

DEVELOPMENT AND COMPARISON OF
AUGMENTED AND VIRTUAL REALITY
INTERACTIONS FOR DIRECT OPHTHALMOSCOPY

BY

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An oral defense of this thesis took place on March 2020 in front of the following examining committee:

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

Direct ophthalmoscopy is a medical procedure whereby a health professional examines the back of the eye, searching for life-threatening risks. The direct ophthalmoscope is used for examining the patient and it requires extensive practice for visualising the anatomical landmarks without causing discomfort to the patient. However, direct ophthalmoscopy skills are declining due to the use of diagnostic equipment available during instruction leading to insufficient practices with the direct ophthalmoscope. Maintaining such skills is important as the ophthalmoscope can be the only available device in healthcare facilities.

The use of cost-effective approaches to address this problem has led to the development of a number of systems employing Styrofoam heads, plastic canisters, and digital technologies including mobile applications and virtual reality to explore accessible complementary solutions. Virtual, augmented, and mixed reality are becoming technologies with the potential to deliver engaging and immersive experiences. While the availability of off-the-shelf immersive technologies is rising due to its recent affordability, there are several challenges associate with developing suitable interactions, particularly in the medical field.

This Master's thesis focuses on the development of a virtual reality direct funduscopy examination tool employing consumer-level technologies, and examines its face validity in comparison to the traditional photograph method and similar immersive tools by performing a Quality Function Deployment analysis. Furthermore, usability and cognitive workload perceptions are gathered to understand the feasibility of employing virtual reality controllers or hand gestures as digital replacements for the ophthalmoscope.

KEYWORDS: AUGMENTED REALITY, EYE EXAMINATION, HAND TRACKING, VIRTUAL REALITY, USABILITY

AUTHOR'S DECLARATION

I hereby declare that this thesis consists of original work of which I have authored. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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The research work in this thesis that was performed in compliance with the regulations of Ontario Tech's Research Ethics Board under REB 15526 certificate file number.

STATEMENT OF CONTRIBUTION

During the development of this thesis I have contributed to the following:

- Joined the MaxSim Health Research Group holding discussions about interactive design for augmented and virtual reality scenarios for medical training purposes;
- Conducted augmented reality eye examination demos with the Microsoft HoloLens for Lakeridge Health, Purdue Pharma, and the Canadian National Institute for the Blind;
- Demo presentation on Virtual eye fundus examination. In Proceedings of the 2017 Healthcare Simulation Network (SIM-one) SIM Expo, Virtual Showcase. Nov. 30 - Dec. 1, 2017, Toronto, Canada.
- Demo presentation: David Acosta, David Gu, Michael Chan, Alvaro Uribe-Quevedo, Bill Kapralos, Michael Jenkin, Norman Jaimes, Kamen Kanev, "An Augmented and Mixed Reality Approach to Eye Fundus Training." Realities in Medicine, Sick Kids, Toronto, ON, Canada, April 7-8, 2018.
- Short paper preparation for conference submission: Chan M., Uribe Quevedo A., Kapralos B., Jaimes N., "A Mixed Reality Direct Ophthalmoscopy Simulator";
- Submitted book chapter: Chan M., Uribe Quevedo A., Jaimes, N., Kapralos B., Jenkin M., Kanev K., "A Review of Virtual Reality-Based Eye Examination Simulators." Recent Advances in Technologies of Inclusive Well-Being: Virtual patients, gamification and simulation.

- Full paper preparation for conference submission: Chan M., Uribe Quevedo A., Jaimes, N., Kapralos B., Jenkin M., Kanev K., "Suitability of Virtual Reality in Eye Examination Practices."
- Participated as a research assistant for the PPSHA on developing a working at heights virtual reality simulator on the creation of 3D assets and interactions.

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ACRONYMS

ANOVA analysis of variance

AR augmented reality

DO direct ophthalmoscopy

CPR cardiopulmonary resuscitation

GP general practitioner

GUI graphic user interface

HOQ house of quality

IDE integrated development environment

MR mixed reality

QFD Quality Function Deployment

RoG Republic of Gamers

SBME simulation-based medical education

VE virtual environment

VR virtual reality

INTRODUCTION

In the context of medical education and training, simulation is defined as “an artificial, yet faithful, representation of clinical situations through the use of analog and digital apparatuses” [50]. Simulation can include manikins, cadavers, standardized patients, animals, devices, computer programs and virtual spaces, amongst other methods of imitating real-world systems [4]. Simulation-based training allows for the development of clinical psychomotor skills within the cognitive domain, in addition to skills within the affective domain (e.g. communication skills) [16]. Here, we concentrate on the use of simulators in training related to direct ophthalmoscopy.

Eye examinations are regarded as an integral component of standard regulation physical check-ups [39]. Although there are different types of eye examinations, many require high-end and costly equipment to perform [34]. For instance, eyelid examinations employ the use of slit lamps, while a tonometer is required to gauge the intraocular pressure of the eye [70]. Despite this however, the direct ophthalmoscopy (DO), or direct fundoscopy, is relatively inexpensive in regards to the cost of performance and equipment maintenance. In addition, this examination focuses on the observation of the back of the eye, also known as the eye fundus.

Direct ophthalmoscopy (DO), or direct fundoscopy, is a procedure whereby a health professional examines the eye fundus using a direct ophthalmoscope or direct fundoscope, while operating the lens, light, and aperture filters associated with the device. The examination allows for the observation of the eye fundus through the identification of the red reflex (light reflection on the back of the eye), the optic disc, the macula, and blood vessels while searching for signs of clinical emergencies, such as retinopathies, diabetes mellitus, and miliary tuberculosis

[44]. Some conditions, such as cytomegalovirus retinitis and papilledema, can be recognized and diagnosed through eye fundus examinations [44]. The direct ophthalmoscope is a light, compact, hand-held tool that allows users to see the fundus through the pupil. It projects the fundus as an upright image with a magnification of up to 15 times [34], and it consists of two primary components: i) the handle, and ii) the head. The handle of a typical direct ophthalmoscope contains the power supply and light source, while the head houses the viewing window and lenses as presented in Fig. 9.

Training for the DO examination includes the following [35]: i) theoretical lessons including eye semiology and an introduction to various pathologies, and ii) practice identifying various fundus conditions through hands-on practice with classmates, or fundus photographs [47]. The DO procedure requires precision and timely execution to minimize patient discomfort due to the direct ophthalmoscope light exposure [33].

The DO is a procedure that is taught to students as a full medical examination. Eye fundus examinations are considered to be a critical constituent to the diagnosis of many life and sight-threatening diseases such as diabetes mellitus, intracranial pressure, and miliary tuberculosis [44]. In addition, conditions such as cytomegaloviral retinitis and papilloedema - which need to be recognised by family physicians, can only be seen through fundus examinations [65]. Through the use of a direct ophthalmoscope, or direct fundoscope, this examination allows for the observation of the fundus through the manipulation of the tool's lens, light, and the aperture filters.

Although education and training for DO's has been incorporated into general medical education, studies have shown that the examination is rarely performed by practising or in-training doctors [18]. Many trainees find this procedure difficult to master due to factors such as a lack of examiner confidence, poor training, and

proper skill maintenance [47]. In addition, the intricate anatomy of the human oculomotor system can prove to be exceptionally confusing, which is especially problematic since the clinical intervention of many ocular disorders occurs within this particular set of muscles [5]. Furthermore, trainee competency can be particularly challenging since only one person is able to see the fundus at a time as a result of the direct ophthalmoscope's inherent design [57].

1.1 PROBLEM STATEMENT

Although the direct ophthalmoscope has traditionally been the dominant tool for eye exams, other types of diagnostic equipment has become available, such as the tonometer, which measures fluid pressure within the eye; the phoropter, which allows for the identification of refraction error; and the vision screener, which allows for the diagnosis of major ocular problems. The introduction of these pieces of equipment has led to reduced dependence on the direct ophthalmoscope, which remains a critical health care tool when health professionals do not have access to high-end equipment. Becoming proficient with the direct ophthalmoscope is not trivial due to the intricate nature of the eye. For example, experienced clinicians may have difficulties correctly diagnosing fundus-related conditions [63].

Teaching and evaluating fundus examination competency is particularly challenging since only one person is able to perform the procedure at a time; thus instructors must rely on verbal descriptions provided during the evaluation [57]. Students are required to visualise the volumetric shape of the eye fundus through a bi-dimensional (2D) lens, and identify the locations and overall conditions of the anatomic landmarks [47]. The procedure requires precision and timely execution in order to prevent patient discomfort from the fundoscope light exposure and the examiner is able to explore the fundus correctly, compensating for the equipment operation and patient cooperation [33].

Various tools and techniques have been developed to help the trainees and the instructor practice and evaluate eye ophthalmoscopy. Training tools include high-definition photographs [32], illustrations, video demonstrations [25], mobile applications [62], practice with patients [43], multimedia websites [25], and most recently, 3D computer-generated models [6] with various levels of realism. Additionally, simulators including low-fidelity approaches employing plastic canisters [14] and Styrofoam heads [29] [47].

Currently, there is a lack of immersive DO solutions as cost-effective alternatives to higher-end simulators that enable remote practice without depending on specialized hardware. Moreover, the use of photographs and videos limit the content interactivity and does not resemble real-life practice. Such scenario has led to the exploration of VR and AR as complementary solutions to traditional training, where learners can examine virtual patients in simulated conditions [62].

1.2 MOTIVATION

Traditional ophthalmoscopy training relies on patient practice, cross-student examination, pictures, illustrations, videos, and narrated demonstration from an instructor [35]. These methods present challenges associated with limitations that are inherent to each approach. Cross-student examinations provide a realistic approach, but is limited to conditions the students have, thereby making it difficult to examine certain rare or common disorders. Patient practice suffers from a similar challenge, where a richer environment for training under real conditions is provided, although the practise can be intimidating [14]. Pictures, videos and illustrators are flat (e.g., 2D and thus lack and three-dimensional structure) and lack examiner-patient interactions that are inherently present in real examinations, which results in students preferring photos for training, due to a lack of human interaction, and content can be observed at any time in high-definition [29].

1.3 OBJECTIVE

The goal of this thesis is to understand the face validity of a VR DO interactive scenario for practicing the examination of a healthy fundus in comparison to photograph-based, and exploratory AR and VR approaches reported in the literature. The face validity is done employing a Quality Function Deployment (QFD) by comparing the ratings of user and technical requirements between one traditional method of fundus examination training, and three alternate solutions. Additionally, a usability and cognitive load study is performed to understand how VR controllers and hand tracking affects task completion. Through the design evaluation of four examination training methods, and a usability and cognitive load study between different physical user interaction methods, this thesis will answer the question of, “What are the design, usability and cognitive load perceptions associated with virtualising the ophthalmoscopy examination with immersive technologies?”

1.4 METHODOLOGY

In order to achieve the research goal, a literature review was conducted to analyse past and current simulators for DO examination training, as well as the procedure. In conjunction with the takeaways from the literature review, the DO procedure is analysed to determine the VR system’s architecture. Once the system is designed, the development process begins. First, an analysis of the VR and AR headset available for the project is conducted to design appropriate user interactions that capture the ophthalmoscope operation through VR controllers and hand tracking. Next the virtual examination scenario, hereby referred to as “Oculated”, is developed including the examination room, eye fundus models, virtual patients, and graphical user interface components for the users to interact during the experience. Finally,

the environment is programmed to respond to user inputs and create a report to keep track of task completion.

After completing the development process, an experiment was designed to gather information about the developed VR DO. For the study, the QFD methodology allows for the gathering of face validity in terms of the development requirements from a user and technology point of view. This approach will allow for a comparison of the developed tool against others, in this particular case, photograph-based, VR, and AR tools. Additionally, since DO eye examination employing VR novel, an additional study to analyse usability and cognitive load is performed to understand ease of use challenges and opportunities for future work.

Finally, the results are analysed through the use of a paired t-test to determine if there were any significant differences between the sets of collected data, along with the Shapiro-Wilk test of normality.

1.5 ORGANISATION

- **Chapter 2: Related Works** presents a recount of simulation in medical education, and previous work related to direct ophthalmoscopy training with simulations.
- **Chapter 3: Development** provides more detailed explanations of the ophthalmoscopic examination, the anatomy of the eye, as well as the functionality of the direct ophthalmoscope. The chapter also details the inputs and outputs of the AR/VR system, and a breakdown of the virtual examination scenario.
- **Chapter 4: Experiment Design** describes the design, execution, and results of the test used to study and evaluate user interactions within the AR/VR examination scenario.
- **Chapter 5: Results** presents the results of the study detailed in Chapter 4.
- **Chapter 6: Discussion** provides an overall summary of the research.

- **Chapter 7: Conclusion** summarises the impact of research findings on the research question, hypotheses, and influences on future work.

LITERATURE REVIEW

This chapter presents an overview of simulation in the history of medical education leading to simulators for DO training. The reviewed works have been categorised based on the type of training method including traditional education, part-task trainers, and electronic patients.

