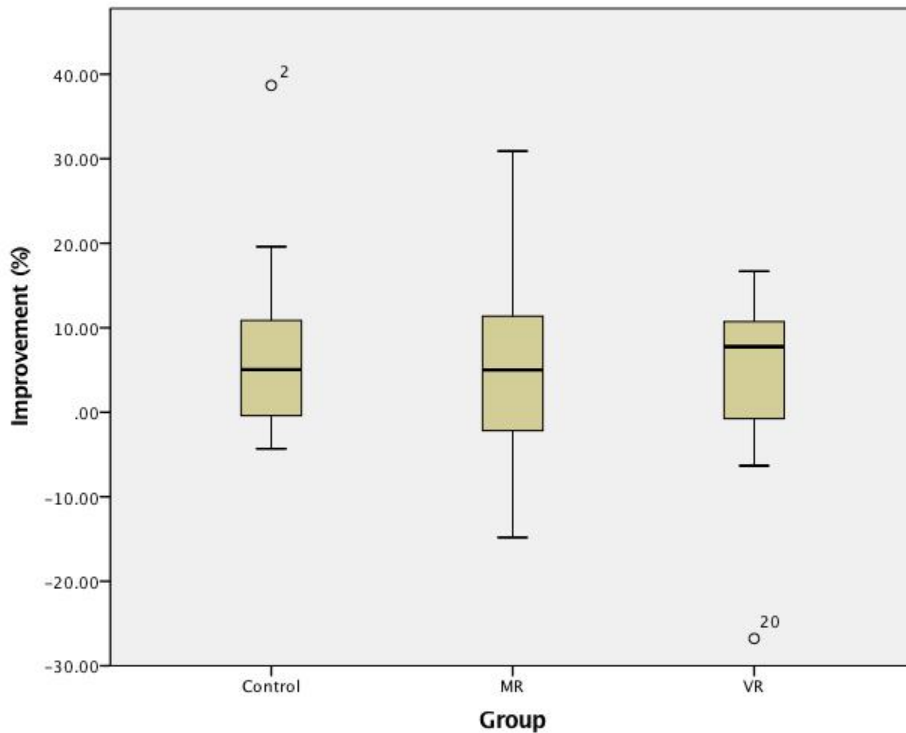
The same improvement parameter defined in Chapter 3 was used to analyze the results of this experiment. Figure 4.9 shows an initial visualization of the improvement data of the participants in the three groups across the entire course, excluding the doorway task. The median values, represented by a thick black horizontal line, for both VR and MR groups are clearly higher than that of the control group, 14%, 16.7%, and 10.2% respectively. The data in the first and third quartiles also general contain higher improvement values. This suggested that there was more improvement from the VR and MR groups compared to the control. A one-way ANOVA was carried out to find the significance of the improvement between the three groups. Not including the outlier in the Control group, the overall improvement scores for the course gave a  $p$ -value of 0.399, which is not indicative of a significant result.



**Figure 4.9:** The overall improvement across the entire course. The outlier is marked with a circle

A box-plot was used to visualize the results from each stage of the course. If the box-plot for any particular stage indicated a difference between the groups, an ANOVA was carried out on the data from that stage to determine whether the results were significant. Due to the significant difference shown between the groups in the first stage of their initial run, no analysis was undertaken on the first task. In the second task, navigating around a pillar, the box-plot (see Fig. 4.10) showed the median improvement values for the Control, MR, and VR groups were 5%, 5%, and 7.7% respectively. The results from a one-way ANOVA, excluding the two outliers indicated in the box-plot, showed a  $p$ -value of 0.930 and no significant difference was found between any of the three groups and the distribution of data in the first and third quartiles were similar.

An initial visualization of the data from the Slalom task (see Fig. 4.11) shows that the median improvement values for the Control, MR, and VR groups are very similar, 13.6%, 13.7%, and 13.4% respectively. However, the mean overall improvement for the task in the MR group was higher,



**Figure 4.10:** The improvement for a circular path around a pillar

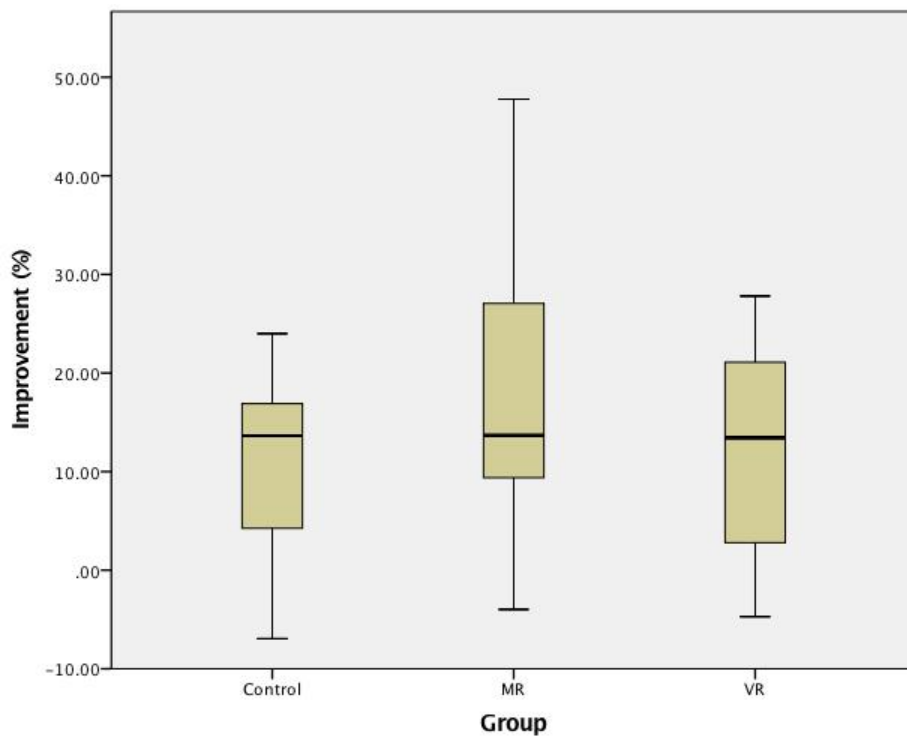
17%, than the other two groups, 11% for control and 12% for VR. Due to this, a one-way ANOVA was carried out but generated a  $p$ -value of 0.359 for this task and no significant difference.

In the final task, reversing into a small space, the initial box plot showed that the median improvement values for the Control, MR, and VR groups were 14.5%, 18.6%, and 31% respectively (see Fig. 4.12). Although the VR group does general upward trend of improvement, a one-way ANOVA, with the outliers removed, gives a  $p$ -value of 0.662, meaning that there was no significant difference between the groups.

