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Extending Vision with Extended Reality

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Abstract

Extended Reality (XR) head-mounted displays (HMD) are equipped with a camera system and a dichoptic display system. The sensory data captured by the camera system is not an accurate representation of the reality. Furthermore, the video-pass through to the HMD has compromised fideliy. In this body of work we describe the observer's vision by (a) quantifying their visual function into camera parameters in the Visual Function Testing framework and (b) simulating their functional visual capability on normal subjects by using those camera parameters on a virtual camera in the Functional Vision Testing framework. A direct by-product of such an approach is an XR countermeasure that can compensate perceptual loss brought on by these impairments by performing inverse mathematical operations on the camera input (c) in the Vision Rehabilitation Testing framework. This research tests and identifies improvements in XR systems in terms of rendering latency, simulation accuracy, objective modeling and display calibration to expand the functional capabilities of people with perceptual loss.

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Chapter 1

Introduction

"The most important thing about a technology is how it changes people."

- Jaron Lanier, You Are Not a Gadget.

The natural drive towards greater pixel density, lower latency, larger field of view, wider color gamut, and higher dynamic range in a lightweight, portable head-mounted display (HMD) in the entertainment industry has pushed the boundary of the Extended Reality (XR) domain. However, the current generation of display technologies known as virtual and augmented reality (VR and AR), require significant compromise between one or more of these properties that lead all of the HMDs to fail at the visual Turing test [224]. The biggest hurdle for XR displays is image quality. To pass the visual Turing test, the XR display needs to be incredibly dense (70 pixels per degree). Furthermore, to match our natural vision, 13000 pixels would be necessary just in the horizontal direction. Foveated rendering uses the premise of pixel concentration in the center of vision (4 degrees) the requirements for pixel density drop by 90% at 20 degree eccentricity. XR systems such as the Varjo XR-3 utilize this premise to render high-fidelity graphics. However, real-time rendering of such realistic environments is not yet feasible due to GPU, bandwidth, and memory constraints.

Nevertheless, utilizing a subjective test such as the visual Turing test to evaluate whether a display can reconstruct virtuality that is indistinguishable from reality to a human observer must be used with caution. As perception varies considerably between observers and conditions, a failure for one may not be a failure for all. The current body of work will focus on identifying appropriate metrics to gauge the capabilities of different XR systems. These capabilities will primarily focus on Visual Function, Functional Vision, and Vision Rehabilitation.

Neuroscientists have developed clever experiments called Visual Function tests (VFT) to reliably measure the perceptual abilities of observers. Some of these quantified perceptual deficits can also serve as early indicators of underlying ophthalmic pathology. They can also serve as blueprints to create imitations of impaired perception to evaluate quality of life with Functional Vision tests (FVT). Finally, with a set of tools validated with Visual Function and Functional Vision tests, the performance of individuals may be increased with Vision Rehabilitation tools (VRT). Chapter 2 provides a detailed review of past contributions in this domain, along with terminology, definition, and techniques.

When designing VFT, FVT, and VRT, the influence of the underlying display system such as color gamut, brightness, field of view, and pixel density must be considered before measurement. The goal is to create a single system that shares calibrated display property and measured observer property between the VFT, FVT, and VRT subsystems so that the influence of display specifications is minimized. This process will be detailed in Chapter 3

The results of a calibrated XR system can be compared with established gold standards in psychometric VFT tests. This work will describe the traditional implementation of acuity, contrast, color vision, swinging flashlight test, aniseikonia, and metamorphopsia tests and how these were adapted for HMDs. Special consideration will be given to utilizing the full capabilities of the system with limited resources. Each section of Chapter 4 will describe the diagnostic usage of the XR-based VFT system on diseases such as Spaceflight-Associated Neuro-ocular Syndrome (SANS), Age-related Macular Degeneration (AMD), Color Vision Deficiency (CVD) and Glaucoma.

The FVT subsystem will be demonstrated on blurred and distorted perception in Chapter 5. Eye-tracking was leveraged to make gaze-contingent and selective postprocessing masks for metamorphopsia simulation. Challenges to simulating impaired perception in a photo-realistic environment in real-time, with accuracy required altering the post-processing pipeline of a game engine (Unreal Engine) and leveraging the Native SDK of Varjo XR-3 for composite dichoptic viewing. Photo-realistic environments and agents were created using Lumen, Nanite, Quixel Megascan, Metahuman, and Procedural Content Generation (PCG). Environments include a forest hike and simulated gameplays based on actual NBA and NFL games.

Chapter 6 shows improvement in visual performance using case studies of AMD patients with eye-tracked central metamorphopsia correction.

Finally, in Chapter 7 we detail how the three components extend the understanding of vision within and outside extended reality environments. Future extensions of this framework utilizing Deep Learning for adaptive postprocessing for color discrimination is also proposed outlining how each component fits into the larger framework.

1.1 Included Publications

The research presented in this dissertation is a compilation of earlier publications as well as under-review work. The published studies are restructured to have a shared background. The following lists where each publication appears in this text:

1. *Advanced visualization engineering for vision disorders: a clinically focused guide to current technology and future applications* [236] is reproduced and adapted in Chapter 2.

2. *Calibration of head mounted displays for vision research with virtual reality* [234] is reproduced and adapted in Chapter 3. (Github).

3. *Terrestrial health applications of visual assessment technology and machine learning in spaceflight associated neuro-ocular syndrome* [146] is reproduced and adapted in

Chapter 4.

4. *Neuro-ophthalmic imaging and visual assessment technology for spaceflight associated neuro-ocular syndrome (SANS)* [145] is reproduced and adapted in Chapter 4 (Github).

5. *Stroboscopic augmented reality as an approach to mitigate gravitational transition effects during interplanetary spaceflight* [219] is reproduced and adapted in Chapter 4 (Github).

6. *Head-mounted dynamic visual acuity for G-transition effects during interplanetary spaceflight: technology development and results from an early validation study* [216] is reproduced and adapted in Chapter 4.

7. *Minified augmented reality as a terrestrial analog for G-Transitions effects in lunar and interplanetary spaceflight* [217] is reproduced and adapted in Chapter 4.

8. *Dynamic visual acuity as a biometric for astronaut performance and safety* is reproduced and adapted in Chapter 4 [215].

9. *Addressing Empty Space Myopia to Enable Deep Space Travel with Extended Reality Auditory Biofeedback* [214] is reproduced and adapted in Chapter 4 (Github).

10. *Test–retest reliability of virtual reality devices in quantifying for relative afferent pupillary defect* [174] is reproduced and adapted in Chapter 4.

11. *Extended reality quantification of pupil reactivity as a non-invasive assessment for the pathogenesis of spaceflight associated neuro-ocular syndrome: A technology validation study for astronaut health* [173] is reproduced and adapted in Chapter 4

12. *A parametric perceptual deficit modeling and diagnostics framework for retina damage using mixed reality* [9] is reproduced and adapted in Chapter 4

13. *Optimizing screening for preventable blindness with head-mounted visual assessment technology* [218] is reproduced and adapted in Chapter 4.

14. *Long-term and short-term adaptation leads to improvement in visual search but has no effects on visual discrimination.* is reproduced and adapted in Chapter 5.(Github)

15. *National Football League Game Officials Self-Rating of Knowledge in Neuro-Ophthalmic Principles and Practice: A Pilot Program to Improve Precision and Accuracy of Game Official Calls* [29] is reproduced and adapted in Chapter 5.

16. *Dynamic Visual Acuity, Vestibulo-Ocular Reflex, and Visual Field in National Football League (NFL) Officiating: Physiology and Visualization Engineering for 3D Virtual On-Field Training* has been submitted for publication and features in Chapter 4 (Github).

17. *A Mixed Reality System for Modeling Perceptual Deficit to Correct Neural Errors and Recover Functional Vision* [235]

18. *Head-mounted digital metamorphopsia suppression as a countermeasure for macular-related visual distortions for prolonged spaceflight missions and terrestrial health* [144] is reproduced and adapted in Chapter 6

Chapter 2

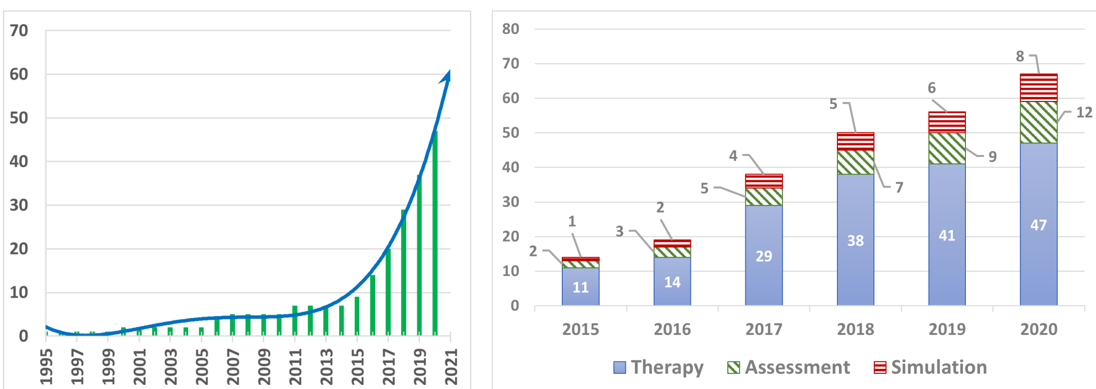
Background

The majority of the chapter is adapted from [236].

2.1 Overview of Virtual, Augmented and Mixed Reality

A participant in virtual reality (VR) perceives a world that does not exist. This is generally achieved by presenting computer generated images through a binocular head-mounted display (HMD) to invoke sensory immersion [179]. In order to produce artificial binocular disparity, the 3D computer generated scene is projected onto two virtual cameras located at the observers interpupillary distance apart. These virtual projections are then perceived as a single 3D simulation forming the immersive VR environment [18]. In addition to binocular disparity, VR technologies use visual cues for estimating 3D properties of a scene to produce motion parallax [78, 179], a monocular depth cue arising from the relative velocities of objects moving across the retina of a moving person [105]. Oculus was among the first to introduce a consumer grade VR system [163]. FOVE0, developed by FOVE Inc. [63] and GearVR by Samsung [170] are additional examples of VR HMD technologies.

Similar to VR, augmented reality (AR) and mixed reality (MR) technologies utilize computer generated image to make the brain interpret the simulation as real. Whereas in a VR system, users perceive an environment that is not real [12], in an AR system, simulated 3D content is superimposed onto a view of the real world. Hololens developed by Microsoft [137] and Google Glass developed by Google [69] are examples of optical see-through AR. In an MR system, everything a user sees is computer generated, but much of the content is directly scanned from the environment and rendered in real time. Vive developed by HTC [**vive**] is an example of an MR system. Apart from these HMD hardware, realistic XR technologies depend on graphical computation. Graphics processors and software development kits such as Unity3D [42, 202] and Unreal Engine [196, 87] work in concert to create high-fidelity renderings. Together, these technologies have come a long way since the first VR device was invented [193].



(a) (b)

Figure 2.1: Trends in ophthalmic XR publications.

Aided by this affordable realism, research into human behavior and psychophysics has benefited immensely from virtual simulations [20, 81, 168]. VR creates safe, manageable, and life-like environments that allow study subjects to behave as they would in a real-world scenario. XR environments are ideal for studying visual impairments as they offer researchers comprehensive control over user experience and stimuli. For instance, VR dichoptic rendering allows for VR investigators to closely assess an individual's monocular vision by presenting different stimuli to eyes independently. Moreover, external illumination from the environment has very limited effect on the assessment outcomes as the individual's vision is isolated from external stimuli. In addition, the utilization of eye tracking in XR allows for updating gaze contingencies to correct for fixation changes and abnormalities. Therefore, it is not surprising to see that VR is proving to be an important means to study human vision in novel ways. This is evident in the explosive growth of the number of publications (Figure 2.1(a)) in the fields of vision science, ophthalmology, and optometry that utilize XR technologies for research and clinical practice that coincides with the rapid development and adoption of consumer XR technology. Figure 2.1(b) shows the recent trend in research in the area of ophthalmic XR for assessment of visual deficits, simulation and education, and therapy. It should be noted that currently the usage of HTC Vive and Oculus Rift systems dominate other XR hardware for ophthalmic applications, while other systems such as Microsoft Hololens, Magic Leap, FOVE, and other consumer-grade systems are emerging as market contenders. To our knowledge, our survey is the first compendium of ophthalmic studies that leverage XR-based technologies. We undertake this survey to map out the landscape of this emerging new field from the past to the present advances, and discuss further avenues of investigation to pave the way for future developments.

News articles, journal manuscripts, dissertations, theses, presentations and pre-prints were consulted to identify all studies, both published and unpublished, that propose or demonstrate distinct and innovative VR programs in vision science and ophthalmology. The primary criteria for inclusion were that the studies use immersive and interactive three-dimensional (3D) VR/AR/MR environments presented through a head-mounted display, or a wide, immersive computer screen. Papers were included in the review if they: (a) were written in English; (b) used empirical methods; (c) met the aforementioned criteria for immersive and/or interactive VR. Consequently, n=83 studies relevant to the current survey were selected. The included studies are divided into three primary categories: Simulation (n=23), Assessment (n=15) and Rehabilitation (n=45).

2.2 Modeling Visual Function

Prompt evaluation and treatment by an eye surgeon for vision-threatening diseases and ocular trauma is essential for ophthalmic health, with the foundation for successful treatment and preservation of vision most often laid in the initial phases of the diseases by medical specialists at all echelons of care [66]. In many severe cases (e.g., retinal detachment) rapid diagnosis and immediate treatment can prevent permanent vision loss. This highlights the need for early assessment and screening for any vision alterations even in remote and austere environments. Unfortunately, ophthalmic resources are highly specialized and are available only sparingly in very select locations. Despite the urgent need to have comprehensive medical consultation with an eye surgeon immediately after vision alterations are noticed, ophthalmology services and ophthalmic care are available only at the highest echelon of care in large cities or advanced medical facilities. Even more pressing is the very limited state of practice in tele-ophthalmology, i.e., via phone or video conference with an eye surgeon. Even in the most urgent cases, the information available via video conferencing is limited to pictures of the eye and self reported symptoms. This prevents robust evaluation of potentially vision threatening injuries for patients who do not have convenient access to ophthalmology services, putting the patient's vision at risk of irreparable loss.

One of the most promising solutions that advances in XR science and technology can bring to ophthalmic care is addressing this gap in telemedicine for ocular health, especially for populations with limited resources and access to comprehensive ophthalmology services. There are several challenges that need to be addressed in order to revolutionize assessment, monitoring, and treatment of neuro-ocular disorders beyond what is currently only available at advanced ophthalmic care facilities. Although a number of ocular imaging technologies such as optical coherence tomography (OCT), fluorescein angiography (FA), and fundus imaging, produce robust measurements of the anatomical structure of the eye and are widely utilized in clinical settings for diagnosing a vast range of pathologies affecting the neural pathways of the visual system [75], these devices have very little utility outside of an ophthalmic clinic due to cost and levels of expertise required for their operation. On the other hand, behavioral assessments such as visual field perimetry (VF) [110], color and contrast sensitivity [28], and visual acuity [95] provide measures of visual function and can be conducted with relative ease. Unfortunately, most functional assessments are subjective and require a controlled environment and effective visual stimulation to yield reliable results. Complicating the issue is that sometimes pathological signs appear before any functional change in vision, while in other instances functional changes are perceived before any pathological signs can be detected [198]. For instance, some pathologies, such as the Spaceflight Associated Neuro-Ocular Syndrome (SANS), can cause significant structural ocular changes with little discernible functional impacts observable by standard visual function assessments [190, 119].

The rest of this chapter will present a comprehensive view of the main contributions in XR-based visual assessments. We will discuss how these approaches revolutionize the state of telemedicine in eye-care and ophthalmology via a single, affordable, and portable system. A discussion of additional research and development needed to mature current XR technologies for their adoption as standard-of-care ocular assessments will be presented. We will conclude this section by discussing future directions in developing advanced machine learning capabilities within XR-based assessments for remote screening of the risk of ocular diseases and their progression.

Table 2.1: VR in Assessment.

Type	Test	Contributors	Hardware	Software	Track	N
Non-Pattern	Visual Acuity	[114]	Virtual Research Flight Helmet	World-ToolKit	✗	24
		[132]	HTC Vive and Oculus Rift	Unity	✗	1
		[187]	HTC Vive Pro and Oculus Rift	Propriety	✗	8
		[150]	HTC Vive Pro	Unreal Engine 4	✗	15
		[147]	Epson Moverio B350	Android Studio	✗	60
		[49]	Oculus Rift	Virtual Desktop	✗	22
	CS	[187]	HTC Vive Pro and Oculus Rift	Propriety	✗	8
Pattern	Perimetry	[230]	VirtualEye	Propriety	✓	80
		[201]	smartphone VR	Propriety	✓	10
		[101]	imo	Propriety	✗	273
		[4]	smartphone VR	Android Studio	✗	10
		[184]	Samsung GearVR	Android Studio	✗	18
		[134]	C3 Field Analyzer	Propriety	✗	157
		[73]	Vivid Vision	Propriety	✗	12
		[140]	Pico	Propriety	✗	3
	VEP	[10]	nVisor SX	Propriety	✗	58
		[237]	GearVR + Neuromonitor	Oculus mSDK	✗	18
		[211]	NeuroDotVR	Daydream	✗	24
	Amsler	[9]	HTC Vive Pro	Unreal Engine 4	✗	n/a
		[235]	HTC Vive Pro	Unreal Engine 4	✗	3

2.2.1 Overview

Table 2.1 presents and overview of the main contributors to the field of visual assessment with XR technologies. We categorize the approaches in two main groups. Visual Acuity and Contrast Sensitivity testing are grouped as non-pattern tests, i.e. tests that provide a singular assessment for the entire eye. Patterned assessments are those tests that provide precision measurements across the entire visual field of the eye. Perimtery and Amsler grid testing are among the pattern assessments. It is worth noting that a system may have multiple uses, e.g. for testing visual acuity and contrast sensitivity. We refer to these multi-use cases in each of the application assessments. The main hardware and software system discussed in each contribution is also listed and further discussed in the following section. We also indicated whether a technology uses eye tracking. The impact of each work is measure as the number of citations the work has received per year. Finally, if a contribution was evaluated in a user study, the number of subjects in the study is presented in the Table 2.1 .

2.2.2 State-of-the-Art in XR Technology for Vision Assessment

All the properties that make XR the ideal medium for immersion, also make it ideal for visual function assessment. Consequently, improvement in XR hardware and software have improved visual function tests by creating high-fidelity displays, more efficient graphics rendering and reliable gaze tracking. Earlier studies such as the Virtual Environment Performance Assessment Battery (VEPAB) [114] and Dichoptic Visual Field (DVF) [10] had very limited dynamic range, resolution, pixel density and field of view. Recent XR HMD have greatly improved in all of these areas, and yet cost a fraction of the older hardware. This has led to their wide adoption and commercial success. This is also reflected in State-of-the-Art XR technology in vision assessment. Commercial-of-the-shelf VR (COTSVR) [132], 3D Scanned Visual Acuity (3DSVA) [187], Visual Acuity in Virtual Reality (VAVR) [150], Vivid Vision [73], and Perceptual Modeling in VR (PMVR) [235] all use commercially available XR hardware for their tests. Smartphone display technology has also improved significantly while dropping in price, leading to even more affordable alternatives such as smartphone based VR. Home based Visual Field (HomeVF) [201], Mobile Virtual Perimetry Frequency Doubling Technology (MVP-FDT) [4] are using these alternatives to develop assessment systems for poorer communities. Next, we will explore how these software and hardware combinations are used along with novel assessment protocols to offer improved visual function estimation.

2.2.3 Non-Pattern Assessments

Non-pattern assessments such as VA and CS are highly effective in determining the overall clarity of vision in individuals. These efficient tests are common in the various setting and can be carried out relatively quickly to identify if the subjects central vision has any deficit. Non-pattern assessments are clinically important for assessing vision because we rely heavily on our central or foveal vision for most of our tasks. In the following section, we will present how VA and CS assessments have evolved to provide precise measurements. We will also discuss the current utilization of non-pattern assessments in XR technology.

Visual Acuity

Visual acuity (VA) refers to the measure of an individual's ability to resolve fine details in visual cues [56]. VA is an extremely useful ability, as well as assessment, that facilitates facial, letter, sign, and feature recognition at varying distances. VA is a very useful indicator clinically for refractive errors and ophthalmic pathologies, including cataracts, diabetic retinopathy, and corneal opacities [148].

There are two types of VA tests: Static VA and Dynamic VA. Static VA is performed more commonly in the clinical setting and is measured by showing the individuals stationary, high-contrast alpha-numeric symbols of varying sizes at a predefined distance. These alpha-numerals or clinical optotypes are typically presented at a distance of 20 feet. Individuals who are able to discern an optotype that spans 1.75mm at this distance is considered normally-sighted. When optotypes are mobile with respect to the subject, the test is called dynamic visual acuity. Dynamic VA, on the other hand, measures the individual's ocular spatial resolution as well as the function of the oculomotor system. It has historically been one of the best predictors of success in athletic activities [199].

Static VA is widely utilized even outside of the clinical setting. It is often used to determine an individual's level of disability, fitness for specific jobs, and similar evaluations. Similarly, the VEPAB study [114] also had non-clinical aspects to assess an individual's visual performance in a virtual training environment. VA was one of the metrics that they used; they conducted this by sending 24 participants down a 20-ft virtual corridor that had a Snellen chart at the end. At each 1-ft interval, the number of lines visible to the participant was noted. The study reports a mean acuity of 20/860 which is significantly low compared to the acuity limit of 20/250 imposed by the display density (4.05 ppd). During their pilot testing, the authors experimented with black and white stripes of different orientations to measure the acuity but found that stripes would often disappear into solid fields of black and white at some set distances and become discernible again at a greater distance. Moreover, these earlier headsets would show artefacts caused by viewer movement and temporal changes.

Similarly, in COTSVR, [132] evaluated commercial off-the-shelf virtual reality devices (Oculus Rift and HTC Vive) based on their compatibility with specific military applications. The authors simulated a Snellen chart directly in front of the user at a fixed distance of 20 feet. The chart was scaled so that the topmost "E" was 88.6mm tall. They report a single user in their study. The subject had normal vision (20/20) which deteriorated to 20/40 in the Oculus and 20/50 in the Vive. Considering COTSVR devices have a significantly higher pixel density (9.81 ppd) than the VEPAB system (4.05 ppd), it is expected that they report a higher acuity than VEPAB. However, COTSVR results stand in stark contrast with the average acuity of 20/100, reported by [187], who used a HTC Vive Pro (13.09 ppd). In 3DSVA, these authors conducted a more controlled experiment, where they ensured that the real and virtual test environments were as similar as possible. The participants were tested in a room with a real Snellen visual acuity chart. Next, a 3D scan of the room was used to create a virtual test where the visual acuity chart was rendered in the exact same place as its real-world counterpart. This setup ensured that the placement of the chart, the illumination and dimensions of the room were not going to influence the outcome of the experiment.

All of the previous tests have simply adopted the physical visual acuity tests into the virtual space. However, the next few tests have designed VA tests that leverage the advantages of a controllable simulation. For example, in VAVR [150] Landolt C optotypes of 8 different orientations were projected to the center of the subjects field of view, one at a time. When, more than half of the randomly oriented C of the same size are recognized correctly, the size is decreased. This continues until the case where more than half of the orientations are misidentified. The size is then set to $l = \frac{l_{wrong}+l_{correct}}{2}$. Such resizing continues until a threshold is reached. The authors report a VA collapse from (20/15 - 20/10) range to (20/35-20/25), clearly displaying significant improvement over the previously reported methods. In ARVA [147], the authors proposed a similar approach to VAVR, where an automated system would go through three phases to assess the VA of the subject. However, the authors used augmented reality glasses that had significantly higher pixel density (31.6 ppd) than virtual reality glasses, due to their small field of view. ARVA was used to measure the acuity of 53 subjects, and resulted in acuity disagreement of .05 logMAR between automated AR and manual measurements. Their 3 phased automated approach meant that the mean test time was half as long as the manual test.

[49] assessed the dynamic visual acuity of 22 participants in a virtual environment. The user's head was rotated with a constant speed while a they were being tested with a virtual and stationary Sloan acuity chart. The authors report that dynamic VA is not affected by

the low pixel density of VR displays the way static VA is. This is highly promising because, because a VR-based dynamic VA could accurately predict the driving capability of a user, more so than static VA can.

Static visual acuity is widely used whereas dynamic visual acuity is mostly limited to assessing athletes [199], despite the evidence that it is a useful marker for various daily activities such as driving, reading road signs etc. [39, 125].

2.2.4 Stereo Acuity

Aniseikonia is a visual condition where the perceived image size differs between the two eyes, leading to unequal magnification and potential visual discomfort. Stereoacuity, or stereopsis, is the ability to perceive depth based on the slight differences in the images seen by each eye. Aniseikonia can affect stereoacuity because if the size of the images perceived by each eye is different, it can disrupt the binocular fusion necessary for depth perception. This binocular disparity can manifest as static aniseikonia, where the size difference is constant, or dynamic aniseikonia, which involves variations in perceived image size during eye movements. Visual assessments for aniseikonia typically involve direct comparison methods, where images are presented separately to each eye to evaluate size perception differences. Alternatively, space eikonometry tests binocular space perception to assess aniseikonia. These assessments are crucial for devising appropriate corrective measures, such as isokonic lenses or refractive surgery, to alleviate the symptoms and improve visual function. Due to the dichoptic nature of VR HMDs, they are highly suitable for stereacuity measurement and therapy.

Contrast Sensitivity

Contrast sensitivity refers to a measure of how much contrast a person requires to see a target. Like VA, CS is examined through charts with test targets that are either sine-wave gratings or letters. Pelli-Robson CS is a letter chart, which is simple, quick and provides significantly more repeatable measures than sine-wave grating charts such as the Vistech25, FACT25, or CSV-1000 charts [98]. Abnormal contrast sensitivity is a sign of optic nerve dysfunction. Some patients with optic neuropathy have good acuity but may have reduced contrast sensitivity thresholds. It is also helpful in patients with congenital dyschromatopsia. A decrease in the contrast sensitivity function can lead to a loss of spatial awareness and mobility as well as an increase in the risk of accidents. Contrast sensitivity may also affect the ability to: walk down steps, recognize faces, drive at night or in the rain, find a telephone number in a directory, read instructions [165].

In 3DSVA [187], the subjects were virtually 3m away from contrast discs of 7mm diameter, which had two spatial frequencies, six contrast levels and three orientations. The authors record the lowest contrast circle that the observer is able to correctly identify the orientation of. The preliminary results show that the subjects performed worse in the virtual CS test as well. The suboptimal resolution of the VR display was likely responsible for this poor result.

Color Vision Deficiency

Color vision may degrade as a result of age-related diseases such as AMD. However, more common forms of color vision deficiency is caused by genetic disorders. Standard methods to test color vision deficiency include screen or paper based Ishihara test, Farnsworth-Munsell 100 hue test, Cambridge Trivector test etc. However, only a handful of such tests or their equivalent have been used in virtual reality settings. In [46], the authors implemented a virtual version of the Farnsworth-Munsell 100 Hue test and compared physical and virtual results between 17 normal and 3 defective observers. The final diagnosis was the same in both systems. The same authors previously implemented the Ishihara test [53] in virtual reality to demonstrate how color fidelity can be improved by using well-defined light sources and hyperspectral textures.

2.2.5 Pattern Assessments

While non-pattern tests are highly localized to the foveal region of the eye, pattern tests seek to assess the functionality of the entire retina. These tests include visual field perimetry, pattern-reversal stimulus in visual evoked potentials, and metamorphopsia via Amsler grid. These tests can precisely determine how acutely each point in the visual field is affected by various conditions. In this section, we cover these pattern assessment tests that have been utilized with XR systems.

Perimetry/Visual Fields

Perimetry is the assessment of differential light sensitivity throughout an individual's visual field by detecting specific visual targets on a defined background. It is used to detect and monitor various ophthalmic pathologies such as open-angle glaucoma and optic gliomas [83, 152].

Perimetry may be further divided into kinetic or static perimetry. In kinetic perimetry, spots of light are shown on the white interior of a half sphere and slowly moved inwards until the observer sees them (Goldmann Perimetry). In static perimetry, spots of light are flashed at varying intensities at fixed locations until detected by the subject (Humphrey Field Analyzer). Central VF tests central 10° but more common are 24-2 and 20-2 HFA which measure wider fields of view with more locations (54 and 76 respectively). Target sizes of stimuli used in modern perimeters frequently use the convention introduced with the Goldmann perimetry. Five different stimulus sizes are defined by Roman numerals I through V. Each stimulus covers a 4-fold greater area, ranging from 0.25 mm^2 for a size I stimulus, to 64 mm^2 for a size V stimulus. For the Humphrey perimeter, a test stimulus of 4 mm^2 (corresponding to a Goldmann size III stimulus) is most commonly used, though larger stimulus sizes may be employed for individuals with poor visual acuity. The minimum intensity required for the detection of a light stimulus is called the threshold sensitivity level of that location. Visual field tests employ either threshold or suprathreshold algorithms. In suprathreshold tests, an intensity of pre-determined brightness is employed at each test location. Thus, the precise sensitivity of each test location is not known. In threshold testing, an attempt is made to measure the intensity of the dimmest stimulus which can be detected 50% of the time. Several algorithms exist for approximating threshold values in standard automated perimetry (SAP) such as Full threshold and some variations of SITA, which take 2 to 7 minutes per eye to complete.

The resulting sensitivity map of the visual field is used to detect dysfunction in central and peripheral vision which may be caused by conditions such as glaucoma, stroke, pituitary disease, brain tumours or other neurological deficits.

