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I See Therefore I Read: Improving the Reading Capabilities of Individuals with Visual Disabilities through Immersive Virtual Reality

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Abstract We aim to help improve the quality of life of people with visual disabilities through the application of emerging technologies. Our current research investigates the viability of Virtual Reality (VR) as an aid for persons with visual disabilities. In this article, we explore the potential of VR assisted reading. We investigate the reading effects of VR equipment on persons with visual disabilities by utilising variations of standardised optometry-informed reading tests conducted across 24 participants. Test results uncovered that, when comparing a worn VR head-mounted display (HMD) to physical unaided tests, results within a HMD scaled better at closer distances while unaided tests scaled better with further distances. Using the findings collected and requirements elicited from participants, a prototype document reader was developed for reading text within a VR immersed 3D environment, allowing low vision users to customise and configure accessibility features for enhanced reading. This software was tested with 11 new participants alongside user evaluations, allowing us to discover how users perceived text best within our 3D virtual environments, and what features and techniques are required to evolve this accessibility tool further. The user test reported an overwhelmingly positive response to our tool as a feasible reading aid, allowing persons who could not engage (or, due to the difficulty, refusing to) in the reading of material to do so. We also register some limitations and areas for improvement, such as a need for non-functional requirements to be improved, and the aesthetics of our design to be improved going forward.

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Code availability: Source code of our prototype software is not available, but use of our test scenes can be requested. This work presents all testing variables and conditions to allow for reproduction.

1 Introduction and Motivation

We are concerned with the lack of assistive technology available compared to the increasing number of people recognised as having a visual impairment. Our private encounters[1] with leading tech companies have returned

[1] Due to confidentiality agreements we are not permitted to name or identify the companies by name or features. We

a general consensus that commercial products advertised specifically for visual disabilities do not constitute a substantial enough return on investment for mainstream adoption due to the limited market. We note that 'this market' numbers in the millions, yet it is still a challenge to provide assistance to these users. To put things into perspective, studies reported that in the UK alone there were 513,000 reported cases of Macular Degeneration in 2012 (a degenerative, non-reversible disease which causes major central vision loss)[42], by 2018 this increased to nearly 1.5 million people affected by Macular Degeneration in the UK[57], in the US 11 million people, and 'Estimates of the global cost of visual impairment due to age-related macular degeneration is $343,000,000,000 including $255,000,000,000 in direct health care costs.'[14].

Despite this need, there is currently very little evidence of updated, affordable, and commercially available assistive hardware and software that is making its way to both the homes of people with visual disabilities as well as care facilities for those with visual impairments. Many people with visual disabilities still rely on magnifying glasses to read, screen reader software to help them read and navigate menus, and caregivers or force feedback (basic touch) to navigate around environments, with a reliance on equipment such as walking canes or railings. Assistive apparatuses that have been present and dominant for decades without significant evolution from the advances of digital technology point to a gap in opportunity which has not yet been executed well; namely, successfully integrating 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. Unfortunately, to many low vision users smart phones run into the same issues as screen readers and screen magnification tools[4,18,70], such as partial viewing causing a loss of context[32]. Many smart phones rely heavily on web-based content as well, where web-based content has been scrutinized for failing to meet accessibility requirements[32]. In our studies with 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, were not interested, or did not think a smart phone was helpful to them. Some participants noted that they have tried smart phones in the past, but due to their very limited vision they were not able to see the screen comfortably and had not attempted further use.

In the work presented in this article we use commercially available emerging technology which has the potential to act as the catalyst to address this gap. Noting that Virtual Reality (VR) advancements have seen dramatic improvement (after the failed hype of the 1990's[33][68]), we capitalise on the opportunity to test their potential to assist our target audience. We ran optometry inspired tests to study and investigate the visual benefits of VR over natural unassisted vision for people with visual disabilities across 24 participants. In doing so we record where benefits are present while eliciting requirements for software development alongside hardware considerations. Using the data collected from this exploratory study, a follow-up prototype VR reader was developed and tested with 11 participants to determine software usability, feedback, and to gather data on how visually impaired participants would use a virtual reader that is represented in 3D space, and what accessibility features they preferred. Participants asked for the ability to read independently within VR, and we have implemented this in prototype software.

When compared to existing equipment 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 been realised thus far, and could vastly improve accessibility techniques to allow disabled persons to access information and technology in ways not previously achieved.

Our research question was 'can we identify where (if so) VR Head Mounted Displays assist in the reading ability of those with visual disabilities while worn?'. We then subdivided these question with regards to the (a) visual acuity relating to letter recognition, (b) reading ability [speed], (c) reading ability [accuracy], (d) colour reading, and (e) effects of brightness and contrast.

By identifying benefits we then analyse the findings to inform the construction of a VR document reader specifically for those with visual disabilities, as well as presenting our results for researchers to build upon further. We also report the limitations of current hardware and point to the development requirements of the bespoke technology for maximising the potential of VR Head Mounted Displays (HMDs) for our specific user group.

Our findings uncover where this emerging technology benefits and is able to assist visually impaired users, especially since we are using devices not designed for

can however disclose that the companies mentioned employ over 100,000 employees each and are related to the creation of hardware and software solutions.

any kind of visual enhancement. Between VR tests, VR performed better when tested at closer distances compared to further away, particularly with letter recognition. If these devices are providing increased clarity for users with visual disabilities under certain conditions, it serves as evidence and justification for specialised software and equipment built upon this existing technology to 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 article is organised as follows: Section 2 introduces to the reader the different topic areas that current and previous work has produced. These include areas such as the conditions of patients, previous vision aids and current emerging technology surrounding VR and AR systems. Section 3 covers the testing methods used and equipment. This includes test details, procedure, and results. Section 4 presents our prototype software alongside user evaluations, profiles, and results. Section 5 concludes the article, giving our final summary of the research and future or related works currently being undertaken.

1.1 Visual Disabilities

Our research focuses around assisting individuals with visual impairments, low-vision (LV) users with very limited sight that fall under the classification of blindness[49]. 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[41]. Looking at the number of visual impairments world wide it is estimated that 2.2 billion people have some form of vision impairment[40], with 237 million of these falling under the category of 'moderate to severely' impaired[2]. Figure 1 helps to highlight the number of people that have 'moderate to severe' visual impairments, this research target group, as well as the importance of the number of people affected by severe visual impairments.

Within the classification of LV 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. shortsightedness), 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.