### **Simulator Sickness Questionnaire**

To analysis the effects of cybersickness when using the MR application and compare it to the VR simulator, each of the participants in the VR and MR groups were asked complete a simulator sickness questionnaire (SSQ), devised by Kennedy *et al.* [59], before and after their respective training sessions. The scores for the three symptom clusters; Nausea (N), Oculo-Motor (O), and Disorientation (D), were calculated along with



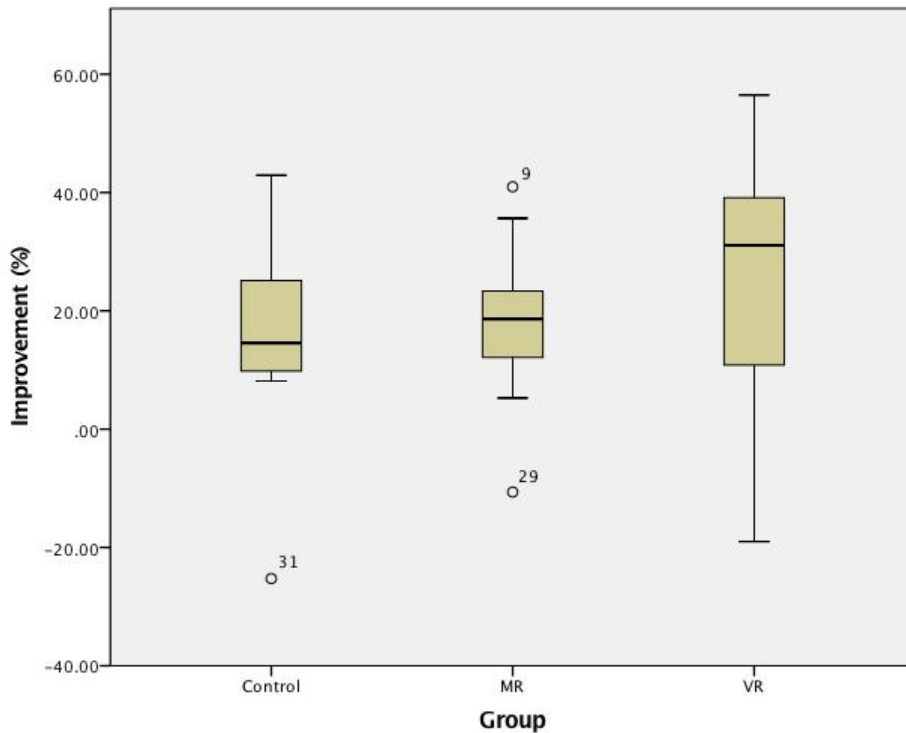


**Figure 4.11:** The improvement for the slalom

the Total Severity (TS) of their symptoms. The results for both groups are displayed in Table 4.2, which shows the scores before training, and Table 4.3, which shows the scores after training.

Table 4.4 shows the score ranges for each symptom level (*none, slight, moderate, severe*), across the symptom clusters. Each level is calculated using the sum of the scores for each symptom, each with a value ranging between 0 (*none*) and 3 (*severe*), and multiplying that sum by the coefficient for the cluster. For example, if a person scored moderate levels for all symptoms of disorientation, the calculation would be  $(7 \times 2) \times 13.92 = 194.88$ , where 7 is the number of symptoms in the cluster, 2 is the integer value of the moderate symptom level, and 13.92 is the coefficient for that cluster. Refer to [59] for more details about the calculations and symptom clusters.

The average scores for the VR group before their training session showed slight levels of discomfort across the three symptom clusters, although there were several participants that had reported severe levels for symptoms such as stomach awareness and eye strain. After their



**Figure 4.12:** The improvement for performing a reverse parking manoeuvre

training sessions, most of the participants in the group showed increased levels across the symptom clusters, with two noting severe levels of discomfort in at least one symptom. One participant in the group could only use the VR simulator for a very short period before having to take the headset off. After several attempts at using the simulator, the participant reported moderate levels of nausea.

Similar to the VR group, the MR group's average scores before training showed slight levels of discomfort. The scores after the training session, however, were significantly lower across the three symptom clusters than that of the VR group. Some of the participants in the MR group reported that using the MR device made them feel better afterwards. The results from the MR post-training SSQs (see Table 4.3) shows that the scores for the MR group were roughly half of that of the VR group.

An Independent Samples t-test was performed on the difference between each symptom cluster before and after training for the VR and MR groups. The results of the analysis showed that there was a significant difference between the groups for each of the clusters. For Nausea, the

**Table 4.2:** SSQ - Pre-Training Scores

Group	Nausea		Oculomotor		Disorientation		TS	
	VR	MR	VR	MR	VR	MR	VR	MR
<b>Mean</b>	8.8	4.4	6.3	8.8	11.6	10.4	4.9	4.5
<b>SD</b>	14.9	9.5	7.8	15.8	20.4	24.6	7.8	9.5
<b>Min</b>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Max</b>	47.7	28.6	22.7	45.5	69.6	69.6	26.7	25.7

**Table 4.3:** SSQ - Post-Training Scores

Group	Nausea		Oculomotor		Disorientation		TS	
	VR	MR	VR	MR	VR	MR	VR	MR
<b>Mean</b>	47.7	2.2	27.8	3.5	67.3	3.2	26.7	1.6
<b>SD</b>	39.9	5.7	22.5	7.6	64.7	12.1	23.6	4.4
<b>Min</b>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Max</b>	104.9	19.1	75.8	22.7	222.7	41.8	79.8	15.2

**Table 4.4:** SSQ - Reference Scores

	Nausea	Oculomotor	Disorientation	Total Severity
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

VR and MR conditions produced a value of  $t(22) = 3.442$ ,  $p = 0.002$ . In Ocular-motor, VR and MR conditions produced values of  $t(22) = 3.915$ ,  $p = 0.001$ . In Disorientation, VR and MR conditions produced values of  $t(22) = 3.317$ ,  $p = 0.003$ , and Total Severity, VR and MR conditions produced values of  $t(22) = 3.616$ ,  $p = 0.002$ . These results suggest that the participants in the MR group displayed significantly reduced effects of cybersickness when compared the participants from the VR group. The means and standard deviations are reported in Table 4.5.

**Table 4.5:** T-Test Data

	Group	Mean	Standard Deviation
Nausea	VR	38.96	40.36
	MR	-2.89	10.07
Ocular-Motor	VR	27.16	25.54
	MR	-5.05	12.66
Disorientation	VR	55.68	62.25
	MR	-6.96	20.13
Total Severity	VR	22.63	23.08
	MR	-2.79	7.73

## 4.6 Conclusions

A MR training environment was created to allow people to practice driving a real wheelchair around within the real world with virtual obstacles overlaid via the MR headset. A validation study was conducted based on the methodology that was used during the validation of our VR simulator in Chapter 3. After completing an initial run of an obstacle course, the participants received a short training session based on the group that they were allocated to. The results from our validation study for the VR simulator showed that the VR trained group demonstrate statistically significant improvement for some of the tasks during the obstacle course. The results from the MR validation study did not produce the same statistically significant results as the previous project but did still show indications that both the VR and MR groups showed more improvement than the Control in certain tasks. As there was no statistically significant difference between the results from any of the groups, the conclusion that the MR group did not perform worse than the other groups can be drawn. This could be because they are still "present" within the real world while being able to view the virtual using the MR HMD. However, because of the small viewport that is available on the current generation of MR HMDs, the value of the virtual training may have been reduced. There is also a strong indication that the MR group showed the most improvement during the slalom task. It is believed that if a participant was to undertake a training program based around the use of the Wheelchair-MR system over an extended period of time, statistically significant improvement would be produced, so this is an avenue that will be investigated in the future.