VirtualEye [230] is one of the earliest virtual reality based portable perimetry with eye-tracking. It offers both 24-2 and 32-2 perimetry, similar to HFA. However, in order to increase the angular coverage for the 32-2 protocol, the fixation point is dynamically positioned. Based on the manner of fixation point presentation, the procedure is divided into two modes: manual mode and visual grasp mode. Eye tracking is not crucial in the manual mode, where the fixation points only change nine times to predetermined positions. However, in the visual grasp mode, the user must track the stimuli with their gaze and therefore, must lose fixation in the process. The eye tracker registers whether the user was able to detect the stimuli, in which case the stimuli becomes the new fixation point. This process is inherently unreliable as ocular motion may place a stimuli in a relatively unaffected part of the retina, corrupting the results. However, the authors must have some compensatory methods as their results show high degree of agreement with HFA over various sensitivity levels.

In HomeVF [201], the authors eliminated several important limitations of web-based perimeters: Peristat, Visual Field Easy, Testvision [26, 86, 212, 48]. The VR implementation of their software lacks the web-camera based fixation detection and display calibration available in the computer display, but is not influenced by external illumination. HomeVF dynamically regulates stimuli presentation time. HomeVF allows the investigating physician to combine the results of multiple tests to achieve higher statistical accuracy. The authors suggest that HomeVF is primarily for screening and not yet capable of accurate threshold measurement.

Imo [101] is a portable VR-based perimetry that offers more extensive testing over a larger visual field (30-2) compared to HomeVF (24-2). In addition, the authors designed 24plus(1-2) test, which is considerably faster than HFA 30-2 (takes 30.8% less time) without significant loss of sensitivity. However, their system has higher false positive and false negative rates compared to HFA.

The MVP [4] frequency doubling technology (FDT) is a low-cost, smartphone based, portable visual field screening device. The smartphone had LCD screen and therefore, could not produce the subtle contrast differences possible in Humphrey Zeiss FDT. However, the authors conducted a comparative study on 10 subjects and found that MVP FDT had comparable retinal sensitivity maps to Humphrey Zeiss FDT and may be used as an easily accessible screening tool for glaucoma.

Gearvision [184] is a portable and very low-cost solution for underdeveloped countries where standard automated perimeters are prohibitively expensive. Gearvision offers both 30-2 and 24-2 protocols of the HFA. However, they do not have access to the age-based intensity prior distribution of the HFA and utilize Correlated Neighborhood Thresholding (CNT) to reduce the test duration (mean duration 11.45 min) without compromising accuracy (detects 81.94% of defects).

C3 Field Analyzer or CFA [134] has a 30° field of view but for this study, the authors followed the 24-2 protocol. When their results are compared with 24-2 carried out by HFA, the performance of CFA proves inadequate. Patients with an 18dB or worse deficit at a point in their visual field on the HFA failed to see the CFA at the same position 38% of the time. The authors attribute the poor results to poor luminance calibration. Even though the CFA offered more positive experience to its users because of its fast testing (3min), it is too expensive ($6000) for home use.

VisuAll [140] uses a proprietary algorithm to determine the subject's visual field. This study has various limitations such as Visuall does not have eye tracking for fixation compliance, only tested on 3 subjects and didn't report how their approach performs relative to HFA.

NeuroDotVR [210] utilizes dark adapted vision recovery (DAR) test for AMD diagnostics. They further devise DAVEP1 score, a simple metric for DAR, that combines the signal recovery amplitudes and times of the transient VEP. Using this score they identified all 100% of AMD subjects (n=13) and classified 90% of subject eyes (n=24) correctly.

Amsler Grid Test

The Amsler Grid is an alternative to central VF analysis if a quick assessment of macular function is required, and it is particularly useful in cases with metamorphopsia or visual distortion. It is a grid of horizontal and vertical lines used to visualize the distorted perception of individuals. This test is generally administered using a paper. The 3-D Computer-Automated Threshold Amsler Grid Test [x] is a less subjective, more robust variation of the paper-based perceptual test. 3D Amsler grid is performed on a laptop computer with a touch sensitive screen that takes about five minutes per eye to complete. With one eye covered, a person sits in front of a computer screen divided into a grid. The subject stares at a central spot on the touch-sensitive screen and, using a finger, outlines missing areas of the grid. The same procedure is then repeated at various greyscale levels - simulating increasing degrees of contrast - and the respective results are recorded and later automatically displayed by the computerized test program.

In [9], the authors proposed a parameterized model to assess and simulate metamorphopsia. Their model uses the Amsler grid to measure neuro-ocular damage in the form of luminance degradation, rotational distortion and spatial distortion. The authors propose to use this simulated model of individual perception to predict and track disease progression. In [235], the authors conducted a small preliminary study with healthy participants, presenting them with already simulated perceptual loss in one eye. The participants then had to adjust parameters of the model to replicate the distortion in the other eye. Such a method is very helpful in communicating specific perceptual loss to physicians and would greatly aid in designing specific compensation.

2.2.6 Discussion

XR is fast becoming the medium of choice for investigating sensory processing. One of the key advantages of assessing visual function with XR is that it allows an experimenter to probe the user's vision in a more naturalistic way than has been possible previously. However, current XR technology still has some major limitations that constrain the accuracy and reliability of assessment. In this section we will explore these limitations in more detail.

None of the Visual Acuity tests in VR was able to accurately measure the VA of the users. The primary reason is certainly the low pixel density of the headsets. The results get closer to the real VA with the improvement of the pixel density. Ideally, accurate visual acuity can only be determined with near-eye displays that have a pixel density of at least 60 pixels per degree [149]. Such dense display technology is already available in top of the line VR headsets such as Varjo VR-3 [1]. However, these headsets are prohibitively expensive and require very high-end computer systems to operate optimally. A better alternative is to use XR headsets with limited field of view, as it will greatly reduce the total number of pixels while increasing the pixel density at the center. Although, commonly we have 190° of field of view, we primarily use the central 20° while reading text and characters. For dynamic VA and CS, when the eye follows the moving stimulus, the gaze smoothly moves over pixels that do not change over the duration of the frame. This introduces blur in the image that is integrated on the retina – an effect known as hold-type blur. Typically, by shortening the time pixels are switched on, either by flashing the backlight [61] or by inserting black frames. However, rapidly switching the display on and off reduces the peak luminance of the display, and may also result in visible flicker.

Unlike VA and CS tests, VF does not heavily depend on the resolution of the HMD. For VF tests, the dynamic range of the screen is important, otherwise the dimmest stimulus which can be presented would not be that different from the intensity of the brightest target. This limited range means that people with good vision reach a ceiling (where all of the targets can be seen at the dimmest intensity), and those with retinal disease may reach a floor (where none of the targets are seen even at maximum brightness). Moreover, comprehensive central and peripheral VF testing require a wide field of view. However, a wide field of view means more a larger display which leads to bulkier headsets. Although this would lead to better results, the increase in price and discomfort would limit its adoption.

VR is being used extensively to create new assessment techniques for detecting traumatic brain injury (TBI) [172]. Combining multimodal data from fundoscopy, angiography and visual function tests along with patient data would be ideal for training deep neural networks to predict ocular health and individual eye physiology. This would render monitoring of sophisticated and unknown diseases more accessible.

The greatest need for virtual reality for visual function assessment comes from the importance of detecting early on-set visual defects caused by age-related diseases. However, as we have seen, many researchers opted to focus on perimetry due to the challenges of measuring visual acuity in VR. This is not ideal, as central VF screening has a high false-positive rate when performed on patients with minimal risk factors. Wide scale adoption of such a tool would lead to many incidents of misdiagnosis.

Table 2.2: VR in Simulation.

Type	Citation	Hardware	Software	Track	N
Awareness	[131]	V8 HMD		✗	9
	[90]	ImmersaDesk	Teledu	✗	0
	[208]	Emagin Z800 3DVisor	OpenCV	✗	5
	[222]	Oculus Rift	Unity	✗	20
	[92]	iPhone 7 Fove0 VR	Unity	✓	0
	[109]	HTC Vive		✓	0
	[104]	HTC Vive	Unity	✗	0
	[192]		Unity	✗	0
	[91]	HTC Vive, Oculus Rift, Google Cardboard		✗	0
Quality of Life	[203]	fixed-base driving simulator		✓	56
	[47]	4kAVE		✗	51
	[231]	NVis SX60 HMD		✓	36
	[106]	HTC Vive	Unreal Engine 4	✗	30
	[108]	HTC Vive	Unreal Engine 4	✓	21
	[93]	FOVE0HTC Vive	Unity	✓	23
	[113]	HTC Vive	Unity	✗	148
	[238]	Oculus Rift		✗	23
Accessibility	[244]	HTC Vive	Unity	✗	11
	[11]	Oculus Rift	VR Player	✗	12
	[41]		Unity	✗	0
	[205]	Oculus Rift	Unity	✗	14
	[100]	Samsung GearVR			12

2.3 Evaluation of Modeled Visual Function

Table 2.3: The functionalities offered by studies that simulate visual impairment.

		[90]	[11]	[208]	[222]	[205]	[92]	[108]	[93]	[109]
Tech	**Eye Tracking**	✗	✗	✗	✗	✗	✓	✓	✓	✓
	Stereo	✓	✓	✓	✓	✗	✗	✗	✓	✓
	VR	✗	✓	✓	✓	✓	✓	✓	✓	✓
	AR	✓	✓	✗	✓	✗	✓	✗	✓	✓
Impairments	**Blur**	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Contrast Loss	✗	✗	✓	✓	✗	✗	✓	✗	✓
	Light Sensitivity	✗	✗	✗	✗	✓	✓	✓	✗	✗
	Spatial Distortion	✓	✗	✗	✓	✗	✓	✓	✗	✓
	Shadow	✓	✓	✗	✓	✓	✗	✓	✗	✓
	Color Vision	✓	✓	✗	✗	✗	✓	✓	✗	✗
	Perceptual Filling-in	✗	✓	✗	✗	✗	✓	✗	✗	✗
Condition	**Refractive Error**	✗	✗	✗	✗	✓	✗	✓	✗	✓
	Color Deficit	✓	✓	✗	✗	✗	✗	✗	✗	✗
	Macular Degenration	✓	✓	✓	✗	✓	✗	✗	✗	✓
	Glaucoma	✓	✓	✓	✓	✓	✗	✗	✗	✗
	Cataracts	✗	✓	✓	✓	✓	✗	✓	✓	✓
	Diabetic Retinopathy	✓	✓	✓	✗	✗	✗	✗	✗	✗
	Double Vision	✗	✓	✗	✗	✗	✗	✗	✗	✗

To many, vision is a powerful tool that shapes their perception of the world. Most use their eyesight extensively in order to function and further understand themselves and the society they live in. Thus, chronic eye disorders and vision loss will broadly affect individuals both mentally and physically. Vision loss can be a significant barrier to the personal narrative that is crucial to life satisfaction and well-being [16]. Depression occurs in patients with vision loss more often (about 17%) than in patients with no vision loss, placements in nursing homes are demanded in 25.3% more, injuries happen in 33.4% more cases and femur fractures in 67.4% more cases [24]. The authors find that use of visual aids is associated with improvements in life satisfaction but not depressive symptoms. Their study suggests that improving structural conditions is important, particularly to enhancing life satisfaction, the findings also imply that intervention efforts will be limited if they fail to consider more subjective aspects of living with a visual impairment — particularly its effect on one's sense of personal agency. So, in this section we focus on the societal impacts of vision loss that can be countered through education, awareness, empathy and support. As we shall see, XR can contribute in all of these aspects.

From an epidemiology perspective, disorders of the eye and resulting vision loss impose a significant burden to the United States, both economically and socially. It is estimated that the total economic burden of eye disorders and vision loss is $139 billion, based on the 2011 US population in 2013 dollars. The worldwide societal costs of VI have been estimated at $3 trillion in 2010, [72] partially explained by direct medical costs related to health care utilization, [154, 127] and indirect costs characterized by loss in work participation. These numbers are likely to continue to increase with an aging population and quickly growing healthcare expenses.

With vision loss significantly impacting the physical, mental, and economical health of the world, XR technology seeks to alleviate these burdens with its unique ability to simulate vision loss. While this may not be an intuitive solution to the problems aforementioned, research has shown that a further understanding of vision loss in many environments can positively impact accommodations for the visually impaired. For someone who has never experienced such impaired vision, it may be difficult to understand the impact such afflictions have on activities of daily living and by extension on the quality of life. Especially for individuals looking to have better insight into a loved one's VI, VR helps create a safe, yet immersible, environment where users can experience what it is like to be visually impaired, both in terms of perception and daily function. These can also be used in the workplace to help employers understand how visually impaired employees navigate the workplace and what aspects can be improved to help with their workday. This impact can trickle down on the personal level and lead to better mental health and healthcare costs in the long run.

To help comprehend the societal impacts of VIs and vision loss, we divide this section into three subsections. In the first part subsection 2.3.1, we explain how individuals perceive different ocular diseases. We describe XR systems that use these insights to raise public awareness through simulations of such perceptions. In the next part subsection 2.3.2 we describe how individuals with different ocular disorders have difficulties performing different tasks. We discuss XR environments that measure the visual function of these individuals in a safe and controlled setting. The measure of visual function enables researchers to gain a closer understanding about the change in quality of life brought on by specific disorders. Finally, in subsection 2.3.3 we use the insights gained from the previous parts about the nature and extent of these impairments to propose countermeasures that can improve the quality of life of those affected. We discuss XR systems that have the potential to transform the lives of visually impaired people by enhancing the accessibility of workplaces, public places, websites, mobile apps etc.

2.3.1 Insight into Visual Impairments with XR

As previously mentioned, day-to-day quality of life is tied to activity limitation and independence. Authors [16] report that visual aids or assistive technology can improve life satisfaction by enabling people to participate in daily activities. Social integration and a system of support to reinforce self-efficacy can help combat depression among impaired individuals. Such support exists in the USA in the form of National Federation of the Blind (AFB), American Council of the Blind, Lighthouse for the Blind and Visually Impaired, etc. However, these organizations don't have sufficient resources to educate and support the increasing number of visually impaired people. Moreover, such support is scarce in rural communities, developing countries, etc. Under the COVID-19 restriction, many of these organizations had to suspend various activities. According to the CDC, vision disorders, including cataracts and diabetic retinopathy, are expected to increase within the next decade (Table 6). It is imperative to combat these impairment trends with large scale adoption of innovative technology. As such, VR can facilitate a wider reach and impact by providing a safe, cost-effective, interactive, and supportive platform. Not only can this be applied directly to individuals with vision disorders, but it can significantly impact the way communities can understand and provide for individuals with vision disorders. The large scale adoption of XR technology can provide novel, unified insight for communities to help attenuate the difficulties associated with vision impairment. In this section, we will cover three critical aspects in communicating insights about visual disorders. First, creating awareness among the general population who have limited knowledge, or even misconceptions about VI.

Table 2.4: Current Estimate and Projections of Prevalent Populations with Vision Problems.[30]

	2010	**2014**	**2032**
Cataract	24,409,978	25,666,427	38,477,608
Diabetic Retinopathy	7,685,237	8,084,767	10,938,504
Impaired	2,907,691	3,058,852	5,073,572
Glaucoma	2,719,379	2,858,572	4,275,758
AMD*	2,069,403	2,176,985	3,387,560
Blind	1,288,275	1,355,248	2,161,164

Significant portion of the population is predicted to be impacted by eye pathologies Table 2.4. Ocular diseases are diverse in the way they manifest in a patient's vision. For example, cataracts occur due to opacification of the natural crystalline lens. This clouding of the lens present with blurry, dim, or even altered color vision. Patients with serious cataract progression often cannot recognize faces. This presents as a serious detriment to the quality of life, such as meeting new family members like grandchildren but not being able to identify their face. Severe cataracts can also limit independent transportation options such as driving a vehicle or riding a bike, significantly limiting freedom and quality of life. While cataracts severely diminish the quality of life, other ocular symptoms that present differently but have similar results. Severe AMD, which affects the retina, often presents with significant loss of central vision and vision distortion, often leading to the inability to drive or recognize individuals. In a survey on public perception of vision loss, “loss of independence” was ranked as the second most concerning consequence of vision loss with “quality of life” as the top concern [182]. The definition of legally blind is visual acuity in one eye of 20/200 or worse [62]. Both cataracts and AMD can cause one to be legally blind but affect completely different parts of the eye and present completely differently. In the vision loss survey, 25% of individuals were unaware of any eye conditions [182]. While blindness is one of the most feared conditions, aspects regarding eye health such as important eye diseases and behavioral/hereditary risk are not well known to the public. The lack of awareness about these eye conditions [176, 117, 130, 97, 7] are a key driver behind the high rates of late diagnosis [183]. Campaigns seeking to increase awareness on the importance of regular eye examinations and eye care services have been shown to be effective among older populations and those with diabetes [118, 141]. VR can supplement to the success of these campaigns and increase public awareness of eye conditions and risk factors. Basic simulations would help participants recognize precursors of various eye conditions in themselves and others, allowing them to seek professional help before a disease can reach a debilitating stage. By integrating more engaging and realistic experiences of different types of eye conditions into campaigns, the public may develop a deeper insight into the serious consequences for the affected individuals. Accurate simulation of patients' perception would help physicians better understand and address the needs of their patients [25]. Clinicians can use these simulations to design and administer care that is more personal to the patient.

The earlier technologies relevant to this section Table 2.2 are primarily concerned with giving a rudimentary idea about the perceptual difficulties faced by patients of the more prevalent conditions such as cataracts, glaucoma and AMD. The later studies focus on a wider array of conditions such as DR, color deficit, double vision, among others. These studies also use photo-realistic environments, high-fidelity impairments to accurately portray the actual perception of individual people. We can also see the tendency to use AR more in the later studies as commercial HMDs are equipped with more capable stereocameras and eye-tracking. What technologies are used to show the different conditions are summarized in Table 2.3.

In 2002 [131] demonstrated that letting caregivers experience the perceptual effects of stroke influenced their empathy and understanding of patients' daily difficulties. In addition to restricting the view of the participants' left hand side, the authors simulated nausea and dizziness through motion blur and camera movement. As a result, healthy participants reacted like a typical stroke patient, reinforcing the efficacy of VR as an educational tool that can be utilized in a wide array of settings.

In 2006, a similar tool was developed by [90] for patient education and healthcare practitioner training but for common eye conditions instead of stroke. The authors use a drafting table format VR display to simulate impaired sight caused by glaucoma, AMD, protanopia and DR. However, the VR system was neither portable nor affordable, making it unsuitable as a learning tool.

In 2016, [208] developed a portable and inexpensive system that simulated the effects of eight common eye pathologies. The authors use a single camera to create a video see-through system that uses image processing to black out the scotomatous regions. For a better, stereoscopic simulation, [222] used two cameras to simulate cataracts, glaucoma, and lower latency due to natural aging. [158] developed a VR simulation that can effectively communicate the sensation of oscillopsia. However, none of these techniques offer user calibration, which enforces that there is considerable variation in the impairment caused by most diseases. People exposed to these variations will not misjudge an individual's capabilities based solely on common manifestations. Researchers have shown that people with VIs can perform a wide range of tasks with assistive technology [228, 43, 111, 133, 151]. Yet the employment rate for visually impaired people is still very low. Misconceptions regarding the disabling nature or generalization of various diseases are the leading cause of this phenomenon [129].

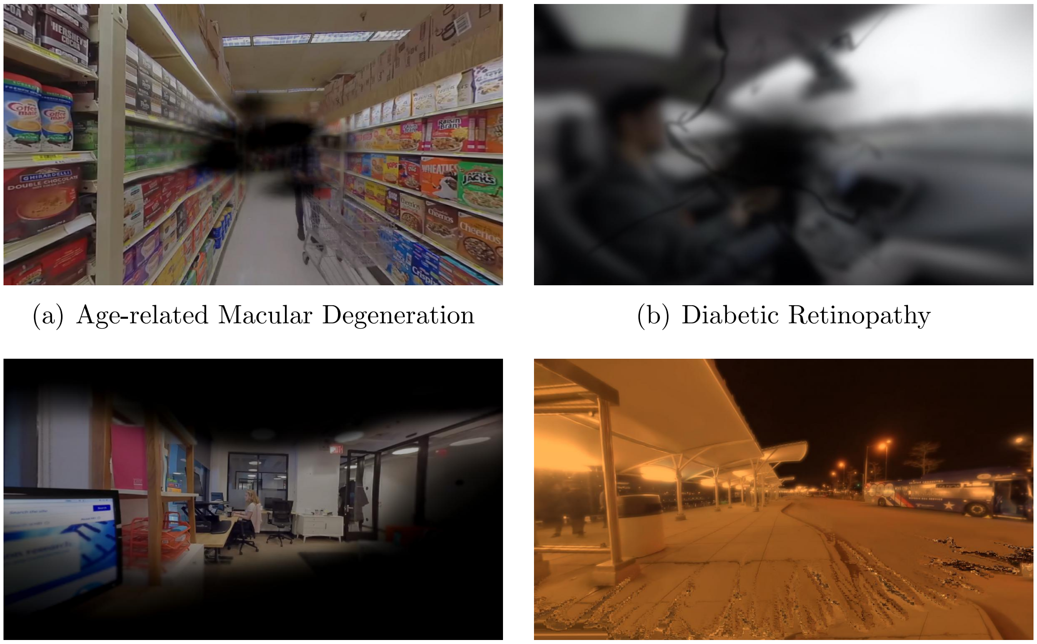
Raising public awareness regarding the manifestation, variety and characteristics of these eye diseases can therefore help curtail this practice. Sight-enhancing medical devices, such as bioptic telescope glasses, in certain states allow for visually impaired drivers to drive on the road [221]. A 2020 study demonstrated that there was no statistical significance in low-vision individuals with bioptic telescope glasses being more prone to near-collision accidents compared to regular drivers [139].

[92] address this issue by integrating eye-tracking and symptom adjustment. Their work overcomes one of the limitations of previous simulations where central vision loss was central to the screen instead of the users' gaze. Now, irrespective of the user's head position the scotoma will move along with their line of sight. The system proposed by [192] is able to display the progression of vision diseases using multiple ophthalmic assessments. Their monocular and binocular modes enable patients and their relatives to better comprehend the severity and progression of a vision disease. In monocular mode, the visual field of the worse eye can be examined with the better performing one. [109] shows a medically informed AR/VR simulation of AMD, refractive errors and cataract that has eye-tracking, stereoscopic video see-through and user calibration.

Recently, as part of a federal effort to disseminate accurate eye health information, the National Eye Institute (NEI) has launched a smartphone VR app [91] to simulate common eye diseases, including AMD, cataracts, glaucoma, and DR. Even though this application can't be tweaked to simulate vision loss of individuals, it can serve as a pioneering tool to inform the public about these ocular diseases.

2.3.2 Effect of Simulated Visual Impairment on Quality of Life

Different visual impairment impact perception in different ways as is shown in Figure 2.2. Severe visual impairment often has a large impact on the mental health and overall quality of life [51]. This can often be due to a decline in performance of tasks from everyday life and



(a) Age-related Macular Degeneration (b) Diabetic Retinopathy

(c) Glaucoma (d) Cataracts

Figure 2.2: Impaired Perceptions

difficulty with mobility [223, 169]. Studies have shown that individuals with visual impairment have higher risks for mental health impairments [51]. In addition, visual impairments are more highly prevalent in lower socioeconomic communities where access to mental health providers may be more limited and are at a higher risk of developing mental health problems, compounding these deteriorating medical issues [51, 162]. Rubin et al. conducted a study that reported the psycho-physical measures of visual impairment and difficult with daily tasks in individuals aged 65 to 84; the authors found multiple independent risk factors for self-reported visual disability, including visual acuity, visual fields,. and contrast sensitivity. They concluded the study that additional vision measures are critical to further understand the impact of vision loss on everyday life [166]. Building off this study, it is imperative for clinicians and researchers to understand the difficulties that patients are dealing with, and the longitudinal impact it can have on independence. In this section, we discuss XR simulations have been designed to simulate visual disorders with the goal of allowing non-visually impaired individuals to understand the diverse effects of vision impairment.

In the previous subsection we surveyed simulations that let users experience different kinds of sight perception. Similar simulations can be used to understand the quality of life under such impairments. The complete understanding of vision-related abilities must consider both functional vision and visual function [17, 36]. Most tests of visual function were developed for clinical diagnostics and thus are not optimized to understand quality of life. For example, visual acuity and contrast loss can correspond to deficits in performance relative to a population. However, the cutoff points depend on the task, suggesting that defining disability using a single threshold for visual acuity or contrast sensitivity loss is arbitrary and can be less informative compared to subjective experience.

Functional vision on the other hand, describes performance in everyday vision-related activities. Compromised vision impedes a wide array of such activities like reading, driving, preparing meals, watching television, and attending to personal affairs. Moreover, among independent adults it has been shown to result in social isolation, family stress, and ultimately a greater tendency to experience other health conditions or die prematurely [57]. [40] talks about patients perception during various stages of glaucoma. They specifically looked at the different impacts of self-reported and objective low vision on feelings of social isolation, finding that these were predicted by self reported low vision, but not by objective low vision [22]. This highlights the importance of understanding the lived experience of loneliness for people who have a VI. Functional vision studies can measure objective values such as maximum recognition distance (MRD), object recognition rate, and task completion time and provide insight into an individual's quality of life. Virtual Reality can provide a standardized environment where these tests can be carried out safely.

The technologies we shall discuss here are geared towards vision related laboratory usage. Therefore, the earlier papers use more expensive devices. However, once the commercial-off-the-shelf HMDs gained sufficient graphical power, researchers started to use them for their studies. Moreover, as game engines also started supporting these devices, their ease-of-use and customizability increased rapidly. Also, hardware capabilities now allowed simulation of more complicated aspects of some of these impaired perceptions. This in turn increased the reliability of the results as aspects of the bias induced by limitations in the hardware were eliminated.

[203] developed an immersive simulation to investigate the effects of age and lighting condition on the night-time driving performance in a population of 56. The study subjects consisted of a young and an older age group who were all free of ocular pathologies. However, the older drivers showed prominent variation in driving speed and lane-keeping at night. In a real closed-road night-time driving experiment, [229] observed significant reduction in participant's ability to recognize road signs and avoid road hazards under the effects of simulated impairments. It is easy to understand why carrying out such experiments in a public road would be very dangerous. The study participants performed the same tasks under different visual conditions; once without impairment, once with simulated cataracts and once with simulated refractive blur. This allowed the authors to analyze the effects of different impaired vision without having to correct for variance in user skill. Modified goggles were used to simulate these perceptions. However, VR would help create simulations of exceedingly high complexity. For example, [108] created high fidelity simulation of cortical cataracts, posterior subcapsular cataracts and nuclear cataracts that react to user gaze and lighting condition. It would be impossible to replicate this perception in static goggles or lenses.

The authors [108] note that participants liked a well-illuminated work space but had difficulties with luminaires in their field of view due to blinding effects. Results also show that cataract vision can lower the MRD by more than 50% compared to clear vision. This means people with cataract would have to get closer to signs to be able to read them clearly. This would lengthen the process of determining and following a route between two locations which is sometimes called wayfinding. In a previous study [106], the authors observed the effect of different blur strength alongside cataract and AMD simulation on the average MRD. They find that reducing the visual acuity by a factor of 4 translates to a reduction of the MRD by a factor of 2.25. [93] gave similar attention to various ignored or misunderstood aspects of the glaucomatous perception and created a VR simulation with comprehensive versatility. The main goal of this study was to determine if the simulation is capable of reproducing, in normally-sighted observers, the same basic patterns of difficulties that real glaucoma patients exhibit when faced with everyday tasks of daily living. They observed that with visual field loss (VFL), participants took longer to complete tasks, especially when the VFL is inferior rather than superior. VFL also prompts users to make more frequent head and eye movement to compensate for their limited vision. They also gelt anxious when climbing stairs. All of these behaviors agree with previous studies with real glaucoma patients, establishing the usefulness of such studies.

One of the challenges when studying the effect of VI on a sufficiently meaningful sample, is aggregating participants with similar conditions. Since the severity of the symptoms differ widely, it is more suitable to do preliminary research on participants with normal vision and have them experience the same visual deficit. On the other hand, for eye diseases such as cataracts, diabetic retinopathy, glaucoma or macular degeneration, it is difficult to determine exact and objective perception information from subjective and verbal descriptions. Traditional eye exam cannot always capture these subjective differences. [6] used contact lenses to create gaze-contingent experiment to study street-crossing decision-making performance. In virtual reality, however, eye tracking has yet to go a long way before it can be a reliable method, but it is still essential for these types of research. That is because if the eye deviates from its central position, the impairments such as scotoma, metamorphopsia simulation would have to move along with it in a fast and reliable way.[106] used VR simulations to study the mean recognition distance (MRD) for finding an escape route with levels of compromise to visual acuity. Their work uses simulation of cataracts and AMD to give the experience of real impairments, though they do not report MRD or time to complete based on these impairments. [108] however, shows that MRDs with cataract vision are significantly lower than with clear vision. [231] studied crossing decisions of young normally sighted subjects simulated with a gaze-contingent central field loss within a virtual environment. They found that, with increasing scotoma size, subjects had longer curb delay and selected longer time gaps between traffic when crossing an exit lane of a virtual roundabout. However, not requiring participants to fixate centrally should give more reliable answers.

[229] demonstrates how modest amount of VI has the ability to reduce components of nighttime driving ability, including recognition and speed and the effects are greater for simulated cataracts than refractive blur, despite the fact that the VA levels were matched between conditions. [77] proposes to use optokinetic drum or sphere to investigate what effects color and color blindness have on simulator sickness.

It is important to understand that basing the quality of life of real or virtually impaired individuals on objective measures such as mean recognition distance, time to completion of tasks may not paint the actual picture. Subjective measures may be better indicators and almost all of these papers posed subjective questions to do just that. In spite of that, quantitative scores are naturally easier to compare. This way it is easier to verify whether the simulations have the same effect as the real ones. Naturally most visual search tasks concerning functional vision were objective [59, 128]. [93] examined whether gaze-contingent simulations of VI elicit similar difficulties in normally sighted observers as those experienced by real glaucoma patients. Their findings suggest that mixed reality (AR/VR) technologies have interesting potential as a means of simulating the functional effects of VI in normally-sighted. Until a widely accepted system is established to convincingly interpret the perception of a person with complex metamorphopsia or the interactive construction of these impairments [235, 9] are improved, the trend of expert validation and objective comparison should continue. The current progression of some age-related diseases may be better reflected in these interactive simulation studies.