There are many different kinds of visual disabilities (See Figure 2 for examples) that distort vision in various ways and by various degrees. These complex conditions can be very difficult to manage with many missing adequate resolutions that can repair or supplement an individual's vision to a reasonable level, or to a level they desire. Regardless, 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. One of the more impressive technologies to come out in the last 5 years, VR headsets, is one such equipment we believe will revolutionise the way we look at accessibility.

2 Related Work

In order to situate the reader we will cover areas that both current and previous work has reported on within the multidisciplinary field of assistive technology relating to VR and AR work. In this section we begin by covering different medical conditions that the reader will come across during our work. We then introduce the technical content such as VR and Augmented Reality (AR). Finally, we present the evolution and recent research of assistive tools and devices for visual impairments.

2.1 Virtual and Augmented Reality

Virtual Reality is a relatively old concept compared to the contemporary advancements in consumer level available products[68]. 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[68]. Currently several types of Head-Mounted displays (HMD) exist 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, phone, or internally to the device. Popular VR headsets typically work by displaying a horizontal screen that splits visuals between the frontal left and right sides of the user's eyes, which are calibrated via lenses into creating stereoscopic 3D imagery, mimicking how the eyes would see realistic depth

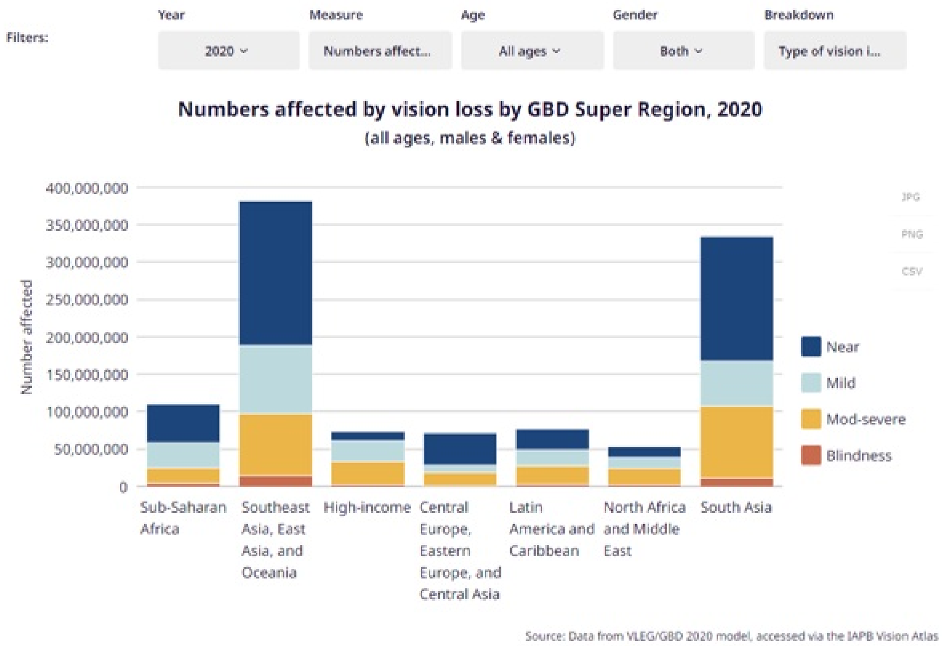

Fig. 1: The number of people affected by visual impairments by the Global Burden of Disease regional classification system, 2020 model (taken from [21]).

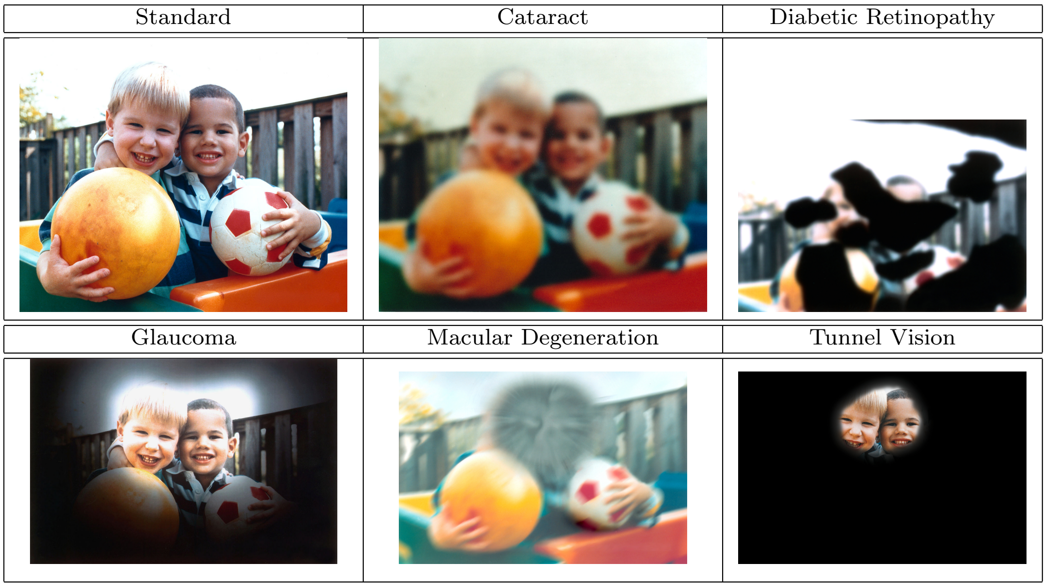

Fig. 2: Images of how different conditions may interfere with visuals (taken from[35]).

and 'tricking' the brain into perceiving realism[17]. Recently, the technique of using less processor intensive and portable means (such as mobile phones) as the VR HMD screen is gaining momentum[52], while keeping the same type of lens manipulation. This idea of projecting VR within a device is not a new one, and VR has had several attempts in the past but has failed due to technological limitations such as resolution, colour, and limited motion tracking[33]; limitations that are no longer blockades using contemporary advancements.

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[55]. 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[23], yet VR and AR are not necessarily exclusive, as elements from both can be combined for a more complete experience.

VR Devices & Capabilities

VR Devices have come a long way since their first proposed concept in 1966[61]. Once quite primitive in their capabilities, newer headsets are now able to push high levels of realistic imagery while immersing the user in realistic 3D stereoscopic visuals, emulating our natural perception. We are also seeing an improved focus on size and ergonomics, where the level of visual fidelity is being matched with smaller, more portable kits that are moving away from being tethered to a dedicated machine and are now capable of being portable. Although realistic depth and visuals are a key component of VR kits today, the interaction methods available with such devices have also been a focus point of improvement. Headsets are not only capable of rendering visuals that are observable through rotation of the head, coined as 3 Degrees of Freedom (DoF)[51], but also 6DoF where the user can dynamically move their head and have their position tracked alongside the visuals updated in a 3D space in real time. Adding to this, most modern VR kits also focus on motion controls[67,36,64], allowing for both the head and the hands of the user to be tracked either through external or internal cameras to the device and advanced gyroscope tracking. This allows for a complete immersive experience, where both the head and often hands are being tracked dynamically within a 3D space, with the headset updating visuals live to accommodate and simulate realistic movements taking place, as well as 3D audio to complete the experience.