Results obtained from the SSQs indicated that using VR still causes cybersickness due to the disruption caused to the vestibulo-ocular reflex by perceiving motion but not experiencing it. A comparison between the VR and MR groups showed that the MR group demonstrated significantly reduced effects of cybersickness after their training session. This could be linked to the requirement for the user to move around within the real

world as well as the virtual environment when using MR. This removes the cause of the neuro-conflict, significantly reducing the effects of cybersickness. However some effects are still present, such as eye strain and general discomfort, as the user does still require wearing a HMD and using an optical see-through display.

During the validation of the application, comments were made about different aspects of the training and simulation. For example, several participants commented that the small field of view that is used by the HoloLens made navigating the virtual obstacles more difficult because they couldn't see any objects in their peripheral vision. They stated that not being able to see multiple objects, due to the lack of peripheral vision, makes it harder to navigate between the objects. Another comment made during the study highlighted that some of the virtual objects would shift their positions as the participant moved around within the environment. This issue was primarily due to the device getting confused about its current position within the real world, causing it to compensate and shift the virtual world to a new position.

```

public class CollisionTrigger : MonoBehaviour {
    public TextMesh hitCounter;
    public Material hitMaterial;
    private AudioSource source;
    private List<Material> sourceMats;
    private List<Renderer> renderers;
    private int hits;
    void Start () {
        renderers = new List<Renderer>();
        sourceMats = new List<Material>();
        source = gameObject.GetComponent<AudioSource>();
        hits = 0;
    }
    void OnTriggerEnter(Collider other) {
        renderers.Clear(); // Reset renderers
        sourceMats.Clear(); // Reset original materials
        if (other.gameObject.tag == "Obstacle") { // Get object
            ↪ renderers
            if (other.GetComponent<Renderer>() != null) {
                renderers.Add(other.GetComponent<Renderer>());
            } else {
                foreach (Renderer renderer in other.gameObject
                    .GetComponentsInChildren<Renderer>()) {
                    if (renderer.gameObject.tag == "Obstacle")
                        ↪ renderers.Add(renderer);
                }
            }
            if (renderers.Count > 0) // Change object material
                foreach (Renderer renderer in renderers) {
                    sourceMats.Add(renderer.material);
                    renderer.material = hitMaterial;
                }
            if (hitCounter != null) hitCounter.text = "" + hits++;
            if (source != null) source.Play(); // Play sound on hit
        }
    }
    void OnTriggerExit(Collider other) { // Reset object
        if (other.gameObject.tag == "Obstacle" && renderers.Count
            ↪ > 0)
            foreach (Renderer renderer in renderers) {
                renderer.material =
                    ↪ sourceMats[renderers.IndexOf(renderer)];
            }
        renderers.Clear();
        sourceMats.Clear();
    }
}

```

**Code Snippet 4.9:** Script to detect the wheelchair colliding with an object and updating the metrics

## Chapter 5

# StrokeVR - Stroke Rehabilitation

### **5.1 Chapter Overview**

This chapter describes the implementation of a VR application that aids in the rehabilitation of patients who have suffered from a stroke, and the acceptability of this approach from the perspective of the patients using the application and the staff members who would administer the therapy.

### **5.2 Motivation**

In the particular case of stroke, the normal rehabilitation routine of a patient consists of them being taken to a therapy room, sometimes referred to as a gym, or a therapy kitchen where they would complete different tasks with the assistance of an occupational therapist and/or therapy assistant. These tasks would be designed to help them to recover their physical and cognitive abilities through repetitive actions. As mentioned in Section 2.5.1, VR has been used in physical and cognitive rehabilitation of different conditions, however these applications tended to be non-immersive and used a TV or normal computer monitor to display the environment, and would often use off-the-shelf technologies, like the Nintendo Wii, to allow the patient to interact with a game environment. Because therapy requires the assistance of specially trained staff, the amount of therapy time that the patients receive is rather small. According to the National Institute for Health and Care Excellence (NICE) (2013) guideline for the intensity of stroke rehabilitation, patients should receive at least 45 minutes of therapy a day, 5 days a week, with the amount being tailored at later stages depending on the patients requirements [50].

Using the non-immersive VR therapies that have been developed still requires specialized members of staff to move the patient to the room where they conduct the therapy. Using immersive VR as a tool for cognitive rehabilitation could allow patients to receive therapy without the need for them to leave their bed. This could increase the amount of therapy time that the patients receive and would not require a specialized staff member to administer the therapy, but could be done by anyone, including a member of the patients family.

## **5.3 Initial Implementation**

### **5.3.1 Software Implementation**

StrokeVR was developed using the Unity 3D game development platform (Unity Technologies, San Francisco, CA). Unity was chosen as it provided built in support for VR content development and the application needed to be usable in situations where an internet connection is not available. Unity is capable of providing realistic rendering of virtual objects, accurate lighting, and physics-enabled modelling of interactions between objects. The system can be run on any computer capable of supporting the HTC Vive and SteamVR systems.

#### **Tasks**

The tasks that were identified for inclusion within the application were designed in collaboration with the Senior Occupational Therapist (OT) and Consultant Physician at the Stroke Unit in the Countess of Chester Hospital (CoCH) and comprises of:

- Making Toast
- Pouring water from a Jug
- Using a toothbrush

Each of these tasks are common tasks that patients would practice during their rehabilitation process and represent ADLs that are important to leading a normal life. Training courses, such as the AMPS (Assessment of Motor and Processing Skills) [4] include these types of task, as well as a



long list of other similar tasks, as a method of assessing the cognitive and physical abilities of patients while performing ADLs.

The implemented tasks and subtasks were:

- Toast:
  - Picking up a slice of bread
  - Place the bread in to the toaster
  - Press down the button on the toaster
  - Take the bread out of the toaster
- Pouring Water:
  - Pick up the jug
  - Move it to the glass
  - Tilt the jug so the spout is pointing towards the glass
  - Fill up the glass
- Brushing Teeth:
  - Pick up the toothbrush
  - Put water on the brush
  - Pick up the toothpaste
  - Squeeze the tube over the brush

Although these are relatively simple tasks, they require a high level of complexity in terms of their implementation to accurately simulate the tasks.

### **Interactions**

To allow the user to practice the tasks that are included within the application, simple methods of interaction were added. Using the VR controllers, the user is able to pick up slices of bread and push down on the plunger to start the toaster. Figure 5.1 shows a view of the initial prototype of the StrokeVR application. The user can be seen picking up a piece of bread, turning on the toaster and taking out a piece of

toast. Snippet 5.1 shows an example of basic grab mechanics using the SteamVR SDK within the Unity3D engine.

```
public class GrabObject : MonoBehaviour {
    SteamVR_TrackController controller; // Reference to
    ↪ controller script
    Transform goParent; // Original parent of object

    void Start(){
        // Get reference to controller script
        controller = GetComponent<SteamVR_TrackController>();
    }

    void Update(){
        if (grabbableObject != null){
            if (controller.Gripped){ // If gripped pressed, make
                ↪ object a child of the controller
                grabbableObject.transform.parent = this.gameObject;
            } else { // otherwise, reset parent object
                grabbableObject.transform.parent = goParent;
            }
        }
    }

    // When controller intersects with an object, get object
    ↪ reference
    void OnTriggerEnter(Collider other){
        goParent = other.transform.parent;
        grabbableObject = other.gameObject;
    }

    // Remove reference when controller leaves object
    void OnTriggerExit(Collider other){
        grabbableObject = null;
    }
}
```

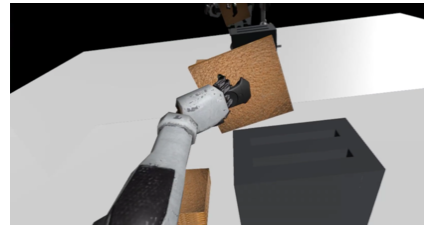
**Code Snippet 5.1:** Basic grab example using SteamVR

### 5.3.2 Hardware Components

The initial prototype for the StrokeVR rehabilitation simulator was developed using the HTC Vive. The Vive includes a much larger potential tracking area than other commercial HMDs. This means that a full room environment could be implemented and the user could move around within it and interact. The Vive also included two tracked controllers that



**(a)** The initial view seen by the patient.



**(b)** A slice of bread in the users hand.



**(c)** A view of the toaster while it is on. A red light can be seen in the bottom right of the toaster to indicate that it is currently on.



