ON INFORMING THE CREATION OF ASSISTIVE TOOLS IN VIRTUAL REALITY FOR SEVERELY VISUALLY DISABLED INDIVIDUALS

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A thesis submitted in partial fulfilment of the requirements of the
University of Wolverhampton for the degree of Doctor of Philosophy

This research programme was carried out in collaboration with the
Beacon Centre for the Blind

May 2021

This work or any part there of has not previously been presented in any form to the University or to any other body whether for the purposes of assessment, publication or for any other purpose (unless otherwise indicated). Save for any express acknowledgments, references and/or bibliographies cited in the work, I confirm that the intellectual content of the work is the result of my own efforts and of no other person.

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Date........30/05/2021................

Abstract

Virtual Reality (VR) devices have advanced so dramatically in recent years that they are now capable of fully immersing users in experiences tailored to fit a multitude of needs. This emerging technology has far reaching potential, yet is primarily contained to the entertainment or gaming market, with limited considerations made for disabilities and accessibility. Identifying this gap, evaluating these newer VR devices for their suitability as accessibility aids is needed, and clear standards for successful disability VR design need to be defined and promoted to encourage greater inclusively going forward. To achieve this, a series of ophthalmology-informed tests were created and conducted against 24 participants with severe visual impairments. These tests were used as comparative benchmarks to determine the level of visual perception impaired users had while wearing a VR device against natural vision. Findings suggest that, under certain conditions, VR devices can greatly enhance visual acuity levels when used as replacements to natural vision or typical vision aids, without any enhancement made to account for visual impairments. Following findings and requirements elicited from participants, a prototype VR accessibility text reader and video player were developed allowing visually disabled persons to customise and configure specialised accessibility features for individualised needs. Qualitative usability testing involving 11 impaired participants alongside interviews fed into a iterative design process for better software refinement and were used to informed the creation of a VR accessibility framework for visual disabilities. User tests reported an overwhelmingly positive response to the tool as a feasible reading and viewing aid, allowing persons who could not engage (or, due to the difficulty, refusing to engage) in the reading and viewing of material to do so. Outcomes highlight that a VR device paired with the tested software would be an effective and affordable alternative to specialist head gear that is often expensive and lacking functionality & adaptability. These findings promote the use and future design of VR devices to be used as accessibility tools and visual aids, and provide a comparative benchmark, device usability guidelines, a design framework for VR accessibility, and the first VR accessibility software for reading and viewing.

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List of Abbreviations

AMD - Age-related Macular Degeneration

AR - Augmented Reality

CBS - Charles Bonnet Syndrome

CCTV - Closed-circuit television

DBS - Disclosure and Barring Service

DoF - Degrees of Freedom

ELVA - Electronic Low Vision Aid

ETDRS - Early Treatment Diabetic Retinopathy Study

FoV - Field of View

HMD - Head-Mounted Display

IPD - Interpupillary Distance

LV - Low-Vision

LVA - Low-vision Aid

LVIS - Low-Vision Imaging System

MNRead - Minnesota Low-Vision Reading Test

MR - Mixed Reality

OCR - Optical Character Recognition

OST - Optical see-through

PCSC - Pelli-Robson Contrast Sensitivity Chart

VST - Video see-through

VR - Virtual Reality

XR - Extended Reality

Acknowledgements

I would like to thank Beacon Centre for the Blind for co-funding this Studentship and providing much support throughout the project and aiding with participant selection and testing. Thank you to Arwyn Jones, previous CEO of Beacon, Lisa Cowley, current CEO of Beacon, and Matthew Harrison, former Technology Innovations Manager, for their support and interest in the project.

All of the participants that have volunteered in many test sessions, interviews, and general discussions have been invaluable to the completion of this research, and I would like to thank all of you who have been involved in the testing process.

I would also like to thank my supervisors for their continued support throughout the completion of this doctorate. Dr Fernando Loizides for providing immeasurable support and who without this project would not have started. Dr Vinita Nahar for her dedicated support as the Director of Studies. Prof. Andrew Pollard as the dedicated business supervisor and collaborator with external companies. Prof. Amar Aggoun for his vast experience in supervising projects.

Finally I would like to thank my family and friends who have supported me throughout this endeavour, and especially my father Philip Douglas Weir who spurred me to further my academic pursuits with years of encouragement.

Chapter 1

Introduction & Motivation

With recent technological advances, we are at a point where we can occupy and entertain the human senses in increasingly interesting and complex ways. One of the most impressive developments is the leap in Virtual Reality (VR) devices, and specifically the evolution of Head-Mounted Displays (HMD), which are able to fully replace one of, if not humanity's most important sense, sight (Majid et al. 2018; Jerald 2015). Through sensory input users of these devices can fully explore any number of visualisations that we can think of and create, realistic or not, through computer-generated or real-world projections. The applications for this kind of technology are impressive, yet there has not been enough attention on utilising VR for sight assistance.

An exploration of assistive technology shows a disparity between the technologies currently available compared to the rising number of the population diagnosed with severe visual impairments. Private encounters[1] with leading tech companies exploring their intent to develop commercial and affordable products specifically aimed towards those with visual disabilities have returned a general consensus that such products do not constitute a substantial enough return on investment for mainstream adoption due to the limited market. To put things into perspective, studies reported that in the UK alone there were 513,000 reported cases of macular degeneration (a degenerative, non-reversible disease which causes major central vision loss) in 2012 (Owen et al. 2012), by 2018 this increased to nearly 1.5 million people in the UK (Macular Society 2018b), in the US 11 million people, and "Estimates of the global cost of visual impairment due to age-related macular degeneration is $343 billion, including $255 billion in direct health care costs." (BrightFocus 2019).

It is evident that severe visual impairments are a growing concern, yet there is currently very little evidence of affordable, commercially available assistive hardware and software that is reaching both homes and care facilities of people with severe visual disabilities. Interviews with involved participants have shown that severely impaired people are still relying on basic equipment for sight assistance, such as magnifying glasses and screen reader software, for reading and navigating interfaces, often falling back

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[1] Due to confidentiality agreements the names, identities, or features of these companies are not permitted to be disclosed. It can be disclosed however that the companies mentioned employ over 100,000 employees each and are related to the creation of hardware and software solutions.

on caregivers for aid or other sensory stimulation, such as force feedback (basic touch) with reliance on walking canes or railings.

There are many assistive apparatuses that have been dominant for decades without substantial evolution and are simply out of date, pointing to a missing gap in the field that has not yet been realised; namely, successfully integrating modern digital technology to assist the general public beyond specific use cases. That is not to say, of course, that no noteworthy advances have been made in recent years, and one of the most successful pushes towards accessibility has come through the ever increasing adoption of smart phones, devices that can be used as capable accessibility tools. A study looking at whether mainstream devices are replacing traditional visual aids reported that from 466 participants, 87.4% believed this to be true (Martiniello et al. 2019). Unfortunately, to many low vision users smart phones run into the same issues as screen readers and screen magnification tools (Arrue et al. 2019; Gowases, Bednarik, and Tukiainen 2011; Xiao, Xu, and Lu 2010), such as partial viewing causing a loss of context (Moreno et al. 2020). Many smart phones rely heavily on web-based content as well, where web-based content has been scrutinized and found not meeting accessibility requirements (ibid.). In our studies with severely low-vision participants, less than half used a smart phone, and only a third utilised accessibility features, with most commenting that they were either not aware of available features or were not interested.

1.1 Academic Questions and Aims

The main goal of this research is to develop an understanding of whether and how emerging VR HMDs can be used as visual aids to enhance the lives of users with severe visual disabilities. This work looks at how a newer VR HMD may be advantageous over existing techniques for visual aid, what they are capable of, and their shortcomings. To reach these research goals, the following academic questions were devised:

(i) Can we identify where (if any) VR Head Mounted Displays show improvement to the visual acuity or reading ability of those with severe visual disabilities?

(ii) What are the usability needs of severely visually impaired users that would allow for the most effective utilisation of a VR HMD as visual aid replacements?

To answer these research questions, the following objectives are addressed:

(i) The exploration and evaluation of current literature surrounding VR, VR devices, visual disabilities, and existing visual aid research.

(ii) The creation and implementation of optometry-inspired tests that cover: (a) visual acuity relating to letter recognition, (b) reading ability [speed], (c) reading ability [accuracy], (d) colour accuracy, and (e) effects of brightness and contrast.

(iii) The testing and evaluation of severely impaired participants on comparative visual acuity ability between physical and VR equivalents.

(iv) The development and testing of informed prototype accessibility reading/viewing application for VR devices.

(v) The evaluation of usability testing to determine appropriate needs for effective accessibility.

(vi) The development and testing of a usability and design framework for successful accessibility with virtual devices for persons of severe visual impairment

1.2 Methodology

To reach the proposed research aims, an iterative design process was followed split between two main research stages and two testing stages. As there are multiple approaches to design, solutions are influenced by design decisions that appear unpredictably as iterations (Gero 1990). The first stage involved the investigation of literature surrounding the area of current VR HMDs as well as research on similar visual aid technologies published not only in the past but also most recent iterations. A theoretical framework is developed and presented that introduces visual disabilities as a whole and relates virtual reality concepts towards sight-loss, assistive aids, and modern adaptations. As commercial VR devices are a newer type of technology, and this research first commenced in 2017 not long after modern VR devices started to appear, there was and still is limited research on the applications of newer VR headsets towards visual impairments, resulting in a higher reliance on older system analysis. Following a review of the literature, the efficacy of a VR headset was to be determined as there is limited existing evaluation that shows the predictability of usability of such devices for persons with severe visual impairments. As these devices are emerging technologies there has not been enough official validation through ophthalmology standards to be verified as assistive for eye wear, acuity, or as assistive technologies. Due to this there is limited research towards standardised testing for evaluation of acuity or vision designed for current VR HMD devices. To be able to determine the level of efficacy a VR device could provide, the first research stage investigated different types of existing and standardised optometry tests that can be used as a baseline for comparison and adapted for a VR environment. As these tests were not designed for VR they cannot be used to accurately compare using the standardised scoring system, yet they can provide a template and framework for comparative practices and be used to give indications of performance without necessarily diagnosing a user's acuity or other typical outcomes. To achieve this a series of tests were selected, based on consultation and recommendations from registered optometrists and ophthalmologists, and then adapted towards the VR equipment used. Several aspects of vision ability were considered and the target focus of each test, looking at Letter Recognition, Word Recognition, Contrast Detection, Reading Speed, and Colour Detection/Accuracy. Collaborations with Beacon Centre for the Blind were set in place to find appropriate participants within the target audience of persons with severe visual impairments. Succeeding the first test stage an analysis was performed looking at statistical significance in a quantitative nature as well as a qualitative exploration of data between each participant's profile and scoring. Findings were used to inform the second research stage, taking feedback from participants, interactions with the VR system and testing process, as well as what elements appeared from results. The second research stage focused on the development and implementation of accessibility software designed around the findings of the first research stage and feedback. This software would allow further exploration into the efficacy of VR devices for use as vision replacement aids and allow the deployment of focused improvements that were shortcomings of the previous study. To achieve this further literature was explored looking at current assistive technologies and what they provide; what was done well, what was missing, and what are the areas that persons with severe visual impairments struggle with and could be improved. Feedback from the previous study highlighted that the desire to independently read and view media was particularly important, and thus shifted the focus of this study towards this goal. As VR devices are newer to the public and control methods are an ongoing development, design principles can be problematic and encouraged an iterative design process.

Development of the software was to go through several stages of iterations, advised and demonstrated through both unstructured test trials with volunteers of the targeted group, and fed back into the development cycle until a final usability study was performed with a more complete prototype of the software. The usability study would focus on the overall evaluation of the software as well as user experiences and feedback. To determine effectiveness an interview process was conducted utilising unipolar scale questions, likert scale questions, and semi-structured open ended questions. Testing was done following the think-aloud protocol(Lewis 1982), encouraging participants to verbalise what they are thinking as they perform tasks and allowing for constant data to be gathered. Following the second test stage an analysis of data would be again completed looking at both results from the conducted experiment and the follow up questionnaire results. Findings are then used to create a framework, presenting a set of heuristics for designing around VR accessibility. The results of both research and test stages allow for the evaluation of VR devices to be used as accessibility aids for persons of severe visual impairments, as well as providing a framework and set of adapted tests for evaluating vision and designing for VR accessibility for the visually impaired.

1.3 Thesis Contributions

This thesis uses commercially available emerging technology which has the potential to act as the catalyst to address this gap. Noting that VR advancements have seen dramatic improvement in the last 5 years (after the failed hype of the 1990's (Murphy 2016; VRS 2015)), it capitalises on the opportunity to test their potential to assist the target audience. To evaluate the suitability of VR devices to be used as visual aid replacements, optometry-inspired tests were developed to be used as benchmarks in gauging the visual acuity and performance of participants compared to real-world equivalents, and determine any visual benefits. As no medically validated test currently exists for VR to the best of knowledge, and mainstream VR devices have had no design considerations for severe visual impairments, these tests had to be created as replacements to validated existing optometry tests using natural vision. These tests were performed alongside 24 severely visually impaired participants that were service users from Beacon Centre for the Blind (Beacon 2020), a charity that supports people living with sight loss. Each participant performed tasks to measure their ability to detect letters within VR, their reading speed, reading accuracy, colour accuracy, and effects of brightness/contrast on reading. Each test involved a pre and post interview that allowed the identification of key benefits and weaknesses of utilising a VR device as a reading aid, and eliciting requirements for software development and hardware considerations. One such repeated elicited requirement shared by participants was the ability to read and watch videos again, which was the main inspiration for a VR accessibility application.

The identification of benefits helped to build a framework allowing future work to develop towards successful accessibility VR design, and designed alongside and concluding the construction of a prototype VR reading and video viewing accessibility application, specifically designed for those with severe visual disabilities. This prototype software was developed and tested along 11 further participants to determine software usability, feedback, and to explore how visually impaired users make use of a virtual viewer that is represented in 3D space, as well as what accessibility challenges are faced. Once again a pre and post interview and evaluation was conducted, allowing for further user requirements to be identified and tested, and used to inform the created framework. The limitations of current hardware are also reported on, and point to the development requirements of bespoke technology for maximising the potential of VR for the specific user group.

When compared to existing equipment and tools used for accessibility, VR has the capability of current mediums, such as screen readers, audio books, or specialist software on typically 2D screens, but has the added benefit of being able to translate these existing techniques into a 3D space with realistic depth. This extra dimension to sight with specialist software has not become widespread thus far and could vastly improve accessibility techniques to allow disabled persons to access information and technology in a way not reached previously.

The findings uncover where this emerging technology benefits and is able to assist visually impaired users, especially since the devices used are not designed for any kind of visual enhancement outside of entertainment immersion. With all charts tested at two distances, VR results showed increased performance when testing at closer distances compared to further away, particularly with letter recognition. If these devices are providing increased clarity for users with particular visual impairments or lacking acuity under certain conditions, it serves as evidence and justification for specialised software and equipment that can build upon this existing technology and enhance it, thus enhancing the lives of a large portion of the community that have otherwise been restricted from the VR market, or even emerging technology in general.

This research provides the following main contributions to the field:

1. The creation of optometry-inspired tests for VR standardisation, where currently there is limited research on standards for measuring visual acuity within VR devices.

2. The comparison of visual acuity capabilities of severally impaired users between a tested VR device to physical equivalents, highlighting device suitability.

3. The creation of a design framework and set of guidelines for success-

ful accessibility design for visual impairments, as no considerations are currently made for sight impairment within VR in both hardware design and software.

4. The creation of the first accessibility reader/viewer for VR devices, as none currently exist (commercially available and released).
5. The evaluation of usability testing of the prototype VR accessibility reader and video viewer, used to inform future works and design considerations for VR assistive software for visual disabilities.

Thesis Structure

This Thesis is organised as follows: Chapter 1 introduces the area of interest, covering the existing problem and solutions in the form of research questions and thesis contributions. Chapter 2 introduces the reader to a literature review covering areas of research related to this project. These include areas such as current and previous vision aids, current emerging technology surrounding VR and AR (Augmented Reality) systems, and definitions of various visual disabilities common amongst tested participants. Chapter 3 discusses the design and methodology of the first comparative study, alongside device and test specifications. Chapter 4 presents the selection, adaptation, and implementation of devised tests, as well as statistical analysis and summaries of each test's results. Chapter 5 presents the individual participant portfolios and results, followed by the main analysis and discussion of results gathered from the first study. Chapter 6 discusses and presents the prototype software alongside user descriptors, results, the findings, and presents a framework built from both studies. Chapter 7 concludes the thesis with final conclusions and future work going beyond this research.

Chapter 2

Related Works

Virtual reality research towards accessibility and disability have been extensive over the past years (Ghali et al. 2012; TeamProject 2019), where even the concept of virtual reality itself has been redefined as the technology changes. Older research defines virtual reality in the broader sense, where any computer simulation can be classed as virtual reality, such as video games (Ghali et al. 2012) or 3D renders. Other frameworks have defined virtual reality as the experience of presence through a communication medium, or where one perceives experiencing telepresence (Steuer 1992). While there are many frameworks and definitions that detail virtual reality concepts in broader terms (Steffen et al. 2019), or for specific setups (Blonna et al. 2018; Boges et al. 2020), this research defines virtual reality devices within the context of visual impairments and sight augmentation. One of the shortcomings of current virtual reality devices is their limited design towards visual accessibility, despite existing research suggesting that older conceptual devices show good evidence of improvement towards persons of visual disability, something that is expanded upon within this chapter and reiterated. There is still not enough awareness of the capabilities of virtual reality towards visual accessibility, perhaps partly due to the looser definitions of the term described previously, often leaving concepts segmented towards more general use. To overcome this confusion the framework of the literature review is split between 3 main sections: What are the visual disabilities involved in this research and how do they affect one's vision, what is considered virtual reality and augmented reality within the context of this research, and finally the varying technological devices, aids, and solutions produced for both older and newer systems. Figure 2.1 shows the design methodology of this chapter, with topics pertaining to each section.

In order to situate the reader, this chapter covers areas that both current and previous work has reported on, within the multidisciplinary field of assistive technology; specifically, relating to assistive VR and AR devices. Section 2.1 begins by covering and defining the different medical conditions that are common amongst the participants within this research. This helps to give a better understanding of how one's vision might be affected by each condition, as well as the motivations and need for this research. Section 2.2 then defines what VR and Augmented Reality (AR) is, looking at both the history of the terms as well as the current technical

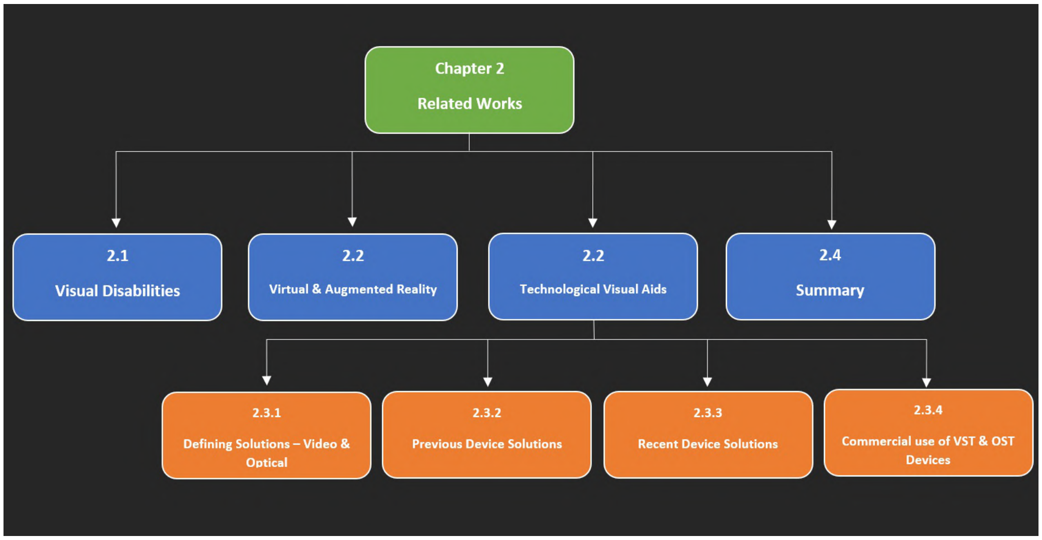


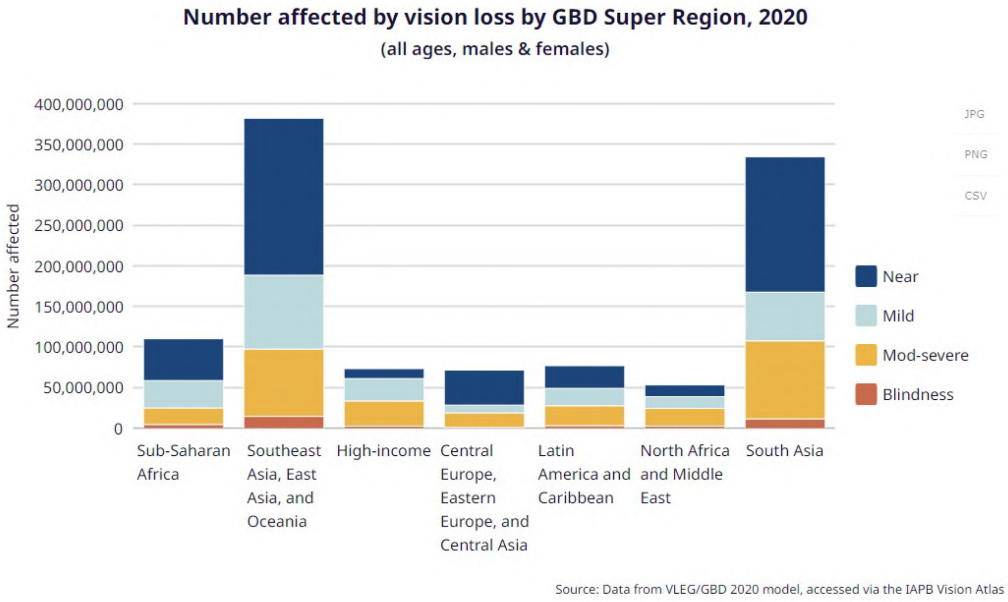
Figure 2.1: A design chart representing the structure of the related works.

expectations of a system within the context of this research. Section 2.3 identifies past publications by giving an overview of older research's findings towards the efficacy of electronic assistive aids, with some examples of studies that have taken place. Gaps in the research are highlighted and emphasise the need for future innovations. Sub section 2.3.1 defines and categories the most common types of VR/AR HMDs today with device examples from research as well as limitations of each approach. Sub section 2.3.2 covers older system approaches towards electronic vision aids and what previous perceptions and results from such devices were. Sub section 2.3.3 presents current advancements in recent years of systems that closer resemble what we see as modern VR/AR devices towards visual accessibility. Sub section 2.3.4 highlights some of the commercial use of HMD devices that have become available to purchase and sold as solutions for multiple contexts. Finally a summary is presented in section 2.4 that covers all of the findings presented in this chapter with final comments.

2.1 Visual Disabilities

This research focuses around assisting individuals with severe visual impairments, low-vision (LV) users with very limited sight that fall under the classification of severely sight impaired (blind) (RNIB 2019), or “legally blind”, without full blindness. The World Health Organisation classifies ‘Severe’ vision impairment as acuity lower than 6/60 to 3/60, and ‘Blindness’ as acuity lower than 3/60 (WHO 2019b). Looking at the number of visual impairments world wide, it is estimated that 2.2 billion people have some form of vision impairment (WHO 2019a), with 237 million of these falling under the category of moderate to severely impaired (Adelson et al. 2020). Figure 2.2 helps to highlight the number of people with moderate to severe visual impairments, this research’s target group, as well as the importance of the number of people affected by severe visual impairments.

Within the classification of severely visually impaired individuals, there are multiple conditions that an individual might have. Although some conditions produce the same effects on one’s vision and may overlap (i.e. short-sightedness), the underlying reason for these effects are different. We may therefore be able to address an effect, but not the specific underlying cause for that effect. It is worth noting that often individuals, such as the participants within this research, may have more than one conditions that share similar symptoms and as such descriptions may overlap. This research does not focus on any specific condition as it is a broader look at the effects of VR on visual impairments, and the findings from this research will feed into more specific approaches that will be better guided towards individual conditions.



Source: Data from VLEG/GBD 2020 model, accessed via the IAPB Vision Atlas

Figure 2.2: The number of people affected by visual impairments by the Global Burden of Disease regional classification system (IAPB 2020)

The effects of impairments can vary vastly between different conditions, and within specific conditions the level of visual distortion itself can greatly differ between individuals on a case by case basis. (See Figure 2.3 for examples) These complex conditions can be very difficult to manage, and many do not have solutions to repairing or supplementing an individual's

Standard[a] Cataract[b] Diabetic Retinopathy[c]

Glaucoma[d] Macular Degeneration[e] Tunnel Vision[f]

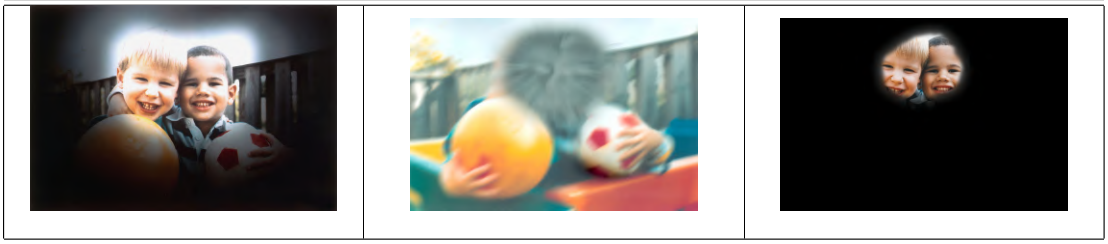


Figure 2.3: Images of how different conditions may interfere with visuals (NIH 2012)

vision to a reasonable level, or at least a level they desire. Regardless of this there are solutions we can apply to alleviate these problems by either helping the individual to see clearer with specialist equipment and techniques, or with accessibility equipment that can assist with tasks and everyday comforts to stand in for damaged vision. One of the more impressive technologies to become popular in the last 5 years, VR headsets, is one such equipment this researcher believes will revolutionise the way we look at accessibility.

Below is a selection of the most common visual conditions participants reported during this thesis' studies. A brief definition and description of each condition is given, along with sources for further reading. Conditions not included in this descriptor are omitted either due to their scarcity amongst the test groups, being a sub-condition of a overarching condition, or sharing similar symptoms with a more frequent condition. These descriptors help to give context to both participant profiles and results presented in Chapter 4, 5, and 6.

Macular Degeneration, (See Fig. 2.3[e]) often referred by its most common form Age-related Macular Degeneration (AMD), is where the macula of the eyes is damaged causing central vision loss by blocking the middle of a person's vision (NHS 2016b). This can follow with other symptoms as well, such as weaker colour detection, objects appearing smaller, distorted vision, and hallucinations. Macular Degeneration typically comes in two forms, wet or dry, with dry being a slower deterioration process that has no known permanent treatment, whereas wet is a more severe condition that leads to rapid deterioration if not immediately treated, and roughly 10% to 15% of dry macular cases develop into wet ones (Macular Society 2018a). Another specific juvenile form of macular degeneration (which one of the participants had) is called **Stargardt Disease** (Blindness.org 2018), which is typically inherited from diseased genes from both parents.

Glaucoma (See Fig. 2.3[d]) is diagnosed when the optic nerves connecting the eyes to the brain become damaged caused by pressure of the fluid inside the eye (RNIB 2018b). This condition is often associated with others, but its symptoms include the damaging of peripheral vision around the edges of the eye, and overall blurriness of vision. If untreated, Glaucoma can cause blindness (NHS 2016d). Typically, Glaucoma affects both eyes, although not always at the same time or level of strength.

Nystagmus is the constant involuntary movements of the eyes out of the control of the person affected (RNIB 2018c). Although typically discovered from childhood and diagnosed as congenital nystagmus, it can also develop in adults and is diagnosed as acquired nystagmus. Nystagmus is normally a result of how the eyes send information back to the brain, or how the brain interprets eye movement and tries to understand this information. An individual with this condition may struggle to hold their gaze and focus onto objects, making them appear blurry, and sometimes causing sensitivity to light and or difficulty seeing in the dark, as well as the world appearing to move or shake on its own leading onto other possible problems with mobility balance and dizziness (Boyd 2017).

Optic neuritis is the inflammation around the optic nerve which is what transmits visual data from the eyes to the brain and can cause loss of vision (Mayo Clinic 2018b). Symptoms from optic neuritis can include pain, various levels of vision loss which may be temporary or permanent, loss of visual field (a side of the eye's vision), loss of colour vision and perception, and perceiving flashing/flickering lights. Although the exact cause of optic neuritis is unknown, it is believed to be linked to the immune system targeting the substance over the optic nerve and can be influenced or triggered by infections, diseases, or drugs (RNIB 2018d) (Mayo Clinic 2018b). Optic neuritis typically affects one eye but can affect both.

Diabetic retinopathy (See Fig. 2.3[c]) is a condition that can develop in diabetic people, regardless of type, with the risk increasing the longer one has diabetes and the less controlled the blood sugar is (Mayo Clinic 2018a). Symptoms of diabetic retinopathy can vary but can include floaters or spots within the vision, blurred vision, fluctuating vision, impaired colour vision, dark or blank areas in vision, and ultimately vision loss. Diabetic retinopathy usually affects both eyes.

Hemianopia is the loss of sight in one half or section of your eye caused by brain damage (Iftikhar 2018). Two types of hemianopia are most common; Homonymous hemianopia affects the same side of each eye, so both eyes could have the left side of the eye blinded. Heteronymous hemianopia affects different sections of each eye, so the left eye might be blinded at the right, but the right eye is blinded at the left. In addition to sections of the eyes being blinded, other symptoms include double vision, dimmed vision, decreased night vision, distorted sight, and visual hallucinations.

Charles Bonnet syndrome (CBS) is the hallucination of vision typically resulting from vision loss and how the brain copes with this vision change (RNIB 2018a) (NHS 2016c). These hallucinations can appear and range from a variety of things, such as simple patterns to complex imagery of people, places, or detailed objects. Different factors can influence the type of hallucination that appears or the frequency of their appearance, such as birds appearing in a tree that aren't real. There is little information on the exact cause of CBS, or how it can be treated, but CBS can become easier to cope with and less frequent the longer a person has the condition, as they become used to and better at recognising the patterns they might see.

Cataracts (See Fig. 2.3[b]) are the forming of cloudy patches via the transparent disc within the eyes causing blurring or “mist” over vision (NHS 2016a). Cataracts are more common in older adults, recognised as age-related cataract, and are associated with smoking, diabetes, eye injury, drinking, extended steroids use, or cataracts running in the family history. Often cataracts can be treated when severe enough via surgery to replace the affected lens. Typically, cataracts appear in both eyes, but not always developing at the same time or strength.

Photophobia is the sensitivity to light, such as sunlight, that can affect people differently depending on the severity of the condition (G. Bailey 2018). Photophobia is often caused by another disease or condition, one of the most common being Migraines (Kim 2018). In more severe cases photophobia can also be caused by Ocular albinism, Cataracts, Macular Degeneration, Uveitis, or corneal related problems (RNIB 2018e). In stronger cases protective eye-wear like shaded glasses can help prevent symptoms of photophobia.

Marginal keratitis is the inflammation of the cornea which can be caused by sensitivity to bacteria, skin conditions, or from wearing contact lenses (Hingorani, Kang, and Langton 2016). Treatment for marginal keratitis is usually managed through good care of the eyelids and lid hygiene. Sometimes antibiotics or steroids are helpful in calming down eye inflammation allowing for easier treatment via other methods.

Retinal detachment is the separation of the retina from the back of the eye, leading to possible permanent sight damage (S. Taylor 2018). Symptoms of retinal detachment can include floaters or spots, flashing/flickering lights, or dark shadows spreading amongst the vision. Retinal detachment can be caused by numerous things, including age deterioration, lattice degeneration, short-sightedness, past eye surgery such as for cataracts, eye injuries, family history, and diabetic retinopathy.

2.2 Virtual and Augmented Reality

Virtual Reality is a relatively old concept compared to the contemporary advancements in consumer level available products (VRS 2015). The definition of ‘virtual reality’ has had many adaptations or iterations over the years, but ultimately conveys the idea of computer simulations that are not real. Originally, many VR concepts were different adaptations of stereoscopic views that would be placed over the user’s eyes to give the illusion of depth (ibid.). Today, there exist several types of HMD that fall into different types of technological fields and areas. VR devices that we refer to today are usually headsets that sit over the user’s eyes, simulating a virtual environment via lenses processed through a computer, console, phone, or internally to the device. Today’s mainstream VR headsets typically work by utilising 2 lenses calibrated to a smaller display or dual displays, in creating stereoscopic 3D imagery, mimicking how the eyes would see realistic depth and ‘tricking’ the brain into perceiving realism (Goradia, Doshi, and Kurup 2014). Many of these headsets are powered through a cable that is connected to a personal machine that handles the processing load of the visuals, although smart mobile phones combined with VR kits have been popular due to their portability, inspiring the creation of wireless standalone headsets that handle all processing and power needs themselves, something that is gaining momentum in the market (Rogerson 2018) (Feltham 2019). This idea of projecting VR within a device is not a new one, and VR concepts have had several attempts in the past that have failed due to technological limitations such as resolution, colour, and limited motion tracking (Murphy 2016); limitations that are no longer blockades using contemporary advancements.

VR Devices & Capabilities

VR Devices have come a long way since their first proposed concept in 1966 (Sutherland 1968). For a typical PC grade VR HMD today, one would expect the device to be able to render realistic 3D stereoscopic imagery alongside mobility alongside 6 degrees of freedom (DoF) (Roetenberg, Luinge, and Slycke 2009), while a mobile grade VR HMD might only utilise 3DoF. 6DoF from a VR headset describes the motion tracking of the equipment, in that the position, location, and rotation of the head is updated live on all axes (X Y and Z) to allow the user to navigate, interact, and explore an environment more freely and realistically to our natural perception, while 3DoF is restricted to axis rotation only. Most PC VR devices also include motion controllers (HTC Vive 2020; Oculus 2020a; Valve 2020), allowing for both the head and hands of the user to be tracked, although the method of tracking as well as what is tracked may differ between devices, such as hand tracking via headset cameras, or full body tracking through external devices. Some motion controllers are designed similarly to traditional game console controllers, utilising analogue sticks for movement alongside a set of buttons (e.g. A,B,X,Y) and triggers, while some are more minimalist focusing more so triggers and track pads. To summarise, a modern VR headset is capable of immersing one's vision with realistic depth, while tracking motion to allow for realistic interactions, and would be expected to output reasonable audio as well.

The lenses a VR headset uses vary between different brands and device models, yet all use similar techniques to create the illusion of realistic stereopsis. Most PC VR headsets have a limited field of view (FoV) (See Figure 2.4), with devices like the Oculus Rift going up to 86°of horizontal vision, although newer headsets have a expanded FoV for a more immersive experience (See Figure 2.5). For natural sight to perceive depth, our eyes rely on two systems called accommodative demand and vergence demand. Accommodative demand is how the eyes adjust the shape of their lenses to fixate onto a depth plane, while vergence demand is the degree the eyes rotate inwards so their line of sight intersect at a particular depth plane (Oculus 2020d). With VR the accommodative demand is at a fixed point, while the vergence demand is still dynamic, meaning that the true depth of the individual is not replicated but is a best guess estimate. Although the accuracy of depth will vary per each individual, the perception of accuracy is influenced by visual cues, allowing the brain to adjust and ignore slight inaccuracies if the environment is convincing enough (Elisabetta, Miller, Connor, et al. 2020). This uncanny effect helps keep the illusion of realistic depth convincing, and may help to explain reported findings later in this research.

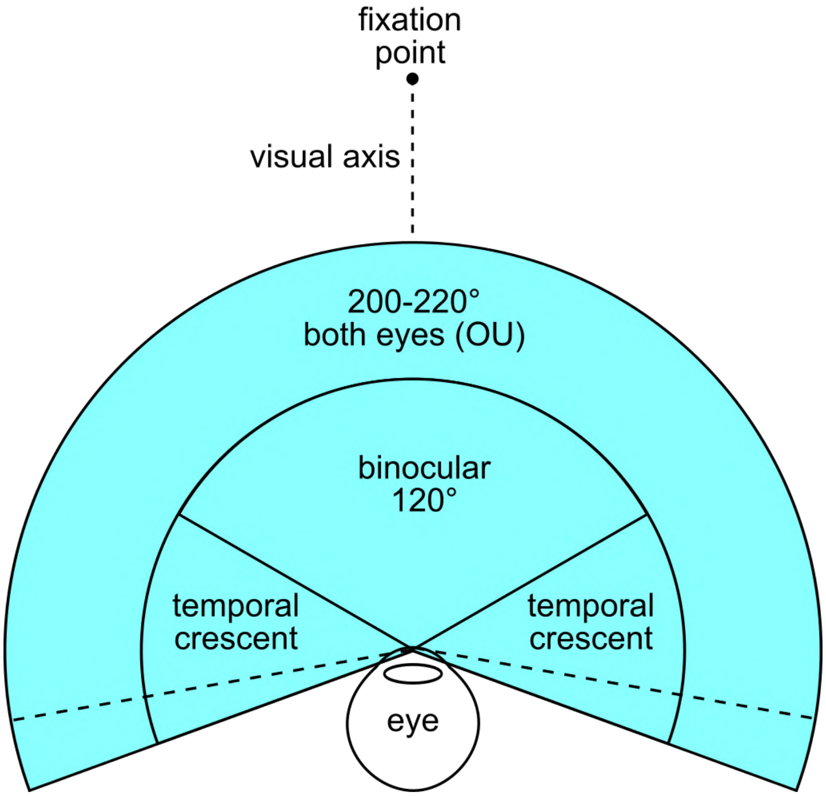


Figure 2.4: A visual representation of a person's line of sight (Zyxwv99 2014).

Figure 2.5: An example of the Pimax VR headset and it's higher FoV lenses.

Some VR headsets are equipped with built-in cameras either utilised as part of the motion tracking method, or to enable AR capabilities (See the Augmented Reality section below). These front-facing cameras are able to render the physical world back to the HMD itself, allowing the user to see their surrounding environment and potentially digitally interact with it, without taking the headset off. Outside of displaying the user's room, these cameras are often underutilised despite being capable of advanced AR techniques, suggesting that their inclusion may be closer to proof of concepts or even future proofing for additional features. Regardless of their limited attention, these included cameras allow many VR headsets to be capable of 'mixed-reality' (Milgram and Kishino 1994) type features, expanding the capabilities of these headsets outside of just VR.

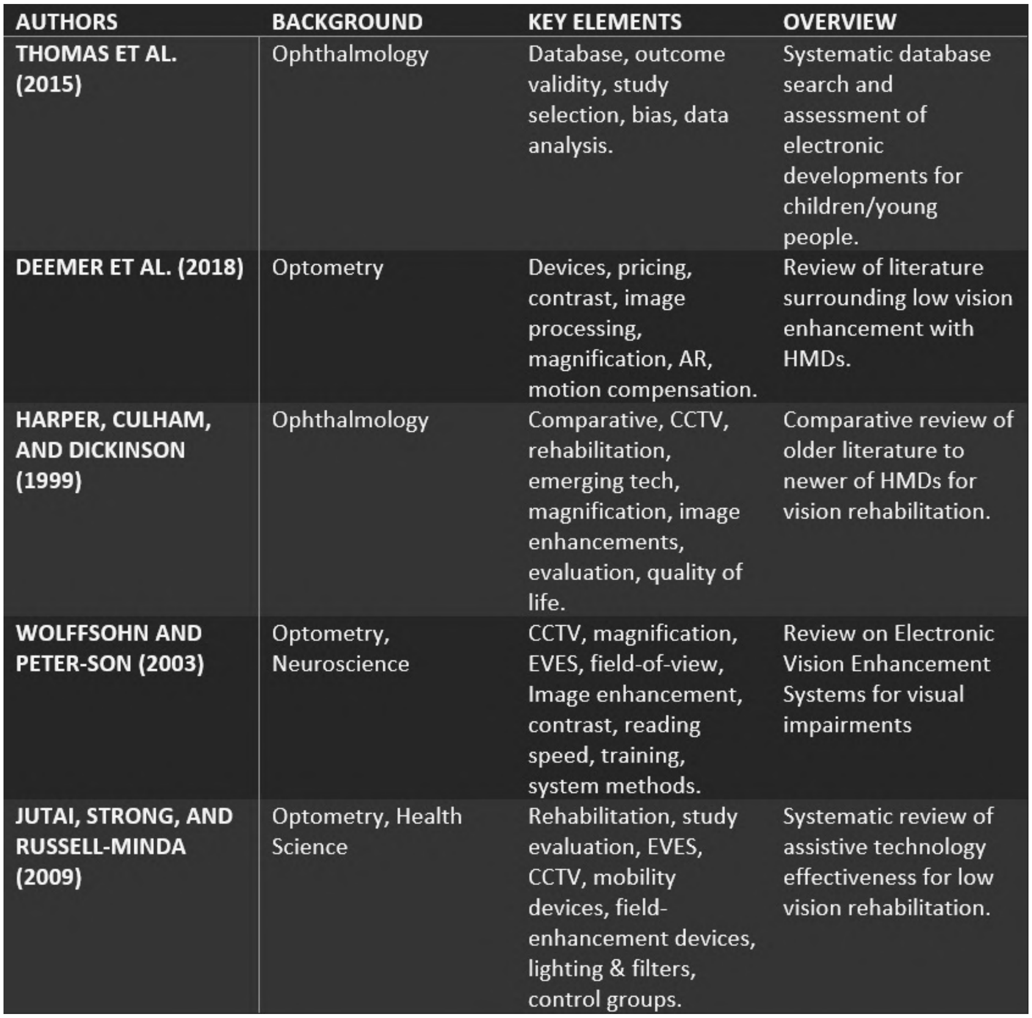
Augmented Reality can be described as a bridge between the virtual and the real world, combining elements to present information registered to a physical environment (Schmalstieg and Hollerer 2016). Modern AR solutions allow us to display virtual components overlaying the real world, such as a floating screen in front of your normal vision. The key distinction between AR and VR is that VR replaces all vision with a virtual one whereas AR overlays virtual elements over normal vision (The Franklin Institute 2018; Overby 2019), yet VR and AR are not necessarily exclusive, as elements from both can be combined for a more complete experience. As described previously, many VR headsets are capable of AR due to having built-in cameras.

While VR today may be closer associated to headsets and marketed as such, although AR devices are headsets as well they are often branded as “Smart Glasses”. As AR devices do not envelop a user’s vision completely like VR devices typically do, only needing to overlay over their existing vision, they are closer designed to glasses which can have several advantages, such as lighter weight design and easier setup. AR devices are fully capable as being used as accessibility tools (Coughlan and Miele 2017), but suffer similar growing pains as VR devices do in that there has been little adoption and limited attention towards this area. While this research does not focus on AR devices specifically, the bridge between these types of devices is shortening, leading to the term Mixed Reality (MR), with many devices falling under this new category despite not necessarily being labeled as such. The advantages of AR techniques can be utilised towards a VR system in creating a better accessibility tool overall, thus AR should not be considered entirely separate.

2.3 Technological Visual Aids

Looking at past publications on various electronic vision systems it is apparent that many adaptations of devices have appeared over the years, yet there is often a lack of consistent terminology or classification between devices, methods, and research. Additionally, a review of current literature and clinical trialling by R. Thomas et al. (2015) showed that there was still a lack of high-quality research in the subject area of assistive technology assessment on reading, educational outcomes, and quality of life for children, possibly due to these technologies still being new. Although this review was focused primarily on children, it highlights that the technology had still not been recognised enough to be used as an alternative to traditional vision aids and that there is a gap in clinical research. Further supporting this, a more recent study looks again at low-vision enhancement HMDs, their history, and techniques for aiding with vision (Deemer et al. 2018). Their conclusions suggest that still, after 20 years of the first engineered concepts up to the more powerful HMDs available today that have solved many past limitations, there needs to be a greater focus on low-vision research. They predict that soon there will be significant change for the way low-vision evaluation and rehabilitation services will be delivered via newer HMD type systems, and that research will need to focus on low-vision systems for newer technologies. Supporting this further, a newer study (Calabrese et al. 2021) comments using the same language, that VR accessibility for low-vision is in its infancy and effective design remains an open challenge. Despite early emerging research, (such work is presented in this section) there is clearly an opportunity for exploring the potential of this newly available technology. In order to identify the right avenues to explore, and the potential that exists, investigation of existing work and where there is indication of potential is discussed, perhaps hindered by a lack of technological advancement or capability when the work was undertaken. Existing aids are scrutinised, which are used to gain understanding of benefits which we can adopt or improve on.

A study in 1999 looked at the current Low-Vision Imaging System (LVIS), one of many names of vision devices that were not finalised and still are not today, underlining that similar devices were underdeveloped as previous technology had been focusing on solutions for blind users, rather than low-vision users (Harper, Culham, and Dickinson 1999). Case reports from their study suggested that LV subjects with high motivation could operate an low-vision aid (LVA) for 8-10 hours a day, noting the pressing need to properly evaluate and trial these newer devices against existing LVA. Looking at technologies available at that time, they accentuated that one of the shortcomings of previous work on LVAs has always been ergonomics yet emphasise that a head-mounted device used for video magnification and contrast enhancements would be increasingly beneficial to low-vision users as technology improves to overcome this limitation (Harper, Culham, and Dickinson 1999). Contrast is a crucial component of vision, as contrast sensitivity loss attributes to facial recognition difficulty (Fiorentini, Maffei, and Sandini 1983; Näsänen 1999). There have been many attempts at creating electronic devices to provide magnification, and although their first appearance was in the late 1960s (Sutherland 1968), the original concept was first described by Potts et al. (Potts, Volk, and West 1959). Another study (Everingham, B. Thomas, and Troscianko 1998; Everingham, B. Thomas, and Troscianko 2003) looked at combining virtual reality with vision enhancing algorithms via a head-mounted display changing the contrast and saturation the user perceives, increasing their visibility, with results showing object recognition increasing from 40% to 87.5%. A later review of existing electronic enhancement systems commented that despite the many years that have been dedicated towards these different technologies, there are still many flaws when it came to the practicality of said devices, such as expense, portability, and image quality, noting that continued research is required (Wolffsohn and Peterson 2003). Supporting this, another review looked at the effectiveness of assistive technologies, highlighting that although results gathered from electronic vision-enhancement systems showed statistically significant increases in improved reading speed than traditional prescribed optical aids, there were too few studies to form a strong conclusion, as well as noting similar challenges with participants such as unfamiliarity with devices (Harper, Culham, and Dickinson 1999; Jutai, Strong, and Russell-Minda 2009).