Although medical professionals possess reasonably sound knowledge of medicine, a number of studies including the work of Fischer et al., have found that they are deficient in regards to clinical skill performance, problem-solving, and the application of knowledge to patient care [23]. These deficiencies have led to an interest in the way in which doctors are trained, and in the mechanisms used to train them. The increased demand for patient safety has driven the adoption of more advanced simulation to reduce medical error, which is estimated to be the third leading cause of death in the United States [16]. However, due to the costs associated with high-fidelity medical simulation, recent development have seen the use of mobile applications, gaming technologies, VR and AR, and makerspace as complementary solutions for students to gain access to remote practices through consumer-level devices [61].

2.1 MEDICAL SIMULATION HISTORY

Simulation has been established as a training tool that can be used standalone or complementary to training as learners are able to practice delicate procedures, and equipment handling without exposure to hazardous conditions and life-threatening repercussions [47]. This method of learning also facilitates the transition from the traditional apprenticeship mode, or in other words, “See one, do one, teach one”, into the more contemporary and successful, “See one, practice many, do one” [19].

By way of simulation-based training, learners are provided with the opportunity to practice using cognitive, psychomotor, executive, and interpersonal functions [50]. Prior to the use of computer-based simulators in modern-day training, physical models were used as educational tools regarding anatomy and disease, along with literature and theatre representations of various medical signs and symptoms [9]. In addition to these techniques, cadavers, live practice with students and patients have been used to help further develop cognitive and psychomotor skills in future doctors [59]. Medical education has evolved considerably since the 1900's from the apprenticeship model of learning where students see, learn, and do, to demanding precise objectives to measure competency in medical knowledge, skills, and behaviours [54]. The apprenticeship model, long a cornerstone of medical training, has limitations associated with reproducibility and reproducibility of conditions required to train competent health professionals, quantitative assessment in terms of the training received, and feedback on the efficacy of the training [48].

A simulation is typically comprised of two components: i) the scenario, and ii) the simulator. The scenario describes the simulation and includes the goals, objectives, feedback or debriefing points, narrative description of the clinical simulation, staff requirements, simulation room set up, simulators, props, simulator operation, and instructions for standardised patients (SPs) [4]. Simulators can include manikins, cadavers, animals, devices, technologies, computer programs and virtual spaces, scenarios, SPs, and a host of other methods of imitating real-world systems [4]. Debriefing sessions following such simulation-based training enables learners to reflect on their actions and make connections to real events, which further facilitates learning, abstraction, and conceptualisation [61].

The history of simulation in training and education spans many centuries and is widespread throughout various fields of human endeavour. The oldest description of simulation in health care education can be found in the *Sushruta Samhita*, a collection of medical texts written in approximately 500 CE. These

writings describe 1100 illnesses, including their management, and approximately 300 surgical procedures. This collection also contains sections dedicated to the production and use of simulators. The simulators described in these passages are primarily comprised of natural materials, such as holes in moth-eaten wood to represent wounds for probing. A majority of these simulators would be categorised as part-task trainers - manikins that have been modelled to represent specific parts of the body [31], although a whole-body patient simulator for skills practice is also described [58].

Signs of simulation-use in education has also been noted in ancient China, where the practise of acupuncture was taught through the use of life-sized wax-coated bronze figures filled with water, invented by *Wang Weiye*, the court physician of Emperor *Song* in 1023 CE [38]. The skills of the user were evaluated based on whether or not water leaked from the acupuncture point after needling. Alongside the simulators, a manual was printed and distributed by the central government health bureaucracy for students to use as a reference. However, the acupuncture channels described in Wang's manual were not aligned to any body structure because the study of anatomy was non-existent, and dissection was forbidden [67].

Although simulation has been a prevalent component of medical education throughout human history, the systematic and sustained use of simulation in health care education is more recent, dating to the start of the 18th century [49]. It was during this time period that the Chamberlen family, responsible for the invention of the obstetric forceps, lost their monopoly on instrumental deliveries, and more men (later known as men-midwives) had expressed interest in attending births [49]. Simulators were used to educate midwives and men-midwives on baby delivery, and how to manage more complicated births [49]. The use of simulation increased throughout the following two hundred years, along with the recognition that appropriate education and training would lead to applications in other fields

as technology advanced.

In order to help allay issues related to medical performance deficiency, medical education has shifted towards a system-based core curriculum that allows for the development of skills targeting patient safety [50]. One of the primary goals of simulation-based medical education (SBME) is a focus on the learners obtaining and honing clinical psychomotor skills within the cognitive domain, in addition to developing skills within the affective domain (such as communication training with simulated patients) [16]. Although simulation does not guarantee learning, when used in the proper environment, it can prove to be instrumental in the education and training of adult learners through experiential learning [16].

2.1.1 *Modern Manikin-based Simulation*

Technological advancements have led to the resurgence and development of more sophisticated simulators in medical training, particularly in ophthalmoscopic training [66]. One example of a more modern sophisticated medical simulator is the Resusci-Anne, a simulation manikin developed for practising ventilation during cardiopulmonary resuscitation (CPR) in the 1960's by Norwegian toy manufacturer Asmund Laerdal [36]. Although the model lacked any computer components, it presented an airway capable of obstruction where trainees were able to realistically hyper-extend the neck, and tilt the chin to open the airway for sufficient inflation [28]. An even more advanced simulator named Sim One was developed in 1967, by Dr. Abrahamson, an engineer, and Dr. Judson, a physician, both from the University of Southern California School of Medicine [1] [24]. Documented as the first computer-controlled manikin capable of visible chest rising and falling during breathing, Sim One included a synchronised heartbeat, blood pressure, coordinated temporal and carotid pulses, and a movable jaw and eyes. Sim One was used to teaching anaesthesia residents endotracheal intubation in a safe environment, and could also provide physiological responses to four intravenously-administered

drugs, and two gases through a mask or intubation tube. An analytic comparison was conducted between five medical residents using the simulator, and a control group consisting of another five medical residents. The medical residents who used the simulator yielded better performance ratings and required fewer trials to reach success in time than those in the control group [1]. Despite the effectiveness of the simulator, adoption was limited due to the cost associated with the software and hardware.

2.1.2 *Standardised Patients*

The concept of SPs originated in 1963 by a neurologist from the University of Southern California and revolved around using real people acting as a patient as a method of training. These 'patients' are carefully trained actors who are taught to utilise specific verbal and physical triggers to portray various patient conditions accurately. As such, these actors are also knowledgeable in the context of the simulation [20]. SPs are used to realistically imitate healthcare environments in order to engage medical education learners and to enhance the suspension of disbelief [9]. Although the first experience was formally reported in 1964, the method of training was not very popular initially as it was regarded to be too expensive and unscientific [54].

SPs can be considered to be a desirable alternative to medical education with real patients for a number of reasons. The first advantage of SPs lies in the readiness and availability of the simulator, as students are able to practice procedures at times and locations suitable for the specific training, instead of relying on real patients at a hospital or clinic [66]. Students are also able to experience multiple scenarios with SPs, rather than a single encounter with a live patient. SPs are also able to modify their behaviour to replicate patient behaviour during the period of consultation and treatment. This allows learners to familiarise themselves with continuous care within a reasonable amount of time. Lastly, SPs are considered to

be more ethical as a method of medical education as they are not real patients with real medical conditions or emergency scenarios [7]. The use of SPs also presents a few disadvantages. The overall reliability of a SP to consistently recreate the same simulation experience for all learners has been called into question [20], and the amount of time required for adequate training is limited. Nonetheless, Barrows argues that SPs are not meant to replace traditional methods of training, rather they are meant to act as supplements to enrich the overall learning experience, and to provide more practice for learners while working with live patients [66].

2.1.3 *Computer-based Simulation*

Computer-based simulators in medical training began with the introduction of mathematical models for physiological and pharmacologic anaesthetic drug effect simulation [17]. Simulators such as SLEEPER and the Anesthesia Simulator Recorder were developed for anaesthesia training, allowing trainees to practice the procedure through repetition and feedback, and have been praised for their realism and affordability [40]. Despite their convenience, computer-based models may lack key experiential and kinesthetic elements provided by higher fidelity training mechanisms (i.e., realism) that are critical for the development of psychomotor proficiency and dexterity used in clinical skills [66]. A comparison study conducted by Beal et al. concluded that although higher-fidelity simulation was more effective than low-fidelity simulation, in terms of skills acquisition, there were no significant differences with other teaching approaches [66].

2.1.4 *Virtual/Augmented/Mixed Reality*

Virtual reality (VR) is defined as the replication of an environment that simulates the physical presence of places in the real or virtual world, allowing users to interact in that world [51]. Through the use of specialised hardware and software,

environmental replication is achieved by stimulating a number of the human senses such as sight, hearing, and touch [56]. For instance, tactile and kinesthetic perception can be replicated through the use of haptic systems such as controllers with vibration feedback sensors. In addition, visual and audio cues can be provided through appropriate computer displays and speaker systems. A common concern with virtual reality systems is that their goal is to completely replace the normal perceptual cues with those from some alternate (virtual) reality [45]. VE's are typically isolating, requiring other team members and instructors to be simulated in the environment as well, if they are required, as medical tasks typically require social skills [26].

Augmented reality (AR) can be defined as a technology that projects virtual elements, such as menus and objects, into the real world [3]. AR was first introduced as a method of training for airline and United States Air Force pilots in the 1990's and is widely used as a tool for education in the present day. Similarly to VR, AR initially required expensive hardware and sophisticated equipment to use, although augmented reality programs can now be developed for more consumer-friendly devices such as mobile phones and computers. As a result, augmented reality can be used within classrooms from kindergarten to university [13].

AR has been shown to be a beneficial learning tool in education [12]. For example, AR allows students to engage in authentic explorations of the real world. By overlaying virtual elements such as menus, over real-world objects, users are able to make more detailed observations that would otherwise be overlooked to the naked eye [3]. In 2009, Dunleavy, Dede, and Mitchell observed that AR's greatest advantage lay in its unique ability to create immersive hybrid learning environments that combine digital and physical objects, thereby facilitating the development of processing skills such as critical thinking, problem-solving and communicating through interdependent collaborative exercises [22].

2.1.5 *Simulation in Ophthalmology*

With respect to simulation in ophthalmology, the need to improve eye training has led to the development of various simulators, from those employing interchangeable images (e.g., printed or digital pictures) examined through sockets simulating the eye in a manikin head [53]. From the earliest days of ophthalmoscope training, educational resources included the use of imagery (sketches, photographs) to guide students through the training process. Pictures, illustrations, multimedia, 3D models, cadavers, videos, lectures, and live demonstrations provided complementary media to enable learners further to explore content.

2.2 DIRECT FUNDOSCOPY TRAINING

Traditionally, eye fundus examination education begins with an introduction to the concepts associated with the semiology of the eye and the various pathologies related to the visual apparatus. Following this knowledge acquisition phase, a practical component takes place, where trainees learn and apply their knowledge towards identifying various fundus conditions by way of practice with classmates, or through the use of digital photographs [10]. Digital photographs are regarded as a standard method of fundus examination practice, as trainees are able to analyse a variety of common and rare physical afflictions otherwise challenging to observe in real-life practice as a result of patient availability [32]. Photographs also enable the trainee and instructor to confirm specific aspects of the ophthalmoscope view as both can visualise the same structures. In addition, students are expected to utilise direct ophthalmoscopes in real-life examination practice [57].

Photographs are a crucial training aid in ophthalmoscope training. They present a number of advantages over practice examinations with SPs, as they allow the instructor and the trainee to visualise the same image [29]. As a result, this allows

for better guidance and assessment in comparison with an ophthalmoscope, where the trainee obtains descriptions and directions, and reports orally on these while having the sole view of the fundus [29]. In a retention study, Kelly et al. [29] found that trainees prefer digital fundus photographs over direct ophthalmoscopy, with 20% of the trainees citing discouragement by clinical preceptors as a primary reason for not performing the full examination during training exercises. Trainee enthusiasm for the clinical usage of ocular fundus photography, suggests that more widespread availability of non-mydratic fundus photography could allow for more frequent and accurate examinations within the clinical setting [10]. Student preference for images led Kelly et al. to conclude that trainees preferred them because of their higher resolution, larger size, and lack of both patient and ophthalmoscope interactions that can increase the examination assessment. Building on photography-based training, multimedia tools often include interactive mechanics that allow the instructor and student to share the same view of the eye fundus with the objective of providing better guidance, feedback, and a full examination training experience [57].

The direct ophthalmoscopy examination procedure involves interpreting the intricate anatomy of the eye, when viewed through the lens of an ophthalmoscope. DO is a difficult procedure to master as it requires extensive practice to properly interpret the intricate anatomy of the eye [27]. Van Velden et al. [65] proposed a series of three factors for ophthalmoscopy training; formal instruction, adequate practice time, and refresher training. Benbassat et al. [8] suggested that although different medical associations have varying expectations concerning what medical trainees should know, all students should be able to identify the red reflex, optic disc, and recognise signs of clinical emergencies and retinopathies.