**(d)** A slice of bread after it has been toasted.

**Figure 5.1:** Initial implementation

allows user to interact with the virtual environment using their hands, increasing the rehabilitation potential of the system.

## 5.4 Initial Experiment

An initial experiment was conducted to obtain feedback from current in-patients and staff members about a prototype of the application. The study was also a chance to determine if there were any issues present with the current iteration. The study was conducted in the presence of the resident clinician and lead occupational therapist on the ward, as well as a few of the nursing staff.

### 5.4.1 Experimental Design

Three highly functioning patients with left hand paralysis tested out the toast making scenario. The HTC Vive was setup in one of the therapy rooms at the stroke ward using a single sensor and a high-end gaming laptop with an nVidia GTX 1060 graphics card (See figure 5.2).

The study was conducted as a group discussion. Each of the participants were given time to use the application while others could watch. During the study, the participants were asked to provide their



**Figure 5.2:** The setup for our initial pilot test of our toaster scenario

own feedback on the application and were asked questions about their experience with the application.

#### **5.4.2 Feedback**

There were some issues setting up the Vive initially, with the tracking box not syncing correctly. It was discovered that the sensors work on a slave master system, so using the master tracking box fixed the issues.

Each of the patients had some difficulties using the application. Two of the participants struggled to reach the table to pick up the bread and put it into the toaster, the other participant did have more success, potentially due to their familiarity with games and game controllers, but still found it difficult to interact with the side button to activate the toaster. One of the members of staff pointed out that the patient had to over-rotate their wrist into an un-natural position to successfully put the bread into the toaster.

The participants also provided insightful comments about using the application. One of the comments was about how using the equipment and headset didn't feel intimidating and that they felt that the headset was comfortable to wear while they were doing the task. One of the participants also stated that they felt it was more beneficial than some

simpler games, like throwing darts at a dart board. The participants did feel that more therapy using this equipment would be beneficial.

## **5.5 Revised Implementation**

After the initial experiment, the application was re-designed and improved to accommodate the feedback that was given by the participants and members of staff.

### **5.5.1 Hardware Components**

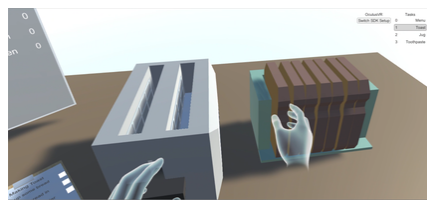
The second implementation of the simulator was designed to support a wider range of desktop-based VR headsets. This was so the user did not require a specific hardware configuration to run the application, they only require a headset that is supported by the application and a computer capable of running the simulator. Although the application was developed to work with a range of HMDs, it was designed with the Oculus Rift in mind as the hand controllers are more ergonomically designed and would potentially feel more natural for the user. The Oculus system also includes hand models within the application to make the simulator more realistic and immersive. Other vendors will most likely include hand models in future iterations of their software to increase the immersiveness as well.

### **5.5.2 Software Implementation**

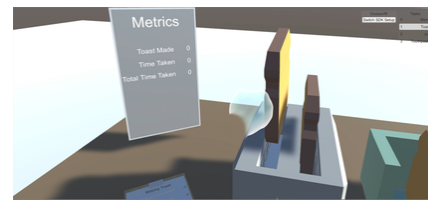
The updated version was developed using the Unity 3D game development platform and the Virtual Reality Toolkit (VRTK) [107]. This toolkit was designed to make VR development quicker and easier, and also allows for more in-depth interactions within the virtual environment.

The tasks included within the application were built directly within the environment using the games engine and more tasks of varying complexity can be added as and when they are desired. Figure 5.3 shows some snapshots of each stage of the updated "Making Toast" task being completed. The tasks also include a set of instructions for the user to

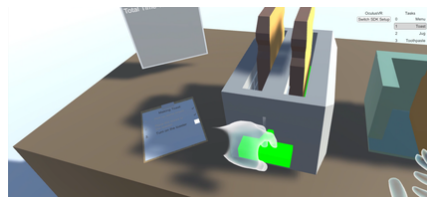
follow. These instructions are on a clipboard (See Fig. 5.4) that the user can pick up and place anywhere within the virtual environment.



**(a)** The initial view seen by the patient.



**(b)** A slice of bread in the users hand.



**(c)** A view of the user pushing down the toaster. The lever turns green when the user is interacting with it.



**(d)** A slice of bread after it has been toasted.

**Figure 5.3:** Updated Prototype

To allow for real-time interaction within the environment and real-time update of the task states, an event system was implemented that could be accessed in any script and used to update the state of the application and different aspects of each task. The event system was primarily used for two functions. The first was to update the list of instructions for each task as each instruction was completed, and the second was to update the metrics associated with each task in the application state so the metrics panel could be updated within the virtual environment to provide the user with immediate feedback.

To register an event with the Task Event system, the `StartListening` method is called and the name of the event and a callback method are passed in as arguments (See snippet 5.2). For example, snippet 5.3 shows the "UpdateMetrics" Event being registered.

The user can choose to follow the instructions and refer to the clipboard to check their progress, or completely ignore the clipboard and attempt to complete the task without any assistance. The clipboard is able to track the users progress using the task event system, and places a tick next to any of the instructions that they have completed

```

// Event class that inherits from UnityEvent and takes a
↳ string and float as parameters
public class FloatEvent : UnityEvent<string, float> {}
// Start listening for float event trigger
public static void StartListening(string eventName,
↳ UnityAction<string, float> listener) {
    FloatEvent evt = null;
    if (Instance.eventDictionary.TryGetValue(eventName, out
↳ evt)) {
        evt.AddListener(listener);
    } else {
        evt = new FloatEvent();
        evt.AddListener(listener);
        Instance.eventDictionary.Add(eventName, evt);
    }
}
// Event trigger method that invokes the event callback with
↳ supplied parameters
public static void TriggerEvent(string eventName, string
↳ metric, float value){
    FloatEvent evt = null;
    if (Instance.eventDictionary.TryGetValue(eventName, out
↳ evt)){
        evt.invoke(metric, value);
    }
}
}