AUTHORS	BACKGROUND	KEY ELEMENTS	OVERVIEW
THOMAS ET AL. (2015)	Ophthalmology	Database, outcome validity, study selection, bias, data analysis.	Systematic database search and assessment of electronic developments for children/young people.
DEEMER ET AL. (2018)	Optometry	Devices, pricing, contrast, image processing, magnification, AR, motion compensation.	Review of literature surrounding low vision enhancement with HMDs.
HARPER, CULHAM, AND DICKINSON (1999)	Ophthalmology	Comparative, CCTV, rehabilitation, emerging tech, magnification, image enhancements, evaluation, quality of life.	Comparative review of older literature to newer of HMDs for vision rehabilitation.
WOLFFSOHN AND PETER-SON (2003)	Optometry, Neuroscience	CCTV, magnification, EVES, field-of-view, Image enhancement, contrast, reading speed, training, system methods.	Review on Electronic Vision Enhancement Systems for visual impairments
JUTAI, STRONG, AND RUSSELL-MINDA (2009)	Optometry, Health Science	Rehabilitation, study evaluation, EVES, CCTV, mobility devices, field-enhancement devices, lighting & filters, control groups.	Systematic review of assistive technology effectiveness for low vision rehabilitation.

Figure 2.6: An overview of the main authors conducting systematic reviews in section 2.3

An overview of aspects covered in the main systematic reviews are summarised in Figure 2.6.

2.3.1 Defining Solutions - Video & Optical

There are various types of VR and AR devices today, and most will fall into the category of either video see-through (VST) methods, and optical see-through (OST) methods. VST devices, such as an older concept and setup designed by Massof et al (Massof and Rickman 1992) (Massof, Baker, et al. 1995), function by displaying a video feed to the user's eyes typically by an HMD mounted with cameras. A VST design allows increased control over visual manipulation as video feed is being transmitted digitally and is thus fully configure-able, allowing for a greater variation of enhancements and modifications. These platforms tend to share similar shortcomings with VR equipment (if they are not already classified as VR), such as being heavier on the user's head, difficult to control and configure (Harper, Culham, and Dickinson 1999), and can cause disorientation via motion sickness, something which affects a large number of users (LaViola Jr 2000). OST devices today are more akin to glasses but with overlay interfaces, such as the popular Microsoft HoloLens (Microsoft 2020a) or Google Glass (Google 2020). OST technology combines a digital visual over the user's normal vision, allowing a more natural experience with possible enhancements (Rolland, Holloway, and Fuchs 1995). Since OST glasses sit in front of the user's normal vision, the gained benefit of said devices may vary depending on the user's existing visual capability, and what can be modified is sparse compared to VST setups. The benefit is usually a slimmer more compact device, although some devices are still hefty in space and size. Since standard OST techniques only overlay enhancements over optical sight, some image manipulation techniques will not be possible without VST integration. In this work, the VST approach is focused on. This method was chosen to avoid falling into the trap of using technology which is underdeveloped, and therefore suffer the same hurdles previous researchers faced with VST; namely, not having the required hardware capabilities needed at the time. It is believed that VST methods have matured enough in hardware capabilities, granting the opportunity to use them successfully within this research and development to the level they may have been envisioned in previous iterations. A recent article published by a LV author titled “A rare disease robbed me of my sight. VR brought it back”, shows the potential for these newer devices, with the author claiming they were able to see clearly for the first time in five years while playing a VR game using the HTC Vive (A. Lee 2018). Although this article presents no scientific testing performed to determine the visual comparison between a real world or virtual simulation, it opens the dialogue into the possibility of visuals being easier to see within certain HMD devices that are not designed as visual aids, as is the case with this article.

An overview of findings covered in this section’s literature are summarised in Figure 2.7.

AUTHORS	SYSTEMS	FINDINGS/CONCLUSIONS	OVERVIEW
MASSOF AND RICKMAN (1992)	LVES (VST)	Multiple organisations needed for development of complex devices, and ongoing funding.	Obstacles in the development of a LVES
MASSOF, BAKER, ET AL. (1995)	LVES (VST)	All patients exhibited improved visual function with the LVES	LVES Improvements in acuity and contrast sensitivity
HARPER, CULHAM, AND DICKINSON (1999)	Various VST	Limitations are present, but devices could have significant impact on rehabilitation and further research is needed.	Comparative review of older literature to newer of HMDs for vision rehabilitation.
LAVIOLA JR (2000)	VST	Cybersickness is a significant concern, particularly for younger females, and must be mitigated in several ways.	A discussion of cybersickness in virtual environments.
ROLLAND, HOLLOWAY, AND FUCHS (1995)	VST & OST	OST systems offer unhindered views of environments, while VST give this up for many other improvements, if delivered correctly.	Comparison between OST and VST displays
A. LEE (2018)	VST	Early reactions show a user was able to perceive elements within an HMD that they normally couldn't	The effect on an individual's visual impairment while gaming with a VR HMD.

Figure 2.7: An overview of some of the main authors' findings in section 2.3.1

2.3.2 Previous Device Solutions

When considering new avenues to providing visual aids to the visually impaired, we must look at what types of visual technologies were used both in the past and present, their effectiveness, and any shortcomings each solution may have. One of the most common forms of severe visual impairments is AMD amongst the elderly, usually resulting in significant loss of reading capability (Nguyen, Weismann, and Trauzettel-Klosinski 2009). Results from a study showed that only 16% of 530 AMD patients could read prior to the use of a LV aid, and 94% gained reading ability after utilising a LV aid (ibid.). These patients made wide use of some form of magnifying lens, but closed-circuit television (CCTV) systems as a preferred LV aid stood out. CCTV systems are a form of electronic vision aids that would typically be referred to today as HMDs, yet as mentioned previously, the name for these systems were not fully established and were referred to differently across the field. Nguyen, Weismann and Trauzettel-Klosinski (ibid.) remark that electronic vision aids can provide a high magnification alongside a wide FoV, while high optical magnifiers would restrict the FoV distinctly, making reading much harder to achieve. Research has shown that a reduced field of vision reduces walking speed (Leat and Lovie-Kitchin 2008) and mobility, meaning solutions that assist users with AMD can provide practical improvements. Although the research here suggests that a CCTV system can provide more effective visual enhancements compared to competitors, there is no continued work from the authors that focuses on this discovery directly. As this research contains tested participants with AMD, studies surrounding the effectiveness of LVAs are important in evaluating success.

Previous studies highlight that people with certain disabilities oftentimes feel stigmatised by specialist equipment or devices (Parette and Scherer

2004; Shinohara and Wobbrock 2011), particularly noting public perception of disability. There are multiple factors that play into this stigmatization but one of the most prominent distinguishes is the majority of disability equipment, and specifically LV equipment, being designed for just people with disabilities, often leading to a high cost and ultimately device abandonment (Riemer-Reiss and Wacker 2000). This attributes to why, although there are some electronic LV solutions today, they do not garner much attention or are not commonly seen due to large initial costs for specialised equipment paired with very little mainstream knowledge; if said equipment were multipurpose, they would potentially gain a lot more mainstream attention while not being as isolating to the visually impaired public. With advances to technology, and VR and AR devices becoming more affordable and accessible to a wider audience that can even access VR/AR from just their phones, one of the largest barriers to entry with these types of devices can be overcome. More specifically, if today's VR headsets that are available for cheaper costs, are not designed for disability use, and are more socially acceptable can produce the same benefits from previously studied VST aid devices, their use in assisting others may become wider spread.

Another approach towards visual assistance is focusing on sonification techniques, where information is represented through audio. A previous paper (Torres-Gil, Casanova-Gonzalez, and González-Mora 2010) looks at utilising a simulation setup called Virtual Reality Simulator for Sonification Studies (VRS3) comprised of 3d distance sensor glasses, a pair of headphones, and hardware for tracking and producing audio. This system allowed for early studies and training towards auditory perception and how users respond to audio cues, but unfortunately does not expand on the testing process much beyond the proposed hardware itself, and a future device was never continued. Another system called NAVIG (Navigation Assisted by artificial vision and Global Navigation Satellite System) took a similar approach, utilising a stereoscopic camera system, an orientation tracker, headphones, a microphone, and a laptop carried (Katz et al. 2012). This solution was aimed towards fully blind users, and thus navigation is done entirely through audio directed through the headphones as the environment is tracked utilising sonification techniques. Through GPS tracking data is translated live through camera mounts and back to the user's ears aiming to improve independent navigation. Although designed for entirely blind users, the techniques for image translation for GPS and navigation are not exclusive, and the techniques here could be integrated into an improved HMD that assists visuals with positional tracking and sonification. Supporting this, further work has looked at combining sonification and eye tracking via another device worn over the eyes (Dietz et al. 2016). This technology would receive data via tracking the user's eyes, looking at weaknesses in their visual movement patterns, and be able to supplement these damaged areas via sonification; audio supporting visuals. Information surrounding sonification used for assistance can be found within papers presented by (Cavaco et al. 2013) and (Ribeiro et al. 2012). These studies show the potential for hybrid systems where VR headsets can implement audio cues as further assistance to visuals, and potentially track the visual pattern of the user's eyes to provide further enhancements, such as enhancing objects where the user is looking directly. Another noteworthy study (Striem-Amit, Guendelman, and Amedi 2012) looked at video to audio translation utilizing headphones attached to a video camera. An application was developed that can translate audio between different shapes, objects, object detail, and object location, once again translating information through audio. Their results showed that all participants obtained a higher visual acuity score using this device, looking at thresholds above 60% compared to equivalent existing techniques. The equipment for this approach was noted as inexpensive as basic tools were used, but participants needed extensive training prior to testing to make use of the equipment effectively. Training for the device average 73 hours over several months depending on each participant's personal performance via one-to-one sessions by a personal trainer, increasing costs. These studies show great application for sonification integration towards accessibility aids, particularly for navigation, but are lacking on visual components due to their focus on blind users.

An overview of findings covered in this section's literature are summarised in Figure 2.8.

AUTHORS	SYSTEMS	FINDINGS/CONCLUSIONS	OVERVIEW
NGUYEN, WEISMANN, AND TRAUZETTEL-KLOSINSKI (2009)	LVA	AMD reading increased from 16% to 94% using an LVA.	LVA effectiveness on reading speed for AMD patients.
LEAT AND LOVIE-KITCHIN (2008)	Mobility course	Walking speed was best predicted by useful field of vision and age.	Visual function, attention, and mobility performance in low vision.
RIEMER-REISS AND WOBBROCK (2000)	Assistive Technology (AT) of various types.	Consumer involvement was a high predictor of tech abandonment, as well as cost to benefit ratio	Factors associated with AT abandonment among users with disabilities.
SHINOHARA AND WOBBROCK (2011)	AT	Disabled users balance relationships between AT and other people. Using devices users felt self-conscious and unproductive.	Assistive technology's use and how it effects social interactions.
STRIEM-AMIT, GUENDELMAN, AND AMEDI (2012)	Sensory Substitution Devices	5/9 blind participants exceeded visual acuity levels defined as blindness using an SSD	Visual acuity of the congenitally blind using visual to audio SSDs.
DIETZ ET AL. (2016)	Sonification Device, goggles.	All participants were able to complete tasks involving colour, text, and facial recognition.	Eye tracking driven sonification for the visually impaired.
KATZ ET AL. (2012)	Sonification Device, CCTV, laptop.	The trialled NAVIG system restores fundamental visuomotor processes and allows for adapted routes	The presentation of NAVIG, an AR guidance system for the visually impaired.

Figure 2.8: An overview of some of the main authors' findings in section 2.3.2

2.3.3 Recent Device Solutions

A paper released in 2015 looked at various image processing techniques for low vision subjects, looking at what is available and recorded statistical differences (Moshtael et al. 2015). Moshtael et al showcase some examples of image processing techniques, such as edge detection for sharpening visuals, or direct video manipulation with lens distortion, which can be integrated directly into newer electronic head-mounted devices. Some of these techniques are not exclusive to electronic visual aid devices, nor are they new ideas, as other studies have utilized similar methods (Everingham, B. Thomas, and Troscianko 1998; Everingham, B. Thomas, and Troscianko 2003), but they do showcase the potential for newer systems to integrate multiple techniques into one device that can aid in a multitude of visual impairments as a complete package. The results from averaging multiple image processing techniques showed that contrast related enhancements were significantly preferred by testers unless facial recognition was required. Word recognition was increased by 101% of their initial performance for severely visually impaired users as well as emotion identification between 100% to 180%, although some tests measuring object or object detail detection showed no difference in performance. Time taken to count objects was reduced by 50% with FoV modification, with 88% of LV users preferring video enhancements over no enhancements. These results show that there is already tested evidence to support these techniques' use, and their benefit for integration into an HMD. Interestingly, the paper written by Moshtael et al (Moshtael et al. 2015) mimics many of the conclusions shown in previous studies decades before, in that despite there being large potential for these systems there is not enough research or clinical validation, and the area of discussion is still one in a state of evolution but not yet adequately realised. One of their final conclusions suggests that a multidisciplinary approach would be most effective, combining fields such as image processing, microelectronic engineering in optics, and clinical ophthalmology, to better refine and deliver patient care.

Work by Hwang and Peli (Hwang and Peli 2014) explore AR edge enhancement through the use of Google Glass (Google 2020). Participants suffered from AMD, which is said to impact emotional well-being (Lamoureux et al. 2008) and social engagement (Bennion, Shaw, and Gibson 2012), due to visual difficulties such as differentiating between fine details and facial recognition (Peli, Goldstein, et al. 1991; Peli, E. Lee, et al. 1994). Using the Google Glass a portion of the user's vision is overlaid with contrast altering edge enhancement through both positive and negative Laplacian filters. The positive Laplacian filter causes enhanced bright edges with clear surroundings, while the negative Laplacian filter causes edges to become transparent while the outer surroundings are highlighted. 3 participants of "normal-vision" were chosen and a diffuser film was applied to simulate vision loss. When attempting to read contrast sensitivity charts, results showed substantial improvements with the diffuser applied, but none recorded without. Again, the same limitations in regards to FoV are described in their study as with the HoloLens with similar research. Another limitation discussed was the OST nature of the device, where dark/black edges in a see-through display become transparent, limiting the types of contrast modifications used. This highlights where VST solutions may be stronger, as the video aspect of an HMD avoids transparency and potential glaring issues caused by OST limitations. This work highlights a strong need for this type of equipment, as a VR/AR solution that would be able to comfortably restore a user's vision to the acuity of being able to recognise facial details, and thus people, would be tremendously beneficial to their mental and emotional well-being, restoring confidence that can be often lost with low-vision sufferers. Previous studies have shown that AMD patients have preferred high-contrast edges to static images (Satgunam et al. 2012) or videos (Wolffsohn, Mukhopadhyay, and Rubinstein 2007), improving visual search performance in a simulated central loss scenario with older people (Kwon et al. 2012). By implementing features not yet supported by Google Glass they were able to test several effects, with results showing from a preliminary test that three participant's contrast sensitivity was improved using edge enhancement. Their conclusions highlighted that an OST AR HMD can provide improved visual function through edge enhancement while also being cosmetically and ergonomically attractive, as well as inexpensive compared to competitors, something that many HMD devices have failed to do in the past and present. This opens the question of whether a VST solution could be just as effective using the same enhancements highlighted in Hwang and Peli's (Hwang and Peli 2014) work but using the modern advancements of VR headsets today allowing for better ergonomics, and combination of both AR and VR features.

Research conducted by Zhao, Szpiro and Azenkot (S. Zhao Y. S. and

Azenkot 2015) resulted in the creation of an application called ForeSee, which used a prototype of the Oculus Rift (Oculus 2020b) HMD called the DK2, allowing the user to customise several visual enhancements of a video feed sent to the HMD via a camera mount. This setup uses the DK2 to push AR features by overlaying enhancements to existing visuals to allow for things such as magnified text, or text extraction. Although it appears that this research was purely exploratory, it shows the potential for VR HMD combined with camera feed to use AR techniques for enhancing vision. One of the key advantages discussed from their findings is the adaptability of the device, where the ability to customise between multiple enhancement settings combined was received well by participants. From all participants tested, none used the same visual enhancement combinations with each tailoring the device to their own individual needs, and participants requested that extra visual options be included for further customisation. If the HMD itself can already improve visuals by default, then being able to push for further enhancement techniques overlaying the user's vision would greatly enhance their potential vision.

Continued research built upon the findings of ForeSee looked at pushing an AR approach to visual assistance with a device that can search for and highlight objects with visual enhancements to a LV user by looking for a placed tag and overlaying enhancements on a marked object such as edge enhancement and contrast amplification, increasing clarity (Zhao et al. 2016). The tagging method used to highlight objects was done via

Chilitags, a detection technique used primarily for AR applications (Bonnard et al. 2013). Using a similar setup to the ForeSee with an Oculus DK2 and a camera mount, they created an application called CueSee, able to test multiple visual cues for object location to determine whether the search time was reduced in finding an item. Searching for specific items is particularly troublesome for those with visual impairments, especially in everyday areas such as grocery stores, as the dense array of products on store shelves create a crowding effect (DG Pelli 2008). Their results found that although participant reactions were mixed based on their impairment and the type of enhancement used, trialled types of enhancements were useful to them, with their overall conclusion showing that CueSee outperformed their typical assistive tools in all participant cases for reduced object search time. This research shows potential for quality of life enhancements and tools by allowing LV users to be able to read, identify, and gather items with greater ease, granting more independence and faster efficiency for tasks that those with poor vision may struggle with, or even with older adults in general.

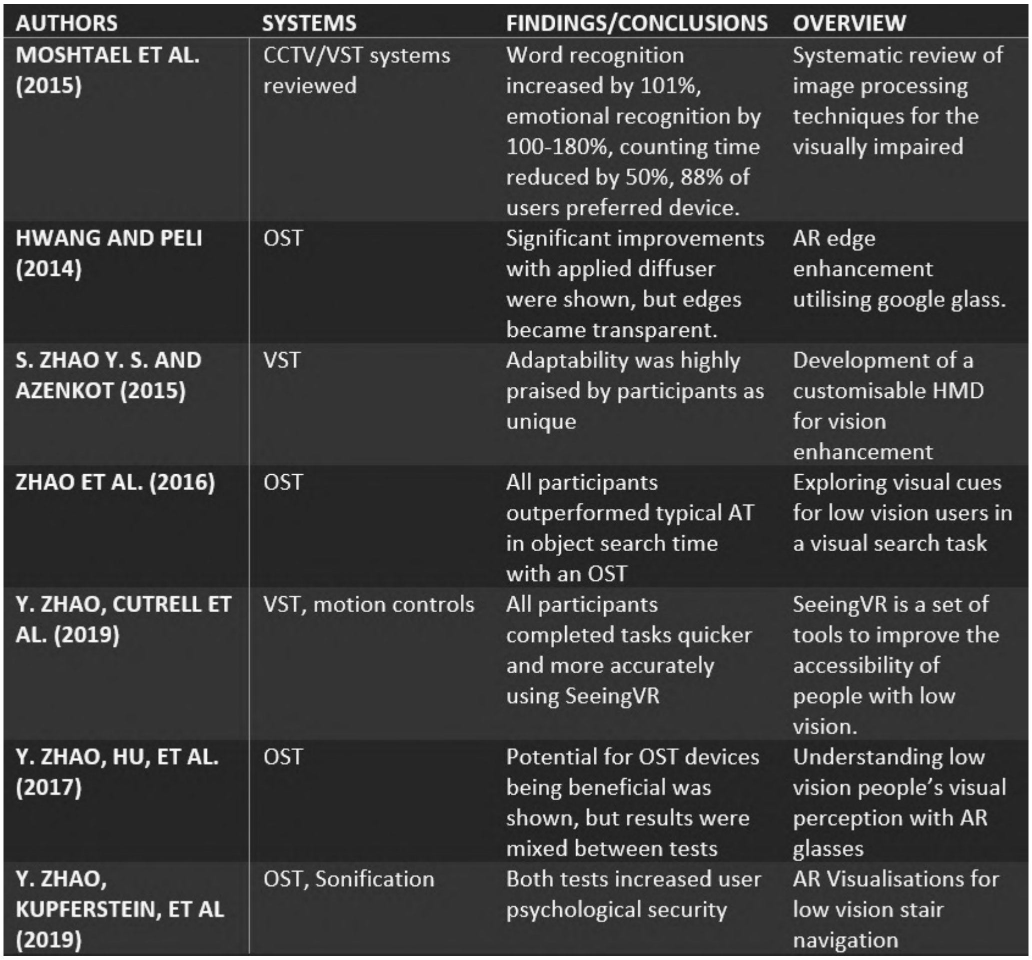
Further developments from Zhao et al. (Y. Zhao, Cutrell, et al. 2019) looked at the creation of specialist tools for making VR more accessible to people with LV. Utilising the Unity engine, a plugin and toolkit was developed that allows the user or developer respectively to be able to implement visual aid techniques into existing VR applications, such as magnification, text to speech, and peripheral remapping. To evaluate effectiveness of their software, 11 participants were recruited to test 13 LV tools through 3 task procedures; menu navigation, visual search, and target shooting. Results found that all participants experienced improved efficiency and accuracy while utilising SeeingVR, preferring to use it over not, and some commenting that the use of the tools increased task confidence. As visual accessibility is severely lacking for VR hardware and software, this research is particularly valuable in highlighting the effectiveness of accessibility techniques within VR systems, as well as demonstrating the types of techniques and solutions that may be applicable for different kinds of software. This is further highlighted by their evaluation of their software with developers, where developers noted that they were “unaware of any accessibility guidelines they could follow to make a VR product accessible”. Currently their software is only compatible with Unity applications (as they report is the most common engine for VR applications currently), but with enough traction and push for VR accessibility these types of enhancements can be implemented either directly from developers themselves, or from the ground up with future developments to VR hardware.

Additional research from Zhao et al. (Y. Zhao, Hu, et al. 2017) examines the visual perceptions of LV people on commercial AR glasses. Instead of utilising a VR headset like their previously mentioned works, they demonstrate whether a AR device can be used as an effective LVA. Comparing physical visual acuity charts without AR equipment to using AR equipment, results were mixed with LV participants suggesting that visual acuity levels could not be accurately used as a predictor for performance against AR elements, and that factors may have affected acuity (such as limited resolution or semi-transparency of the AR glasses). Although acuity level results were mixed, the study demonstrates that a AR device could be used as a visual aid tool if considerations are appropriately met. A later study from Zhao et al. (Y. Zhao, Kupferstein, et al. 2019) also focuses on a AR solution, looking at designing AR visualizations to facilitate stair navigation. Designed upon the HoloLens (Microsoft 2020a), the tool tackles stair navigation for LV users by displaying glow visualisation for stairs, path visualisation for stairs and railings, and beep sonification that informs the user of their current position on stairways. This is particularly useful as navigation is one of the most problematic tasks for people with visual impairments (Katz et al. 2012). This study demonstrates the usability of AR devices as vision aid tools, building upon the prior works of their previously mentioned research, with results showing increased participant psychological security while utilising the tool. Looking at the work done in both VR and AR within these authors highlights the overlap between AR and VR devices, both capable of being accessibility tools and both utilising similar approaches.

Another direction some research has focused on is accurately simulating visual impairments through the use of a VR display. A study looked at how visual impairments effect the recognition distances of escape-route signs in buildings utilising an HTC Vive headset and a swivel chair to simulate a wheelchair (Krösl et al. 2018). To gather data on how someone with a visual impairment might perform in this test, visual blurs were processed to the headset's display allowing for mimicry of conditions such as macular degeneration or having a cataract in a particular eye. Additionally, navigation is a consideration when safely exiting a building, and to limit the speed that someone might travel to escape a building due to mobility restrictions a wheelchair was also simulated in testing. Half of the participants for this study had normal vision, with the other half having minor forms of short-sightedness, and the majority with corrective lenses to compensate. As one might expect, maximum recognition distance was reduced when a stronger blur was applied compared to a weaker one across all participants tested. Their conclusions suggest that by calibrating all participants to the same level of reduced visual acuity, investigation and design into visual impairments should be easier to conduct and advance accessibility. While this type of approach has its merits and streamlines the participation selection process, the authors note that a larger range of acuity levels and conditions would be needed to cover a more accurate representation of vision. There is also a risk that generalising visuals through simulation may not fully capture the targeted audience, and that more accurate levels of design and usability testing can only come from the user groups themselves. Nevertheless, this study highlights the practicality of devices enhancing the design and testing phase for impaired users, promoting greater accessibility through first-hand simulations. A very similar study (Jones et al. 2020) looked at the evaluation of VR and AR in simulating visual impairments as well. This study utilised a Vive HTC Pro Eye, which includes integrated eye-tracking, as well as ZEDmini stereoscopic cameras attached to provide the simulation of visual field loss. As with the previous study a simulated visual field loss was able to accurately produce results in line with real-world data of participants with the actual visual impairments in question. One additional finding that this study highlights is the psychological effect on participants who were involved which varied greatly, with higher performers keeping a more natural gaze pattern compared to participants that were more startled from observing with lower than their natural vision. The same levels of anxiousness were shown when users attempted to climb stairs, which mirrors existing research of anxiety levels of people with severe vision loss (D. J. Taylor et al. 2020). This shows great promise in proper the proper simulation and thus education of low visual acuity levels and visual disabilities, again contributing towards the awareness and need for adequate accessibility and design towards visual impairments.

Research in AR development has also looked at solutions for displaying text and image processing techniques. Work by Stearns et al. (Stearns, DeSouza, et al. 2017) investigate magnification using a HoloLens combined with a finger-worn camera. Hovering the finger above text would display a floating magnification within the HoloLens. This setup was exploratory and was used as the foundation for Stearns, Findlater and Froehlich's follow up research (Stearns, Findlater, and Froehlich 2018) that made use of a smartphone in lieu of a finger-camera connected to a computer. Although a finger-camera was lighter-weight, a smartphone allowed for portability and several new user interactions to control display settings as well as a motion sensor. The setup allows for 3 modes of display: attached to headset where the text follows the user's head movements, attached to world where the text would be mapped to a 3D location independent of head movement, and attached to phone where the motion sensors of the smart phone dictate where the text is displayed within the HoloLens. Different colour swaps can be applied to the text and text background using the smartphone. Reported results showed that participants were positive with this setup over the previous iteration, as participants tried both versions of the authors' work. Limitations bring attention to the HoloLen's limited FoV, something also mentioned in previous studies that have built upon the HoloLens and, although modern VR setups have a larger FoV, it is still worth considering the implications.

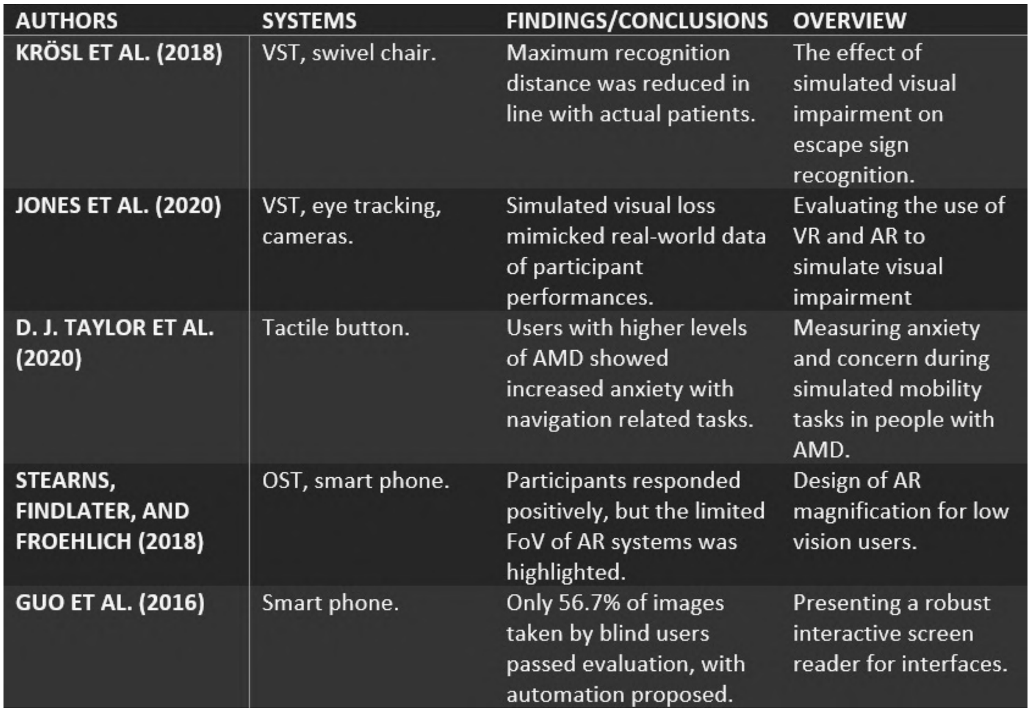
Adapting newer VR or AR systems around accessibility must build upon the work of current technology available used for assistance today, such as electronic screen readers, and exploration into how accessible current technology is. Although accessibility is a forefront of design and is increasingly important today, there are many previous studies that suggest that many services are still inaccessible to a large margin of the population. Kristina and Jacquelyn report on some of these findings, highlighting that a past study conducted on academic libraries websites rated only 40-42%



AUTHORS	SYSTEMS	FINDINGS/CONCLUSIONS	OVERVIEW
MOSHTAEL ET AL. (2015)	CCTV/VST systems reviewed	Word recognition increased by 101%, emotional recognition by 100-180%, counting time reduced by 50%, 88% of users preferred device.	Systematic review of image processing techniques for the visually impaired
HWANG AND PELI (2014)	OST	Significant improvements with applied diffuser were shown, but edges became transparent.	AR edge enhancement utilising google glass.
S. ZHAO Y. S. AND AZENKOT (2015)	VST	Adaptability was highly praised by participants as unique	Development of a customisable HMD for vision enhancement
ZHAO ET AL. (2016)	OST	All participants outperformed typical AT in object search time with an OST	Exploring visual cues for low vision users in a visual search task
Y. ZHAO, CUTRELL ET AL. (2019)	VST, motion controls	All participants completed tasks quicker and more accurately using SeeingVR	SeeingVR is a set of tools to improve the accessibility of people with low vision.
Y. ZHAO, HU, ET AL. (2017)	OST	Potential for OST devices being beneficial was shown, but results were mixed between tests	Understanding low vision people's visual perception with AR glasses
Y. ZHAO, KUPFERSTEIN, ET AL (2019)	OST, Sonification	Both tests increased user psychological security	AR Visualisations for low vision stair navigation

Figure 2.9: An overview of some of the main authors' findings in section 2.3.3

of them accessible against accessibility testing software (Southwell and Slater 2013). Another author conducted similar research noting that accessibility rates had minimal improvements in a 4 year period (Providenti and Zai III 2007). A newer screen reader that allows impaired users to capture photos of inaccessible interfaces (Guo et al. 2016) and send them



AUTHORS	SYSTEMS	FINDINGS/CONCLUSIONS	OVERVIEW
KRÖSL ET AL. (2018)	VST, swivel chair.	Maximum recognition distance was reduced in line with actual patients.	The effect of simulated visual impairment on escape sign recognition.
JONES ET AL. (2020)	VST, eye tracking, cameras.	Simulated visual loss mimicked real-world data of participant performances.	Evaluating the use of VR and AR to simulate visual impairment
D. J. TAYLOR ET AL. (2020)	Tactile button.	Users with higher levels of AMD showed increased anxiety with navigation related tasks.	Measuring anxiety and concern during simulated mobility tasks in people with AMD.
STEARNS, FINDLATER, AND FROEHLICH (2018)	OST, smart phone.	Participants responded positively, but the limited FoV of AR systems was highlighted.	Design of AR magnification for low vision users.
GUO ET AL. (2016)	Smart phone.	Only 56.7% of images taken by blind users passed evaluation, with automation proposed.	Presenting a robust interactive screen reader for interfaces.

Figure 2.10: An overview of some of the main authors' findings in section 2.3.3

to staff for fast response feedback, demonstrates that still many technologies are inaccessible to much of the public and the need for a third party tool to interact with external elements is needed. The screen reader requested assistance via pictures taken by blind participants in their study, yet only 56.7% of images passed evaluation, suggesting that participants struggled to accurately take photos to be analysed, and that a more automated approach may be needed. It has taken years of improvement for accessibility features and focus to rise, but with the rise of new VR headsets that do not account for accessibility features out of the box, we have to question whether this newer technology will be playing catch up to the visually impaired community as previous technologies have done so.

An overview of findings covered in this section's literature are summarised in Figure 2.9 and Figure 2.10.

2.3.4 Commercial use of VST & OST Devices

From a commercial point of view, there have been some attempts at product releases for visual aiding headwear integrated with sight enhancing technology, such as the OST eSight glasses (eSight 2018). eSight glasses utilize a camera embedded into its frame to capture video feed and display it back to the user with enhancements such as magnification, text colour inversion or swap, brightness, focus and so on. The downside to these glasses, and similar products that have experimented with this area, is usually availability and cost as the eSight glasses are available via an application and then purchasable for $5,950 USD currently, with previous costs going for as high as $15,000. This paired with limited clinical research and exposure makes many of these devices unavailable to a vast amount of people that could benefit from these devices. Adding on to this the same issues arise as pointed out by Riemer and Wacker (Riemer-Reiss and Wacker 2000) where these LV headpieces are still designed for use only by people with disabilities, running into concerns again such as social stigma and high cost. Another device is the OxSight, utilising a similar OST glasses setup designed for people with peripheral vision loss (henshaws

2019). The glasses focus primarily on image processing techniques to enhance elements such as contrast, text, brightness, objects, and field of vision. Sharing a similar pricing setup as eSight, originally the device was sold for roughly $15,000, but is available currently in the UK for £4,000. The OrCam MyEye is another visual aid device that focuses on reading instead by attaching a small camera onto the user's normal glasses that allows text to be scanned and read back to them via a small speaker (OrCam 2020). The device allows the user to place their finger in front of real world text and highlight what is to be read, mimicking how a cursor might operate. This device is simpler than a typical VST HMD in that no sight is assisted directly, yet is still noteworthy due to it's popularity. Again, however, the pricing of this device is too high even with its limited feature set, as it is currently priced at £3,500. A paper critiques the high pricing of current HMD vision aids, commenting that 90% of the people that are visually impaired live in developing countries where this technology is unattainable due to the cost (Zuniga and Magee 2018). As with past electronic LV solutions, these modern takes still do not gain the attention required for widespread adoption, are too expensive, and public knowledge of said solutions are still limited.

A more affordable alternative is Samsung's Relumino (Deahl 2018), an application launched via Samsung approved smartphones that fits into the Samsung Gear VR headset helping the user to see through vision enhancing techniques. Using image processing, it can magnify or minimise, adjust brightness and sharpness, outline objects or text, and more impressively manipulate the user's field of vision to potentially combat conditions such as macular degeneration or tunnel vision. According to their website (Relumino 2018), a new version of Relumino that offers enhancements via physical glasses are in development to incorporate these features outside of the Gear VR, potentially signalling that the application may be replaced with this new iteration. These glasses promise to be an improvement over the existing application but are not expected to be ready for another two years (Langley 2018). Very similar to Relumino is GiveVision's SightPlus, another headset that allows the user to insert their phone and use its camera combined with the lenses inside to impose magnifications and other adjustments to the user's vision via a remote controller (GiveVision 2018). GiveVision's SightPlus gained popularity being featured on BBC Click where the device was featured 'giving back' sight to a visually impaired participant in front of an audience (BBC 2019), as well as previous articles where sight had been 'restored' to an 8-year-old child (Venkat 2017). SightPlus' attention is promising as the device has helped raise public awareness of the benefits an HMD can provide towards visual disabilities. Unfortunately, the device itself is very costly sold at £2,955 currently, reducing how accessible it is to the public and widespread adoption. Much like the Relumino team, it appears that GiveVision have decided to take their technology away from a phone inserted headset and are in the process of developing a pair of glasses that will simulate the same technology without the need for a phone headset combination (VentureBeat 2020). This may hint that there are some shortcomings to such a method, such as the weight of the device, if multiple companies are looking into eye-wear alternatives to HMD configurations after previously working on them. A statement from the company's CEO claimed that the new device in development will be smaller, lighter, less than 100g of pressure on the nose, and boasts a higher level of comfort (Kent 2020).

As VR has advanced as a medium in both technology and popularity, we are seeing an ever more increasing number of practical applications spread across multiple sectors. The most common of these applications, outside of the obvious entertainment and gaming scene, appear to be for training purposes for areas such as medical, military, industrial, or educational simulations and experience; as well as therapeutic routes, medical recovery, rehabilitation, or phobia/anxiety control. One such example is Luminous Group (Luminous Group 2021), a company that builds advanced applications for 3D virtual training designed around industrial environments. These would allow trainees the ability to observe and interact within a virtual space with sensitive equipment, such as a motorised engine or crane operation, without the real-life safety risks involved, granting a safer way to offer training and confidence building prior to actual equipment use. Another example is from the company BioflightVR (BioflightVR 2021), who partnered with Oculus and Children's Hospital Los Angeles (Oculus 2017) to produce a realistic training simulation for paediatric emergencies, featured on CBS News (CBS 2018). BioflightVR offers a range of VR and AR training and simulation services in the medical and education sector, pushing for the use of VR in clinical and learning environments and promoting the use of VR in hospital settings. With the increased interest for VR and AR for skilled training and educational use, the need for clinical evaluation of said devices, as well as the integration of disability features for the visually impaired unable to access technology not designed for their accessibility, becomes apparent.

Crossland et al look at evaluating the benefit of electronic head-mounted LV aids utilising GiveVision's SightPlus (Crossland et al. 2019). Using the standardised Visual Acuity (ETDRS), contrast sensitivity (Pelli-Robson) and reading performance (MNREAD) charts, a comparison was made with visually impaired participants between no device, the device using a magnified mode, and the device using magnification combined with one of four image enhanced modes. Results found that distance acuity, contrast sensitivity, and reading performance improved significantly, while reading speed decreased significantly. When participants were asked whether they would personally use such a device, 47% indicated they would use one especially for television, reading and entertainment. The authors highlight that there is a lack of clinical evidence for the efficacy of VR eLVAs (Electronic Low Vision Aid), such as SightPlus. This study highlights the improvements a electronic LV aid can bring, as well as the types of comparative tests that can better demonstrate their effectiveness. This also begs the question of why, if results are so effective for such a device, is adoption limited, with the company themselves moving away from their current system?

Much of the technology surrounding glasses or HMD setups tend to share similar solutions and techniques for tackling impairments, yet seem to fall short in combining the successes of individual projects into a complete product. With the recent attention newer VR and AR devices have gained within the industry, along with advances to technology that allow us to produce equipment that is smaller and capable of faster processing, it is hypothesised that the near future will show rise to specialist equipment that incorporate the strengths and features of many past devices, all combined into one device that will be able to supplement vision loss through multiple techniques and solutions.

DEVICE	PRICE	YEAR	TECHNIQUES
ESIGHT	$5,950	2017 (2020 eSight4)	Magnification, colour swap, brightness, focus
SIGHTPLUS	£2,955	2017	Edge enhancement, contrast, inverted, text, zoom
OXSIGHT	£4,000	2016	Field of view, contrast, brightness, object/text enhancement
ORCAM MYEYE	£3,500	2017	Text to Speech audio playback
RELUMINO	Free app	2017	Magnify, minimise, brightness, sharpness, object/text outline, field of view

Figure 2.11: An overview of some of the recent available electronic visual aids for vision impairment.

An overview of some of the newer available commercial electronic visual aids discussed in this section is displayed in Figure 2.11.

2.4 Summary

Research shows that visual disabilities are an ongoing problem with the number of people affected predicted to increase in the upcoming years. Although there is research on the use of CCTV type systems to be used as LV aids, such as the work from Nguyen et al (Nguyen, Weismann, and Trauzettel-Klosinski 2009), it appears that still today there is a lack of high quality and accessible aid equipment that is widely available to the public, further supporting Thomas et al's (R. Thomas et al. 2015) conclusion.

Studies involving ELVA of the past compared to what we consider modern HMD setups show consistent patterns in participant performance, namely that in most situations an ELVA will outperform natural vision or existing LVAs. The performance indicators gathered from the reviewed literature also match up within this study, such as with Crossland's findings (Crossland et al. 2019) suggesting that despite an overall in accuracy, time taken to read was decreased. As many researchers have pointed out there is still not enough research towards evaluating and utilising modern HMDs as ELVAs, and greater contributions towards this area are needed, particularly if preliminary research are producing promising results. Another identified limitation highlighted through the literature is the lack of standardisation between terminology and testing, where modern HMDs are still not fully recognised as currently capable LVAs and classification is loose between different studies.

There are multiple attempts at OST & VST type LV aids, yet there are still remaining limitations that have slowed consumer interest. Some of these devices are not commercially available from a typical storefront, requiring an application process to trial a device. If available for purchase, typically these devices are very expensive making them less accessible to the public, and likely discourages adoption from local health care services (VisionAid 2021). Although these devices are useful and a step in the right direction, these shortcomings stop them from reaching the majority of visually impaired people, reducing their effectiveness. Additionally, many users may be more familiar with typical screen-reader type accessibility software (Freedom Scientific 2021; Kurzweil Education 2021; AFB 2021), but talks with participants involved in this research revealed that many severally visually impaired users' do not engage with this software, particularly older adults, with many preferring device abandonment. Despite these shortcomings, however, there has been a steady decrease in pricing over the years as device leaders recognise that users are unwilling to pay for large upfront costs, both in the LVA sector and the gaming VR HMD market. Another push towards more adaptable devices has been the recognition of weight and comfort concerns, where many manufacturers are now learning towards slimmer and lighter devices that can be worn for extended periods of time. With the technology available in current VR devices, it is entirely possible to provide at least similar level enhancements, particularly with VST devices, while expanding on them for multipurpose use at a fraction of the cost, as VR headsets are far more affordable as well as capable.

Chapter 3

VR Comparative Study

This chapter discusses the specifications and design methodology for the first research stage. Following the presented related works, it was hypothesized that VR devices could be used as suitable accessibility tools or replacements. Although some studies exist that compare VR devices in certain aspects, there is limited published research that looks at comparing vision between unmodified VR devices and natural vision. Due to this gap a comparative study looking at performance with and without a VR device is required to better gauge the capabilities of a VR device, as well as contributing to the design process of future accessibility applications. To achieve this goal the methodology is split into 3 components: the selection of a VR device suitable to represent current VR technology and capabilities, the identification of visual aspects/elements to be evaluated, and the design and or selection of vision tests that are suitable for comparisons between VR and natural vision. Figure 3.1 highlights the first research stage's design process via a flowchart.

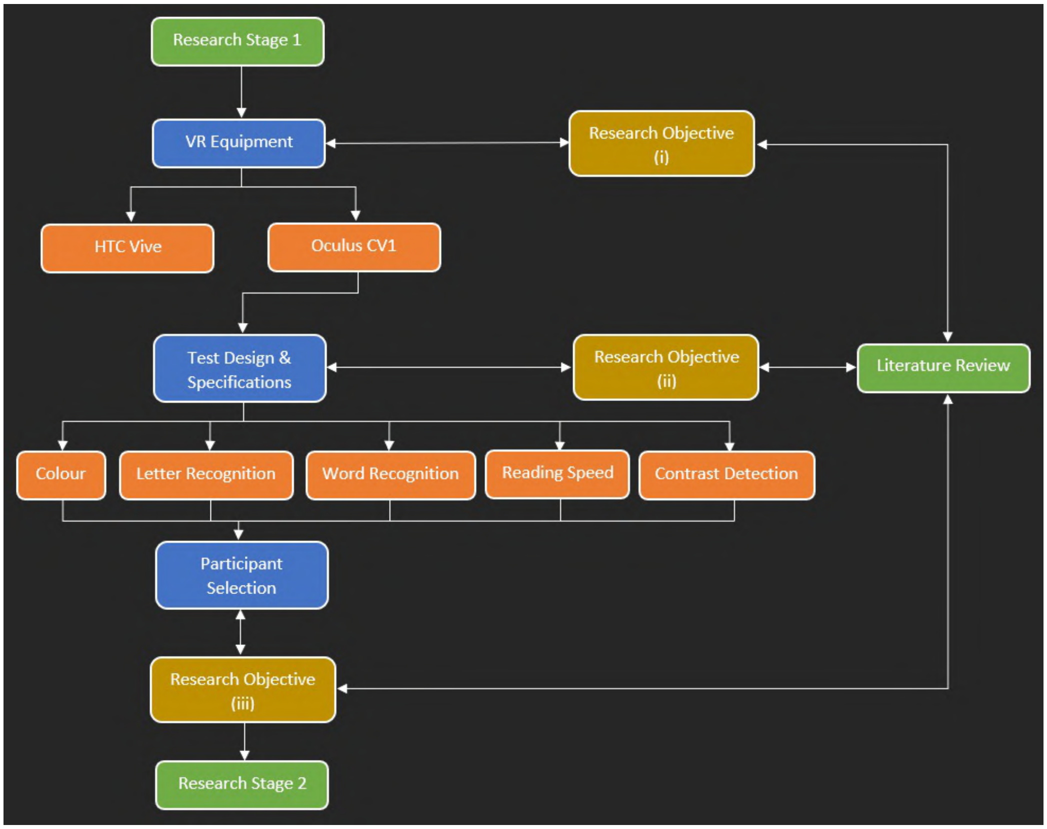


Figure 3.1: A flowchart representing the first research stage's design process

3.1 Chosen VR Equipment & Requirements

The start of this design process required the selection of a VR headset that would be suitable throughout the testing process to represent the state of current VR devices, requiring 6 DoF and an appropriately high resolution. At the time this research began the top two commercially available headsets available for PC machines were the Oculus Rift CV1 (Oculus 2020b), and the HTC Vive (HTC 2020). Both of these headsets support Room-scale 6DoF, allowing user movement and location to be tracked via sensors on the headset itself, as well as motion controllers. Due to local availability, the Oculus Rift CV1 (See Appendix E, F, and J) was chosen as the VR equipment in building the comparative study, although both headsets have very similar functionality and specifications. It is worth noting that newer and direct successors to these headsets have commercially released since the start of this study, sporting improved lenses and higher resolutions, and a newer headset is utilised in the subsequent research stage. The Oculus Touch motion controllers were used, alongside 2 Oculus USB sensors for better head and hand tracking. To utilise the Oculus Rift CV1 without latency issues, a Asus Zephyrus GX501VIK gaming laptop was chosen as the connected machine to be able to run a VR device effectively with experiments.

Although the Oculus Rift CV1 is now deprecated hardware and has been replaced by the Oculus Rift S and the Oculus Quest 1 & 2, the technology behind the headset still possesses all of the core fundamentals of PCVR headsets in the market today, albeit with a lower resolution.

3.2 Test Design & Specifications

Before testing began, the identified gap in research was the lacking evaluation of VR devices utilised for people with severe visual impairments. To solve this the design goal of this study was to be able to determine the efficacy of using VR devices compared to physical space on visual clarity for severely impaired users. In reaching this goal a set of measurable variables that represent visual factors to be observed in evaluating vision had to be established. These visual elements were determined based on a preliminary study conducted (Weir, Loizides, Nahar, Aggoun, et al. 2020), as well as consultation with a registered optometrist. Visual factors that were determined to be investigated were: **Letter Recognition**, **Word Recognition**, **Contrast Detection**, **Reading Speed**, and **Colour Detection/Accuracy**. These variables represent different aspects of reading and thus are good indicators for measuring visual ability. These variables and a descriptor of their purpose are displayed on Table 3.1.

A series of tests were selected to measure and indicate the visual acuity of participants within a VR HMD environment and to compare them directly to a physical equivalent. These optometry tests were selected to be translated into a VR environment with collaboration and consultation with a registered optometrist, as with the visual factors, and were picked due to their widespread use. Tests were created using the Unity engine (Unity 2021) and run via a laptop connected to a Oculus CV1 HMD (Oculus 2020b).