Yusuf et al. [27] identify limited practice as a concern regarding the ophthalmoscope training. The inadequate levels of competency and proficiency in ophthalmoscope operation have been identified resulting from the limited time dedicated

to eye examination training, which, when coupled with the inherent complexity of interpreting 2D eye fundus images and patient interactions, can lead to a challenging training experience [27]. Moreover, the deficiencies in examiner aptitude are not limited to just novice trainees; it also encompasses experienced doctors in the field of ophthalmology as well [63].

Although the “traditional” method of ophthalmoscopy training may not be universal, there are particular steps and key points that are generally followed [35]. The first general step pertains to general knowledge and taking lessons in theory, including those related to eye semiology, and an introduction to the various pathologies related to visual affectations. Following the “knowledge phase”, students and trainees apply their knowledge towards identifying various fundus conditions by way of practice diagnosis with classmates, or through the use of digital fundus photographs. Digital photographs are regarded as a common method of fundus examination practise, as trainees are able to analyse a variety of common and rare physical afflictions [32]. Lastly, students are expected to utilise direct ophthalmoscopes for real-life examination practise.

Direct ophthalmoscope (DO) simulators development has focused on overcoming the limitations of traditional ophthalmology training by enhancing different aspects of the simulation task. This section reviews low- to high-end eye fundus examination simulators, including both physical and computer-simulated tools. Ophthalmoscopy training can be conducted using different didactic tools (e.g., pictures, illustrations, multimedia, 3D models, cadavers, videos, lectures, and live demonstrations). The procedure follows appropriate steps and techniques that are generally taught for a successful examination [2].

2.3 PART-TASK TRAINER METHODS

2.3.0.1 *The Plastic Canister Model*

The Plastic Canister Model, described by Chung and Watzke in 2004, is a training model for direct ophthalmoscopes that simulates a mydriatic pupil. Through the use of a plastic canister with an 8-mm hole in the centre of one end, users are able to view a 37-mm photograph of a normal retina through the use of a traditional direct ophthalmoscope as shown in Figure 1 [14]. Results with this simulator have been mixed. A review by Ricci and Ferraz [52], highlighted common problems with the device including low photograph quality, intense light reflection and a loss of spatial perception by the examiners. A study performed by Kelly et al. [30] aimed at examining first-year medical student preferences for eye examination learning to assess accuracy used three different modalities; human volunteers, the plastic canister model simulator, and photos of the ocular fundus [57]. Post-test results showed that 71% of students preferred human volunteers to simulators with regards to learning how to use the direct ophthalmoscope. Furthermore, 77% of the students preferred utilising fundus photographs over simulators for ocular anatomy education. The students were also more accurate at identifying ocular fundus features through the use of fundus photographs over simulators, with 70% preferring the use of photographs over direct ophthalmoscopy. Despite this, Ricci and Ferraz describe how enhancements to the model, such as the use of high-quality photos, matte printing paper, and an indication of where the patient's nose would be, yielded a more favourable outcome regarding student efficiency for the initial practice of ophthalmoscopy [53].

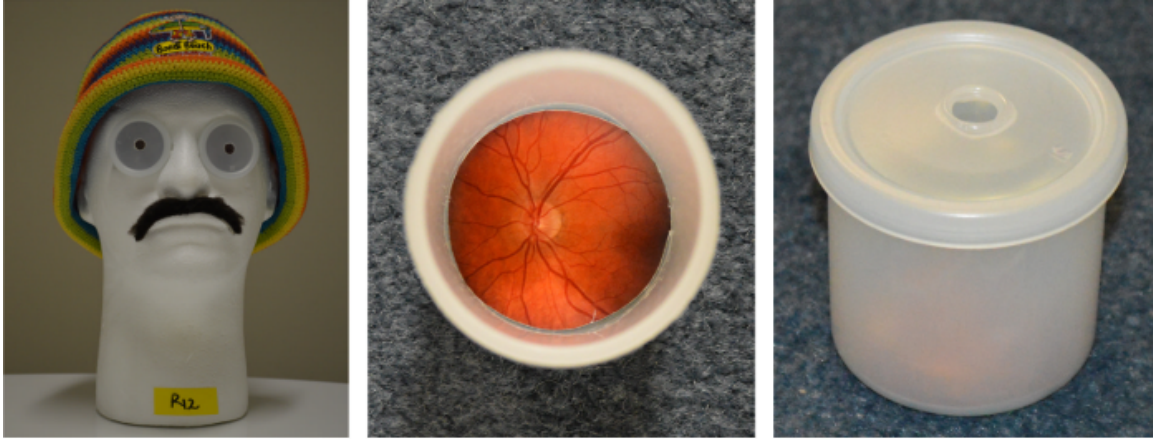


Figure 1: Depiction of the eye examination plastic canister. Interchangeable circular eye fundus photographs are placed at the back of the canister and then covered with the lid that has a hole mimicking the pupil aperture [14]

2.3.1 *The Human Eye Learning Model Assistant, The EYE Exam Simulator, and The EYE Retinopathy Trainer*

One problem with the use of a plastic canister to provide a simulated display is its lack of a simulation of the patient's head. This limits training of the approach to the patient and proper alignment of the ophthalmoscope with the eye itself. In 2007 the Human Eye Learning Model Assistant (THELMA) addressed this issue by including a Styrofoam head in their system. THELMA employed two different types of equipment to simulate the ocular fundus; the Slide Method, and the Plug Method [53]. The Slide Method consists of fundus photographs projected into a device similar to the Plastic Canister Model, and the Plug Method utilises an apparatus that is similar to an eyeball, with a diameter of 17-mm to allow for a field of view of 60° when viewed with a direct ophthalmoscope. Real-sized photographs of the fundus are placed within the device to increase realism. However, the amount of light required to view the photos depends on the ophthalmoscope, as well as the quality of the printing paper. In the following years, The EYE Exam Simulator (developed by Kyoto Kagaku Co., Kyoto, Japan and shown in Figure 2a), and

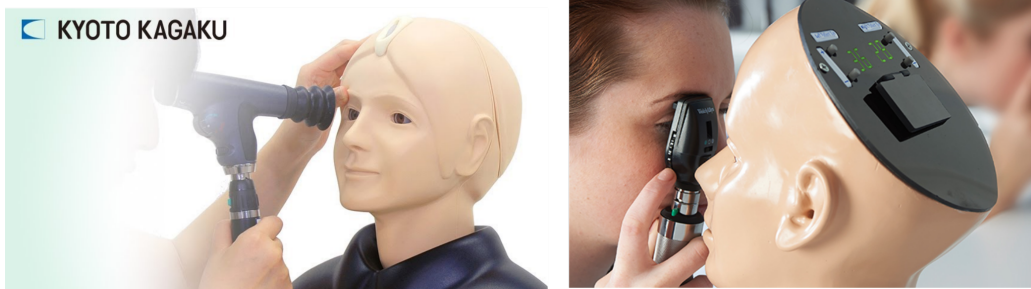


Figure 2: This figure presents two eye fundus simulators that employ interchangeable pictures. The panel on the right presents the Eye Exam Simulator. The panel on the left presents the Eye Retinopathy trainer.

the Eye Retinopathy Trainer (developed by Adam Rouilly Co., Sittingbourne, UK and shown in Figure 2b) were released, building upon THELMA's core features [6].

McCarthy in 2009 [42] made use of a modified EYE Exam Simulator to assess its feasibility as an assessment of fundoscopic skills. During the test, a group of 11 ophthalmology students and 467 emergency medicine (EM) residents were instructed to make visual contact with the ocular fundus using a handheld ophthalmoscope. Participants drew everything that could be visualised, and recorded any pathology seen. The drawing analysis at the end of the participant's use of the ophthalmoscope revealed that many participants failed to create any visual representation, and if there was one, it was usually of low quality. Feedback from the simulator provided by the participants was regarded as "neutral", with no indication of support for training with the model, although the EM residents did express interest in future simulation training. Some explanations regarding as to why the test yielded unfavourable results include the small group size of participants, the use of dark pictures with low illumination, and the eccentric placement of visual markers. Despite the results of McCarthy's test in 2009, a similar study was conducted in 2014 by Larsen [33] regarding the use of the simulator but with an instructor present during training to assist students. At the end of each session, the students were asked to identify what was seen in the simulation



Figure 3: The EYESi DO simulator in use. The monitor shows what the trainee is seeing while capturing performance metrics associated with the examination for assessment.

with a photograph. The study concluded that even a high-quality simulation had a lesser impact on students without guidance [33].

2.4 VIRTUAL REALITY

2.4.1 *EYESi Direction Ophthalmoscopy Simulator*

VRmagic, a company based in Mannheim, Germany, developed the EYESi Direct Ophthalmoscope Simulator (EYESi DOS) to offer a more realistic training experience for students. Ricci and Ferraz described the simulator as a complex and highly sophisticated piece of equipment, featuring a touch-screen interface attached to an artificial human face, allowing for an evaluation of a normal pathological fundus with a handheld ophthalmoscope as shown in Figure 3 [53]. As an enhancement to the teaching of the diagnostic skills required for direct ophthalmoscopes, the simulator's ability to provide feedback based on the user's view, and control of technical and physiological elements (e.g., light, blood vessel colour, and pathological spots), provides a distinct advantage over other traditional simulators [14]. Its biggest drawbacks are its cost, the need for trained staff, and the lack of comparative studies to prove its efficacy [52].

In 2017, a VR ophthalmoscope trainer was developed at Birmingham City University [69]. This device was designed to engage students in learning complex ophthalmoscopic skills by combining VR and gamification techniques (i.e., the use of game mechanics in routine activities for increasing engagement, adhesion and participation). This VR-based learning application contained five sections; an interaction tutorial, red reflex and retinal navigation, pathology identification, and a final quiz. Within the tutorial level, users were taught how to use the application, including the head-based movement for locating objects and utilising the VR headset's triggers to interact with them. The red reflex, a component of the application was focused on teaching the user how to locate the red reflex of the eye by shining the virtual ophthalmoscope into the patient's eye at a certain angle and zooming in and out with the lens settings. After the red reflex tutorial is completed, users are provided with background information on retinal examinations before being guided through a series of procedure steps to help navigate the anatomic landmarks of the virtual eye. Users are then instructed on how to follow the four main blood vessels out from the optic disc, and then to navigate the four quadrants of the retina through the use of audio-visual commentary and feedback. Upon completion of each section, users are presented with a set of eight different images of the eye and are tasked with identifying the conditions of the eye utilising the skills they obtained previously. The application applies standard gamification strategies and makes use of virtual rewards, such as badges, that are given to users as a method of recognising task progress. Rewards and reward tiers are granted based on metrics such as accuracy and task completion time, and this is done to indicate the user's level of achievement when learning ophthalmology skills with the simulator.

The application was tested with a group of fifteen undergraduate medical students to evaluate its efficacy as a learning tool for ophthalmoscopes [69]. Students were asked if the application improved their understanding of the processes undertaken with the examination procedure. They were also asked whether or not they were able to recognise the anatomic landmarks of the eye and any physical

abnormalities. Questions that assessed ease of control with the application, user confidence, and the effectiveness of the teaching method were included with the evaluation. Students reported an increase in their overall understanding of eye anatomy, their ability to identify anatomic landmarks, and physical abnormalities within the eye. An increase in confidence with the ophthalmic examination was also noted amongst participants, and they felt that the application was easy and enjoyable to use [69].

Given the nature of the ophthalmoscope examination and the ophthalmoscope itself, it can be difficult to provide training in a group setting. Tangible user interfaces can provide an effective approach to overcome this problem. Codd-Downey et al. [15] describe an AR-based approach that utilizes a tangible user interface to enable multiple trainees to interact with a common eye simulation. Figure 4 shows the tabletop structure used in their system with AR markers positioned at its corners. Individual users can use their own AR device – a tablet-based interface is shown in the figure – to provide personalized per-user overlays to the common shared training experience. The integration of both technologies presents an active learning experience that could be used to engage all learners in a common educational experience.