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), 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. 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[39]. With VR the accommodative demand is at a fixed point, while the vergence demand is still dynamic, meaning that true depth is not achieved 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 our brain to adjust and ignore slight inaccuracies if the environment is convincing enough[12]. This uncanny effect helps keeps the illusion of realistic depth convincing, and may help to explain reported findings later in this research.

2.2 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 Thomas et al.[62] 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. Despite early emerging research, (we present such work 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, we begin by investigating the existing work, and where there is indication of potential, perhaps hindered by a lack of technological advancement or capability when the work was undertaken. We also scrutinise the existing aids which are used to gain understanding of benefits which we can adopt or improve on.

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.[29][28], function by displaying a video feed to the user's eyes typically by an HMD mounted with cameras. OST devices today are more akin to glasses but with overlay interfaces, such as the popular Microsoft HoloLens[30] or Google Glass[16]. OST technology combines a digital visual over the user's normal vision, allowing a more natural experience with possible enhancements[53]. In our work, we focus on the VST approach. We chose this method 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. We believe VST methods have matured enough in hardware capability, giving us the opportunity to use them successfully within our research and development to the level they may have been envisioned in previous iterations. A recent article published by a low vision 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[25]. 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.

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 LV visual impairments is AMD in older adults, usually resulting in significant loss of reading capability[34]. Results from a study showed that only 16% of 530 AMD patients could read prior to the use of a low vision aid, and 94% gained reading ability after utilising a low vision aid[34]. These patients made wide use of some form of magnifying lens, but closed-circuit television (CCTV) systems as a preferred low vision 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[34] remark that electronic vision aids can provide a high magnification alongside a wide field of view, while high optical magnifiers would restrict the field of view distinctly, making reading much harder to achieve. 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 our research contains tested participants with AMD, studies surrounding the effectiveness of LVAs are important in evaluating success.

Research conducted by Zhao, Szpiro and Azenkot[74] resulted in the creation of an application called ForeSee, which used a prototype of the Oculus Rift[37] 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 focused on AR techniques with a device that can search for and visually enhance objects to a LV user by looking for a placed tag and overlaying enhancements on a marked object through methods such as edge enhancement and contrast amplification, increasing clarity[75]. The tagging method used to highlight objects was done via Chilitags, a detection technique used primarily for AR applications[7]. 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[44]. 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 with reduced object search time. This research shows the 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 lower vision may struggle with, or even with older adults in general.

Further developments from Zhao et al.[71] looked at the creation of specialist tools for making VR more accessible to people with low vision. Utilising the Unity engine, a plugin and toolkit was developed that allows the user or developer 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 low vision 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.[72] examines the visual perceptions of low vision people on commercial AR glasses. Instead of utilising a VR headset like their previously mentioned works, they demonstrate whether an AR device can be used as an effective low vision aid. Comparing physical visual acuity charts without AR equipment to using AR equipment, results were mixed with low vision 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 an AR device could be used as a visual aid tool if considerations are appropriately met. A later study from Zhao et al.[73] also focuses on an AR solution, looking at designing AR visualizations to facilitate stair navigation. Designed upon the HoloLens[30], the tool tackles stair navigation for low vision 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 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.

Similar works in AR development have also looked at solutions for displaying text and image processing techniques. Research by Stearns et al.[59] investigates magnification using a HoloLens combined with a finger-worn camera. Hovering the finger above text would display a floating magnified panel within the HoloLens. This setup was exploratory and was used as the foundation for Stearns, Findlater and Froehlich's follow up research[60] 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 field of view, something also mentioned in previous studies that have built upon the HoloLens and, although modern VR setups have a much larger field of view, it is still worth considering the implications.

Work by Hwang and Peli[20] explore AR edge enhancement through the use of Google Glass[16]. 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. Three 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 field of view are described in their study as with the HoloLens within 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.

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% of them accessible against accessibility testing software[58]. Another author conducted similar research noting that accessibility rates had minimal improvements in a 4 year period[46]. A newer screen reader that allows impaired users to capture photos of inaccessible interfaces[19] and send them 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.

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[13]. 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 $9,995 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 majority of disability equipment, and specifically low vision equipment, is designed for use only by people with disabilities, often leading to a high cost and ultimately device abandonment[48] due to factors such as social stigma. Although there are some electronic low vision solutions today, they do not garner much attention or are uncommon due to large initial costs for specialised equipment paired with limited mainstream knowledge

A more affordable alternative is Samsung's Relumino, an application launched via Samsung approved smartphones that fits into the Samsung Gear VR headset helping the user to see through vision enhancing techniques[11]. 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[47], 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[24]. Very similar to Relumino is give-vision's sight+, 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[15]. Much like the Relumino team, it appears that give-vision 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. This may hint that there are some shortcomings to such a method, if multiple companies are looking into eyewear alternatives to HMD configurations after previously working on them.

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, we believe 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.

3 Study Methodology and Findings

In this section we describe the participant selection, the first series of tests that were conducted, and report their results. These tests aimed to investigate and report on the visual acuity of our participants with low vision within a VR environment compared to physical equivalents. Using these tests we were then able to determine whether the use of VR would, at the very least, not negatively impact the visual abilities of our users. Each test will detail specifications of specialised testing conditions and equipment, as well as a summary of data collected.

3.1 Participant Selection

Participants were selected based on their visual conditions and required to be LV persons, (registered legally blind) but not entirely blind. Table 1 lists the individual properties of the tested participants. Ethical approval was obtained prior to the testing. The investigators have also completed a Disclosure and Barring Service (DBS), which is a mandatory police background check procedure in the UK to allow one's work with underage or vulnerable participants.