Table 3.1: The baseline visual test variables used to determine aspects of vision

Visual Test Variables	
Letter Recognition	The ability to recognise individual letters, useful for measuring baseline acuity, based on distance and size.
Contrast Detection	The level of recognition between contrast changes, useful for measuring the effects of brightness and light levels, particularly in VR devices, through gradient changes.
Word Recognition	The ability to recognise and read full words, needed to evaluate overall reading capabilities, based on distance and size recognised.
Reading Speed	The evaluation of reading performance, supplementary to evaluating reading ability, looking at total time taken to read given segments.
Colour Detection/Accuracy	The ability to both recognise colours and also the accuracy of colours seen through comparative colour gradients.

As there are no existing validated standardised tests for measuring acuity designed to be used alongside newer unmodified VR HMDs, the selected tests were adapted for suitability to be used as benchmarks within a VR environment. These adapted tests will be used as evaluators for the technology itself and can be used going forward as a method for standardising the measurement of acuity within a VR environment, as none currently exist. As such, these tests should not be seen as full recreated optometry tests, but instead adapted tests used purely as a comparative tool with similar existing tests that are already well established. Each test or scene was designed to test a specific element of each participant's vision and split into its own section. Testing environments and conditions were considered to avoid imbalances between physical and VR tests, and participants read charts in a clearly lit room with no background noise. Measuring and validation of whether VR representations were the same distance and size as the real world through tracking tests to determine whether movement matched up in real life at the same time as the virtual environment (Yifan 2015) were performed. All test constraints are mirrored between physical and virtual versions, such as participants not moving their head within VR if they did not in the physical, and vice-versa. By default testing conditions, this behaviour is expected, i.e. participants are expected to remain still with their head facing forward to read any charts within both VR and physical spaces. However, movement is still allowed if deemed appropriate due to specific participant conditions, needs, or limited vision, such as head tilting due to central vision loss, and if so will be allowed in both VR and physical versions for that individual. Tests that have specific rules will highlight these changes.

To begin with, the testing procedure had to be defined to be followed throughout the testing period amongst all participants. Many VR headsets require precise positional calibration to ensure visual displayed match up with expected outputs. Improper calibration leads to blurred imagery, greatly reducing the effectiveness and accuracy of visuals the further away from correct calibration. With the Oculus CV1 in particular, the users' eyes must be centered between both lenses of the HMD, with the 'sweet-spot' being fairly sensitive. This headset features a Interpupillary Distance (IPD) slider allowing spacing adjustment of the lenses to match up with most people's IPD requirements. To ensure this calibration was done effectively, IPD calibration was done prior to every test and if the headset was ever removed. Some headsets may not require IPD calibration and may have a much wider viewing angle for the lenses, not requiring as accurate central positioning.

Although some VR headsets have a built-in calibration tool for IPD, they are often limited due to the calibration remaining static and un-customisable by the user, and as such a bespoke calibration scene was created that allowed for more control and options for monitoring participants (See Figure 3.2). This calibration scene was used to determine whether participants were correctly fitted with the headset and whether IPD values were accurate by asking them to read an example sentence and observe a green cross for any abnormalities while the headset is adjusted, until visuals are the clearest they can be. The Oculus Rift CV1 HMD used was not modified in any way from a standard model and should follow its factory specifications, although the manufacturing process for screens can often cause slight variants or defects in screen quality. To determine brightness was at expected levels, a Luminance Meter was used to measure the Luminance of the OLED panels within the HMD, and the surfaces of the charts and walls in the physical world, allowing the adjustment of the VR environment to match the correct levels of brightness. It is worth noting that as a VR headset surrounds the eyes and isolates light by shining visuals directly onto the pupils with minimal outside interference, light sources are not accurate representations to real life within VR and cannot be accurately compared.

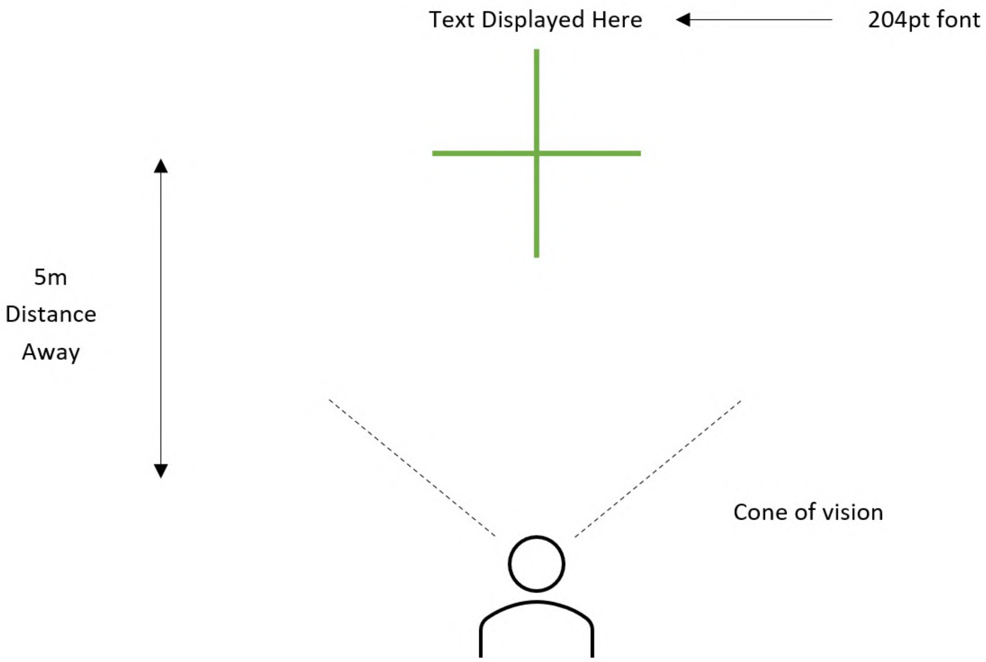


Figure 3.2: The calibration scene. A green cross and two sentences of text are displayed to the user and adjusted based on their feedback to determine whether the headset is adjusted accurately.

Through discussions with users prior to testing, it was clear that the participation selection group consisted of multiple people that required specialist lenses, eye gear, and other specific equipment that helps aid with their visual conditions. The Oculus Rift CV1 is required to fit over the head and eyes, and has limited room for any inserted or worn apparatus. Two approaches would be to either allow participants to use eye related aids within the headset, or for them to remove all eye wear and utilise only the headset. Participants with the lowest acuity levels that relied on equipment entirely, or required equipment for health reasons (such as goggles to prevent photosensitivity), were allowed to keep their equipment on for the tests providing the equipment could fit into CV1 HMD. Any eyewear worn while testing within VR had to be also worn for physical tests. Any constraints that would limit the participant's ability to wear the headset correctly or would cause any danger, discomfort, or unease invalidates them for the test, such as hypersensitivity to light, or specialist apparatus required to be worn that is not compatible with the headset.

If the device is removed prior to the completion of a test, then that specific test is invalidated and a re-calibration of the headset is required going forward. A visual feed of what the participant could see was displayed via the connected machine, and a screen recorder alongside a webcam was used to record all physical movements as well as what participants could see during the test. Adjustments made to the environment, such as re-alignment of camera position and distance, is done by the facilitator via the machine connected through use of a keyboard.

Prior to all tests an interview was conducted with each participant gathering details about their conditions and lifestyles associated due to these conditions. Any particular needs or concerns for wearing the headset were noted (e.g. facial skin sensitive to bacteria) and suitability for the test was determined, following removal of the data if suitability was not met. For physical tests the participant was asked to sit or stand in front of a clearly illuminated chart with no shadows or glare overlapping, staying eye-level with the middle of the chart, and would be required to stay still while attempting to read what is in front of them. For VR tests the participant would sit down with the headset worn and have their distances calibrated so that the digitally displayed tests match up with expected real world measurements for reading distances (i.e. chart shown 1m distance away measured within virtual space to the same requirements as the physical).

Tables shown in Chapter 4 with each test contain the results of each participant from the initial comparative study held within both physical and VR environments. Participants with a score of 0 could not determine well enough what was in front of them, and scores marked with N/A are participants who did not participate in a particular test. Tests have been abbreviated to Letter Detection, Contrast Sensitivity, Word Detection, Speed Reading, Colour Detection, and Colour Accuracy respectively. Test results are colour coded in green to highlight when a participant's VR test performed better, red highlights when the physical test performed better, and white signifies there was no change within a 20% range between VR and physical results.

3.3 Participant Selection

This section details the selection criteria for each participant, as well as a overview of their conditions and the types of aids they use daily, and ethics obtained. For full individual profiles of each participant, as well as their test results, see section 5.1. Participants were selected based on their visual conditions, requiring severe vision loss as previously defined in section 2.1. Table 3.3 lists the individual properties of the tested participants.

24 participants were involved in this first study. This participant group have a range of visual conditions which is listed in Table 3.2, many of which have been defined and can referred to in section 2.1. Some of these conditions are common among groups of participants whereas other conditions may be specific to only an individual or a select few participants. For this reason a summary of conditions and aids used is presented here while a more in-depth and qualitative descriptor of participants is presented in section 5.1. The selection criteria for each participant was as follows:

(i) Participants need to be classified as “severely sight impaired” (RNIB 2019; WHO 2019b), as defined in 2.1 with 20/100 or 6/30 or equivalent vision, or (See Point ii).

(ii) Participants need to be classified as “Legally Blind” with 20/200 or equivalent vision (RNIB 2019; SSA 2018) yet not be entirely without vision.

(iii) Participants who are completely blind in one of two eyes are eligible

(iv) Participant needs to be “sound of mind” in order to be able to reliably explain their experience without the need for a caregiver. NOTE: this does not mean that there is an absence of a caregiver, but that the carer should be only responsible for mobility rather than for cognitive assistance.

(v) Participants need to be fluent in reading and speaking the English language.

(vi) Participants must be willing to go through an interview.

(vii) There is no age or gender restriction.

In order to perform the experiments, ethical approval was obtained by the Beacon Ethics committee upon presentation of the experimental design (See Appendix D). Ethical approval was additionally obtained through the University of Wolverhampton prior to testing (See Appendix C). A Disclosure and Barring Service (DBS) check was passed, which is a mandatory police background check procedure in the UK to allow one's work with underage or vulnerable participants. Consent forms and bill of rights were presented to the participants which outlined the study aim and the procedure, as well as any likelihood of discomfort. Participants were able to also opt in or out of using identifying features, such as their images being used in public domain media or publication. Participants could opt out of the experimentation at any time without needing to provide a reason, and could additionally take a break whenever desired. There is no financial or in-kind compensation for the participants who volunteered their own time. Signed

Table 3.2: A list of all of the primary conditions each participant reported with how many participants reported in each category

Participant Primary Conditions	
Condition	**Total**
Macular Degeneration	10
Cataracts	10
Nystagmus	6
Photosensitivity	5
Charles Bonnet Syndrome	2
Diabetic Retinopathy	2
Glaucoma	2
Astigmatism	1
Cornea Damage	1
Detached Retina	1
Hemianopia	1
Marginal keratitis	1
Myopia	1
Optical Neurosis	1
Salzmann's Nodular Degeneration	1
Tunnel vision	1

consent forms were presented and collected. All data is stored in a secure encrypted location, accessed only by the the author of this project and all the data has been anonymised.

Consent forms used are shown in Appendix A. As participants were of severe low vision and most were unable to read, forms were read out to each to ensure they understood what they were signing.

The next chapter presents the comparative tests chosen based on the design methodology discussed.

Table 3.3: Table of the test group's recorded diagnosis' and what aids they use. Left or right shown in brackets denote which eye is affected by a condition if specified by the participant. Descriptors in quotations are how the participant described their condition themselves.

ID	**Sex**	**Diagnosis**	**Aids Used**
A1	F	Wet Macular, Cataracts, Lower vision(left) Charles Bonnet Syndrome	Mobile text-to-speech Magnifying glass
A2	F	Hemianopia, Blinded(right) "Foggy"(left) Limited vision(left)	Shaded glasses, Sight books, Magnifying glass Mobile enlarged font, Computer Tablet Talking Watch, Walking cane
A3	F	Corneal Graft(left), Limited(left), Blurred(right) Tube inserted(left), Double vision(right)	Thick shades Smart phone, Walking cane
A4	M	Optical neurosis Lower vision(right), "Thick fog" Limited colours	Mobile text-to-speech, Cooking Timers, iPad Magnifying Glass(x15), Talking books, iMac White Cane, Microwave, Speaking Scales
A5	F	Wet Macular, Cataract Fatigue affects vision, "Misty" vision Lower vision(right), Double vision	Magnifying glass Walking cane, Radio Audio books, Glasses
A6	F	Dry Macular, Cataract removed(right) Charles Bonnet Syndrome, Blinded(left)	Spy glass
A7	F	Macular, Cataract(left), Lower vision(left)	Magnifying glass
A8	F	Wet Macular, Possible detached retina Cataract(left), Blinded(right), Watery(left)	Speech assisted TV, Audio books Mobile phone, Walking cane
A9	F	Wet Macular, Cataract(right), "Misty" vision Lower vision(left), Light sensitivity	Magifying glass
A10	M	Nystagmus, Glaucoma, Blinded(left) Detached Retina, Congenital Cataracts	Guide cane Computer, Distance glasses
A11	M	Marginal keratitis, Eye ulcars, Floaters Cataract removed(left), Yellow "stars" Double vision, Photosensitivity	Shades
A12	M	Diabetic Retinopathy, Detached Retina(fixed) Cataract removed(right), Blinded(left)	Walking cane, Daisy player, iPad Mobile text-to-speech
A13	F	Wet Macular(left), Photosensitivity Dry Macular(right), Cataracts Eye pressure Thicker Cataract(right), Glaucoma	Magnifying glass, Audio books, iPad Protective shades, Walking Cane, Mobile large font, Non-guide dog Accessibility toilet, Microwave, Buzzers
A14	M	Tunnel vision, Split(right), Blurry(right) Cataracts removed Lower vision(right), Photosensitivity	Walking frame Crutches, Enlarged phone, Talking watch Home stair lift

Table 3.2 Continued.

A15	F	Macular Cataract(left)	Magnifying glass(x5), Wheelchair Talking watch, Talking alarm, Glasses
A16	F	Diabetic Retinopathy Lower vision(right), “Hazed” vision	Talking clock, Talking microwave White cane, Glasses
A17	F	Dry Macular, Low vision(left) Cataracts removed	Magnifying reading machine Walking stick
A18	M	Stargardt disease Lower vision(right)	ORCAM, Magnifying software(x6/x4), Apple watch iPad, iPhone, Siri, TV telescope, Travel LED lighting
A19	M	Nystagmus Longer distance(left)	Bar magnifier(x2), Phone shortcuts Glasses, White cane, Portable screen ZoomText(x16), Backlit keyboard, large fonts
A20	F	Nystagmus, Photophobia Ocular Albinism, Myopia, Lower vision(right) Dry eye disease, Cataract(left)	Zoom software, White cane, Sunglasses Cooking equipment, iPad, Mac iPhone large print, Siri, Alexia
A21	F	Astigmatism, Optic Atrophy Sponge inserted(right), Minor Nystagmus Detached retina (right, fixed)	Glasses, Gripped utensils, Magnifer(x7), Monocular Reduced brightness monitor, Zoomed kindle Anti-glare shades, Flat screen TV, large print Large font computer, White cane, Tablet, Phone
A22	M	Nystagmus, Lower vision(left) Photosensitivity(left)	large font, White cane, Monocular Magnifier(3.5x), Tablet, iPhone, Glasses Tablet, iPhone, large font
A23	F	Nystagmus, Fixed lens inserted(left) Lower vision(right), Dyslexia	Glasses, Shades, Computer, walking cane Long cane, iPhone, iPad, Amazon Echo, Siri
A24	F	Salzmann’s Nodular Degeneration Marfan syndrome, Cataract(right) Fixed lens inserted(left), Lower vision(right) Cataract removed(left)	Glasses Zoom software Tactile stickers

Chapter 4

Evaluative tests of VR vision

This chapter discusses the selection, adaptation, and the findings of a series of user tests designed to evaluate the visual capabilities of severely visually impaired users utilising a VR headset compared to physical equivalents. 6 tests are presented as existing optometry tests that focus on gauging a particular aspect of vision, as well as their adaptations and changes made to ensure compatibility with the selected participant group but also translation into a virtual environment. Each section presents the test itself, how it was conducted throughout this study, specifications used, and the overall findings of results amongst all participants. Further discussion of these results is presented in Chapter 5.

4.1 Letter Detection

ETDRS Visual Acuity Chart (Letter Detection). This selected test is based on the LogMAR Visual Acuity Chart ETDRS (VectorVision 2014) (Early Treatment Diabetic Retinopathy Study), as recommended by an optometrist. Users of this test are required to look towards an evenly lit chart and attempt to read individual visible letters that gradually decrease in size the further down the user can observe (See Figure 4.1, 4.2). This is documented by a facilitator to determine the visual ability of the user in question. The user is asked to read from a set distance where they are not permitted to move their head forward or backwards due to risk of inaccurate measurements, although this may vary depending on the users' condition where movement may be required, such as central vision loss. All charts or paper used within the tests were scanned and translated with the same measurements and resolution when inserted into the software, as well as distances having been measured to scale to fully replicate both environments. Both physical and VR test environments were done in empty rooms behind clearly lit white backgrounds to avoid as much visual noise as possible, with light levels being appropriate to clearly illuminate testing apparatus and avoid any obstruction of vision.

The LogMAR ETDRS chart was printed physically measuring at 66 cm at a pixel resolution of 3000x2883. Distance between the participant's head and chart was tested at both 1 metre and 0.5 metre distances. The selected

Figure 4.1: ETDRS Visual Acuity Chart

size and distances used were determined based on the visual ability of the selected participant group, which was severely limited. Participants were asked to start reading each letter from the top left of the chart and continue reading left to right for each row, before continuing to the line below. Sessions were recorded by a facilitator and each letter read is documented,

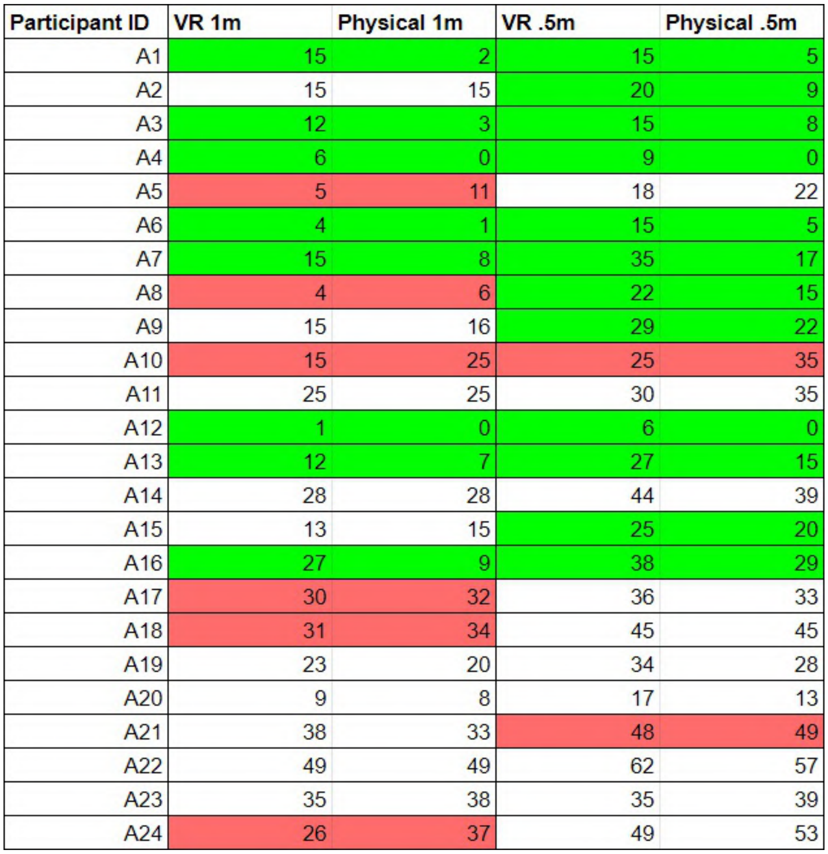
Figure 4.2: ETDRS Visual Acuity Chart in Unity

including letters missed, or letters that were misread. After each line is read at both distances (1 m and 0.5 m), a tally of all the correctly identified letters is compared between both VR and physical versions.

Table 4.1 shows how many letters were read by participants in both VR and Physical tests at either 1 m or 0.5 m distances.

Letter detection reported the most significant increase in performance by participants in VR compared to the physical equivalent. At 0.5 m, 17 participants had a mean increase in readability of *148%*, 6 participants had a smaller average decrease in readability by *17%*, and 1 participant had no differences. A Wilcoxon Signed-Ranks Test indicated statistical significance with $Z = 2.925 \cdot p = .003 \cdot$ *effect size* ($r = 0.422 \cdot n = 24$). At 1 m, 11 participants had an average increase of *214%*, 9 participants had

Table 4.1: Data sheet of each participant's results for the ETDRS chart (green highlights an increase in VR, red a decrease, and white no changes within 20%.)



Participant ID	VR 1m	Physical 1m	VR .5m	Physical .5m
A1	15	2	15	5
A2	15	15	20	9
A3	12	3	15	8
A4	6	0	9	0
A5	5	11	18	22
A6	4	1	15	5
A7	15	8	35	17
A8	4	6	22	15
A9	15	16	29	22
A10	15	25	25	35
A11	25	25	30	35
A12	1	0	6	0
A13	12	7	27	15
A14	28	28	44	39
A15	13	15	25	20
A16	27	9	38	29
A17	30	32	36	33
A18	31	34	45	45
A19	23	20	34	28
A20	9	8	17	13
A21	38	33	48	49
A22	49	49	62	57
A23	35	38	35	39
A24	26	37	49	53

an average decrease of *36%*, and 4 participants had no changes. This showed no statistical significance with $Z = 0.841 \cdot p = .400 \cdot (r = .121 \cdot n = 24)$ Results show that the majority of users had an overall average increase of *181%* towards the number of letters read between both tests within VR overall, but significant results were produced when participants were closer in the 0.5 m test, with acuity decreasing at 1 m distances. Interestingly, when isolating participant data to those with central vision loss (n=10) at 0.5 m, VR results were greater favoured, while 1 m distances were mixed. Out of 10, 1 participant had a decrease of *22%*, and 1 having no changes. This produces a statistically significant result where $Z = 2.433 \cdot$ $p = .015 \cdot (n = 10)$. At 1 m distance, 4 participants had an average increase of *277%*, and 5 participants had an average decrease of *35%*, producing a statistically insignificant result with $Z = 0.409 \cdot p = .683 \cdot n = 10)$. Most participants tested with different types of central vision had an increase in letter detection at closer distances in VR, while at further distances 4 out of 10 participants had a significantly smaller decrease in vision, 4 had a significantly large increase in vision, and 1 participant had decreases in both tests.

4.2 Contrast Sensitivity

Pelli-Robson Contrast Sensitivity Chart (Contrast Detection). A test was needed to determine how the brightness of letters was affected using a VR HMD, as headsets shine light directly to the user's eyes. The chosen test for contrast sensitivity testing was the Pelli-Robson Contrast Sensitivity Chart (PCSC), which is similar to the letter detection test (DG. Pelli, Robson, et al. 1988).

This test functions similarly to the ETDRS chart and other letter detection charts in that the user is prompt to read each letter line by line to determine the acuity of their vision. In this case, the chart displays letters

Figure 4.3: Pelli-Robson Contrast Sensitivity Chart

of all the same size and spacing, but the level of contrast or brightness between each letter is gradually reduced, or faded, as the user reads from left to right (See Figure 4.3, 4.4). This effect is more noticeable the further down they attempt, with the letters becoming very faint towards the bottom. The standard procedure for this test asks the user to read from a set distance and to refrain from moving their head to avoid inaccurate readings (sometimes assistive tools such as a head clamp are used). The contrast sensitivity chart was printed at the same measurements as the EDTRS

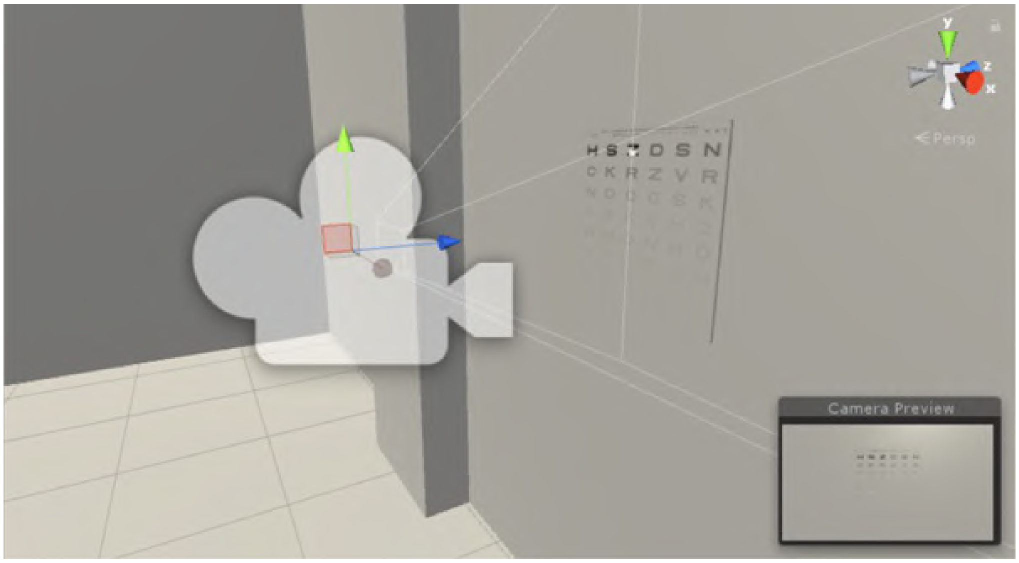


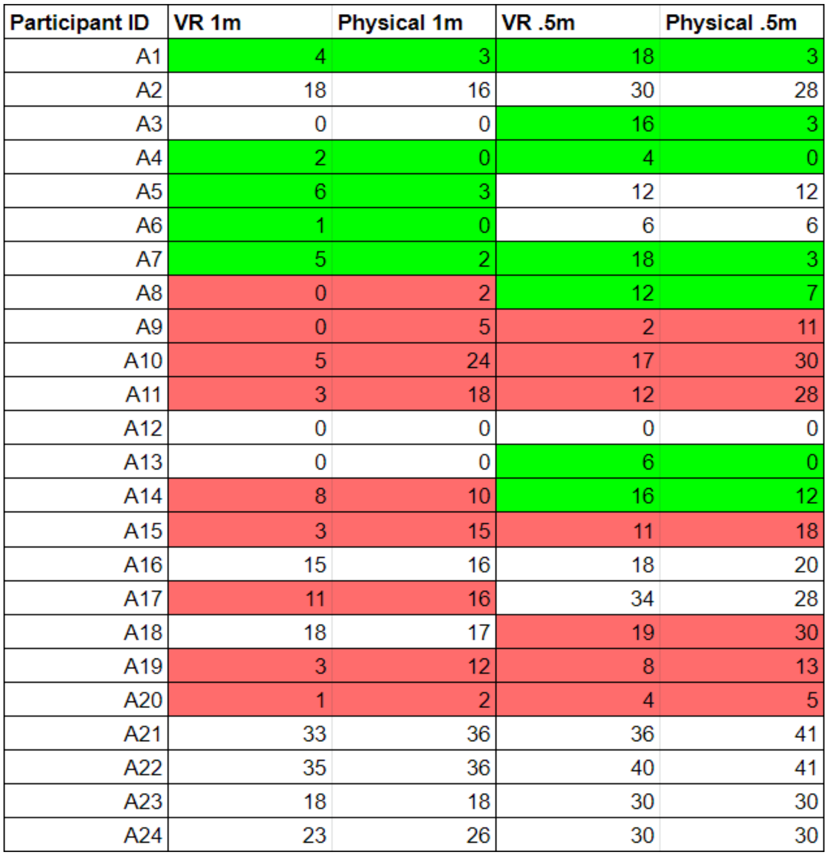
Figure 4.4: Pelli-Robson Contrast Sensitivity Chart Unity Scene

chart, at 66x66 cm, to keep letter sizes similar for comparison. Each user was asked to read the chart left to right and were asked to comment on how they perceive the clarity of the letters in front of them (See Appendix G). Each attempted character was documented as well as any missing gaps in the chart that were not attempted. A total tally of correctly guessed attempts was documented to formulate the basis of their performance, before greater analysis.

Table 4.2 shows how many letters were read by participants in both VR and Physical tests at either 1 m or 0.5 m distances.

Contrast detection results for VR were less successful than the letter detection test despite the similarities between the tests. At 0.5 m 9 participants had a mean increase in readability by *285%*, 10 participants had a

Table 4.2: Data sheet of each participant's results for the Pelli-Robson Contrast Chart (green highlights an increase in VR, red a decrease, and white no changes within 20%.)



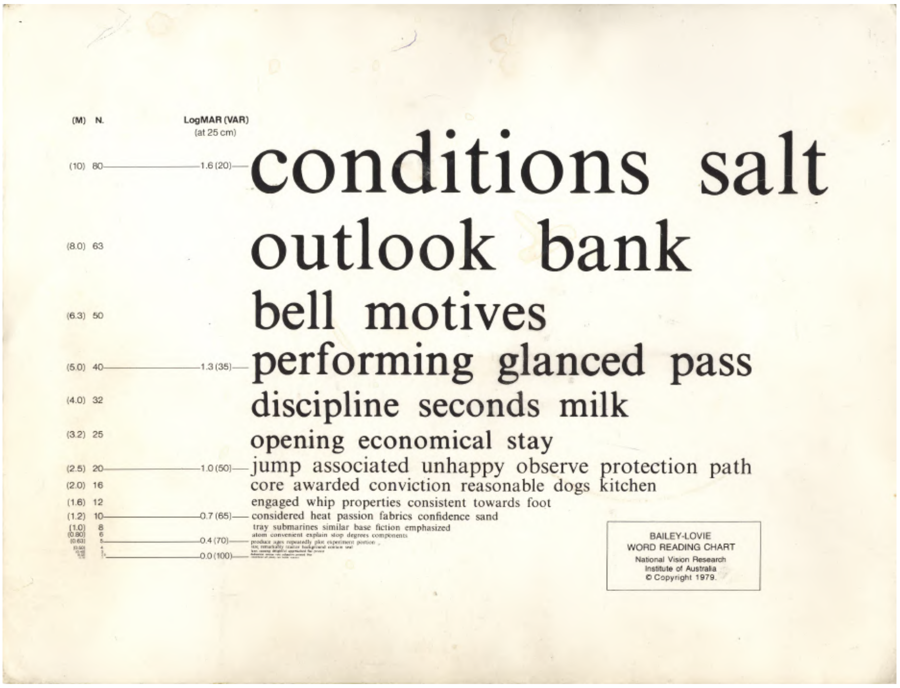
Participant ID	VR 1m	Physical 1m	VR .5m	Physical .5m
A1	4	3	18	3
A2	18	16	30	28
A3	0	0	16	3
A4	2	0	4	0
A5	6	3	12	12
A6	1	0	6	6
A7	5	2	18	3
A8	0	2	12	7
A9	0	5	2	11
A10	5	24	17	30
A11	3	18	12	28
A12	0	0	0	0
A13	0	0	6	0
A14	8	10	16	12
A15	3	15	11	18
A16	15	16	18	20
A17	11	16	34	28
A18	18	17	19	30
A19	3	12	8	13
A20	1	2	4	5
A21	33	36	36	41
A22	35	36	40	41
A23	18	18	30	30
A24	23	26	30	30

decrease by *90%*, and 4 participants did not see any increase or decrease between both tests. Using the Wilcoxon test, there was no statistical significance with $Z = 0.040 \cdot p = .968 \cdot (r = .006 \cdot n = 24)$. At 1 m, 7 participants had an increase of *86%*, 12 participants had a decrease of *191%*, 3 participants could not read anything at 1 m in with or without VR, and 1 participant had no increase or decrease. This test showed statistical significance with $Z = 1.970 \cdot p = .049 \cdot (r = 0.284 \cdot n = 24)$. These results show that again results seem to be poorer at 1 m distances rather than 0.5 m, but VR results performing worse than the letter detection test. It is noted that further distances within a VR headset causes distorted graphics as the maximum resolution is exceeded the further away an object is, depending on the resolution of the object and the resolution of the HMD itself. It is expected that the release of further higher resolution VR HMDs will improve VR results in terms of acuity reading. These results can also highlight a large performance discrepancy when reading letters with or without contrast manipulation between the letter detection and contrast detection tests. Results may indicate that without light adjustments VR does not perform as clearly as physical reading, and that contrast or brightness manipulation is an important factor to consider for VR clarity. It is worth noting that 0.5 m measurements were closer to an even split between participants at *53/47%* with a decrease being the slight majority between VR and physical results, whereas 1 m showed a larger *65/35% split*, suggesting there may be some correlation between distance and contrast. Isolating those with central vision loss again, this test does not show the same pattern as the previous letter detection test. Out of 10 participants tested at 0.5 m, 5 participants had a mean increase of *338%* in VR, 3 participants had a mean decrease of *190%*, and one participant had no changes. This showed no statistical significance, with $Z = 0.421 \cdot p = .674 \cdot (r = 0.094 \cdot n = 10)$. At 1 m 5 participants had an increase of *79%* in VR, 4 participants had a decrease of *286%*, and 1 had no changes. Again, no statistical significance was found, with $Z = 0.655 \cdot p = .512 \cdot (r = 0.146 \cdot n = 10)$. Overall results are a lot closer here, with VR having 10 instances of increases between both tests to 7 decreases, yet the gap between the number of letters read within these instances is more significant at 1 m distances than 0.5 m, a common trend with results so far.

4.3 Word Detection

Bailey-Lovie Word Reading Chart (I. Bailey and Lovie 1980) (Word Accuracy). A test was created to determine whether users of a VR HMD would be able to read full words with the same clarity compared to real world equivalents. The test chosen for this was the Bailey-Lovie Reading Chart which is designed for determining distance visual acuity at varying print sizes (ibid.). This test requires the user to read from a given list of words displayed on a chart (See Figures 4.5, 4.6) to evaluate their visual acuity based on their performance.

An existing printed copy of the Bailey-Lovie Reading chart was scanned and saved at a standard size of 28x21.5 cm. Rather than enlarging the chart's size itself, the distances required for participants to read had to be reduced to compensate for smaller character sizes from a smaller chart, instead of enlarging the chart and introducing pixelation and resolution noise. Participants were asked to read this chart at 0.5 m and 0.25 m distances,


(M) N. LogMAR (VAR)
(at 25 cm)
(10) 80 1.6 (20) conditions salt
(8.0) 63 outlook bank
(6.3) 50 bell motives
(5.0) 40 1.3 (35) performing glanced pass
(4.0) 32 discipline seconds milk
(3.2) 25 opening economical stay
(2.5) 20 1.0 (50) jump associated unhappy observe protection path
(2.0) 16 core awarded conviction reasonable dogs kitchen
(1.6) 12 engaged whip properties consistent towards foot
(1.2) 10 0.7 (65) considered heat passion fabrics confidence sand
(1.0) 8 tray submarines similar base fiction emphasized
(0.80) 6 atom convenient explain stop degrees components
(0.63) 5 0.4 (70) produce ages repeatedly plot experiment portion
0.0 (100)

BAILEY-LOVIE
WORD READING CHART
National Vision Research
Institute of Australia
© Copyright 1979.

Figure 4.5: Bailey-Lovie Word Reading Chart

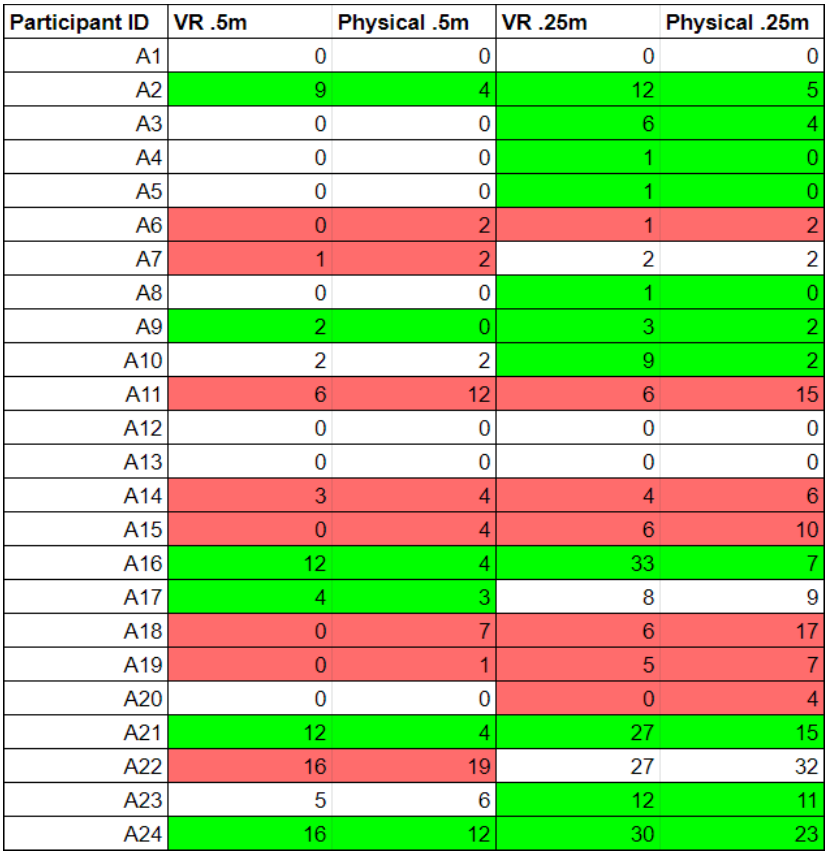
Figure 4.6: Bailey-Lovie Word Chart Unity Scene

placing them very close to the chart. When told to start by the facilitator, each participant attempted to read as many words as they can via the chart until they believed they could not read any further. Due to the distance of the chart, and certain forms of vision loss, participants were allowed to move their heads horizontally or vertically if deemed appropriate, but not forwards or backwards to get closer to the chart. The facilitator recorded each correct word, including replications of any word they did not get correct, or noting where words were missed entirely. This final score of how many words they correctly read then produces a rough indication of the level of acuity they have when reading words, before further analysis.

Table 4.3 shows how many words were read by participants in both VR and Physical tests at either 0.5 m or 0.25 m distances.

Word accuracy results showed a smaller gap between the number of overall increases and decreases. At 0.25 m distances the mean of increases within VR between 11 participants was *125%*, the mean of decreases between 9 participants was *113.5%*, 2 participants could not see anything regardless of VR or not, and 1 participant had no increase or decrease. This showed no statistical significance using the Wilcoxon test, with $Z = 0.300 \cdot p = .764 \cdot (r = 0.043 \cdot n = 24)$. At 0.5 m 6 participants had an increase of *132%*, 9 participants had a decrease of *197%*, 8 participants could not see anything at this distance, and 1 participant had no changes. Again, no statistical significance was shown, with $Z = 0.057 \cdot p = .954 \cdot (r = 0.008 \cdot n = 24)$. If we separate participants that had larger signif-

Table 4.3: Data sheet of each participant's results for the Bailey-Lovie Chart (green highlights an increase in VR, red a decrease, and white no changes within 20%.)



Participant ID	VR .5m	Physical .5m	VR .25m	Physical .25m
A1	0	0	0	0
A2	9	4	12	5
A3	0	0	6	4
A4	0	0	1	0
A5	0	0	1	0
A6	0	2	1	2
A7	1	2	2	2
A8	0	0	1	0
A9	2	0	3	2
A10	2	2	9	2
A11	6	12	6	15
A12	0	0	0	0
A13	0	0	0	0
A14	3	4	4	6
A15	0	4	6	10
A16	12	4	33	7
A17	4	3	8	9
A18	0	7	6	17
A19	0	1	5	7
A20	0	0	0	4
A21	12	4	27	15
A22	16	19	27	32
A23	5	6	12	11
A24	16	12	30	23

icant increases or decreases, we have 5 participants that had an increase between 7-16 extra words read, while 5 participants had a decrease of between 4-11 less words read both at 0.25 m distance. If we look at the same at 0.5 m, we have 4 participants that had an increase between 4-8 words, and 2 participants that had a decrease between 6-7 words. This demonstrates that some participants were receiving large increases and decreases, again with 0.5 m distances showing more of the latter, although more research is needed to determine the discrepancies between participants and the amount read. There is little connection between any eye conditions participants may have and results shown in the word speed test. Participants with central vision loss scored lower in VR in this test, with no significant difference between distances read. At 0.5 m 2 participants had an increase in VR, and at 0.25 m only 3 participants. At 0.5 m 4 had a decrease and 3 could not see anything, and at 0.25 m 4 had a decrease, 2 could not see anything, and 1 had no differences. This gives us an overall mean increase of *83%* and a *91%* decrease at 0.25 m, and an *166.5%* increase to a *350%* decrease at 0.25 m. These tests were not statistically significant with $Z = 0.877 \cdot p = .380 \cdot (r = 0.196 \cdot n = 10)$ at 0.25 m, and $Z = 1.160 \cdot p = .246 \cdot (r = 0.259 \cdot n = 10)$ at 0.5 m. The results for central vision loss participants are opposing to the letter detection results, with letters appearing far easier to read within the letter detection test in comparison, while words were more difficult in VR. Results suggest that reading entire words when letters are combined is more difficult for central vision loss users, and perhaps there is a cut-off point where distance is no longer beneficial, as the distances measured in this test were closer at 0.25 m and 0.5 m instead of the usual 0.5 m and 1 m, as participants were not able to see this far for smaller words. As with other tests, at a closer distance VR performed better than it’s further distance equivalent.

4.4 Speed Reading

MNRead Acuity Chart (Reading Speed). The testing method used to determine each participant's reading speed is the MNRead Acuity Chart (Legge 2018).

Lighthouse Low Vision Products
36-02 Northern Boulevard
Long Island City, NY 11101
800–453–4923
Cat. No. C400

MNREAD™ ACUITY CHART 1

M size **Snellen** **logMAR**
for 40cm (16 inches)

8.0 **20/400** **1.3**

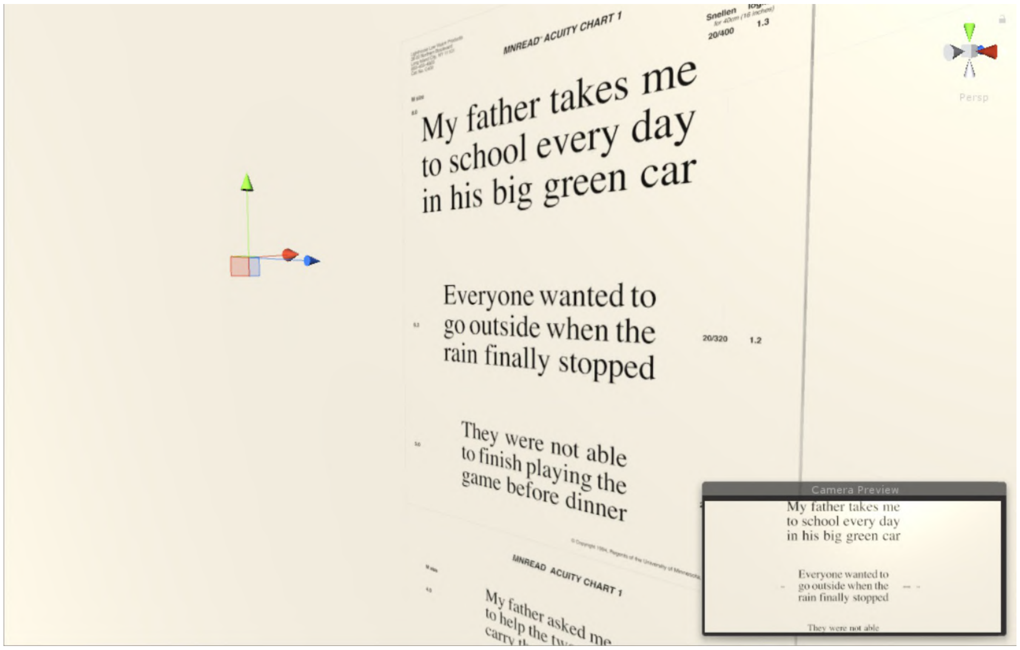
My father takes me
to school every day
in his big green car

Everyone wanted to
6.3 go outside when the **20/320** **1.2**
rain finally stopped

They were not able
5.0 to finish playing the **20/250** **1.1**
game before dinner

© Copyright 1994, Regents of the University of Minnesota. MNREAD™ 3.1–1 600

Figure 4.7: MNRead Acuity Chart



My father takes me to school every day in his big green car

Everyone wanted to go outside when the rain finally stopped

They were not able to finish playing the game before dinner

My father asked me to help the tw

Figure 4.8: MNRead Acuity Chart Unity Scene

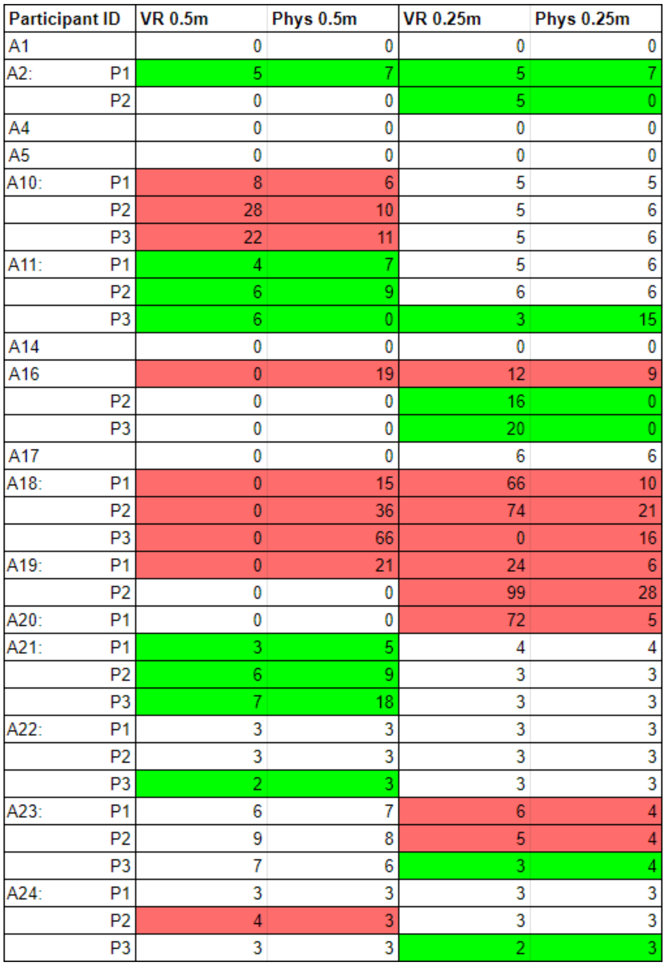
This examination chart relies on an observed environment where the participant is asked to read displayed sentences (See Figure 4.7, 4.8) to the best of their ability at set distances along a timer, while a facilitator records their results. The timer is set alongside the participant's first word, and their overall time taken is calculated as well as any words incorrectly guessed. Table 4.4's P1/P2/P3 labels represent how many paragraphs a participant was able to complete, up to a total of 3 on the chart.