The system described in [15] leverages commodity cell phone and tablet devices to provide tracked visual displays to each user. The exploitation of such commodity hardware provides a cost-effective mechanism for integrating intangible devices into ophthalmoscope training. Soto et al. [62] describe a cellphone-powered VR-based system that combines a mobile VR headset with interpupillary adjustable lenses in conjunction with a Bluetooth game controller. Figure 5 presents the stereoscopic visualisation of the eye fundus and the external eye anatomy available with this system. The process requires trainees to locate the red reflex while rotating the eyeball. Once located, the scenario changes to an internal view of the eye where the optic nerve, macula and diverse blood vessels can be identified. User interactions to navigate the examination are based on a first-person shooter

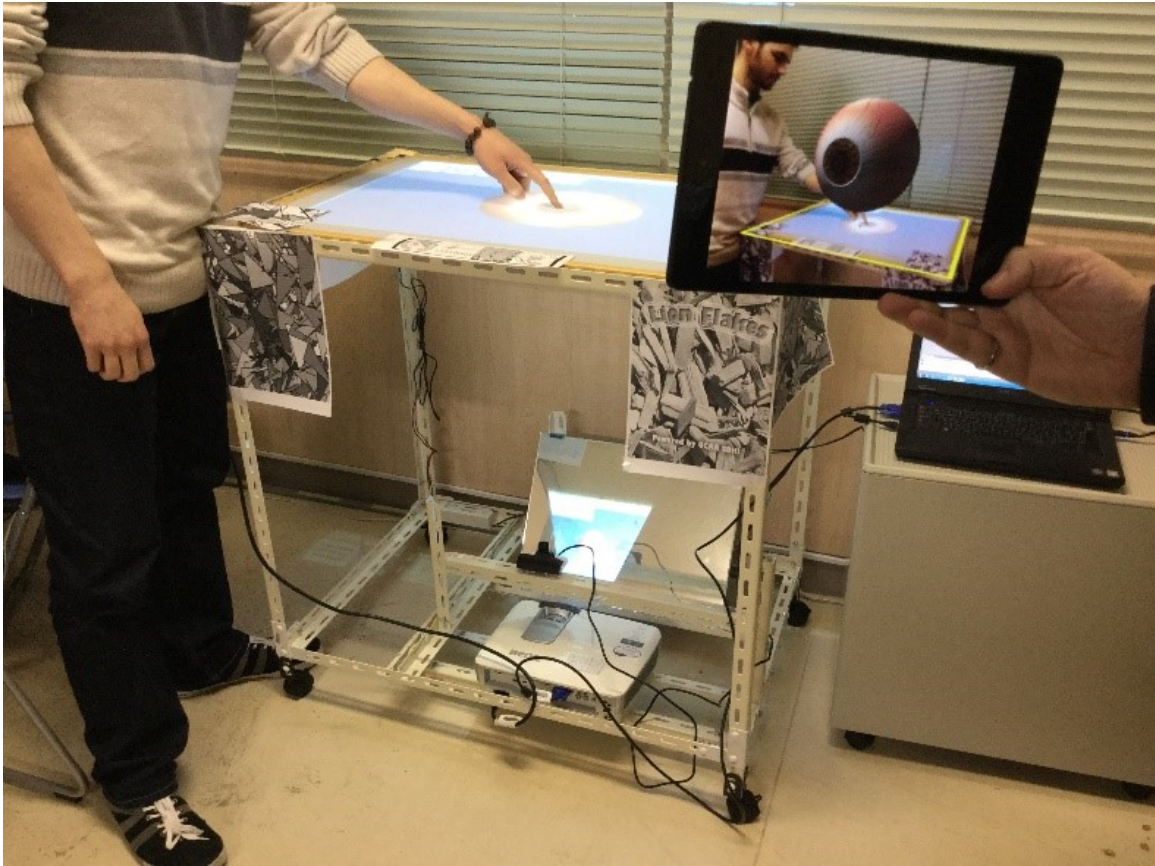


Figure 4: Multiple users interact with an intangible display (the tabletop) while being presented with personalized AR views through commodity hardware (here through an Android tablet) [15].

setting, where the left joystick allowed moving the camera towards the eye, while the right joystick allowed rotating the camera, and actions were confirmed with a button. A user study revealed that although stereoscopy was well received by participants, interactions employing a game controller were challenging because of the unfamiliarity with such device as participants expressed that they were not experienced in playing video games [62].

A later refinement by Acosta et al. [2] of the eye fundus examination trainer focused on overcoming the challenges identified when using a game controller as a user input device. AR was employed as the underlying technology and interactions were modelled employing touch gestures, as shown in Figure 6. In this iteration, the learner employs a printed marker that serves as a reference for rendering the

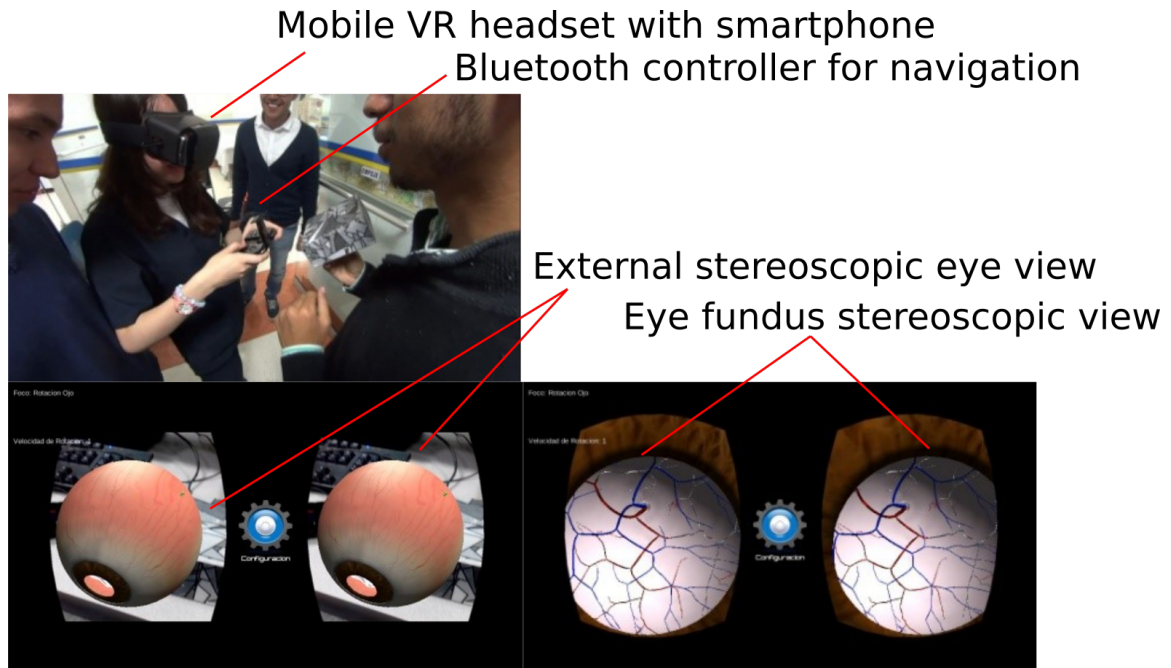


Figure 5: Mobile VR eye fundus examination. Upper panel shows the user wearing the HMD and interacting with the simulation using a wireless Bluetooth control. Lower panels show simulated stereo imagery presented to the user. The lower left panel shows the external eye view while the lower right shows the simulated ophthalmoscope display [62].

virtual head to perform the eye examination. The marker can be placed on any flat surface. Figure 6 shows the application flow from start to examination. Here, the interactions were more natural due to the familiarity with touch screens, but the model visualisation was challenging due to the limitations of the AR technology used. For example, lighting, the quality of the marker, and how the markers are held can negatively affect the experience.

One of the main challenges associated with the AR interactions shown in Figure 6 is pointing the mobile device to the target, and holding the target so that the information is properly visualised. Holding the marker and device can lead to arm strain if used for prolonged periods. To remove this interaction problem and facilitate the interactions and marker manipulation, a Styrofoam head was added to the system as a tangible reference for the user, as shown in Figure 7 [2]. The use

of the head and the marker attached in the position of the eye required learners to employ both hands to operate the virtual ophthalmoscope within the mobile application and the Styrofoam at the same time. As a consequence, the interactions were difficult to master as the smartphone required to be kept as still as possible to ensure good tracking and AR rendering. A further refinement to this work saw the inclusion of a 3D printed ophthalmoscope replica to use in conjunction with AR [2]. The objective was to improve the interactions and facilitate the virtual examination while using a device mimicking the basic operations of a real ophthalmoscope. This approach provides both a physical cue to its location as more accurately modeling its input controls. The device includes an Arduino Micro, a Bluetooth module, and a potentiometer for operating the magnification of the lens. A flat surface attached to the simulated ophthalmoscope handle provides a surface for placing a tracking target. When the marker is within the field of view of the smartphone camera, the virtual eye is rendered for examination, as shown in Figure 7.

The previously described AR and VR approaches provide only a localized simulation of some VE's. More sophisticated and large scale simulations have also been developed. Nguyen et al. [47] describes a VR ophthalmoscope simulation for replicating the direct ophthalmoscopy procedure on a simulated patient Figure 8. The virtual ophthalmoscope controls are mapped to an HTC Vive controller and allow for users to adjust lens zoom and light intensity. The system includes a number of visual aids within the VE for aiding the user in conducting the procedure, as well as the instructor to evaluate trainee progress. For instance, a separate window appears on the wall behind the virtual patient allowing both the instructor and the user share the examination. Other visual aids include a heads-up display that contains anatomic landmark information to aid trainees in diagnosing the patient's physical condition.

The virtual simulation features two navigation modes; one for training, and the other for evaluation. While both modes enable the user to conduct a full ophthalmoscopic examination, the training mode includes the visual aids, as well as a

set of tasks that are meant to debrief the user following patient diagnosis. After completion of the training mode, users can begin the evaluation mode, where the full examination is conducted with metric evaluation. Users are assigned scores for both modes, where cognitive tasks are evaluated in questionnaire form, and skills are evaluated based on the user's performance during the examination. Factors that are considered during the skills evaluation process include maintaining fundus visibility, keeping the examination duration to 35 seconds or less, identification of the anatomic landmarks, and the proper procedure approach and patient treatment.

Formal testing was conducted to gauge the efficacy of the simulator, which involved nine medical students who possessed a basic understanding of human eye anatomy [47]. The participants were tasked with approaching the virtual patient, adjusting the lens and light settings of the ophthalmoscope, and establishing a visualisation of the fundus. Although each person completed the tasks within a five-minute time frame, four of the participants were not able to see the fundus correctly as a result of not moving close enough to the virtual patient. All participants reported difficulty in operating the HTC Vive controller, and it is hypothesised that this is a result of the controller having a different button and dial layouts than a real-life ophthalmoscope. However, the participants expressed interest in seeing similar software developed for other medical procedures.

2.5 SUMMARY

The DO eye fundus examination is a procedure that allows medical practitioners to observe the back of the eye as a method of diagnosing patient physical health. Although fundus examinations are regarded as a critical component for full-body diagnosis, the skills necessary to perform the examination are regarded as difficult to teach and require a considerable amount of time to practice and master. From perhaps the earliest days of DO, training has adopted a range of training tools and simulators to enhance the training received by direct examination of patients and

patient stand-ins. Unlike any medical procedures, the use of an ophthalmoscope has, until very recently, been restricted to the operator of the device. This makes training extremely challenging as it is difficult for the student and the instructor to exist within a common representation of the task. One can easily imagine the teacher asking the student if they see a particular feature, and the student, not wishing to appear foolish, answering, "Of course", even though they do not.

Beyond the unique nature of the DO in restricting the shared experience of the instructor and the pupil, the use of patients is not an ideal solution for training. Patients may present many wonderful examples of normal conditions, but on-schedule presentation of disease/damage can not be guaranteed. Simulation, even as simple as the use of photographs, helps to provide the trainee with a broader range of disease/damage that is likely to be available in a trainee.

Given the difficulties associated with direct ophthalmoscopes, alternative methods of practice have been implemented as supplements to traditional forms of exercise such as peer-to-peer practice with an ophthalmoscope. Through the use of simulation, students and trainees are able to practice medical procedures that would otherwise require limited allotted time and supervision. Although there are a number of techniques that have been used for instruction, many modern-day training methods cannot still be used as easily accessible forms of practice, and lack an accurate manner of user progress evaluation. These devices, when coupled with proper supervision and training, can provide a highly effective training regime for medical professionals. One can only hope that advances in simulation systems for other medical procedures and tests will advance as well. As technology continues to evolve, simulated clinical experiences allow for delicate procedures to be practiced with greater accuracy and variety than traditional learning methods.