3.2 Generic Study Setup

The selected VR headset for our initial study was the Oculus Rift CV1[37], as it was one of the original VR headsets available for computers with a high-quality tracking solution and resolution. Participants were allowed to choose whether to keep wearing any prescription glasses or additional eyewear (such as goggles to prevent high lights), 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. The Oculus Rift CV1 requires the user's eyes to be positioned centrally between both lenses of the HMD, which is determined by the user's Interpupillary Distance (IPD). During setup, the HMD must be appropriately adjusted around the user's head, and lenses calibrated to the correct IPD which is manipulated via a physical slider on the headset. Failure to achieve appropriate calibration results in imagery becoming out of focus and blurred, resulting in inaccurate measurements. Although many VR headsets have a built-in calibration tool, 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 by us that allowed for more control and options for monitoring participants (See Figure 3). 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 our charts and walls in the physical world, allowing us to adjust 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.

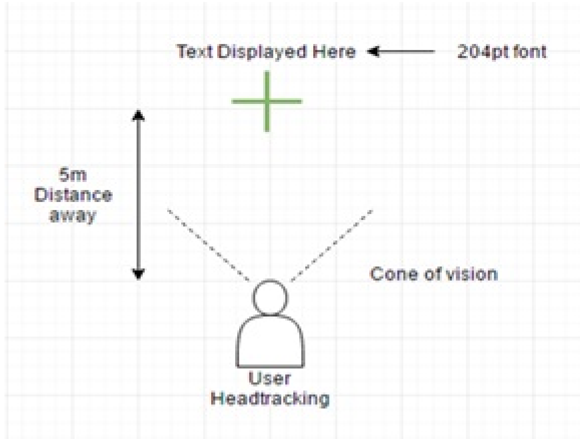

Fig. 3: The calibration scene. A green cross and two sentences of text are displayed to the user and adjusted based on their feedback to determine whether the headset is adjusted accurately.

Participants were permitted to take breaks at any point if needed and could leave at any point. If the device was removed prior to the completion of a test, then that specific test would be invalidated and repeated, and a re-calibration of the headset be required. A visual feed of what the participant could see was displayed via a 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 realignment of camera position and distance, is done by the facilitator via the machine connected through use of a keyboard. To ensure motion sickness was minimised, no movement was ever forced or simulated to the user with the location of the environment remaining static (sitting down) and displayed at a high and stable frame rate. From our tests with participants covering both studies, no kind of motion sickness was ever reported.

ID	Sex	Diagnosis	Aids Used
A1	F	Wet Macular, Cataracts, Lower vision(left) Charles Bonnet Syndrome	Mobile text-to-speech Magnifying glass
A2	F	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), Blurred(right) Tube inserted(left), Double vision(right) Extremely limited(left)	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 Photosensitivity, 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
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) iPad, iPhone, Siri, TV telescope Travel LED lighting, Apple watch
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) Phone, large print, Monocular, Anti-glare shades, Flat screen TV Large font computer, White cane, Tablet Reduced brightness monitor, Zoomed kindle
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	Salzmanns Nodular Degeneration Marfan syndrome, Cataract(right) Fixed lens inserted(left), Lower vision(right) Cataract removed(left)	Glasses Zoom software Tactile stickers

Table 1: Table of test group A's recorded diagnosis' and what aids they use.

A series of tests were selected to better measure and evaluate the visual acuity of participants within a VR-HMD environment and to compare them directly to a physical equivalent. Tests were created using the Unity engine and run via a laptop connected to the Oculus HMD. These established optometry tests were selected with collaboration and consultation with a registered optometrist, and needed to be able to produce meaningful comparative results between real-world and digital simulations of the same tests. Visual factors that were investigated were: Word Recognition, Letter Recognition, Contrast Detection, Reading Speed, and Colour Reading. All tests in VR are designed to follow their real-world equivalent along with any constraints, such as participants not moving their head within VR if they did not in the physical, and vice-versa. Although existing optometry tests were used as a baseline, the tests themselves are not conducted to standard specifications and instead followed our own altered rules due to their incompatibility with the majority of our extremely low-vision level participants. As such, these tests should not be seen as full recreated optometry tests, but instead inspired tests used purely as a comparative tool with similar existing tests that are already well established. 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. We measured and validated 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[27]. Each test or scene was designed to test a specific element of each participant's vision and split into its own section. By default testing rules, participants are expected to remain still with their head facing forward to read any charts within both VR and physical spaces. 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.

All tests were supervised by a test facilitator who conducted a short interview prior to each test that noted any particular needs or concerns for wearing the headset (e.g. sensitivity to bright lights). 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 activated and alignment for distances calibrated digitally by the test facilitator via a keyboard.

Tables shown 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, and Colour Blindness respectively. Table 5's P1/P2/P3 labels represent how many paragraphs a participant was able to complete, up to a total of 3 on the chart. Table 6 and 7 represent whether a participant correctly guessed each plate's number with a Yes/No. 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 between VR and physical results.

3.3 Letter Detection

This selected test is based on the LogMAR Visual Acuity Chart ETDRS (Early Treatment Diabetic Retinopathy Study)[65], 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, 5). 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 our 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 66cm at a pixel resolution of 3000x2883. Distance between the participant's head and chart was tested at both 1-meter and 0.5-meter distances. The selected size and distances used were determined based on the visual ability of our selected participant group, which was severely limited. Participants were asked to start reading each letter from the top left of the chart

Fig. 4: LogMAR Visual Acuity Chart.

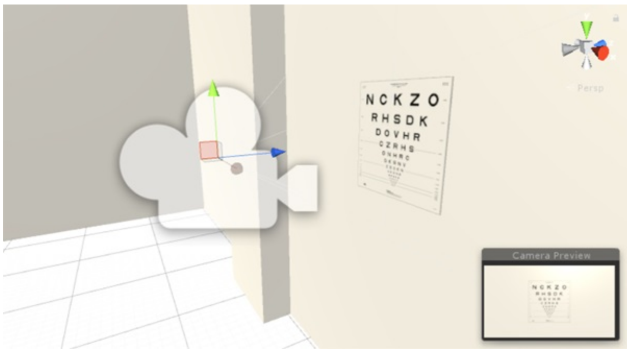

Fig. 5: LogMAR Visual Acuity Chart in Unity.

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, including letters missed, or letters that were misread. Under normal circumstances this test's scoring system would follow standard LogMAR Scoring (i.e. 12 letters read in order would produce a score of 0.250), but due to the low levels of vision our participant group had, resulting in both the chart to be enlarged and viewed at much closer distances than typical testing, the scoring has instead been simplified to letters counted to reduce similarity to standard measurements. All tests going forward have followed this same procedure. Instead, after each line is read at both distances (1m and 0.5m), a tally of all the correctly identified letters is compared between both VR and physical versions.