The chart is designed to replicate the reading of modern everyday passages, simulating a natural reading experience. Legge (Legge 2018) defines successful reading in his specification write up as requiring the dynamic integration of perceptual processes, oculomotor control, and higher cognition. Based on the performance recorded from the factors listed above, a prediction of a user's normal reading ability can be made. The MNRead chart is printed at 3600 DPI and measured at a size of 11 x 14 inches. Distance between the participant's head and chart was tested at 2 stages; 0.50 m and 0.25 m. Participants were asked to read from the largest sentence presented and continue reading decreasing sizes until they could no longer read any words in a sentence. Any errors in reading were documented along with the time taken to read to the nearest 0.1 seconds. A total reading time was determined between the facilitator's starting mark (i.e., the verbal expression of the word 'go'), to the very last word spoken. Words that were said incorrectly but then corrected before a sentence is completed were not counted.

Table 4.4 shows how fast each participant read each paragraph of the chart, with P1/P2/P3 relating to each respective paragraph. The faster each participant read, the better their score was, with the final outcome being the lowest number overall for the chart between VR and physical distances (not including 0, which means the paragraph was not able to be read or completed). If an overall attempt was faster in VR (P1+P2+P3 combined), then that participant's attempt is highlighted in green, red if the physical equivalent was faster, or white if no difference in time is shown overall.

Thus far, participant VR results at closer distances outperform further distances trialled. Participants struggled to complete this test, and as such

Table 4.4: Data sheet of each participant's results for the MNRead Acuity Chart (green highlights an increase in VR, red a decrease, and white no changes within 20%.). Numbers represent the seconds taken for completion, lower being better, excluding 0 which means the chart could not be read.



Participant ID		VR 0.5m	Phys 0.5m	VR 0.25m	Phys 0.25m
A1		0	0	0	0
A2:	P1	5	7	5	7
	P2	0	0	5	0
A4		0	0	0	0
A5		0	0	0	0
A10:	P1	8	6	5	5
	P2	28	10	5	6
	P3	22	11	5	6
A11:	P1	4	7	5	6
	P2	6	9	6	6
	P3	6	0	3	15
A14		0	0	0	0
A16		0	19	12	9
	P2	0	0	16	0
	P3	0	0	20	0
A17		0	0	6	6
A18:	P1	0	15	66	10
	P2	0	36	74	21
	P3	0	66	0	16
A19:	P1	0	21	24	6
	P2	0	0	99	28
A20:	P1	0	0	72	5
A21:	P1	3	5	4	4
	P2	6	9	3	3
	P3	7	18	3	3
A22:	P1	3	3	3	3
	P2	3	3	3	3
	P3	2	3	3	3
A23:	P1	6	7	6	4
	P2	9	8	5	4
	P3	7	6	3	4
A24:	P1	3	3	3	3
	P2	4	3	3	3
	P3	3	3	2	3

the n value was not large enough for an accurate p-value to be determined. To summarise, at 0.5 distance, 4 participants were able to read the chart within VR faster and 6 slower, while at 0.25 distance 5 were able to read faster within VR, 4 read slower within VR, and 1 had no difference. Many participants were unable to read at all and were not able to produce results due to their limited vision, resulting in failed attempts with no score. Due to the majority of participants not producing results due to their limited sight, the sample size for this test is smaller and would require a larger pool for accuracy, but from the results gathered the gap between further and closer distances is not as dramatic as previous tests. This could be attributed as reduced effectiveness at 0.25 m distances, but it is likely influenced by limited results overall.

4.5 Colour Detection

Ishihara Test for Color Blindness (Colour Detection). This test is the Ishihara Test for Color Blindness (Clark 1924) (Color Blindness 2019), selected by a optometrist for its wide familiarity and ease of use. This test was used to determine how colour was affected and perceived by using a VR HMD, particularly in numbers, as this could give a good indication of how colours perform overall. The test requires the user to go through a series of plates with numbers displayed on them (See Figure 4.9, 4.10), some with just patterns, and determine whether they can correctly identify each number or shape. Table 4.5 and 4.6 represent whether a participant correctly guessed each plate's number with a Yes/No. If plate changes cannot be distinguished or are incorrectly identified then results can suggest signs of colour blindness, such as Deuteranopia (red & green) or Tritanopia (blue

& yellow).

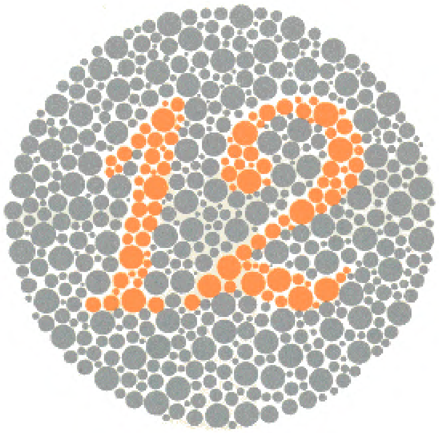


Figure 4.9: Ishihara Color Plate 12

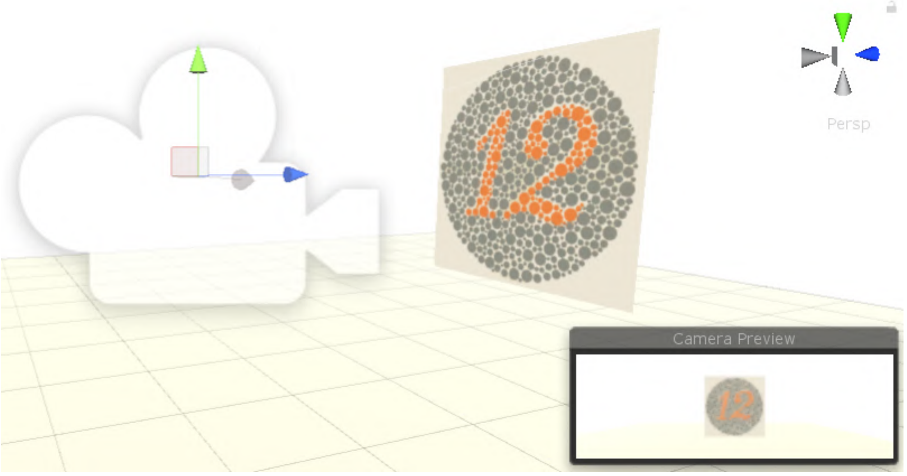
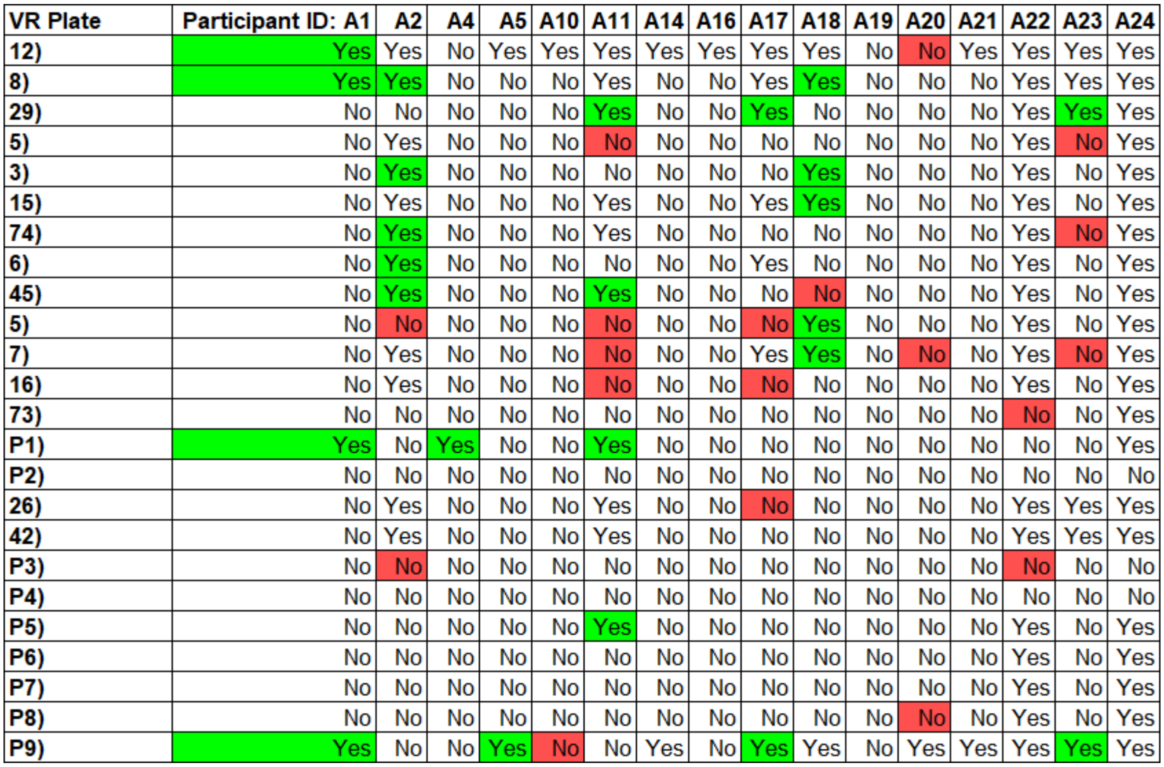


Figure 4.10: Ishihara Color Plate 12 Unity Scene

Each plate was printed on a reinforced matt coated paper at standard A4 size, to prevent glare from lighting. This test, compared to the other charts, does not have any set distances or movement restrictions to how each participant may observe each plate. For the physical part of the test each participant was asked to sit at a desk with a stack of plates presented to them. Participants were allowed to hold each plate in however way they wanted, including leaning in, getting closer, or holding them at an angle. The VR version of this test allowed users to hold a replicated version of each plate in virtual space via the use of VR motion controllers that acted as their hands. Again, each participant was allowed to hold and move the plate or themselves in whatever way best helped them perceive what it was. This allowed the observation and recording of what techniques were used by participants for optimal viewing physically, and to document whether these behaviours translated well or the same into the VR environment, or were necessary.

Table 4.5 and 4.6 shows a table for each participant on whether they correctly identified each number or shape plate within the test. The left column shows what each plate's original number is, while P1 to P9 represent plates that were patterns instead. Green highlights show when a plate was correctly guessed in VR, but not in its physical equivalent, and red if a plate was incorrectly guessed in VR, but correctly guessed physically. White indicates answers were the same between both VR and physical tests for that plate.

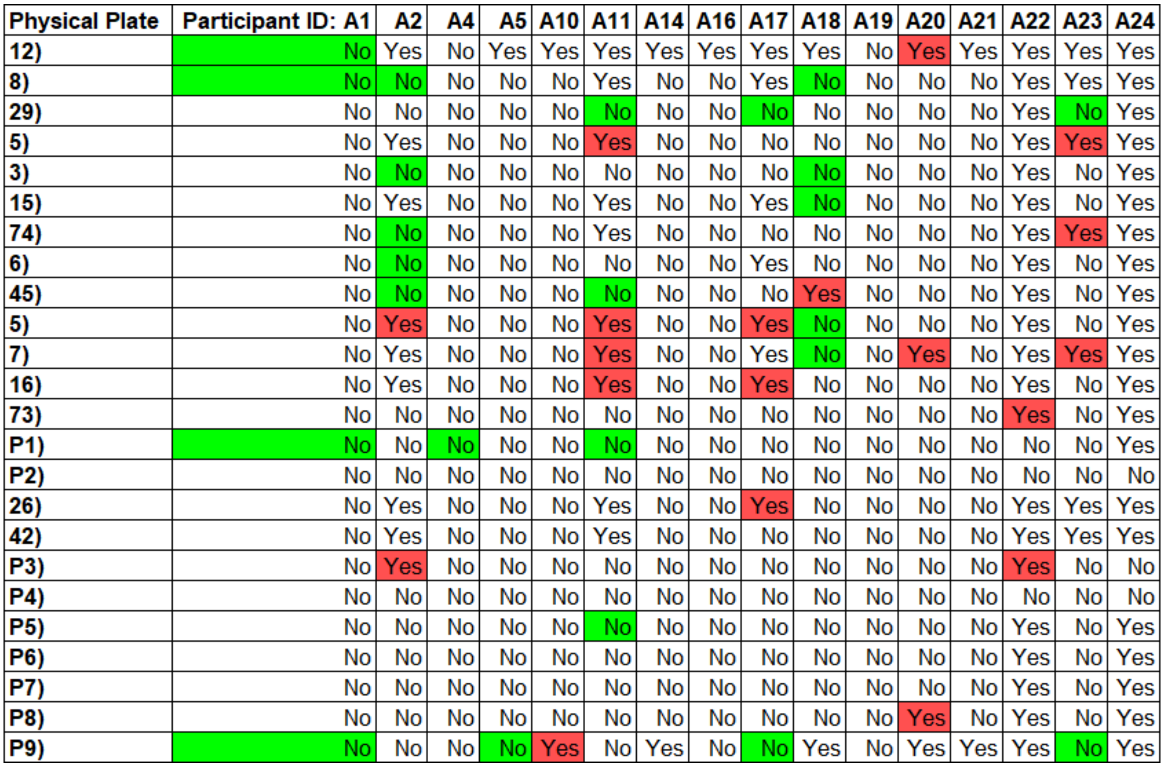
Ishihara test results were problematic in that the majority of plates were unable to be seen by participants, with many struggling greatly during this test in both VR and physical forms. This is more likely to suggest that the test group's overall visual acuity was too limited to perform this test accu-



VR Plate	Participant ID: A1	A2	A4	A5	A10	A11	A14	A16	A17	A18	A19	A20	A21	A22	A23	A24
12)	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes
8)	Yes	Yes	No	No	No	Yes	No	No	Yes	Yes	No	No	No	Yes	Yes	Yes
29)	No	No	No	No	No	Yes	No	No	Yes	No	No	No	No	Yes	Yes	Yes
5)	No	Yes	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
3)	No	Yes	No	No	No	No	No	No	No	Yes	No	No	No	Yes	No	Yes
15)	No	Yes	No	No	No	Yes	No	No	Yes	Yes	No	No	No	Yes	No	Yes
74)	No	Yes	No	No	No	Yes	No	No	No	No	No	No	No	Yes	No	Yes
6)	No	Yes	No	No	No	No	No	No	Yes	No	No	No	No	Yes	No	Yes
45)	No	Yes	No	No	No	Yes	No	No	No	No	No	No	No	Yes	No	Yes
5)	No	No	No	No	No	No	No	No	No	Yes	No	No	No	Yes	No	Yes
7)	No	Yes	No	No	No	No	No	No	Yes	Yes	No	No	No	Yes	No	Yes
16)	No	Yes	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
73)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes
P1)	Yes	No	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	Yes
P2)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
26)	No	Yes	No	No	No	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes
42)	No	Yes	No	No	No	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes
P3)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P4)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P5)	No	No	No	No	No	Yes	No	No	No	No	No	No	No	Yes	No	Yes
P6)	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
P7)	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
P8)	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
P9)	Yes	No	No	Yes	No	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes

Table 4.5: Data sheet of each participant's VR results for the Ishihara Color Test (green highlights an increase in VR, red a decrease, and white no changes recorded.)

rately, rather than accurate indications that colour deficiencies are present, or whether reading coloured numbers in VR will present any significant change. Regardless, results showed that there were a total of 95 correct guesses in VR compared to 91 for the physical test. This was surprising originally, as in preliminary tests participants gave very strong verbal reactions to colour identification, commenting that colours were very vibrant and stood out while trialling a VR headset compared to their normal vision, yet results showed no significant difference during testing.



Physical Plate	Participant ID: A1	A2	A4	A5	A10	A11	A14	A16	A17	A18	A19	A20	A21	A22	A23	A24
12)	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
8)	No	No	No	No	No	Yes	No	No	Yes	No	No	No	No	Yes	Yes	Yes
29)	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
5)	No	Yes	No	No	No	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes
3)	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
15)	No	Yes	No	No	No	Yes	No	No	Yes	No	No	No	No	Yes	No	Yes
74)	No	No	No	No	No	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes
6)	No	No	No	No	No	No	No	No	Yes	No	No	No	No	Yes	No	Yes
45)	No	No	No	No	No	No	No	No	No	Yes	No	No	No	Yes	No	Yes
5)	No	Yes	No	No	No	Yes	No	No	Yes	No	No	No	No	Yes	No	Yes
7)	No	Yes	No	No	No	Yes	No	No	Yes	No	No	Yes	No	Yes	Yes	Yes
16)	No	Yes	No	No	No	Yes	No	No	Yes	No	No	No	No	Yes	No	Yes
73)	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
P1)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes
P2)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
26)	No	Yes	No	No	No	Yes	No	No	Yes	No	No	No	No	Yes	Yes	Yes
42)	No	Yes	No	No	No	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes
P3)	No	Yes	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No
P4)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P5)	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
P6)	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
P7)	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes
P8)	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	Yes
P9)	No	No	No	No	Yes	No	Yes	No	No	Yes	No	Yes	Yes	Yes	No	Yes

Table 4.6: Data sheet of each participant's physical results for the Ishihara Color Test (green highlights an increase in VR, red a decrease, and white no changes recorded.)

4.6 Colour Accuracy

Panel 16 Quantitative Color Vision test (Colour Accuracy). This test is the Quantitative Color Vision Test (Lea 2018), or the Lea Color Vision Test, and was also recommended as a well established test from a optometrist. This study is based around an observational experiment that has participants attempting to align a set of colours in sequential order from a given pilot colour. A selection of colours is presented that covers a basic range of hues defined by the P16 Vision Test to gather an understanding of what a user can perceive between similar colour frequencies and to check for any patterns that may suggest deutan, protan, or tritan defects (See Figure 4.11, 4.12). As this test is designed to recognise colour deficiencies, it can be used as an effective comparative tool for evaluating whether colours seen within VR are accurate to natural vision.

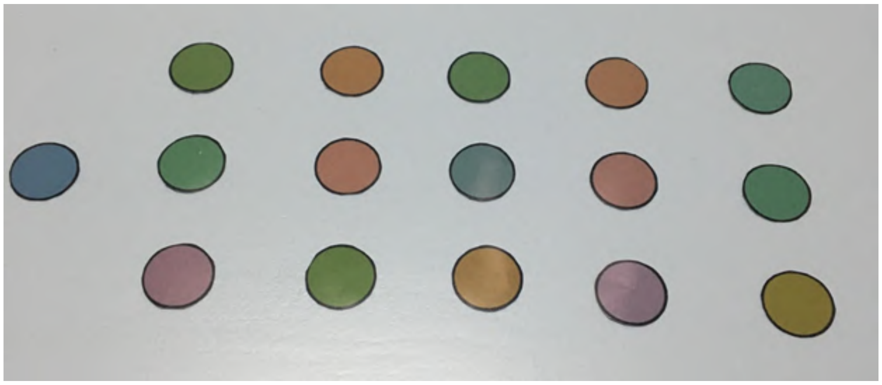


Figure 4.11: Physical version of the Panel 16 Quantitative Color Vision Test.

The colours used within the P16 Vision Test were printed as displayed from their original documentation (LEA Test Intl 2020) and cut out as circles of radius 22 mm. Participants were given a colour setup, with the pilot colour starting to the left, and are recorded as they attempt to rearrange 15 colours by similarity of hue. Each colour links to an assigned number that is hidden to the participant, and if arranged correctly, each colour should range from 1-15 in ascending order. The colours presented were arranged in 3 rows by 5 columns, with the pilot colour positioned to the far left of the

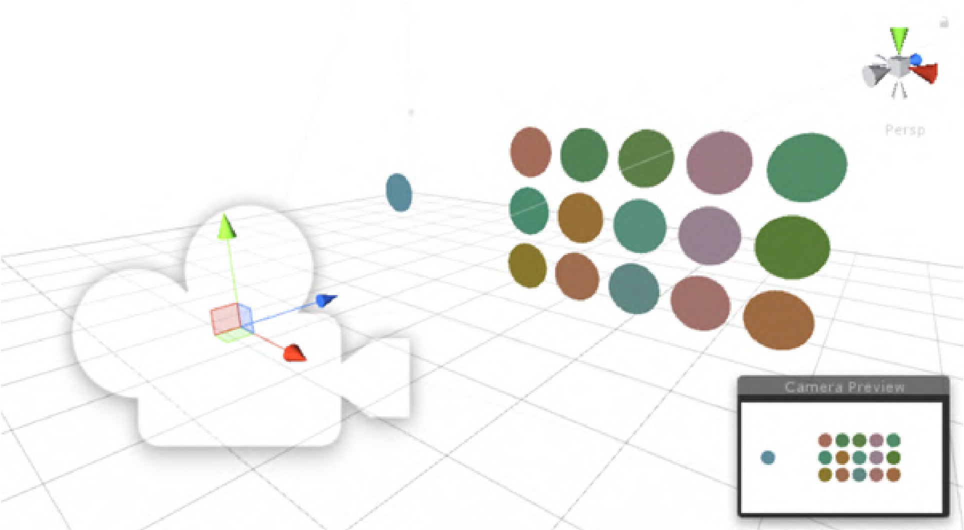


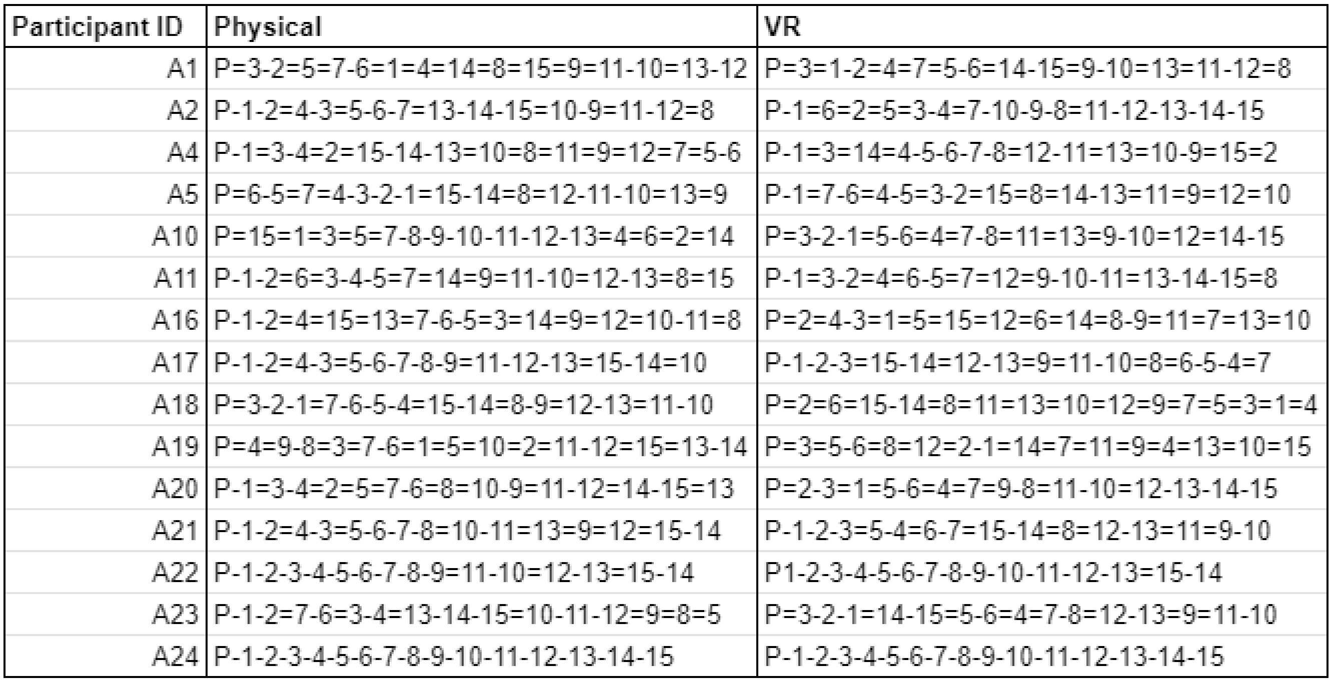
Figure 4.12: Unity scene of the Panel 16 Quantitative Color Vision Test.

arrangement. Participants were asked to not move any colour themselves, and once a participant has confirmed their chosen answer the test invigilator would move and arrange each colour instead to better mirror the VR version of the test. Once a participant has confirmed an answer they may not change it once it is re-arranged into the list. The performance of each participant was measured by checking the distance of jumps between numbers, and whether those jumps align with certain patterns shown to be related to Proton deficiency (red-green colour deficiency with red sensitivity), Deutan deficiency (red-green colour deficiency with green sensitivity), and Triton deficiency (blue-yellow colour deficiency). A perfect score would follow the structure of: PILOT-1-2-3-4-5-6-7-8-9-10-11-12-13-14-15. The VR equivalent of this test was created to mirror this same selection process. A scanned copy of all colours used within the physical was imported into the platform with precise colour values extracted for accuracy. 16 colours were displayed within the environment as circles that are placed floating in front of the viewer. The VR setup utilised only head-motion/tracking to avoid confusion, so as such a selection tool was developed to bridge the gap for interaction. Colour selection was chosen via the participant verbally, while the facilitator controlled the selection of colours externally from outside of the HMD via a keyboard. Once a participant chose a colour from the displayed row, the invigilator inputs this colour as the next to be arranged, until every colour is displayed in a row and arranged. After every colour was eliminated from the original pool of 15 (15 as the pilot colour is not counted), the full list of colours is observed and recorded.

Table 4.7 and 4.8 show overall test results for each participant. Assuming a perfect score is P-1-2-3-4-5-6-7-8-9-10-11-12-13-14-15, any mistakes made are highlighted with a ’=’, such as 4=6, while 5-4 would be accepted. If 4 or more mistakes are recorded that follow an axis pattern that would suggest either Tritan, Deutan, or Protan deficiency, then this is displayed on Table 4.8. Mistakes have to be close enough to a particular axis to suggest a certain colour deficiency, such as in Figure 4.13 where jumps between 7-15, 14-8, 8-12 and 11-9 may suggest Tritan deficiency.

Results from the Panel 16 Vision test are varied and in some participant cases seemingly erratic, but still produce similar scores between both VR and physical versions of the test. When following the assumption that 4 or more notable errors are indicators of colour deficiency, where *(n=15)*

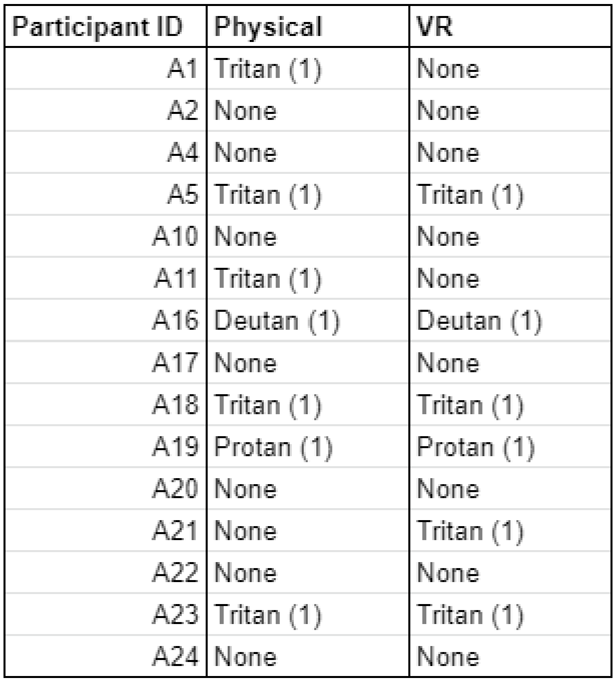
Table 4.7: Panel 16 Vision test results of each participant, with '-' symbols showing correct moves made, and '=' denoting mistakes made.



Participant ID	Physical	VR
A1	P=3-2=5=7-6=1=4=14=8=15=9=11-10=13-12	P=3=1-2=4=7=5-6=14-15=9-10=13=11-12=8
A2	P-1-2=4-3=5-6-7=13-14-15=10-9=11-12=8	P-1=6=2=5=3-4=7-10-9-8=11-12-13-14-15
A4	P-1=3-4=2=15-14-13=10=8=11=9=12=7=5-6	P-1=3=14=4-5-6-7-8=12-11=13=10-9=15=2
A5	P=6-5=7=4-3-2-1=15-14=8=12-11-10=13=9	P-1=7-6=4-5=3-2=15=8=14-13=11=9=12=10
A10	P=15=1=3=5=7-8-9-10-11-12-13=4=6=2=14	P=3-2-1=5-6=4=7-8=11=13=9-10=12=14-15
A11	P-1-2=6=3-4-5=7=14=9=11-10=12-13=8=15	P-1=3-2=4=6-5=7=12=9-10-11=13-14-15=8
A16	P-1-2=4=15=13=7-6-5=3=14=9=12=10-11=8	P=2=4-3=1=5=15=12=6=14=8-9=11=7=13=10
A17	P-1-2=4-3=5-6-7-8-9=11-12-13=15-14=10	P-1-2-3=15-14=12-13=9=11-10=8=6-5-4=7
A18	P=3-2-1=7-6-5-4=15-14=8-9=12-13=11-10	P=2=6=15-14=8=11=13=10=12=9=7=5=3=1=4
A19	P=4=9-8=3=7-6=1=5=10=2=11-12=15=13-14	P=3=5-6=8=12=2-1=14=7=11=9=4=13=10=15
A20	P-1=3-4=2=5=7-6=8=10-9=11-12=14-15=13	P=2-3=1=5-6=4=7=9-8=11-10=12-13-14-15
A21	P-1-2=4-3=5-6-7-8=10-11=13=9=12=15-14	P-1-2-3=5-4=6-7=15-14=8=12-13=11=9-10
A22	P-1-2-3-4-5-6-7-8-9=11-10=12-13=15-14	P1-2-3-4-5-6-7-8-9-10-11-12-13=15-14
A23	P-1-2=7-6=3-4=13-14-15=10-11-12=9=8=5	P=3-2-1=14-15=5-6=4=7-8=12-13=9=11-10
A24	P-1-2-3-4-5-6-7-8-9-10-11-12-13-14-15	P-1-2-3-4-5-6-7-8-9-10-11-12-13-14-15

there are 12 participants recorded with the same results, 2 where the physical test reported a deficiency but not the VR test, and 1 where the VR test reported a deficiency but not the physical. A closer look at individual scores show greater variances in the patterns taken, despite overall scores remaining similar. Overall the similarity between test results may suggest that colour representation and recognition within VR is accurate to real world equivalents, with no evidence being strong enough to imply any version out performs the other within this sample size.

Table 4.8: Panel 16 Vision test results of each participant with any Tritan, Protan, or Deutan deficiencies recorded.



Participant ID	Physical	VR
A1	Tritan (1)	None
A2	None	None
A4	None	None
A5	Tritan (1)	Tritan (1)
A10	None	None
A11	Tritan (1)	None
A16	Deutan (1)	Deutan (1)
A17	None	None
A18	Tritan (1)	Tritan (1)
A19	Protan (1)	Protan (1)
A20	None	None
A21	None	Tritan (1)
A22	None	None
A23	Tritan (1)	Tritan (1)
A24	None	None

4.7 Chart Limitations & Typography

As already previously declared, each test was chosen due to its familiarity as an optometry test, each specialised to measure a particular aspect of vision, as recommended through discussions with an optometrist. Unfortunately, due to the low reading ability of many of the participants that partook in this study, as well as the low readability of persons with severe visual disabilities in general, many of these charts become unsuited for many differing acuity levels and conditions. Adjustments were made to make them more accessible, yet there are many other factors that would in-

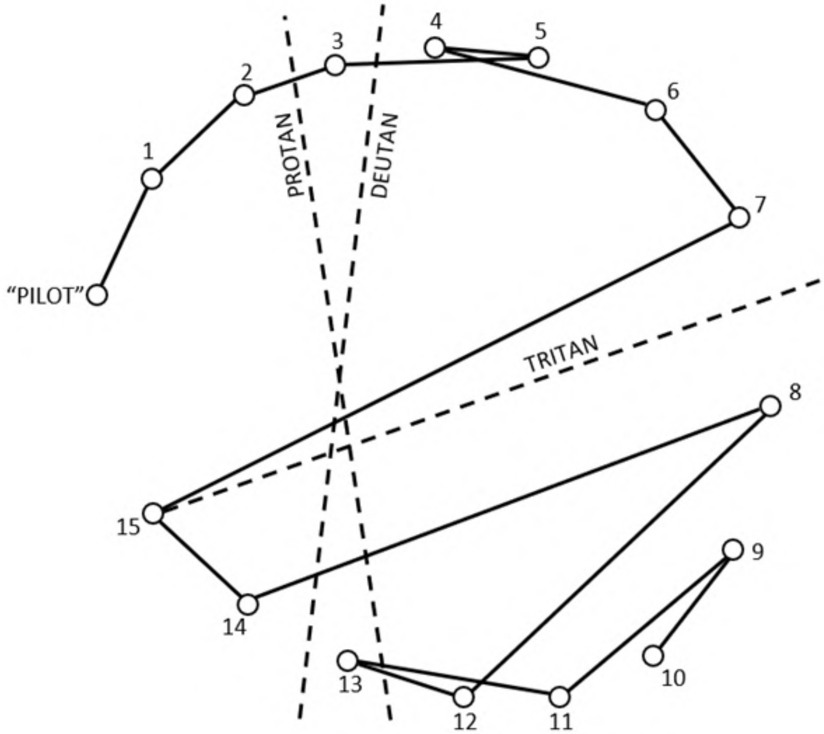


Figure 4.13: Participant 21's VR test results of the Panel 16 Vision test, suggesting Tritan deficiency.

fluence readability on an individual case by case. There are many ways to incorporate typography to increase visibility and readability, yet as these charts were based on already recognised measurement systems, it was deemed appropriate to utilise broader tests, despite how some users may struggle as the typography has been adjusted to them specifically. Despite the typography not being designed specifically for the user group, utilising well established tests has the advantage of well-balanced neutral fonts and letters, said to be effective for readability. The ETDRS and Pelli-Robson Contrast Sensitivity charts, for example, utilise a Sloan/ETDRS modification of sans serif letters that are known to be good for equal legibility (PrecisionVision 2021; Kaiser 2009) and make use of balanced spacing. Similarly, the Bailey-Lovie Word Reading Chart and the MNRead Acuity Chart both use Times New Roman, a serif typeface, chosen to replicate commonly used reading fonts as one might expect in a newspaper, and are still considered good for accessibility. Unfortunately, due to the general design of these charts, other aspects of typography such as colour are not utilised, although can be explored further in the follow up study.

The next chapter discusses the results presented from this study, as well as the individual profiles and results from each participant, and a framework built upon the findings.

Chapter 5

Participant Profiles & Discussion of Results

This chapter presents participant profiles alongside individual results and comments, and discusses the findings of the comparative study.

5.1 Participant Profiles & Results

This section presents the full profiles of each participant as recorded through several interviews, as well as individual results from each test. These profiles aim to give context to the conditions mentioned and described within this study, and shed light onto how the lives of severally visually disabled persons are affected by their conditions, as well as how the solutions mentioned in this research could apply to individual cases. Some participants may have test results missing meaning that they were not able to take part in a particular test. For tests they were able to participate in both VR and physical versions, unless identified to be invalidated for another reason, their results are counted in the overall discussion and presentation of data. As these were low-vision participants the inability to complete a test is not uncommon. In some cases due to the nature of their conditions, the availability of participants was not always possible for follow up sessions and profiles and or results are limited.

Medical records for the participant group were not available and were not documented through the Beacon Centre for the Blind. As such, diagnosis and description of each participant's conditions were recorded through their own testimony although many were not completely sure with what they had, nor could they recall their past medical history. Due to this, descriptions may appear stronger depending on the participant's own knowledge of their conditions and history, or whether they were available for multiple sessions.

Participant A1

Participant Profile & Conditions. Participant A1 is an 85-year-old female with a history of Macular Degeneration. She was first officially diagnosed in 2007 but the condition had originated years earlier. Originally suffering from dry (slow deterioration of the macula's cells), her macular had transitioned into wet (Macular Society 2018b) (abnormal blood vessels in the macular causing leakage and scarring) macular degeneration during the first interview with this participant, but when returning to visit her again her macular had reverted back to being dry. Her left eye has had 3 Lucentis injections and is substantially weaker than her right eye, with blurred vision remaining from its original appearance 3-4 years ago. Her right eye is her best eye for vision. Both eyes suffer from cataracts. The participant commented that sometimes she has trouble with the movement of her eyelids, but this plateaus at random. This participant wears glasses but noted that they do not improve vision anymore and are “simply worn for aesthetic purposes”. She described reading tasks as only possible with very large fonts. Sight in daylight was described to be better than in darker lights. Her central vision loses features or detail when focusing directly on an object. The participant additionally reported that she has had CBS for 5 years, which causes hallucinations to appear in the eyes as basic colours, or more complex imagery such as people or places. This can be severe, but she can exercise her eyes for 10 seconds to remove any hallucinations which is effective.

Daily Impact & Aids Used. This participant requires family for transportation/travelling, but is otherwise independent at home. She commented that she leaves a TV on but watching is difficult requiring her to be very close, so listening to the TV is preferred for company rather than visual stimulation – something she reports that she misses. She reports needing more help with everyday support, something she finds frustrating, although does not feel helpless if this is not provided.

Participant Results. ETDRS testing results for Participant A1 showed large improvements within VR space, with a score of *1.402* at both 1 m and 0.5 m distances, and a score of *1.66* and *1.60* at 1 m and 0.5 m distances respectively. Pelli-Robson Contrast Sensitivity Chart (PCSC) results had little difference at 1 m distance, with *1* extra letter read in VR compared to the physical, but at 0.5 m distance the participant was able to read *18* letters in VR and only *3* when done physically. For the Bailey-Lovie Reading Chart test, the participant was unable to read any words within VR or physical space at both 1 m and 0.5 m tested distances, so no results were gathered. Again, no words were detected in the MNRead Acuity Chart test either at tested distances and equipment, so no results were gathered. While attempting the Ishihara Color Plate Test, this participant struggled to perceive any numbers or identify any shapes for the physical version of the test. In the VR version they were able to identify *4* plates correctly and made several incorrect attempts. The P16 Vision Test showed similar results between both physical and VR tests (See Figure 5.1), yet the physical version records a Tritan deficiency while the VR version is just under score. This may be within margin of error due to similarity. Overall this participant was able to detect further characters within a VR space under all conditions. Words were still too difficult to read regardless of equipment, however, suggesting that HMD virtual enhancements would need to be necessary to gain further use. Colour performance was slightly improved

Table 5.1: Participant A1's individual results for the first 4 tests.

ID: A1	VR Far	Physical Far	VR Near	Physical Near
Letters	15	2	15	5
Contrast	4	3	18	3
Words	0	0	0	0
Speed P1	0	0	0	0

within a VR headset suggesting colours were enhanced somewhat. See Table 5.1 for this participant's results for the first 4 tests.

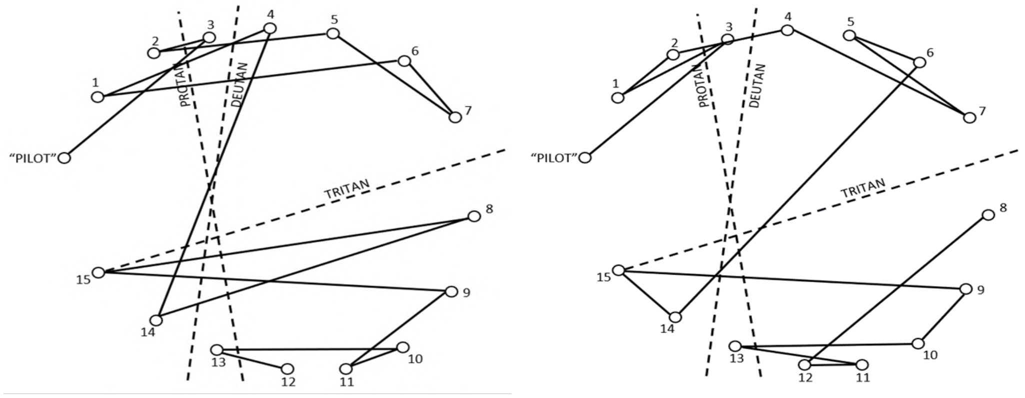


Figure 5.1: (left) Participant A1's physical Panel 16 Vision test results. (right) VR test results.

Participant A2

Participant Profile & Conditions. Participant A2 is a 51-year-old female who suffers from a fully blinded right eye and a damaged left, described as having limited blurred vision due to Hemianopia (Iftikhar 2018). The Arteries in the back of her eyes are blocked. In the past, this participant stated they have always required glasses but had not been near blinded until a recent deterioration. Since then, glasses are required for any reading and seeing, otherwise vision is blurred; glasses make her visuals sharper in general. Her reading is limited overall, requiring her to put her face right up to text to recognise detail, or for the font to be enlarged. The participant's vision decreases throughout the day based on how long she has been awake due to fatigue with a sensitivity to light, causing bright lights and sun to blind her, and shaded glasses are worn throughout most of the day to combat this. At night time she is not blinded by stronger lights such as sunlight, but her vision is weaker due to fatigue. Her family does not have a history of visual impairments, although her father had a cataract removed when he was older. She described her ability to perceive colours as "fine". Currently she is on antidepressants due to suffering from depression and frustrations caused from her damaged vision.

Daily Impact & Aids Used. This participant makes use of low-vision sight books (RNIB 2021) via the use of a magnifying glass. She commented that she does watch TV, but it "must be very close to view it properly". The participant makes use of a white cane when travelling due to her vision, and owns a mobile phone with enlarged font, but does not know how to use any other accessibility features, as well as owning a tablet with enlarged font and owning a talking watch. She expressed that she needs assistance to travel and otherwise doesn't travel alone. The participant has children at home to cook for her, or otherwise uses a microwave for meals, and added that she enjoys cooking at Beacon Centre, and is interested in learning more about technology assistance. Any sort of outdoor shopping requires assistance, usually performed by family. She describes her condition overall as very impacting on her life, limiting her independence, commenting that she would like to be able to travel without needing assistance, which is frustrating to her. Her final comment was that she tries to "make the most out of everything" but would want her condition removed more than anything.

Participant Results. ETDRS testing results showed no difference reading letters at 1 m, with a score of *1.40* both within and outside of VR but results at a closer 0.5 m distance produced a score of *1.52* acuity in the physical test and *1.30* within VR. PCSC results showed minor differences, with *18* letters read within VR compared to *16* physically at 1 m distance, and *30* letters read within VR compared to *28* done physically at 0.5 m distance, showing a difference of *2* extra letters within VR for both tests. Bailey-Lovie Reading Chart results showed an increase at 0.5 m distance with *9* words read within VR compared to *4* physically, while larger differ-

Table 5.2: Participant A2's individual results for the first 4 tests.

ID: A2	VR Far	Physical Far	VR Near	Physical Near
Letters	15	15	20	9
Contrast	18	16	30	28
Words	9	4	12	5
Speed P1	5	7	5	7
Speed P2	0	0	5	0

ences were shown at the closer 0.25 m distance with *12* words being read within VR compared to 5 physically. MNRead Acuity Chart results showed the exact same results between 0.5 m and 0.25 m, with Participant A2 taking *5* seconds to read both distances within VR and *7* seconds when done physically. An extra paragraph was read within VR at 0.25 m distance that took *5* seconds to read, but the physical chart was not readable at the same distance. Ishihara test results showed *3* more correct guesses within VR compared to physical performance. P16 test results (See Figure 5.2) show no significant sign of a colour deficiency in both versions. Overall performance while utilising a VR headset appear to be increased amongst most tests, with no test recording a better score while physically testing. Participant comments towards the use of this device are positive, and despite sometimes only minor increases shown, this participant said they would like to benefit from a similar device such as this for aiding with vision. See Table 5.2 for this participant's results for the first 4 tests.

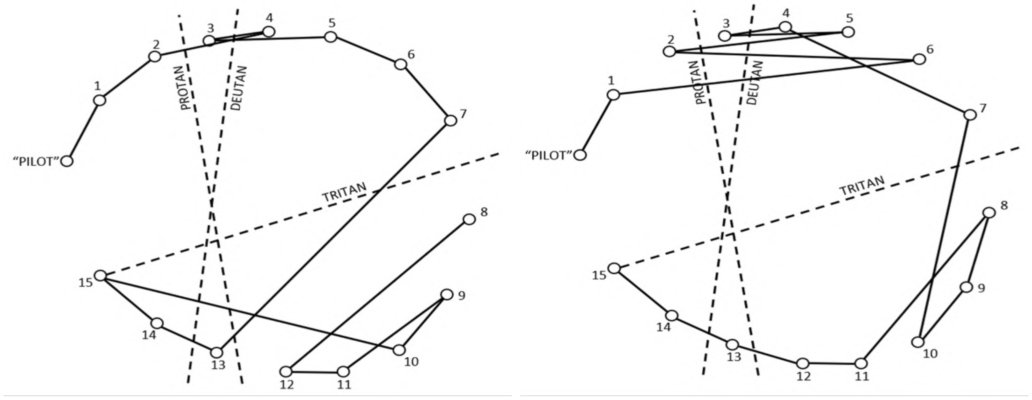


Figure 5.2: (left) Participant A2's physical Panel 16 Vision test results. (right) VR test results.

Participant A3

Participant Profile & Conditions. Participant A3 is a 38-year-old female that has undergone surgery to fix her limited vision but with minimal success. She has had a rapid decline in her vision that has occurred suddenly over the past 5 years. She originally had short vision and wore glasses from an early age, with her family having a history of poor eyesight, and can read only if the text displayed is extremely close to her eyes, usually preferring to hold text up to her right eye to scan single characters/words individually. The participant had a corneal graph transplant in her left eye, replacing the corneal tissue, which has left a small tube within her eye that protrudes out slightly. She wears glasses in fear that something may push against this tube by protecting from any potential contact, but the glasses themselves do not improve her vision. Her right eye is heavily blurred and has double vision. This participant was unsure of what her condition was called and could only describe the symptoms.

Daily Impact & Aids Used. The participant makes use of a mobile phone with enlarged font sizes and brings it close to her eye to scan each letter for communication. She has not been able to read books for 5 years since her deterioration started and expressed that she would love to be able to “just read again”. She described the massive impact on her life losing the majority of her vision has caused and regretted not trying other potential solutions earlier such as laser eye surgery, before she became illegible.

Participant Results. ETDRS results showed a large increase in reading ability at 1 m distances, with a score of *1.46* within VR compared to *1.64* when done physically. At 0.5 m distance the participant scored *1.40* within VR and *1.54* physically. PCSC detection results were not recorded at 1 m distances as no letters were visible within or out of VR, but at 0.5 m distance she was able to read *16* letters in VR and 3 outside of VR. With Bailey-Lovie Reading Chart results again nothing was readable at the further 0.5 m distance, but at 0.25 m distance she was able to read *6* full words within VR compared to *4* read outside of VR. Testing for reading speed an older legacy version of the test (prior to using the MNRead version) was used, in which she read a passage of text in VR taking her *229* seconds in total but was unable to read any parts of this same passage outside of VR. This data is not included in the overall results due to a different test being used but is noteworthy due to her ability to read within VR and her

Table 5.3: Participant A3's individual results for the first 4 tests.