```

**Code Snippet 5.2:** TaskEventManager: StartListening Method for events that take a float argument



**Figure 5.4:** A clipboard with a list of instructions printed on it.

```

public Task : MonoBehaviour {
    void Start() {
        // Start listening to the "UpdateMetrics" event
        TaskEventManager.StartListening("UpdateMetrics",
            ↪ UpdateMetrics);
    }
    // Method used to update the task metrics
    private void UpdateMetrics(string name, float value) {
        for (int i = 0; i < metrics.Count; i++) {
            MetricData metric = metrics[i];
            if (metric.name == name) {
                metric.value = value;
                if (metric.name.ToLower().Contains("time")) {
                    metric.display.text = string.Format("{0}:{1:00}",
                        ↪ (int)metric.value / 60, (int)metric.value % 60);
                } else {
                    metric.display.text = metric.value.ToString();
                }
            }
            metrics[i] = metric;
        }
    }
}

public Toaster : MonoBehaviour{
    void Update(){ // Update the task metrics
        TaskEventManager.TriggerEvent("UpdateMetrics",
            ↪ "TimeTaken", timer.time);
    }
}

```

**Code Snippet 5.3:** Starting the UpdateMetrics Listener and Triggering the event



```

void Start() {
    // Start listening to the "TaskCompleted" event
    TaskEventManager.StartListening("TaskCompleted",
    ↪ TaskCompleted);
}
void Update(){
    // If there are instructions, update them if the user
    ↪ completes that subtask
    if (instructionsList.Count != 0){
        foreach (InstructionData instruction in instructionsList){
            if (instruction.state){
                instruction.instruction.GetComponentInChildren<Text>()[0].color
                ↪ = Color.grey;
                instruction.instruction.GetComponentInChildren<Text>()[1].color
                ↪ = Color.grey;
                instruction.instruction.GetComponentInChildren<Image>().sprite
                ↪ = tickSprite;
            }
        }
    }
}
// Method to invoke when the "TaskCompleted" event is
↪ triggered
void TaskCompleted(int i){
    // Updates subtask state
    InstructionData instruction = instructionsList[i];
    instruction.state = true;
    instructionsList[i] = instruction;
}

```

**Code Snippet 5.4:** Setting up the TaskCompleted Event

and greys out the text to make it more obvious which instructions have been completed by the user. It does this by invoking a "TaskCompleted" event and sending the id of the completed task which is then used to update the clipboard (See snippet 5.4).

### Interactions

To increase the immersion of the simulator, hand models have been used to represent the controllers within the environment. Each of the fingers on the hand model are linked to a specific button on the controller. For example, when the trigger is pulled, the index finger is closed, the grip button controls the middle, ring and pinkie finger simultaneously, and

the thumb-pad controls the thumb. This gives added control over the built-in interactions and adds more realism to the environment.

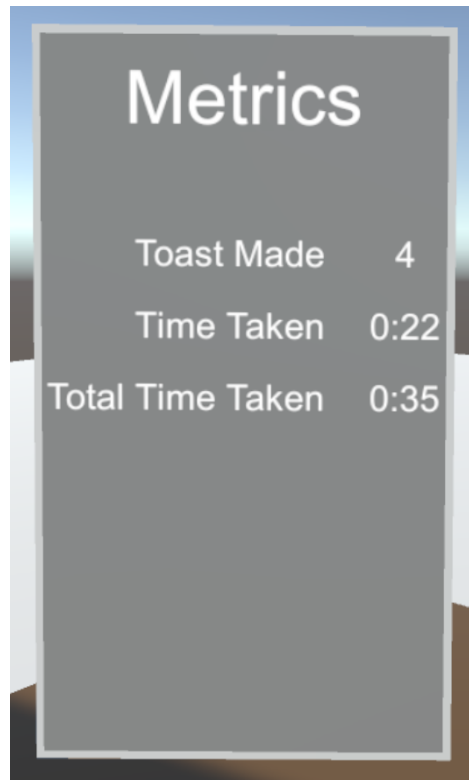
Object highlighting has also been included to provide visual feedback to the user. When the user attempts to interact with an object within the virtual world, if they are able to interact with the object, it becomes highlighted. For example, when the user picks up an object, an outline appears around it to indicate that their hand is close enough to pick it up.

### **Visual Feedback**

To track the users progress, metrics were added to the tasks that are present within the application. Each metric is captured using the task event system. For example, when the participant first picks up an object, it triggers a grabbed event that starts recording the total time taken to complete the task. Once the task is completed, another event stops the timer and updates the metrics for the tasks. An example of the metrics that are used in the toaster task can be seen in Fig. 5.5. Each task has a different set of metrics associated with them, including the total time taken to complete the task, the time taken to complete specific parts of each task, and other useful metrics such as amount of toast made, or how full the cup is. These metrics are displayed within the environment to allow the user to see how well they did. This can enable them to attempt to beat their previous score for that task by trying to complete it faster on their next attempt.

## **5.6 Acceptability Study**

An acceptability study was conducted to answer two questions. The first is whether VR could be used to aid in the cognitive rehabilitation of stroke patients over the age of 65 by allowing them to practice ADLs in a safe environment, and whether the patients and staff would accept VR as a rehabilitation tool. Ethical approval for this study was obtained from the NHS through the IRAS application process. Any indemnity and/or compensation for the study was covered by the NHS.



**Figure 5.5:** The metrics for the toaster task

### 5.6.1 Inclusion Criteria

For participants to be accepted into the study, they must be current inpatients at the Countess of Chester Hospital and meet the following criteria:

- 65 years old or over
- M-ACE (Mini-Addenbrookes Cognitive Examination) [40] Score between 15 and 25 (Suggesting mild to moderate cognitive impairment)
- Does not suffer from paranoia, mental illness or epilepsy
- No known diagnosis of Dementia
- Able to give consent and complete study procedure

Any participant that does not meet the specified criteria were not deemed to be eligible to take part in the study.

### **5.6.2 Experimental Design**

Eight in-patients at the CoCH Stroke Unit were approached and asked if they would take part in a semi-quantitative study and was provided with an information sheet detailing what happens during the study and what is expected of them. The study was conducted over a four week period. All of the participants were aged over 65, and had a recorded M-ACE score pre-study ranging between 15 and 25. Each of the participants received a single therapy session using the StrokeVR trainer, where they were immersed into the virtual world and asked to practice several of the tasks that were available within the application. The training was done while the participants were in a seated position on a plinth or wheelchair in a therapy room. The participants were also asked to answer some questions based on a structured questionnaire after the session to assess their thoughts about the simulator. The questions were split into two sections. A likert scale was used to gauge their enjoyment of the application, whether they thought it was helpful, whether they would continue using the application, and whether they thought it would benefit them in the long term. Three open questions were also included. These were used to find out what was good and bad about the therapy session and what could be improved.

As part of the study, some of the staff members on the ward were also given an information sheet describing the purpose of the study and were asked to help to run the therapy sessions. Those who agreed were trained up on how to setup and run the StrokeVR trainer. After a therapy session with a patient using the application, the staff member(s) that ran the session were also asked questions based on a structured questionnaire, similar to those given to the patient, to gauge their feelings towards the simulator and whether they believed it would be beneficial to the patients and would make a good addition to the normal therapy process.

#### **Staff Training**

Prior to starting the study, a group training session was conducted to show the members of staff what the patients will be experiencing and

how to set up the equipment on their own. A member of the therapy team volunteered to be a patient and was immersed into the environment and asked to attempt each of the tasks (See Fig. 5.6). This was also an opportunity for the staff members to ask any questions they had about the application and the study.