Table 2 shows how many letters were read by participants in both VR and Physical tests at either 1m or 0.5m distances. Letter detection reported the most significant increase in performance by participants in VR compared to the physical equivalent. At 0.5m, 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

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
A10	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

Table 2: Data sheet of each participant's results for the LogMAR chart (green highlights an increase in VR, red a decrease, and white no changes within 20%).

Wilcoxon Signed-Ranks Test indicated statistical significance with Z=2.925, p=.003 (effect size r=0.422, n=24). At 1m, 11 participants had an average increase of 214%, 9 participants had an average decrease of 36%, and 4 participants had no changes. This showed no statistical significance with Z=0.841, p=.400 (r=.121, n=24). Results show that the majority of users had an overall average increase of 181% between both tests within VR overall, but significant results were produced when participants were closer in the 0.5m test, with acuity decreasing at 1m distances. Interestingly, when isolating participant data to those that had central vision loss (n=10) at 0.5m, VR results were greater favoured, while 1m 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, p=.015 (n=10). At 1m 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, p=.683 (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.

3.4 Contrast Sensitivity

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[43].

Fig. 6: Pelli-Robson Contrast Sensitivity Chart.

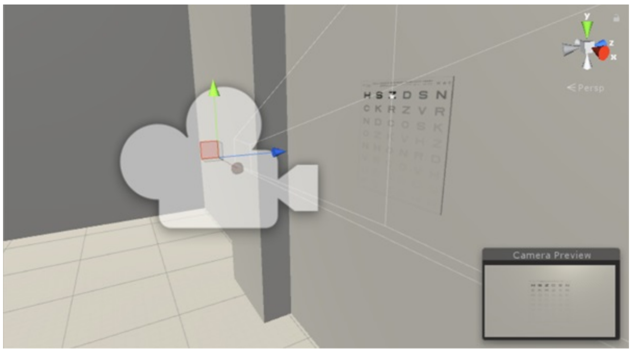

Fig. 7: Pelli-Robson Contrast Sensitivity Chart Unity Scene.

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 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 6, 7). 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 chart, at 66x66cm, 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. Again as with the EDTRS chart, the scoring system for this chart was modified due to very low vision levels. 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 3 shows how many letters were read by participants in both VR and Physical tests at either 1m or 0.5m distances.

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

Table 3: 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%).

Contrast detection results for VR were less successful than the letter detection test, despite the similarities between the tests. At 0.5m 9 participants had a mean increase in readability by 285%, 10 participants had a 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, p=.968 (r=0.006, n=24). At 1m, 7 participants had an increase of 86%, 12 participants had a decrease of 191%, 3 participants could not read anything at 1m in with or without VR, and 1 participant had no increase or decrease. This test showed statistical significance with z=1.970, p=.049 (r=-0.284, n=24). These results show that, again, results seem to be poorer at 1m distances rather than 0.5m, but VR results performing worse than the letter detection test. We note that further distances within a VR headset cause 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. We expect 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 0.5m 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 1m showed a larger 65/35% split, suggesting there may be some correlation between distance and contrast. Isolating central vision loss again, this test does not show the same pattern as the previous letter detection test. Out of 10 participants tested at 0.5m, 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, p=.674 (r=0.094, n=10). At 1m 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, p=.512 (r=-0.146, 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 1m distances than 0.5m, a common trend with results so far.

3.5 **Word Detection**

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[5]. This test requires the user to read from a given list of words displayed on a chart (See Figure 8, 9) to evaluate their visual acuity based on their performance.

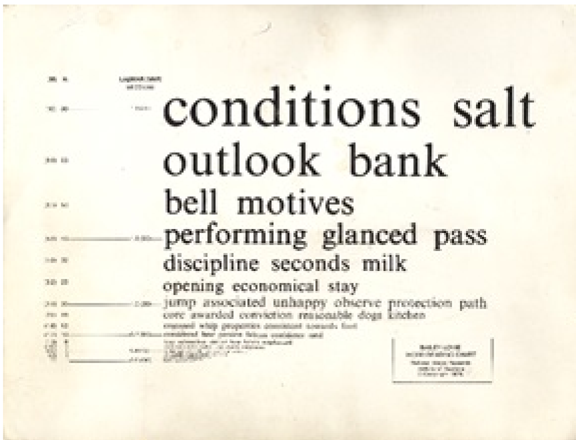

Fig. 8: Bailey-Lovie Word Reading Chart.

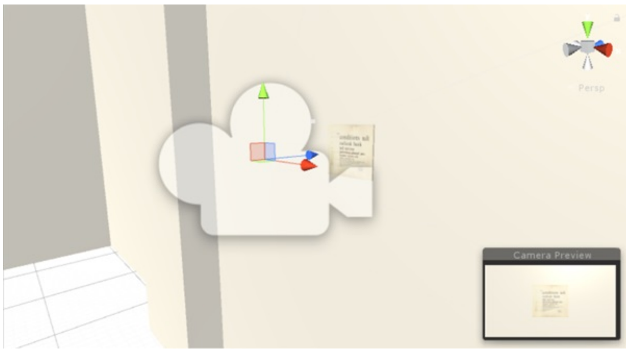

Fig. 9: Bailey-Lovie Word Chart Unity Scene.

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

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

Table 4: 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%).

Word accuracy results showed a smaller gap between the number of overall increases and decreases. At 0.25m 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, p=.764 (r=0.043, n=24). At 0.5m 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, p=.954 (r=-0.008, n=24). If we separate participants that had larger significant 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 0.25m distance. If we look at the same at 0.5m, 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 0.5m 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 performed worse in VR in this test, with no significant difference between distances read. At 0.5m 2 participants had an increase in VR, and at 0.25m only 3 participants. At 0.5m 4 had a decrease and 3 could not see anything, and at 0.25m 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 0.25m, and an 166.5% increase to a 350% decrease at 0.25m. These tests were not statistically significant with z=0.877, p=.380 (r=-0.196, n=10) at 0.25m, and z=1.160, p=.246 (r=-0.259, n=10) at 0.5m. The results for central vision loss participants are opposite to the letter detection results, with letters being almost unanimously easier to read within the letter detection test, while words were almost always 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 0.25m and 0.5m instead of the usual 0.5m and 1m, 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.

3.6 **Speed Reading**

The testing method used to determine each participant's reading speed is the MNRead Acuity Chart[26].

This examination chart relies on an observed environment where the participant is asked to read displayed sentences (See Figure 10, 11) 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. The chart is designed to replicate the reading of modern everyday passages, simulating a natural reading experience. Legge[26] 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

Fig. 10: MNRead Acuity Chart.