ID: A3	VR Far	Physical Far	VR Near	Physical Near
Letters	12	3	15	8
Contrast	0	0	16	3
Words	0	0	6	4
Speed P1	N/A	N/A	N/A	N/A

reaction from this test in which the participant started crying joyfully as they had not been able to read accurately for some time. No colour tests were attempted with this participant as she was not available for any follow up tests. See Table 5.3 for this participant's results for the first 4 tests.

Participant A4

Participant Profile & Conditions. Participant A4 is a 59-year-old male that suffers from optical neurosis, with damaged optic nerves. First damage to his optic nerves happened in 2005 caused by a viral attack to the eyes, with sight being extremely limited at first and causing greyscale, described as near-blindness. After intravenous steroids were taken for 18 months, with oral medication afterwards, sight had improved significantly since the first attack but was still severely limited. The participant has inflammation in his optic nerves, with visual signals not reaching the brain correctly. Whenever he is ill it directly affects his vision, with any illness making his sight lower temporarily. He has noticed some minor deterioration since his first attack in 2005 but it has been slow enough not to be able to notice it short term. His vision was described as a thick blur around the eyes with very limited colour, close to grey but not entirely, and his left eye is slightly better than his right. Additionally, he has had a heart attack since we last spoke which has caused him to be short of breath, but through cardiac rehab and weekly gym sessions he is improving; he has a heart condition which interferes with the arteries opening but is unsure of the name. Reading is extremely limited for this participant, requiring vision enhancing aids.

Daily Impact & Aids Used. The participant makes use of multiple accessibility technologies and equipment, such as iPhone text-to-speech (Siri), an iPad and iMac with text-to-speech and very magnified font. Normally he requires a magnifier at x15 with built-in light in order to read. He is independent enough to cook, using cooking timers and scales that are audible, speaking out timings. He makes use of a microwave primarily for cooking but can on occasion cook hot foods usually with assistance or heavy reliance on audible appliances. He uses audio books to read if they are available to him, or just for stories. The participant owns a white cane that he uses when outside, but otherwise relies on memory/railings to navigate; normally he has assistance with navigation from others. If a destination is near, he uses his family to travel. He described his mobility as reasonable overall, booking taxis to travel to places like the Beacon Centre, or going out for walks but at a limited distance. He receives care support for the main weekly shopping. This participant does not use a TV at all. When asked about his independence, he mentioned that he likes to think he is independent in general, although some assistance is required, such as needing help to read documentation which he finds the most difficult. He misses the ability to drive, as his passion was riding bikes and getting out a lot. This participant detailed that he has to force himself to perform tasks, push himself further to stay active, keep fit and social, and adapt his lifestyle since the changes to his vision. Makes use of the Beacon Centre to keep social saying that “places like this really help him keep up to date and coping”.

Participant Results. ETDRS results were positive within VR, with a score of *1.58* achieved at 1 m distance and *1.52* at 0.5 m. No letters were detected when reading physically at both distances and were only seen within VR. PCSC results were similar, that nothing could be seen in the physical test but within VR *2* letters were read at 1 m distance and *4* letters at 0.5 m distance. Bailey-Lovie Reading Chart results were very limited, with no words being read physically and only *1* word read within VR at 0.25 m distance. MNRead Acuity Chart results could not be gathered as participant A4 was not able to read any words or characters in both VR and physical space. Ishihara test results were difficult to gather as the participant was unable to see much, and only *1* plate was correctly guessed within VR but none were able to be identified during the physical version. P16 Vision test results (See Figure 5.3) do not show significant enough deviation between versions to claim any colour deficiencies with certainty, although

Table 5.4: Participant A4's individual results for the first 4 tests.

ID: A4	**VR Far**	**Physical Far**	**VR Near**	**Physical Near**
Letters	6	0	9	0
Contrast	2	0	4	0
Words	0	0	1	0
Speed P1	0	0	0	0

there are signs of a deuteranopia deficiency between both versions. Overall this participant's results were favourable within VR, as many tests were not able to be attempted normally within physical conditions but with the extra aid of the headset some minor results were gathered. This participant was one of the earliest tested during a pilot study and was one of the initial that prompted the interest of this project as they were someone that could not participate in any early tests physically, yet within the VR headset was able to participate in some, even if results were not dramatic. This participant commented that the headset was much clearer to see and overall was very positive with its use. See Table 5.4 for this participant's results for the first 4 tests.

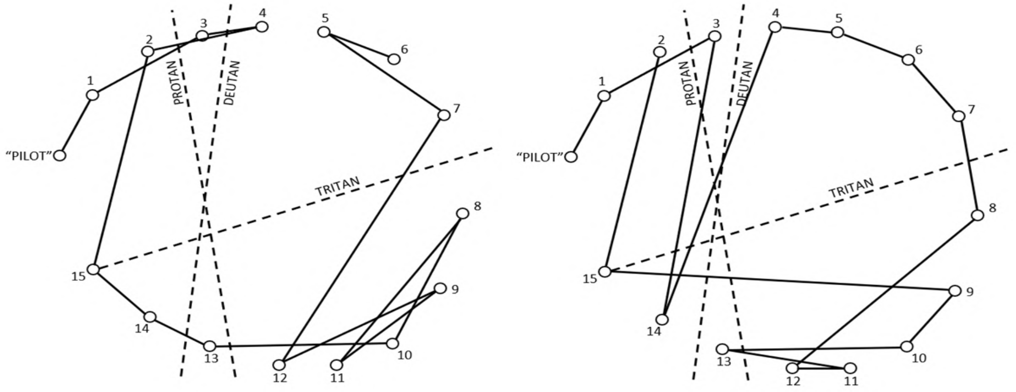


Figure 5.3: (left) Participant A4's physical Panel 16 Vision test results. (right) VR test results.

Participant A5

Participant Profile & Conditions. Participant A5 is a 94-year-old female that believes she has Wet Macular Degeneration but is unsure of her condition. She described her vision as blurry or having "mist" blocking her ability to see. She has a mild cataract in one eye but is unsure which. The participant has scarring in the left eye which is her strongest eye, whereas her right vision was described as only having some vision. She was unsure when her vision first showed severe signs of damage, but mentioned she had an operation at the age of 11 and had always wore glasses as well as having a squint. She divulged that her daughter also had a squint and that her parents may have worn glasses but struggled to remember. This participant has had 4 injections in her eyes in the past and recalled that her eyes had blood in them. She had a fall on her head 2 years ago saying it hadn't affected her vision, but it is possible this may have had some effect on her vision. Since the last session conducted in the pilot study, this participant was seeing double vision which she hadn't seen previously and had increased difficulty with mobility. Wearing glasses does help her to see, but they are now creating a double vision effect with them on; taking them off removes this effect but her vision is less clear. Her reading ability is limited requiring very large fonts and a magnifier, and any prolonged reading causes a loss of visual focus, described as difficult to keep going for long. She commented that she has a sister that is near blind as well but still has some vision. Finally, she mentioned that the tablets she takes sometimes cause hallucinations, although couldn't remember what her medication was called. Before testing and after, it was noted that the physical activity of walking had caused a mist to appear around her eyes and detail was lost. During testing she mentioned that this mist had disappeared and that she could see me clearly, but when getting up and needing to walk to leave the room, she commented that the mist had returned, and detail was again lost.

Daily Impact & Aids Used. The participant uses a stick when walking outside but mobility is very limited. She takes a dedicated support bus to the Beacon Centre that travels to and from her house every week and takes a taxi to travel to hospital appointments. Taking public transport via bus is done by asking either the driver or those around her what number the bus is when it stops. She described her travelling as independent and alone, as she organises transportation herself. She cooks her own meals and makes hot drinks. The participant commented that she receives a lot of help from her family in general, such as help with her shopping. She has her son cut her tablets if she can't, as she finds this difficult alone. She does not watch TV much, but if she does, she sits sideways for viewing due to her central vision blur. This participant listens to the radio as well as audio books. She does not use a phone and is not familiar with phone accessibility technology. The participant described herself as being "frustrated with her sight sometimes" and would "love to be able to see clearly" but makes do with what she has.

Participant Results. ETDRS results were greater in the physical version, with a score of *1.48* at 1 m distance physically compared to *1.60* within VR, and *1.26* at 0.5 m distance physically compared to *1.34* within VR. PCSC showed no changes at the shorter 0.5 m distance, with both VR and physical results showing *12* letters read, but at 1 m distance *6*v letters were read within VR and *3* were read within physical space. Bailey-Lovie Reading Chart results showed that only *1* word was able to be read at 0.25 m distance within VR, but at all other distances no letters could be seen in both VR and physical space. No words could be read within the MN-Read Acuity Chart test within all ranges. Ishihara results produced limited results, with *1* more correctly guessed plate within VR compared to the physical version. P16 test results (See Figure 5.4) strongly suggest a Tritan deficiency between both versions of the test. Overall results are mixed and vary for Participant A5. Letter detection was noticeably worse for VR,

Table 5.5: Participant A5's individual results for the first 4 tests.

ID: A5	VR Far	Physical Far	VR Near	Physical Near
Letters	5	11	18	22
Contrast	6	3	12	12
Words	0	0	1	0
Speed P1	0	0	0	0

but contrast was somewhat better in VR and word detection showed only one word read within VR compared to none physically. P16 Vision results also showed very similar patterns and results between physical and VR, as well as Ishihara plate differences being minimal, suggesting colour is perceived no differently. It appears that if there was any visual difference between both setups, it was limited. See Table 5.5 for this participant's results for the first 4 tests.

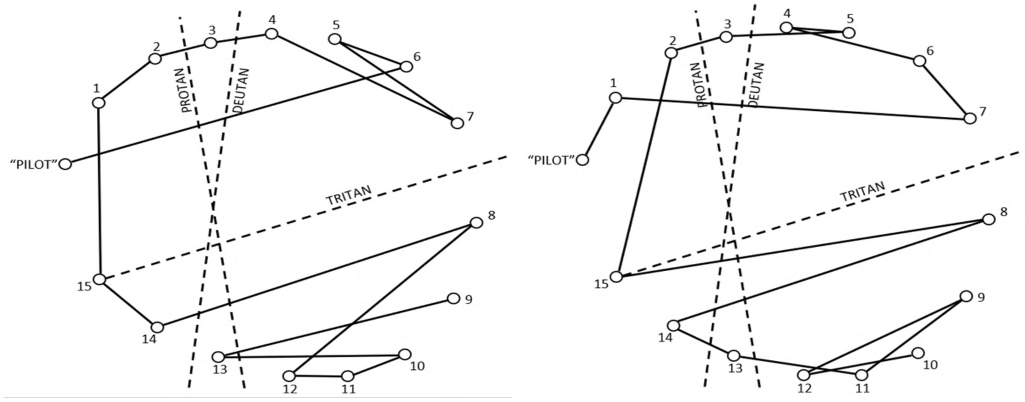


Figure 5.4: (left) Participant A5's physical Panel 16 Vision test results. (right) VR test results.

Participant A6

Participant Profile & Conditions. Participant A6 is a 90-year-old female that believes she has Dry Macular Degeneration, but is unsure, as well as suffering from CBS which is hereditary. The syndrome has affected mostly women in her family with her mother and sisters having it, including a niece. She said her left eye has a cataract and is degenerative, completely blinded now, while her right eye had a cataract removed and is the only lens working. Her CBS causes hallucinations to appear, which she said can be triggered by bright colours.

Daily Impact & Aids Used. She uses spy glasses to see and read, although limited. She mentioned that she does watch a TV that is around 42 inches at roughly 1 meter away.

Participant Results. ETDRS results showed that there was some improvement within VR, with a score of *1.62* acuity at 1 m distance within VR compared to *1.68* in physical space, and *1.40* at 0.5 m distance within VR compared to *1.60* physically. PCSC results showed little difference, with *1* letter detected at 1 m distance within VR compared to *0* physically, but at 0.5 m distance both tests had *6* letters read within and out of VR. Bailey-Lovie Reading Chart results were slightly better when done physically, with *2* words read in the physical test at 0.5 m distance compared to *0* in VR, and *2* words read within physical space compared to *1* within VR at 0.25 m distance. No results could be gathered for the MNRead Acuity Chart test

Table 5.6: Participant A6's individual results for the first 4 tests.

ID: A6	**VR Far**	**Physical Far**	**VR Near**	**Physical Near**
Letters	4	1	15	5
Contrast	1	0	6	6
Words	0	2	1	2
Speed P1	N/A	N/A	N/A	N/A

or P16 Vision test due to her condition worsening and fear that any testing may trigger her CBS. Looking at overall results, it appears that there is a clear improvement within the letter detection test, but other tests vary with very little differences. Follow up tests would be desired to determine whether the first test was anomalous. See Table 5.6 for this participant's results for the first 4 tests.

Participant A7

Participant Profile & Conditions. Participant A7 is an 84-year-old female that suffers from Macular Degeneration. She has a slight cataract in the left eye, and her right eye has the most vision. This participant had fallen ill for a long period of time preventing her from visit, so further data collection was not possible.

Conditions Impact. A magnifying glass is used mostly for TV, as reading is hardly done anymore.

Participant Results. ETDRS results were significant, with a score of *1.34* within VR at 1 m distance compared to *1.54* via the physical chart

Table 5.7: Participant A7's individual results for the first 4 tests.

ID: A7	**VR Far**	**Physical Far**	**VR Near**	**Physical Near**
Letters	15	8	35	17
Contrast	5	2	18	3
Words	1	2	2	2
Speed P1	N/A	N/A	N/A	N/A

and scoring *1.00* within VR at 0.5 m distance while a score of *1.36* was achieved within the physical test. PCSC results showed some difference at 1 m distance, with *5* letters read within VR to *2* letters read physically, but at 0.5 m distance there was a significant difference with *18* letters read within VR compared to *3* physically. Bailey-Lovie Reading Chart results were less varied, with *1* word read in VR compared to the physical tests *2* words at 0.5 m distance, and at 0.25 m distance only *2* words were read both in and outside of VR. The remaining MNRead and Colour related tests could not be attempted due to the health decline of the participant. Looking at results recorded, it seems that tests involving the detection of letters, i.e. contrast and letter detection, yielded better results within VR, especially at closer distances, but Bailey-Lovie Reading Chart did not improve and actually decreased by 1 word at a longer distance, although this may not be significant. See Table 5.7 for this participant's results for the first 4 tests.

Participant A8

Participant Profile & Conditions. Participant A8 is an 84-year-old female that has had a significant change in her vision from the two sessions she was last seen. The first session she described previously having wet macular degeneration that had turned into dry macular. She added that she might have had a detached retina but had not finalised any results with her doctor. She mentioned possible scarring from previous surgeries, with a cataract in her left eye which has had a lens inserted, and her right eye is blinded. She described her left eye as watering sometimes, which was apparent in testing, and that she takes steroid drops to prevent this. This participant suffered from a car crash in 2011 causing her to be hospitalised, mentioning that the trauma may have damaged her sight and that prior to the accident she could read fine. Her condition is not hereditary. This participant was able to see and read to some degree during their first session. During the second session she revealed that she has recently had surgery which had failed and caused severe damage to her eyes. Her vision was now much worse, as she was unable to make out simple distinctions and now required guidance in walking, which she did not previously. Testing could not continue as no results could be gained now as she is near blinded. She had extreme pain and irritation in her eyes with emergency services called, prompting the surgery. An injection in her eye caused tingling, and she underwent surgery that also caused extreme pain. Her retina at this point was confirmed detached. At night it is harder for her to see anything, described as pitch black, but otherwise her vision is mostly blurring.

Daily Impact & Aids Used. She has a TV but can no longer see it after her surgery, so she listens to speech assisted shows. The participant makes use of ordered audio books but was unfamiliar with technology such as the Kindle or iPads which may be of more use to her. Her family cooks and cleans for her, and she has a caregiver that assists otherwise sent from the family. She cannot travel alone, using specialised bus transportation to and from Beacon Centre. This participant uses a walking cane or a walking crutch to travel but has recently had trapped nerves in her legs causing further immobility. Glasses are said to be useless to her now, whereas prior to the surgery she had minor assistance from them. She is happy when receiving help which lightens her mood, as it brings her great relief. She described herself as close to housebound now, as she requires help to travel anywhere or is otherwise unable to leave the house. Her mood has significantly dropped since the surgery, as she has found herself unable to do most activities now. The participant mentioned that the Beacon Centre does not have enough activities for herself and the others there to do, and that many elderly visually impaired find themselves lost in keeping themselves active. She has a mobile phone but cannot see it anymore. She does not know how to operate assistive technology and has not received any support for this, but mentioned she wants to learn how.

Table 5.8: Participant A8's individual results for the first 4 tests.

ID: A8	VR Far	Physical Far	VR Near	Physical Near
Letters	4	6	22	15
Contrast	0	2	12	7
Words	0	0	0	0
Speed P1	N/A	N/A	N/A	N/A

Participant Results. Results shown here are prior to this participant's surgery which rendered her near blind. ETDRS test results showed at 1 m distance, a score of *1.62* was achieved within VR and *1.58* when completed physically, yet at 0.5 m distance a score of *1.26* was recorded within VR compared to *1.40* outside of VR. PCSC results showed a similar pattern, with 1 m results showing *0* letters read in VR to *2* words read physically, and at 0.5 m distance *12* words were read in VR compared to *7* physically. Bailey-Lovie Reading Chart results showed minimal results due to difficulty of reading, with nothing read at 0.5 m distance, and at 0.25 m distance only *1* word was read within VR, but nothing was read physically. Due to her surgery which further damaged her eyesight, no results were gathered for the MNRead Acuity Chart or the P16 Vision test. Overall it appears that this participant, prior to further damage to her eyes, appeared to perform better within VR at closer distances, but somewhat worse further away. It is unfortunate that further tests could not be performed due to her condition worsening and surgery results. See Table 5.8 for this participant's results for the first 4 tests.

Participant A9

Participant Profile & Conditions. Participant A9 is an 85-year-old female that suffers from Wet Macular Degeneration. She described her vision as outlined, and blurry or “hazy”. Her macular was described as covering her central vision like a thumb print in both eyes, resembling an oval shape. She was first officially diagnosed as having Macular Degeneration two and a half years ago but described her condition’s effects having lasted for as long as 20 years ago. She has very little vision in her left eye, and her stronger right eye has a cataract. Her reading ability is limited, describing the ability to read the headline of a newspaper as far as she could go. The participant has a sensitivity to bright lights, but they are also the clearest to her.

Daily Impact & Aids Used. The participant uses a magnifying glass if required to read. She commented that using the VR headset during testing was taxing, and that she would have liked the ability to change the brightness herself. Another session could not be scheduled with this participant to follow up with any further tests or record any extra information.

Participant Results. ETDRS results showed that at 1 m distance, a score of *1.40* was recorded within VR, while *1.36* was scored on a physical chart. At 0.5 m distance, a score of *1.12* was recorded within VR, and *1.26* in the physical version. PCSC results showed that VR performed worse, with *0* letters read within VR at 1 m distance compared to *5* letters read

Table 5.9: Participant A9's individual results for the first 4 tests.

ID: A9	**VR Far**	**Physical Far**	**VR Near**	**Physical Near**
Letters	15	16	29	22
Contrast	0	5	2	11
Words	2	0	3	2
Speed P1	N/A	N/A	N/A	N/A

physically, and *2* letters read within VR at 0.5 m compared to *11* physically. Bailey-Lovie Reading Chart results showed minor improvements within VR, with *2* words read at 0.5 m distance compared to *0* when read physically, and *3* words read at 0.25 m distance within VR compared to *2* words without VR. No results could be obtained for the MNRead, Ishihara, and P16 tests due to this participant not being available for any follow-up sessions. Overall results seem to be varied for this participant. Contrast appeared to be clearly worse within VR, and this ties together with the comment made she made stating she would like the ability to change the brightness within the headset. Overall results seemed mixed for this participant, as letter detection seemed to be better at a shorter distance but *1* letter worse further away, and Bailey-Lovie Reading Chart results showed a slight increase within VR but not by any significant amounts. See Table 5.9 for this participant's results for the first 4 tests.

Participant A10

Participant Profile & Conditions. Participant A10 is a 52-year-old male that suffers from Nystagmus, which is involuntary movement of the eyes. He has a detached left retina and Glaucoma, as well as having previous congenital cataracts from a very early age. His left eye is completely blind. The participant's reading ability was described as "okay". He mentioned that his condition might have originated from his premature birth, as he was given too much oxygen. He wears glasses that help slightly with distance vision, but not much. Light can influence the way his visuals are perceived, noted as affecting how his TV looks.

Daily Impact & Aids Used. The participant stated that he does watch his TV but listens more than watching. He has a walking cane for outside use but doesn't use it. He makes use of technology for accessibility, such as his mobile phone with enhanced text and text-to-speech. The participant has a home PC but can't use it. He described himself as having full mobility, getting around a lot and keeping active. Overall, he described his life as "fine" and being "okay" with his condition since has had it from birth.

Participant Results. ETDRS results showed a decrease of acuity within VR, with *1.40* scored at 1 m distance VR compared to *1.20* when read on the physical chart, and *1.20* scored within VR at 0.5 m compared to *1.00* physically. PCSC results were worse within VR as well, with *5* letters read at 1 m distance compared to *24* physically, and *17* letters read at 0.5

m distance within VR compared to *30* letters read physically. Bailey-Lovie Reading Chart results showed no difference at 0.5 m distance with both versions having *2* words read, but at 0.25 m distance VR results shown *9* words read compared to *2* in physical. MNRead Acuity Chart results showed that at 0.25 m distance VR testing took *15* seconds to read while physical testing took *17* seconds, a minor decrease of *2* seconds. Ishihara test results showed *1* additional plate read within the physical test, yet the two plates read were both control plates designed to be easy to read. P16 Vision test results are unusual (See Figure 5.5), as VR results appear just under the threshold for a possible Tritan deficiency, while the physical results appear under the threshold for a Deutan deficiency. Mistakes between the Pilot colour and colour 15/1 are not uncommon, so do not necessarily suggest any deficiency. Overall it appears that acuity within VR had decreased for this participant, despite some slight increases when reading words at some closer distances. Colours show no significant difference in measurements, and although P16 results showed errors of different deficiencies, the number of errors made were very similar. See Table 5.10 for this participant's results for the first 4 tests.

Table 5.10: Participant A10’s individual results for the first 4 tests.

ID: A10	VR Far	Physical Far	VR Near	Physical Near
Letters	15	25	25	35
Contrast	5	24	17	30
Words	2	2	9	2
Speed P1	8	6	5	5
Speed P2	28	10	5	6
Speed P3	22	11	5	6

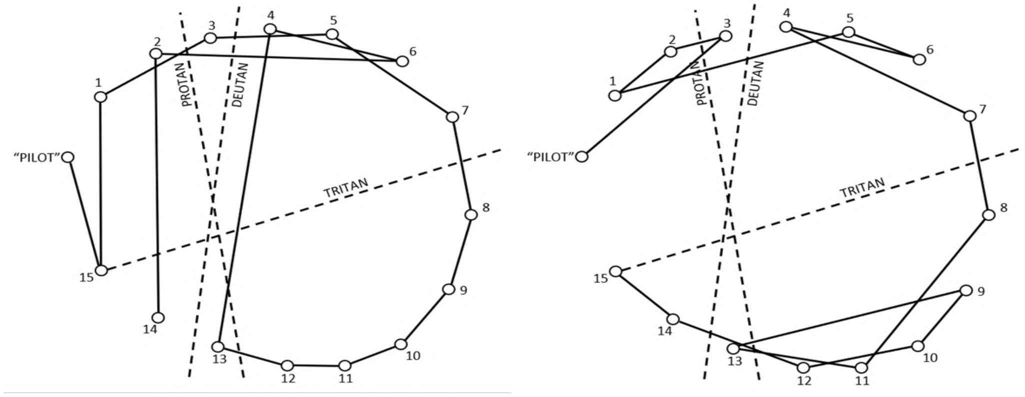


Figure 5.5: (left) Participant A10’s physical Panel 16 Vision test results. (right) VR test results.

Participant A11

Participant Profile & Conditions. Participant A11 is a 44-year-old male that suffers from Marginal Keratitis caused via bacterial damage. He has a cataract in his right eye, and a cataract in his left eye was first diagnosed in 2005 and removed in 2006; he is awaiting surgery to remove the right cataract in 18 weeks’ time as of the first session with him. His left eye also has ulcers and scarring down the middle. First signs of symptoms or damage was in 2012, and his vision was fine prior to 2013 when huge deterioration occurred. His father passed away the same year these symptoms appeared, meaning there could be a possible link to stress or trauma. He suffers from eczema (NHS 2019) and very sensitive skin that requires his eyelids to be constantly cleaned and kept to a high hygiene level. He has his eyes cleaned 12 times a day, requiring saline, ointment, and drops that are preservative free. His cleaning requires hot water and pads for his eyes and skin; if cleaning is not performed properly or delayed, he develops swelling in his skin and around his eyes. This participant suffers from swelling in the back of his eyes and eyes become crystallised at times. He suffers from eczema which first developed when he was 16 but has calmed down since. He has photosensitivity to light, requiring him to wear thick shades issued by the Beacon Centre to block out bright lights. Without shades he is blinded by brightness if the sun is out and can only see yellow. He has double vision, and what is described as “floaters” in his vision. He is short of hearing, and suffers from “dizzy spells”, which leaves him prone to falling. He receives a lot of medication to calm down many of his symptoms, which he has said side effects can often affect him just as bad as the symptoms themselves. Sometimes when standing he has mentioned that his vision becomes “muddled” and described what appears to him as “yellow stars” in his vision. His family does not share a history of any of the symptoms he has mentioned.

Daily Impact & Aids Used. He makes use of some technology but is limited to what he can use, such as a mobile phone and very basic computer use. He commented that he used to love playing video games but can no longer do so as he cannot see the monitor or TV anymore, and would like to have the ability to see and play them again. He describes his condition as very impacting on his mood and happiness, saying that sometimes he requires anti-depressants to be able to get up in the morning.

Participant Results. ETDRS results showed no difference at 1 m between VR and physical tests both scoring *1.20* exactly, but at 0.5 m distance a score of *1.10* was achieved in VR while *1.00* was scored from the physical. PCSC results were more varied, with *3* letters read in VR at 1 m compared to *18* letters from the physical chart, and *12* letters read within VR at 0.5 m distance compared to *28* letters read in the physical test. Bailey-Lovie Reading Chart results showed consistency with previous tests, with VR showing *6* words read at 0.5 m distance to the *12* words read in the physical version, and again *6* words read within VR at 0.25 m distance to *15* words read in the physical. MNRead Acuity Chart results were more varied, with results showing VR reading speed taking *16* seconds to read 3 sentences compared to *16* seconds to read 2 lines physically with the final sentence unreadable at 0.5 m distance, as well as the VR chart reading an extra paragraph taking *6* seconds. At 0.25 m distance VR took *14* seconds to read while the physical chart took *27* seconds to read. Ishihara test results produce *4* correct guesses for both versions of the test. P16 Vision test results (See Figure 5.6) for the physical test sug-

Table 5.11: Participant A11's individual results for the first 4 tests.

ID: A11	**VR Far**	**Physical Far**	**VR Near**	**Physical Near**
Letters	25	25	30	35
Contrast	3	18	12	28
Words	6	12	6	15
Speed P1	4	7	5	6
Speed P2	6	9	6	6
Speed P3	6	0	3	15

gest a strong Tritan deficiency, while the VR version does not suggest any deficiency. Overall results for Participant A11 suggest that VR was not beneficial for the majority of tests conducted. There seems to be an increase in reading speed and acuity for the MNRead Acuity Chart test, but these results are not consistent with other tests conducted. Performance for the physical version of the P16 test were lower, but Ishihara results showed no significant differences. See Table 5.11 for this participant's results for the first 4 tests.

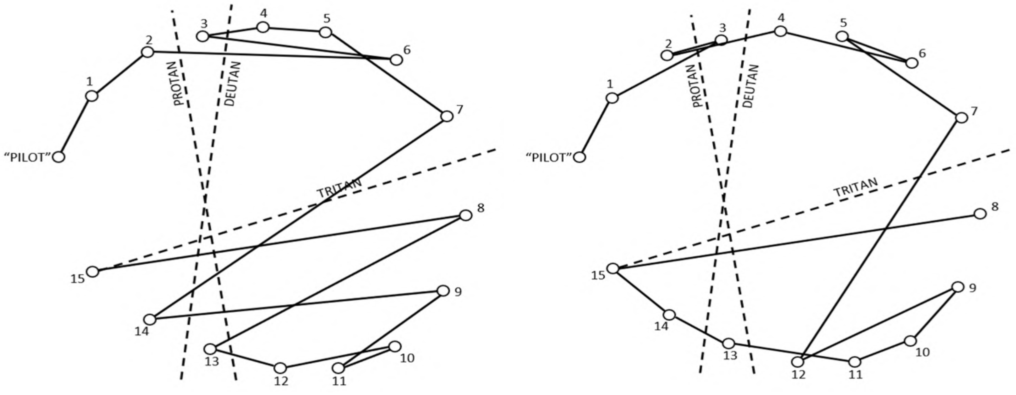


Figure 5.6: (left) Participant A11's physical Panel 16 Vision test results. (right) VR test results.

Participant A12

Participant Profile & Conditions. Participant A12 is a 44-year-old male that suffers from diabetic retinopathy related to his blood vessels and has extremely limited vision. He has had a retinal detachment but had operations to fix this in both eyes. His left eye is blinded as of 2013, with a cataract remaining. His right eye is described as seeing shadows, or shadows being inside the eye. A cataract was removed in his right eye, and there is fluid inside his right eye as well as oil to keep his retina in place. He cannot read anymore. Brightness heavily affects his vision and can be manipulated to help him if used correctly. It has been 5 years since his condition appeared, with vision being fine prior needing only long-distance glasses. He has had diabetes for 35 years, and his father also had diabetes. Originally had "floaters" in his eyes to start with, and by 2013 he could not see his TV anymore.

Daily Impact & Aids Used. A cane is used for his mobility, as well as railings and a wheelchair. He makes use of text-to-speech features on his phone but otherwise cannot use the phone under standard conditions. This participant uses a daisy player for books (RNIB 2021), and uses an iPad for assistance although this is very limited. He is unable to make use of technology in any visual capacity, so he relies on voice accessibility software/techniques whenever technology is used for a task. He commented that he receives a lot of help from others, and has constant guidance from his family, which is required. He owns a TV but only listens to it as he is unable to see it. He mentioned that he is very dependent on assistive technology to be able to function with basic tasks throughout the day. The participant described his whole experience since his damaged vision as if it was like being in a whole different world to him.

Participant Results. This participant had very limited vision, mostly seeing only shades and lights, and only responded well to one test where he was able to read out some letters in a VR headset, something he normally cannot do. Due to this, limited results were gathered from his sessions, but are noteworthy due to the severity of his vision loss. The participant was only able to observe any changes within 1 test, which was the ETDRS test. In this test, a score of *1.68* was recorded at 1 m distance within VR, and *1.70 (0)* on the physical chart, while *1.58* was recorded at 0.5 m distance within VR and *1.70 (0)* again without VR. All other tests yielded no results with a score of 0. Despite the very limited results gathered here, it is

Table 5.12: Participant A12's individual results for the first 4 tests.

ID: A12	VR Far	Physical Far	VR Near	Physical Near
Letters	1	0	6	0
Contrast	0	0	0	0
Words	0	0	0	0
Speed P1	N/A	N/A	N/A	N/A

important to highlight that this participant has a very severe form of visual impairment that is close to blindness, with his vision being described as looking at shades of light to perceive anything. This participant described himself as incapable of reading at all currently yet was able to make out some letters within VR which he otherwise could not accomplish. This surprised both invigilators and the participant himself when performed, and although there is limited practicality in such a limited improvement for this individual, it shows the potential for improvements in general. See Table 5.12 for this participant's results for the first 4 tests.

Participant A13

Participant Profile & Conditions. Participant A13 is an 84-year-old female that is suffering from the early stages of Glaucoma and Macular. She suffers from dry macular in the right eye, and wet in the left. The left eye has high pressure and a cataract, and the right eye has some pressure and a painful thick cataract which require eye drops. The participant has had a haemorrhage in the front of her left eye a little under a year ago from her first session. She has an extreme sensitivity to brightness that requires very large thick goggles that go over her normal glasses. Her normal glasses have limited effectiveness, but help somewhat with her double vision, and her first prescription for glasses were done in 1967. She is very nervous/anxious without her goggles on. She went from long sighted to short sighted just before December 2017. She described her reading as fine in the past, so her condition has gradually worsened damaging her reading capability. The participant was first referred to an eye specialist in 2000, and between 2009-2010 had trialled some new eye drops that gave her a bad reaction, changing her pulse rate and blood pressure possibly causing further damage. Originally, she took a brand called "Beta-blockers" (BHF 2018) in 1990, which caused initial problems. She has 3 daughters, with 2 of them wearing glasses, and the third requiring "heavy learning difficulty lenses" due to her vision having a "fishbowl" effect. Her sister has fine vision and parents wore glasses due to old age. The participant requires a magnifier to read. She described her vision of other people as seeing an outline, but not very clearly.

Daily Impact & Aids Used. The participant stated that she does not watch TV and does not have a computer at home. She uses a walking stick for travel/mobility, or a trolley to go outside. She goes outside with her dog occasionally but is limited to familiar places such as her local park due to fear of falling. She has accessibility toiletries, such as a specialised toilet seat and shower unit. Kitchen appliances that she owns have accessibility features as well, such as a buzzer for her teapot. The participant owns an older mobile phone that has large print text displayed as well as increased volume for accessibility. Her dog is not a specialist sight dog and has not had any training, but she relies on her dog to lead her around objects. She describes going outside as scary, with risks for falling or injury being high, causing her to limit walking to 20 minutes outside at a slow pace. She makes use of Beacon Centre travel services throughout the week as she is otherwise unable to travel to Beacon. She is thankful of Beacon services, which has enabled her to get involved in tasks such as the gym and clothes shopping, as she had previously lost the confidence to go out. The participant has help from her daughter for shopping or any other assistance outside, or otherwise gets help within shopping centres. She relies on microwave cooking for food, as she is frightened of gas or electric cookers due to her poor vision. Her description of her condition and lifestyle was “frustrating”, and that she is prone to depression but tries to take comfort in serenity prayers when she is struggling. She mentioned that the hospitals didn’t have time to see her, and that recently she was supposed to see a consultant but met a doctor instead, only to be told briefly that there wasn’t much they could do for her due to her age.

Participant Results. ETDRS results for participant A13 were positive within VR, with a score of *1.44* at 1 m distance compared to *1.56* from the physical chart, and scoring *1.16* within VR at 0.5 m distance compared to *1.4* physically. PCSC detection results showed limited results, with nothing

Table 5.13: Participant A13's individual results for the first 4 tests.

ID: A13	VR Far	Physical Far	VR Near	Physical Near
Letters	12	7	27	15
Contrast	0	0	6	0
Words	0	0	0	0
Speed P1	N/A	N/A	N/A	N/A

read at 1 m distance, but at 0.5 m distance *6* letters were read within VR, but *0* letters were read on the physical chart. Bailey-Lovie Reading Chart testing yielded no results as no words could be read regardless of distance or chart versions. No further testing was attempted due to a change in prescribed equipment which was not compatible with the equipment. See Table 5.13 for this participant's results for the first 4 tests.

Participant A14

Participant Profile & Conditions. Participant A14 is a 78-year-old elderly male participant that suffers from tunnel vision, glaucoma, and asthma. This participant has broken his hips from a fall due to his limited vision and requires 2 crutches to walk since the last session. He appeared to struggle in recollection and memory when describing his condition and past events. He was only partially sighted when first coming to the Beacon Centre, but his condition has deteriorated over the recent 5 or so years. He has had cataracts in both of his eyes and has had surgery to remove both. His eyes are heavily influenced by bright lights and colours, which he wears sunglasses to counteract when outside. When in dark environments, he is almost entirely blind. The participant takes multiple eye drops administered by his carers, one for glaucoma, but the rest he is unsure what they are for. He also takes insulin injections administered by carers twice a day. He described his left eye as being his strongest for vision, and his right eye being blurry, as well as split downwards. The participant stated that he had no more reading ability and would struggle to read a newspaper's headline. None of his conditions appear hereditary, although both his mother and his sister wore/wear glasses, with his sister being able to drive currently. He also mentioned that he has had an operation for his knees.

Daily Impact & Aids Used. The participant described himself as housebond, requiring assistance to travel and move. He uses Beacon home transportation to come to and from the Beacon Centre back home, or otherwise uses a Taxi for travel with accompanied support, although this is infrequent. He has carers that come 4 times a day to assist with house work and arranging food, as well as organising food shopping. The participant mentioned that he would not be able to make hot foods alone and would be limited to toast or sandwiches if carers did not help with the cooking. He uses a walking frame at home as well as a stair-lift that is installed on his stairs. He has an enlarged house phone at home designed for low vision users but does not make use of any other assistive mobile technology. He also owns a 45-50-inch TV that he sits at roughly 0.5-1.0 m distance away. To change the channels on his TV, he has memorised the position of numbers and buttons on his remote. He has a talking watch to tell the time, but no modern assistive tools. This participant described himself as isolated in some respects, due to being house bond and his restricted mobility, and that the TV is often left on for company. He shared that he does not have much family but is very close with his neighbours that provide aid and have helped him a great deal over the years, looking out for him. He mentioned specifically that he has acquired a fair amount of wealth and saved it for his current care now, but if he could not afford the services he has now things would be a lot worse for him. When discussing his mood and overall happiness, he described himself as getting on with things, making the most of his situation, and not one to get depressed, as well as commenting that his mental health is fine.

Participant Results. ETDRS results were fairly consistent, with a score of *1.14* in both VR and physical versions of the test at 1 m distance, but at a score of *0.84* was reached in VR while *0.92* was achieved from the physical. PCSC detection results showed that at 1 m distance, *8* letters were read within VR compared to *10* from the physical chart, whereas at 0.5 m distance *16* letters were read within VR, while *12* were read outside of VR. Bailey-Lovie Reading Chart results were close, with *3* words read within VR at 0.5 m distance to *4* words read via the physical chart, and *4* words read within VR at 0.25 m distance while *6* words were read in the physical version. MNRead testing showed no results, as the participant was unable to fully read any paragraph at any distance. Ishihara test re-

Table 5.14: Participant A14's individual results for the first 4 tests.

ID: A14	**VR Far**	**Physical Far**	**VR Near**	**Physical Near**
Letters	28	28	44	39
Contrast	8	10	16	12
Words	3	4	4	6
Speed P1	0	0	0	0

sults showed no differences between tests, with only the two control plates guessed correctly for both versions. P16 vision test results (See Figure 5.7) were incomplete as this participant struggled to understand the instructions of the VR version and could not complete it. Results gathered for the physical version were very erratic, with major errors performed throughout, but were disregarded. Overall results for Participant A14 show little consistencies between VR and physical versions, and the results from the ETDRS test are surprisingly high compared to other tests. It appears that when closer, letters from both the ETDRS test and PCSC test were easier to see than physical versions, but further away at 1 m results were either the same or slightly worse. VR performed somewhat worse when detecting entire words with *1* to *2* words less between tests. Colour test results were either incomplete or yielded no differences. See Table 5.14 for this participant's results for the first 4 tests.

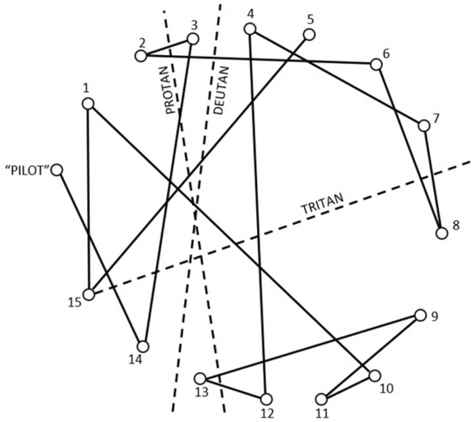


Figure 5.7: Participant A14's physical Panel 16 Vision test results. VR results were not gathered due to confusion understanding the test thus this participant's results were disregarded in the overall presented data.

Participant A15

Participant Profile & Conditions. Participant A15 is a 74-year-old woman that suffers from dry macular degeneration in both eyes. Originally, she was diagnosed with short sightedness from the age of 8 and has worn glasses all her life. 2 years ago, she was suddenly diagnosed with macular, causing rapid changes to her life-style. She was diagnosed with Bipolar 22 years ago, and has been taking medication since then (Mirtazapine, Quetiapine). She suffered from Lithium poisoning prior to her medication taken for Bipolar. She does not take any medication or drops used for her eye conditions. The participant does not read anymore, usually getting someone else to read, although she has a 5x magnifier with a built-in light if needed, but she described her eyes as not focusing properly when reading or using her magnifier recently. Colours are very confusing to her, with inaccuracies in matchings and shades. Her glasses help somewhat with long sighted vision, yet they have degraded in effectiveness recently. Her condition is not hereditary, with only her mother wearing glasses from old age.

Daily Impact & Aids Used. She has an old mobile phone that is out-dated and does not have any modern-day accessibility features, and when asked about this she commented that she would be interested in learning about an assistive phone. She has a talking watch and a talking alarm clock at home, but otherwise has no other assistive technology and no computer at home. She has a wheel chair to go out but is currently trying to get about by walking more as she used to be obese. She struggles with travelling and cannot go out alone without support, requiring things like the Beacon Centre bus service. Any shopping or correspondences are done via her family, which she describes herself as dependant on. She cannot do any cooking and relies on her family for hot meals, or otherwise can use the microwave but typically makes sandwiches instead. When asked to talk about her life and how her condition has affected her, she revealed that the changes that have happened to her over the past 2 years have been very fast and very impacting, changing her entire life. She described herself as getting frustrated, depressed, but having to get on with it, with everyday being a struggle and effort. She wishes that she could still do sowing and knitting, as they were a big part of her life prior to her macular progressing. Follow up sessions was not possible with this participant as they did not wish to continue testing as they did not believe their condition could be helped in any way.

Participant Results. ETDRS results showed that at 1 m distance a score of *1.44* letters was achieved in VR compared to *1.4* physically, yet at 0.5 m distance *1.22* was achieved in VR compared to *1.32* in the physical. PCSC detection results showed a larger leap at 1 m distance, with VR having *3* letters read compared to *15* letters read via the physical chart, and at the closer 0.5 m distance *11* letters were read within VR compared to *18* in the physical version. Bailey-Lovie Reading Chart for VR was worse, with *0* words read at 0.5 m distance to *4* words read in the physical, and *6* words read within VR at 0.25 m compared to *10* in the physical. Due to the participant's withdrawal from further testing, no follow up tests were conducted. Overall from the results gathered from Participant A15, all tests performed worse within VR compared to physical versions with the exception of letter detection at 0.5 m distance. It appears that little gain could be achieved from using a headset with this participant, which may have prompted her withdrawal from continued testing. See Table 5.15 for this participant's results for the first 4 tests.

Participant A16

Participant Profile & Conditions. Participant A16 is a 68-year-old female that suffers from diabetic retinopathy. She has been short sighted from the age of 12, with glasses being prescribed at this age and worn ever since,

Table 5.15: Participant A15's individual results for the first 4 tests.

ID: A15	**VR Far**	**Physical Far**	**VR Near**	**Physical Near**
Letters	13	15	25	20
Contrast	3	15	11	18
Words	0	4	6	10
Speed P1	N/A	N/A	N/A	N/A

although her condition was first diagnosed in 1986 (36 years old). The participant had suffered from a rheumatic fever when she was 7/8 years old. Her eyes have deteriorated over the years with age. She described her right eye as her weakest, being able to only see light and detect movement, while her left eye has limited but better vision. The left side of her left eye seems to have less vision than her central vision. She mentioned that she had surgery that removed a part of the back of her eyes but could not recall what this procedure was called or what it was for. She takes insulin for her diabetes, and eye drops for her diabetic retinopathy. Diabetes has a history of running in her family, with her brother and sister having it, and her sister also wearing glasses. The glasses she wears currently are used for minor magnification and reduce blurriness, although their effectiveness is limited. Colours to this participant are very washed out and dim and are something she struggles with distinguishing. Brightness is also a large factor with the clarity of her vision, being positive if adjusted correctly. Eye strain seems to cause her vision to blur, which happened during testing. The participant does not read anymore unless required to as she is limited to enlarged fonts such as a newspaper headline.

Daily Impact & Aids Used. The participant owns a TV and watches it occasionally yet has to be close to make out detail and mentioned that she usually leaves it on for the company of audio. She has a talking alarm clock and a talking microwave for food, and her cooking is limited to ready-made meals unless her family is around to supervise her. She owns a long tapping stick for mobility, although she tries not to use it and instead makes use of things like railings. The participant has an outdated mobile phone that doesn't support accessibility features and is unaware that such things exist. She was not eager at the idea of learning new technologies, as she said they scare her, and she is unfamiliar with them. She rarely goes out alone and is usually accompanied and supervised when travelling. Her family additionally does her shopping for her as well, providing her with a lot of support in general. She described her living as independent but with a lot of support or help. When talking about the help she receives and whether it was sufficient, she mentioned it was "fine" overall but that she was very dependent on it, and without her family she would need to be put into care or have specialised care support. She lives in assisted living housing that is next to Beacon Centre, meaning she has cleaners come to help as well as other assistance. Additionally, mentioned that she would not want a guide dog if given the choice, as she feels she would be unable to properly take care of it.

Participant Results. ETDRS results were noticeably improved within

VR, with a score of *1.16* at 1 m distance compared to *1.54* via the physical chart, and at 0.5 m distance a score of *0.94* within VR compared to *1.12* from the physical. PCSC detection results showed results at 1 m as *15* letters read within VR compared to *16* from the physical, and at 0.5 m distance *18* letters read within VR compared to *20* from the physical. Bailey-Lovie Reading Chart results showed a large increase for VR, with *12* words read at 0.5 m compared to *4* via the physical chart, and *33* words read within VR at 0.25 m distance compared to *7* without VR. MNRead Acuity Chart results showed that at 0.5 m distance had only P1 read at *19* seconds for the physical chart, but the chart was unreadable for VR. At 0.25 m distance only P1 of the physical chart was read at *9* seconds, and the VR P1 was read at *12* seconds, but additionally P2 and P3 was also read in VR, meaning that the first paragraph was read faster from the physical chart, but the VR chart allowed a lot more to be read for a total of *48* seconds. Ishihara test results were unable to gather anything as the participant was only able to correctly guess the first control plate in both versions of the test. P16 Vision tests results (See Figure 5.8) show that both versions of the test show signs of Deutan deficiency. VR patterns seem to be noticeably worse than the physical test, and could show Tritan deficiency instead of Deutan. Overall the results from the tests with Participant A16 show that the majority of reading related tasks seem to be improved quite significantly within VR depending on the task. Contrast however did not receive any benefits and performed slightly worse within

Table 5.16: Participant A16's individual results for the first 4 tests.

ID: A16	VR Far	Physical Far	VR Near	Physical Near
Letters	27	9	38	29
Contrast	15	16	18	20
Words	12	4	33	7
Speed P1	0	19	12	9
Speed P2	0	0	16	0
Speed P3	0	0	20	0

VR, suggesting that brightness is a large factor towards the participant's vision. MNRead test results had a decrease within VR at 0.5 m, but better at 1 m. Colour results showed no significant differences, although the rate of error for the VR P16 test seems to be noticeably higher. See Table 5.16 for this participant's results for the first 4 tests.