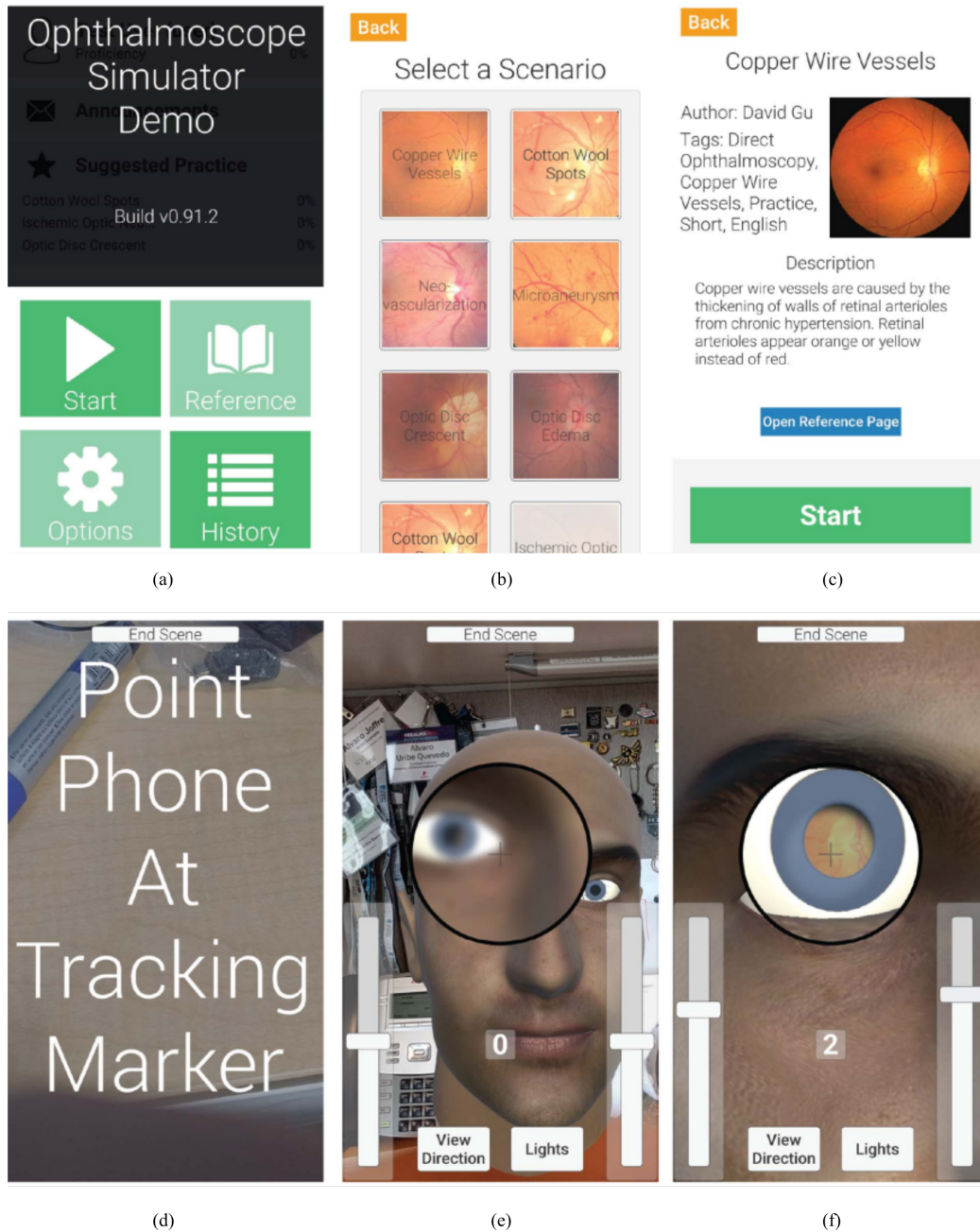


Figure 6: AR eye fundus examination flow. The numbering indicates a sample order, (a) is the main menu where users can start the examination or view their history. (b) provides a list of scenarios for practising. (c) shows information about a chosen condition and it allows the user to start the examination. (d) informs the user to point the phone at the marker to start the training. (e) shows the virtual patient head overlaid on top of the marker. Finally, (f) shows the touch controllers for light intensity and lens magnification [2].

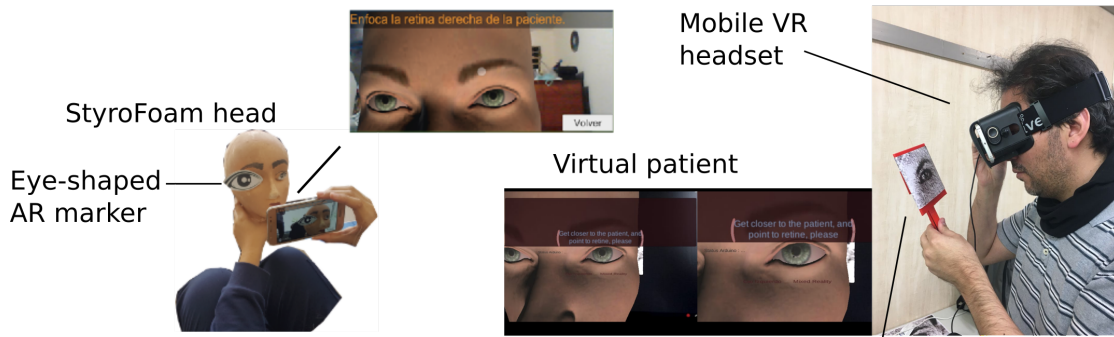


Figure 7: Two mobile augmented reality modes are presented. On the left, a Styrofoam head with an eye-shaped printed markers overlays a virtual head for conducting the fundus examination. On the right, a mobile VR headset is used in conjunction with a 3D printed ophthalmoscope replica holding a printed marker where the eye fundus is projected for examination [2].

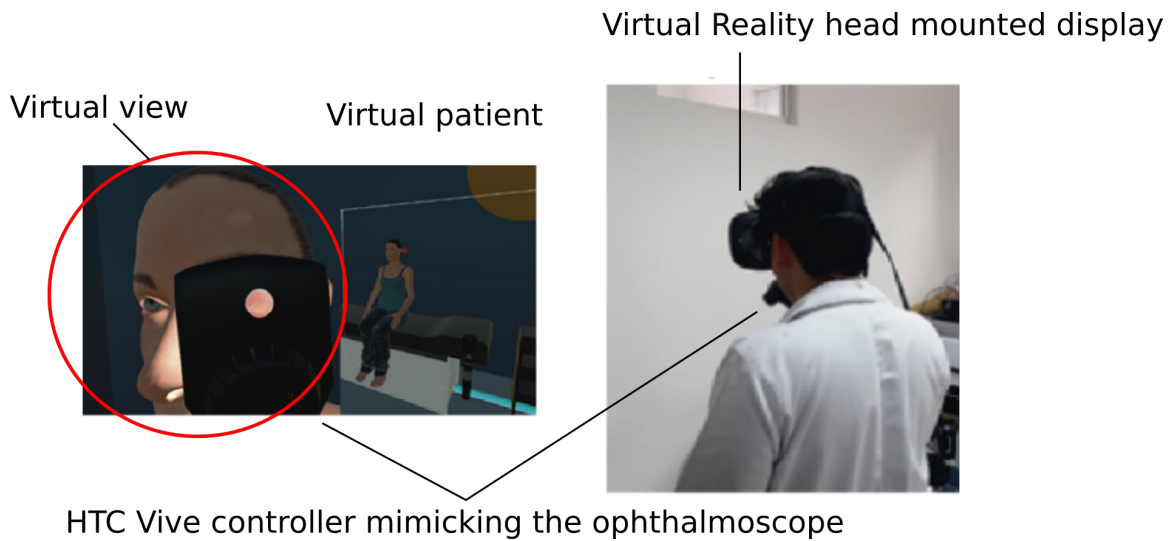


Figure 8: User employing the HTC Vive VR headset and an HTC Vive controller to perform an eye fundus examination on a virtual patient. The image on the left shows the virtual patient and a view taken from the headset showing the virtual ophthalmoscope [47].

CHAPTER 3

3.1 DEVELOPMENT

This chapter presents the design and development of the OcuLED program, a virtual DO eye fundus scenario employing VR controllers and hand gestures. The scenario allows users to move and rotate a virtual direct ophthalmoscope to view different anatomic landmarks within the fundus representation.

3.1.1 *Direct Ophthalmoscope Operation*

The direct ophthalmoscope is a light, compact, hand-held tool that allows health professionals to see the fundus through the pupil. The device projects the fundus as an upright image with a variable magnification up to 15 times [34]. The direct ophthalmoscope consists of two primary components; the handle and the head. The handle of a typical direct ophthalmoscope contains the power supply and light source, while the head houses the viewing window and lenses. The device's apertures include large, medium, and small circles, as well as a slit beam. In order to reduce the amount of pupillary constriction within the patient's eye, it is advised to set the ophthalmoscope to a brightness level between 80% and 90%, with the small or medium circle aperture [37]. In order to compensate for the possibility of myopia or presbyopia-related errors on part of the examiner and the patient, the ophthalmoscope contains a range of positive and negative diopters that are used to adjust the focus of the lens. For instance, patients who have hyperopia will have retinas that are closer to the pupil than normal, and patients who have myopia will have retinas that are farther from the pupil than normal. As a result of these conditions, the examiner is required to adjust the lens diopters accordingly.

Lens ranges may also vary between direct ophthalmoscope models. For instance, diopters may be segmented as +1-10, +15, +20, +40 on the positive side, and -1-10, -15, -20, -25, and -35 on the negative side [60].

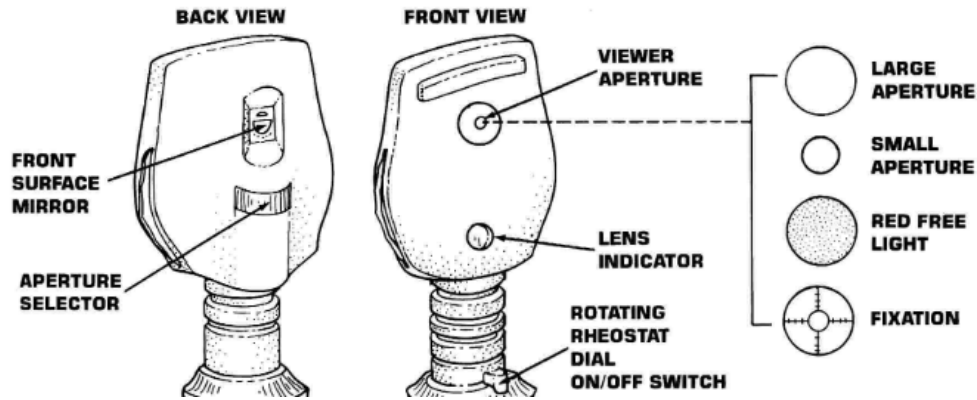


Figure 9: A diagram featuring direct ophthalmoscope head components and aperture selections [55]

3.1.2 *Eye Fundus Anatomy*

The ocular fundus is the primary component of the eye that is visible during ophthalmoscopic examinations, and includes the retina and its vessels, and the optic nerve. Spanning a diameter of 5 - 6 mm, the macula is located in the centre of the posterior retina. Within the centre of the macula lies the fovea, which contains the highest concentration of cones, and is responsible for colour vision and the highest visual acuity [68]. Each of the landmarks can be seen within Figure 5.

3.1.3 *Direct Ophthalmoscopy Procedure*

A DO examination begins with the user holding the handle of the ophthalmoscope and aligning the aperture of the device with the user's eye. Examiners are expected to use their right eye to examine the patient's right eye, and their left eye for the patient's left eye in order to avoid nose-to-nose contact with the patient [37].

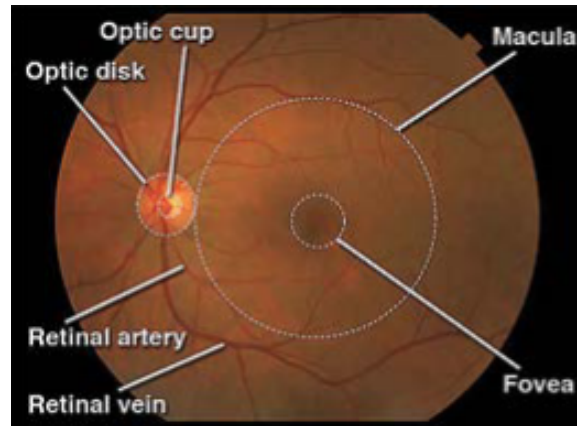


Figure 10: A healthy retina featuring the optic cup, optic disc, retinal arteries and veins, fovea, and macula [37].

Regardless of which hand operates the ophthalmoscope, the lens wheel is manipulated with the index finger of the hand that holds the device. The ophthalmoscope's light should be switched on, and the lens diopters set to zero. The procedure can be performed with or without pupil dilation, although dilation is encouraged and can be promoted through the use of a topical mydriatic/cycloplegic solution, in addition to darkening the room [37] [55]. Natural eye and head movement can be reduced by instructing the patient to focus on objects around the room [37], as well as placing an empty hand upon the patient's forehead to support and steady it [60].

The DO examination consists of a set of procedural objectives that allow the examiner to make a full fundus diagnosis:

- Locating red reflex
- Focus on retina
 - Locate and examine optic disc
- Follow ocular blood vessels to view retinal quadrants
- Examine macula
 - Determine if macula colour is homogeneous

Look for presence of foveal reflex

The red reflex is the reflection of light from the retina, and acts as the first step in examining the fundus. With the lens diopter level set between +8 and +10 (light strength between models may vary), the light of the ophthalmoscope should be directed towards the patient's pupil at a distance between 30 cm and 50 cm, and at a slight temporal angle from the patient's line of sight [37] [55]. The examiner is able to move closer towards the patient in order to locate and follow the red reflex, turning the lens diopters clockwise until the retina is in focus. A diminished reflex or entirely absent reflex is indicative of light obstruction, which can be caused by irregularities such as cataracts [37]. It is possible to determine the placement of the obstruction by asking the patient to look in the four cardinal gazes to note the movement of the opacity. Movement against ocular movement means that the opacity is behind the nodal point of the eye (i.e. in the lens or vitreous), while movement with would indicate corneal or anterior segment opacity [60].