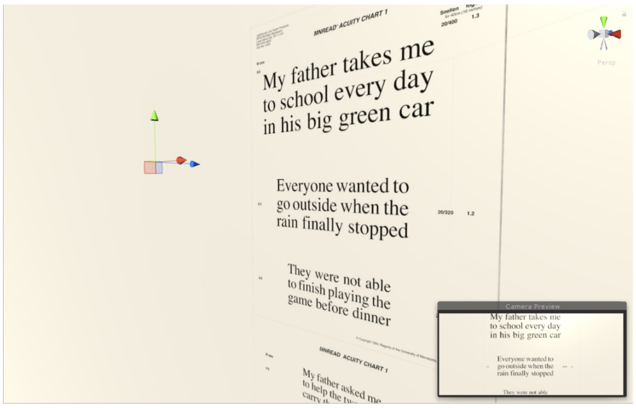

Fig. 11: MNRead Acuity Chart Unity Scene.

14 inches. Distance between the participant's head and chart was tested at 2 stages; 0.50m and 0.25m. 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 5 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.

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

Table 5: 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%).

Thus far, participant VR results at closer distances outperform further distances trialled. Participants struggled to complete this test, and as such 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 results show again that VR performance was worse at a further distance compared to a closer distance.

3.7 **Colour Blindness**

The test is the Ishihara Test for Color Blindness[9][6], selected by our optometrist for its wide familiarity and ease of use, 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 in them (See Figure 12, 13), some with just patterns, and determine whether they can correctly identify each number or shape. 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).

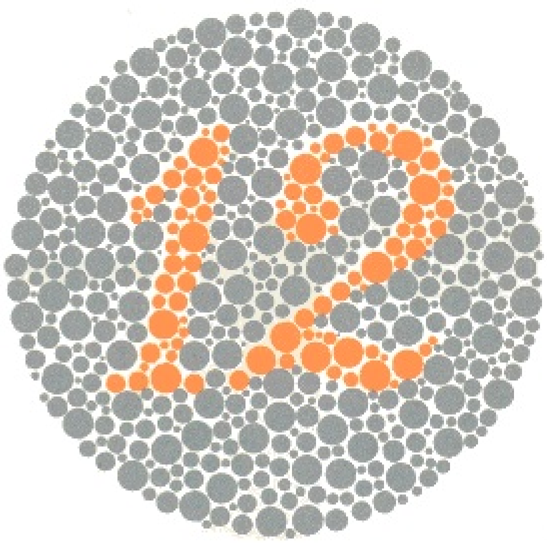

Fig. 12: Ishihara Color Plate 12.

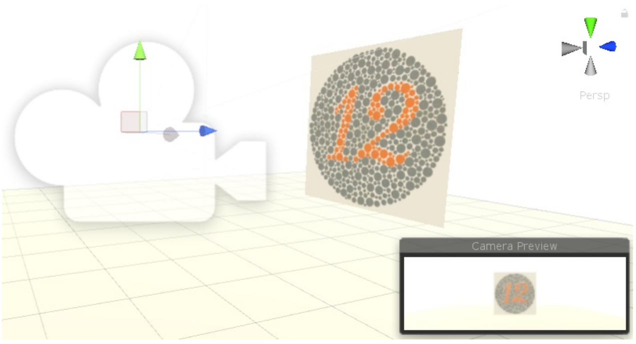

Fig. 13: Ishihara Color Plate 12 Unity Scene.

Each plate was printed on a reinforced matt coated paper at standard A4 size, to prevent glare from lighting. This test, compared to our 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 us to observe and record 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.

Tables 6 and 7 show a data sheet 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 our test group's overall visual acuity was too limited to perform this test accurately, 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 to us originally, as in preliminary tests participants gave us very strong verbal reactions to colour identification, commenting that colours were very vibrant and stood out compared to their normal vision, yet results showed no significant difference during testing.

3.8 Summary

This study explored the visual capabilities on a selected VR headset through a user study of 24 LV participants. Overall our findings showed mixed results between reading performances in VR compared to physical equivalents. While some of the participants showed an increase in visual acuity, others with either the same,

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 6: 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).

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 7: 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).

similar, or differing conditions did not show improvement. Results show a pattern in that VR results were better at closer distances when compared to VR results at longer distances. There is statistical evidence to show that physical space performs better than VR when detecting contrast at a distance (1 meter), but this finding is not replicated when we isolate our participants with macular degeneration specifically. Otherwise results did not show any statistical significance between other tests, suggesting that a qualitative approach may be more effective in identifying why specific individuals, with particular conditions, may perform better or worse. We also note that, based on the VR headset used, the resolution of the HMD will naturally produce blurring, or pixelation, for letters at further distances, and the HMD used in this study had a lower resolution compared to newer ones available now. Newer headsets with higher resolutions would likely improve these results in favour of the VR environment, something we suggest in Section 4's summary following the use of a newer headset. Our first study provided the preliminary evidence that LV persons could benefit from a typical VR headset, and it's findings were used to inform our second study; the creation of the first VR accessibility e-reader.

The next section details our software prototype developed based on the findings from this section and study.

4 Software Prototype and Testing

After observing participant reactions and analysing results from our exploratory study, we realised that some participants with 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, but 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 wasn't perfect. It is worth emphasising that the equipment we used (the Oculus CV1) was not designed for visual disabilities nor were any enhancements made to the device or the software we were running.

As per our participant's requests, a text reader prototype was developed to look at 2 focus areas following the results of our exploratory 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 different headset with a wider field of view and a high resolution; would reactions be similar to our previous study with an older headset, or would there be any significant changes in responses? This study is more qualitative in nature, as we desired direct feedback through a iterative design process.

Prior to development, we looked through both research and what is currently available alongside 3 main VR software marketplaces and noted that no storefront supported accessibility features of any kind, nor did they promote any, and no accessibility reading applications currently exist available through these digital stores (Oculus[37], Steam[38], Microsoft Store[31]).

4.1 Software Prototype

The application discussed was developed in the Unity engine and was run via a laptop, the Pimax 5K Plus VR[45] HMD, and Vive Wand controllers. A detailed explanation of the application can be found in[69]. The application is designed to work alongside most common PC VR devices, and a machine that supports the minimum specifications for VR. The prototype allows the user to insert text files into the application to be transcribed into our digital reader. The software displays a calibration scene for the user, and then allows them to observe a digital VR reader 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 our application's pilot test our digital reader contains 5 example books to read from with the ability to manipulate the reader in different ways to tailor the viewing experience.