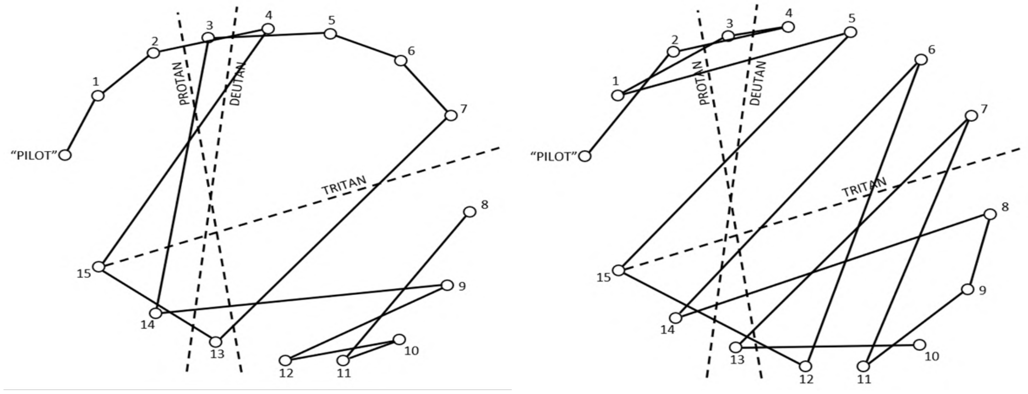


Figure 5.8: (left) Participant A16's physical Panel 16 Vision test results. (right) VR test results.

Participant A17

Participant Profile & Conditions. Participant A17 is an 86-year-old female that suffers from dry age-related macular degeneration in both eyes. This condition has run in her family, with her father having it towards the end of his life. She was first diagnosed in 2012 but has said to have noticed having macular for 20 years now. Additionally, she had a fall in 2017 and mentioned that her vision may have decreased since then but is ultimately unsure. Her eyes “used to be good”, described as 20/20 vision prior to her condition showing symptoms, although she also mentioned having reading glasses when she was 38. She started to wear glasses as her condition developed but can no longer wear them now as they have no effect on her. She has had cataracts removed from both eyes. She commented that her left eye used to be her strongest eye but is now the worst. The participant can read if the font is large enough, although she commented that she would not be able to read the headlines of a newspaper without assistive tools and said it has been 10 years since she could read normally.

Daily Impact & Aids Used. The participant has a magnifying machine used for reading if necessary. She does not watch a lot of TV, although she owns one. For mobility she has a walking stick, but she commented that it is used more for peace of mind and mental comfort, rather than being needed physically. Aside from her walking stick, she described her mobility as fine, but that she wouldn’t go alone when travelling to an unfamiliar location. Public transport is used frequently via buses and taxis, and she can see the numbers on arriving buses. She has a mobile phone but mentioned that it is rarely used and has not tried any type of text-to-speech technology. She is fully capable of cooking at home and described herself as home independent, although she does receive some support from her family and the Beacon Centre. When asked about how she copes with her condition, life, and how she feels emotionally, she described her experience as frustrating or irritating at times, and specifically that social interaction can be awkward due to her lack of vision and ability to recognise, or that she sometimes walks into people accidentally. She praised the ability to come out and socialise with people with places like the Beacon Centre, although she commented that she can get bored and by nature she is introverted and keeps to herself. One thing she mentioned that she finds difficult with is reading the mail she receives, and that she would like more support for this specifically. Overall, she described herself as being happy with things overall, and doesn't like to be a bother to anyone else.

Participant Results. ETDRS results show a slight decrease in VR at 1 m distance with a score of *1.1* achieved compared to *1.06* via the physical chart, while 0.5 m distances scored *0.98* within VR compared to *1.04* from the physical chart. PCSC results showed at 1 m distance *11* letters were read within VR compared to *16* from the physical, yet *34* letters were read at 0.5 m distance within VR compared to *28* from the physical. Bailey-Lovie Reading Chart results showed *4* words read at 0.5 m within VR to the

Table 5.17: Participant A17's individual results for the first 4 tests.

ID: A17	VR Far	Physical Far	VR Near	Physical Near
Letters	30	32	36	33
Contrast	11	16	34	28
Words	4	3	8	9
Speed P1	0	0	6	6

3 words read from the physical, and *8* words read at 0.25 m distance within VR compared to *9* words read from the physical. Limited results were gathered from the MNRead Acuity Chart test due to lack of vision, with the only paragraph being read at 0.25 m, taking *6* seconds from both VR and physical tests. Ishihara results were limited, yet the physical version of the test had *1* more correct guess. P16 test results (See Figure 5.9) show no clear sign of any colour deficiencies. VR results show *2* more significant errors over the physical version. Overall results suggest a larger improvement in VR when displaying charts at a closer distance, with the exception of the Bailey-Lovie Reading Chart which showed no variants between distances to equipment used. Colour measurements product similar results, yet VR performance seemed to be slightly worse than the physical version. See Table 5.17 for this participant's results for the first 4 tests.

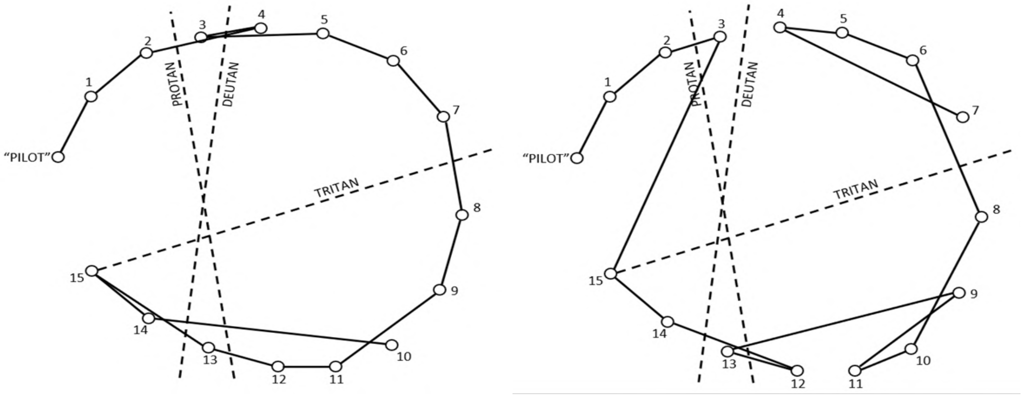


Figure 5.9: (left) Participant A17's physical Panel 16 Vision test results. (right) VR test results.

Participant A18

Participant Profile & Conditions. Participant A18 is a 45-year-old male that suffers from Stargardt disease, a form of inherited macular degeneration like dry macular. His condition is late-onset, first appearing between 10 to 12 years ago. There is a problem with his ABCA4 gene, which is responsible for producing protein that is found in the retina. His left eye is his strongest, and his eyes have scarring at their back. His field of vision is described as a torus shape, requiring him to use the outside parts of his eyes frequently, and repositioning of his eyes to fill in blanks. His condition has progressed slowly but can have plateaus over time. He has lost his depth of perception, and his colours have become diminished. The participant does not wear glasses, but his parents wore glasses and his children also wear glasses. He is capable of reading if the text is very close to his face, or with assistive technology.

Daily Impact & Aids Used. The participant makes use of a large array of technologies for assistive use. He uses OrCam (OrCam 2020), which plays text back as audio. He has magnification software on his computer at 4x or 6x, as well as owning a physical magnifying glass. He owns an iPhone and iPad, making use of their accessibility features such as Siri, as well as owning an Apple watch, which links to these other mentioned devices and their accessibility features. The participant makes daily use of technology, saying that his life would be drastically worse without it and much less mobile. He owns a TV and watches it, but requires a small telescope to avoid motion sickness, or otherwise sits very close to the TV watching from the side and commented that this gets in the way of his family. He requires lighting for travel and carries a LED device with him to help with visibility. The participant can get around via public transport such as taxis and is mobile thanks to technology. When asked how he felt about his condition and lifestyle overall, he said that he has accepted his disability, but finds it frustrating. Being able to accurately see his children in detail is difficult, and he can find himself getting in the way of his family due to accommodations being made for his vision. His quality of life has been drastically improved from assistive technologies however, and it is something he has heavily invested in.

Participant Results. ETDRS results showed that at 1 m distance a score of *1.08* was achieved within VR compared to *1.02* from the physical chart, although no differences were found at 0.5 m distance with both charts having a score of *0.8*. PCSC detection showed at 1 m distance *18* words being read within VR to the *17* from the physical, while at 0.5 m distance *19* letters were read within VR to *30* outside of VR. Bailey-Lovie Reading Chart results showed *0* words read within VR to *7* from the physical at 0.5 m distance, and *6* words read within VR compared to *17* from the physical chart at 0.25 m distance. MNRead Acuity Chart results showed that at 0.5 m distance VR was unable to be read while the physical version all paragraphs were read taking *117* seconds. At 0.25 m distance only P1 and P2 were read within VR taking *140* seconds, compared to the physical chart taking *31* seconds for P1 and P2, but additionally P3 was also read via the physical totalling at *47* seconds to read all paragraphs. Ishihara results show *5* more correct guesses in VR over the physical version. P16 Vision results (See Figure 5.10) show a Tritan deficiency for both versions of the test. Overall it appears that all tests performed worse within VR. This participant commented that colours seemed more vibrant and clearer within VR, which may reflect the *5* additionally identified plates within the Ishihara test. See Table 5.18 for this participant's results for the first 4 tests.

Table 5.18: Participant A18's individual results for the first 4 tests.

ID: A18	VR Far	Physical Far	VR Near	Physical Near
Letters	31	34	45	45
Contrast	18	17	19	30
Words	0	7	6	17
Speed P1	0	15	66	10
Speed P2	0	36	74	21
Speed P3	0	66	0	16

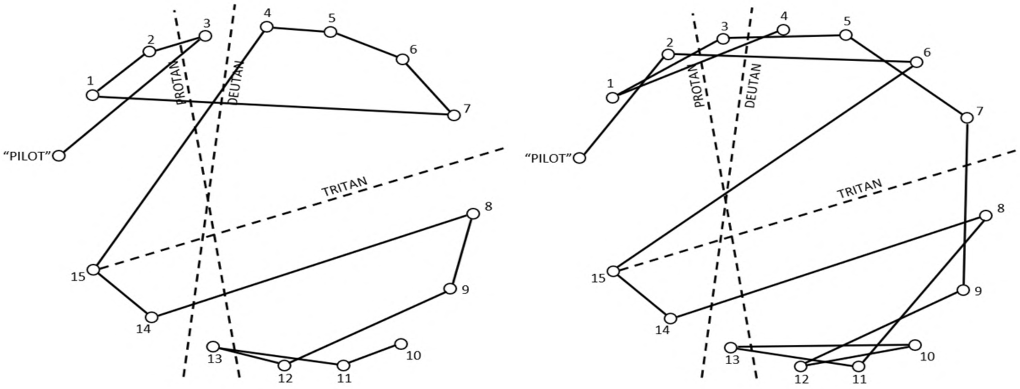


Figure 5.10: (left) Participant A18's physical Panel 16 Vision test results. (right) VR test results.

Participant A19

Participant Profile & Conditions. Participant A19 is a 23-year-old male that suffers from nystagmus. He has had this condition from birth, with changes to his eyesight over the years being very slow. This participant also has limited mobility, which makes travelling difficult outside of his visual impairment. He wears negatively prescribed lenses that provide slight clarity in both long and short vision. His condition has not appeared in his

Table 5.19: Participant A19's individual results for the first 4 tests.

ID: A19	VR Far	Physical Far	VR Near	Physical Near
Letters	23	20	34	28
Contrast	3	12	8	13
Words	0	1	5	7
Speed P1	0	21	24	6
Speed P2	0	0	99	28

family, but his family has a history of weakened vision, with 5/7 family members wearing glasses, the majority long sighted, and his father using reading aid glasses. He prefers print size 18/20 for reading, and non-sans serif for font. The participant stated that he could read text at multiple sizes potentially, but smaller sizes would require a longer time and increased strain. He requires one eye to be closed to read, to help stabilize and focus on the involuntary movement of one individual eye. In the past he used to make use of speech recognition and higher magnification but has trained himself to use a lower magnification of 16x and to no longer use speech software for increased independence. He uses a bar magnifier of 2x strength. The participant previously used high contrast text when he was younger, but it no longer influences his reading ability now. See Table 5.19 for this participant's results for the first 4 tests.

Daily Impact & Aids Used. The participant makes use of mobile phone accessibility features, such as shortcuts and enlarged fonts. He has a backlit keyboard for computer use, which helps to see individual keys, as well as a Philips large black cursor on Windows machines. He owns a white cane for mobility which is used in all travel. He is a university student, and originally had a sighted guide to assist with traversing the university campus, but no longer needs the extra help. With unfamiliar places, he still requires supervision or assistance to travel, and makes heavy use of building accessibility features such as railings. The participant described himself as independent at home but has difficulty with finding things. When asked about how his condition affects his life and mood, he described himself with getting on with his disability and dealing with it. He commented that he receives a strong sense of achievement or pride when overcoming barriers in his life.

Participant Results. ETDRS results showed that at 1 m distance a score of *1.24* was recorded within VR compared to *1.3* from the physical chart, and at 0.5 m distance *1.02* within VR compared to *1.14* from the physical. PCSC showed at 1 m distance *3* words being read within VR to the *12* from the physical, and at 0.5 m distance *8* letters were read within VR to the *13* outside of VR. Bailey-Lovie Reading Chart results showed *0* words read within VR to *1* from the physical at 0.5 m distance, and *5* words read within VR compared to *7* from the physical chart at 0.25 m distance. MNRead Acuity Chart results showed that at 0.5 m distance VR was unable to be read, while P1 of the physical version was read taking *21* seconds. At 0.25 m P1 and P2 were read taking *123* seconds, while the physical version took *34* seconds. No Ishihara results could be gathered as the participant could not identify any plate. P16 Vision results (See Figure 5.11) shows a lot of jumps between both graphs. P16 Vision test results were very erratic here, with a strong Protan deficiency shown for both versions of the test. Overall results from Participant A19 show some improvement from letter detection for VR, but otherwise all tests performing worse. It appears that colours are problematic for this participant regardless of the method used.

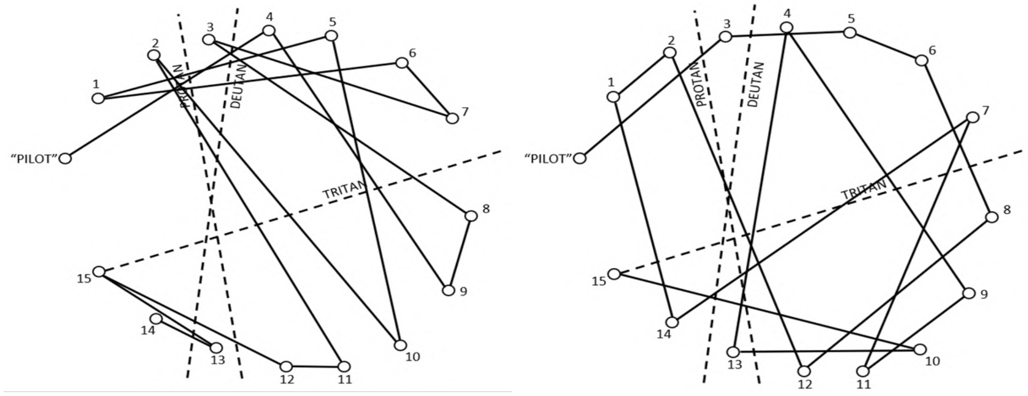


Figure 5.11: (left) Participant A19's physical Panel 16 Vision test results. (right) VR test results.

Participant A20

Participant Profile & Conditions. Participant A20 is a 33-year-old female that suffers from nystagmus in both eyes from birth. She has a condition called Ocular Albinism, which causes a lack of pigment in her eyes and is also linked to nystagmus, as well as myopia (near-sightedness). She also suffers from photophobia, which is a high sensitivity to light causing discomfort which causes her to wear sunglasses when outside, and additionally was diagnosed with dry eye disease 12 months ago. The null point of her nystagmus spreads light, decreasing clarity (the null point is where vision has the least movement, usually being the best section of their vision). These conditions make reading very difficult, and she prefers not to, but can read enlarged fonts if necessary. Additionally, when reading she uses a technique of squinting and turning her head to try and calibrate her vision. Her left eye is her best but has a cataract. She has commented that in the timespan of the last 18 months, her vision has gotten a little worse, with her vision having less detail. She used to wear specialist glasses but stopped due to their cost being very expensive (£500) when she was 21-23. She has no depth of perception. Her condition does not appear to be hereditary, with her families overall vision seeming to be normal.

Daily Impact & Aids Used. The participant owns an electronic magnifier that zooms and changes contrast. She has accessibility cooking equipment through coloured cooking utensils, highlighted liquid levels, and other similar setups. Cooking food for herself at home is possible but she prefers to buy foods pre-chopped as this is difficult. When dealing with hot liquids she usually gets someone to assist with managing them or draining them instead of herself, due to the increased risk. She makes use of some accessibility technology, such as speech recognition with Amazon Alexa and iPhone's Siri, as well as large print on her phone. She owns a Mac computer at home with zoomed text, although this is rarely used, and instead an iPad is used much more frequently. The participant has a 42-inch TV that she mostly listens to, but tries to watch from half a meter away, although this can be straining to focus on, and she loses focus after half an hour of watching requiring a break. For travel she uses a white cane, and usually only goes out if the weather is appropriate as she is prone to tripping if the ground is wet, muddied, or slippery. Usually has help when travelling, and especially if a place was unfamiliar to her. Public transport is not taken alone, and her most usual form of transportation is taxi. When asking about how she copes and deals with her condition, she commented that since she has had her conditions from birth, they are normal to her and she is more accepting of them as a result. She mentioned that she appreciates what she's got, and that she is still capable of performing normal tasks but must achieve them differently, finding new ways to do things. She said she was not miserable and was very positive with her life, finding the best out of what she has.

Participant Results. ETDRS results showed that at 1 m distance a score of *1.52* was recorded in VR compared to *1.54* physically, and at 0.5 m distance *1.36* compared to *1.44* in the physical. PCSC detection results showed a smaller difference at 1 m distance, with VR having *1* letter read compared to *2* letters read via the physical chart, and at the closer 0.5 m distance *4* letters were read within VR compared to *5* in the physical version. Bailey-Lovie Reading Chart had limited results, with *0* words read at 0.5 m distance in both VR and physical, and *0* words read within VR at 0.25 m compared to *4* in the physical. MNRead Acuity chart results yielded only one pair of results at 0.25 m distance, with P1 being read at *72* seconds within VR and *5* seconds outside of VR. It was noted by this participant that she had remembered the text when performing the physical version somewhat, despite timing differences and randomisation of orders, potentially speeding up the time. Ishihara results showed *3* more correct guesses in the physical test over the VR version. P16 Vision test results (See Figure 5.12) show no significant sign of any colour deficiency. Overall results are mixed from Participant A20, with an increase from the ETDRS test within VR, a slight decrease for the contrast detection test within VR and decreases within VR for both word reading tests. Colours did not appear to have any significant changes between both versions. See Table 5.20 for this participant's results for the first 4 tests.

Table 5.20: Participant A20's individual results for the first 4 tests.

ID: A20	VR Far	Physical Far	VR Near	Physical Near
Letters	9	8	17	13
Contrast	1	2	4	5
Words	0	0	0	4
Speed P1	0	0	72	5

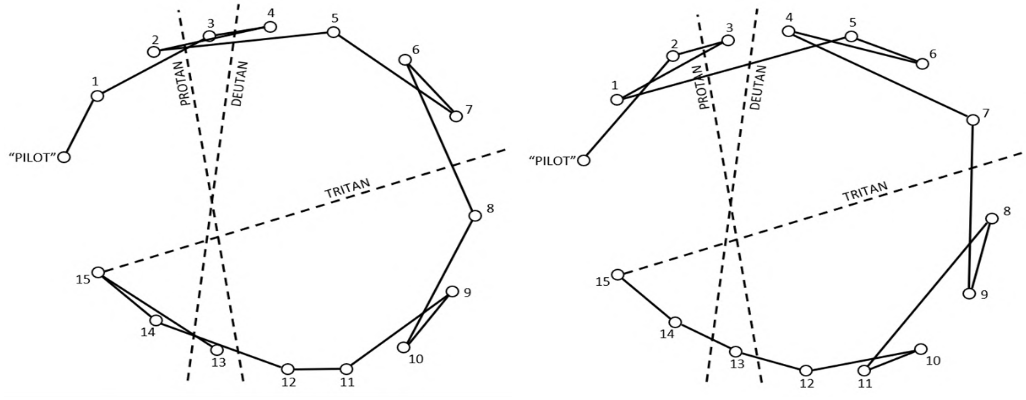


Figure 5.12: (left) Participant A20's physical Panel 16 Vision test results. (right) VR test results.

Participant A21

Participant Profile & Conditions. Participant A21 is a 58 year-old female that suffers from multiple eye conditions. She suffers from optic neuropathy (R. Sharma and P. Sharma 2011), which affects the optic nerves, astigmatisms in her eyes, possibly chromophobia (the fear of colours) but she is unsure, partial colour-blindness, and minor nystagmus. She also had a detached retina in her right eye in 2004, which was operated on in 2005 with a buckle and sponge surgery which she can physically feel the insert on her eye. Her left eye may also have a slight detachment, but she is awaiting a diagnosis to confirm this. Her eyes have a sensitivity to brightness, which causes pain, glaring, and reflections, and she wears large anti-glare shields (goggles) to block sunlight. She was registered legally blind in 1990. Her vision is heavily dependent on individual days, as it can be drastically better or worse at random between different days, and over the years her vision has become better or worse, but she is unsure what it is like currently. She has always worn glasses, and without them her vision is drastically worse. None of her family have had sight problems. She stated she could read text if it is very close to her face or enlarged font, such as her zoomed in kindle for books, and has a 7x magnifier (28D) to help with this.

Daily Impact & Aids Used. A Samsung phone and tablet are used by her with accessibility features, such as large print mode and black backgrounds, as well as contrast and brightness lowered. A computer is also used, with large font and lowered contrast/brightness on a 23-inch monitor. She owns a 32-inch TV and watches it at just over a meter distance. Originally, she had older models of televisions, commenting that flat-screen TV’s today are much clearer to see than older depth televisions. A walking cane is used when travelling, as well as a monocular to see in public and public transportation, such as bus numbers. Any travelling usually requires some assistance in preparations, such as planning, but otherwise she travels alone and independently quite frequently. She also does her own shopping and cooking, and her kitchen contains low vision stickers for appliances, as well as strong grip utensils. When asked to describe how her life is affected by her condition, and how she feels emotionally about it, she described herself as someone who just gets on with things and makes the most of what she has. She commented that street signs are difficult to see, and that she would like to be able to see them better as a quality of life improvement. She also mentioned that she finds it very difficult to tell where she is when travelling on transport, and that she can get lost on busses requiring her to ask for the driver's assistance which is not always reliable as they can forget.

Participant Results. ETDRS results showed that at 1 m distance a score of *0.98* letters was recorded in VR compared to *1.04* physically, yet at 0.5 m distance a score of *0.74* was documented compared to *0.72* in the physical. PCSC detection results showed VR having *33* letters read at 1 m compared to *36* letters read via the physical chart, and at the closer 0.5 m distance *36* letters were read within VR compared to *41* in the physical version. Bailey-Lovie Reading Chart for VR showed *12* words read at 0.5 m distance to *4* words read in the physical, and *27* words read within VR at 0.25 m compared to *15* in the physical. MNRead Acuity Chart results at 0.5 m distance showed that VR took a total of *16* seconds to read compared to *32* seconds from the physical chart. At 0.25 m distance results were identical between test versions, both taking *10* seconds to read. Ishihara results showed no difference between both versions of the test. P16 test results

Table 5.21: Participant A21’s individual results for the first 4 tests.

ID: A21	VR Far	Physical Far	VR Near	Physical Near
Letters	38	33	48	49
Contrast	33	36	36	41
Words	12	4	27	15
Speed P1	3	5	4	4
Speed P2	6	9	3	3
Speed P3	7	18	3	3

(See Figure 5.13) suggest no colour deficiency with the physical version, but the VR version just crosses the threshold for suggesting a Tritan deficiency. Overall Participant A21’s results show large improvements when reading words within VR, and some improvement reading letters at 1 m distance, but otherwise tests either show no improvements or a decrease when using VR. See Table 5.21 for this participant’s results for the first 4 tests.

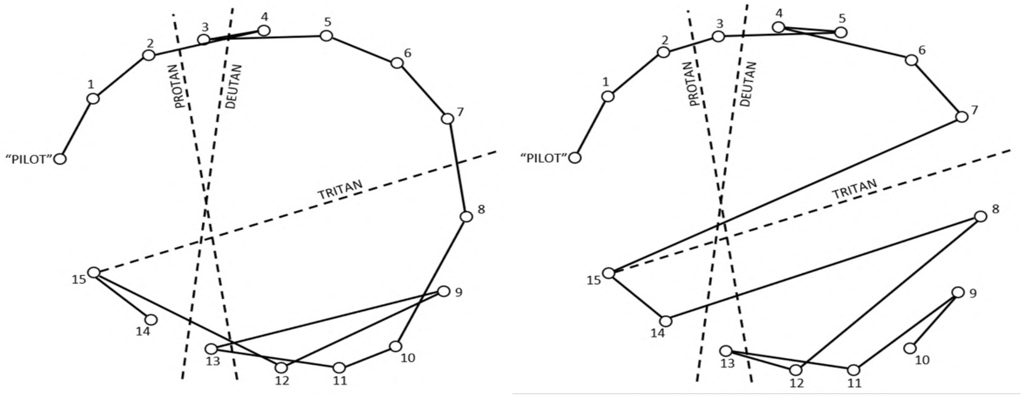


Figure 5.13: (left) Participant A21’s physical Panel 16 Vision test results. (right) VR test results.

Participant A22

Participant Profile & Conditions. Participant A22 is a 33-year-old male that suffers from minor nystagmus from birth, as well as some other defects during birth and early years. He had suffered a birth condition caused by the heart being backwards when born from too much oxygen being given (Talabi et al. 2013), requiring heart surgery that was performed 6 weeks after birth. Both eyes had cataracts from this birth defect, and surgery was performed 6 months after birth to remove both. His right eye is the strongest, and he believes this is due to it being the first eye to be operating on while young as his eyes and brain were still developing. His left eye is much worse and is a lazy eye. Thick bifocal lenses were worn from a very young age, and eyesight did not change. Recently this participant had an infection influenced from sleeping with contact lenses in September 2017, causing a massive deterioration in vision. Since this infection, the right eye has some scarring, both eyes are affected by brightness with strange effects seen and blurring, and the left eye can't be kept open in brightness. He is awaiting surgery in a month's time to have lenses inserted inside his eyes to hopefully improve vision and remove the need for multiple glasses (operation called Artisan Intraocular Lens Surgery (Ophtec 2004)), as he finds swapping between glasses very “annoying” and time consuming. The participant requires very thick glasses or he is otherwise mostly blinded and cannot read. He owns two pairs of glasses, both of which use very thick lenses, but his reading glasses are the largest. His distance glasses provide limited reading ability, his reading glasses provide near reading, and without both glasses he is unable to read at all. His conditions do not run in the family.

Daily Impact & Aids Used. The participant uses a 3.5x magnifier to assist with reading and detail, and he uses a monocular lens for public travel signs and bus numbers. He makes use of an iPhone and tablet, using their enlarged font modes but no other settings changed. He owns a 30-inch TV but doesn't use it, using his tablet primarily for YouTube videos at a medium distance to his face. The participant has no problem with cooking, although it takes him more time, and no assistive tools are used at home as he lives with his family. He uses a white cane when travelling outside primarily to let others know that he's impaired, but otherwise his mobility is good. He has someone assist him when travelling to an unfamiliar place for the first time but travels alone in future revisits once he has gained confidence. The participant uses public transport via buses primarily, although he sometimes takes a taxi. His ability to perform general tasks can be sometimes limited, requiring some aid which is usually provided via his family. He described himself as independent but living at home, mentioning that he would like to move out to supported housing similar to what Beacon Centre residents have, where aid is available if and when needed. He pays a professional to manicure his toes, as he cannot see them, and cutting his hair and shaving has become difficult since his eye infection, especially since his glasses get in the way but he needs them to see. When asked to comment on how his conditions affect his lifestyle, and how he feels about them, he added that during his early 20's, he was very low of mood due to his disability but has come to accept them now. Since his conditions are from birth and have always been with him, they are normal to him, although his infection damaging his eyesight has been distressing to him. He also mentioned that he is someone who knows what he wants, has clear goals, and is comfortable with his position in life, so is overall happy with what he is doing.

Participant Results. ETDRS results were fairly consistent, with a score of *0.72* in both VR and physical versions of the test at 1 m distance, but at 0.5 m distance a score of *0.46* was recorded in VR while the physical chart scored *0.56*. PCSC results showed that at 1 m distance, *35* letters were read within VR compared to *36* from the physical chart, and at 0.5 m distance *40* letters were read within VR, while *41* were read outside of VR. Bailey-Lovie Reading Chart results showed *16* words read within VR at 0.5 m distance to *19* words read via the physical chart, and *27* words read within VR at 0.25 m distance while *32* words were read in the physical version. MNRead Acuity Chart results showed VR taking *8* seconds to read all paragraphs in VR while the physical version took a similar *9* seconds at 0.5 m distances. At 0.25 m distance both VR and physical took exactly *9* seconds to complete. Ishihara results showed *2* more correct guesses in the physical test than the virtual. P16 test results (See Figure 5.14) show

Table 5.22: Participant A22's individual results for the first 4 tests.

ID: A22	**VR Far**	**Physical Far**	**VR Near**	**Physical Near**
Letters	49	49	62	57
Contrast	35	36	40	41
Words	16	19	27	32
Speed P1	3	3	3	3
Speed P2	3	3	3	3
Speed P3	2	3	3	3

no sign of colour deficiencies between both test variants. Overall results did not show massive discrepancies, with many results being very similar to each other. This participant had a much higher acuity than the average participant of the testing group, scoring highly on most tests. The letter test showed some increase in VR at 0.5 m, while the contrast test showed a single less letter in VR for both distances, although this is very minor compared to the number of letters read. Bailey-Lovie Reading Chart showed a similar result, although slightly worse for VR than the previous test. MN-Read Acuity Chart results were similar in VR and physical. See Table 5.22 for this participant's results for the first 4 tests.

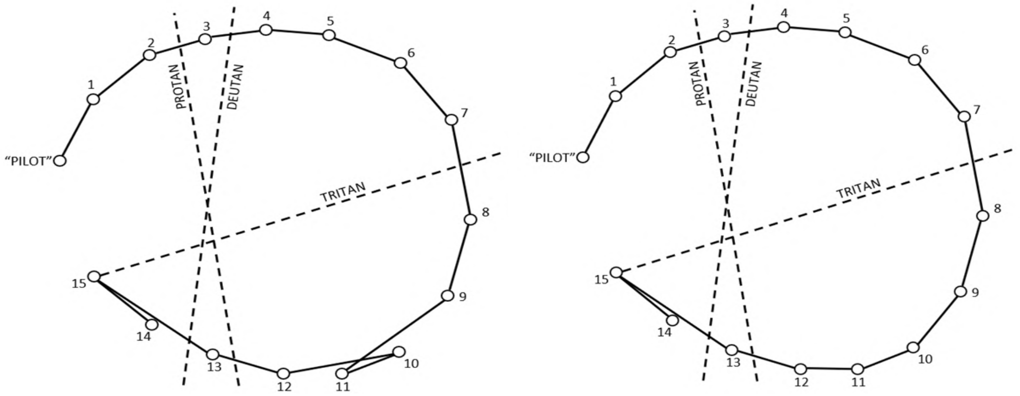


Figure 5.14: (left) Participant A22's physical Panel 16 Vision test results. (right) VR test results.

Participant A23

Participant Profile & Conditions. Participant A23 is a 30-year-old female who suffers from non-rotational nystagmus, which requires head-movement to focus. She has also been diagnosed with autism and dyslexia, which she said increases the difficulty of reading regardless of her vision. Both of her eyes have equal strength, and she has always worn glasses that are designed to correct nystagmus, but not to aid with distance. Without glasses it is harder for her to focus, and any focus causes straining, although she said it is still possible for her to read without glasses. Her vision seems to be fine apart from her nystagmus, with no other conditions conflicting, although she seems to be sensitive to brightness. Bright lights can affect the way she perceives vision, making it harder to see, as well as causing strain and headaches, requiring her to use sunglasses or large goggles to block sunlight, or additionally a sun hat. Her eyes get fatigued after prolonged focus and require rest in-between reading and watching. When she is sick or ill, she receives headaches as well. Her conditions are not evident anywhere in her family, although her parents wear glasses. She receives yearly check-ups for assessment on her conditions.

Daily Impact & Aids Used. The participant makes use of a cane when travelling outside and uses a longer one when travelling longer or unfamiliar distances. She has no major mobility issues and makes full use of public transportation and taxis, although she prefers to wear boots for extra balance in harsher weather conditions. She owns and watches a 32-inch TV from what she describes as a “sofa distance”. She uses some technology, such as an iPhone with Siri, but this is limited and otherwise she does not make use of accessibility features. The participant uses a desktop/iPad, which she likes to use the touch screen for when struggling, as well as an Amazon Echo for music or asking questions. She has no trouble with cooking foods, and lives in supported living, although she commented that she would not manage without the extra support. She describes herself as evenly split between independent and dependent, as some aspects of her life she can cope with better, but others she is reliant on aid for, such as supported living or assistance at night. When asked how she is coping with her life and conditions, she commented that she “gets on with things” and is trying to become more active with things. She mentioned that she recently joined the choir and linked up with someone who understands her conditions that she can confine with, and overall, she is reasonably happy and semi-independent.

Participant Results. ETDRS results show that at 1 m distance VR showed a score of *1* compared to *0.94* from the physical chart, and at 0.5 m distance a score of *1* within VR compared to *0.92* outside of VR. PCSC results were the same across chart versions, with VR and physical scoring the same at 1 m distance with *18* letters read, and the same at 0.5 m distance with *30* letters read. Bailey-Lovie Reading Chart results show similar results, with *5* words read within VR at 0.5 m distance compared to *6* from the physical version, and *12* words read within VR at 0.25 m distance compared to *11* from the physical. MNRead Acuity Chart results show at 0.5 m distance VR took *22* seconds to read compared to *21* seconds from the physical. At 0.25 m distance the VR chart took *14* seconds to read compared to *12* seconds from the physical chart. Ishihara test results show *1* more correct guess from the physical version of the test. P16 test results (See Figure 5.15) show a Tritan colour deficiency for both versions of the test. The VR version is further split between Deutan and Tritan deficiency, but leans closer towards Tritan. Overall results showed minimal variants between tests, with a slight decrease in VR performance overall. See Table 5.23 for this participant’s results for the first 4 tests.

Table 5.23: Participant A23's individual results for the first 4 tests.

ID: A23	VR Far	Physical Far	VR Near	Physical Near
Letters	35	38	35	39
Contrast	18	18	30	30
Words	5	6	12	11
Speed P1	6	7	6	4
Speed P2	9	8	5	4
Speed P3	7	6	3	4

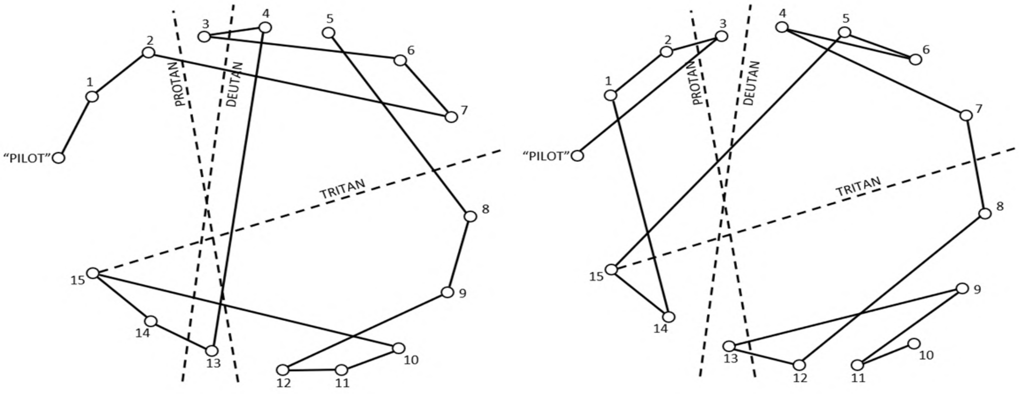


Figure 5.15: (left) Participant A23's physical Panel 16 Vision test results. (right) VR test results.

Participant A24

Participant Profile & Conditions. Participant A24 is a 49-year-old female that suffers from Salzmann's Nodular Degeneration (Roszkowska et al. 2011) (decreases visual acuity), Marfan syndrome (NHS 2016e) (in this case, dislocated lenses) as well as some other eye defects. She was born with her eye lenses shifted off their normal axis, becoming subtracted lenses. Her left eye was operated on due to its dislocation in August 2017, with fixed stitches significantly increasing its vision, and her left eye has a squint. Her right eye is still due to be operated on, with the lens not being centred on its axis. Due to her Salzmann's Nodular Degeneration, she has little spots on her corneas which were too dry due to not enough moisture. This problem formed patches in her eye, causing glaring in her vision. The left eye had a cataract removed, but the right eye is still waiting for its cataract to be removed. She originally found out about Salzmann's degeneration a year ago yet commented that she could have had it as far as her teenage years. She has always worn glasses since she was 5, and her vision has always been poor since she was young. Her grandma had a similar condition to her, and her grandma's father was blind. Her parents have poor sight, although her brother is fine, and all her grandparents wore glasses. Her glasses currently worn are not the correct prescription, since her left eye has had surgery, so they decrease the vision in her left eye but improve it in her right. Due to this, her left eye can see much clearer than her right eye, and wearing glasses brings them closer to balance reducing the level of haze, but still require a new prescription. Her vision has degraded gradually over the years. Brightness seems to affect her vision a lot, causing dazing if very bright. She finds night times to be okay, although she dislikes street lamps at night as they also daze her, and she can cope with day times if they are not too bright either. Her colours are washed out, or "muted", but after her operation her left eye can see colours much more vividly. Her depth of perception is limited and has always been limited.

Daily Impact & Aids Used. Currently she studies at an Open University, with the university providing specialist software to help her access the content available. The participant has had some issues with student software over her time at the university, but other software has been able to alleviate some of the accessibility problems she has faced. She originally utilised voice synthesis software, but it has become outdated. She uses online shopping, which she finds much easier than navigating for in-store items. She also makes use of standard PC accessibility features via Windows such as zoom text. Commented that she's had increasing struggle with monitors over the years as resolutions have increased, due to interfaces becoming smaller and harder to see along with things like fonts. The participant owns a 50-inch TV which she sits about 1.5 metres away, and she has a smart lamp. She has an Android phone which she doesn't use the accessibility features on but would like to know more about them. The participant stated she a fair amount of mobility, although travelling can vary based on the familiarity of the location and distance. She usually requires pre-planning to travel and likes to have someone accompany her for support but finds it difficult to find someone; she used to travel with her husband before he passed away. If necessary or lost, she takes a taxi for travelling. She lives alone with no additional support, and so makes use of accessibility equipment and setup such as tactile stickers on kitchen appliances. She used to enjoy cooking but can't anymore and prefers ready-made meals instead. She does not use any mobility assistive equipment such as a cane, as she does not want to advertise her condition, although she tends to hug walls when moving about. When asked to talk about how her condition affects her life and mood, she mentioned that prior to her operation, she would sometimes feel down but still get on with things. She described her relationship with her husband as him being her eyes, and her being his legs, as he was wheelchair restricted, and that with his passing she has found it a lot harder to cope with her vision as she once relied on his sight. She has since tried to become more active and get out more, as well as looking into more ways to help her vision, which was the reason she went for her eye operation. After the operation, she has become a lot more cheery, optimistic, and overall happy, although she still sometimes has issues with things due to her vision.

Participant Results. ETDRS results showed that at 1 m distance a score of *1.18* was achieved in VR compared to *0.96* physically, and at 0.5 m distance *0.72* within VR compared to *0.64* in the physical. PCSC results showed *23* letters read within VR at 1 m distance compared to *26* letters read via the physical chart, and at 0.5 m distance both VR and physical tests showed *30* letters read. Bailey-Lovie Reading Chart results showed *16* words read at 0.5 m distance compared to *12* via the physical chart, and *30* words read within VR at 0.25 m distance compared to *23* words read from the physical chart. MNRead Acuity Chart results showed at 0.5 m VR took *10* seconds to read compared to *9* seconds from the physical. At 0.25 m distance VR took *8* seconds to read compared to *9* from

Table 5.24: Participant A1's individual results for the first 4 tests.

ID: A1	**VR Far**	**Physical Far**	**VR Near**	**Physical Near**
Letters	26	37	49	53
Contrast	23	26	30	30
Words	16	12	30	23
Speed P1	3	3	3	3
Speed P1	4	3	3	3
Speed P1	3	3	2	3

the physical. Overall results for this participant were fairly similar between versions, although letter detection was noticeably worse in VR. The Bailey-Lovie Reading Chart was better within VR, and reading speeds were very close together between VR and physical, varying depending on distance and chart used but with no consistencies shown. Ishihara results showed no difference between both versions of the test, and the participant was able to correctly guess all but 3 plates shown. This participant's colour was strong enough that a perfect score was achieved within the P16 Vision test (See Figure 5.16), and it appears that only their reading ability has been damaged. See Table 5.24 for this participant's results for the first 4 tests.

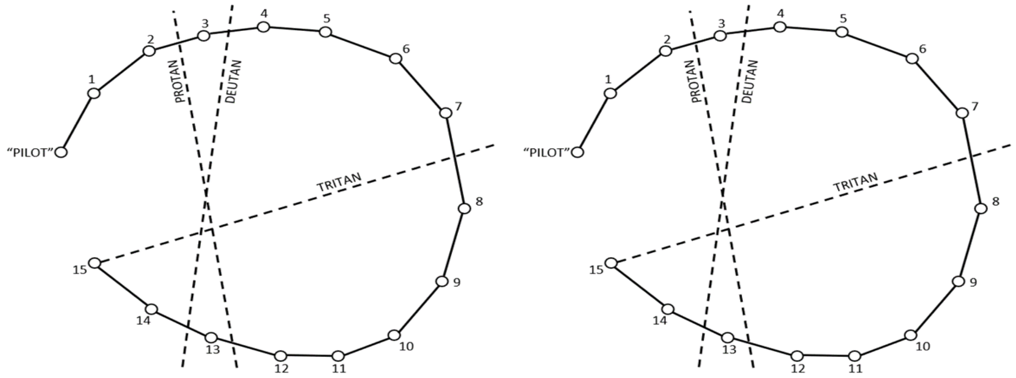


Figure 5.16: (left) Participant A24's physical Panel 16 Vision test results. (right) VR test results.

5.2 Discussion of Results

The research presented thus far looks at evaluating the suitability and visual potential of VR headsets to be used as accessibility tools for persons with severe visual disabilities. Looking over the data there are some consistent outputs found, although overall results are still mixed. Before discussing the results themselves, it is worth re-iterating the participant group's conditions and the device itself. This was an exploratory study utilising a VR headset that has no design considerations for visual disabilities and was made to target an entirely different user group that assumes vision is sufficient for operation. The user group focused on in this study are severely impaired participants with a vast range of complex conditions that can influence vision in a multitude of ways. To say that a user with the same classification of severe low vision may perceive things any similarly to others within that same category would be a gross oversimplification; there are any number of complications that can cause incompatibility. Despite these challenges initial examinations show some users experiencing visual benefits to utilising a VR headset as an aid, prompting further investigation.

Looking at an overview of the findings, there appear to be mixed results between test performances in VR compared to physical equivalents. Overall statistical significance could not be found for a number of tests, and some tests either show close to an even split in performance, or certain distances performing better in one but less in the other. Taking a more qualitative approach shows further details, however, such as with the Letter Detection test. At 1 m distance no statistical significance is recorded amongst all participants, although individual results show some significant jumps in test performance. Participant A1, for example, is able to read 15 letters within a VR device as opposed to 2, suggesting a notable increase in clarity. Although jumps in clarity are not as wide with many other participants, there are multiple cases of large jumps in performance recorded, even if general scores do not highlight this when compared. Similarly there are instances of large decreases, as with participant A10 who scored significantly higher with the physical test, yet this appears to be the only participant out of 24 with this kind of result for this test. At 0.5 m statistical significance is recorded showing a clear increase in performance when utilising the VR headset at a closer distance, something which appears consistent throughout testing.

For the Letter Detection, Contrast Detection, and Word Detection tests it appears that there was a greater increase in VR performance when conducting each test at a closer distance compared to further away. This does not mean statistical significance was identified or that VR performance outperformed physical performance at a closer distance, but overall VR scores were consistency increased when operating at closer distances. Within the Letter Detection test participants A8, A17 and A18 highlight this more clearly as their performance was worse at 1m distance, yet better at 0.5m for the VR versions of the test, and with the exception of A18 this is repeated within the Contrast Sensitivity test. The Speed Reading test does not highlight this same consistency as the other tests, although this can be explained through looking at how it is scored and participants results. As the test looks at total time taken of a section, with the section needing to be fully read, there is a more obvious limit to how well a participant can perform. There are a few instances where, if the participant was able to read the chart at 0.5 m, they are able to fully read it at 0.25 m between both versions at roughly the same speed as there is little more they can do to read any faster. The other attributing factor is memorisation, where if reading the chart at a further distance was successful it is likely that the participant is partly reading from memory and thus increasing their speed. Due to memorisation it is best if the text passages are changed between distances, but unfortunately only one version of the MNRead chart was able to be obtained and presented within this study. Due to these factors it is more difficult to attain whether there is a notable difference at a repeated shorter distance unless there are obvious performance differences, such as with participant A18.

If we are to assume that VR clarity is producing higher results at a closer distance but fewer further away, then there are some factors to investigate. One explanation may be the pixel count or resolution of the VR headset affecting results, as further away objects in VR are more susceptible to a max resolution count and a cut off point before things become increasingly blurred or pixelated. This may mean that with VR headsets with higher screen quality and resolutions, the gap between distance scoring may become closer until the limit of that headset is also reached. Another explanation may be the way depth is simulated within a VR headset which is an approximation but not perfectly accurate. This depth simulation may have increasing or decreasing effects depending on the distance causing variations in performance depending on how close the user is to what they are focusing on. This could also be an influencing factor to produced scores, where a simulated depth may be better for some participants and particular conditions, but detrimental to others. Repeating these tests with further VR headsets that display higher resolutions and simulate depth at modified levels may help to explore these occurrences.