2.3.3 Optimizing Environments for the Visually Impaired with XR

With XR's ability to simulate vision impairment, this technology opens up the opportunity for designers to understand how to best accommodate for visually impaired individuals. This insight can be implemented into a diverse assortment of categories such as emergency exit planning, website color combination, user interface arrangement, staircase color scheme are some of the areas that can benefit from this technology. These ideas have already been implemented for the public. [11] presents an AR approach to simulate VIs and evaluate usability of an existing environment, whereas [205] addresses the planning phase with a VR approach that can directly use 3D models of an environment to help inspect accessibility. A combination of these two approaches would be to use reinforcement learning to train on good and bad design choices to propose an environment that is significantly more inclusive with the least amount of structural change. These would be invaluable in assisted living facilities where people have significant VIs. The changes to these environments can be as subtle as changing the intensity or color of a light source or the position or orientation of a sign.

Similarly, [41] designed a testing protocol for web-designers to determine whether their products function as intended for users with color vision deficiency. [100] allows app developers to perceive their apps through a virtually rendered phone with glaucoma or cataract impairment. [239] helps user choose appropriate glasses by virtually rendering 3D glasses onto videos of the user along with appropriate distortions caused by prescription lenses and illumination.

Although VR environments are susceptible to occasional poor design choices, [244] seeks to address some of these issues through a plugin that overlays augmentation at runtime to allow low vision users to have a better experience. [112] allows for automated focus adjustment of VR HMD with images of eye prescriptions.

2.4 Augmenting Visual Function

As visual information is processed throughout the visual pathway starting at the retina all the way to the primary visual cortex, deficiencies in any part can lead to different types of visual function loss. In the Section 2.2 we reviewed strategies that leverage limited vision loss to diagnose diseases early to prevent further vision loss or even blindness. After successful diagnosis medical interventions such as gene and vision therapy can halt vision loss. However, even with the optimal usage of vision screening strategies, clinical assessments and interventions, normal vision cannot always be preserved. Such circumstances complicate specific visual function recovery because of complex neural mechanisms such as visual adaptation [33]. Rehabilitation measures are more robust to such effects as they improve daily task performance instead of specific visual abilities such as sensitivity or color perception. Social interventions are also necessary to reduce impacts of the remaining deficits. In the following sections we will demonstrate how XR can be used to prevent blindness and facilitate activities of daily living with multifaceted strategies.

2.4.1 Overview

Table 2.5: VAMR-based Vision Therapy.

Citation	Hardware	Software	Track	N
[54]	CyberscopeCustom I-BiT		✗	7
[157]	Custom VisionVR	Embedded Visual C++		
[213]	Cy-Visor DH-4400I-BiT			
[207]	Crystal Eyes shutter glasses			11
[246]	Oculus Rift			17
[23]	Oculus Rift	Unity		18
[120]	Bangerter foil (BF) and HMD			22
[15]	Oculus Rift	Unity		0
[233]	Oculus Rift	Unity	✓	9
[178]	HTC Vive	Unity	✓	20
[177]	HTC Vive	Unity	✓	23
[138]	Samsung GearVR	UnityMATLAB	✓	14
[235]	HTC Vive	Unreal Engine 4	✗	0
[71]	Samsung GearVR	Relumino	✗	100
[122]	HMD		✗	7
[206]	Google CardboardAura VR	Unity		11
[74]	HTC Vive Pro	Unity	✗	0

The following sections will showcase XR technologies with two different approaches to improve the quality of life of impaired individuals. First being vision therapy and training to prevent progressive visual disorders. Amblyopia treatment, Stereovision training, and Preferred Retinal Loci (PRL) training are examples of vision therapy. Previously these regimens were carried out with widescreen displays. Advances in the field of VR have nurtured growth in VR delivered vision therapy. Specially children who are still visually developing (5-10) [21], can benefit from these video game-like treatments. Table 2.5 presents such training and therapeutic tools. Another approach is to use XR tools as visual aids to utilize the remaining sight in an impaired person to improve ability to perform daily tasks. Table 2.6 shows examples of such digital eyeglasses. In the following sections we review their hardware and software implementation, strengths and limitations. One crucial strength is gaze-contingent interaction which is noted in the table. The overall impact of each device is measured by the number of citations the work has received per year. Moreover, if a user study was conducted, we report the number of subjects in that study.

2.5 State-of-the-Art in XR based Visual Rehabilitation and Vision Therapy

Advancement in graphics and VR display technology are largely driven by demand for more immersive and realistic gaming experience. Understandably, these same technical principles are advantageous to the development of visual aid and therapy. Current XR tools are highly compact and affordable. This is crucial as visually impaired individuals tend to have limited opportunities to afford costly aid products due to the economic burden associated with impaired vision (Figure 2.3)sss. However, earlier vision therapy tools such as the I-BiT system were essentially large computer screens re-purposed for dichoptic stimulus presentation. .

2.5.1 XR Assistance for Activities of Daily Living

Activities of daily living (ADL) is defined as a minimum set of fundamental skills that are required to live an independent life [55]. It is an important indicator of an individuals functional status. It is often used as a reliable indicator of assistance and rehabilitation

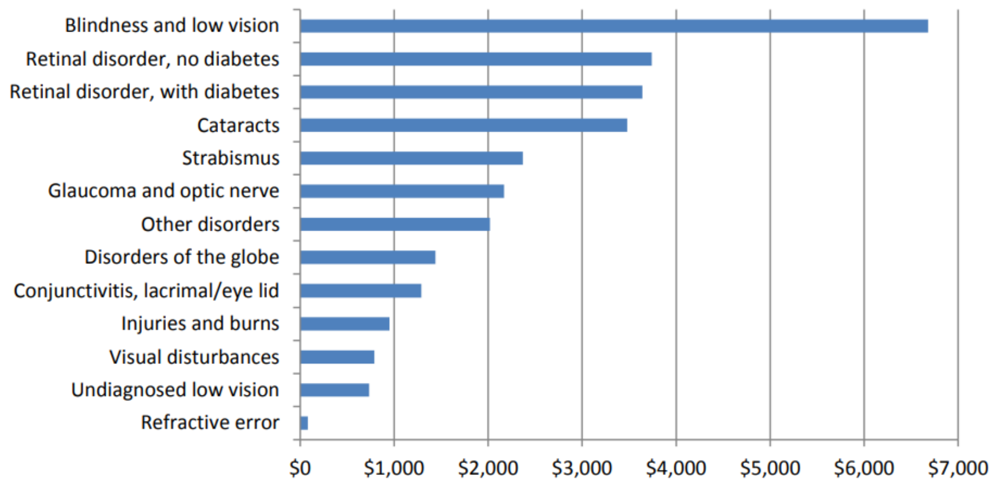


Figure 2.3: Ecomonic Burden of Vision Loss [31]

requirements. Substantial loss in different aspects of vision such as acuity, color, depth and contrast loss can cause low vision which may compromise activities of daily living. [38] defines a person with low vision as someone "who has measurable vision but has difficulty accomplishing or cannot accomplish visual tasks, even with prescribed corrective lenses, but who can enhance his or her ability to accomplish these tasks with the use of compensatory visual strategies, low vision devices, and environmental modifications". Assistive technologies are widely used to help people with low vision function normally. Assistive technology professionals such as mobility specialists, occupational therapists train individuals to make the best use of adaptive technology devices. Specifically for people with significant visual impairment, these technologies can be the difference between independence and assisted living.

We have divided the visual aid technologies into two categories: Impairment Oriented and Target Oriented solutions. Impairment oriented solutions use the particular impairment properties and apply image processing techniques in order to mitigate the impact of the impairment to some extent such as applying color correction for Deuteranopia. On the other hand, target oriented visual aids employ image processing techniques that are specific to some tasks such as interpreting signs, highlighting or magnifying texts, augmenting staircases etc.

Table 2.6: VAMR-based Visual Aid.

Citation	**Hardware**	**Software**	**Track**	**N**
[204]	Sony Glasstron			4
[128]	Custom HMD		✓	12
[155]	Glasstron PLM-50		✓	0
[136]	Custom HMD		✗	0
[79]	Custom HMD		✗	25
[195]	GoogleGlass	Glass Development Kit	✗	23
[240]	Oculus Rift	Unity and OpenCV		19
[241]	Oculus Rift	C# and OpenCV		12
[167]	Epson Moverio BT-200			3
[135]	OVRVision Pro			24
[126]	eSight OST HMD			13
[227]	eSight OST HMD			60
[226]	Custom OST HMD			0
[3]	GDM-F520EyeLink II	OpenGLPsychoPy	✓	10
[189]	HoloLens + iPhone	ARKit		7
[116]	Epson MoverioBT-300			19
[5]	Custom set of tools			6
[194]	Custom OST HMD			0
[247]	Smartphone HMD VR	Affectiva API		2
[76]	Sensics zSight HMDOculus Rift	C++ OpenCV MATLAB	✓	35
[102]	HoloLens	Unity HoloToolkit		48
[32]	Custom HMD			4
[243]	HoloLens			12
[242]	Oculus RiftSmartwatch			31
[220]	Custom OST HMD			27
[82]	HoloLens	Unity HoloToolkit		24
[245]	HoloLens			16
[112]	Samsung GearVR	Oculus Toolkit		0

Most of the earlier techniques 2.6 use display multiplexing and nominal image processing to aid people with peripheral vision loss widen their functional field of view. As the hardware limitations were resolved, more advanced digital and intelligent processing such as scene-to-audio, face/object recognition were incorporated. However, the earlier iterations of such techniques could only function at low refresh rates. The later generation of solutions integrated more customizable parameters and configurations along with higher fps to provide a personalized, flexible and immersive experience to the impaired users. This allowed users to considerably improve both their task range and performance.

Recent advances in low cost wearable computers opens up new possibilities for the development of innovative visual aids. Such visual prosthetics often appear ad-hoc. [171] set out to identify what functionality visually impaired users need in various contexts to reduce barriers. Information was gathered via interviews of visually impaired individuals. The results show that recognizing faces and text is the most important functions while the idea of smart glasses where questioned. Research on vision disabilities [220] has largely focused on audio or vibrotactile interaction. Admittedly, OrCam is geared towards legally blind users. Unlike [50, 45, 44] the wearable aids mentioned in this section focus on making the best use of the users existing functional vision. [240, 242] has Magnification, Contrast Enhancement, Edge Enhancement, Black/White Reversal, and Text Extraction. eSight [126, 227] report increased Visual Acuity, Contrast Sensitivity and Face recognition capabilities in users. OxSight [226] goes beyond basic image enhancement to provide higher-level functionality, such as rendering the scene in cartoon-like layers to highlight important foreground features (e.g., a person nearby) relative to background features. Many of these wearable technologies do not go for the commercial low cost head-mounted displays, rather choosing to design their own expensive alternatives.

[89] explores the role of HMD and their design on visually impaired people. They observed distinct preferences for different HMD solutions based on the type of visual impairment.

[50]. [67] demonstrates audio navigation and product search in a supermarket with the help of a computer vision system. [241] demonstrates capability of visual product search with aid superior to user's best corrected vision. It should ideally be possible to mimic the results of the high-end low vision aids with the help of computer vision in concert with low cost smartphone based virtual reality solutions with minimal hardware modification. Smartphones are now widely being used for VR exploration and augmentation, and some have excellent displays for a reasonable price, poised to impact a lot of lives.

Counter to magnification methods, techniques that work to increase the field of view minimizes the desired view and displays it in the portion without vision loss [204]. [128] increased perception of video details by converting the feed to grayscale.

2.5.2 Preventing Irreversible Blindness with XR based Vision Therapy

While XR can help clinicians assess and monitor VI status, this technology can also aid in the rehabilitation and prevention of several ophthalmic pathologies. [177, 178, 35] reports that VR technology can be used as a rehabilitation tool to exploit the sensory-motor adaptive capacity of the nervous system to compensate the deficits given in different pathologies, providing a technological method for intensive and repetitive training. This therapy approach also allows researchers to manipulate the specificity and frequency of sensory feedback provided to the patient, resulting in adaptive learning algorithms and graduated rehabilitation activities that can be objectively and systematically modified to create individualized treatment paradigms.

Certain common features include:

- Long periods of therapy repeated over and over to induce changes to the visual pathways

- Patients need to concentrate steadily and respond correctly to visual cues
- Guidance for the procedure and compliance for the effective duration of the therapy needs to be ensured

Perhaps one of the most notable uses of XR in blindness prevention is with pediatric patients with strabismus most concerning for amblyopia. Strabismus occurs due to an inability to align the eyes and amblyopia from strabismus occurs when the brain favors the input of one eye and fails to process the other during pediatric neuro-development. This process can lead to permanent vision loss. Amblyopia is often seen in children with strabismus and is the most common cause of monocular visual impairment; up to 2-5% of the general population is affected by this condition of VI [70]. Fortunately, strabismus and subsequent amblyopia can be prevented with early intervention. One of the early interventions utilized by ophthalmologists is dichoptic training which trains the weaker eye [123]. Vivid Vision is a company that has recently released a VR system that provides therapy and patching for strabismus, amblyopia, and convergence disorders. The device utilizes engaging images (e.g. spaceships) and can be utilized at home for accessible training [14]. Over 390 eye clinics provide Vivid Vision VR therapy and this number is likely to increase. This is a promising look into the likely future of VR as a tool for vision rehabilitation in eye clinics and at home.

[54] report that older children, with dense amblyopia, are notoriously challenging to treat with traditional occlusion therapy and are frequently noncompliant. In two children, the vision has remained stable, in two children the vision has improved (one with the use of atropine) and in one the vision has reduced, but not to pretreatment level.

In the case of amblyopia, few studies have explored the possibility of integrating perceptual learning and dichoptic stimulation approaches, which have a long history of suggesting effectiveness in improving visual skills, into VR environments. The prevalence of amblyopia as quoted in the literature can vary from 0.2% to 5.3%, this is due to the population selection and the diagnostic criteria used to define amblyopia. It has been estimated that around 90%

of patients' visits to children's eye services involve treatment for amblyopia [191], due to the large numbers of children with visual defects who have squints and/or anisometropia. Therefore, amblyopia is an entity frequently encountered by clinicians in the clinic.

In this context, results obtained from this line of research are positive, but there is still an important lack of well-designed studies suggesting a sustained effect on vision outside the intervention period. Likewise, the full potential of VR-based interventions will only emerge after we gain a deep understanding of how various sensory and haptic manipulations affect neural processes, so imaging studies to evaluate the effects of VR-based interventions on brain activation patterns and of various training parameters on long-term changes in brain function are needed to guide future clinical inquiry.

2.5.3 Discussion

XR technology is starting to delve into vision rehabilitation for patients that have irreversible vision loss. Similar to Physical and Occupational Therapy, XR has diverse capabilities in addressing functional impediments and helping individuals become more independent. In addition, research regarding vision rehabilitation therapies may also help individuals regain certain aspects of their vision. With the advent of 5G technology and edge computing, XR technology can now help visually impaired individuals read books, recognize faces and signs, locate objects, and navigate many new environments. These innovations can augment the remaining vision through dynamic binocular rendering to improve visual function and enhance the quality of life.

Traditionally, magnification has been accomplished using conventional optics, however there are limitations including fixed level of magnification, reduced field of view, narrow depth of field. Traditional optics cannot change contrast of the scene dynamically, a feature that is very important because of its occurrence in a variety of different ocular diseases. Instead, XR headsets can use its cameras to capture and process the stimulus in such a way as to elicit magnification, remapping, contrast, color adjustment etc. Wearable technology such as optical see-through head mounted displays can directly superimpose the input to the eyes with augmentations.

Nevertheless, one needs to improve the environment accessibility features alongside these wearable technologies. That is because none of these solutions are cheap and thereby would only help the rich with improving their functional capabilities. Even then, these have their own flaws. Afflicted people generally do not want to draw attention to their disabilities, therefore, conspicuous wearable technologies are not widely adopted. Social acceptance of the wearable device is as important to some as its usability. When they are used, some of these aids omit secondary information and solely focus on some apparently salient features of the scene which can have unintended consequences. One possible way around this problem is to use remap the scene around the blind spots or spots of low acuity, as discussed in the simulation section. But to be appropriate for this situation, the the remapping needs to be carefully formulated so that the cognitive load is minimal for scene interpretation, if compared to magnification. Traditional text enhancement could potentially lead to crowding effect [156]. Instead, a synergy between the environmental and augmentative components, when feasible, would be the best of both worlds.

Chapter 3

Towards Device-Agnostic XR Framework

The majority of the chapter is adapted from [234]. Recent advances in virtual reality (VR) head mounted displays (HMD) have enabled wide adoption of the technology in diverse research areas. High acuity screen resolution [Varjo [1]], wider field of view [Pimax [2]], higly affordable wireless VR [Oculus [163]], all-inclusive AR, VR and eye-tracking capabilities [Vive Pro [60]] showcase how different commercial products have varied utility for research on fields such as vision science [124], psychology [209], therapeutics[58, 80], training [96, 121] and simulation [192]. Increasingly, researchers are adopting game engines such as Unreal Engine and unity to design and present immersive environments and stimuli to their subjects. Some of these applications require precise color specification and display. However, no standard procedure exists that help researchers calibrate these HMDs and specify a color in their chosen color space for visualization.

Increasingly, virtual reality technology is replacing traditional displays for more immersive experiments and assessments. For example, virtual simulation of ocular pathologies such as color vision deficiency [46], cataracts [108, 107], and macular degeneration [235] are helping researchers quantify the effects of these diseases on quality of life. Additionally, VR-based visual assessments are being used to diagnose glaucoma [185], age-related macular degeneration (AMD) [235]. Binocular compensation available in AR displays are being used to correct neuronal loss in experimental settings. Traditional optics may soon be replaced digital spectacles that manipulate the camera feed for recovery of visual function loss. However, such solutions in the fields of assessment, simulation and rehabilitation would entail a module that can be easily calibrated for accurate color representation that is common for most medical usage of color displays.

Several lines of work exist, that characterize the chromatic properties of different virtual reality headsets and compare the perceptual performance with more traditional displays [200], physical objective tests [53, 68, 46], etc. In [52, 53, 46], the authors have implemented a way to reconstruct hyperspectral representation of physical scenes from multispectral images using CS-2000 tele-spectroradiometer. The reconstructed virtual scenes were Colorchecker box, Ishihara test and Farnsworth-Munsell 100 Hue test. While such a line of work is focused on creating accurate virtual representation of captured scene components, in a separate line of work[99, 200], have identified complex behavior in virtual reality renders with Unity and Unreal Engine 4 (UE4) respectively, that invalidate standard color calibration practices. In [99], the authors experimented with different render configurations to find the most perceptually correct representation for medical applications. In [200], the authors have disabled this behavior and formulated how to accurately control color and luminance in HTC Vive Pro Eye with Unreal Engine. However, their solution involved disabling system-wide tonemapping that is set by default in Unreal. Although this procedure causes clipped linear gamma behavior per channel and normal luminance additivity, it changes the behavior of many built-in shaders and materials, compromising the realistic effects default to Unreal Engine levels. Therefore, if researchers require fine-grained control over behaviors of specific shaders without altering the appearance of the rest of the scene, a modular approach is necessary. More detailed differences between this work and ours will be discussed in the next section. In their subsequent work [68], the researchers showed the application of such a system to a real-world scenario, establishing the color constancy of a virtual scene calibrated using their approach. However, disabling the post-processing routine means that the scene appears brighter and the light sources are clipped, contrary to the more realistic postprocess-enabled pathway. In [142], the authors use look-up tables (LUT) and color grading built into Unity to calibrate the luminance of VR headsets. Their procedure does not include color correction.

In this work, we present a framework for Unreal Engine 4 that calibrates and shows any viable color expressed in xyY, Luv, or Lab color spaces to the displays of a VR HMD in a modular manner. The main contribution of our proposed approach is the ability to present the scene such that parts of the view preserve default properties while specific stimuli behave according to specified chromaticity. Our packaged abstraction would allow researchers to create and render realistic stimuli without requiring extensive knowledge of the specific HMD device, spectrophotometer, or color representation in UE4. Furthermore, unlike [200], the proposed work would allow for a greater number of researchers to use virtual reality technology for their workflow.

Our contributions in this work include measuring and comparing spectral distributions of major commercial head-mounted displays, including HTC Vive Pro Eye, Oculus Rift, Pimax, Fove and Varjo XR-3 using the i1 Pro 2 spectrophotometer [85]. We build a novel UE4 camera asset that, when placed in any map, allows the scene to be processed along two different graphic pipelines. One pathway allows default Unreal rendering behaviour to persist, so that objects in the scene appear realistic and provide a sense of immersion. The second pathway objects in the scene to display color-correct properties which are imperative for verifiable and reproducible vision research. This is achieved by modifying the post-process material so that every object in the scene would go through the first pathway or if given a certain custom-depth stencil value would be processed along the second pathway.

Furthermore, it works alongside i1Pro 2 to calibrate and preserve parameters of conversion for a specific HMD with regards to CIE xy, CIE Luv and RGB. Finally, we validate whether the predicted and measured values of random color space coordinates match up closely.

3.1 Rendering with selective color correction

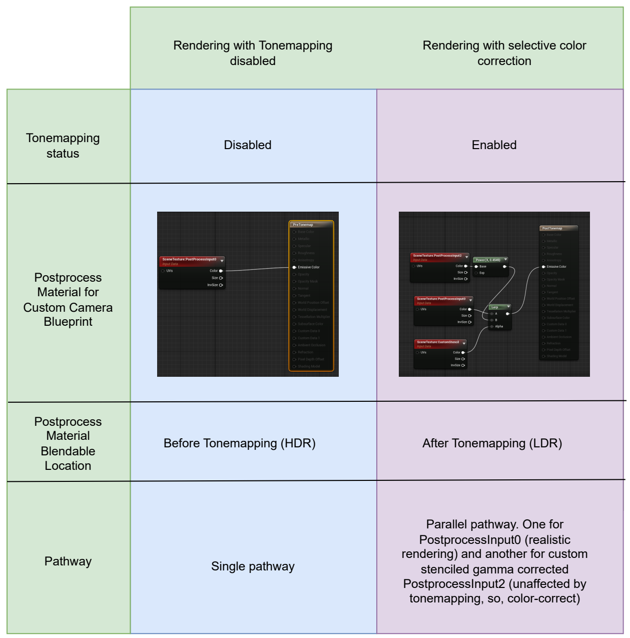
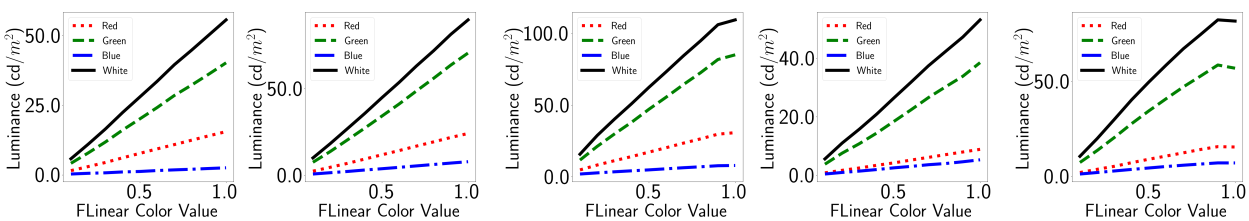


Figure 3.1: Difference between the two rendering pipelines (i) tonemapping disabled, and (ii) tonemapping and LDR enabled, gamma-corrected.

We do scene rendering with our PostCamera substitution of standard camera. However, we enable tonemapping Figure 3.1. To correct all the effects of tonemapping, we rely solely on the post-process material now. Instead of using the blendable mode that "before tonemapping", we now use"after tonemapping" so that the material output is now the final render phase. To selectively use custom processing on only the stimuli and leave the rest of the scene with Unreal Engine's default realistic rendering, we make use of custom render depth pass. This property allows the post-process material to selectively only apply counter-tonemapping to the stimuli target. In the post-process material we use scene texture: PostProcessInput2 which is the scene texture before the tonemapping pass but without gamma correction. We simply correct gamma and it has the intended corrective effect, as will be demonstrated in the following subsections.

3.1.1 Relationship between input intensity and luminance



(a) Vive (b) Oculus (c) Fove (d) Pimax (e) Varjo

Figure 3.2: **Tonemapping Countered:** The X axis shows emissive values x in : $RGB(x, 0, 0)$ for red, $RGB(0, x, 0)$ for green, $RGB(0, 0, x)$ for blue, $RGB(x, x, x)$ for white. The Y axis shows luminance in cd/m^2.

Figure 3.2 shows the luminance (cd/m2) corresponding to the input R, G and B channels. The figures demonstrate how our post-processing material alone alters different head mounted display rendering, without changing other post-process routines. All the displays now exhibit properties of a clipped linear function as the input emissive values. However, one distinction from the clipped linear function of default behavior is that now the saturation does not occur immediately. This is due to the proxy shutdown of auto exposure through post process materials. Now, the relationship between input intensity and luminance is similar to when the works of [200] disabled post-processing.

Vive, Oculus and Pimax show complete linearity in the given emissive ranges in Figure 3.2. This means that vision experimenters can smoothly change the emissive values to increase the display brightness. Fove and Varjo show slight clipping, showing that the experiments would need to be mindful of the brightness beyond the threshold and either restrict the protocols within the cutoff brightness or account for the two different gradients for luminance variation. Interestingly, Varjo primaries are again a little dimmer compared to the 0.9 shade. While Fove primaries are not dimmer, the rate of change is diminished.

3.1.2 Luminance Additivity

Table 3.1: **Tonemapping Countered:** Luminance Ratios

	HTC Vive	Oculus	Fove	Pimax	Varjo
$(L_R + L_G + L_B)/L_W$	1.04	1.11	1.12	0.95	0.97

When post-process tonemapping is enabled and our $\alpha(RGB)$ function is applied to counteract tonemapping for stimuli, luminance additivity is reinstated. For different devices, the ratio of predicted (sum of individual channels) and measured luminance are shown in Table 3.1. Table 3.1 and Figure 3.3 demonstrate that all the displays are now showing almost perfect additivity, while OLED displays are very slightly off. Table 3.2 shows the corresponding values of m_X, t for each head-mounted displays:

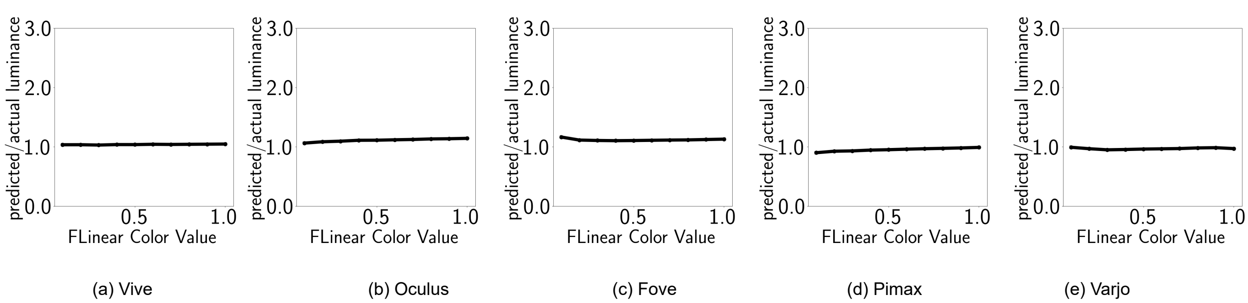


Figure 3.3: **Tonemapping Countered:** The X axis shows emissive values x while the Y axis shows the ratio $(L_R + L_G + L_B)/L_W$.

Whereas Fove used to be the dimmest display in the previous settings, now Fove is one of the brightest displays. It is now 7 times as bright as before. Brightness of all HMDs have increased in the current settings, while the dimmest point has remained similar. This results in the overall increase in dynamic range of the system. Transforming Fove from one of the worst devices to render HDR images to one of the best HMDs for that purpose. However, the difference would be more indicative of true potential with auto exposure disabled in the normal camera settings.

Table 3.2: **Tonemapping Countered:** Slope and Threshold for modeled relationship between luminance and emissive values

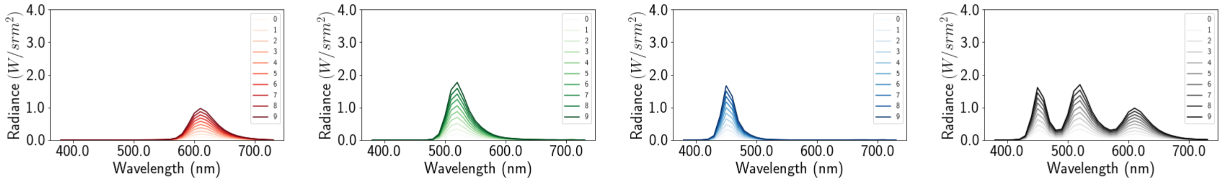
	HTC Vive		Oculus		Fove		Pimax		Varjo	
	m_X	t	m_X	t	m_X	t	m_X	t	m_X	t
Red Channel	15.5	15.5	24	24	30	30	8.7	8.8	17.3	15.4
Green Channel	40	40.2	67.2	70.5	87.8	85	37	38.5	67	57
Blue Channel	2.5	2.5	7	7	7.3	7.8	5	5	8	7

3.1.3 Channel Constancy

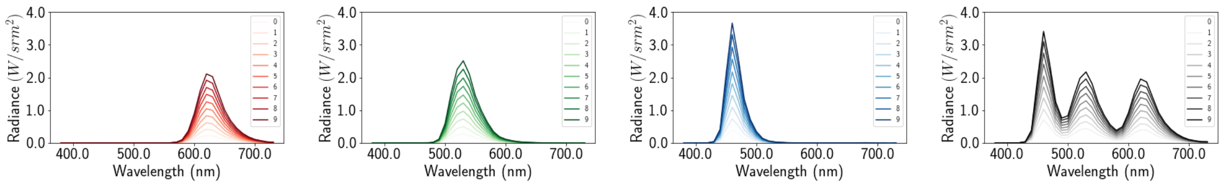
Table 3.3: **Tonemapping Countered:** Channel constancy scaling

	HTC Vive	Oculus	Fove	Pimax	Varjo
c_{red}	0.012	0.028	0.052	0.021	0.028
c_{green}	0.013	0.026	0.046	0.021	0.012
c_{blue}	0.009	0.019	0.041	0.024	0.026

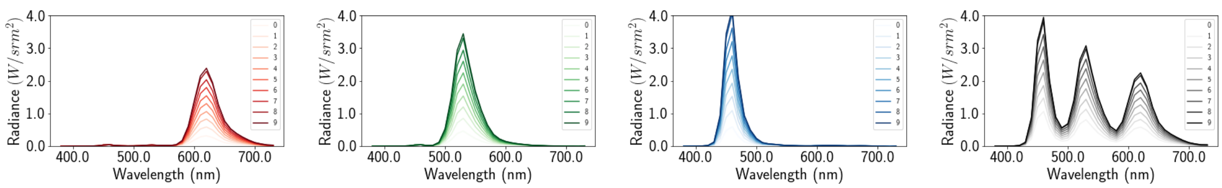
By applying our corrective material, the new distributions have a higher peak corresponding to the overall increase in luminance (Figure 3.4). Moreover, constant scaling factors c across channels of a device represent multiplicative spectral profile and channel constancy. Table 3.3 shows the least squared error is consistent with our expectations of channel constancy.