The advantage VR has over traditional accessibility solutions, as well as digital reading solutions, is that the rendered environment can be fully manipulated with any number of benefits while also being weightless and taking no physical space. Many older accessibility devices are large, cumbersome, expensive, and restricted in their functionality[66,50,1,22,56], and although we are seeing newer accessibility technologies that are smaller factor, many are not available for consumer purchase and if so their cost are often a barrier to adoption. Large television sets and monitors, for example, take up a lot of physical room and the user can be restricted with their viewing angles and positioning. On the opposite side, more modern solutions to accessibility such as mobile phones are great multi-purpose tools, but still suffer the drawbacks of being handheld and too small for some users with limited vision to be able to see, leaving reliance on alternatives, such as voice playback. Utilising VR's 6 DoF capabilities we merge the benefits of both types of technologies, where we can have enlarged displays that can be seen from any distance, any angle, in any setup desired at no cost to the physical environment surrounding the user.

4.2 Software Primary Attributes

Several features and enhancements were designed and implemented with considerations to low vision reading. Building upon previous research, such as the works of Zhao et al.[71], we can identify a number of techniques that would best aid in readability. Although these techniques already exist and can be applied with alternative methods, no dedicated reading application for VR exists today that implements these enhancements from the ground up. While AR systems can overlay enhancements to existing material, or superimpose them, and image processing techniques can be used to try and interpret existing material to make it more accessible, our approach allows for the material to be repopulated or reproduced based on the desired adjustments, allowing for greater customisation and control.

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 14 for an example of different possible combinations used by our participants).

4.2.1 Book/Text Selection

The software allows for the translation of standard text to be transcribed into our application's format, including all of their chosen accessibility choices designed for VR. Although books are what have been displayed in our tests and in our descriptions, any text that is compatible (standard UFT-8 format) can be loaded into our software to be read with customised visuals. For our test only books were shown to our participants. This is the main feature of our software and was influenced by participant testimony from our preliminary test.

4.2.2 Font Size & Type

The software allows for font types 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 our 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. Our Letter Detection test (see 3.3) and our Word Detection test (see 3.5) highlighted the need for this feature, as static sizes did not always work for our participants without decreasing distances.

4.2.3 Book Size & Model

The size of each book read can be manipulated freely by the user. These 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 our tests only the default panel was presented to users.

4.2.4 Object location/rotation

Within the device, any object can be grabbed and picked up, including the book to be read, 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 our test only the book and primary tools were toggled as move-able.

4.2.5 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 spoken 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 our test. Despite our mixed results from our Colour Blindness test (see 3.7), our participants commented positively towards the use of bright colours when trialing our VR headsets. We believe that the ability to change overall colours will be desired by users, and will assist in higher levels of clarity alongside contrast.

4.2.6 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. 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 our tests. This feature was highlighted to be important due to the weaker results of our contrast test (see 3.4) compared to our letter detection test 3.3. Being able to customise light levels to the individual level should greatly increase clarity.

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

4.2.8 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 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. We noted this feature would be useful based on the results of our Word Detection test (see 3.5 and our Speed Reading test (see 3.6), as the display of how many words were on a single sentence or row affected the readability for some of our 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.

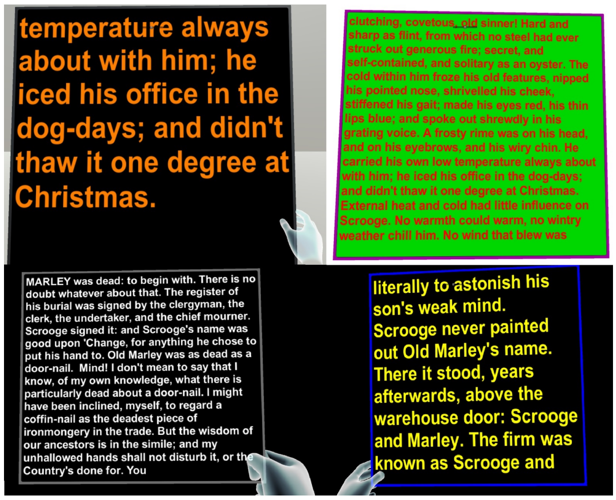

Fig. 14: An example of 4 different configurations setup of the digital reader.

4.3 User Evaluation Methodology

We carried out a user test in order to (a) evaluate the efficacy of using the application and, (b) determine some benchmark findings on designing document reader VR applications for persons with visual disabilities. We recruited 11 individuals (9 male and 2 female) advertising for persons with visual disabilities to test our application. The precise individual conditions or our participants can be see in Table 8[2].

The testing process lasted approximately one hour per participant. 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 and colours chosen. The tasks required by the participants were the following:

[2] 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 8: Table of test group B's recorded diagnosis' and what aids they use.

1. Expand and Contract the document reader window to what is the most comfortable size for you;
2. Move the document around and find the most comfortable position to locate it for you;
3. Increase and Decrease the font size of the text until you find the most comfortable reading size for you;
4. Change the text and background colour to a combination that suits your reading best;
5. Select and Read through different books from the collection;

After the task, the participants were asked to fill in (verbally) a questionnaire with a 5-point Likert type answering scales and subsequently asked open-ended questions in a semi-structured interview style. All questions related to the usability of the system and the requirements of the users. We adapted two methods for our post-study questionnaire. The first, was based on the physiological effects that the apparatus caused the users, for which we adapted the methodology found in[3]. In this, we took out the relevant sight questions as they were deemed inappropriate for participants already with visual impairments. We then adapted the questions found in[54] to evaluate the usability of our system, post-task.

4.4 User Evaluation Results

We transcribed the participants' comments from the think-aloud protocol and post-task semi-structured interviews, and analysed the transcripts using a basic method of the method found in[8].

4.4.1 Physiological Symptoms

VR has been known to be uncomfortable and sometimes create some physiological discomfort[10]. As the technology progresses, we see the effect being felt less and less. However, due to the nature of our end-user target group, we consider comfort and any physiological effects to be important to address. For this reason, we asked our participants to comment on five specific factors namely, the fatigue, drowsiness, dizziness, nausea and any headaches caused by the apparatus (method adapted from[3]). We also asked the participants to comment on any other physiological factors they may experience during their testing time which we did not ask them about. Our participants unanimously responded with no feelings of nausea, drowsiness, headache or dizziness. Two of our 11 participants reported a moderate level of fatigue and when asked attributed this to the weight of the HMD. These results are positive, as we speculate that with future HMD advancements, these issues will become even less frequent. When directly questioned as to the comfort of the headset, no participant rated the setup *very uncomfortable* or uncomfortable. Four participants rated the headset with *average comfort*, while the remaining 7 either as *comfortable* or *very comfortable*.