Looking back at Contrast Detection, we see another example of performances improving at 0.5 m. This test produced statistical significance, this time at 1 m distance showing that VR results were worse than the physical results. As the test operates similar to the Letter Detection test, one might assume the results produced would have had greater similarity, yet this was not the case. Again however, when looking at individual scores we see a greater increase in VR scores at 0.5 m than at 1 m, such as participant A1's difference of 1 letter at 1 m, but difference of 15 at 0.5 m. Even with some participants who performed better in the physical test we see this as well, such as participant A15 or A19, where there was a significant decrease at 1 m but far less so at 0.5 m, or even an increase at 0.5 as with A14 or A8. Again however, this is not entirely consistent and there are some participants such as A11 where this is not recorded. If reading letters is producing stronger results in VR for most participants but performing a similar test when regarding contrast is not, this could suggest that contrast and brightness settings within VR are a larger influence on clarity if not adjusted for. Again, with the tests brightness was not increased or enhanced in any way beyond standard use, and simulated tests were displayed at the same luminance levels of the physical room. As the VR headset used is placed directly over the eyes and shines light straight into the retina, some conditions may receive less of a benefit from utilising a HMD when looking at darker contrasts, reducing effectiveness beyond natural sight. Looking at the 8 participants who performed better with the physical contrast test, we see that 3 have macular Degeneration, 3 have nystagmus, 1 has macular and light sensitivity, and another with photosensitivity. Trying to isolate these, if we look at all participants who have nystagmus and their results overall by removing the 20% difference in score criteria, we see that no participant with nystagmus scored better within the VR test and only participant A23 tied their score between both tests. One of the known possible symptoms for nystagmus describes difficulty with darker lights and a sensitivity to bright lights, which may explain the consistent lower scoring in this test for this condition. Out of all macular participants, only A9 and A15 scored better in the Letter Detection test than in the Contrast test at closer distances, although as A9 also has photosensitivity their decrease in score could be attributed to that aspect of their vision.

There are further unexpected results shown between similar tests. As in the Word Detection test, for example, we would assume that a participant that performed better in the Letter Detection test might also receive similar results in Word Detection, yet this was not always the case. There are some participants, such as A24 and A10, where they had performed noticeably better in one test but noticeably worse in the other. This test still shows that VR results at 0.25 m were generally better than at 0.5 m, but not as comparable to the Letter Detection test. Trying to isolate these participants for any trends again shows that out of the 8 participants with inconsistent scores, 3 had macular degeneration, 2 had nystagmus, 1 had photosensitivity, 1 had tunnel vision, and the last had nodular degeneration. Out of these 8, 3 were the same participants with differing results in the Contrast test (A10, A11, A15), although including or excluding these participants does not show dramatic consistency between conditions making it difficult to isolate exactly why scores may have differed here.

Although there were many variations of conditions between each participant, some were more common than others, such as macular degeneration. If we isolate results to macular participants, which are participant A1, A5, A6, A7, A8, A9, A13, A15, A17, and A18, we can see how scores are affected with further detail (See Table 5.25) . With Letter Detection at 1 m 4 out of 10 with macular performed better within VR, 2 performed worse, and 4 performed minimally worse within a 20% margin, yet at 0.5 m 6 out of 10 participants performed significantly better, 2 performed slightly better but within a 20% range, 1 performed worse within a 20% range, and 1 received no difference. As one might expect macular participants may perform better at closer distances as less of their central vision is blocked, yet with the Word Detection test this isn't as obvious. Macular participants would be expected to perform worse with reading whole words, and this is reflected by their overall lower scores in this test, yet at 0.25 m there are minimal differences between the 0.5 m results for VR performance, despite seeing the opposite effect in the Letter Detection test.

The remaining Speed Reading and Colour related tests highlight the limited visual levels of the participants. Many participants were simply unable to participate in these tests due to their low visions, or produced limited to no scores while attempting them. The MNRead charts used in the Speed Reading test had an additional chart, originally displaying 6 paragraphs in total instead of the 3 recorded. This chart was a continuation and displayed

Table 5.25: Data sheet of macular degeneration test results for the ETDRS chart (green highlights an increase in VR, red a decrease, and white no changes within 20%.)

Participant ID	VR 1m	Physical 1m	VR .5m	Physical .5m
A1	15	2	15	5
A5	5	11	18	22
A6	4	1	15	5
A7	15	8	35	17
A8	4	6	22	15
A9	15	16	29	22
A13	12	7	27	15
A15	13	15	25	20
A17	30	32	36	33
A18	31	34	45	45

3 smaller paragraphs from the ones highlighted on Table 4.4. These were omitted as results were too weak to gather any data, and the vast majority of participants could not attempt to read or complete the chart. From the participants able to complete the test, results are fairly mixed and it is difficult to determine any significance, adding into question the suitability of the test.

Early exploration and test trials with residents of the Beacon Centre for the Blind resulted in users interacting with VR devices and experiencing several virtual environments. Initial reactions from users with severe impairments suggested that colours were more vibrant than their natural vision and was enhanced in some way. Even in the comparative tests participants expressed this same feeling, yet results from both colour tests were not as positive. The Ishihara Plate test was too difficult for many participants to participate in, and if they did most could not produce many results and typically could not read beyond the two control plates which are the first and last plate. For those that did produce results there seems to be no significant difference overall between versions, and no significance was recorded. Individually there are some participants that experienced some noteworthy improved attempts, such as A1, A2, and A18, but there is not enough data to conclude anthing. Similarly there are some cases of weaker performances in VR as well, such as A20. Yet, if we look at the P16 test results these are not exactly consistent either. Despite A1, A2 and A18 performing better with the Ishihara test, their P16 tests show no noticeable differences. One thing that the P16 test does highlight, however, is that colours perceived within a VR environment to severe low vision users appear to be accurate for the most part. Out of 15 participants, 12 participants were recorded with the same evaluation of colour deficiency (i.e. none or one) while 3 had a different score. Out of these 3 participants, the scores produced were very similar but were pushed over classification in one area or another. The lack of significant colour score differences suggests that colours are at least accurate, with no significant improvements or reductions in detection or accuracy. This, however, does not match up participant testimony and reaction, suggesting that the perceived benefit may be a placebo effect of trying on the headsets for the first time.

Looking at an overview of the tests and results it is difficult to determine any strong significance between findings. From individual results and profiles there are more interesting findings that, in some cases, strongly suggest that VR devices can be an effective new accessibility aid and can improve visual clarity while worn. These findings help evaluate the effectiveness of a VR device for persons of severe low vision and were the motivation used in the development of a prototype accessibility software. The findings presented here were used to directly inform the creation of the prototype discussed in Chapter 6.

5.3 Limitations & Mitigation

As mentioned previously, the targeted user group in this research involved persons with severe visual impairments. Looking at visual acuity as a measurement, the lower someone's acuity is the more likely the causes involve increasingly severe and complex conditions, increasing difficulty for accurate comparisons. As such, accurate comparisons within this group are difficult and can produce noisy data. Even within isolated groups, such as participants with macular degeneration, or participants with nystagmus, there are still many different factors to each participant's conditions and vision that make comparisons difficult. Adding to this was the lack of recorded participant acuity levels, which could have helped alleviate this issue somewhat. To attempt to mitigate for this lacking detail each participant was thoroughly interviewed before and after testing and probed to describe how their vision works and given examples of typical day to day tasks that they might experience, and how their vision affects these tasks. Going forward it would be important to isolate a more specific group of participants suffering with similar conditions to allow the investigation of how equipment and differing enhancements affect particular conditions individually.

The equipment used in this test is appropriate as a starting benchmark for representing VR headsets, but as it was one of the first headsets to market the visual quality of the display is lacking compared to newer devices. If this test was to be repeated with a newer headset it is possible that VR performance may be further enhanced due to increased resolutions, pixel count, and the quality of lenses. To work towards this the subsequent study utilised both a older headset and a newer headset during its development cycle to be able to get an early gauge at whether there are obvious differences before a thorough follow-up study is conducted.

The tests selected for this participant group give us a good indication of the visual abilities of different individuals, yet the severity of the group meant that many adaptations had to be made to produce worthwhile results. To try and accommodate the participant group some of the adaptations included performing each test at closer distances than the original use case, as well as multiple distances to try and capture results if acuity levels were too low for further distances but not another. Another was printing some tests at a higher size or dimension than typically used, again to increase clarity to a level most participants could try to attempt. Some of these were less effective than others, such as the MNRead test, where many participants were unable to produce scores due to severe low vision despite adjustments. It is apparent that further accommodation would be needed to accurate test a larger range of participants going forward, with further adaptation needed for persons of severe low vision who are unable to partake in standardised optometry tests.

Another limitation was potential memorisation through the types of charts used, as we were only able to obtain one variation of each chart meaning that letters and passages would have been the same through repeated attempts. To mitigate for this tests were conducted 2 weeks apart between the physical and VR versions to try and reduce this factor, as well as test sequences randomised. This was less of a concern for tests where simple identification was required, such as the reading of a letter or a randomly placed word, but was more apparent for the MNRead chart where an entire coherent passage was required to be read. To better accommodate for data accuracy future tests will require either additional variations of tests to be acquired, or new variations created following the same specifications and format to be consistent with existing material.

Chapter 6

Prototype Software & Testing

After observing participant reactions and analysing results from the exploratory study, it was realised that some participants with severe visual disabilities were, through the use of VR, able to read again. Participant reactions to this were very positive, and they expressed the desire for a tool that would allow them to read something akin to a book again without needing to rely on text-to-speech software. Participants noted that there was a level of independence and joy that they had not felt for a while, and do not currently get with current reading alternative aids; they could read things at their own time and leisure, even if performance or accuracy wasn't perfect. It is worth re-iterating that the equipment used in the previous study (the Oculus CV1) was not designed for visual disabilities nor were any enhancements made to the device or the software that was running.

During the evaluative study of a VR device through several vision related tests, responses were recorded throughout all participants and the most requested desire was the ability to read again utilising a tool like the one trialled. As per participant's requests, a prototype text reader prototype was developed to look at two focus areas following the results of the comparative study. The first was what a virtual reader would consist of in terms of features, functionality, and the controls schemes of navigating such a tool using motion controllers; how would users best utilise a tool like this, and what aspects would be the most influential/beneficial? The secondary focus area, although smaller, was how users would react to using a headset with designed features for accessibility and aid? Additionally a different headset was selected with a wider field of view and a high resolution; would reactions be similar to the previous study with an older headset, or would there be any significant changes in responses? This study is more qualitative in nature, as direct feedback was desired through a iterative design process.

Prior to development, an exploration of current VR applications was done looking at 3 main VR software marketplaces, with findings noting that no storefront supported visual accessibility features of any kind at the time, nor did they promote any, and no accessibility reading applications existed to the best of knowledge available through these digital stores (Oculus (Oculus 2020b), Steam (Oculus 2020c), Microsoft Store (Microsoft 2020b)). Although there are some existing reading applications, these applications are not designed for accessibility or impairments and focus primarily on ease of use/comfort for a person with typical acuity levels.

6.1 Software Prototype

The application discussed was developed in the Unity engine and during testing was run via a laptop, the Pimax 5K Plus VR (Pimax 2020) HMD, and Vive Wand controllers (See Appendix I). The Pimax headset was chosen for its increased resolution, but more importantly it's increased FoV (See Figure 2.5). An brief overview of early versions of the application can be found in (Weir, Loizides, Nahar, and Aggoun 2019; Weir, Loizides, Nahar, Aggoun, et al. 2020; Weir, Loizides, Nahar, and Aggoun 2021). The application is designed to work alongside most common PC VR devices, and a machine that supports the minimum specifications for VR. The prototype is split between 2 different modes, one for reading text-based files, and the other for playing video files. The reading mode allows the user to insert text files supporting standard UTF-8 formats into the application to be transcribed into the digital reader. The video viewing mode allows the user to insert typical video formats into the player and display them (e.g. mp4, wav). The software displays a calibration scene for the user and then allows them to observe either a digital VR reader or video player that is displayed in front of them. Controls for the application are done via voice commands, or via either the Vive controllers or the keyboard via the invigilator. With the application's pilot test the digital reader contained 5 example books to read from with the ability to manipulate the reader in different ways to tailor the viewing experience, and 3 example videos to view and manipulate. Figure 6.1 shows the system architecture of the prototype software.

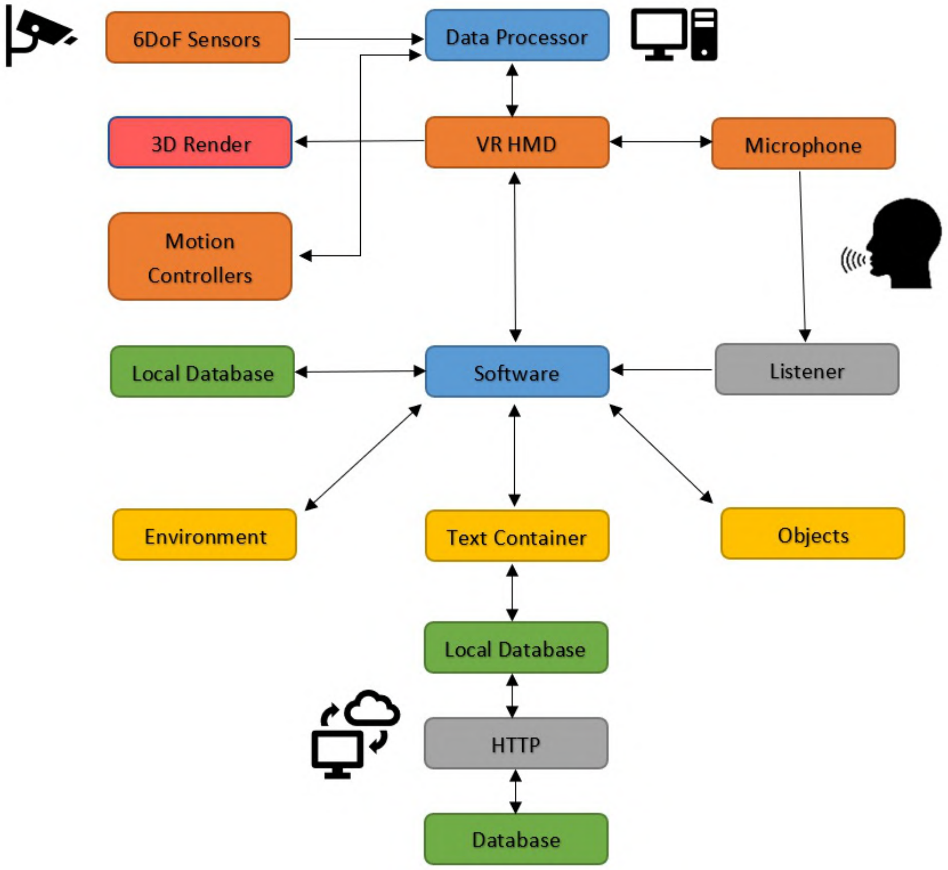


Figure 6.1: The prototype software's system architecture

6.2 Software Primary Attributes

The software primarily focuses on manipulating the following options, allowing for the user to fine tune how they would like to read the digital book displayed to them (See Figure 6.11 for an example of different possible combinations used by participants).

Book/Text Selection: The software allows for the translation of standard text to be transcribed into the application's format, including all of their chosen accessibility choices designed for VR. Although books are what have been displayed in the tests and in descriptions, any text that is compatible (standard UTF-8 format) can be loaded into the software to be read with customised visuals. This allows for compatibility with many text files providing the file has made the text readable in a typical format, and is especially compatible with most digital books that allow for raw text to be displayed. For this user test only books were shown to each participants. This is the main feature of the software and was influenced by participant testimony from the previous study.

Webpage Downloads: The software is setup to allow direct downloads from given URLs to then automatically insert into the application. This is compatible if the given domain allows for downloads and uses a typical format (i.e. txt file, mp4).

Font Size & Type: The software allows for font types, typefaces, and sizes to be adjusted to the user's preferences. This defaults to a 30pt Arial font, but once modified is saved for future translated texts the user transcribes. In the usability test only font sizes were adjusted. These are controlled by either the console of the machine, or via spoken voice commands to adjust fonts dynamically. Feedback from the Letter Detection test (See Section 4.1) influenced the necessity for this functionality and highlighted the need for full control over fonts as well as sizes. Static sizes did not always work for tested participants and relying on distance was insufficient. 1 participant also commented on whether fonts were changeable as they had a preferred font type, which was not available for the EDTRS chart nor the adapted test.

Sentence Structure: As well as the manipulation of fonts, the way sentences are displayed to the user can also be manipulated. The amount of letters each line displays, the amount of lines each paragraph displays, and the amount of lines a page can display can all be tailored to the user's preferences. Participant comments in the first research stage highlighted that these factors attribute to the levels of fatigue a user can feel while reading, and that controlling and limiting how text is displayed can alleviate this issue, reducing visual noise and stress on the eyes.

Adjustable Size & Book Model: The size of each book read and the video player can be manipulated freely by the user. The books by default are represented as 0.3m by 0.3m panels by default, but can be swapped between multiple visual models with size adjustments available as well. Text sizes are scaled along with book sizes, although these can be independently or separately adjusted for additional control. In the test only the default panel was presented to users. The video player's initial size is determined by the video file used and will adjust for ratio and resolution, but can be manipulated further by the user. Figure 6.2 shows an example of the video player shrunken down to be roughly the size of a tablet device.

Figure 6.2: An example of the video player's size shrunken down to be hand held.

Object location/rotation: Within the device, any object can be grabbed and picked up, including the book or video player (See Appendix H), to allow for better positioning, viewing angles, to reduce visual noise, or for any other preference. Positions are saved within a log that displays coordinates to the console that are loaded for future sessions if desired. Objects do not have any physics applied to them, and as such remain static and float until grabbed. Grabbing is done via motion controls that allow the user to 'grip' onto objects until they are at the desired new location, or alternatively done through the machine's console via coordinates. In the user test only the book, primary tools, and video player were toggled as move-able.

Scene/Environment Customisation: The environment around the user can be customised based on their viewing preferences. Just as with object location being saved within a log, the user can create new objects from a list of prefabs and save their setup to a file. This allows users to either have increased complexity to their environment or less, depending on their visual needs. Participants in the user test were given a blank environment to keep visual noise levels and distractions to a minimum. See Figure 6.3 and 6.3 for two examples of different personalised setups with the video player.

Figure 6.3: An example environment setup to look like a living room with the video player positioned similarly to a TV.

Environmental Colours: Scene elements can have their colour tint adjusted depending on the user's preference. This is primarily used for changing background and wall colours, but any object can have its colours adjusted along red/green/blue values if desired. This is controlled via spo-

Figure 6.4: An example environment setup to look like a bedroom with the video player positioned similarly to a TV.

ken voice commands for backgrounds and walls, or via the machine's console for individual objects for now. Users were limited to modification of all background colours simultaneously during the test. Despite the mixed results from Colour related tests (see 4.5, 4.6), participants commented positively towards the use of bright colours when trialing the selected VR headset. It is hypothesised that the ability to change overall colours will be desired by users, and will assist in higher levels of clarity alongside contrast.

Light and Contrast: The light levels of the scene can be adjusted by the user based on their preferences or individual requirements. Overall brightness of the entire scene (the overall HMD) can be adjusted, but also individual light elements within the scene can be manipulated as well. This is done via multiple light source locations that can be toggled on or off, or additionally moved, if specific angles or ray directions are desired for better reading. A torch tool can be additionally grabbed and held if preferred (See Figure 6.5). Light sources are modified via grabbing sliders next to light sources with the motion controllers, or through the machine's console. Only the HMD's overall light levels and the torch were enabled to be modified during the user tests. This feature was highlighted to be important due to the lower results of the contrast test (see 4.2) compared to the letter detection test 4.1. Being able to customise light levels to the individual level can greatly increase clarity. Figure 6.6 shows an example of a scene with black & white mode enabled.

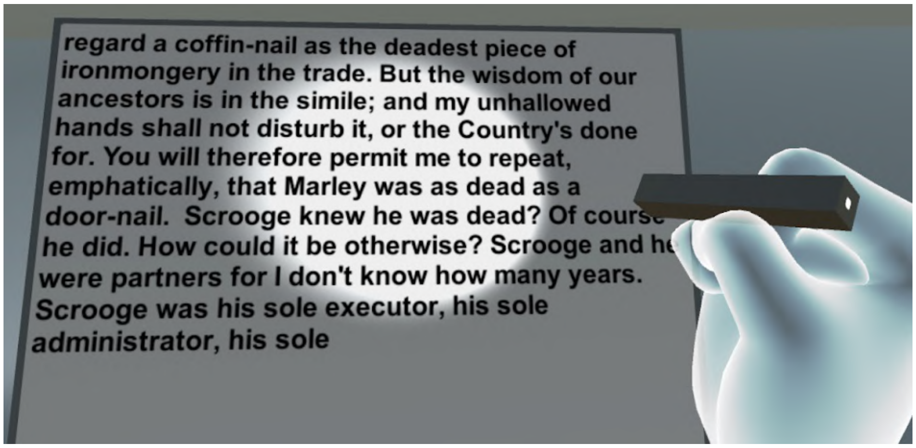

regard a coffin-nail as the deadest piece of
ironmongery in the trade. But the wisdom of our
ancestors is in the simile; and my unhallowed
hands shall not disturb it, or the Country's done
for. You will therefore permit me to repeat,
emphatically, that Marley was as dead as a
door-nail. Scrooge knew he was dead? Of course
he did. How could it be otherwise? Scrooge and he
were partners for I don't know how many years.
Scrooge was his sole executor, his sole
administrator, his sole

Figure 6.5: An example of the text reader with a torch enabled and shone at the reader.

Video Brightness & Contrast: As with the scene adjustments, the content of the video player can also have it's brightness and contrast adjusted but to a greater level. The levels of contrast, saturation, and post-exposure can all be manipulated to produce a clearer image to the individual's needs. Figure 6.7 shows an example of post-exposure applied to

Figure 6.6: An example of the video player with black and white mode enabled in the environment and the video enlarged.

increase the brightness of the video compared to its default settings.

Figure 6.7: An comparative example of the video player with brightness settings applied on the second to increase clarity.

Video Colour Blindness Settings: The video player can also have additional colour blindness settings applied, outside of standard brightness adjustments or black and white modes applied as seen in Figure 6.6. The individual hue of the video input can be adjusted to change overall colours towards a certain spectrum. This can be used to allow people with certain colour blindness to better configure the video player for better visibility. The levels of adjustment are variable so the user can make slight changes (See Figure 6.9) or stronger changes to the colour (See Figure 6.8).

Figure 6.8: An image of a dog with the colours adjusted by a user with protanopia.

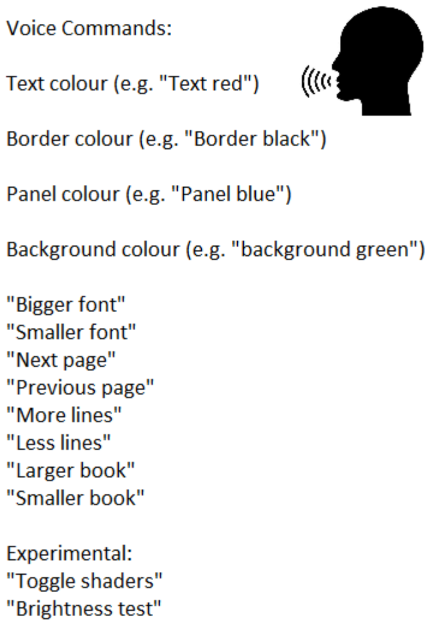
Text & Book Colour: The colours of the font, and several book elements, can be adjusted by the user for greater accessibility. Common accessibility colours can be chosen by the user, but ultimately any combination can be chosen if desired. These are individual elements within the book, so font, background, and panel highlights can be contrasting.

Figure 6.9: An image of a duck and a dog with the colours adjusted somewhat for tritanopia.

Depending on the book model, additional colour elements may be manipulated, such as a book's back cover. Again this feature was influenced from participant testimonies, despite mixed performance when evaluating colour detection.

Voice Input: The application supports voice commands read via the headset's built-in microphone. This was implemented as a way for participants to perform interactions in the environment that are slightly more complex than hand gestures may allow. A floating list of some voice commands were presented to participants during testing and can be seen in Figure 6.10.

Reading Preferences: How each sentence is displayed to the user can be manipulated depending on the preferred reading style. For users with certain visual impairments, limiting the text displayed through character limits, word limits, or sentence limits, allows for an easier reading



Voice Commands:

Text colour (e.g. "Text red")

Border colour (e.g. "Border black")

Panel colour (e.g. "Panel blue")

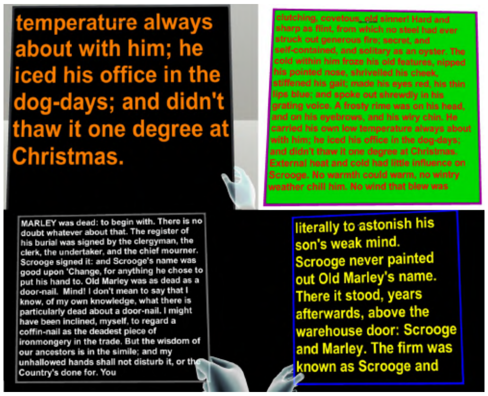
Background colour (e.g. "background green")

"Bigger font"
"Smaller font"
"Next page"
"Previous page"
"More lines"
"Less lines"
"Larger book"
"Smaller book"

Experimental:
"Toggle shaders"
"Brightness test"

Figure 6.10: A list of voice commands that were displayed to users on a chart during the reading text test.

experience. The number of lines displayed can be adjusted dynamically along with how many words show up on each line. This is controlled either via verbal voice commands or through the machine's console. It was noted this feature would be useful based on the results of the Word Detection test (see Section 4.3) and the Speed Reading test (see Section 4.4), as the display of how many words were on a single sentence or row affected the readability for some of the participants. Some lines would blend together, be skipped entirely, or a participant could get lost with where they were, highlighting that the ability to control this would be necessary for comfortable reading.



temperature always about with him; he iced his office in the dog-days; and didn't thaw it one degree at Christmas.

clutching, covetous, old sinner! Hard and sharp as flint, from which no steel had ever struck out generous fire; secret, and self-contained, and solitary as an oyster. The cold within him froze his old features, nipped his pointed nose, shrivelled his cheek, stiffened his gait; made his eyes red, his thin lips blue; and spoke out shrewdly in his grating voice. A frosty rime was on his head, and on his eyebrows, and his wiry chin. He carried his own low temperature always about with him; he iced his office in the dog-days; and didn't thaw it one degree at Christmas. External heat and cold had little influence on Scrooge. No warmth could warm, no wintry weather chill him. No wind that blew was

MARLEY was dead: to begin with. There is no doubt whatever about that. The register of his burial was signed by the clergyman, the clerk, the undertaker, and the chief mourner. Scrooge signed it: and Scrooge's name was good upon 'Change, for anything he chose to put his hand to. Old Marley was as dead as a door-nail. Mind! I don't mean to say that I know, of my own knowledge, what there is particularly dead about a door-nail. I might have been inclined, myself, to regard a coffin-nail as the deadest piece of ironmongery in the trade. But the wisdom of our ancestors is in the simile; and my unhallowed hands shall not disturb it, or the Country's done for. You

literally to astonish his son's weak mind. Scrooge never painted out Old Marley's name. There it stood, years afterwards, above the warehouse door: Scrooge and Marley. The firm was known as Scrooge and

Figure 6.11: An example of 4 different configurations setup of the digital reader

6.3 User Evaluation Methodology

A user test was carried out in order to (a) evaluate the efficacy of using the application and (b) to determine and benchmark findings on designing VR text reader and video player applications for persons with visual disabilities. 11 individuals were recruited (9 male and 2 female) advertising for persons with "severe visual disabilities" to test the application. An overview of individual conditions of each participant can be see in Table 6.1[1].

The testing process lasted approximately an hour per participant. The selection process for this test follows the same criteria as outlined in section 3.3. As with the previous test participants were asked to repeat the test within 2 weeks and scores were collected as an average. One participant

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[1] The participants in this test were not the same individuals used in the previous study

ID	Sex	Diagnosis	Aids Used
B1	F	Pseudoxanthoma elasticum, Macular Lower vision(left)	Magnifier(14x), Magnifier(x7) Smart phone, Siri, Alexa, BT card Talking books, Guide dog
B2	M	Nystagmus, Photosensitivity Cone dystrophy, Lower vision(left)	Magnifying glass, Thick goggles Mobile phone, TV(subtitles), Amazon tablet
B3	M	Retinal dysfunction Nystagmus, Long-sighted	Glasses, Magnifier(x2), TV Smart phone(large font), Coloured-coded kitchen
B4	M	Glaucoma, Fuchs dystrophy 5 Corneal Grafts, Astigmatic Keratotomy “Foggy” vision	Liquid temperature reader, Grip plates Large TV remote buttons, Dictaphone, Alexa Smart phone, Computer(magnified screen)
B5	M	Tunnel vision, “Foggy”, Optic neuritis Lower vision(left), Peripheral damage	Cane, TV, Screen reader, Magnifier Computer, Smart phone, text to speech
B6	M	Retinitis pigmentosa, Cataracts Retinal dystrophy, Tunnel vision Night blindness, Inflamed eyes	Glasses, ZoomText, inverted screen, Braille Magnification software(x3), Smart phone, Siri Guide dog, Cane, Tactile markers, Alexa
B7	M	Retinitis pigmentosa, Cataracts, Night blindness, Lower vision(right)	Glasses, Smart phone, text to speech, ZoomText Amazon echo, Tablets, PC, Cane, TV
B8	M	Glaucoma, Congenital cataracts Trabeculectomy, Lower vision(left)	Glasses, TV, Smart phone Tablet, PC, Cane
B9	F	Diabetic retinopathy(right), Cataracts Macular(right), Maculopathy(left) Detached retina(right)	ZoomText(x5), Keyboard stickers, Cane text to speech, Smart phone, Zoom, Alexa Tactile bumpers, Magnifying glass, Guide dog Talking clock, Audible toaster, TV
B10	M	Lower vision(left), “Bubbled” vision Peripheral vision damaged	Glasses, Railings, Alexa Mobile phone
B11	M	Glaucoma, Cataracts No vision(left), Depth perception gone	Magnifying glass, Glasses, TV Wheel chair, Laptop, Talking watch

Table 6.1: Table of test group B’s recorded diagnoses and what aids they use

was familiar with the concept of the system as they had trialled earlier versions through the iterative process but had not tried the hardware used and control method as it was new for this test. Participants were permitted to have breaks should they wish and refreshments. None of the participants opted to take this option. An initial briefing took place with each participant where they were introduced to the hardware and software that they would be using. A full explanation of the controls and how to use the book reader was given. The participants were given a set number of tasks, but were asked to explore the application, performing the tasks in any order they wished. A think-aloud feedback protocol was used while the participants used the application and the investigator would only interfere to remind the participants of the controls as well as the different tasks the participants should go through. The video and audio of the participants within the VR environment and within the physical environment was recorded for analysis. The recordings also included all the measurements that the participants changed, such as brightness, text font size, reader size, colours chosen, video player angle, and player hue adjustments. The test was split between the text reader and video player and included these tasks:

Text Reader

(i) How visible is the text from the reader in front of you currently?

(ii) Expand and contract the text reader window to what is the most comfortable size for you.

(iii) Move the document around and find the most comfortable position for reading.

(iv) Increase and Decrease the font size of the text until you find the most comfortable reading size for you.

(v) Change the text and background colour to a combination that suits your reading best.

(vi) Select and Read through different books from the collection.

Video Player

(i) How visible is the video player currently in front of you?

(ii) Expand and contract the video player to what is the most comfortable size for you.

(iii) Move the video player around and find the most comfortable position for viewing.

(iv) Stretch, increase and decrease the video player until you find a size that is most comfortable for viewing.

(v) Adjust the levels of brightness/contrast/hue until the video looks the best for you.

(vi) Select anf watch through different videos and comment on what looks clear.

After the test, the participants were asked to fill in (verbally due to their conditions) a questionnaire with 3 seven category unipolar scale questions, 10 5-point Likert scale questions, and subsequently asked 5 open-ended questions in a semi-structured interview style (See Appendix B). All questions related to the usability of the system and the requirements of the users. Two methods were adopted for the post-study questionnaire. The first method for the opening 3 questions was based on the physiological effects that the apparatus caused the users, for which the methodology found in Ames et al.'s article (Ames, Wolffsohn, and Mcbrien 2005) was adapted. In this the relevant sight questions were taken out as they were deemed inappropriate for participants already suffering from visual problems. Remaining questions were formed and adapted based on guidance from Sauro et al.'s article (Sauro and Dumas 2009) to evaluate the usability of the system, post-task.

6.4 User Evaluation Results

Participant comments were transcribed from the think-aloud protocol and post-task semi-structured interviews, and transcripts were analysed using methods presented by Burnard (1991).

6.4.1 Physiological Symptoms

VR has been known to be uncomfortable and sometimes create some physiological discomfort (Cobb et al. 1999). As the technology progresses, we see the effect being felt less and less. However, due to the nature of the end-user target group, it is considered that comfort and any physiological effects to be important to address. For this reason participants were asked to comment on five specific factors; namely, the fatigue, drowsiness, dizziness, nausea and any headaches caused by the apparatus (method adapted from (Ames, Wolffsohn, and Mcbrien 2005)). Participants were asked to comment on any other physiological factors they may have experienced during their testing time which they did not explicitly mention. Participants unanimously responded with no feelings of drowsiness or headaches. 2 participants reported levels of *Slight (2, 9.09%)* and *Moderate (3, 9.09%)* fatigue, and when asked attributed this to the weight of the HMD. These results are positive and it is speculated that with future HMD advancements these issues will become even less apparent. When directly questioned as to the comfort of the headset, participants overall leaned towards a higher comfort level. 2 participants rated the headset as *Very Uncomfortable (18.18%)*, 2 as *Uncomfortable (18.8%)*, 5 as *Comfortable (45.45%)*, and 2 as *Very Comfortable (18.8%)*.

6.4.2 Clarity of the Headset

Participants were asked in the post-task questionnaire to provide a score on the clarity of their vision within the headset. Although this was asked throughout the tasks themselves, an overall score was recorded from participants. This rating would be based on the entire experience, so the perception of clarity within the Pimax VR headset alongside the levels of enhancements used and sampled. No participant gave a rating of *Very Unclear* and *Unclear* when asked to provide a score. 4 participants rated the clarity as *Average (36.36% of participants)*, 5 participants gave a rating of *Clear (45.45%)*, and 2 participants gave a rating of *Very Clear (18.18%)*. These results are positive, suggesting that *63.64%* would be able to see and utilise a VR headset for accessibility based on clarity, and that *36.36%* of participants had an average level of clarity which is potentially open for improvement.

6.4.3 Ease of Use of System and Controls

Participants were asked to rate the ease of use of the system as a whole, and also the individual parts, such as the headset, physical controls and voice commands. Participants rated the ease of use of the headset as *Difficult (9.09% of participants)*, *Average (9.09%)*, *Easy (45.45%)* or *Very Easy (36.36%3)* to use. The controls also received the same rating when being tried and tested by the participants. Interestingly, when asked to provide a rating for the ease of use of the combination of the headset and the controls, 1 participant rated it as *Difficult (9.09%)*, 3 participants rated it as *Easy (27.27%)* and 7 rated it as *Very Easy (63.64%)*. When questioning the participant with the low rating they reported that when trying one action at a time the controls seemed to make sense and were easy to use. It was when the participant was left alone to utilise all learned actions within the 3D space that it became hard to remember and to perform different actions wanted. The participant also reported that had they have been given more time this would probably not be an issue and the rating would change. When asked about the ease of software navigation via the used motion controllers, 1 participant rated the navigation as *Average (9.09%)* difficulty, 4 rated it as *Easy (36.36%)*, and 6 as *Very Easy (54.55%)*. Participants were asked about whether they perceived voice commands to be more useful or preferable over the use of controller buttons. 6 participants said they *Agree (54.55%)* with voice controls as more useful, 3 said they *Somewhat Agree (27.27%)*, 1 responded neutral with a *Average (9.09%)* rating, and 1 said they *Disagree (9.09%)* that voice controls were preferable over buttons. The participant that disagreed with the question commented that they found the voice commands difficult to use, unnatural, and would prefer not to have them at all or to find alternatives without using voice commands, especially in public. Lastly, participants were asked if they thought if they would need an expert to help them use a similar system in future, or if they believe they would be able to handle its use alone. 4

of the participants commented that they would prefer, at least the first few times, for an expert to be there to assist them in using the system, with 2 saying they *Somewhat Agree (18.18%)* and 2 stating they *Agree (18.18%)*. 1 participant answered with an *Average (9.09%)* rating, 1 participant said they *Somewhat Disagree (9.09%)*, and 5 participants said they *Disagree (45.45%)* that they would need the help of a technical person. When asking the open-ended questions, 5 participants commented that they particularly liked the “grabbing and zooming in and out” feature, using a natural hand gesture. When asked for their preferred method of controlling the VR environment, 6 participants reported that using controllers was the easiest solution for them, 4 participants favoured the voice commands for everything, while one participant wanted a combination of both. When asked for any further control that they might wish to be implemented, 4 participants asked for hand and finger detection instead of using a controller (possibly by using technology such as the Leap Motion Controller (Ultraleap 2020) or generic camera AR tracking) and 1 participant asked if possible to detect his gaze while giving commands.

6.4.4 Reading Efficacy and Configuration

Participants were asked to comment on the clarity and readability of text within the headset at all times. It was found that all the participants were able to read text within the reader once adjustments were made. The settings for brightness and text, as well as positioning of the reader varied between participants. Participants tried out a number of settings before deciding what their preferred settings were, where they were most comfortable reading the text as well as being able to. The measurements of the book defaulted to being 0.3 meters long and wide, and on average participants increased this to 0.4 m. Font size preferred on average among each participant was 42 pt. The distance at which participants were comfortable reading at was averaged at 0.5 m. Out of 11 users, 4 *(36.36% of participants)* preferred text to be black on a white background, 1 *(9.09%)* preferred black on yellow, 4 *(36.36%)* preferred white on black, 1 *(9.09)* preferred yellow text on a blue background, and 1 *(9.09%)* preferred yellow text on a black background. Viewing angles were fairly neutral across all participants, with small variants within the ranges of 10 degrees, although one participant with a damaged eye preferred reading with the text angled vertically down by 30 degrees and 10 degrees to the right. Participants commented that the freedom to choose how large text is and their ability to position it anywhere from any distance was something they wouldn't normally be able to do, and was helpful.

6.4.5 Video Viewing Efficacy and Configuration

Participants were asked to comment on the different elements displayed on the screen in front of them as each video played. All participants were able to view the video at varying levels of capacity, but some scenes were clearer or harder to perceive depending on various factors, such as brightness. 7 participants *(63.64% of participants)* preferred the brightness higher, while 3 *(27.27%)* kept the brightness at its default levels, and 1 participant *(9.09%)* significantly reduced brightness due to their photosensitivity. The default measurements of the video player were 0.6 m long by 0.25 m wide, and on average most participants chose to increase this by one increment to 0.7 m by 0.3 m. All participants preferred an increase in contrast at varying levels, some doubling the contrast and some only by smaller increments, but in all cases an increased contrast made visibility clearer. The distance at which participants were comfortable viewing the player at was averaged at 0.63 m. Again as with the reading test, viewing angels were neutral across all participants with smaller variants, although the range of angles were sometimes closer to 20 degrees than 10. Again one participant preferred viewing angles changed, with the video angled 20 degrees vertically down and 20 degrees to the right. Participants commented again on the ability to position the video from any angle and location was very impressive and contributed well towards viewing. The ability to change the brightness and contrast was also very positively received, and was one of the largest contributors to successful viewing.

6.5 Perceived Usefulness of the Prototype

The aim was not simply to build a VR reader and video viewer, but to ensure its impact and adoption. Therefore, it is just as important to probe the perceived usefulness and likely acceptance of the system by end-users. Participants were asked for their honest view on the perceived usefulness of the tool in terms of their own habits and needs. All participants were positive in their responses and agreed to some extent that what they experienced was useful to them and would like to be able to have use of the system in their lives. 5 participants gave a rating of *Somewhat Agree (45.45% of participants)* to this answer, and 6 participants gave a rating of *Agree (54.55%)*. When asked about the frequency of use, the majority of participants *(72.73%)* commented that they could see themselves using it daily to read and view content. 6 participants said they *Agree (54.55%*, 2 participants said they *Somewhat Agree (18.18%)*, 1 participant gave an *Average (9.09%)* score, 1 participant said they *Somewhat Disagree (9.09%)*, and 1 participant said they *Disagree (9.09%)* that they would wear a headset daily. One participant commented that they would use it when they wanted to read, which was not a daily activity, and that they were not used to watching TV or video content so they were unsure on whether it could become a regular hobby. Participants were also asked if they saw themselves using the headset as a visual aid in their everyday lives, beyond just the text reader and video player that was created. Unanimously, their response was positive, including participants who previously answered Disagree and Somewhat Disagree that they would use the headset daily to read. 4 participants answered *Likely (36.36%)* and 7 participants answered *Very Likely (63.64%)* to seeing themselves using a VR headset as a visual aid in the future.

One participant who was an active assistive technologies expert who had trialled several electronic assistive technologies, including CCTV like systems, commented that the trialled prototype software was the best they had ever experienced for visual clarity. This was particularly encouraging as the participant had the perspective as someone with severe visual impairments, while also expert knowledge on what was available to assist people and what both the group and themselves needed for successful accessibility.

It is likely that this type of software combined with VR technology will be a new and invigorating way for users with severe visual impairments to access appropriate accessibility content. Based on feedback, participants were optimistic and excited to see how this kind of technology would develop in the upcoming future in allowing them to view content in new and immersive ways that would benefit their daily lives.

User evaluations of the prototype software shows promising feedback suggesting that participants can see using this technology in the future overall, and that the technology can be seen as a visual aid tool if developed further alongside hardware adjustments (such as less weight and reduced size). Although users were mixed in whether the tool could be used as a overall accessibility tool, or was more specific for specialised tasks, the general consensus was that it would be significantly useful in some way to the visually impaired test groups. All of the participants were able to read to some level once accessibility configurations were made, regardless of visual acuity levels or conditions, and all participants were able to distinguish key elements of the video displayed, and perceive further details with enhancements made. This suggests the software had worked as intended, and has allowed data to be gathered on different aspects of how a virtual reader and video player in 3D space might operate, but it may also suggest the headset that was used, the Pimax 5K Plus, may have performed better than the previous tests with the Oculus Rift CV1, which displayed a lower resolution and lower field of view. Further investigation between these two comparisons is needed.

One participant with very low visual ability tried both the CV1 and the Pimax headsets with the software, and noted a significant improvement in their reading ability and acuity, unable to read at all using the lower resolution and lower field of view CV1, but far more ability within the Pimax. Although this is a single case and further research is required to come to anything conclusive, it is possible that the increased field of view may benefit low vision users within a VR device significantly, as more light will be allowed towards the eyes and hit healthier parts of the retina, particularly useful for suffers of central vision type conditions such as macular degeneration. Although this is hypothesised, the level of visual increase this could provide is not known, if any, yet it is worth noting for future works as it was not a focus point of the software evaluation.

Chapter 4 (see section 4.7) mentions the limitations of static charts make it more difficult to explore how typography affects users with visual disabilities, and that one of the benefits of a HMD used as a ELVA is that the content is easily changeable. This study allows us to explore that concept better and already there appears to be benefits from basic adjustments to size, position, angle, and combinations. Although this study did not expand into this area in too much detail a system like this can potentially provide unlimited combinations of modifications allowing for a truly greater accessible experience. As this was a prototype system a limited number of typefaces were available, and participants did not explore these in too much detail as they were comfortable with the defaults, yet aspects such as line or character spacing were modified in a natural way that allowed for better readability. It is hypothesised that outside of a test scenario participants may have spent more time customising and tailoring displayed text to better suit their preferences as interest in customisability was already noted from participants.

6.6 Suggested Framework

Based upon observations and results from each participant group, a set of heuristics is proposed (See Table 6.2) within a framework to guide VR designers for designing accessible software for VR applications for users of severe visual impairments. As most severe visual impairments are age related, this framework includes considerations for interaction methods specifically for older adults, which may be less applicable for younger audiences.

This framework was designed alongside the development of the prototype software based on initial feedback given up until the final user study. A diagram of the design process can be seen in Figure 6.12, highlighting that this type of development needs to be built upon the responses and reactions from willing participants of appropriate groups.

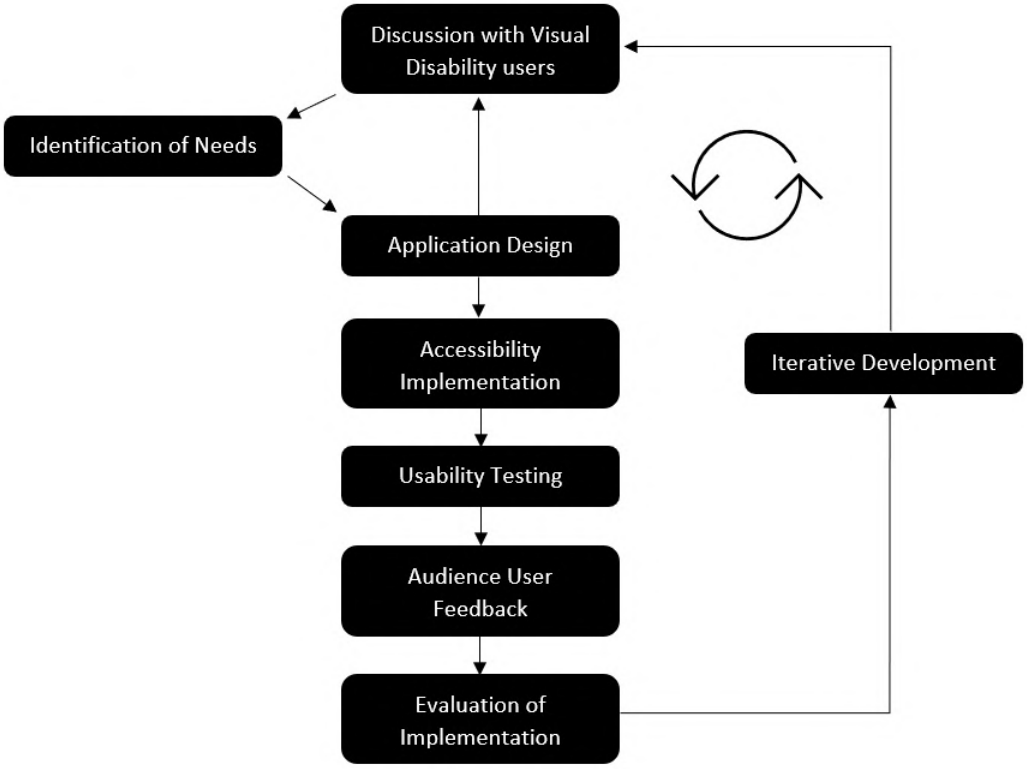


Figure 6.12: Application Design Process

As the application was in development throughout testing periods, the design of the software has gone through several iterations as feedback was received and results were analysed through the comparative study. Some of the earlier iterations were made alongside the Oculus Rift CV1 (Oculus 2020b), as initial development carried on with the same headset until the newer one could be obtained. Many design challenges had to be faced, such as designing the control method for a multi-function VR application, as the target group are users with severe visual impairments and typically this group consists of more mature adults that are less familiar with technology. Early versions tried mapping many functions to the motion controllers themselves but participant reactions to these were unfavourable, with participants expressing confusion and difficulty of use. An example of an early control scheme presented in early versions can be seen in Figure 6.13. These responses pushed for the development of alternative controls, such as voice commands as presented in Section 6.2, but further testing had to be made to garner participant reactions of different control schemes and configurations.