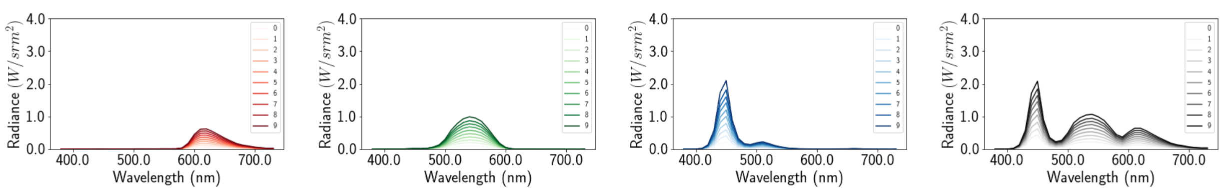
(a) Vive



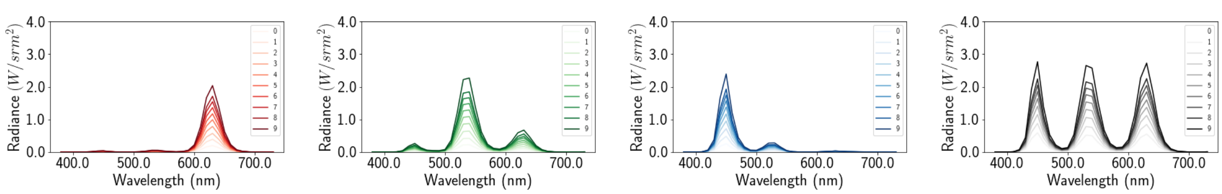
(b) Oculus



(c) Fove



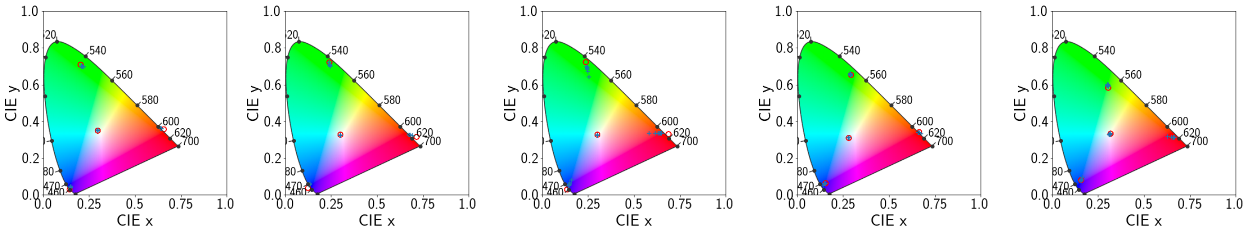
(d) Pimax



(e) Varjo

Figure 3.4: **Tonemapping Countered:** Per channel spectral distribution graph. The X axis denotes the wavelength in nanometers and the Y axis denotes the spectral output at that wavelength. The spectral distribution of different shades of red, green, blue, and white (from left to right) are shown for each device (top to bottom)

In Figure 3.5 we see that the drift in Fove HMD for the chromaticity coordinates of intermediate shades of the whites and primaries is still present. All the primaries theoretical positions now reside within the chromaticity diagram and except for Fove, agree perfectly with measurements.



(a) Vive (b) Oculus (c) Fove (d) Pimax (e) Varjo

Figure 3.5: **Tonemapping Countered:** CIE 1931 Chromaticity diagram with 'x' denoting actual device output for different shades (0.1 through 0.9) of the primaries. 'o' denotes the theoretical position of the actual primaries using the calibration matrix.

3.1.4 Calibration Test

3.2 Rendering with post-process tonemapping disabled

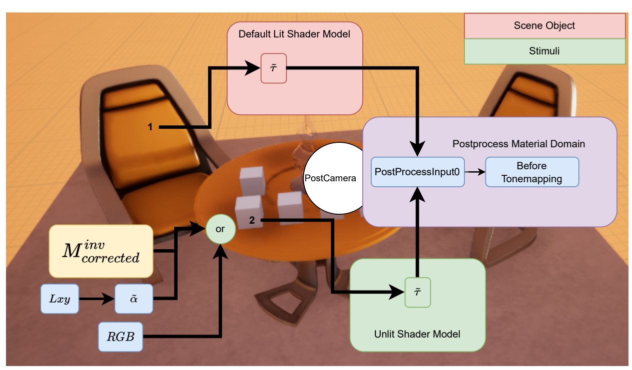


Figure 3.6: Demonstration of rendering pipelines for scene object and stimuli object in selective correction pipeline.

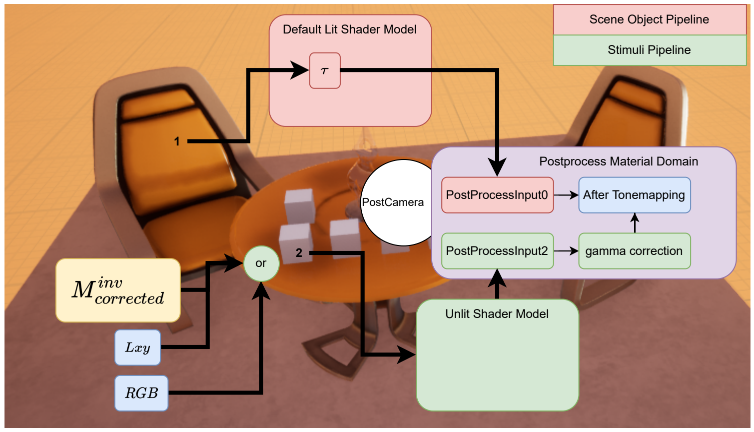
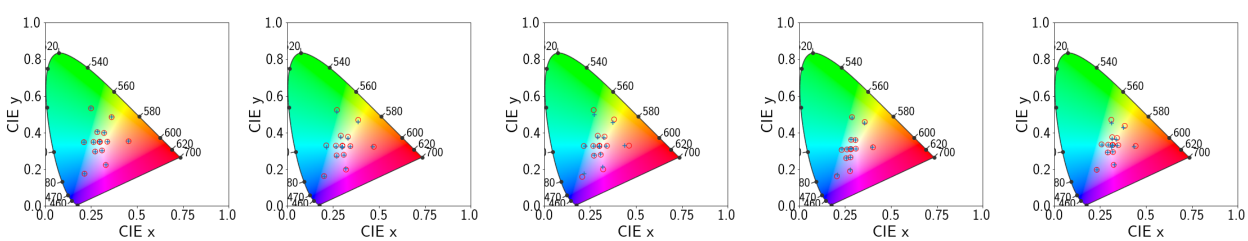


Figure 3.7: Demonstration of parallel rendering pipelines (i) Default-lit, and (ii) gamma-corrected and unlit.

The approach shown in Figure 3.7 offers better results compared to the approach in Figure 3.6. This rendering pipeline shows how the input emissive or chromaticity values are interpreted to render accurate pixels to the HMD. With the post-processing routines re-enabled and application of corrective material, the HMDs now conform to standard calibration procedure. Again, we tested its accuracy by rendering the cube corners. We used the newly calibrated $M_{corrected}$ to compute the nominal values $XYZ = M \cdot RGB^T_{cubes}$ and converting to Lxy space. In Figure 3.8, we see how the measured values and nominal values are very close, indicating that it is possible to control the color of the emitted light with our strategy.



(a) Vive (b) Oculus (c) Fove (d) Pimax (e) Varjo

Figure 3.8: **Tonemapping Countered:** CIE 1931 Chromaticity diagram with 'x' denoting actual device output for different points on the cubes discussed earlier.'o' denotes the theoretical position of the actual RGB values using the calibration matrix.

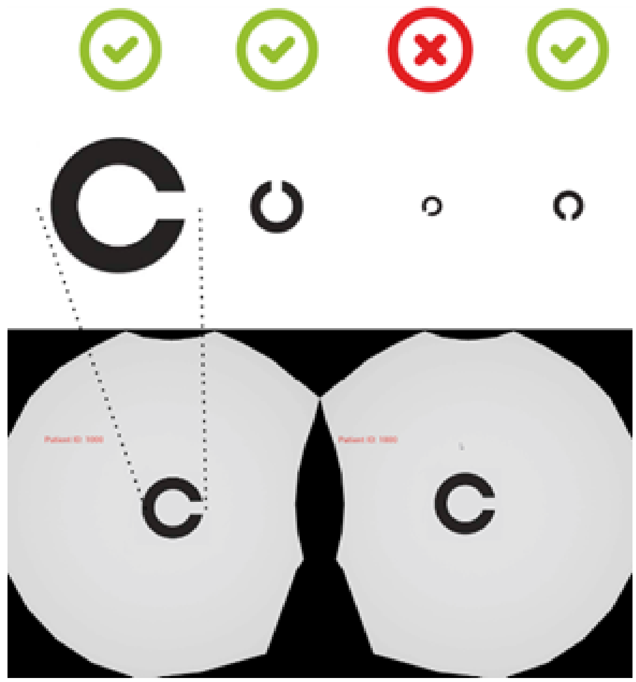
Chapter 4

Towards XR-based Visual Function Modeling Framework

The majority of the chapter is adapted from [146, 145, 219, 216, 217, 215, 214, 174, 173, 9, 218].

4.1 Unified Framework for Multimodal Visual Assessment

Following the hardware and software considerations for this head-mounted display, determining the visual assessments that will be employed on this system is a critical next step. Visual assessments have played an important role in under standing SANS clinical characteristics, such as the initial findings of decreased near visual acuity. Visual outcomes from these tests may not parallel the diagnostic power of imaging modalities for the pathophysiology of SANS; however, these tests can help further characterize SANS clinical symptoms and the functional outcomes may be linked to certain imaging findings observed in terrestrial pathologies. Consistent monitoring of vision will be increasingly important during missions with longer exposure to microgravity than what is currently known. In this section, we provide a discussion of the various visual assessments being considered for this multimodal system and the unique strengths of these tests including visual acuity, color vision, contrast sensitivity, perimetry, and metamorphopsia analysis.

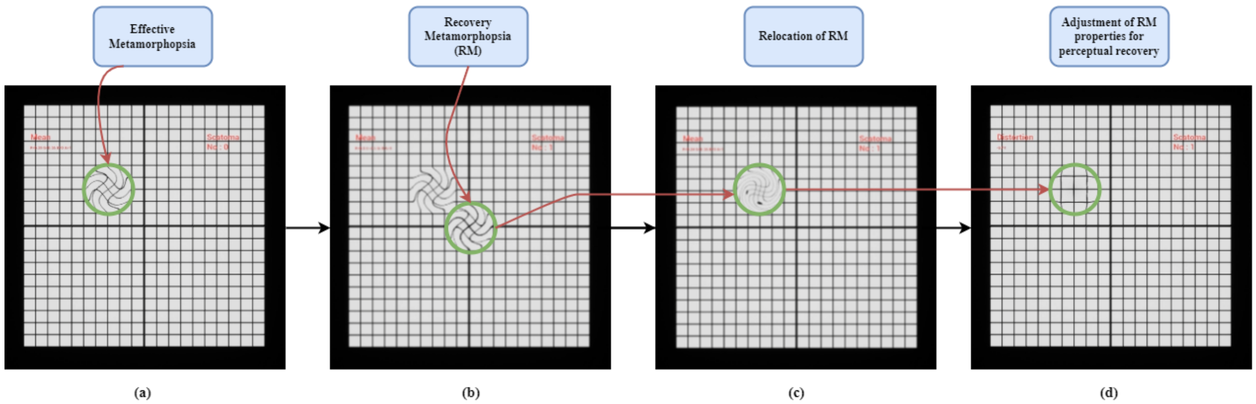


(a)

Figure 4.1: VR-based Visual Acuity Random optotypes are presented to the subject at scales following the staircase method. In the monocular testing variant, only one of the binocular displays is active at a time. In the dynamic VA test, the optotypes move along a horizontal line. Session performance is stored and used to update the parametric model.

4.1.1 Static and Dynamic Visual Acuity

Building upon standard assessments in visual acuity (VA), it is imperative to understand the impact of spaceflight on dynamic VA. Dynamic VA measures the ability of the eye to move in response to moving objects and can be measured when an astronaut focuses on an object when either the object, observer (astronaut), or both are in motion. Assessing dynamic VA in modern sports have been heavily researched and these advances may be leveraged to aid in the integration of this assessment for spaceflight. Because astronauts move differently in microgravity compared to the terrestrial environment and have to adjust their vision accordingly, dynamic VA may provide a more accurate metric for vision-related performance during spaceflight. This can also be used to help astronauts adjust to dynamic vision changes terrestrially. By moving random optotypes with a fixed velocity in the VR system similar to movement in the microgravity environment, astronauts will be able to simulate the dynamic vision changes before launch. In addition to dynamic VA, Bayesian inferential techniques have recently been utilized to develop a more precise vision test and can reduce VA errors compared to chart-based exams. VA tests are usually reported as a single numerical value that does not indicate the confidence in test results. Therefore, studies have utilized Visual Response Curves in the past to more robustly assess the acuity of a single user; however, these models either take too long to compute or are unreliable at specific ranges. A novel method proposed by Piech and coworkers in 2020 takes considerably less time to model accurately the visual acuity of subjects with a parametric model that can be updated with each response and trial. This adaptive approach may well be suited for use during LDSF to further understand SANS. Instead of using only one-dimensional data points such as the logMAR value, utilization of Bayesian techniques would allow for a comparison of multidimensional data, with unique prior probability values collected from terrestrial trials for each subject. This may lead to a more powerful diagnostic tool that can detect subtle variation in the subjects' vision. These portions of research are under development, but its successful deployment may allow astronauts to transition to the microgravity environment sooner and expedite the process for optimal performance during LDSF. The Figure 4.1 shows stimuli presentation procedure for visual acuity based test.



(a)

Figure 4.2: Perceptual Modeling of Visual Distortion. The process illustrates how the VR-based Amsler grid functions. (a) The visual distortion or inherent metamorphopsia (IM) present in the individual. The straight grid lines appear distorted to the user. (b) A computer generated recovery metamorphopsia (RM) is added to the grid to counteract the perceptual impact of the IM. (c) The distortion is relocated to the position of the IM. (d) The subject manipulates properties of the RM to completely nullify the impairment of IM. This method produces a recovery measure as a byproduct of the assessment process.

Given that chorioretinal folds may eventually lead to chorioretinal fold-related maculopathy, close monitoring of macular function during still longer periods of spaceflight is of high interest. The Amsler grid is particularly useful in cases with metamorphopsia, visual distortion that often arises from disorders of the macula. It is a standardized grid of horizontal and vertical lines used to visualize any paracentral or central distortion or loss of visual field. The 3D ComputerAutomated Threshold Amsler Grid Test is a variation of this perceptual test. It is typically performed on a laptop computer (such as on the ISS) that takes about 5 minutes per eye to complete. With one eye covered, the subject sits in front of a display monitor divided into a grid as seen in Figure 4.2. Advances in metamorphopsia assessment include building personalized representations for individuals by establishing a parametric model of their perceptual deficit. This novel method may be useful for astronauts during exploration missions and can be accomplished through the Perceptual Deficit Model (PDM). PDM is modeled with a Gaussian mixture model that can evaluate astronauts based on the location and amount of luminance degradation, rotational, and spatial visual distortion. At the start,the Amsler grid is displayed to both eyes. While looking at a fixation point in grid, if the straight grid lines appear to be distorted in one of the eyes,the user selects which eye has this problem. The eyes are tracked for fixation losses. Their healthy eye is then shown a separate but identical grid. The user will then attempt to emulate the deficient eye's metamorphopsia on the healthy eye using the motion controllers. This manipulation is constructed as a Gaussian mixture model of distortion. When the two grids look similar, the user is done with the test and the Gaussian mixture model parameters are stored. Fig. 11 shows a scene from the VR-based Amsler grid test.

One of the prominent advantages in the multimodal integration of visual function tests is that it builds upon the existing visual function tests on the ISS that do not require additional operators and can be completed relatively quickly compared to in-flight imaging modalities such as funduscopy, OCT, and US. Devices such as fundus cameras and OCT often require the presence of an operator for proper testing, necessitating additional time and crewmember availability to run these tests. As previously mentioned, imaging modalities such as US can be highly operator dependent, whereas visual function tests are generally more independent. Thus, vision assessments, such as VA, color vision, contrast sensitivity, perimetry, and metamorphopsia, are highly complementary to the current imaging modalities for SANS monitoring.

This hardware and visual data must be paired with a computational framework capable of fusing multimodal data for discovering complex relationships between changes made to the physiology and function of systems affected by SANS that are beyond human intuition. Following the fusion of multimodal data,the technology must establish the reliability, validity, and efficacy of this computational framework in predicting both the structural and functional changes in multiple populations when only a subset of data modalities is available. This multipopulation study includes the utilization of deidentified astronaut imaging and medical data from NASA, terrestrial analog patient data (e.g., HDT bed rest), and regular control data on Earth (Fig. 12B). Lastly, the computational framework and VR visual assessment technology must be merged and prospectively validated with subjects from each population for in-flight use onboard the ISS and future LDSF missions (Figs. 12C and 12D).

4.1.2 Contrast Sensitivity

The CS function represents a continuum of sensitivity thresholds sampled using stimuli with varied spatial frequencies to identify the lowest contrast at which the stimulus is still visible to an individual.

Terrestrial evidence suggests that there may be a relationship between CS and RNFL thickness. Amanullah and coworkers demonstrated a correlation in CS in the upper left quadrant of vision and thickness in the RNFL inferior quadrant in patients with glaucoma, supporting the evidence that CS may be used as an indirect indication for RNFL changes. Ultimately, the integration of a rapid CS test would help track RNFL thickness more frequently, reinforcing the OCT based findings, while ensuring that the astronauts have healthy contrast sensitivity. Current studies suggest that, after establishing a base CS, routine VA and letter-based CS can be used to monitor changes in the whole CS function, bringing down the testing time to around 2 minutes. By incorporating CS assessments for spaceflight,this advancement will add invaluable information to increase our ability to study SANS.

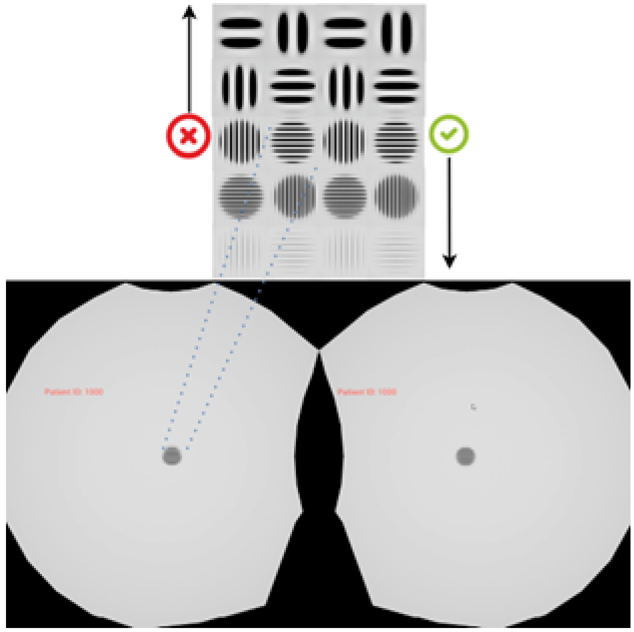


Figure 4.3: VR-based Contrast Sensitivity Test For a given spatial frequency and contrast level, four orientations of Gabor patches are presented per step. If the subject is able to correctly identify the majority of orientation directions, the contrast is reduced, and spatial frequency is increased. Otherwise, spatial frequency is decreased and if more mistakes are made, contrast is increased in an adaptive manner.

The stimuli for measuring CS in a head-mounted device show a gray noise with standardized grating and contrast (e.g., small area of fuzzy bars alternating between light and dark) on a completely white background. The noise is smoothly moved across the screen, while the user's ability to track the stimuli is verified through monitoring the gaze direction, position, velocity, and acceleration, comparing it with actual motion ofthe noise. The continuous success of the test subject decreases the contrast and spatial frequency; however, after significant deviation between the 2 motions, the contrast is increased. The monocular test produces two CS function assessments for the two eyes. This collection of CS implementation into the multimodal VR system will offer a considerable advantage over traditional vision screening systems for SANS. This is due to the ability to control the testing environment from external factors, such as illumination, which can impact testing.

The high-contrast visual tests available at the ISS may not be sensitive enough to capture neuro-ophthalmic disease or disease of the optic nerve. Contrast sensitivity (CS) is a test currently performed when an astronaut is clinically indicated during a spaceflight. The pathophysiology of SANS remains poorly understood; however, having a further understanding of terrestrial analogs of SANS, such as idiopathic intracranial hypertension (IIH), may play a key role in better understanding this condition. SANS and terrestrial IIH share similarities such as optic disc edema and globe flattening. Retinal and choroidal folds have also been reported in both SANS and IIH. Although there is not a perfect terrestrial analog for SANS, this hypothesis and the clinical similarities suggest that IIH may serve as a close analog for SANS. However, several differences exist between SANS and IIH. Astronauts have not reported diplopia, pulse-synchronous tinnitus, or severe headache during LDSF. IIH is a metabolic disease driving CSF hypersecretion, whereas SANS is directly related to the microgravity environment. There is also a much larger proportion of individuals with SANS with asymmetric or unilateral optic disc edema than with the typical symmetrical optic disc edema in IIH. Post-flight lumbar puncture (LP) opening of pressures in the astronauts with SANS has also shown normal to slightly elevated values, which differs from IIH. However, it is important to note that LPs have been done, in some cases, weeks, months, and years following LDSF. In addition, parabolic flight studies have shown that there are no increases in intracranial pressure (ICP) that are above supine level. It should be noted that parabolic flights allow for only minutes of weightlessness in contrast to LDSF, which last several months. The name "SANS" reflects other potential etiologies for these findings, including the ocular glymphatic system, upward brain shift, cerebral blood volume pulsatility, and genetic/metabolic factors. Anemia has recently been implicated in the terrestrial development of pseudotumor cerebri. Astronauts have a lower red blood cell mass than their preflight values, but these do not meet a clinical definition of anemia, so whether or not this has any role in SANS pathogenesis is unknown.

Rehaman et. al.[161] recently reported changes in CS in patients with IIH. This study had 10 IIH patients undergo the Spaeth–Richman Contrast Sensitivity (SPARCS) test, an online test that evaluates contrast sensitivity in one central quadrant and four peripheral quadrants. This novel study demonstrated that peripheral CS (in the inferonasal, inferotemporal, and superonasal quadrants) was significantly more affected than central CS in IIH patients, indicating that peripheral CS testing may play a role in the clinical evaluation of IIH. These results, however, may also have extraterrestrial implications for CS testing in SANS. This syndrome is one of the largest potential barriers to future crewed spaceflight and the potential role of CS in SANS continues to expand. Maintaining adequate CS is vital for mission performance to allow astronauts to discriminate finer details or objects from their background.

The prolonged periods of optic disc edema seen in SANS may lead to retinal ganglion damage at the optic nerve head. As also mentioned in a separate study by Rehman et al., the parvocellular pathway and magnocellular pathway may be affected retinal ganglion cell damage during optic disc edema [160]. This hypothesis that CS decreases during LDSF is much more nuanced and may involve these different pathways. The magnocellular pathway has a higher sensitivity for higher temporal, lower spatial frequencies, which enables contrast detection over a broad luminance range, whereas the parvocellular pathway has a higher sensitivity for lower temporal, higher spatial frequencies, which helps with chromatic processing. By further understanding how these different pathways are affected during spaceflight, we can better characterize how SANS affects the neuro-ophthalmic system. The subsection 4.1.2 shows a conventional VR-based contrast sensitivity test.

4.2 RAPD

4.2.1 VR Implementation & Software

The virtual reality application was developed in unreal engine version 4.24. This specific version was selected because both Fove0[64] and HTC Vive Pro[60] Eye devices had plugins that were supported by that engine version. The programs for the VR environment is written in C++ programming language. Unreal Engine is used to integrate the programs with the VR headsets which made the incorporation convenient and flexible. We used the FoveHMD[65], and SRanipal[188] unreal engine plugins to track pupil diameters in the Fove0 and HTC Vive Pro Eye HMD respectively. For accurate eye-tracking data, each subject went through the same automated calibration process before each session. Unreal engine has a wide support for lighting and illumination that can be configured with real-world units such as lux and cd/m^2. However, our experiments require dichoptic light presentation so that stimuli are only visible to one eye at a time. This makes standard illumination sources unviable as they would be visible to both eyes. Therefore, custom material shaders were created to render in either left or right displays of VR HMDs. As these shaders needed to self-illuminate, they were configured by interpolating the corresponding emissive value from the RGB vs light intensity graph from Figure 4.4.

In this experiment, we needed to ensure that light sources turned on and off with minimal temporal errors. The error is generally not minimal when the event tick functionality in unreal engine is used. Instead, we opted to use time delegates for illumination start, illumination end and a separate pause between mini-sessions. This flexible configuration allowed us to compare different pupillary reflexes to variation in time duration. To induce the effect of a relaxed pupil at the start of a test session, a plane (75cm$\times$75cm) with a red "X" in the middle was gradually moved to a distance of 100m from 2m. After a 5s initial delay, the emissive material corresponding to the left eye starts to illuminate.

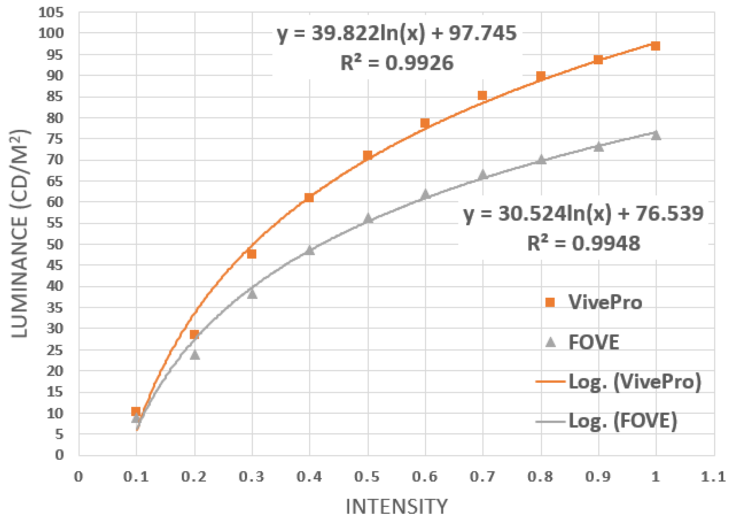
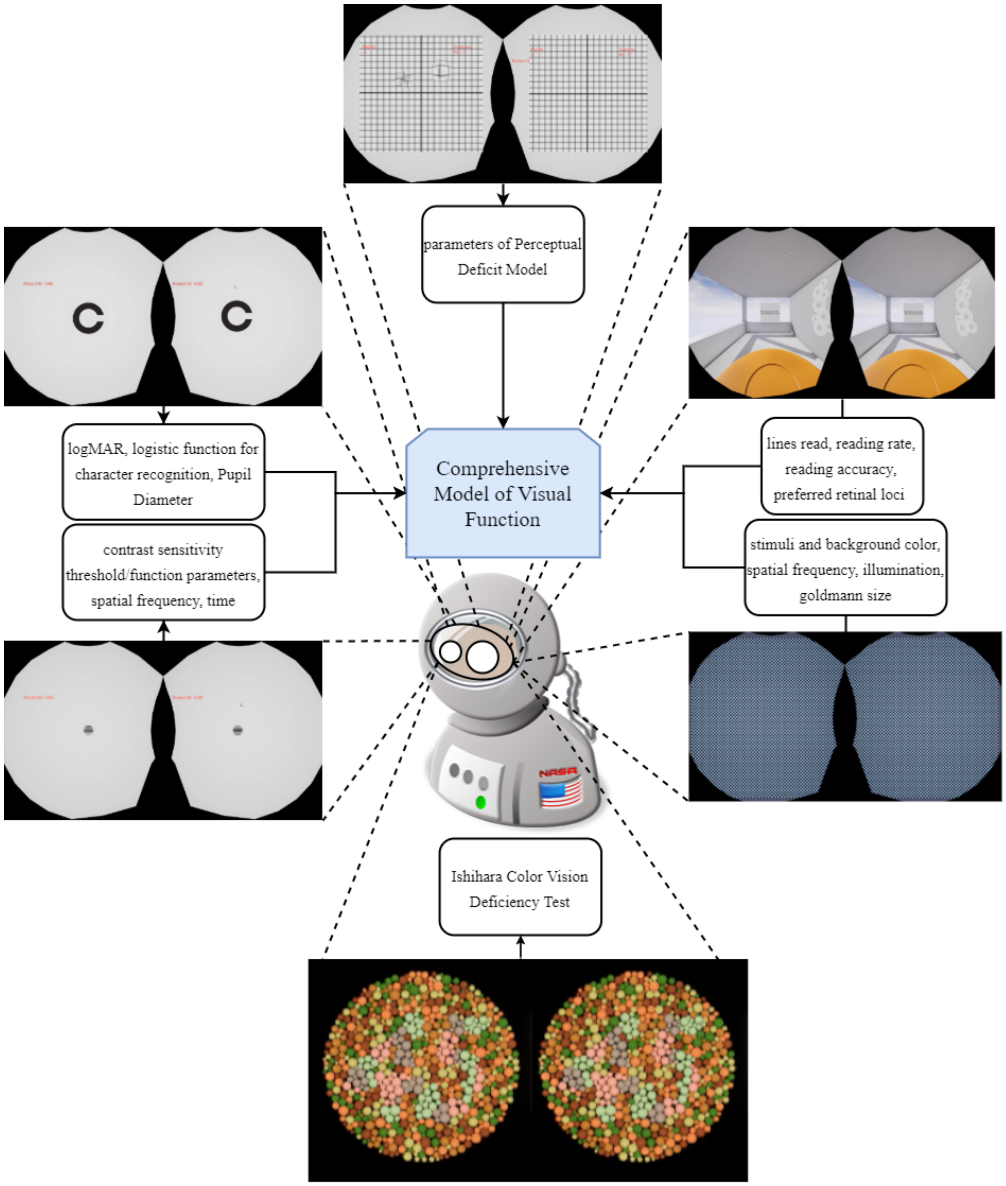


Figure 4.4: Regression curves of RGB values vs luminance of Vive Pro and FOVE 0.