The examiner is encouraged to hold the ophthalmoscope as close to the patient as possible, as only a small portion of the retina is visible through the viewing window [37]. One sign of sufficient distance to the patient is when the examiner's knuckles make light contact with the patient's cheek, which acts as a point of rotation for examination movements [55]. As a result of the limited field of view, the ophthalmoscope can also be tilted as necessary in order to visualise the different areas of the fundus. The first anatomic landmark to be located is the optic disc, or optic nerve head, which is traditionally yellowish-orange, and is located approximately 15 degrees nasal to the patient's visual axis. Once the retina is in focus, any blood vessel can be localised and traced back against the branching pattern to the optic disc. Within the centre of the optic disc is a pale depression that is referred to as the "optic cup".

Following the optic disc, the remainder of the fundus can be examined by following the blood vessels from the optic nerve head into each of the four ocular

quadrants. In retinal vasculature, veins tend to be thicker and darker than arteries [37]. The patient can be instructed to look in each of the four cardinal directions as the fundus vasculature and retinal background are evaluated. Elements such as colour and evenness of pigmentation within the retinal background should be noted. Lastly, the colour of the macula and the presence of a foveal light reflex are to be examined as the focuses for the final component of the examination. The examiner should be positioned along the patient's line of sight to examine the macula, which can be located by instructing the patient to look directly at the ophthalmoscope light.

3.2 SYSTEM ARCHITECTURE

3.2.1 *Inputs*

The examination scenario supports an immersive VR mode employing a head-mounted display such as the HTC Vive with Vive controllers or Valve Index controllers, an immersive AR mode employing the Microsoft HoloLens with its gesticulation system, and a non-immersive VR through the screen. Regardless of the scene, interactions with the examination system require the examiner to use the virtual ophthalmoscope to identify the anatomical landmarks on an eye fundus.

3.2.1.1 *Immersive VR*

An HTC Vive VR head-mounted display, including the headset and a single HTC Vive controller, and one Valve Index controller were used for the VR portion of the study. The Vive was chosen because it is one of the most commonly used VR systems, features accurate room-scaling, where users are able to manually draw their own play-area boundaries using the VR controllers, as well as its ease of use. Room-scaling The HTC Vive system was set up in a dedicated space within the graduate student GAMER Lab, with a tracking area of 2.5m x 2.6m horizontally and 2.4m vertically. Two different controllers were selected for use in the study; a

HTC Vive controller, and a Valve Index "Knuckle" controller.

The HTC Vive controller is the primary method of user interaction with the virtual world, and is shipped with the HTC Vive VR system in a set of two. The controller features multiple input methods including a track pad, grip buttons, and a dual-stage trigger. The head of the controller contains twenty-four infrared sensors that detect the system's base stations in order to determine the controller's position. The system's base stations, also known as the "Lighthouse" tracking system, consists of two black boxes that emit timed infrared pulses at 60 pulses per second in order to create a 360 degree virtual space. The Valve Index "Knuckle" controller is shipped with the Valve Index VR system, and functions in a similar manner to the HTC Vive. The controller allows users to interact with the virtual world using a variety of inputs including a thumb-stick, dual-stage trigger, and track button with a force sensor. In addition, the controller features a set of sensors located across the user's knuckles that allow the positions of the user's fingers to be captured and used directly as input, rather than relying on buttons and trigger input. Lastly, a hand strap is included to allow the user to open and close their hands without releasing the controller.

Although the HTC Vive controller receives user input from a number of sources, the system only utilises the trigger located on the back of the controller, and the head of the controller for input. The base station sensors track the position and orientation of the user's hand in virtual reality through the head of the controller, while the trigger located on the back allows the user to pick up and hold the virtual ophthalmoscope.

3.2.1.2 *Immersive AR*

The AR version of the fundus examination allows for the collection of the virtual ophthalmoscope through the use of the 'Grab' gesture. However, users are unable

to move around and rotate the tool simultaneously as a result of the headset's inability to track hand rotation in conjunction with hand translation. Consequently, users are required to manually switch between the rotation transformation and translation transformation modes by way of voice commands given through the headset's built-in microphone.

The Microsoft HoloLens AR headset provides users with a means of system input through the use of a built-in gesticulation system for navigation and a microphone for voice commands. As a result of a lack of physical controller with a cursor, the HoloLens utilises the user's head position as a means of determining the cursor's on-screen location, while the built-in gestures act as a method of direct input. The HoloLens contains two gestures; the Grab gesture, and the Bloom gesture. The Grab gesture is the system's primary source of input, and acts as the traditional "left-click" function of a computer mouse, while the Bloom gesture allows users to return to the main menu of the HoloLens. Users are also given the option to utilise a Bluetooth "clicker" that can simulate the Grab gesture, although there is no replacement for the Bloom gesture.

3.2.1.3 *Non-Immersive VR*

In addition to the AR gesture and VR controller inputs, a set of mouse and keyboard controls were implemented to the VR scenario in order to accommodate for remote testing due to the COVID-19 pandemic situation. The mouse and keyboard controls consisted of the 'W', 'A', 'S', and 'D' keys to move the camera forward, left, back, and right, respectively, as well as the 'Q' and 'E' keys to pan the camera up and down, respectively. The reason why these keys were selected for computer movement is because the 'W', 'A', 'S', and 'D' keys are traditionally used for movement in video games, and the 'Q' and 'E' keys were selected because they are adjacent to the 'W', 'A', 'S', and 'D' keys, and therefore it is theorised that users may have an easier time with reaching the keys while moving the camera.

Camera orientation is performed by holding down the right-mouse button and moving the mouse, while holding down the left-mouse button allows users to interact with the virtual elements within the scenario.

3.2.2 *Sub-Systems*

There are four sub-systems within the Oculed program. The first is the data presentation to the user, which includes the virtual patient models, the VO, and the graphical representation of the fundus. The second is user input, i.e. how the user controls the camera, the VO, and the buttons. The third sub-system is the state management of the program, where scene advancement is controlled based on user input. Lastly, the final sub-system is data collection, where the button selection choices are recorded and saved on a .txt file to a location of the user's preference.

3.2.3 *Outputs*

The main source of output to the user comes in the form of visual feedback associated with the visual instructions, direct fundoscope operation and eye fundus examination and the task completion results. The system also features audio feedback consisting of a ticking sound that is played when the user successfully grabs an interactive object.

3.3 VIRTUAL ENVIRONMENT

The Unity game engine was used to create the VE and it was chosen due to its compatibility with VR and AR at the time of writing this thesis. Although the environments between each platform were nearly identical in terms of model and

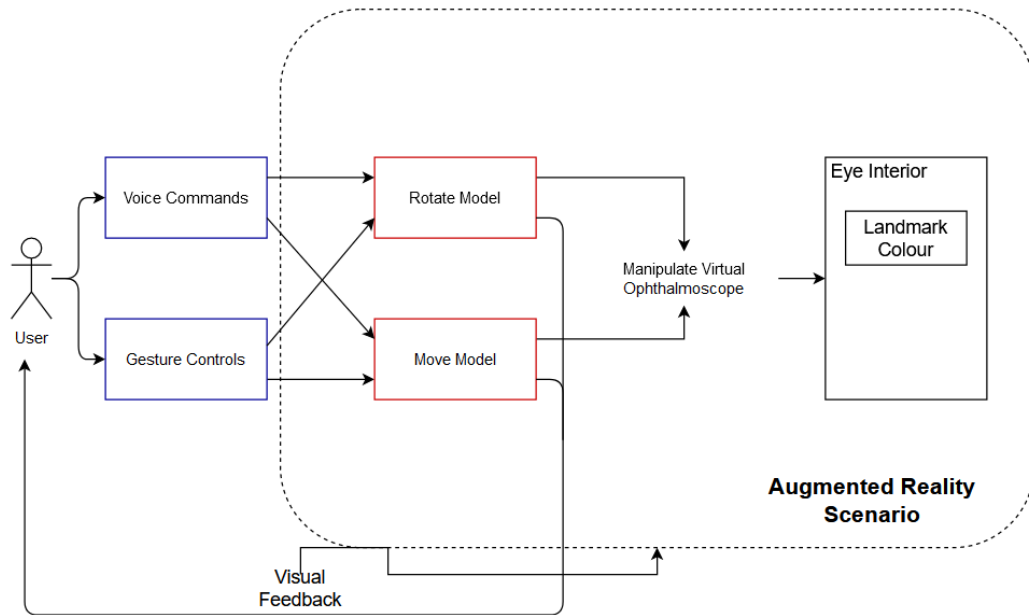


Figure 11: System architecture for AR system.

text placement, the engine versions employed to build the VR and AR scenes were different. The VR version of the environment was built in Unity 2019.3.0f5 with the SteamVR plug-in installed in order to integrate VR capabilities such as controller input. In addition, the mouse-and-keyboard version of the program utilises SteamVR's built-in computer controls for camera positioning and orientation. In contrast, the AR version of the environment was built using Unity 2017.2.5f1, and contains several features from the Microsoft Academy Mixed Reality Toolkit¹ such as hand-tracking, gesture and voice recognition.

3.3.1 Virtual Examination Area

The virtual examination area consisted of dedicated areas for three virtual patients, as well as a set of text boards that provide visual instructions for the user. The purpose behind this particular scene arrangement is to provide users with an environment in which they could practice the procedure and review the material

¹ <https://docs.microsoft.com/en-us/windows/mixed-reality/holograms-101>

without the need to change scenes. In addition, the lighting within the scene is designed to allow the user to locate each of the interactive elements within the environment, without potentially confusing any unlit elements as “deactive” components.

The mouse-and-keyboard version of the VE contains an additional text board (hereby referred to as, “the landmark board”) on the right-hand side of each virtual patient that prompts users to locate one of the anatomic landmarks. Users are able to indicate their success in locating the landmarks via two interactive buttons; one for if the participant managed to locate the landmark, and the other if they were unable to. The purpose behind utilising this method of progress-tracking is to provide users with the freedom to decide if they were successful in achieving the objective, in contrast to implementing an automated system that may advance the scene without the user knowingly locate the target. After the user selects one of the buttons, the landmark board will change to indicate the next identification target. Once the landmark board has cycled through each landmark, the virtual patient will change to the next.

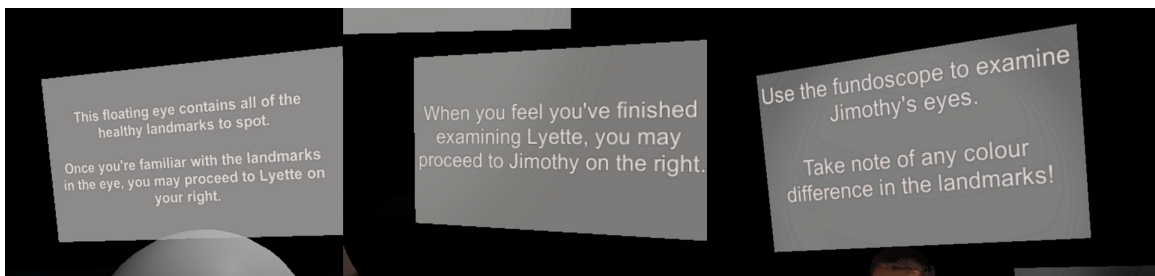


Figure 12: Boards containing instructive text for the users.

3.3.2 *Virtual Patient*

Three virtual patients were selected for the scenario to represent three “tiers”, or levels, of difficulty in examination practice; easy, medium, and hard. The “easy”

level-difficulty patient is a large floating eye that was modelled to include a hollowed interior and a set of blinking eyelids. The eye was hand-animated to slowly move up and down with slight rotational movement to simulate the subtle physiological behaviours that eye examiners would face with a real patient. The purpose of this eye model is to provide users with an enlarged, healthy version of the target for ease of initial landmark location, and to practice using the VO with. The enlarged eye model also featured text boards containing information about the eye's landmark targets, such as the healthy states of each landmark. The “medium” and “hard”-difficulty patients consist of two humanoid models that contained smaller versions of the floating eye, excluding the eyelids, that replaced the patient model's original eyes in order to maintain consistency between each of the patients.



Figure 13: Scene overview with floating eye (left), virtual patients 'Lyette' (centre) and 'Timothy' (right), and instructive text boards.

Similarly to the large, floating eye, the virtual patients were hand-animated to simulate head and eye movements, including blinking, and breathing in order to maintain a certain level of physiological realism between what an examiner would encounter with a real-life patient, and a virtual one.

The “medium”-level difficulty patient, nicknamed “Lurette”, is a stylised humanoid character that was rigged for the purposes of 3D character animation, and therefore contained the necessary controls to create detailed animations such as breathing. The rationale for selecting a “stylised” character model, rather than a realistic one, is to provide users with a gradual increase in realism in order to avoid a rapid descent into the “uncanny valley”, where the perception of human-like characters such as robots, and by extension, virtual avatars can evoke negative or positive valence depending on the subject’s degree of visual and behavioural realism [11].