**Figure 5.6:** Staff training session

### **Infection Control**

Before the study could be conducted, the headset needed to be signed off by the Infection Control department at CoCH. Due to concerns related to the abundance of fabric incorporated in to the design of the Oculus Rift headset, and the inability to ensure the removal of all bacteria from the fabric, the HTC Vive was used for the purposes of this study. Because of similar concerns about the fabric strap, face-pad, and the amount of small spaces that skins cells and other matter could get into, the headset was placed inside a large disposable plastic bag to reduce patient contact and a leather face-pad and disposable head-strap were attached to the headset and bag.

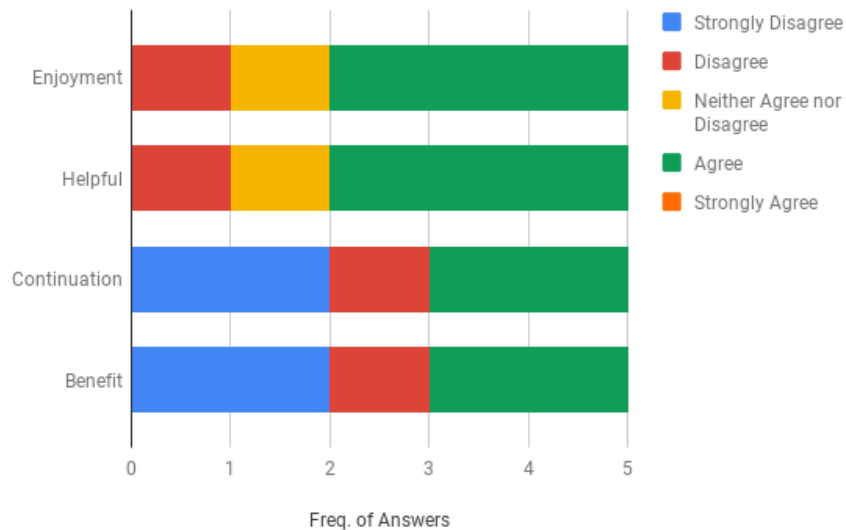
### **5.6.3 Results**

Five of the eight patients that were approached agreed to take part in the study. The results from the questionnaires that the patients completed suggest that VR could be an acceptable tool for rehabilitation. Fig. 5.8



**Figure 5.7:** The HTC Vive with a disposable head-strap, face-pad and encasing bag.

shows how the participants rated the application and their experience based on the four questions provided. Three of the participants stated that they agreed that they enjoyed using the application, and they thought that it would be helpful to their recovery. Two participants expressed that they would continue using the application and that they would benefit from its use over an extended period of time. Two of the patients strongly disagreed with these statements. It is believed that this may have been because they were unable to fully use the application due to the infection control measures that were put in place. Due to the temporary disposable strap and plastic bag that was used to comply with infection control measures, the headset would often slip out of place or feel heavy. The patients that enjoyed the application commented that they liked that the fact that you could reach out and grab objects and that the application has you carrying out day to day tasks. Another comment was that they liked using the application because it was something different from their normal therapy. The patients that were able to interact with the application and complete the tasks spent roughly 15 to 20 minutes immersed within the environment before feeling tired or wanting to remove the headset.



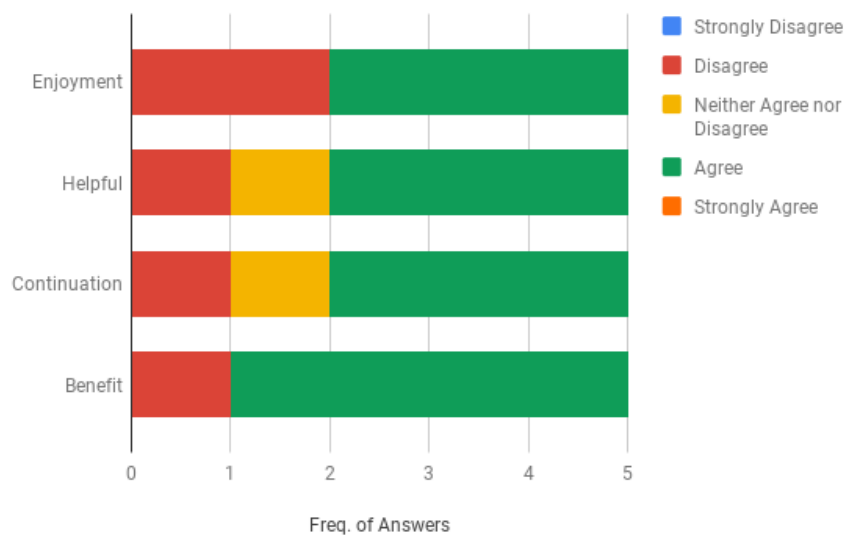
**Figure 5.8:** A graph showing how the patients felt about the application

An exception was made by the consultant physician and senior occupational therapist to include a patient who scored 10 on the M-ACE to be included in the study. This exception was made because, even though the patient scored below the threshold, he was deemed to be cognitively capable enough to understand the instructions he was given and use the application, as well as provide coherent feedback on their experience. The staff members on the ward stated that the two of the patients who did not elect to take part in the study were more focused on getting home and not interested in anything else that was happening at the time.



**Figure 5.9:** One of the staff members using the StrokeVR application with the Infection Control measures

Most of the staff that assisted with patients during the study thought that the application would be of benefit to the patients and help them to recover if used over a long period of time. Some of the comments made were that the application provided something interesting for the patients to do and that they thought it was an enjoyable experience. They also thought that the controls and visual layout were simple and that it allowed the patients to carry out functional tasks that they would not normally be at a level to do in the 'real' therapy kitchen. Some of the staff members commented that the patients couldn't see their hands within the environment, potentially confusing them and distracting them from their experience of the application. It was also commented that although the controller and interface were nice and simple, a much simpler controller would have been better, potentially containing only one or two controls.



**Figure 5.10:** A graph showing how the staff felt about the application

However, a few of the issues that were raised by the patients and staff was about the weight and size of the headset and the plastic bag that was used as a temporary measure to keep the device in line with the Trust's infection control guidelines. They commented that the headset was too heavy and would slip out of place due to the plastic bag. It was also mentioned that the fit of the headset was an issue, potentially



another reason why the headset would slip out of place. One of our participants suffered from complete blindness in their right eye and visual issues in their left. When attempting to use the HMD during the acceptability study, they found that they were having difficulties using the application because they found that their vision was too blurry to fully see the environment and expressed that they would be unlikely to use it again. They remarked that this is most likely due to their visual issues and not necessarily due the technology itself.

## **5.7 Conclusion**

A VR based cognitive rehabilitation simulator was created. This simulator was designed to demonstrate the feasibility of a cost-effective virtual environment for aiding in the cognitive rehabilitation of patients who have suffered from cognitive impairment due to stroke or serious head trauma, using commercial off-the-shelf components. The application allowed users to practice ADLs in a safe, virtual environment without the need to be moved to a therapy kitchen or gym and provides immediate feedback to the user to help them improve.