4.4.2 Ease of Use of System and Controls

The 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. All participants rated the ease of use of the headset as average, easy or very easy 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, one of the participants rated it as difficult, while the remaining participants rated it average or above. When questioned, the participant with the low rating, 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 use all the 3D space and all the learned actions that it became hard to remember and to perform different actions she wanted. The participant also reported that had she been given more time this would probably not be an issue and the rating would change. Ten of our participants agreed that the voice commands were useful and easy to execute, as well as remember. One of our participants however, described them as difficult to use, unnatural and would prefer not to have them at all, or to find alternatives without using voice commands. Lastly, we asked participants if they thought that they would need an expert to help them use our system in future, or if they believe they would be able to handle its use alone. Four of our 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. Five participants 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 (we speculate by using technology such as the Leap Motion Controller[63]) and 1 participant asked if possible to detect his gaze while giving commands.

4.5 Reading Efficacy and Configuration

The first question posed to the participants was to comment on the clarity that the headset gave them, in terms of reading ability. We are happy to report that all the participants were able to read text within the reader. 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 0.4m. Font size preferred on average among our participants was 42pt. The distance at which participants were comfortable reading at was averaged at 0.5m. Out of our 11 users, 4 preferred text to be black on a white background, 1 preferred black on yellow, 4 preferred white on black, 1 preferred yellow text on a blue background, and 1 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.

4.5.1 Perceived Usefulness of the Prototype

Our aim was not simply to build a VR Reader, but to ensure its impact and adoption. Therefore, it is just as important to probe in the perceived usefulness and likely acceptance of the system by end-users. We asked participants for their honest view on the perceived usefulness of the tool in terms of their own habits and needs. All our participants were positive in their responses and agreed that what they experienced was useful to them and would like to be able to have use of the system in their lives. When asked about the frequency of use, all participants apart from one commented that they would use it daily to read. One participant commented that he would use it when he wanted to read, which was not a daily activity. We also asked the participants if they saw themselves using the headset as a visual aid in their everyday lives, beyond just the document reader we had created. Unanimously, their response was affirmative; including, the one participant who said that he would not use the headset daily to read.

We believe that this type of software combined with VR technology will be a new and invigorating way for users with 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.

4.6 Summary and Framework

Our user evaluation 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 an overall accessibility tool, or was more specific for specialised tasks, the general consensus was that it would be significantly useful in some way to our visually impaired test groups. All of our participants were able to read to some level once accessibility configurations were made, regardless of visual acuity levels or conditions. This suggests our software had worked as intended, and has allowed to gather data on different aspects of how a virtual reader in 3D space might operate, but it may also suggest the headset that we used, the Pimax 5K Plus, may have performed better than our previous tests with the Oculus Rift CV1, which displayed a lower resolution and lower field of view.

One participant with very low visual ability tried both the CV1 and the Pimax headsets with our software, and noted a significant improvement in his 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, we believe 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 people with central vision type conditions such as macular degeneration. Although we hypothesize this, we do not know the level of visual increase this could provide, if any, but it is worth noting for future works as it was not a focus point of our software evaluation.

Based upon our observations and results from the participant groups, we propose a set of heuristics to guide VR designers in for designing accessible software for VR applications for LV users with visual impairments. As most LV visual impairments are age related, this framework is tailored around designing for older adults:

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. The visual fidelity of current VR headsets degrades the further away from the central focal point we go; the centre of the lenses are the clearest. 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 most 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 also moved freely to any position or angle 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;

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. We found that our 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. We also noticed that out of all adjustments made, changes to the overall brightness or contrast were 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 we experienced with some of our 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. We suggest that design should include multiple sensory elements, particularly audio, to supplement the visual experience to enhance it but also act as a fail-safe. We also believe touch sensory feedback should be considered as well if possible, such as controller vibrations to notify correct interactions, although our prototype did not have this feature during our test groups.

5 Conclusions

Our work focuses on understanding the potential of using emerging technologies such as VR and AR to assist persons with LV visual disabilities. We apply our findings to build bespoke informed technological aids. In this article, we have investigated the effects of HMD devices to reading ability. We began by investigating what tools are currently available for visual impairments, and identified several aspects of vision we wanted to test in regards to reading. Tests were devised based upon the previous works of well-established optometry tests, using these as a template for our comparative study that would best answer our research question. The tests covered letter detection, contrast detection, word accuracy, reading speed, and colour reading, taken from our research question directly. Our results showed no statistical significance for the majority of tests, although significance was shown for contrast detection at 1m being worse in VR, and letter detection at 0.5m for macular participants. A consistent theme was that VR results were stronger at closer distances compared to their further distances, even if the difference was not significant enough. This suggests that overall, VR is not comparatively better for reading with the headset we used, but does leave room for further studies. We believe hardware limitations may have been a large factor (i.e. limited resolution, field of view), and our participant selection group being too varied between multiple conditions. We also hypothesise that, although a VR headset with no enhancements has not shown any statistical significance, designing a headset with accessibility in mind, or specialist accessibility software, may provide better results. Using these findings and the insight gained from our first study, we then created a VR based document reader, integrating the feedback and benefits of our optometry testing VR such as the ability for users to move texts dynamically and scale text freely. 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, particularly for leisure reading, and that specialist software was desired. Looking at both the results from our studies, as well as user feedback from our prototype software, our 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.

In the future, we would like to investigate in more granularity specific groups and conditions, to allow us to observe the effects of specific enhancements designed to benefit particular conditions (i.e. how field of vision affects tunnel vision/macular). Furthermore, due to the extreme low visual ability of our participants, 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 participants struggled to produce any results. This could have been rectified with further distances allowed within our tests, although there is a risk of quality degradation with VR headsets at longer distances and much shorter distances. We are also in the process of testing similar applications and visual interactions such as sightseeing, navigation, video viewing, and digital shopping.

Our contributions serve as a research platform for further developments in the VR accessibility field as well as the improvement of specialist software. We believe that in the future, 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. We aim to integrate image processing techniques, specifically OCR (optical character recognition) as a component into our 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. This will transition our prototype over from primarily leisure reading or document reading, to 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, it highlights the possibilities for what this technology is capable of.

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