4.3 Comprehensive Assessment using XR

Each of the virtual reality (VR)-based functional modules discussed so far contributes to SANS monitoring by addressing different structural properties impacted by LDSF. Figure 4.5 illustrates how the components complement each other to form a portable, wearable device that can assess indirect indications of SANS. However, considerable terrestrial studies must be carried out to establish normative values for each of the relevant models before the framework can be useful onboard the ISS. In this section we discuss how the component modules can be integrated into a functional whole.

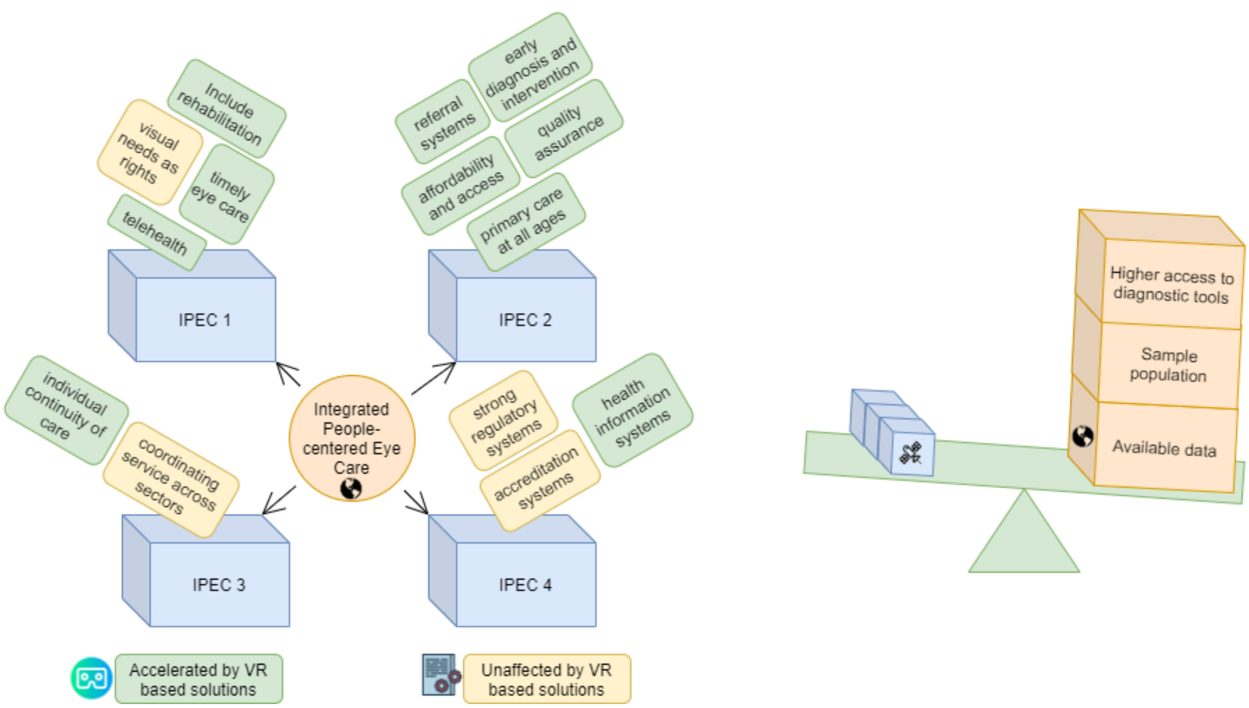


(a)

Figure 4.5: Overview: Teleophthalmology

4.3.1 TeleOphthalmology Implementation

Despite recommendations, only 35–50% of managed care patients receive the recommended annual eye examination. A 2008 study from the National Health and Nutrition Examination Survey showed that over 70% of those with diabetic retinopathy were unaware of their diagnosis [153]. Therefore, the Veterans Affairs have started a telemedicine diabetic retinopathy screening program in the United States which has resulted in decreased commute for eye exams, and screening and treatment at a younger age. The Indian Health Service-Joslin Vision Network also uses tele-ophthalmology at over 80 primary care clinics for screening remote at-risk patients including American and Alaskan Natives [153]. The University of Wisconsin-Madison uses a Topcon NW400 non-mydriatic retinal camera to provide tele-ophthalmology services at their primary care clinics. Upon the primary care physician's recommendation, the patient goes to the tele-ophthalmology unit to obtain fundus photographs prior to going home. However, these telehealth services focus mainly on clinical imaging and ignore more traditional eye exams such as visual acuity and contrast sensitivity. Such an approach to teleophthalmology using VR telepresence can have significant benefits (Figure 4.6).



(a)

Figure 4.6: SANS and the need for VR-based teleophthalmology

4.3.2 System setup

We used the HTC Vive Pro Eye as both the doctor and patient headsets. The eye tracking and AR see-through mode are important features in a tele-ophthalmic tool. For software development we used unreal engine 4.27. Two separate computers were used to run the software as a patient and a doctor. Both LAN and internet connection were implemented. The doctor can choose the 2D or 3D virtual headset view on-demand.

4.3.3 Plugins and services

For eye tracking we use the SRworks plugin for HTC Vive Pro Eye. For network communication we use Unreal Engines EOS plugin. For voice chat we are using the same plugin.

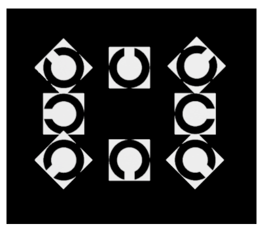


Figure 4.7: Motion controller interaction

4.3.4 Interaction and Interface

The Figure 4.8 shows the workflow until the specific test selection screen. For logging in, the EOS plugin permits a variety of authorization procedures. After the initial login, the agent can either choose to be a doctor or a patient. If there are no active sessions to join to, the patient keeps trying to look for active sessions periodically. If the doctor logs in successfully, a remote session is formed and they can see when a patient joins their session lobby. The doctor can see how long a particular patient has been waiting for and can select anyone from the list to perform the aforementioned visual assessments on. Once the patient is done the doctor moves back to the patient selection screen. The patient session is thus terminated

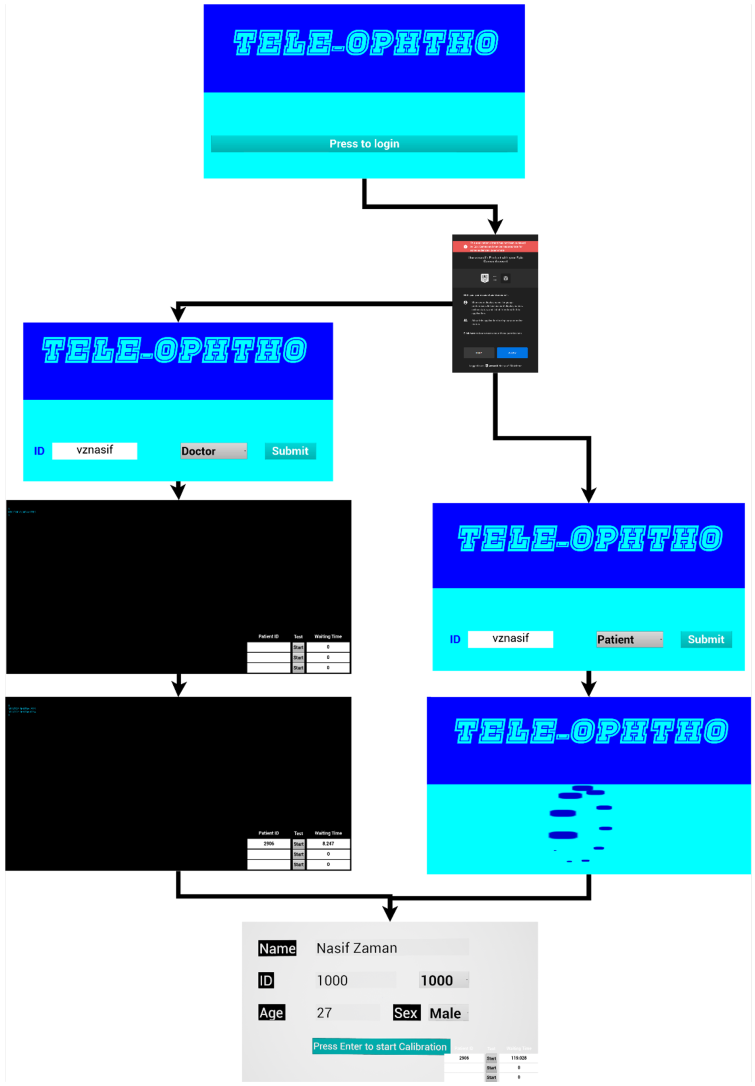


Figure 4.8: User interface workflow

and they are logged out. The doctor can continue to see other patients in the lobby. If the doctor logs out, every patient is logged out of the session.

Currently, the patient cannot interact with the system after the initial log in phase. The doctor has several options to register the verbal response of the patient to the system.

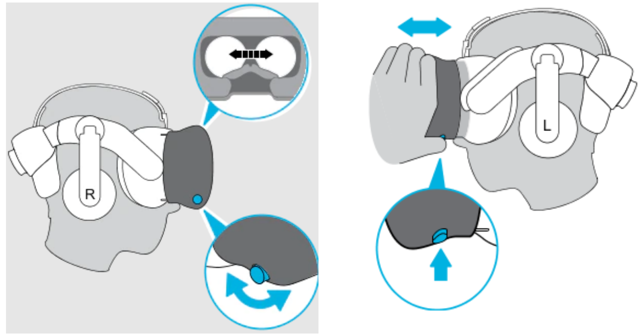
- Keyboard
- Motion Controller

If the doctor is in 2D mode, they can use the keyboard numpad to respond. When the doctor is also in VR mode, they can use the motion controller to register responses. The touchpad on the motion controller can be used for orientation selection for the visual acuity and contrast sensitivity tests. The figure 4.7 shows what the doctor sees while holding the controller. The touchpad can further be used to move the position of the metamorphopsia in the Amsler grid test.

4.4 Case Study 1: VA and CS testing

Any complication in an astronaut's vision during a long duration spaceflight (LDSF) has considerable risk associated with it. As seen in the early era of spaceflight, shuttle cabin members reported difficult reading lists and conducting tasks [19, 190]. With the recent clinical and imaging observations known as Spaceflight Associated Neuro-Ocular Syndrome (SANS) after LDSF, the National Aeronautics and Space Administration (NASA) Human Research Roadmap greatly emphasizes research on understanding and mitigating this neuro-ophthalmic phenomenon for future spaceflight. SANS investigation will be most effective when consistent visual function assessments and ocular imaging can frequently and reliably monitor neuro-ocular health. However, access to state-of-the-art ophthalmic investigative tools is limited during spaceflight due to space and weight constraints. In addition, there is very limited time for astronauts to undergo consistent visual testing and monitoring during spaceflight. Under these constraints, SANS monitoring requires highly efficient utilization of time and resources. The unique environment of ocular monitoring during spaceflight has led to the development of employing visual function tests to monitor SANS progression. Visual function tests conducted through a compact, portable, and standardized system can produce highly relevant data with minimal resources. In this case study, we outline how some human visual functions are measured with our comprehensive VR system.

4.4.1 Eye Tracking Calibration



(a) (b)

Figure 4.9: Calibration of the Headset(a) Interpupillary distance (b) Lenses

Each VR device may be setup slightly differently and the current configuration may not be optimal for each user. If the devices aren't calibrated properly, the visual assessment results may be drastically affected. To mitigate this problem, we start the VR environment and help the participants wear the headset (Figure 4.9). The headset is adjusted so that the participants are comfortable with the fit. Text is displayed in the VR environment to help participants focus by adjusting the interpupillary distance and the lens distance.

Dynamic visual acuity and RAPD use eye tracking to maintain participant fixation. Vive Pro Eye has a plugin called SRanipal for unreal engine. We use the built-in calibration method to start off each test under ideal conditions for the participant.

4.4.2 Visual Acuity with VR

We used Freiburg visual acuity (FrACT) test [13] as well as Metropsis Research Edition [115] to compare the results of each of the static VA tests. The FrACT test was conducted at a distance of 60cm from the screen and with Landolt ring optotypes. For all four of the participants who were tested with FrACT, the test gave the same logMAR value of -0.3 . The results were unchanged when the subjects retook the test. However, the metropsis

Table 4.1: VR-based Visual Assessment of visual acuity, contrast sensitivity, dynamic visual acuity

Subject_ID	**VR VA_L**	**VR VA_R**	**VR VA_B**	**VR CS**	**DVA**
1001	0.475	0.475	0.425	2.401153	0.775
1002	0.725	0.575	0.425	2.52353	0.875
1003	0.575	0.575	0.475	2.52353	0.875
1004	0.625	0.475	0.375	>2.523	0.975
1005	0.475	0.475	0.475	2.195319	0.775
1006	1.375	0.675	0.975	1.914629	0.825
1007	0.525	0.575	0.425	2.195319	0.775
1008	0.475	0.475	0.425	2.382802	0.775
1009	0.475	0.575	0.475	2.335912	0.825
1010	0.625	0.525	0.425	2.52353	0.775
1011	0.475	0.475	0.475	2.24217	0.825
1012	0.475	0.475	0.475	2.24217	0.775
1013	0.625	0.975	0.575	1.914629	0.825
1014	0.575	0.625	0.525	>2.523	0.775
1015	0.475	0.525	0.475	2.476612	0.775
1016	0.425	0.475	0.375	>2.523	0.875
1017	0.375	0.725	0.675	2.054873	0.775
1018	0.675	0.475	0.375	2.429702	0.775

system provided more accurate results. VR based binocular visual acuity gave a maximum result of 0.375 logMAR. That means, a person with a VA of 20/10 would only be able to exhibit a VA of 20/50 inside the VR environment. When trying to recognize the smaller optotypes, the subject reported that the display pixels could be noticed and the optotypes were too small to be represented by those limited number of pixels. The results are shown in Table 4.1. These results are comparable to those obtained by [187]. Although they report that the mean acuity of 20/25 dropped to about 20/100, in our case the drop was from 20/10 to 20/50.

FrACT does not have a way to measure dynamic visual acuity. In VR, the subject exhibited a dynamic visual acuity that correlated highly with the binocular visual acuity with a relative offset. However, the moving stimuli was highly inconsistent during presentation, mostly due to motion blur (although motion blur was disabled in scene camera). The entire character would often disappear and reappear, with some corners getting brighter or darker. This is to be expected, because OLED displays have prominent motion blur. So, a better strategy would need to be devised to better test dynamic visual acuity.

4.4.3 Contrast Sensitivity with VR

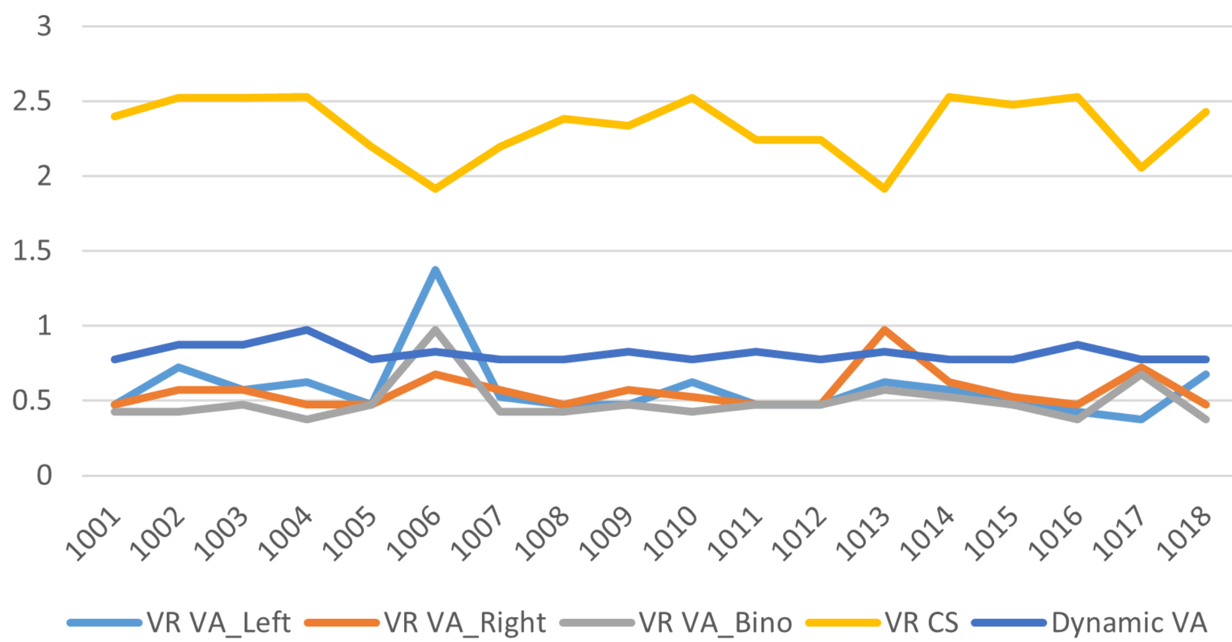


Figure 4.10: VR-based visual assessment subject data

The contrast sensitivity values are shown in subsection 4.4.3. The gabor patch stimuli was used in our VR system. However, the measured value in both systems were very close. FrACT measured the subject's contrast sensitivity at 1.97 logCS, whereas the VR test measured it at 1.913 logCS. The metropsis system provided detailed contrast sensitivity function (not shown). In [187], the authors do not report the contrast sensitivity level in logCS or any other comparable metric, instead counting the number of low contrast object orientations recognized. Our test measure is a considerable improvement over such tests.

4.5 Case Study 2: Dynamic Visual Acuity testing

In our experiment design, dynamic visual acuity is measured binocularly. A single Landolt C is displayed at a fixed distance of 6 meters from the observer and moved horizontally across from left to right and right to left at an angular speed of 30 degrees/sec. In each presentation, the Landolt C can be oriented at any of the eight directions. The participants use the numpad keys to respond to the direction of the gap in the Landolt C. A staircase method is used to vary the size of the Landolt C after each response. If the participant responds correctly for the same-sized stimuli, the subsequent character size will be decreased logarithmically. Otherwise, it will be increased on along the same logarithmic scale.

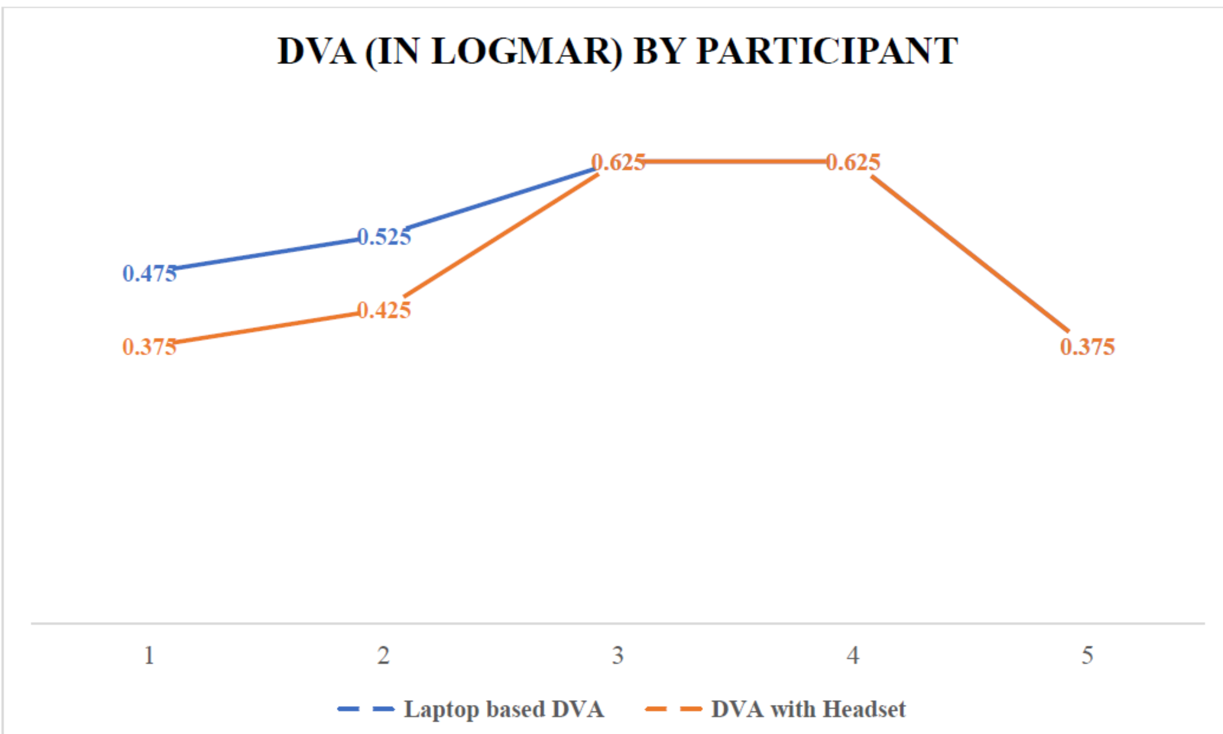


Figure 4.11: DVA plot.

4.5.1 DVA Validation Study Design

An early validation study with 5 participants was conducted comparing this technology verses traditional dynamic visual acuity with a laptop. The laptop-based test was assessed on a 23-inch monitor connected to a PC with Nvidia RTX 2080 GPU, 32 GB RAM and Intel Core-i7 8700. Both tests were conducted during the same session, on the same day and conducted with Landolt ring optotypes. The two assessments were conducted on the same day to minimize bias. The data is plotted in Figure 4.11. Descriptive statistical analysis was primarily conducted due to the nature of the early validation study with a relatively small number of participants. The plot is shown in Figure 4.12. Future studies will likely have comparative statistics.

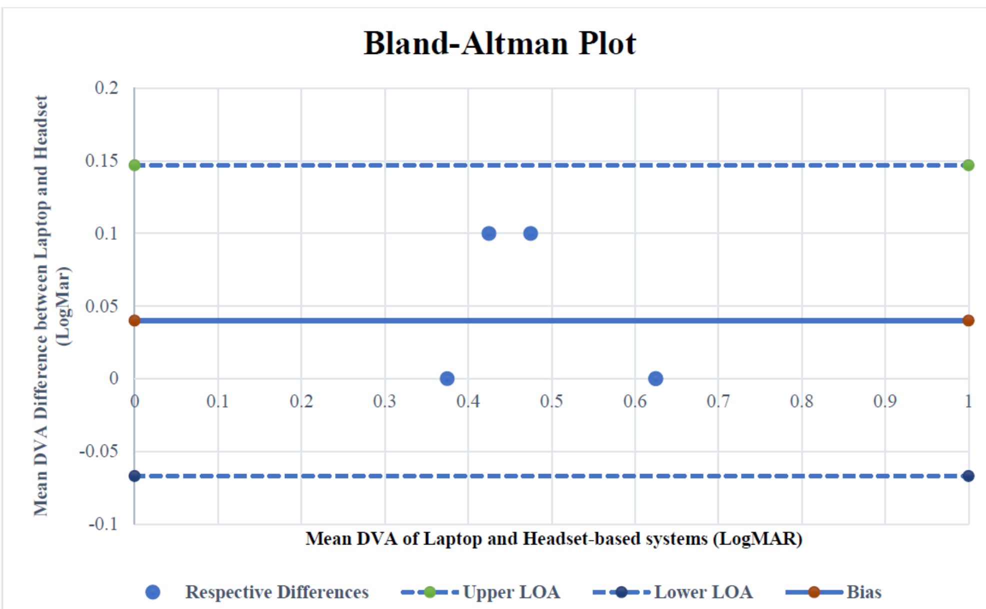


Figure 4.12: DVA Bland-Altman plot.

The mean age of participants in our study was 26.4 ± 1.5 years and 80% of the participants were male. All participants had a best correctable visual acuity of 20/20. Further information of patient demographics can be seen in Table 1. DVA was plotted graphically using Excel version 16.44 (Figure 4). The Pearson correlation greater than 0.9 (0.911) indicating a strong, positive association between both methods of DVA measurement. A Bland-Altman plot was also used to examine the level of agreement (Figure 5). All data points were within the limits of agreement, indicating that our head-mounted system is a promising method to assess DVA.

NASA's Human Research Program (HRP) identified "Risk of Altered Sensorimotor/Vestibular Function" as a potentially significant biomedical risk, with the greatest risk during and following gravitational transitions.5 Gravitational transitions are a critical time for astronauts as they occur while entering and landing on a new planet, which is one of the most difficult spaceflight tasks. Risks during landing include potential loss of life, vehicular damage, or damage to other assets. Although all piloted spacecraft landings to date have been successful, the risk of failure during Mars missions is significantly larger due to a prolonged period in microgravity (6 months), which will lead to more significant sensorimotor adaptations, thus likely lead to a larger physiological response to the gravitational transition on entry to Mars. The ability for astronauts to control complex systems in space, requires a combination of cognitive function, visual acuity and spatial orientation perception, all of which have been shown to be impacted in microgravity.

It has previously been shown that dynamic visual acuity can be enhanced after participating in specialized training involving distinct eye movement patterns. Currently, pre-spaceflight training and post-spaceflight rehabilitation protocols are not optimized to attenuate the changes on sensorimotor function and dynamic visual acuity after gravitational transitions. Our VR dynamic visual framework can potentially serve as a countermeasure for astronauts entering another gravitational environment.

Developing a countermeasure for dynamic visual acuity is key as the inability to focus an image on the retina can create sensory conflict and cause motion sickness. Motion sickness is currently experienced by 60%-80% of astronauts during their first 2 to 3 days in microgravity, which may impact their ability to perform critical tasks during gravitational transitions.

Although symptoms such as nausea and vomiting may seem relatively innocuous in a terrestrial environment, vomiting in an extra vehicular activity (EVA) suit could potentially be a life-threatening situation. The Figure 4.13 shows what the participant sees after lens minifying effect.

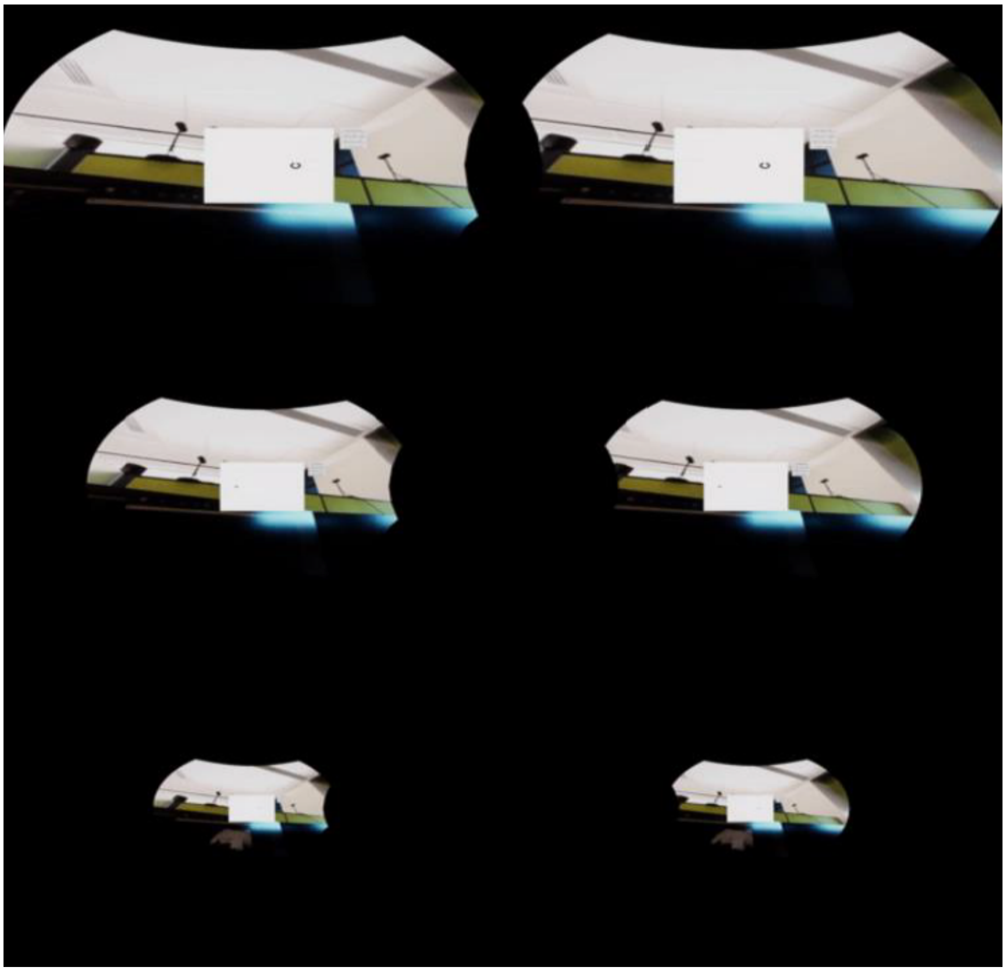


Figure 4.13: DVA Mixed Reality.