An acceptability study was conducted to determine whether patients aged 65 or over would accept a VR application as a tool for cognitive rehabilitation. Eight in-patients at the Countess of Chester Hospital were approached to take part in the study, five of whom agreed and consented to taking part. Results from the questionnaires taken during the study suggested that the majority of the patients and members of staff enjoyed using the application and found it helpful. However, some of the patients didn't feel like they would personally continue using the application. It is believed that this is due to the temporary measures that were put in place to comply with infection control. These measures made the headset less comfortable for the patients and harder for the staff to make sure it fit properly. This reduced the immersion of the headset, and in turn, the sense of presence that the patient would have developed while using the headset. If better Infection Control measures were devised and implemented when using Immersive VR HMDs, then the

application has the potential to have a very positive effect on the patients rehabilitation, as demonstrated in other studies using non-immersive VR [52]. Out of the five patients, three were unable to complete the tasks in the application due to visual impairment or issues with the headset. The other two participants were able to complete the tasks and spent around 15 to 20 minutes using the application and were happy to continue using it and only removed the headset when they were asked if they would like to or they completed all of the tasks.

Observations made during the study highlighted some of the criteria used could be modified during further research. For example, the lower threshold for a patient's M-ACE score could be lowered but the patient would still need to be able to understand instructions and provide feedback. This would require a trained member of staff to assess the patient and make a decision. Another criteria that would need to be assessed would be the severity of visual impairment of the patient, and whether they will be able to fully see the virtual environment.

The outcomes found during this study will be used to inform decisions made during the planning and undertaking of a multi-hospital pilot study that is currently being planned. More details of this are provided in Chapter 6.

## Chapter 6

# Conclusions and Future Work

### 6.1 Conclusions

Activities of daily living (ADLs) are an important part of the daily routine of healthy people. When something happens to a person that means that they are unable to complete ADLs, the process of rehabilitation and training helps them regain their ability to live independently. VR has been used in the past as a way of assisting with the rehabilitation and training of patients in a wide variety of different areas, such as physical rehabilitation, cognitive rehabilitation, medical training and powered wheelchair driver training. However, the majority of these applications misused the term VR to refer to a video game style application viewed on a television or computer monitor. The proper use of the term VR refers to a high-end human-computer interface that allows users to view and interact with a 3D virtual environment using a range of different senses such as sight, touch and sound. Up until recently VR technology was bulky and expensive, however the emergence of low-cost VR technology, such as the HTC Vive and Oculus Rift, has made VR more accessible to a wider range of people. The release of MR headsets and technologies has also made it more accessible through the use of AR for mobile phones and standalone devices like the Microsoft HoloLens.

As presence is important to the success of rehabilitation and training in VR, research has been conducted to find a way to quantify a users sense of presence. One example is a questionnaire devised by Witmer *et al.* [115], which specifies a list of questions that a user can be asked to determine their presence within the environment. In the paper, they also discuss the role of presence in learning and performance, stating that although the results have been mixed when relating presence with

learning, many of the factors that affected presence also enhanced learning and performance. They state that factors that are believed to increase immersion, such as minimizing outside distractions and increasing active participation through perceived control over events in the environment, may also enhance learning and performance. Because many of the factors involved in learning and performance that also increase presence, they believe that it would be very surprising if there wasn't a positive relationship between presence and performance. In retrospect, a questionnaire to determine a users sense of presence could have been used during the studies that were conducted as part of this thesis to determine whether a relationship between presence and the improvement that the participants demonstrated during the study was present.

During this thesis, three novel solutions using low-cost VR and MR technologies were developed to fill some of the gaps in the research previously mentioned. One such solution was a novel virtual training environment created using a low-cost VR HMD and games engine that was designed to provide a method of training powered wheelchair manoeuvres in a safe environment that can be set-up at home to enable the user to practice between their assessments at their local wheelchair centre. The application was capable of simulating a range of different configurations and variations of powered wheelchairs. A validation study was conducted to evaluate the effectiveness of the VR training application. Results from the study showed that the group that used the VR training simulator improved more than the control and desktop groups. This was extremely encouraging as it showed that the Wheelchair-VR application did help with the training of powered wheelchair manoeuvres, however an issue that arose from the study was that some of the participants experienced varying degrees of cybersickness. The results from the SSQs from validation study showed that after using the application they did experience increased levels in the different symptom clusters. There has been research into reducing the effects of cybersickness, including integrating different effects into the

environment. The use of MR was potentially the most effective as it would remove the cause of the issue. A second small study was conducted to determine whether a user could tell the difference in VR between different chair configurations. Results from this study showed that there were definite preferences between the three chairs used depending on the situation.

Because of the issues related to cybersickness in VR, a MR version of wheelchair training environment was developed using the Microsoft HoloLens. This was designed to be used with a real wheelchair in a empty environment. The system would then overlay different obstacles, depending on the scenario that was selected, within the environment that the user could navigate around to help them practice manoeuvring the wheelchair. As the simulator is used with a real wheelchair, the application can be used with any configuration of chair, and can be used with manual and powered wheelchairs. Results from a validation study didn't provide any statistically significant values, however, the mean improvement from the different groups showed that the VR and MR groups did improve more on average than the control group. The SSQs from the VR and MR group also show that the participants in the VR group declared increased levels of simulator sickness after using the Wheelchair-VR application. In contrast, the MR group reported little to no change in any of the symptom clusters, with several reporting that they felt better after use. These results were very promising, however, the participants who used the MR application commented on the narrow field of view and that the obstacles would shift from their original positions. This was an issue with the device as it was only capable of a small FoV and the area used during the study was too large and nondescript for the device to track accurately.

The third solution was a VR application, built using a low-cost VR HMD and games engine, that was designed to aid in the cognitive rehabilitation of stroke patients over the age of 65. The system allowed users to practice tasks that would be part of their normal therapy routine in a

safe and controlled environment. This environment enabled the user to interact with objects using a tracked controller. It also provided visual and audible feedback to enhance the experience and provide immediate feedback to the user. An acceptability study was conducted with in-patients at the CoCH. Results from the study showed that the patients and staff would be likely to accept VR as a tool for cognitive rehabilitation but more consideration needs to be taken in terms of the inclusion criteria used during the recruitment process and the infection control measures incorporated into the VR HMD. Patients that have visual impairments could potentially use the application, but the extent of the impairment is important. I.e. someone that shows neglect towards one of the visual fields could still use the application, but someone with poor eye-sight in one or both of their eyes may not be able to use it properly. Similar with cognitive impairment, there is potential for a patient who scored lower on the M-ACE to be able to respond to instructions and the environment better than that of someone who scored higher, depending on the type of trauma and where it occurred.

VR can be used to support ADLs. The immersive nature of the technology, and the sense of presence that the systems provide, allows the user to practice scenarios that they wouldn't normally be able to carry out. However, an issue with Immersive VR is the sensation of cybersickness that can occur if proper care isn't taken around movement and tracking of the user. MR is one way of negating this effect, however the technology is still in its infancy and requires further development and refinement before its potential can be properly utilised for rehabilitation and training. The effects of cybersickness were not found to be an issue in the StrokeVR application as the user was accurately tracked within the real world. Because of this, and due to the nature of the application and added complexity that would be introduced from using gestures within a MR environment, no research was conducted around the development of a MR version of the StrokeVR application.