As tested concluded and results were dissected, a list of 11 guidelines for designing for people with severe visual impairments was finalised and presented below:

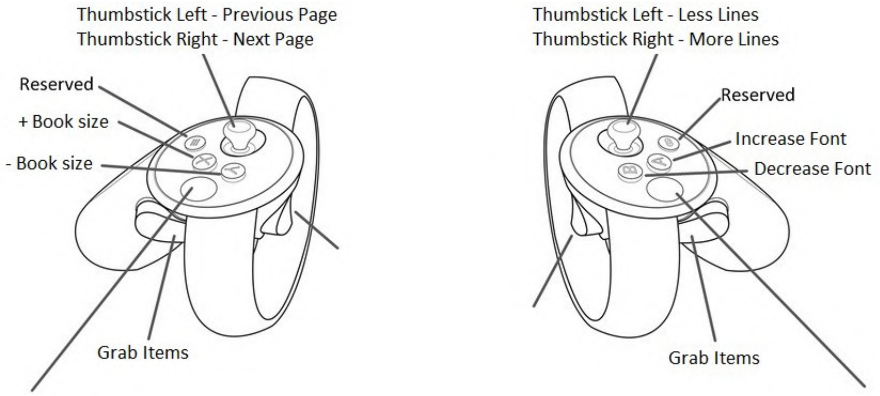


Figure 6.13: An early prototype image of the Oculus control scheme presented to testers before being deprecated by the Vive Wands.

VR devices provide a new form of interaction unseen and unfamiliar to many. VR interactions provide added complexity to traditional interactive systems such as computers or televisions, especially for older adults. It was found that participants struggled with button interactions on a motion controller to operate functions (e.g. changing pages, adjusting sizes), but more natural interactions when using controllers to grab and lift things using motions through squeezing a trigger were better understood, as well as positively received. It was also noticed that out of all adjustments made, changes to the overall brightness or contrast was the most consistent in increasing clarity providing an object was within an appropriate range. It is important to take advantage of the benefits VR provides, specifically the ability to operate and observe within a life-like 3D environment. This means that design should still follow common accessibility considerations, but translate them so that VR features can work alongside them, such as translating font accessibility from a 2D application or screen, to a 3D application that now benefits from translocation on an extra axis. Additional considerations should take place as well, as something such as sudden bright lights in video are problematic already, but would be amplified within a VR headset, as was experienced with some of the participants experimenting with brightness settings. Finally, although VR should bring many advantages to accessibility, it is still a visual experience and is only as effective as the user's ability to see, which could be influenced by any number of factors. It is recommended that design should include multiple sensory elements, particularly audio, to supplement the visual experience to enhance it but also act as a fail-safe. Additionally, touch sensory feedback should be considered as well if available. Vibrations have been shown (Azenkot, Ladner, and Wobbrock 2011; Flores et al. 2015) to be able to assist in providing blind & low-vision users with the ability to navigate and understand interactions. Most VR motion controllers, including the ones used in this research, include motor functionality to provide vibration feedback, and are a great way of communicating additional information through sensory feedback. This feature was not implemented during the user test sessions, but will be incorporated at a later date.

These guidelines are presented based on observations and conclusions gathered from 2 research stages conducted. Working closely with participants throughout an iterative design process was very beneficial as it allowed for key perspectives and input that influenced design decisions and influenced the creation of the tool itself. Following the think-aloud protocol (Lewis 1982) was particularly helpful as prompting participants to be open and verbalise what they are seeing, doing, and feeling allowed for better insights into how someone might operate and interact with the developed system. Throughout both tests this approach lead for a large collection of data, many which were seemingly unimportant, but allows for greater perspectives when returning to recorded data and has allowed for clearer guidelines to be presented.

It is hypothesised that the greatest benefits elicited from utilising a VR HMD as an accessibility tool and presented within the guidelines are 1) the adjustment of brightness, 2) positioning of elements, and 3) dynamic content scaling. These factors draw upon the strength of a VR HMD and grant benefits beyond many available existing LVAs. Although magnification is well known to be one of the greatest ways to enhance visibility and is possible by many LVA, the actual scaling of content in a stereoscopic 3D environment with 6DoF should provide a larger benefit. Instead of zooming into content to read it one is now able to move around it, change angles and positions, modify external visuals not limited to disabling them, achieving greater freedom. This combined with other more obvious methods, such as manipulating light elements for greater visibility, allows for a state-of-the-art approach to accessible content. It is up to accessibility content creators to realise the potential benefits these systems can bring and draw upon their strengths as they become more popular and widespread.

Table 6.2: The Design Guidelines for Accessible VR Content for Visual Impairments Framework

Design Guidelines for Accessible VR Content for Visual Impairments	
1	Allow brightness/contrast to be controlled easily by the user, as it is one of the quickest ways to increase clarity.
2	Focus controls around actions that better mimic natural interactions, such as closing the hand around a trigger to pick something up.
3	Different VR headsets provide varying levels of Field of Vision and screen types/lenses may be better suited for darker or brighter environments. Design elements with this limitation in mind.
4	Introduce a VR experience through simple and lower light environments, to ease and adjust users into an environment, and gradually increase complexity if needed.
5	Avoid sudden spikes in bright lights or strong consistent colours, as users sensitive to lights is common.
6	Ensure that important elements can have their distances and sizes adjusted via the user, as this is a crucial benefit of VR accessibility.
7	Weight of a VR headset is a common complaint, and will affect older adults particularly. Consider designing content that can be digested in smaller bursts and does not need extended time. Hardware designers will want to keep weight as low as possible.
8	Audio elements are great for enhancing VR accessibility, especially during calibration phases. Interfaces should have audio assistance and alternatives as an option.
9	Fonts should be fully customise-able and moved freely to any position through the user's own motion, for best viewing angles and distances.
10	The concept of VR can be confusing to older adults, and many may not try to move around to interact with an environment. Remember to design elements with clear indication that they can be interacted with, and lead users through actions they can take. Haptic feedback with vibrations should be considered to assist with this.
11	Customising content is one of the great benefits of a HMD system, and allowing the user to move and place things freely is crucial towards tailoring the experience. Allow users to move & scale UI elements so they can perceive them under their own requirements.

Chapter 7

Conclusions & Future Works

This work focuses on understanding the potential of using VR emerging technologies to assist persons with severe visual disabilities. The project was split between two main research stages, the first covering the initial study of literature and an evaluative study allowing the benchmark and comparison of a current HMD system to traditional viewing, and the second using these findings and applying them to build the bespoke informed technological aid software.

In this research project, the effects of a HMD device on levels of acuity and the efficacy of an accessibility software through user testing was investigated. The research begun with the investigation of the history of similar visual impairment CCTV systems, an overview of common impairments that would be present during the research process within the participant groups, the investigation of conceptual VR and AR systems, and current tools that are available for persons with severe visual impairments. Several aspects of vision were identified in establishing an accurate representation of visual ability within a VR system. Tests were devised and adapted based upon the previous works of well-established optometry tests, using these as a template for the comparative study that would best answer the research questions. The tests covered letter detection, contrast detection, word accuracy, reading speed, colour detection, and colour accuracy, taken from the research question directly.

7.1 Identifying Improvements of Visual Acuity with a VR HMD

The first academic question of this project asked whether we could identify where any improvements to the visual acuity or reading ability levels of those with severe visual disabilities were found while wearing a VR HMD. Through analysis of the first research stage, statistical results as well as qualitative dissection was completed. With no enhancements made to the HMD device, there were some instances of clear improvement when the device was used to read letters at closer distances. At 0.5m statistical significance was identified with participants showing a noticeable increase to the amount of letters identified. When isolating these results to participants with Macular Degeneration, although no statistical analysis was performed due to small sample size, out of 10 participants, 6 received a large improvement, 1 a minor decrease, and 3 either very small improvements or no difference. At 1m distance however, although still positive, these results are not as strong within VR for macular participants and the same is shown for overall test results. A consistent theme was that VR results were stronger at closer distances compared to their further distances, even if the difference were not distinct enough to form statistical significance. If we look again at individual results and the data from a qualitative perspective, there appears to be significant improvements within VR for certain participants. It is likely that hardware limitations have been a significant factor (i.e. limited resolution, field of view), and if the participant selection was narrowed down to users with the same measured acuity levels as well as the same visual conditions, that more significant results could be produced. Furthering this, this study was conducted with a VR headset designed and configured with no enhancements for persons of visual disabilities in mind, and that designing a headset for visual accessibility or utilising specialist accessibility software, may provide better results.

Using these findings and the insight gained from the first research stage, a VR based document reader and video player was then created in the second research stage, integrating the feedback and benefits of the optometry-inspired and adapted tests, such as the ability for users to move texts dynamically and scale text freely. Although this follow up study was not comparative in nature as the software developed is still within the iterative design process being a prototype, it aims to provide insight into the visual capabilities of severely visually impaired users when utilising a VR device with specialist accessibility software. All participants were able to read full sentences within VR once configurations were made, as well as view the majority of elements displayed in the video viewer, although with more difficulty than the reading task. These results are promising as participants commented that they no longer attempt to read from paper or devices, or if they had to found great difficulty in attempting to without heavy accessibility software, yet expressed surprise and positivity towards the amount they were able to view and read within the device. The comments from the participant who was a accessibility technology expert and had worked for several visual impairment focused charities also suggested the device was effective in providing improved visuals and enhancing reading ability. User evaluation scores were high across questions asked, and reactions and testimonies from participants showed that there was a strong need for VR to be used as a visual aid tool for reading and video viewing, particularly for leisure reading and casual viewing, and that specialist software was desired. Looking at both the results from the studies, as well as user feedback from the prototype software, findings suggest that VR devices have the potential to be used as dedicated accessibility tools, but there are many gaps currently in both available software and hardware design that hold back the medium currently, due to a lack of focus in this area in the market overall.

From the research gathered there are several major parameters that influence acuity that have been identified. As discussed already, distances heavily affect the effectiveness of sight which appear to be amplified within a VR HMD. Beyond this it was identified that brightness is also a major factor, and many previous research emphasises this by showing improved performances when contrast and lighting was enhanced. In the Pelli-Robson Contrast Sensitivity test no such enhancements were used and in some cases the natural, unmodified light of the HMD was insufficient to increase performance over natural vision. The first research stage allowed for a comparative study and benchmark for vision, but also highlights aspects that are problematic to visually impaired users through the use of static tests. The second research stage's usability testing showcased that positional moving, scaling, and overall dynamic customisation greatly enhanced readability and allowed users to access information in their own formats. Scaling gains the benefits of magnification but allows finer tuning of visual aspects, granting increased clarity. Acuity can be positively influenced through improved headsets as well, as providing clearer lenses with higher quality visuals and higher FoV should compound results, and although not investigated further, one of the participants tried both an old and new VR HMD system and saw immediate improvements to acuity levels. Although results for the MNRead Acuity chart for reading speed were mixed, a previous study (Crossland et al. 2019) suggested that, despite performance for acuity increasing in other tests, reading speed was decreased utilising a VR headset, even if more was able to be seen. It is possible results from this study correlate with this finding.

7.2 Identifying the usability needs of Visually Impaired users in VR

The second academic question of this project asked what are the usability needs of severely visually impaired users that would allow for the most effective utilisation of a VR HMD as visual aid replacements. Through both research stages several aspects of accessibility and usability needs were identified. Analysis of results from the first research stage showed a common theme of closer distances producing more beneficial results in VR than further distances in VR, contrasting to physical results. This highlighted the need for dynamic spacial adjustments, as well as the ability to manipulate the sizes of objects within a VR environment. Additionally it is hypothesised that the limitations of resolution and type of lenses utilised may attribute towards this factor, encouraging that VR accessibility devices should target higher levels of fidelity to successfully provide clear visuals for persons of visual impairments, and that software will be restricted by the capabilities of the VR device. Contrast also suggested a concern in VR since, despite similarities to the Letter Detection test which participants performed favourably in, results were not replicated when performing the Pelli-Robson Contrast Sensitivity test. The ability to manipulate the brightness and contrast of the HMD is important to delivering accessible visuals. Supporting this, when this feature was implemented into the prototype software and tested in the second research stage, participants commented that the highest improvement to visuals in the video viewing test was via the manipulation of the levels of contrast and brightness. Although reading letters was favourable, results from subsequent tests suggested that reading full words, either through the Word Detection test or the Speed Reading test, were more difficult. These tests showed static words and sentences using specific typefaces and fonts, which may not be preferable or suitable to each individual's needs. The ability to manipulate these fonts, as well as choose how sentences were formed and displayed, was identified as needed through these results and implemented into the prototype software for testing. Although colour was verbally praised by participants, no tests yielded any results that would suggest any significant or noticeable difference between performance in both VR and physical testing, although these tests do validate that colour perception is recreated accurately to natural vision within a VR HMD.

Focusing further on the second research stage, several configurations were tested by participants and highlighted preferred preferences. Preferences for colour combinations when reading were split almost evenly, accentuating the usefulness of said feature. Average font sizes preferred were 42 pt, suggesting that portable devices for accessibilities, viz smart phones, would be limited in displaying these sizes and persons of severe visual impairments may be restricted to more common screen reader technologies available on PC. One participant preferred less common viewing angles preferring the reader and viewer to be tilted downwards while still producing said enhancements detailed above. This is again something that would be difficult to achieve using existing typical accessibility tools, with smart phones unable to display at the correct size and distances, while PC monitors may be able to but cannot have their angles easily modified, nor their distances without physical of the monitor or the user's position. When testing different control schemes, participants struggled with more traditional control schemes (i.e. multiple buttons) but responded more positively to voice commands and simpler motion controls combined with 1 button press. This is noteworthy as VR control schemes are a newer concept and will be less familiar with the target user group due to unfamiliarity with the technology. As well as the particulars of different configurations and variables, the interviews conducted with participants and comments recorded are also important in identifying usability needs. The prototype software discussed and presented in the second research stage was chosen and designed based on the recommendation and desire of participants wishing to be able to read and view media again. The feedback gained from the usability testing and questionnaire also highlight participant opinions on the device tested itself and whether participants questioned could see themselves utilising such a device daily. Feedback suggested participants desire and would like to use a device like this for every day accessibility providing improvements were made to ergonomics, such as the heavy weight of the device, yielding better comfort, which is an aspect that can already be addressed with newer devices.

7.2.1 Limitations Overview

A recap of limitations helps to highlight areas for further investigation and improvements upon the system. Detailed specifics of the limitations of the first study can be referred to in section 5.3 as well as the limitations of charts in section 4.7. The literature covered combined with review and testimonies of participants involved in this study highlight that there are still some shortcomings to the overall usability of VST HMD devices. Most repeated is the weight of many of these systems, where extended periods of use can cause discomfort and fatigue. Although this is improving through each new iteration of HMD devices, currently, it would be difficult to expect a VR HMD to fully replace current LVA systems at their current sizes. Although OST devices are a step in the right direction, they present a trade-off between functionality and comfort, and OST devices have many shortcomings making them difficult to recommend, such as lower FoV. The literature suggests that there is a lack of uniformity between studies which will likely affect the speed of recognition and adoption towards these systems. One of the hurdles this study faced was accessing the visual impairment community as well as validating their conditions, as optometry equipment was not available it was not possible to use medically validated methods to measure visual acuity levels. This led to a smaller sample size, particularly in the usability study, where additional participants would have produced more accurate data. Unfortunately, this study took place during the 2019 Covid pandemic which made accessing services impossible as well as users, particularly elderly groups that were vulnerable. This halted subsequent studies and correspondences with users. As VR HMDs are constantly improving the types of headsets used in studies can quickly become obsolete, as was particularly seen in the first research stage but to a lesser extent in the second one. Although using earlier headsets provide us with a baseline for improvement, it should be expected that newer headsets with their decreased weight, improved visual clarity and pixel density, and more advanced control methods would produce not only higher acuity levels but also provide more variables to test within the context of usability.

7.3 Final Notes

These findings overall, and the analysis of said findings, sufficiently answer this project's research aims in identifying where improvements to visual acuity or reading ability can be achieved with a VR device for persons of severe visual impairments, and the usability needs for effective utilisation of a VR HMD as a visual aid replacement.

In the future it would be desirable to conduct an investigation with more granularity specific groups and conditions, allowing the observation of the effects of specific enhancements designed to benefit particular conditions (i.e. how field of vision affects tunnel vision/macular). A new study focusing on this was planned to commence early 2020 with agreed collaboration from the NHS New Cross Hospital's Ophthalmology department (The Royal Wolverhampton NHS Trust 2016), but was postponed due to the global pandemic and is on hold until the situation is more desirable. Furthermore, due to the extreme low visual ability of the participants, some further tests were not completed due to the tests themselves being designed for an expected higher acuity level, such as testing for Depth of Perception being omitted as only 2 participants (0.48% of the test group) produced any results. Another noteworthy test that was admitted was an extension of the MNRead Acuity Chart for speed reading, where the additional chart included far smaller letters. The chart was only able to be read by 1 participant at 0.5m, but at 0.25m 3 out of 5 participants could produce a score with the VR chart but not the physical, while the remaining 2 participants could only produce a score with the physical and not the VR version. There is not a large enough sample of data for this data to impact the overall results, so it was omitted, but it loosely follows the same conclusions persistent throughout the other tests. This may have been mitigated with a wider range of distances allowed within the tests, although there is a risk of quality degradation with VR headsets at longer distances and much shorter distances, as well as simulated levels of depths becoming less effective. Future work is already underway in the process of testing similar applications and visual interactions such as sight-seeing, navigation, and digital shopping.

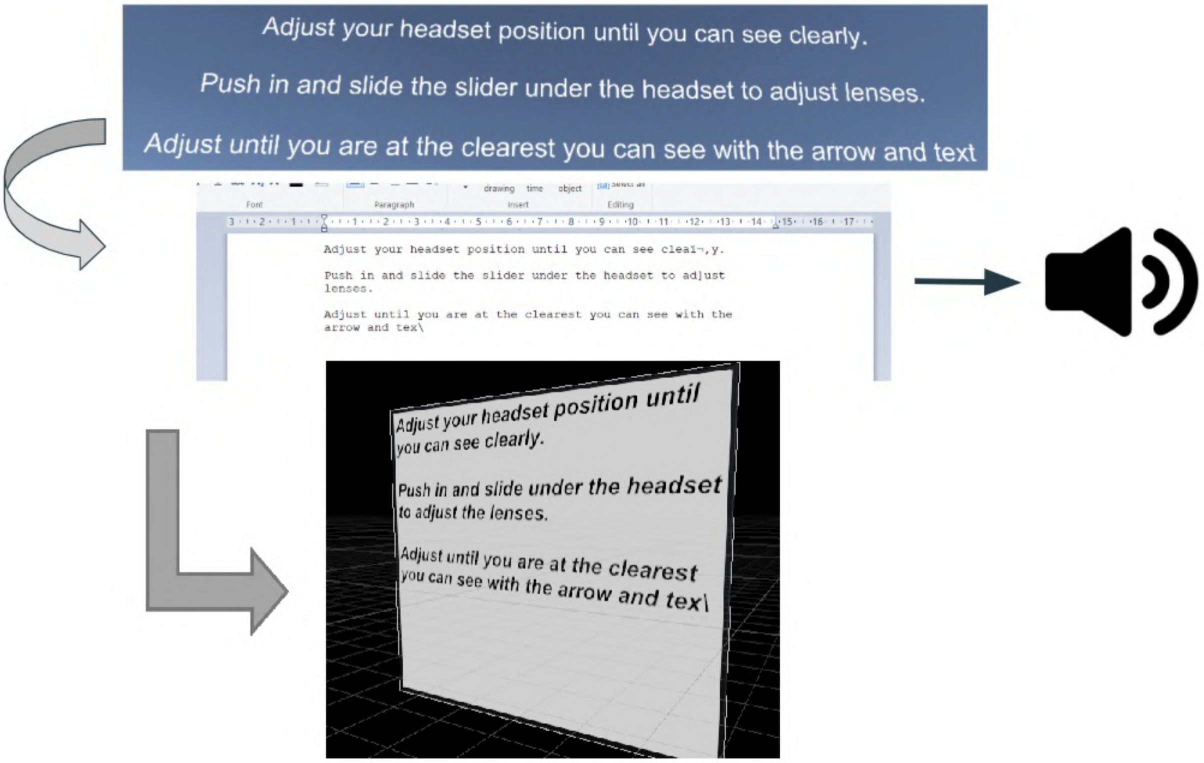
The presented contributions serve as a research platform for further developments in the VR accessibility field as well as the improvement of specialist software. In the future it is likely that VR devices will be capable of delivering advanced accessibility techniques and features to disabled persons, and will allow them to experience and interact with technology in a way they have not yet been able to do with traditional 2D devices.

It is the hope of this research scholar that this project helps to highlight the need for such technologies to improve the lives of persons with severe visual impairments. From the many interactions across different individuals that have volunteered to help and shed light into the discoveries and issues presented, it is clear that, if utilised properly, VR technologies can enrich and provide people with content and practical solutions to problems that they are either no longer to or have not been capable of achieving themselves due to their visual disabilities. If fully recognised, it is likely that VR devices become the next stage to providing people of visual disabilities with high levels of visual assistance, and already it has been seen with individual cases how these devices can impact an individual’s life for the better.

7.4 Future Work

Future work aims to integrate image processing techniques, specifically OCR (optical character recognition) as a component into the software, allowing VR headsets with camera capabilities to scan real-world text into a digital reader so users can translate real-world text into an environment that they can read with their own accessibility requirements independently (See Figure 7.1). This will transition the prototype over from primarily leisure activities of reading and video viewing, into a fully functioning accessibility tool that will have wider use for a much larger pool of users. Finally, the integration of image processing techniques will allow for the integration of AR technologies, such as overlaying enhancements over video see-through and translated visuals. Although this goes beyond the scope of a VR reader and video viewer, it highlights the possibilities for what this technology is capable of.

The successful integration of XR (Extended Reality) (Kaitlyn 2017) techniques would allow for an all-in-one device that is capable of presenting accessible content in a virtual environment, enhancing real-world images through AR and image processing techniques, and deliver rich experiences that are normally inaccessible to persons of severe visual impairments. These techniques would be the foundation for further innovations, such as sight training, therapy, connecting with family, virtual shopping, and other such possibilities. It is down to developers and designers of emerging tech-



Adjust your headset position until you can see clearly.

Push in and slide the slider under the headset to adjust lenses.

Adjust until you are at the clearest you can see with the arrow and text

Adjust your headset position until you can see clea¬,y.

Push in and slide the slider under the headset to adjust lenses.

Adjust until you are at the clearest you can see with the arrow and tex\

Adjust your headset position until you can see clearly.

Push in and slide under the headset to adjust the lenses.

Adjust until you are at the clearest you can see with the arrow and tex\

Figure 7.1: An early test concept for a OCR system for VR devices that scans for text, transcribes it into a text file, which can be read to output both audio and insert text into the prototype text reader.

nology in this area to fully realise the potential these type of visual based equipment can bring.

Additionally, further investigation into typography methods and the effect on vision is required to fully understand and deliver accessible text to text-based systems. Although briefly covered in this research, some of the tests conducted only take a surface level towards typography. Another consideration is how text is affected by different cultures and languages, as this study has only covered visual disability communities at a national level within the UK, but there are additional challenges when looking at visual impairments at a global level, including changing alphabets, economic and education considerations, and so on. Once a full working version of the prototype software has been developed then multilingual trialling is planned, as even aspects such as voice recognition and text to speech need additional considerations when working beyond one's native language.

This research has additionally contributed towards a Patent placed by Beacon Centre for the Blind for a VR HMD designed specifically for visual impairments, and it is this researcher's hope that this technology is developed and promoted in the hopes of improving the lives of people with severe visual impairments and the accessibility community.

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Appendix A

The consent forms used in each study conducted.

UNIVERSITY OF
WOLVERHAMPTON

Research Consent Form Participant ID:

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Please take the time to read this form carefully and to understand any accompanying information.

Research Project Title

Using State of the Art Technology for Improving the Lives of Severely Visual Disabled People

Researcher

Mr Kurtis Weir

Experiment Purpose

The purpose of this work is to observe and examine the differences in visual acuity between a virtual environment and a physical setup. This work hopes to record a measured difference between virtual environments and physical, and show comparative data that will aid in the development and production of devices that will be able to aid those that are visually impaired.

Participant Recruitment and Selection

Severely visually impaired users (Not fully blind). There will be no participants which are considered minors within the UK (under 18 years of age) and no participant which is not sound of mind will be recruited.

Procedure

Each session will require about 20-60 minutes of your time. You will be briefly interviewed or given a questionnaire before each test to describe and determine your visual ability and medical history. After this you will potentially be given a virtual reality headset and will be asked to go through tests via a simulation application displayed within the headset. These tests will be accompanied by verbal instructions and we will monitor and record your reactions and progress to the tests. Alternatively, a physical setup may be produced in which you will be asked to identify text or objects. Finally, a post study interview or questionnaire will take place in order for you to give the investigator feedback and clarity on some of the matters that took place during the test. You will, if required and consent, be recorded both verbally and by video.

Data Collection

Verbal interview data accompanied by video (and audio) recording of the virtual reality head tracking and webcam recording of the participant's movements may take place. This will be done only if a consent is given by the participant.

Data Archiving/Destruction

All data will be kept secure, encrypted and stored within a secure online server and backed up on an external hard drive. This will be destroyed within a specified grace period after the conclusion of the work, typically being 5 years after the data has been recorded. Scientific publications such as journal or conference articles summarising the data may be created.

Confidentiality

Confidentiality and participant anonymity will be strictly maintained. All information gathered will be used for statistical analysis only and no names or other identifying characteristics will be stated in the final or any other reports or publications. Upon publication of images, video or audio, containing participant features, a full consent will have been taken from the participant.

Likelihood of Discomfort

There is a marginal likelihood of discomfort associated with participation. On occasion prolonged use of VR equipment can produce slight nausea. If at any time you feel that the virtual reality headset is creating discomfort, please notify the investigator and action will be taken immediately.

Researcher Profiles

Kurtis Weir is a researcher in the School of Mathematics and Computer Science at the University ofWolverhampton. The research collected here aims to provide insight into building assisting tools for people with visual impairment, and will contribute towards ongoing PhD research. He is supervised by Professor Amar Affoun [email address redacted], Dr Vinita Nahar [email address redacted] and Dr Fernando Loizides [email address redacted]. Kurtis' contact email is:[email address redacted]

Finding out about Results

The Participants can find out the results of the study by contacting the researcher 6 months after the experiment has concluded.

This consent form has been approved by the Faculty of Science and Engineering Ethics Committee (FSEEC).

The following is a list of your rights.

As a research participant, you have the right:

- To be treated with respect and dignity in every phase of the research.
- To be fully and clearly informed of all aspects of the research prior to becoming involved in it.
- To enter into clear, informed, and written agreement with the researcher prior to becoming involved in the activity. You should sense NO pressure, explicit or otherwise, to sign this contract.
- To choose explicitly whether or not you will become involved in the research under the clearly stated provision that refusal to participate or the choice to withdraw during the activity can be made at any time without penalty to you.
- To be treated with honesty, integrity, openness, and straightforwardness in all phases of the research, including a guarantee that you will not unknowingly be deceived during the course of the research.
- To demand proof that an independent and competent ethical review of human rights and protections associated with the research has been successfully completed.
- To demand complete personal confidentiality and privacy in any reports of the research unless you have explicitly negotiated otherwise.
- To expect that your personal welfare is protected and promoted in all phases of the research, including knowing that no harm will come to you.
- To be informed of the results of the research study in a language you understand.
- To be offered a range of research studies or experiences from which to select, if the research is part of fulfilling your educational or employment goals.

The contents of this bill are based on the Canadian Psychological Association's Code of Ethics for Psychologists, 1991. The complete CPA Ethical Code can be found in Canadian Psychological Association *"Companion manual for the Canadian Code of Ethics for Psychologists"* (1992).

Agreement

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to take part as a participant. In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to not answer specific items or questions in interviews or on questionnaires. You are free to withdraw from the study at any time without penalty. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. If you have further questions concerning matters related to this research, please contact the researcher.

I agree to (please tick appropriately what you consent to)

Video ☐

Audio ☐

Images ☐

can be recorded for the use of data collection within this test.

I agree to (please tick appropriately what you consent to)

Video ☐

Audio ☐

Images ☐

that have been recorded to be used in publications that may arise from the findings.

'I consent to the processing of my personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential, unless otherwise stated.'

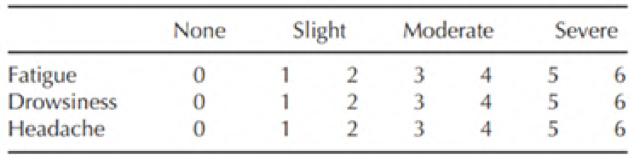
Participant	Date
Investigator/Witness	Date

A copy of this consent form is to be given to you to keep for your records and reference.

Appendix B

The Questionnaire used in software user tests

Test Group 4 Questionnaire:



	None	Slight		Moderate		Severe	
Fatigue	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Headache	0	1	2	3	4	5	6

1) How clear were you able to see within the headset?

Very Unclear	Unclear	Average	Clear	Very Clear

2) How comfortable was the headset to wear?

Very Uncomfortable	Uncomfortable	Average	Comfortable	Very Comfortable

3) How easy was the headset to use?

Very Difficult	Difficult	Average	Easy	Very Easy

4) How easy was the headset to navigate using the controllers?

Very Difficult	Difficult	Average	Easy	Very Easy

5) Did you find the controllers and headset combined easy to understand?

Very Difficult	Difficult	Average	Easy	Very Easy

6) Did you find the voice commands to be useful over pressing buttons?

Disagree	Somewhat Disagree	Average	Somewhat Agree	Agree

7) Do you think you would need the help of a technical person to use this headset?

Disagree	Somewhat Disagree	Average	Somewhat Agree	Agree

8) Do you think something like what you tried today would be helpful to you?

Disagree	Somewhat Disagree	Average	Somewhat Agree	Agree

9) Would you wear a headset daily if they were improved and could help you to see?

Disagree	Somewhat Disagree	Average	Somewhat Agree	Agree

10) How likely could you see yourself using a VR headset as a visual aid in the future?

Very Unlikely	Unlikely	Average	Likely	Very likely

Open questions:

Was there any particular feature you liked the most?

What would you want to use this headset for the most? (e.g. reading, videos, shopping, relaxation, sight-seeing)

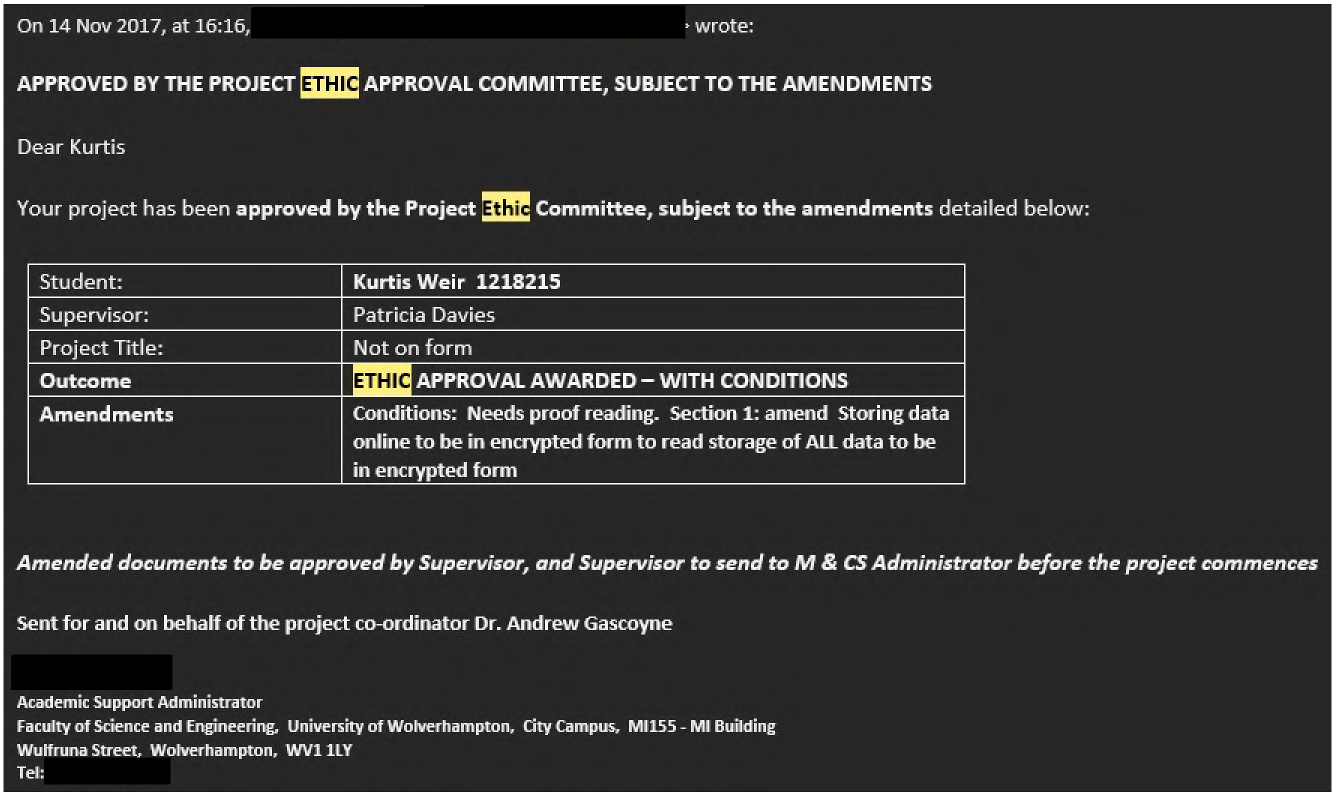
Is there anything else you would want added to this headset, or wish you could do with it?

How would you want to control a headset like this? (e.g. controllers, hand tracking, voice commands, eye tracking)

Could you see something like this headset replacing many other assistive tools that you currently use or know of, or do you think this type of setup is more for specific tasks?

Appendix C

Ethical Approval Evidence A



On 14 Nov 2017, at 16:16, [redacted] wrote:

APPROVED BY THE PROJECT ETHIC APPROVAL COMMITTEE, SUBJECT TO THE AMENDMENTS

Dear Kurtis

Your project has been **approved by the Project Ethic Committee, subject to the amendments** detailed below:

Student:	**Kurtis Weir 1218215**
Supervisor:	Patricia Davies
Project Title:	Not on form
Outcome	**ETHIC APPROVAL AWARDED – WITH CONDITIONS**
Amendments	Conditions: Needs proof reading. Section 1: amend Storing data online to be in encrypted form to read storage of ALL data to be in encrypted form

Amended documents to be approved by Supervisor, and Supervisor to send to M & CS Administrator before the project commences

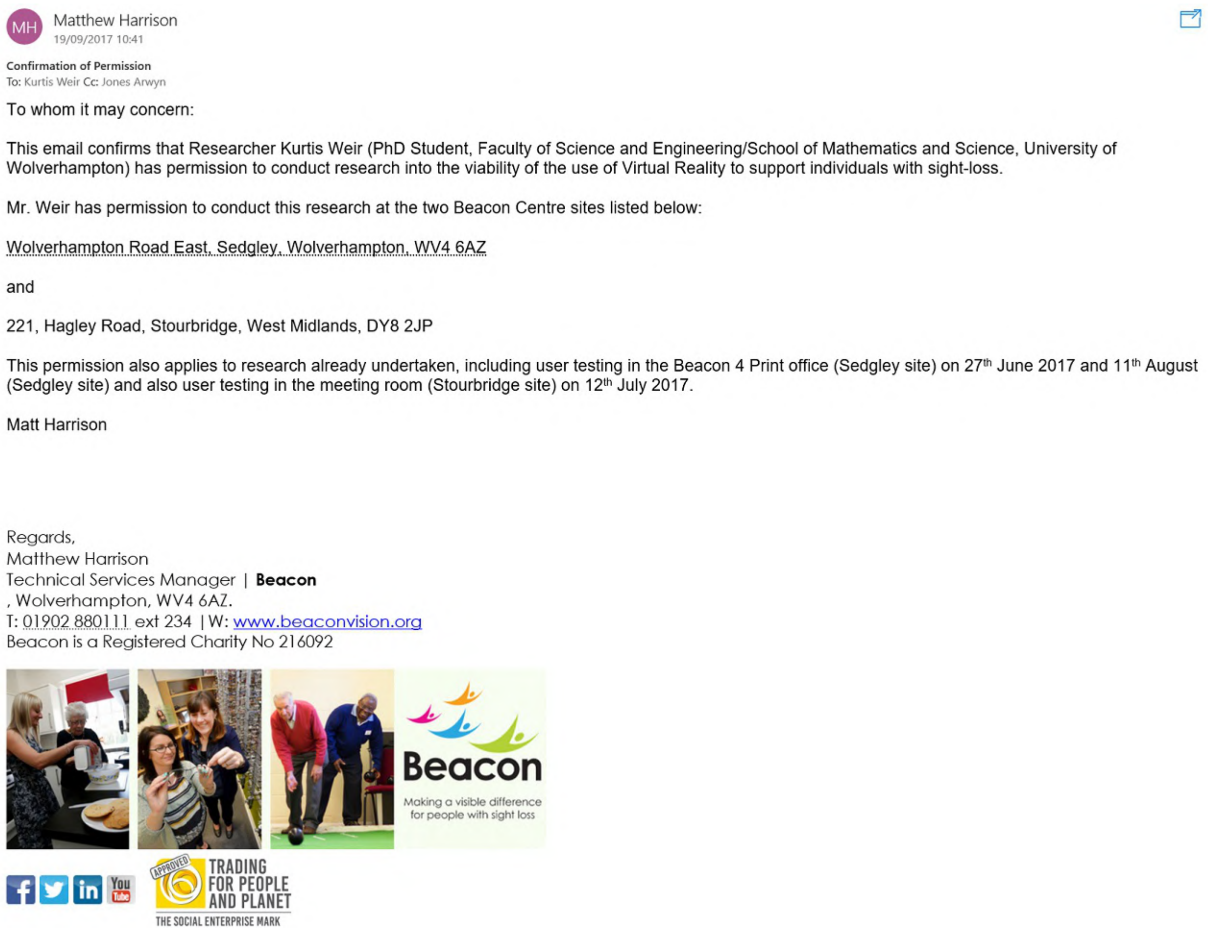
Sent for and on behalf of the project co-ordinator Dr. Andrew Gascoyne

[redacted]

Academic Support Administrator
Faculty of Science and Engineering, University of Wolverhampton, City Campus, MI155 - MI Building
Wulfruna Street, Wolverhampton, WV1 1LY
Tel: [redacted]

Appendix D

Ethical Approval Evidence B



Matthew Harrison
19/09/2017 10:41

Confirmation of Permission
To: Kurtis Weir Cc: Jones Arwyn

To whom it may concern:

This email confirms that Researcher Kurtis Weir (PhD Student, Faculty of Science and Engineering/School of Mathematics and Science, University of Wolverhampton) has permission to conduct research into the viability of the use of Virtual Reality to support individuals with sight-loss.

Mr. Weir has permission to conduct this research at the two Beacon Centre sites listed below:

Wolverhampton Road East, Sedgley, Wolverhampton, WV4 6AZ

and

221, Hagley Road, Stourbridge, West Midlands, DY8 2JP

This permission also applies to research already undertaken, including user testing in the Beacon 4 Print office (Sedgley site) on 27th June 2017 and 11th August (Sedgley site) and also user testing in the meeting room (Stourbridge site) on 12th July 2017.

Matt Harrison

Regards,
Matthew Harrison
Technical Services Manager | **Beacon**
, Wolverhampton, WV4 6AZ.
T: 01902 880111 ext 234 | W: www.beaconvision.org
Beacon is a Registered Charity No 216092

Appendix E

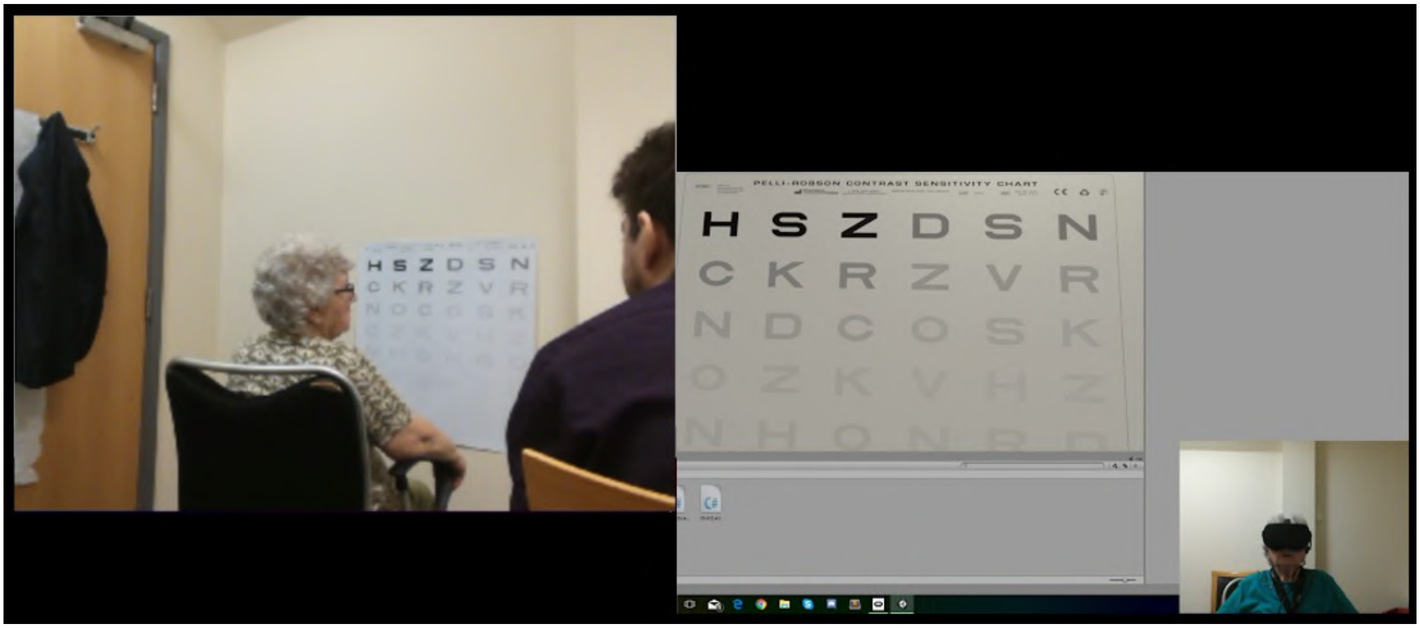
The then current Mayor of Dudley Dave Tyler testing the developed VR software at Beacon Centre for the Blind.

Appendix F

Beacon Centre for the Blind's former Technology Innovation Manager wearing and testing the VR software alongside Researcher Kurtis Weir

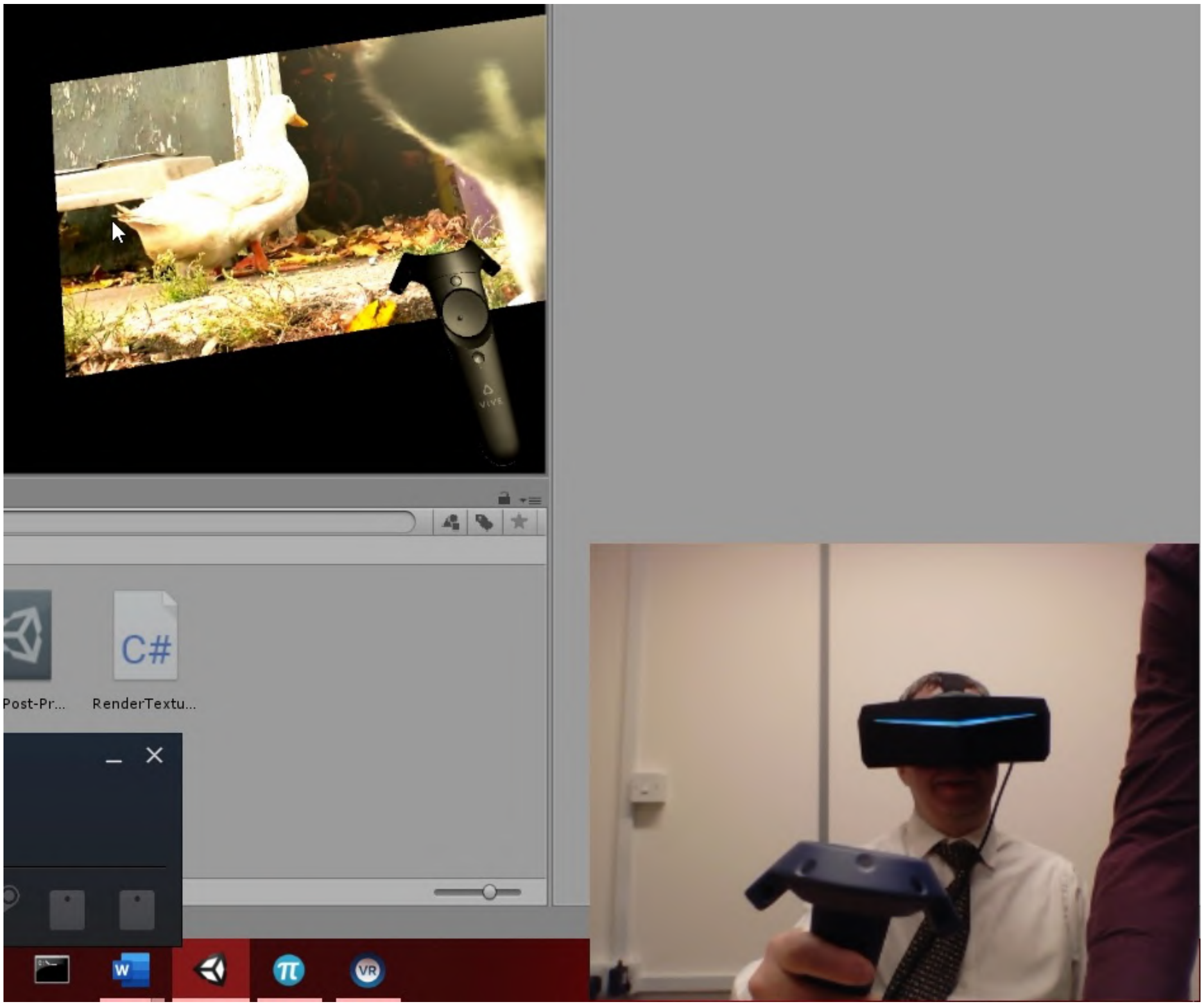
Appendix G

A participant conducting the Contrast Detection test



Appendix H

A participant testing the prototype software and positioning a virtual video to their preferences


C#
Post-Pr...
RenderTextu...
VR

Appendix I

The Pimax Headset and 2 Vive Wands used in the prototype software testing.


VIVE
VIVE

Appendix J

The Oculus CV1 kit used in the first research stage.