Potential drawbacks of our study include not assessing the diagnostic utility of our proposed system as well as not determining the test-retest variability. In future studies, we plan on using a higher resolution VR headset, which will likely improve dynamic visual acuity values. The speed and direction of the stimuli may be varied in future studies to holistically quantify the nature of the deterioration in dynamic visual acuity.

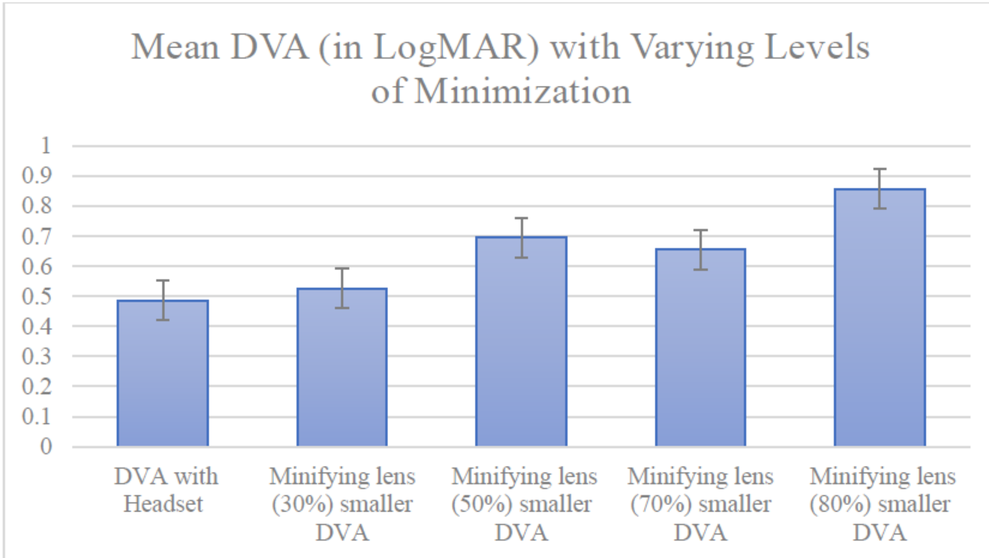


Figure 4.14: DVA minifying lens effect.

There are several limitations to this technology and study. A large study limitation is the small sample size of this early validation study. Future studies will aim to test a larger sample size to increase reliability of this technology when compared to laptop-based methods. There are also technology limitations that can be improved upon. Future improvements from current developments include minimizing motion blur, which commonly occurs in OLED displays and can significantly impact dynamic visual acuity results. Our studies may also be limited by the VR device resolution of 13.09 pixels per degree, as well as minor variations in VR screen brightness at different battery levels. These limitations have been taken into consideration during this ongoing development and are actively being optimized as technological capabilities continue to expand.

4.5.2 XR-based minifying lens effect

A total of 5 participants were enrolled in our trial. Background history was taken to ensure patients had no factors (such as vestibular disorders, vertigo, ocular history, etc.) that would impact DVA measurements. There was a 4:1 male to female ratio.

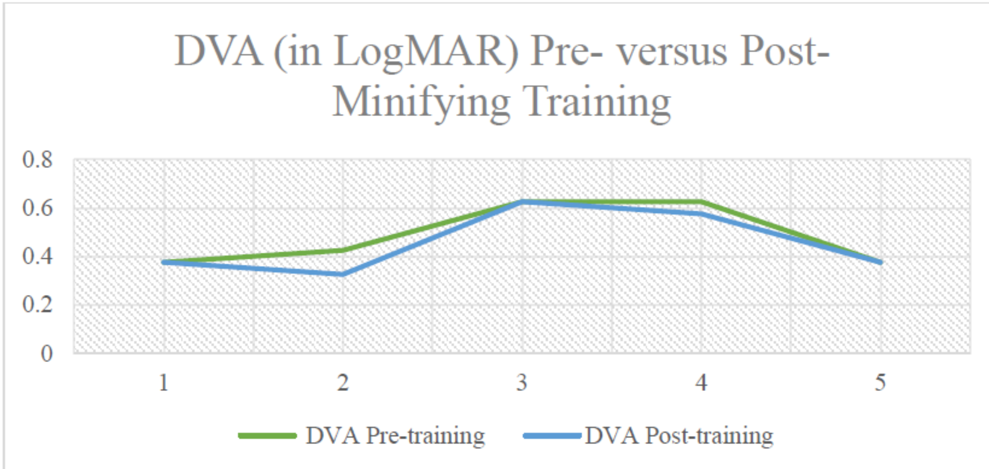


Figure 4.15: DVA minifying lens effect .

DVA of the participants was measured in augmented reality in LogMAR with varying levels of minimization (Figure 4.14). Data was plotted graphically in Figure 6 using Excel version 16.44 (Microsoft). Levels of minimization varied from none, 30%, 50%, 70%, and 80% and the associated mean DVA was 0.485, 0.525, 0.695, 0.655 and 0.855 respectively. Mean DVA tended to decrease as the levels of minimization increased. A mean decrease in DVA (0.370 LogMAR) was noted with the 80% minifying effect, indicating that minified augmented reality can successfully decrease DVA and be used to simulate G-transitions terrestrially.

DVA in augmented reality was measured prior to training, and after training (Figure 4.15). Pre-training DVA of the participants was 0.375, 0.425, 0.625, 0.625, 0.375, while post-training DVA was 0.375, 0.325, 0.625, 0.575, 0.375 respectively. Following the minifying protocol, the mean DVA of the participants tended to increase, with a mean increase of 0.030 LogMAR. This increase in DVA indicates that minifying training can be a potential countermeasure to improve DVA during G-transitions.

To our knowledge this paper was the first to show that minifying training can be used to increase DVA. The minifying training may perform akin to how high-altitude training increases endurance, where the increased difficulties facing DVA in minified augmented re-

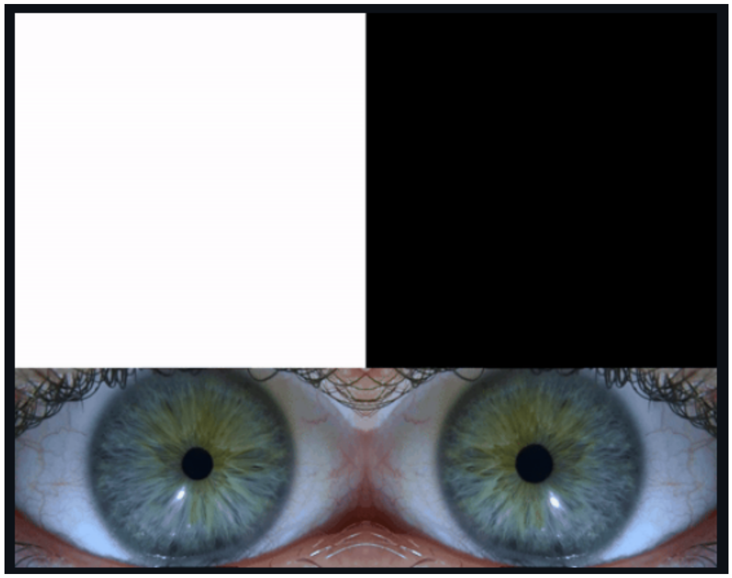


Figure 4.16: Dichoptic Stimulation in RAPD and corresponding pupillary response.

ality may drive visual-cognitive processes to improve. Astronauts training in minified augmented reality may be able to significantly increase mission performance, specifically during G-transitions. A primary limitation to this study was the small sample size of this early validation study. Although our study had a relatively small sample size of 5 participants, we plan to conduct larger studies in the near future examining the effects of minified augmented reality on DVA and on skill-specific tasks. Future studies will employ comparative statistics to assess for statistical significance, which was not performed in this paper to the nature of this early validation study. Future studies will also assess the effect of duration of minified augmented reality on DVA.

4.6 Case Study 3: RAPD testing

Subjects for this research study were recruited from students and scholars of the University of Nevada, Reno. The inclusion criteria for the controls were from ages 18 to 85 years and no history of RAPD. In total, 31 controls participated in the study. However, only 27 participants completed the study. The remaining participants only performed the first

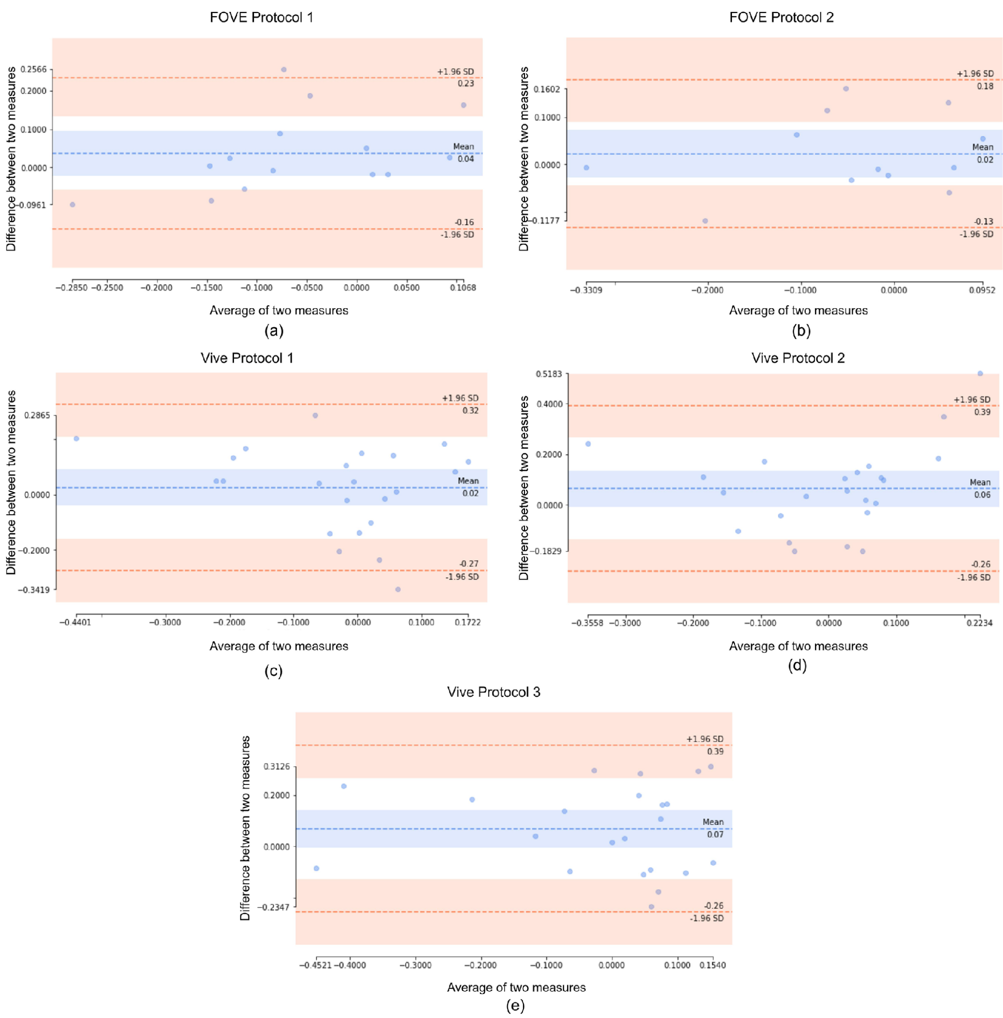


Figure 4.17: Bland Altman Plot of each device and protocol.

round of the study and were excluded from the evaluation of the variability. Out of the 27 participants, 8 participants were female, and 19 participants were male. The Figure 4.16 shows how different stimulation are dichoptically presented to the two eyes.

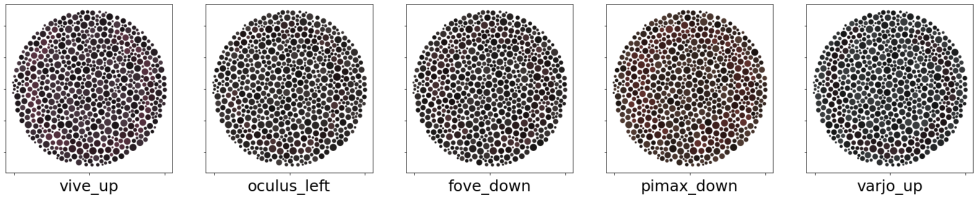
The test–retest variability of results from RAPD testing is shown in Figure 4.17 using Bland–Altman plot.

FOVE protocols 1 and 2 both showed considerably smaller difference values than the Vive protocols. Even though FOVE protocol 2 and Vive protocol 1 showed similar bias values, the spread was much greater in Vive protocol 1. Crucially, for FOVE, most samples were within the 95% confidence interval for RAPD test–retest score difference. For all the test–retest devices and protocols, the line of identity was within the confidence interval, signifying low bias and high accuracy. Some points in Vive protocols showed a high difference between test and retest, which may have led to completely different diagnostic conclusions for physicians. However, in the Vive protocols, the extreme scores had a relatively small test–retest difference, thereby mitigating the chance of wrong classification. Importantly, we can see that for most of the samples, the test and retest scores had a mean within the normal ranges, as expected. For examples that were outside the normal ranges (-0.3, 0.3), the FOVE protocols appeared to be more consistent than the Vive protocols.

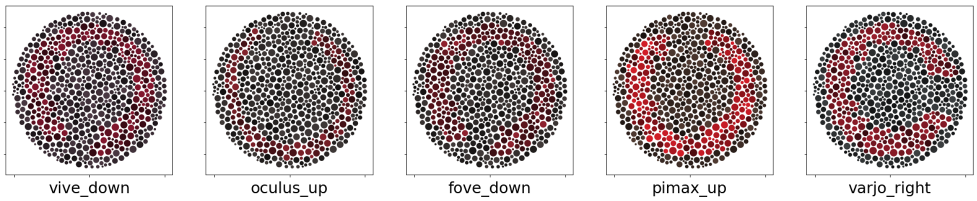
The results are consistent with those reported in earlier literature in terms of the distribution of RAPD scores in controls. For instance, Satou et al[175] and Wilhelm et al.[225] discovered that the distribution of RAPD scores in people with normal vision lies between –0.5 and 0.5 as it is estimated that an RAPD may be detected with these techniques in up to 13% of the population with normal vision. Except for one subject with a history of prior refractive surgery, we also discovered the same distribution of RAPD scores. The subject's RAPD score in the second round of the study was determined to be greater than 0.45 log units for all protocols.

4.7 Case Study 4: Color Vision testing

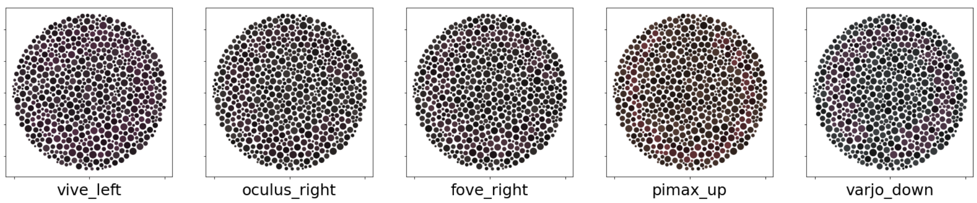
The VR Cambridge Color Test (VR-CCT) is an adaptation of the traditional Cambridge Color Test (CCT) designed to assess color vision deficiencies within a virtual reality (VR) environment. This methodology leverages the calibration scheme devised in 3. The implementation follows the paper [159], where chromatic sensitivity was measured across different axes of color space without the need to define equiluminance for each subject before administering the color test. This is significant because most computer-controlled tests require the establishment of equiluminance, which can be a complex and time-consuming process.



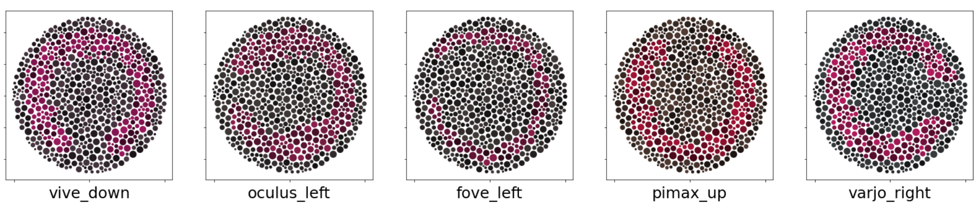
(a) Protan



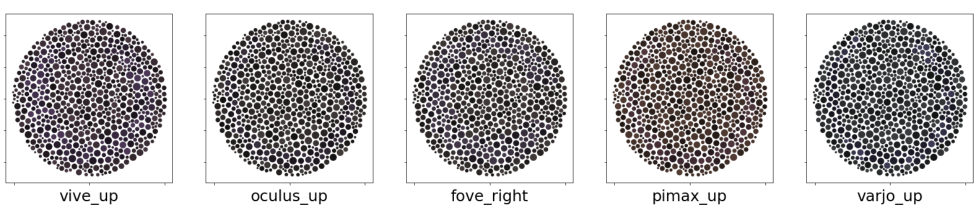
(b) Protan Saturated



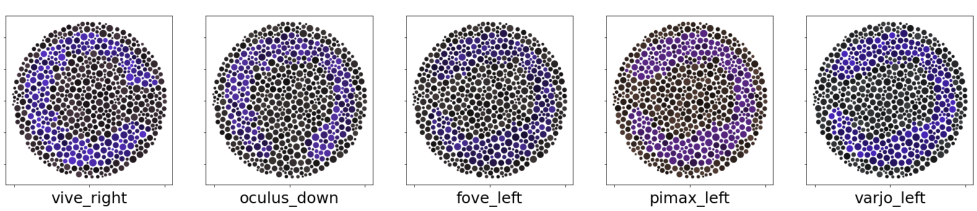
(c) Deutan



(d) Deutan Saturated



(e) Tritan



(f) Tritan Saturated

Figure 4.18: VR-CCT device-agnostic stimuli

Luminance noise was introduced to the visual stimuli to mask luminance cues that could otherwise be used by subjects to perform the test. Masking contours were also employed to ensure that the subjects' responses were solely based on chromatic information. This approach is particularly useful in natural settings where color-deficient individuals often face challenges, such as finding fruit among foliage, where chromaticity defines an object against a variegated background with randomly varying lightness.

The methodology introduced by this study offers a rapid and efficient way to assess color vision and discriminate between different types of color deficiencies. By circumventing the need for equiluminance definition and focusing on chromatic signals, the test provides a more practical and accurate assessment of color vision, especially in real-world scenarios where luminance cues are not always reliable indicators of color differences.

Calibration of the VR headset is required to ensure accurate color representation. As Figure 4.18 shows, the different devices would output highly varied colors if not appropriately calibrated. In the VR-CCT, participants wear a VR headset and are presented with a series of randomly oriented C much like the visual acuity tests.

Recording of responses and assessment of color vision based on performance in the tasks. Analysis of data to determine the presence and extent of color vision deficiencies. This method offers a device-agnostic approach to color vision testing, potentially increasing the accuracy of diagnoses and the ability to detect subtle changes in color perception that may be indicative of underlying health issues.

The Table 4.2 and Table 4.3 show that the results from a standard cambridge test and the VR based test are very similar.

Table 4.2: CCT Result from color-normal subjects.

SubjectID	az	performance	threshold	vr performance	vr threshold
1	0.07	79	2.6	76	4.02
	4.83	66	4.1	75	3.16
	5.98	79	5.7	70	5.69
2	0.07	75	3.77	66	4.5
	4.83	71	3.8	66	3.5
	5.98	78	10.39	68	5.1
3	0.07	69.4	5.75	71	5.15
	4.83	68.75	6.93	71	4.03
	5.98	81.81	9.6	71	8.54

Table 4.3: CCT Result from color vision deficient subjects.

Deficiency	az	performance	threshold	vr performance	vr threshold
Protanomalous	0.07	80	21.5	73	15
	4.83	71	24.5	69	30
	5.98	46	4.2	50	6.2
Protanomalous	0.07	75	53.1	64	74.7
	4.83	75	30.4	69	14.7
	5.98	79	11	72	10.2
Deuteranope	0.07	79	25.3	76	47.9
	4.83	66	100	75	100
	5.98	79	10.4	70	9

Chapter 5

Towards Simulation Training of Ophthalmic Concepts

The majority of the chapter is adapted from [29] FVT can be a very controversial framework if proper considerations are not mandated. One of the greatest challenge of functional vision assessment is to get appropriate participants that meet the inclusion criteria. Although the percentage of population with visual impairment will increase in the future, they are still challenging to come across and recruit for experimentation. Generally, older demigraphies have mobility challenges that compound these restrictions. Simulated impairments have often been used to circumvent this challenge by using healthy adults to perform the FVT tasks. The controversy may arise if such experiments are conducted solely on healthy subjects. The inherent goal of FVT is to determine accessibility needs of participants and leverage that knowledge in VRT phase to address those accessibility needs. The motto of "Nothing about us without us" is a needed reminder that simulated impairments can be a good start off point, but would never be sufficient.

The FVT framework laid out here is motivated by education rather than empirical FVT of impaired perception. The following goals need to be met for education of impaired perception:

1. Consider the rendering capability of the system as a whole rather than just the game engine
2. The framerate must be atleast 25fps
3. Collect gaze, and pose data for Quality of Life assessment
4. Consider making tradeoffs: if a postprocess shader is decreasing framerate, substitute it with something less accurate but faster

5.1 Blur Adaptation

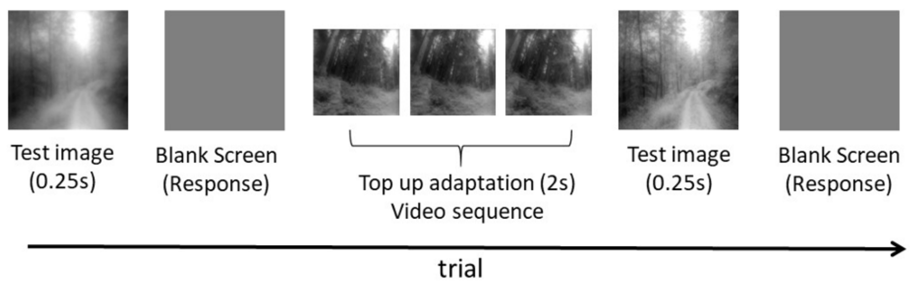
Natural scenes share a statistical regularity called 1/f amplitude spectrum despite considerable variation in their contents [88] (i.e. beaches, forests, and canyons). 1/f amplitude spectrum describes the distribution of energy across spatial frequencies (SF). This distribution becomes linear on a log plot, with a slope generally around 0.8 to 1.5 (mean=1.2) for natural scenes. Our goal is to create a natural 3D environment with realistic foliage, illumination, and shadows so that adaptation to a particular slope for this environment would be analogous to adaptation to real world scenes. In the following section we describe our methods and their challenges.

Unreal Engine is a widely used game engine. It has a vast library of tools targeted to help developers build realistic 3D environments. Features such as Lumen, Nanite, Quixel Megascan and Procedural Content Generation (PCG) are particularly useful for our goal. Lumen renders dynamic diffuse reflections with infinite bounces and indirect specular reflections in large detailed environments. Nanite is a virtualized geometry system that enables rendering of highly detailed mesh objects without compromising the framerate. Quixel Megascan is a huge library of 3D photorealistic assets. Procedural Content Generation is a framework that leverage meshes from Quixel Megascan with photorealistic features. In our work, we combine all of these features to build a photorealistic environment that can be traversed using a Virtual Reality (VR) Head-Mounted Display (HMD). This 3D environment consists of a walk through a forest, amidst trees and on path covered in realistic foliage, leaves and rocks.

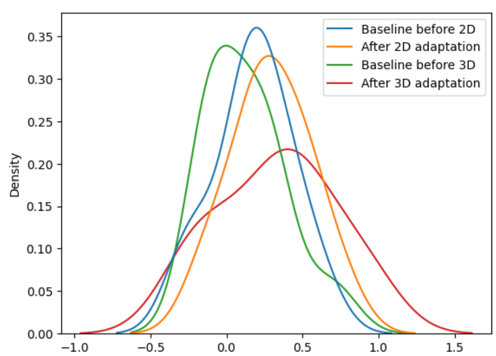
Creating a 3D environment for the purpose of adaptation requires several considerations. Firstly, we need to make sure that the original slope of the majority of rendered frames fall within the expected slope range. Secondly, we need to create an engaging and interactive scenario where users will be motivated to look around the 3D environment. Finally, we need to make sure that the slope transformation that we apply to the 3D environment is real-time for the user to feel completely immersed. We have to remember that Unreal Engine is a game engine and was not purpose built for image processing operations. However, the approach that we previously tried had considerable overhead and was not suitable for real-time rendering in HMD with desired fidelity.

In our second approach, we applied fast fourier transformation (FFT) on a RenderTarget object, computing 1/f slope of the SceneTexture (PostProcessInput0), modifying the 1/f slope for the desired blur adaptation and then applying the RenderTarget to the HMD. Although this approach was considerably faster (11fps vs 5fps) than the previous approach, it was sufficient. We had to upgrade our computer's RAM to accommodate the computationally intensive frame buffer manipulations. Additionally, we built Unreal Engine from source to bypass unnecessary rendering passes that will be discarded through the 1/f slope shift process (FShift) anyway. This approach allowed us to utilize a customized version of foveated rendering that would mask the periphery (¿30 degrees) so that FShift process would not be applied to that section. Our custom HLSL FShift function and the selective foveated application allowed the improvement of framerate (60 fps).

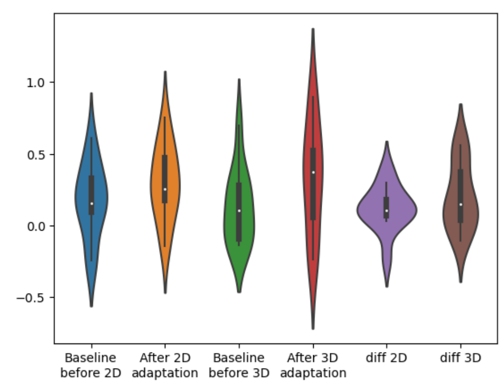
Participants were seated 75 cm from the screen and were shown a test image spanning a visual angle of 5 deg in the center of the screen. In the first trial, the test image was too blurred or too sharpened relative to the original image. During baseline measurements, the test image was shown for 0.25s followed by a blank screen. Participants were asked to judge whether the displayed test image was blurred or sharpened using a two-alternative forced choice task (2-AFC). The next trial started after participants gave the response. Post adaptation, while measuring the adaptation effects we presented the blurred video for 2s as top-up adaptation before the start of each trial. These adaptation effects were measured after 12s of short-term adaptation and every 20 mins for a total of 6 times during the long-term (2hrs) adaptation.



(a) 2D and 3D experiment protocol



(b) Baseline shift with 2D and 3D blur adaptation



(c) Violinplot of blur threshold with 2D and 3D blur adaptation

We carried out user study with the HTC Vive Pro Eye to determine the effect of blur adaptation on perception Figure 5.1(a). The test had two conditions, 2D: where the user would be shown the 2D projection through the HMD and 3D: where the user would see 3D objects with binocular disparity cues and motion parallax etc. With HTC Vive Pro Eye, we were unable to find any adaptation effect. The results are shown in Figure 5.1(b) and

Figure 5.1(c). The reason may be the reduced resolution of the HMD itself. Therefore, our next target was to use the human resolution Varjo XR-3 headset. However, with increased resolution comes increased rendering load and decreased framerate.

The new goal is to record the 3D and 2D renderings and play it in real-time. This would mean that the participant will not be able to look around the scene, but be a passive onlooker. There currently doesn't exist any straightforward way to record high-quality post-processed VR cinematics in Unreal. We are now working on a pipeline that would record the left and right VR output to a RenderTarget that will be postprocessed in a separate python program and the output texture will be projected using Varjo Native SDK that supports 4 views (Left Focus, Left Peripheral, Right Focus and Right Peripheral contexts). The output texture needs to be converted to swapchains for real-time rendering.

5.2 Empty Space Myopia

To combat empty space myopia in pilots, current recommendations are to establish a long-range focal point by focusing on terrain near the horizon, flying outside of smoke or hazy conditions, and focusing on aircraft wing tips in conditions of low visibility to provide additional visual stimulation. However, these tips do not translate well for space travellers in LDSF. One previous suggested countermeasure for this phenomenon in space was to use optical projections outside of the spacecraft windows, to provide astronauts with an opportunity to vary their focal length and focus close to infinity (Skyline, (1963).

This would allow astronauts to be prepared for distance vision to ensure anything incoming towards the spacecraft can be focused on, and identified, immediately.

The advent of extended reality technology has revolutionized how vision can be accessed. Particularly when applying this technology to empty space myopia, there are various strengths to help uphold astronaut accommodation. Extended reality allows for users to continue viewing the external environment through an LED screen. This will be a critical aspect as astronauts can continue to work on tasks onboard the spacecraft while training their accommodation. Eye-tracking technology was used to determine how an individual navigates the simulated aerospace environment and determine which aspects they are focusing on. Foveated rendering was used to reduce the necessary rendering workload.

Our extended reality framework (Figure 5.1) was built in UnrealEngine 4.24 (Epic Games, MD, USA). The UnrealEngine plugin "SRanipal" was used to assess the accuracy of eye tracking. The HTC Vive Pro Eye system (615 pixels per inch, 110 degree field of view) was used to experience the extended reality content. With eye tracking technology, differing auditory feedback was provided based on the location of gaze focus. We also developed an extended reality flight simulator, to provide a realistic simulation of the experience of a pilot. The red dot shows the location of gaze focus, and additional auditory feedback is provided when gaze is focused on a nearby plane (Figure 5.2).