Although the AR and VR versions of the VE contained identical Lurette models regarding the fundus representation, there was a slight difference in the mouse-and-keyboard version. The mouse-and-keyboard version of Lurette contained two different fundi representations; the first being the primitive representation that is seen in the AR/VR versions of the VE, and the second being a digital photograph of a real fundus that contains a labelled optic disc, optic cup, and macula. The second fundus appears after the user states if they were able to locate the anatomic landmarks within the first fundus via the yes/no buttons on the the right-side of Lurette. The reason for this is to continue gradually increasing the level of patient realism to the user until they reach the final virtual patient, who represents a fully realistic patient regarding appearance and anatomy proportions.

The final patient, nicknamed “Jimothy”, is a human model that also included an animation rig. However, unlike Lurette’s rig, Jimothy’s rig lacked a number of controls, such as sternum manipulation and clavicle control, that allowed for detailed animation work. Despite this shortcoming, Jimothy’s model was selected because it was regarded as “a photorealistic, 3D-scanned human”, and therefore contained realistic body proportions. Similarly to Lurette, the mouse-and-keyboard version of Jimothy is slightly different to his AR/VR counterpart. In the mouse-and-keyboard version, Jimothy contains the same digital fundus photograph as Lurette. However, unlike mouse-and-keyboard Lurette, Jimothy only contains the

photographic fundus, rather containing both the primitive fundus representation, and the photographic one.



Figure 14: Virtual patient “Jimothy” with his original eyes (left) and custom eyes(right).

3.3.3 *Virtual Ophthalmoscope*

The virtual ophthalmoscope in the scene was created in the 3D modelling software, Autodesk Maya. The purpose of this model was to act as a basic representation of a real ophthalmoscope, and therefore does not include a visual representation of all the components described in Section 3.1.1. This is due to the focus of the program. However, the model still features the visually discernible details, such as the diopter dial and viewing window in order to maintain . In addition, the virtual ophthalmoscope features a square window located on the examiner side of the tool that provides users with a magnified image of anything in front of the tool. The purpose of this window is to simulate a larger version of what the user would see through the viewing window. The viewing window of the virtual ophthalmoscope was not functionally replicated exactly since users would have a difficult time with lining the virtual ophthalmoscope with their eye due to the design of the HTC Vive headset.

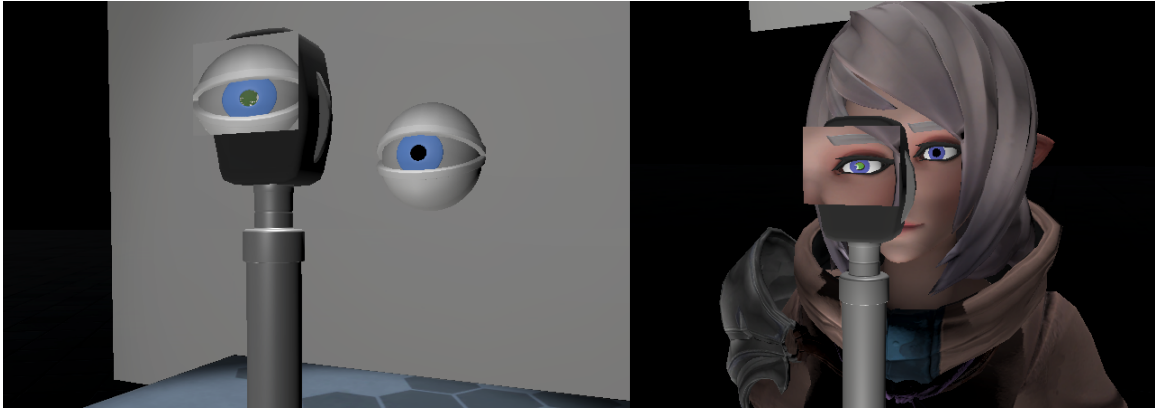


Figure 15: Virtual ophthalmoscope, modelled in Autodesk Maya, with the viewing window screen

3.4 WEARABLE AR WITH THE MICROSOFT HOLOLENS

The AR portion of the study utilised a Microsoft HoloLens headset, and an ASUS Republic of Gamers (RoG) Zephyrus laptop. The HoloLens was selected as the AR headset of choice due to ease of access, in addition to the amount of development documentation that was available at the time of selection. The ASUS RoG Zephyrus laptop was chosen for portability, ease of access, and the Microsoft HoloLens remote viewing app, which allows viewers to see through the headset's lenses. The HoloLens system was set up in the graduate student GAMER Lab observation room. The room was dimly lit to ensure that the 3D models could be seen clearly by the user with as little interference from any external light as possible.

3.4.1 *System Requirements*

In order to develop for the Microsoft HoloLens, the user is required to install a number of tools onto a Windows 10 computer. The first component is Visual Studio 2019, version 16.2 or higher at the time of development, which is a fully-featured integrated development environment (IDE) that allows developers to

code, debug, test, and deploy programs for the HoloLens headset. Users are then required to have installed the Windows 10 SDK, version 10.0.18362.0 at the time of development, which provides the headers, libraries, metadata, and tools for building Windows 10 apps.

3.4.2 *Scene Integration*

The AR version of the environment was built using Unity 2017.2.5f1, and contains several features from the Microsoft Academy Mixed Reality Toolkit such as hand-tracking, gesture recognition, and voice recognition. The Microsoft Academy website offers nine tutorial projects for developers to learn with, and given the nature of the study, the files for the MR211 - Gesture tutorial were downloaded for development. The project contained the libraries and assets required for hand-tracking, gesture recognition, and voice recognition, as well as a sample scene that integrated all of the features.

The sample scene contains a floating astronaut that could be manipulated through the use of the HoloLens' gesture system. Users are able to translate and rotate the model, although the system only allows for one method of transformation at a time. This means that users can either move, or rotate the model, but never both at the same time. Users are also required to use voice commands in order to change the method of transformation, rather than toggling a virtual switch.

Although the HoloLens provides a unique method of virtual interaction, the platform contains a number of software and technical limitations which prevents the development of more advanced system functionality and scenario features. One such limitation is the lack of ability to include custom scripts for additional functionality. It is noted that any programs containing scripts that are not a part of the original tutorial project will crash upon launch from the HoloLens, and the cause of the problem cannot be pinpointed. In addition, development of the

program needed to be started from scratch several times as a result of updates to the headset that would prevent the program from launching.

3.4.3 *Visual Feedback*

As previously mentioned, the Microsoft HoloLens feedback system is the feedback for the AR system is entirely visual-based. While the AR system also provides users with the means to recognise when a virtual element is interactive, a bulk of the visual feedback is designed and implemented to denote when the headset's camera is:

- On and casting the on-screen cursor straight ahead,
- Tracking the user's hand while idle without a gesture being made, or
- Tracking the user's hand while they're performing a gesture.

In order for the user to know what the camera is tracking at the moment, the system changes the appearance of the cursor. For instance, a faded, white circle is used to indicate where the system cursor is currently located, whereas a hollow, purple circle is used to indicate that the camera is tracking the user's idle hand. The system will also display whether the target object is in rotation or translation mode by altering the appearance of the cursor furthermore. The translation transformation is denoted with the system's standard purple circle cursor surrounded by four arrows that point up, down, left, and right. The rotation transformation is denoted by the system's standard purple cursor with two arrows that point left and right.

3.4.4 *User Interactions*

There are three user interactions within the AR version of the scenario; object rotation, object translation, and voice command input. As previously mentioned,

users are able to move and rotate the model in the scene through the use of hand gestures, although only one method of transformation can be performed at a time. In order to change transformation methods, the user must give the system one of two voice commands; "Move model", or "Rotate model".

EXPERIMENTAL DESIGN

Primary Research Question: What are the design, usability and cognitive load perceptions associated with virtualising the ophthalmoscopy examination with immersive technologies?

The study for this thesis is divided into two stages. Stage 1 focuses on examining perceived cognitive load and usability for user interactions with immersive technologies, while Stage 2 focuses on the design aspect of OcuLED as a proposed virtual scenario for fundus examination education in comparison to other alternate training solutions. This study was reviewed by the University of Ontario Tech University Research Ethics Board (REB# 15526), and originally approved on 7 November 2019.

- **Research Question 1:** How does the OcuLED program compare to the digital photograph, Styrofoam AR head, and OphApp applications of fundus examination training regarding compliance with the QFD customer requirements?

Hypothesis 1: *The OcuLED program will be rated higher than the other methods of examination training for compliance with the QFD customer requirements.*

- **Research Question 2:** How does hand gesture-tracking operation of the virtual ophthalmoscope compare to the VR controllers, which employ buttons, trackpad, and finger-tracking in terms of usability?

Hypothesis 2: *Hand gesture-tracking will be perceived as more usable than VR controller interactions.*

- **Research Question 3:** How does the hand gesture-tracking operation of the virtual ophthalmoscope compare to the VR controllers, which employ

buttons, trackpad, and finger-tracking in terms of perceived cognitive load for task completion?

Hypothesis 3: *Hand gesture-tracking will be perceived with lower cognitive load than VR controller interactions.*

4.1 USABILITY

A preliminary usability study is conducted to evaluate how Microsoft HoloLens gesture-based interactions compare to controller-based interactions with the HTC Vive and Valve Index controllers when manipulating the virtual DO are perceived by the participants. The goal is to understand the how each input method affects the virtual DO procedure. The usability assessment allows for the gathering of participant perceptions regarding the level of difficulty associated with manipulating the virtual DO.

The System Usability Scale (SUS) questionnaire is regarded as a quick method for measuring system usability that can be rapidly utilised after users complete evaluation tasks. The questionnaire asks users to rate levels of agreement through a 5-point Likert scale with statements that cover a variety of usability characteristics such as the system's complexity, ease of use, and need for assistance amongst others. After calculating the SUS score according to [21], a score above 68/100 indicates the system considered usable. The SUS score can be calculated by performing the following steps:

- Subtracting a value of 1 from questions 1, 3, 5, 7, and 9.
- Subtracting the scores of questions 2, 4, 6, 8, and 10 from the value of 5.
- Adding the new values together, and multiplying the sum by 2.5.

The end result of the calculation is a value that ranges from 0 to 100, which is meant to act as a clearer representation of the SUS score and not a percentage.

Table 1: SUS questionnaire.

Question	System Usability Scale Questionnaire
Q1	I think that I would like to use this system frequently.
Q2	I found the system unnecessarily complex.
Q3	I thought the system was easy to use.
Q4	I think that I would need the support of a technical person to be able to use this system.
Q5	I found the various functions in this system were well integrated.
Q6	I thought there was too much inconsistency in this system.
Q7	I imagine that most people would learn how to use this system quickly.
Q8	I found the system very cumbersome to use.
Q9	I felt very confident using the system.
Q10	I needed to learn a lot of things before I could get going with the system

4.2 COGNITIVE LOAD

In addition to usability, the cognitive load effects caused by using these three user interfaces is also evaluated. To this purpose, the NASA Task Load Index (NASA TLX) was employed as a means of measuring and conducting a subjective mental workload assessment for each user as they completed the tasks [64]. The NASA TLX score calculation was conducted in a similar manner to the SUS score, albeit with 2 differences. The first difference is that the questions of the NASA TLX were categorised as "positive" and "negative" based on how the questions were posed, in

contrast to the even and odd-number questions of the SUS. The second difference is related to the values used to calculate the NASA TLX score. A value of 1 was subtracted from the sum scores of the "positive" questions to create the positive total, and the sum scores of the "negative" questions were subtracted from a value of 5 to create the negative total. Following this, the "positive" and "negative" total values were added together, and multiplied by 4.1666, which was obtained by taking the maximum value that could be scored and dividing 100 by it, to return a value out of 100.

Table 2: NASA Task Load Index questionnaire.

Question	NASA Task Load Index questions.
Q1	How mentally demanding was the task?
Q2	How physically demanding was the task?
Q3	How hurried or rushed was the pace of the task?
Q4	How successful were you in accomplishing what you were asked to do?
Q5	How hard did you have to work to accomplish your level of performance?
Q6	How insecure, discouraged, irritated, stressed and annoyed were you?

4.3 TASK COMPLETION

User-perceived task difficulty and completion is recorded a five-point Likert scale, ranging from 'Strongly Disagree' to 'Strongly Agree'. The questionnaire focuses on evaluating the user's perception of how difficult they feel the tasks to be with each method of interaction. Specifically, users are asked how difficult it is to locate the VO within the VE, how difficult it is to pick up the VO, how difficult it is to move

the VO, and how difficult it is to locate the landmarks within the floating eye and the virtual patients. Questions related to the users' level of comfort with physically moving through the virtual environment are included to determine whether they are more comfortable with moving in AR or VR. The data are represented as the total number of users who responded with Disagreeing or Strongly Disagreeing.

Table 3: Task Difficulty and Completion Questionnaire.

Question	Task Difficulty and Completion questions.
Q1	It was difficult to locate the virtual fundoscope within the scene.
Q2	It was difficult to pick up and move the virtual fundoscope.
Q3	I felt uncomfortable with moving around the virtual environment.
Q4	I found it difficult to locate the landmarks within the large, floating eye.
Q5	I found it difficult to locate the landmarks within Lyette's and Jimothy's eyes.
Q6	I found that the landmark descriptions helped with "diagnosing" Lyette and Jimothy.
Q7	Lyette's eyes were in regular healthy condition.
Q8	Jimothy's eyes were in regular healthy condition.