## 6.2 Future Work

### 6.2.1 Wheelchair-VR

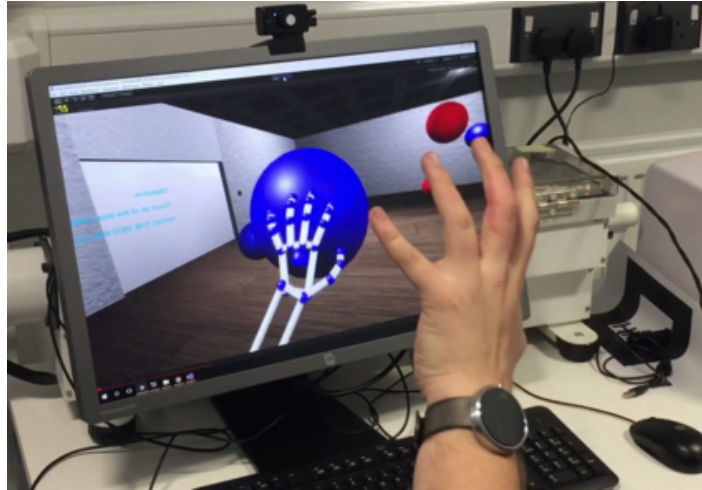
The Wheelchair-VR application could be further expanded by adding more scenarios to practice different skills needed for powered wheelchair usage, and some real world scenarios that would otherwise be difficult to re-enact. This could include replicating the rooms in the users house so they can practice in a realistic environment, as well as more outdoor-based scenarios such as entering or exiting buildings, crossing roads without traffic controls, similar to Zebra crossings.

Other potential future developments could be to include additional technologies to help increase the immersion of the simulator. For example, the leap motion hand tracking device was already partially integrated into the simulator, as mentioned in Sections 3.3.2 and 3.5, which allowed grasping and reaching tasks to be added to the scenarios (see Fig. 6.2). In Fig. 6.1, leap motion device can be seen fixed onto the front of the Oculus rift.



**Figure 6.1:** Participant using the Oculus Rift with the Leap Motion device attached to the front.

Integrating haptic devices, or haptics, into the virtual world may also increase the immersion and training benefit of the wheelchair simulator. Haptics allow the user to "feel" the virtual world through the wheelchair. There are different types of force-feedback device available, tactile and



**Figure 6.2:** In this scenario the trainee has drive the virtual wheelchair around a room filled with coloured balls. The task is to collect the blue balls by reaching out and grasping them with their hand.

force-feedback. Force-feedback has been used in previous projects, Harrison *et. al.* [39] created a wheelchair platform that applied forces directly to the rims of the wheelchair to simulate the bumps experienced by the user in the real world. An alternative approach to controlling the virtual wheelchair is to use a force-feedback device to simulate the control interface of the virtual wheelchair. This will allow the user to navigate through the virtual world while experiencing some physical feedback, but only through their hand and not the entire chair. The Novint Falcon USB Haptic device is one example of a consumer haptic device that would be potentially suitable as a control interface for the Wheelchair-VR simulator (see Fig. 6.3). This haptic device consists of three arms that meet at a central point with a hand grip. Each arm has a motor at the end that is updated 1000 times a second and capable of up to 9 newtons of force. Movement of the grip in the real world translates to movement within the virtual world, and the internal motors on each arm gives force feedback synchronized to events within the virtual environment. Scenarios that include uneven floor surfaces and collisions with objects are already implemented within the simulator, using a haptic device would allow the user to experience these events.

A secondary validation study involving participants that use powered wheelchairs could be undertaken to further assess the effectiveness of





**Figure 6.3:** The Novint Falcon set up as the wheelchair joystick. It has been rotated by 90 degrees so that the grip interface corresponds to the orientation of the wheelchair joystick. The polystyrene foam bead pillow has been vacuum moulded to the shape of the Falcon to provide stability [22].

the Wheelchair-VR simulator. Instead of a single short training session between attempts of an obstacle course, the study could involve each participant doing multiple training sessions using the Wheelchair-VR simulator over an extended period of time. Their ability would be assessed before the study and as well as during and after to assess their progress throughout the duration of the study.

### **6.2.2 Wheelchair-MR**

Due to the insignificant results found during the validation of the Wheelchair-MR project, another study using a larger pool of participants could be conducted to try and recreate the results of the initial Wheelchair-VR validation study. The study would follow the same experimental design as the initial study, however the area used for the study would be smaller for better performance of the MR headset and could use actual obstacles such as doorways and corridors instead of cones for certain parts of the obstacle course, making the obstacle course closer to the Wheelchair-VR study.

Another possible improvement would be to allow the user to recreate familiar environments within the Wheelchair-MR application. These environments could be rooms in their own home or their place of work.

This would allow them to practice in a familiar environment which could increase the training value of the application. The environments could be recreated using predefined 3D objects that can be selected from a list built-in to the system or downloaded from the internet via an API such as the Poly API [86], or designed prior to use by a 3D environmental designer using photos of the intended setting or room that are supplied by the user or user's family. More generic scenarios could also be included that could quickly be loaded if the user doesn't have time to setup or use a more specific environments. These generic scenarios could include situations that a wheelchair user may come across in their daily lives, such as a home or work office, kitchen, living room, or bedroom.

### **6.2.3 StrokeVR**

One possible development for the StrokeVR application would be to identify and integrate a wider variety of tasks that would allow the users to practice a more diverse range of skills that they would normally take part in during their daily lives. AMPS (Assessment of Motor and Processing Skills) [4] could be used to model the ADLs that are included within the application. It includes the assessments and outcome measures of up to 125 different ADLs, ranging from simple self-care to multi-step domestic tasks, that could potentially be implemented within the application to provide better feedback to the patients. The tasks that could potentially be implemented include throwing tasks, such as a ball-toss game where they can practice throwing balls at targets with varying degrees of difficulty, or outdoor tasks such as gardening or shopping. The system could also potentially incorporate some form of leaderboard or multiplayer capabilities. This might make the VR therapy more appealing as it would incorporate a small competitive aspect to the therapy, allowing the patients to be able to try and beat the scores of other users.

Due to the issues that occurred with infection control and the VR headset, instead of the temporary solution that was devised during the acceptability study, a better long-term solution would have to be

developed to make the device more suitable for a hospital environment. This could include a way of smoothing out the surface of the headset so that the headset can be cleaned easier, as well as using low-cost and disposable materials that can be thrown away after each use, or bespoke inserts that could be cleaned in line with the hospital infection control guidelines, potentially using a 3D printer to reduce the cost of the inserts.

A validation study would be undertaken to validate the effectiveness of the StrokeVR application. The study would most likely include in-patients and would be conducted through multiple therapy sessions over an extended period of time. The data that would be obtained for the study would mostly include pre and post-study M-ACE scores to track the cognitive recovery of the patients, basic demographic data such as age and gender, and patients medical data to make sure they would be able to use the application, as well as metrics for each of the tasks that the patients use during each session to provide another way of tracking their progress and recovery. These factors will feed into a project starting in October 2018 and funded by Innovate-UK.

In conclusion, this thesis demonstrates that the combination of low-cost VR and MR headsets with modern games engines can be used to develop virtual environments that can be adapted to accelerate the rehabilitation and training of patients coping with different aspects of daily life. As the technologies develops and becomes more powerful, VR and MR could be integrated into a wider array of applications within the context of rehabilitation and patient support.

## Appendix A

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