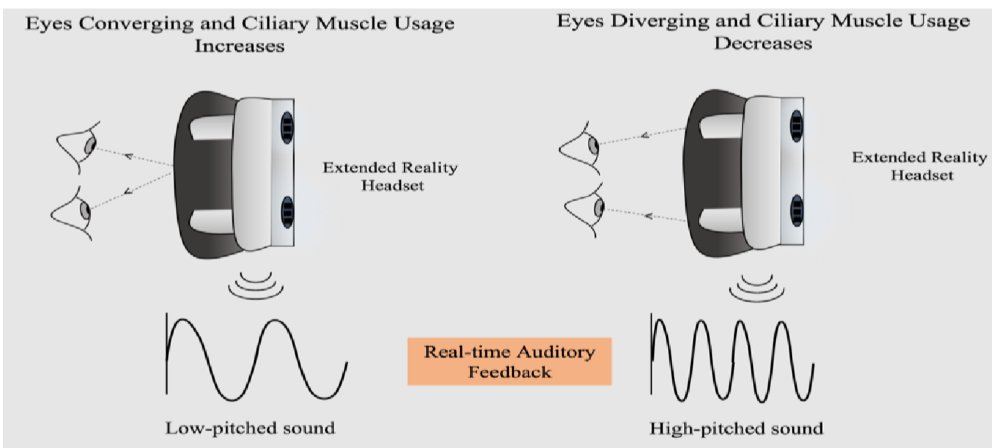


Figure 5.1: Schematic of Extended Reality Framework: Eye detection is used to track eye convergence and eye divergence and real-time auditory feedback is played in real time.

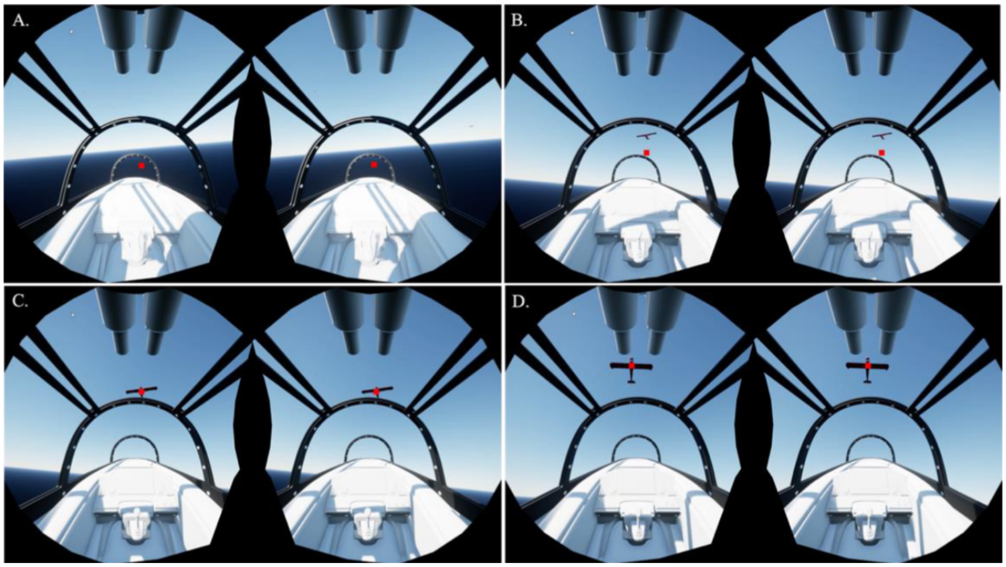
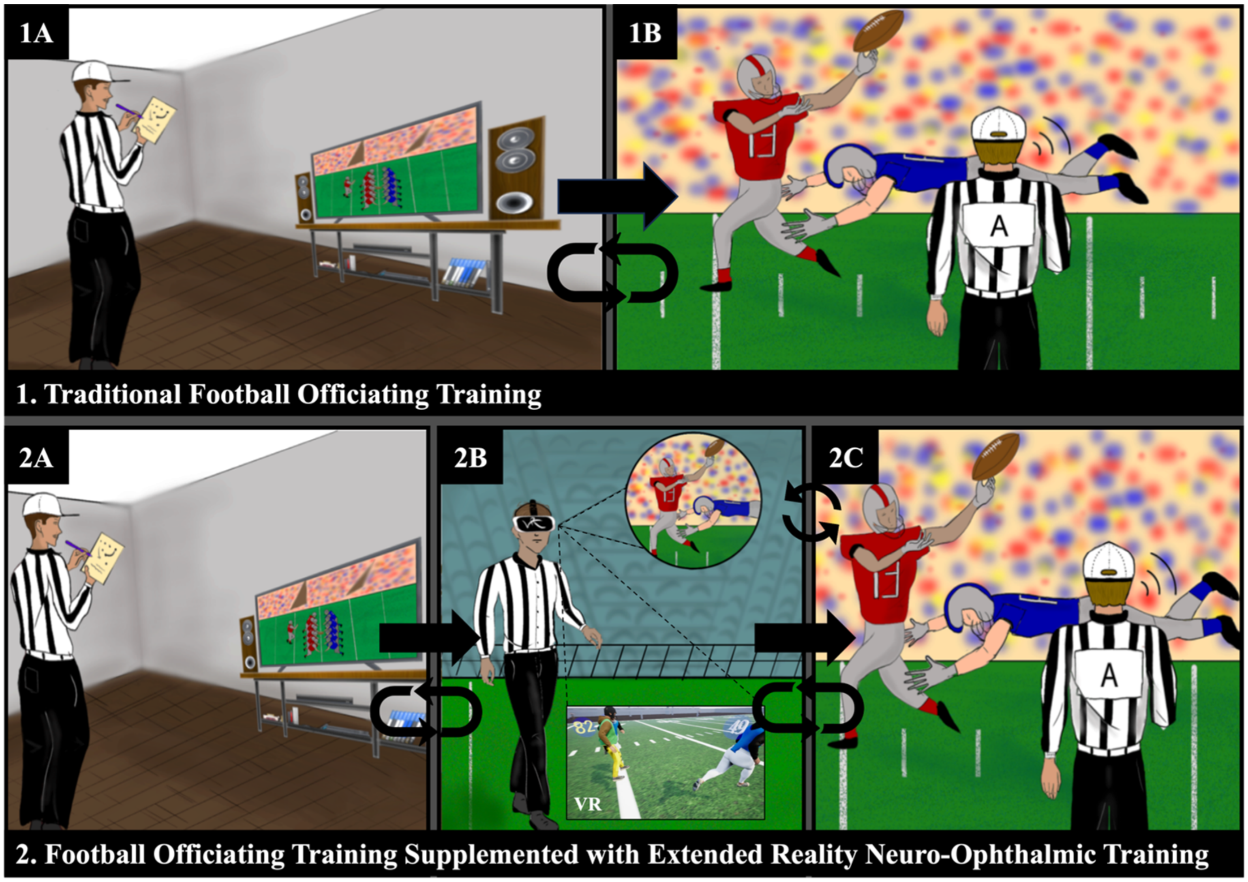


Figure 5.2: Virtual Reality Simulation of a Dynamic Aerospace Environment: The red dot is generated based off eye tracking technology and shows where the participant gaze is focused. A. When gazing into a featureless sky, the focal point is only a few meters ahead (empty space myopia is induced). B. Detection of an approaching airplane is delayed due to this state of empty space myopia. C. Participant gaze is focused on the plane. With no other features in the sky, the direction that the plane is travelling is not yet determined. D. Gaze continues to follow the plane, the path of the approaching plane has been determined.

5.3 Physiology and Visualization Engineering for 3D Virtual On-Field Training

The emergence of VR technology has revolutionized many fields, including sports and medicine 15-20. In this section, we discuss our work in building a 3D virtual reality environment based on real-life NFL play data for simulation and neuro-ophthalmic training for football officiating. We also provide a discussion on the integration of this technology with physiology. We first demonstrate our approach on how we can generate a three-dimensional (3D) explorable environment from limited information about player location and motion without any pre-existing view. The concepts are explained in section 5.3 and Figure 5.3. Future work can then iteratively refine that 3D scene with information from 2D views. If we believe that a full game simulation requires P_Team and B_G, information about each player in the field of



(a) Framework for potential football officiating training with extended reality. Traditional officiating (Top Panels) includes watching gameplay analysis followed by on-field experience. Officiating training with extended reality (Bottom Panels) may include gameplay analysis followed by on-field, actively engaged, extended reality experience to simulate difficult plays that occurred in real-life. This can be cycled with gameplay until officials are comfortable with on-field officiating at any level, particularly when starting to officiate at a higher stakes level.

play and the ball respectively, then 3D reconstruction can be achieved by synthesizing any view V from those set of information using some reconstruction function F:

$$\mathrm{V} = \mathrm{F}\left(\sum_{i=1}^{n} P_{\mathrm{HomeTeam}(\ i)}, \sum_{i=1}^{n} P_{\mathrm{AwayTeam(i)}}\ , P_{\mathrm{Ball}}\right)$$

However, collecting all motion, pose and location data to a about every player with high precision and frequency is itself a non-trivial task. To that end, we have constrained ourselves to using only the information available in the dataset and see how closely the resulting simulation can replicate a real gameplay. So, we introduce a term called G_mechanics that shall encode team and event-related information so that we can adequately synthesize a scene without having access to higher precision and frequency of player pose, motion, and location.

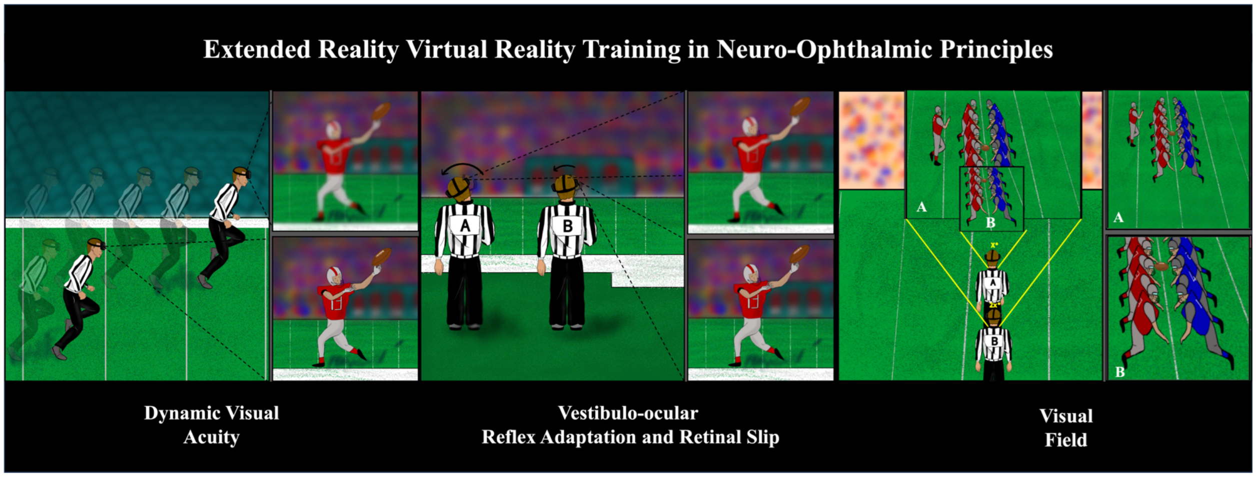
$$\tilde{V} = F\left(G\_\text{mechanics}\ \left(\sum_{i=1}^{n} LP_{\text{HomeTeam }(i)}, \sum_{i=1}^{n} LP_{\text{AwayTeam }(i)}\right), LP_{\text{Ball}}\right)$$

For now, G_mechanics simply uses the distance covered between consecutive frames to predict the player's pose and animation. But future work should use more play-aware conditions such as penalty events, neighboring player animation to construct more precise animation and pose. Here, we collect the component across three publicly available, real-life sports datasets that showcase individual player movement during a real game. Although this paper is focused on football, we utilized large, real-life 2D datasets from various professional sports to build . We discuss later on preprocessing the datasets to ensure it is coherent amongst different sports. This approach allows for including multiple datasets that do not necessarily need to be in one sport. These datasets include:

- NFL Play Data: NFL Big Data Bowl 2022 21
- NBA Play Data: NBA Player Movements 22
- Soccer Data: SoccerTrack 23

consists of the following information:

- Player location information primarily in the form of x and y coordinates with respect to the field of play. So, we had to scale it for representation inside our 3D environment.
- Player jersey number
- Player team
- Only in the NFL data set additional information such as player speed, acceleration and distance covered was included.



(b) Implementation of virtual reality training in neuro-ophthalmic principles to showcase changes in dynamic visual acuity based on running speed, vestibulo-ocular reflex adaptation and retinal slip based on acceleration of head-tilt, and visual field changes based on positioning.

- None of these datasets contained any explicit pose data.
- The soccer dataset had accompanying 2D videos and the NBA and NFL video data can be accessed through official channels if required.

We then preprocessed the dataset to ensure that it is suitable and coherent across the different plays of a single game (1st and 2nd halves) as well as different plays of different sports (1st half of soccer and 2nd play of NBA). All the preprocessing code is available upon reasonable request. The extracted information was stored in csv files for each play for each team and player across different time indices. All csv files available upon reasonable request. For 3D visualization we read and employed the csv files in Unreal Engine 5.3. We created an extension of “Actor” called “FileFormation” that extracts all relevant information to construct LP_Team and LP_ball by taking into account the size of the stadium that the players will be shown in. An instance of that object is placed inside the level with the topfLeft and bottomRight being adjusted to encompass the field. When a specific game is selected, we instantiate each player at the initial location in the field of play according to their team and jersey. The initial player orientation and animation is selected based on subsequent frames. We leverage the MetaHuman plugin by Unreal Engine to generate a random body and face furnished with team specific jerseys. The animations are modified sequences of 3rd person animation available as default. Finally, different referee players are also created at predefined locations where a subject can embody them or virtual cameras at different relative or static locations across the field to explore the 3D gameplay (Figure 5.3). Individuals can switch between different cameras using the following keys: Referees (Numpad 1,2,4,7,8,9,6), Perspective Camera (Numpad 3), Topdown view with respect to the ball (Numpad 5), Random player from either team (Numpad 0). All the UnrealEngine code available upon reasonable request.

(c) Creation of a 3D environment for football officiating training and simulation using real-life NFL play 2D data. Panel A demonstrates preprocessed data from real-life 2D NFL gameplay data that maps out every individual on the field at specific time indices. Panel B showcases the 3D generation of “Actors” and the ball on the field through Unreal Engine that can play out real-life NFL play data. Panel C showcases point of view on the field that can interact with real-life NFL play data and can be utilized with wearable virtual reality for NFL officiating VR simulation and training.

Chapter 6

Towards Rehabilitation of Visual Deficits

The majority of the chapter is adapted from [235, 144] The established frameworks of VFT and FVT provide all the major information for VRT framework to function properly. In this chapter specific use cases will be discussed that leverage the earlier frameworks to make the following decisions:

1. Appropriate device selection
2. Rendering requirements
3. Augmentation customization

When selecting appropriate device for VRT, the following factors are important to consider:

1. Compromised peripheral field: The impaired person will have trouble with navigation, scene context understanding and the selected XR device would need to be lightweight but have greater than usual field of view. The resolution does not need to be significant

as this population generally also has reduced acuity due to advanced age. Luminance also needs to be higher than usual.

2. Compromised central vision: With monocular macula damage, binocular compensation can be useful. In binocular loss, compensation may be provided in the form of auditory feedback or enlarged (or zoomed in) view at the center. High resolution may not be necessary in most cases, but a threshold would need to be met.

3. Compromised color vision: The XR device would need to have high color depth and display gamut should be wide. These users usually do not have compromised acuity, so resolution would also need to be high.

These examples highlight important factors in vision rehabilitation considerations. It may be considerably simpler to use the same device for all parts of the VFT-¿FVT-¿VRT workflow, as the shared properties would reduce variability in the final output. However, this may introduce design, and economic challenges. For example, to measure the peripheral sensitivity map a device with wide field of view is required. However at the FVT and VRT stages, a wide field display would be wasteful, although a wide FoV camera is then an important need. Essentially, the device for VFT needs to have the highest rendering capabilities while the consequent FVT and VRT devices may be selected based on the subject's visual capabilities.

6.1 Case Study 1: Metamorphopsia Correction and Suppression in VR

To simulate metamorphopsia, the HTC Vive Pro Eye headset was used as seen in Figure 6.1. Several technical aspects were taken into consideration when selecting a head-mounted technology to run the countermeasure software for this early validation study. The HTC Vive Pro

Figure 6.1: Simulated metamorphopsia on an Amsler Grid (a) and through the augmented reality camera feed

Eye allows for precision eye-tracking, which allows for additional analytics when conducting assessments. This data will be particularly helpful during spaceflight assessments where there is a higher risk for vestibulo-ocular changes and focus impairments. In addition to assessments, gaze-tracking allows for additional insight on what the user is viewing through the system the most which may allow for optimal performance-based feedback. The headset has a field of view of 110° (diagonal), dual OLED displays with a combined resolution of 2,880x1,600 pixels, and a pixel density of 615 pixels per inch per eye.With currently available head-mounted technology, these specifications represent professional-grade levels in extended reality hardware. Achieving the highest visual fidelity is of utmost importance for this technology for optimal astronaut performance and terrestrial health benefits for individuals with irreversible central vision loss. The headset is relatively light, weighing at 6.05 lbs. which allows for users to wear the technology for extended periods of time without fatigue. The technology also optimizes GPU workload with foveated rendering. This technology allows for the optimization of graphic fidelity in the wearer's central vision and lowers the resolution in the periphery. This technology is particularly helpful when seeking to optimize an astronaut's central visual performance. In resource-limited areas, such as spaceflight, these aspects of efficient computing are highly valuable.

The participants are helped to wear the headset properly and adjustments are made to ensure a comfortable fit. The lens distance and interpupillary distance can also be modified while the participant is in the VR environment to ensure the device is fully calibrated. The results of the user study were recorded on a CSV file. An Unreal Engine Plugin (SRanipal) was used to track the gaze of the participants and dynamically suppress the distortions on the affected eye.

Table 6.1: Parameters tuned to replicate the perceptual deficit caused by AMD

	Parameters	**Range**	**Step Size**
1	Mean	$\mathbf{0} \leq (\mathbf{u}, \mathbf{v}) \leq \mathbf{1}$	0.1
2	Sigma	$\mathbf{0} \leq \lambda \leq \mathbf{0.75}$	0.0075
3	Weight	$\mathbf{0} \leq \mathbf{w} \leq \mathbf{1}$	0.02
4	Rotation	$-\mathbf{360} \leq \theta \leq \mathbf{360}$	2.0
5	Distortion	$\mathbf{0} \leq \mathbf{d} \leq \mathbf{1}$	7.2

The participants are first asked the demographics and computer literacy questions. The coordinator then introduces and explains the procedures for the study. After the introduction, the participants are asked to sign the study informed consent form.

The participant will first take a simple sighting alignment test to determine the dominant eye [37]. We then randomly choose to simulate perceptual deficit to either the participant's dominant or non-dominant eye.

Metamorphopsia is a very common form of visual distortion in various terrestrial macular disorders (e.g., AMD). Metamorphopsia is often described as a distortion or deviation of straight lines or instability of vision. In an assessment of metamorphopsia, approximately 45% of patients with AMD perceived some level of optical distortion. If astronauts encounter these distortions during spaceflight, mission-critical tasks could be compromised. Therefore,

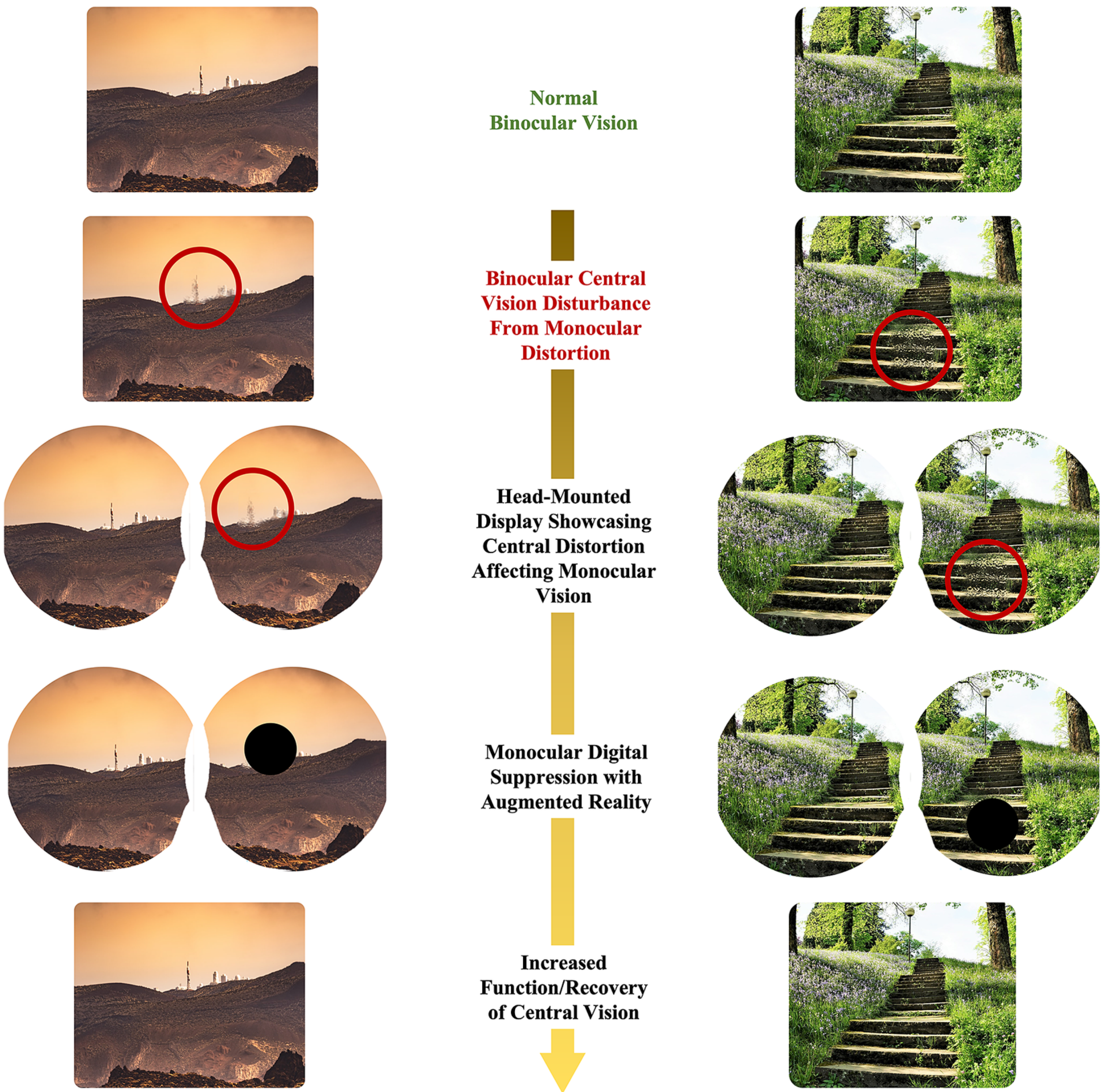


Figure 6.2: Illustration of digital monocular suppression on monocular central distortion with head-mounted augmented reality.

it is important to identify perceptual distortions in individuals and construct appropriate countermeasures. However, the considerable variation in distortion shape, size, and location creates challenges for accurate assessment and countermeasure. Our proposed methodology considers and builds upon a physical-based metamorphopsia modeling called Perceptual Deficit Modeling (PDM). In this model, a mixed reality system simulates distortions in one of the normal healthy eyes and has the participant reconstruct the perceived distortion in their other eye. However, this approach requires extensive cooperation from the participant and is a cause of considerable cognitive stress. As most AMD patients are elderly, a more straightforward process is desired. In this section, we summarize the PDM approach and describe how we improved the modeling and rehabilitation steps (Figure 6.2).

PDM describes perceptual deficit or metamorphopsia in AMD patients Table 6.1 with four different parameters: localization, size, shape, and luminance perception:

$$\mathcal{P} = (\mathbf{\Gamma}, \mathbf{\Omega}_{\lambda}, \mathbf{R}_{\theta}, \mathbf{\Psi}) \tag{6.1}$$

where Γ represents luminance degradation, Ω_{λ} represents the visual field loss region with λ as the cut-off degradation determining the boundaries of the scotoma, R_{θ} is the rotational distortion matrix within Ω_{λ}, and Ψ is the a Sinusoidal mapping function representing the spatial distortion.

$$\mathbf{\Gamma} = \sum_{i=1}^{N} \omega_i \mathcal{N}_{\vec{\mu}_i,\sigma_i}(u, v) \tag{6.2}$$

where u and v are the coordinate locations on the 2-D visual field, N is the number of Gaussian kernels (Normal distributions) modeling the deficit in the luminance perception in the visual field, and ω_i is the amount of luminance deficit caused by each Gaussian kernel. $\mathcal{N}_{\vec{\mu}_i,\sigma_i}(.)$, are the gaussian kernels where $\vec{\mu}_i = [\mu_i^u, \mu_i^v]$ represents the center and σ represents the standard deviation of the distribution. This approach unnecessarily complicates the

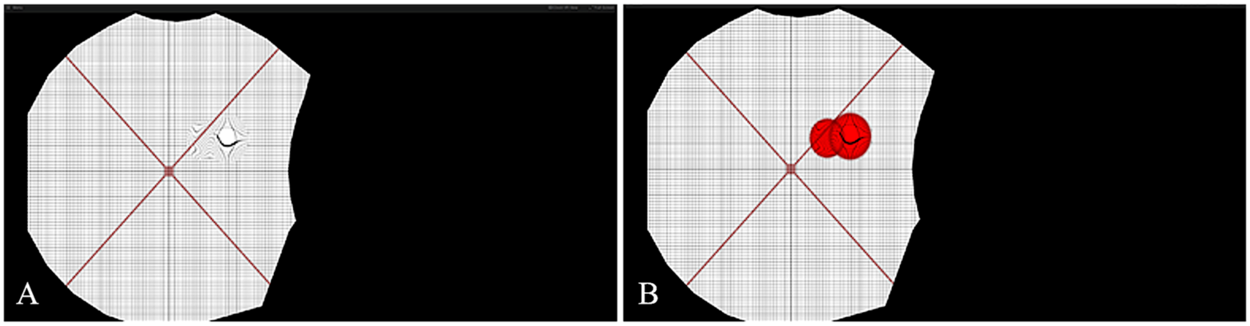


Figure 6.3: Simulation of metamorphopsia with the perceptual deficit model (PDM). (a) showcases a simple metamorphopsia created with a single Gaussian kernel and (b) showcases a more complex metamorphopsia with multiple (denoted by the two red circles) Gaussian kernels applied in conjunction.

process of metamorphopsia parameterization by connecting all the parameters to the same Gaussian kernels. We separated the kernels of perceptual loss, rotational distortion, and spatial distortion, effectively modeling the same complexity of three independent kernels into one where each kernel only shares size parameters. Additionally, the properties of the underlying Amsler grid are parameterized to improve the monitoring capability of the system by permitting finer grids, variable grid line width, and grid chromaticity. Furthermore, diagonal lines were added to the grid to reinforce the point of fixation, as macular vision loss may make it difficult to find the central fixation point (Figure 6.3). However, the most fundamental change in the modeling is from the user's perspective.

In the standard PDM module, the user reconstructs the perception in the impaired eye in their normal eye. For example, in healthy subjects, the approach first simulates a metamorphopsia with given parameters in one of the eyes. The task of the participant is to create a similar metamorphopsia in their contralateral eye with paremeter values $p^{Contralateral}(\Gamma = 0.0, \Omega_\lambda = 0.0, u, v = (0.5, 0.5), R_\theta = 0, \Psi = 0)$.

Initially, a PDM is overlaid on the contralateral eye with parameter values. The participant can change the parameters to find the ideal case, This approach is similar to the traditional article-based Amsler grid test where the participant attempts to draw the perceptual distortion that they are experiencing with a pen. To avoid binocular interaction when trying to reconstruct the metamorphopsia in the other eye, the display input to the test eye is turned off. That display is later turned back on when the subject wants to recheck. This approach is challenging because the position, size, and shape information may be lost during ocular shift caused by the monocular display. Furthermore, due to the subjective bias to the reconstructive parameters, the corrective distortion to counter the perceptual deficit caused by the simulated distortion is not guaranteed when a reverse of the $p^{Contralateral}$ is applied.

To address such limitations, we directly model the corrective action in the impacted eye. For that purpose, a default metamorphopsia $p^{Contralateral}(\Gamma = 0.0, \Omega_\lambda = 0.0, u, v = (0.5, 0.5), R_\theta = 0, \Psi = 0)$. is drawn on the affected eye itself, instead of the contralateral eye Figure 6.4. The participant then manipulates the parameters of this distribution but with a completely different goal compared to the PDM approach. Now, instead of reconstruction, the aim is to make the distortion disappear. This makes it possible to precisely identify the metamorphopsia characteristics. An added benefit of this approach is that we can now model bilateral macular distortions with corrective distributions for each eye separately. This is possible because the contralateral eye display is always turned off during corrective assessment of the test eye.

Furthermore, simply applying the corrective distortion to the see-through camera feed appears to improve vision in some patients. By applying the suppression through a camera feed with an AR system, individuals with monocular macular disruptions may be able to complete daily tasks more effectively despite experiencing functional unilateral macular decline.

As the participants directly model the corrective distortion of their metamorphopsia, very little additional suppression is required. A dark circular spot overlays the area of metamorphopsia in the VR/AR device for the affected eye. An important consideration for this for creating a digital suppression is to only block out the distorted part and not exceed its boundary so as not to cause additional visual information loss. However, if the suppression is too small, the peripheral distortion may cause additional perceptual loss. In our validation studies, we tested various sizes of digital suppression relative to the size of the distortion, including 25 and 120%.

Once the participant is wearing the headset, both eyes are presented with a standard Amsler grid. A distortion questionnaire is used to establish control measurements. A random metamorphopsia template is then simulated in one of the eyes. Suppressing dark circles were superimposed on the simulated metamorphopsia at 0, 25, 90, and 120% relative to the size of the distortions. These suppression sizes are based on preliminary experiments that test different countermeasure tradeoffs Figure 6.5. For example, if 25% suppression is effective, it means that most of the metamorphopsia distribution is concentrated in the central area and the outer area is only slightly noticeable. Ninety percent and 120% suppressions were chosen because of the property of Gaussian distributions which was used in the distortion modeling. These distributions lack a clear boundary and 90% of parameter λ is perceptually close to 100% but allows the user to see slightly more of the field of view. One hundred and twenty percent is selected because it always covers and noticeably exceeds any

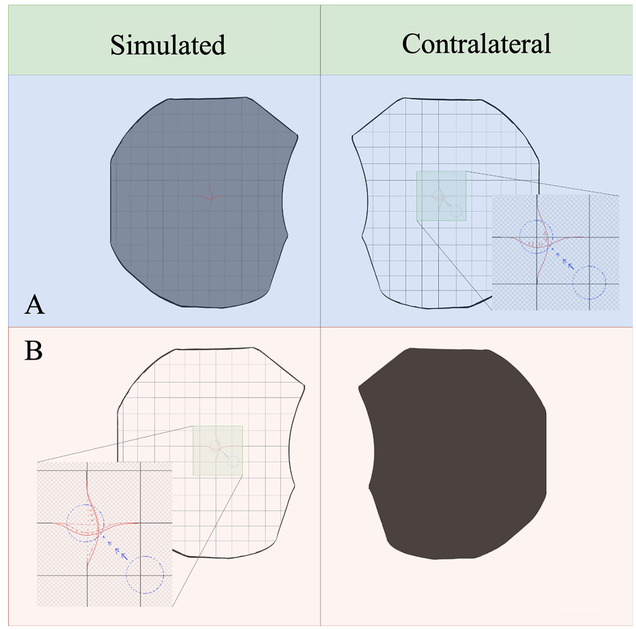


Figure 6.4: (a) Standard perceptual deficit modeling (PDM) approach with recreation of the metamorphopsia on the contralateral eye. (b) Our new approach to digital metamorphopsia suppression by applying corrective distortion to the affected eye directly. This new approach may also allow for binocular macular distortions as the contralateral eye display is turned off.

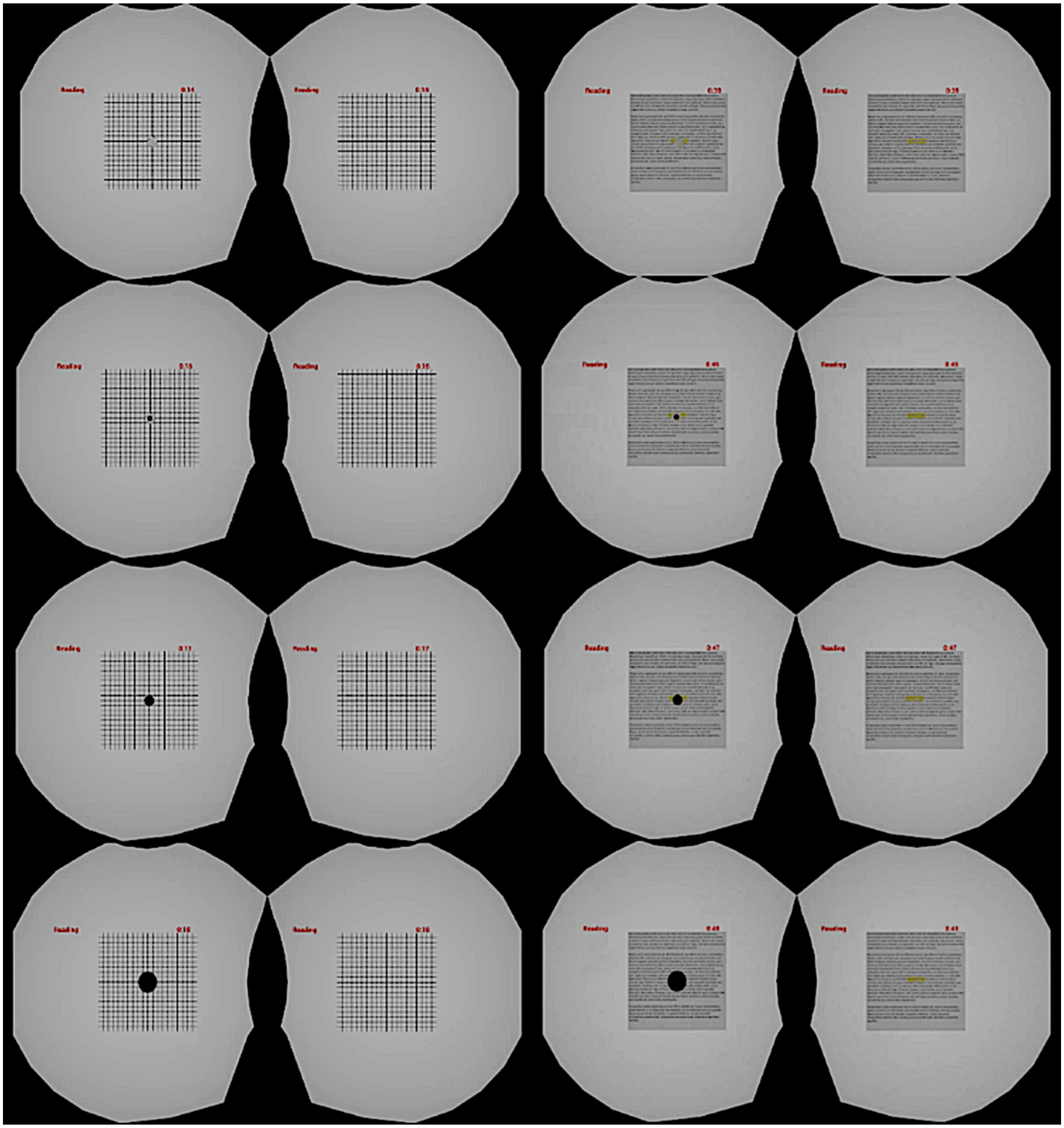


Figure 6.5: Dark spot suppression of various sizes in both Amsler grid (left) and reading tasks (right)

distortion. Future studies will likely explore different parameters of dark spot sizes for fine-tuning of suppression. Subjects then responded to questions regarding the ability to perceive the distortion after levels of suppression via Amsler grid and text-based evaluations. The participant then answers questions related to their perception. The perception was rated between 0 and 5, where 0 signified imperceptible distortion and 5 signified the highest distortion. In the reading task, the participants reported how easily they were able to read some highlighted texts. The text was composed of random Latin so that participants could not simply guess the highlighted word from context. Healthy participants had no trouble reading the highlighted text when no distortion was introduced. To determine how difficult reading became once a simulated metamorphopsia was induced in one eye, we used a subjective scoring method. Five signified complete illegibility and 0 signified complete legibility.

The experiment uses a repeated measures design in which the affected area in the visual field is then increasingly suppressed in a stepwise manner. At each increasing level of suppression, the participant will answer questions regarding their perception of the simulated distortion. The first suppression area at which the distortion cannot be perceived is recorded for each eye, and when the suppression is first noticed is also recorded. The independent variables used in the experiment are the six different conditions associated with different levels of simulated metamorphopsia. It is worth noting that when the eyes of the subject move, the suppression in the simulation moves as well. This allows the healthy eye to fill in the distorted area, and replace distortions created by the scotoma. The data consists of questionnaires with six discrete outcomes does not meet the requirements for analysis of variance (ANOVA). Therefore, nonparametric analysis is performed to evaluate the performance. To perform the statistical analysis, we assigned a numerical value to each of the categories of the dependent variables from the range of 0 to 5, that is, imperceptible distortions category was assigned a value of 0 while the highest distortion category was given a value of 5. We used Chi-square analysis for evaluating the results.

Eighteen healthy subjects (normal eyes with no history of ocular pathology) were recruited for this validation study. Six females and 12 males with an average age of 28.59 $\pm$ 3.22 years were included. Individuals with any history of prior ocular disease were excluded. All participants underwent simulated metamorphopsia with the head-mounted VR system mentioned in the materials section.

All individuals responded that the headset was comfortable, and that they could read the information on the screen clearly. The results are shown in Figure 6.6 and Figure 6.1.

Chi-square analysis shows that using 25% dark spot suppression of the distortion reduced the mean perception of distortion to four (p = 0.005). Ninety percent of dark spot suppression of the distortion reduced the mean perception of distortion to one ($p < .005$). One hundred and twenty percent dark spot suppression eliminated all perception of the distorted grid with a distortion of 0 ($p <= .005$). The highest mean legibility during the reading task was found at 90% suppression with a score of 1.78 (Figure 8). The mean perception of distortion was more reduced in the reading task (0.17) compared to the Amsler grid task (0.61). No adverse events were experienced throughout this noninvasive protocol.

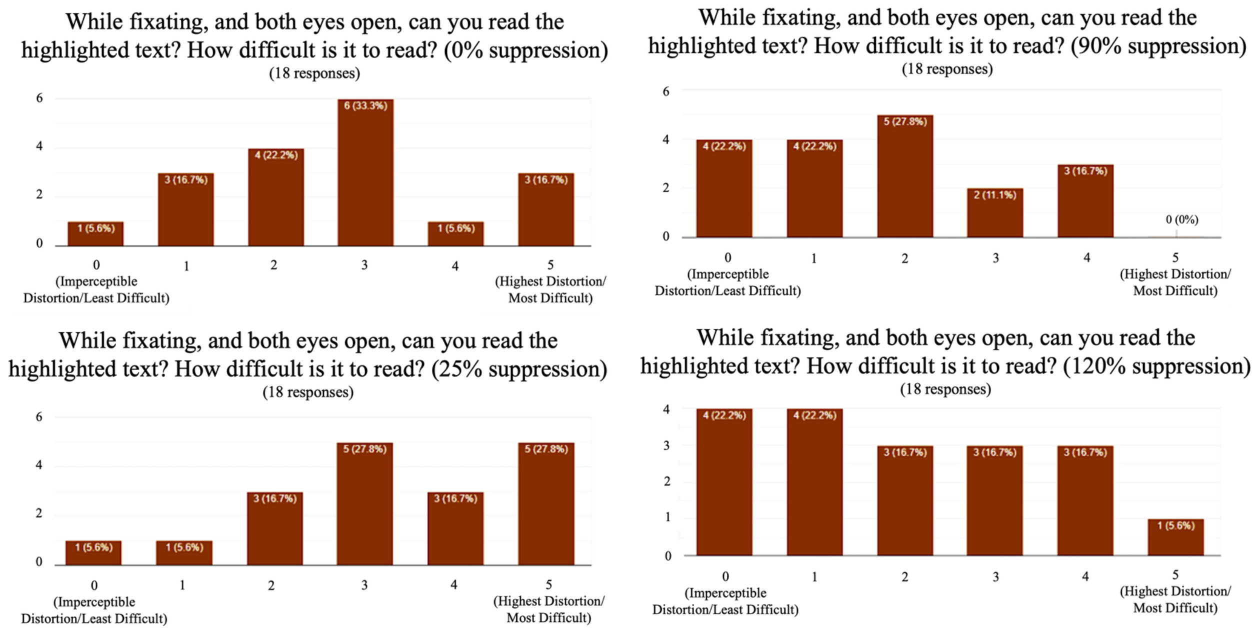


Figure 6.6: Graphical results from highlighted legibility reading task with digital suppression. Ninety percent suppression revealed the highest mean legibility.

This early validation study demonstrates that this digital suppression technique in individuals undergoing simulated unilateral metamorphopsia may reduce central vision distortion in binocular vision. There was a statistically significant binocular compensation with 90 and 120% VR-based suppression of simulated metamorphopsia. Interestingly, dark spot suppression at 120% was effective in removing the distortion but also introduced another impairment because the dark spot was more noticeable, thus indicating that 90% suppression may be the ideal size for suppression. Fine-tuning the suppression in terms of dark spot size may help to further improve legibility. As these early pilot studies for this emerging technology/technique contain small sample sizes, larger studies are being planned to further understand the effects of this digital countermeasure, particularly in conducting real-life tasks that mimic daily activities of living utilizing AR. As the hardware of wearable technology systems continues to advance in visual fidelity, the results from this countermeasure may be further improved. Limitations in this early validation study include metamorphopsia simulation only, limited size choices in dark spot suppression, and a small sample size. It is anticipated that these

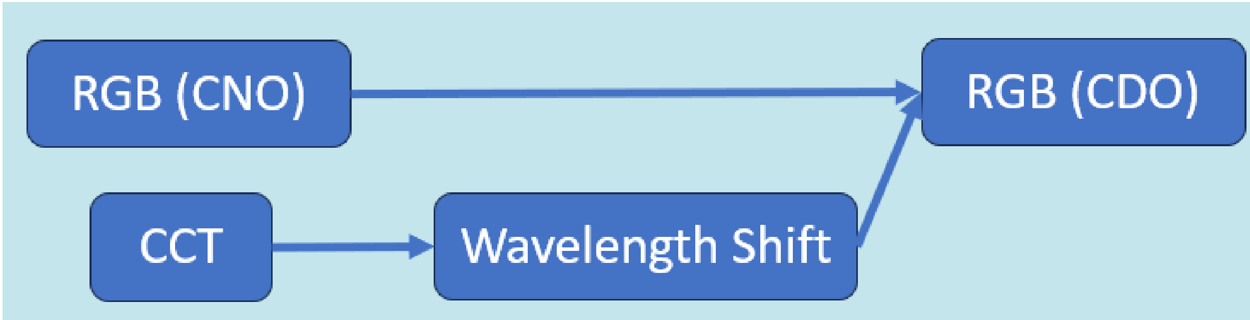


Figure 6.7: Illustration of digital monocular suppression on monocular central distortion with head-mounted augmented reality.

limitations are addressed in future studies.

Table 6.2: Correction of Macular distortion

PatientID	Mean.X	Mean.Y	Size	Rotation	Distortion	Eye	Hole
1	0.5	0.5	0.01	0	0	Left	Left
2	0.5	0.5	0.006	-10	0	Left	Left
3	0.474	0.496	0.007	-17	0	Left	Both
4	0.498	0.49	0.119	-3	0.04	Left	Left

6.2 Case Study 2: XR-based personalized active aid for color deficient observers

Color deficiency is a common condition that affects 3.7% of the US population, impacting their ability to perceive and differentiate colors. Traditional methods for aiding color discrimination have been limited in their effectiveness. This study explores the use of extended reality as a potential solution to this problem by augmenting pass-through video with using gamut mapping catered to the individual and the display.

In a previous study [232], the authors investigated the efficacy of active aid in the form of personalized image enhancement to increase color discrimination ability in color-deficient observers (CDO). The study parameterized severity of color deficiency, the wavelength shift of cone spectral fundamentals, and the spectral distribution of display primaries. The first

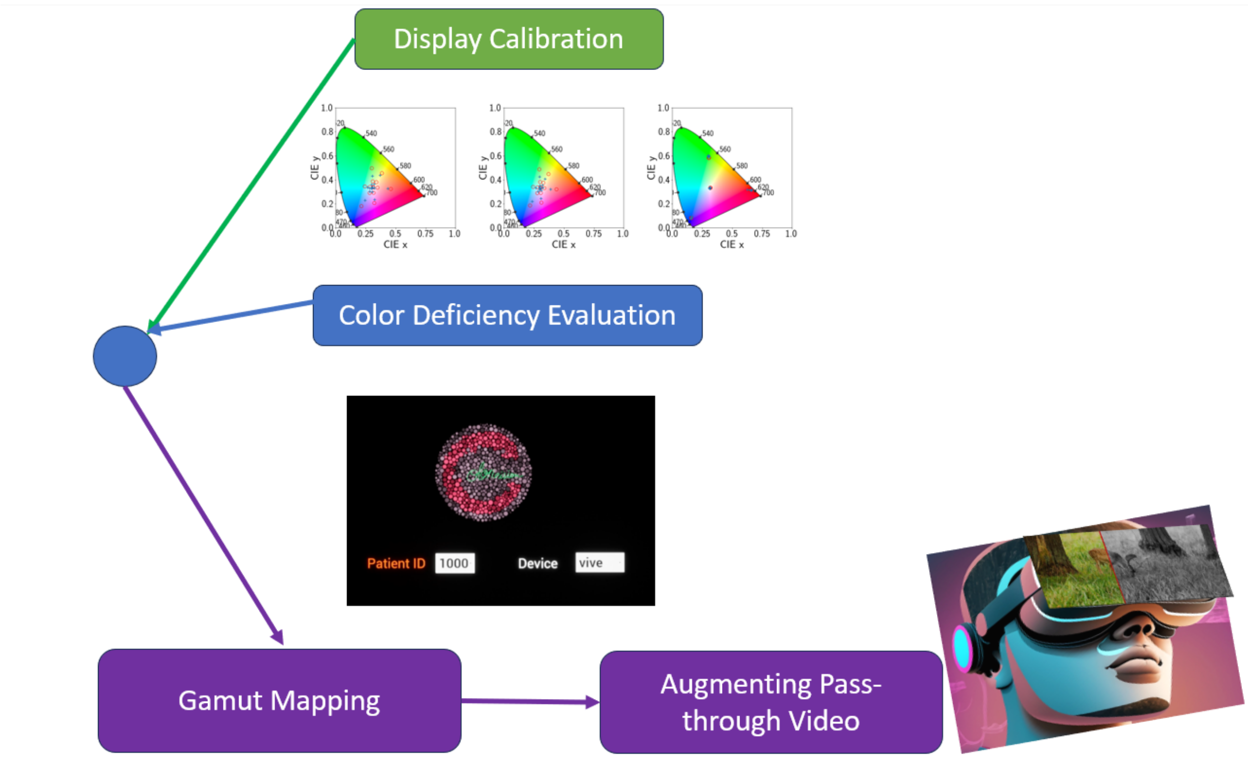


Figure 6.8: Illustration of digital monocular suppression on monocular central distortion with head-mounted augmented reality.

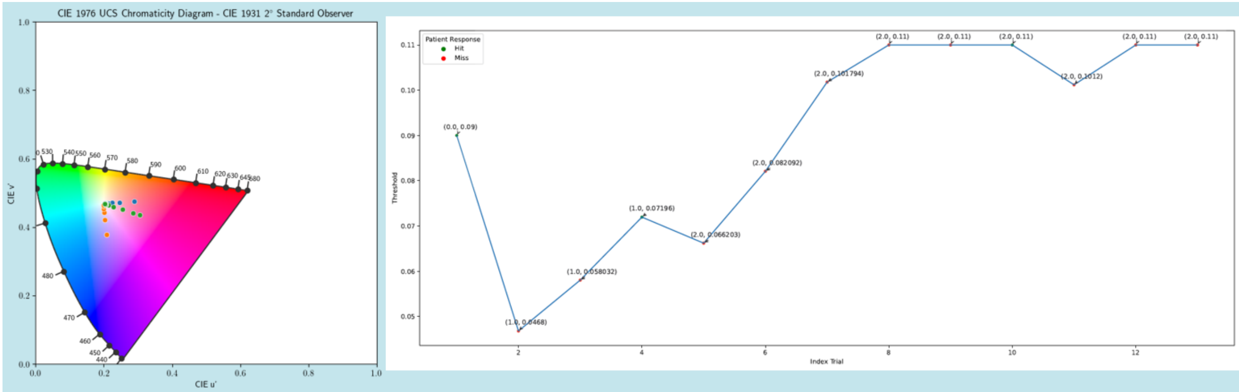


Figure 6.9: Illustration of digital monocular suppression on monocular central distortion with head-mounted augmented reality.

parameter was derived by computing the confusion index of the CDO, employing a modified version of the FM-100 test (ZJU50Hue). The second parameter was determined via evaluation of a wavelength-shifted ZJU50Hue test on color-normal observers (CNO). The three parameters were used to model the gamut mapping between CNO and CDO Figure 6.7.

The methodology to calibrate HMDs and apply correction selectively to parts of the scene was described in chapter 3. Using that framework, a VR-based Cambridge color test (CCT) was created Figure 6.8, described in chapter 4. So, with two of the three parameters required to create an active aid for CDOs, the rener pipeline of 5:Blur Adaptation can be resuded for color compensation Figure 6.9.

The images directly to the right show the least and most saturated images presented during the VR-based color vision test. The following images show a CNO's performance in the Trivector version of the CCT. Our goal is to find the repeatability coefficient, Cohen's Kappa and Bland-Altman analysis on 20 CNO and 6 CDO to compare the results of CCT and our VR-CCT. Preliminary data suggests the VR-CCT can correctly identify CNOs. While the FM-100 and consequently the ZJU50Hue test are both easily reportable in terms of C-Index (confusion index) for severity of deficiency, our goal is to use CCT thresholds to generate the gamut boundary for both CNO and CDO as it should be more objective and relevant.

As the calibration, simulation and modeling processes all take place in the same HMD, we intend to model the CNO-CDO gamut mapping into a post-process graphics shader to directly modify the camera stream from the XR-3. The results can be verified through a paper-based Ishihara test that the CDO would perform while wearing the XR-3.

Chapter 7

Concluding Remarks

7.1 Future Work

Some direct extensions of the work outlined in this paper are:

- Telemedicine server with capabilities to initiate eye exams in remote VR devices.
- Digital twin construction pipeline to create realistic immersive environment for quality of life evaluation.
- Integrating postprocess binaries with Varjo XR-3 to facilitate real-time high-fidelity simulations.
- Utilize color gamut remapping to increase color discrimination capability in color deficient observers.

There are multiple considerations for the optimization of XR. Due to smartphone ubiquity, recent VR HMDs use high resolution displays that are a considerable improvement over previous CRT screens. However, current generation screens still have higher latency, jittery motion and motion blur [180]. Moreover, lenses used to create a collimation effect, like the Fresnel lenses, also create optical distortion or aberrations as a result, which may not be fully corrected [164, 103]. However, the suitability of LCD was challenged by the emergence of OLED screens. While old generation VR HMDs mainly utilize LCD screens, the commercial versions of new generation VR HMDs predominantly use OLED screens. The OLED screens have been found to be better than LCD screens for general implementation in VR, because of their faster response times, lighter weight, and better color quality. OLED screens decrease the likelihood of simulation sickness. However, VR systems still have some limitations. One of the key areas of improvement for Mixed Reality systems is the vergence-accommodation conflict. Vergence and accommodation are neurally coupled [181]. Which is beneficial in the real world where the eye can focus on distant objects accordingly. But the coupling is broken in Mixed Reality systems. Visual cues that the brain repeatedly picks up on are sometimes completely absent from these simulations. Current head-mounted displays all project the image that is at a fixed distance away from the eye. This is because of its fixed lenses. This prohibits the normal coupling of accommodation, retinal blur, vergence that is common in natural vision. This can cause fatigue and discomfort, which can be wrongly attributed to the impairment being simulated. [34] describes a method to render more realistic approximations of how depth creates an effect of defocus and chromatic aberration. Coupling this algorithm with focus-adjustable hardware lenses would allow complete vergence-accommodation. Besides, it would make it possible to create renderings that closely approximate the ocular system.

[197] points at a common misconception that in central vision loss, a “black” spot is visible in the center of the vision. Indeed it is often the case that affected individuals are unaware that they are missing information because the brain is surprisingly good at extrapolating visual information from visible surroundings. The same misconception is held for peripheral vision loss. In order to address this, only two of the reviewed works implemented filling-in features. However, filling-in is not merely a loss of information in that region but may indicate where in the surrounding area the brain is gathering the substitute information

from. Intelligent survey of this information may allow for a design where the filling in can instead be influenced through image remapping to present a more informative picture.

[8] estimated that the accuracy of virtual measurements to be 0.5 mm linear and 0.7° angular. They have further found that linear and angular virtual measurements are highly reproducible in their case.

VR has also been utilized in ophthalmic medical education. On October 2020, FundamentalVR announced their VR surgical skills training capabilities in ophthalmology [186]. The company states that their technology can mimic the physical cues within less of a millimeter of accuracy of resistnace. Traditional learning for surgical skills in ophthalmology often require bovine eyes in a wet lab. Bovine eyes must be either fresh or frozen and subsequently thawed for surgical training, thus making it less convenient than an immediate VR system. In addition, the VR system can emulate the operating room with eyelid retractors, sterile fields, and surrounding orbital tissue. This platforms also allows for a better 3D spatial awareness and can mimic adverse events that require quick thinking and immediate intervention. These skills are invaluable and may provide beginning surgeons with more insight into the procedures. The platform can be easily transported and can be accessed by users through wireless connection, making hands-on surgical learning incredibly more accessible. This can also be a tool to show rare pathologies that may not otherwise be seen in an operating room setting. In summary, VR is beginning to change the landscape of ophthalmic surgical training and provide beginner surgeons with a wealth of accessible, hands-on surgical insight.

As cloud-based technology continues to advance, VR will likely become more standardized in addressing gaps of care. On December 21st 2020, Heru, a medical technology platform received US Food and Drug Administration Class I listing for cloud-based VR diagnostic technology with visual field exams [84]. By deploying accessible and transportable diagnostics, VR technology with cloud-based technology can provide world-class technology to more patients and address long-standing gaps in care. In addition, VR may also push the boundaries of current physiological research. Spaceflight Associated Neuro-Ocular Syndrome (SANS) is a set of neuro-ophthalmic findings that are found in astronauts during long-duration spaceflight missions. These findings include hyperopic shift, optic disc edema, and retinal nerve layer thickening. SANS has been identified as a large potential barrier to future manned space exploration missions such as the mission to Mars. Thus, it is critical to further understand and test countermeasures. However, the neuro-ophthalmic phenomenon is unique to spaceflight and is naturally limited in sample size for study. Head-Down Tilt Bed Rest (HDTBR) has become a promising and emerging terrestrial analog for SANS [143]. VR technology can actively be utilized in HDTBR and other ground-based platforms to assess micro-visual field changes that may occur, and may be of critical use in-flight for future space missions. Supported by the National Aeronautics and Space Administration (NASA) National Space Biomedical Research Institute (NSBRI), VR is already being adapted for astronauts to adapt to life in space [27]. Thus, strengthening VR's role in the future of ocular health both on earth and in space.

One of the great challenges into human senses is the blend of subjective and objective data. With the advent of generative adversarial networks it may not be a far way off to leverage the subjective expression and objective neuronal activation to create accurate replication of individual perception. The discord between subjective expression and brain function may lead to identification of impairment. They may still be some distant off in the future.

Something that seems around the corner, however, is the analysis of anonymized VI information combined with these research findings to formulate automated and personal reverse visual function to allow recovery of functional vision. Some prohibitively expensive wearable technologies already provide this advantage. It is an open research question whether computer vision can come in to supplant some of the burdens from hardware interfaces.

Children and senior people have difficulty concentrating on a task for a long period, so supplanting existing methods that require constant exertion should be replaced with engaging and immersive experiences that require minimal effort. This gamification does not need to be directly copied from existing systems but can be designed by keeping the utilities of the immersive and 3D virtual simulation of the system in sharp focus. As has already been demonstrated in the fields of visual neuroscience, simulation therapy, and medical education, research into impairments can lead to better insight into the factors that impact adjacent, related fields and vice versa.

Many of the presented innovations already realize that the form factor of these systems need to be subtle for social acceptance and comfortable for ease of repeated and long term use. These will be great tools in the arsenal of ophthalmologists to assess their patients remotely and with higher frequency. Assisted living facilities would be able to monitor their senior population through the assessment procedures, increase awareness through simulation, and provide accessible vision therapy under one portable contraption that is affordable even for individuals.

All the technical advances in supporting fields are encouraging further growth. Display technologies are getting higher refresh rates at lower price points. Higher resolution screens are getting cheaper and energy efficient. A recent advancement in OLED technology may lead to VR displays with 10,000ppi [94]. Considerable progress in computer graphics and parallel processing has made real-time ray-tracing possible. Eye tracking is getting more and more accurate. Cameras with small form factor can make up for lens restrictions with image processing. As the divide between human and machine perception is getting smaller, we may be try to ignore some realities. Nonetheless, the current state of hardware and software should be kept in mind while judging the efficacy of these techniques and exploring areas of future research. Many of the current works report a lag between the virtual simulation and the added impairment overlay. Shaders can only help in cases where the users do not have high visual acuity to begin with and therefore cannot perceive the degradation due to rasterization. Accelerated graphics hardware are still expensive and consume a lot of power, thereby restricting the duration a display/camera can stay active for. The best solution may be a distributed system.

A few of these techniques already adopted a server client setup where the client agent would send encoded visual information and current user preferences to the server for processing and the server would return encoded rendering attuned to the user specification. Due to rapid advances in distributed computing, it is now possible to offload most of the heavy work to the servers and decrease the load on the wearable device. This technological advancements will likely serve as a catalyst in the field of tele-ophthalmology to run accelerated and federated learning processes for rapid and precise low vision augmentation and assistance. With the promise of light field display technology and accelerated distributed graphics processing, virtual reality may soon catch up with reality and become the standard of care.

7.2 Conclusion

A critical aspect in innovative research is the development of criteria for diminishing returns. While considering economic costs, it is also important to recognize the point where any further technical improvement would not add any utility to the users of the system. For example, there may be limited utility in developing a display with higher resolution or increased color variation than the human eye can perceive. Similarly, it is important to identify what is a tremendous gain in this field and what has already been fully optimized in XR. If a person with low vision who can barely register hand motions is suddenly able to read texts, this would be considered a remarkable gain. However, if individuals with imperceptible scotomas can function normally without XR, then this may be an area of less ideal utilization and focus. This clinical correlation may help focus the research that will have the greatest impact in the field of vision impairment. This is not to discourage research in bold new areas, but rather to encourage it. Prior to XR, there were countless established techniques that performed well enough for large scale clinical use. However, research into virtual reality in ophthalmology helped optimize a medium of rehabilitation and monitoring that was once thought to be at its peak. Thus, VR technology provides incredible potential to reduce the gaps in care and provide a brighter future for millions suffering from vision impairment across the globe.

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