The aforementioned questions were chosen for the questionnaire because each statement was focused on a particular component of the study, ranging from VO interactions and environment navigation to evaluating task completion accuracy. Questions 2 and 3 pertain to interacting with the VO and moving through the virtual environment, while questions 1, 4, and 5 are focused on the participant's ability to locate virtual elements within the scene. Lastly, questions 6 to 8 are directed towards task completion and completion accuracy.

4.4 QUALITY FUNCTION DEPLOYMENT (QFD)

QFD is viewed as a highly effective and structured tool that is used to evaluate the characteristics of a product in terms of how users perceive them with respect to similar solutions [46]. QFDs allow developers to focus on the design and corresponding criteria that are factors contributing to the users' perception, which subsequently allows understanding where a solution is with respect to others. The structure of a QFD takes the form of a chart called the House of Quality (HOQ), which is the most commonly-used matrix in QFD methodology [41].

HOQ charts traditionally consist of six "rooms" (see Figure 16), where each room is linked to another in regards to customer requirements and technical characteristics.

- Room 1 lists the solution requirements.
- Room 2 provides the technical characteristics, or design characteristics.
- Room 3 ranks the solution requirements based on their relevance and relationship with the technical requirements.
- Room 4, or the "roof" of the house contains the interrelationships between the design characteristics to identify any proportional or inverse relationships.
- Room 5 defines the importance of each requirement based on the users information.
- Room 6 summarises the user ratings for the proposed system and similar ones.

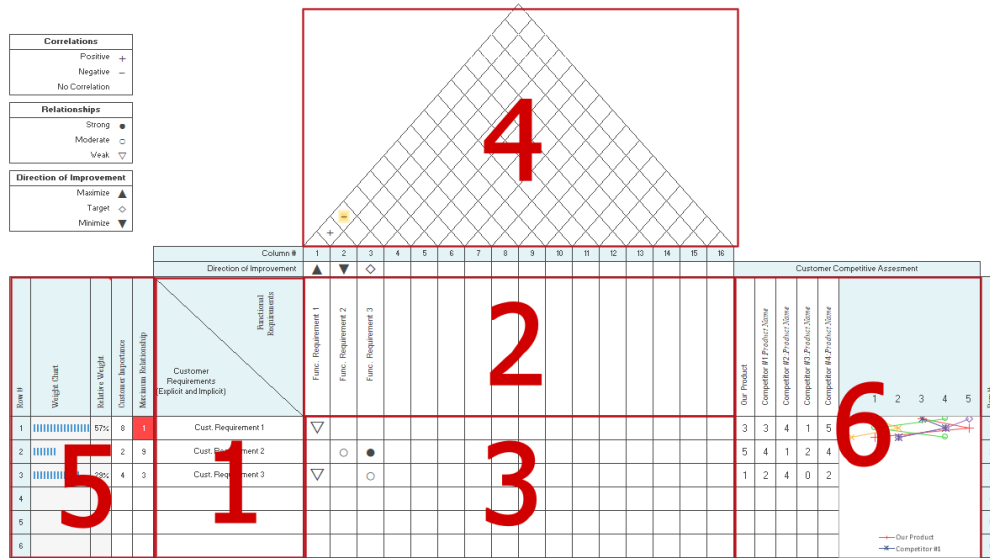


Figure 16: Six-room House of Quality

4.5 STUDY DESIGN

As previously mentioned, the study is designed to be conducted in two stages. The first stage focuses on usability and cognitive load through the operation of a virtual ophthalmoscope employing the Microsoft HoloLens hand tracking, an the HTC Vive controller, and the Valve Index controller. The second stage focuses on assessing how the virtualised eye fundus scenario developed in this thesis compares to other methods for eye fundus practice. The focus of Stage 2 is directed towards the comparison of the solution presented in this thesis to three similar methods of examination training; a set of digital photographs, and two mobile AR apps that utilise marker-tracking for 3D element projection. Due to COVID-19, the second stage was conducted online by deploying Oculed in a non-immersive manner as a mouse-and-keyboard scenario, while the two mobile AR apps were presented as video demonstrations. Because of the non-immersive deployment, usability, cognitive load, and functionality of the scenario perceptions were gathered from the participants.

4.6 PARTICIPANTS

A total of 30 participants were recruited for the study. The following subsections detail the aspects related to the participants and the activities that they performed.

4.6.1 *Stage 1*

Ten participants volunteered in Stage 1, and were recruited through the use of a digital communication platform called Discord. Participants were verbally asked about any prior experience with AR/VR technologies. All ten participants reported prior experience with VR, while five participants reported that they also had prior experience with AR. Participant background was not an exclusion factor since the information being presented in the procedure was basic and introductory. In addition, the virtual scenario was aimed at procedure novices who have little to no experience, rather than individuals who are already familiar with the examination.

4.6.1.1 *Study Tasks*

The study began as soon as the participant arrived at the lab, where they were verbally greeted (See Appendix A.2), and asked to read and sign a consent form (see Appendix A.1). A brief explanation of the task was then provided, where participants were to take the VO and identify the shapes and colours of the three landmarks located within each of the virtual eyes in the scene. Participants were instructed to follow the signs located on the left of where they started in the VE, and were encouraged to voice their thoughts during the study. This was done to understand their thought process and opinions relative to the equipment they were using, as well as to the task at hand. This would also allow for more elaborate, qualitative feedback in addition to any responses recorded in the usability survey.

Following this, they were handed either the Microsoft HoloLens headset, or the HTC Vive headset, and guided to the appropriate testing area. Participants were shown how to put on the assigned headset, and instructed on the methods of user interaction. Before utilising each method of user interaction, the participants were reminded that were allowed to remove the headset if they were experiencing discomfort or wished to withdraw from the test.

Once they had completed the task with one of the headsets, the participants were asked to fill out a SUS survey (See Appendix A.3), a usability questionnaire (See Appendix A.4), and a Task Load Index (See Appendix A.5). Once the participant had completed the task with both headsets, they were thanked for participating in the study (see Appendix A.8).

4.6.2 *Stage 2*

Stage 2 involved 20 volunteer participants. Since Stage 1 allowed for the collection of information about usability, cognitive and task completion from a technical point of view, Stage 2 focused on participants with a background in health sciences, as well as professionals with a background in medical simulation and training. Discord, word-of-mouth, and email were used as the methods of recruitment. As a result of the remote nature of the study, participant background experience with AR/VR was not a reported metric.

The study was conducted within a private call room between the participant and the tester. Participants were given the option of conducting the study in Discord or Google Meet. These platforms were selected because visitors required a specific link in order to enter the call, in addition to needing permission to enter from the tester on a case-by-case basis. Although participants were not required to utilise webcams during the testing session, voice communication via microphone was regarded as essential in order for both parties to adequately convey instructions,

questions, and thoughts. In addition, the tester allowed participants to view their screen through the use of a “screenshare” function, which allows all participants within the call to view the host’s screen in real-time.

4.6.2.1 *Study Tasks*

Upon entering the private call, each participant was verbally greeted by the tester, and asked to read and electronically sign a consent form. Following this, a brief explanation of the task objectives and subsequent questionnaires was provided, similarly to Stage 1. In addition, the participants were also encouraged to voice their opinions during the test in order to understand their thought process and opinions relative to the test materials.

Following this, participants were guided to a questionnaire (See Appendix A.6) that contained a set of “user requirements” that meet their needs. The participant would then rank the requirements based on how important they felt they would be to potential users, i.e. examination instructors. The customer requirements (see Table 4) were constructed and were based on factors that were derived from the problem statement. Requirements were rated on a scale of 1 to 5 from “Not Important” to “Very Important”. The purpose of this stage was to establish a baseline of which requirements are the most important to consider during future development.

In addition, the questionnaire (See Appendix A.6) contained sections for evaluating each training method. Participants would rate each method based on how closely they felt it adhered to each of the customer requirements. Following this, participants were introduced to each of the methods one at a time. The first method was the VR training program, OcuLED, where participants were tasked with locating and identifying the optic disc, optic cup, and macula within each of the virtual patients. The participants were also instructed to select the ‘Yes’ or ‘No’ buttons located next to the patient to indicate if they were able or unable to locate the targets. Once each of the virtual patients were examined, the OcuLED

Table 4: QFD solution requirements.

Requirement	Description.
R1	Affordability
R2	Ease of Preparation
R3	Running multiple instances simultaneously
R4	Capacity for high-fidelity eye model
R5	Multiple viewer experience
R6	Eye model interactivity
R7	Tool manipulation
R8	System Input Feedback
R9	Capacity for immersive/non-immersive VR

experience came to an end, and the participants were referred back to the questionnaire to evaluate the method. In addition, the participant was also asked to fill out a SUS survey (See Appendix A.3), and a NASA TLX survey (See Appendix A.4).

Once the evaluation was completed, participants would be introduced to the next method, which consisted of a set of high-resolution digital photographs of healthy fundi (two labelled and one unlabelled). Each photograph contained the optic disc, optic cup, and the macula, which the participant was to identify. Once the landmarks were identified in each of the photographs, the participant was returned to the questionnaire for method evaluation.

RESULTS

This chapter presents an analysis of the results obtained from Stage 1 and Stage 2. Both stages utilised the Shapiro-Wilk test of normality to determine if the distribution of differences in the dependent variables between the related groups was normal. Statistical significance was determined through a paired t-test for Stage 1, while a one-way repeated measure analysis of variance (ANOVA) was used to analyse the data of Stage 2.

5.1 STAGE 1

In order to be able to use the paired t-test method of analysis, a set of four preconditions must be fulfilled. The first is that the dependent variable should be continuous, a condition that is satisfied by the three dependent variables in this study. The second is that the independent variables should consist of two categorical, related groups. This precondition is fulfilled as the categories in the experiment are the two methods of interactions. The third precondition is that there are no significant outliers between the two related groups. The fourth and final precondition is the distribution of differences in the dependent variable between the two related groups should be approximately normally distributed, which is verified through the use of the Shapiro-Wilk test of normality.

In addition to the comparison of the AR system to the VR system, a supplementary comparison was conducted between the HTC Vive controller and the Valve Index controller to determine if there was a significant difference regarding usability and if the controllers influenced the participant's perception of task difficulty and cognitive load. This comparison was also conducted utilising the paired t-test method, and the results are reported alongside the AR/VR comparison results.

5.1.1 Usability

5.1.1.1 Paired T-test Preconditions

There was one SUS score in the AR/VR comparison that was a significant outlier, and two SUS score outliers in the VR controller comparison, and were removed from the data set. The Shapiro-Wilk test of normality indicated that the data for the AR/VR system comparison (Table 5) and the VR controller comparison did not violate normality for any of the systems (Table 6).

Augmented Reality		Virtual Reality	
W	p	W	p
0.929	0.439	0.882	0.165

Table 5: Results of the Shapiro-Wilk test for normality of the SUS score data for each system.

Vive Controller		Index Controller	
W	p	W	p
0.818	0.113	0.987	0.967

Table 6: Results of the Shapiro-Wilk test for normality of the SUS score data for each VR controller.

5.1.1.2 Statistical Significance

There was a main significant difference of the AR/VR systems on the SUS score ($t = -8.078$, $p < 0.0001$), but no significant difference between the two HTC Vive and Valve Index controllers ($t = -0.934$, $p = 0.403$).

5.1.1.3 *Results*

It was found that the SUS score for the VR system ($M = 91.944$, $sd = 4.6398$) was higher than the AR system ($M = 42.500$, $sd = 16.863$). With these data, it can be concluded that participants found that utilising the VR system was perceived to be easier than the AR system. The SUS score for the Valve Index controller indicated that the Valve Index controller was perceived to be easier to use ($M = 92.50$, $sd = 3.953$) than the HTC Vive ($M = 84.50$, $sd = 15.949$).

5.1.2 *Task Load Index*

The NASA Task Load Index (NASA TLX) was utilised as the final set of quantitative data, and was used as a means of measuring and conducting a subjective mental workload assessment for each user as they completed the tasks. The NASA TLX score calculation was conducted in a similar manner to the SUS score, albeit with 2 differences. The first difference is that the questions of the NASA TLX were categorised as "positive" and "negative" based on how the questions were posed, in contrast to the even and odd-number questions of the SUS. The second difference is related to the values used to calculate the NASA TLX score. A value of 1 was subtracted from the sum scores of the "positive" questions to create the positive total, and the sum scores of the "negative" questions were subtracted from a value of 5 to create the negative total. Following this, the "positive" and "negative" total values were added together, and multiplied by 4.1666, which was obtained by taking the maximum value that could be scored and dividing 100 by it, to return a value out of 100.

5.1.2.1 *Paired T-test Preconditions*

There were four significant outliers in the data set for the AR/VR comparison Task Load Index, and one significant outlier in the data set for the controller comparison.

All were removed from their respective data sets during analysis. The Shapiro-Wilk test reported that the data did not violate normality for either system (See Table 7), and that the data for the Valve Index controller violated normality (See Table 8).

Augmented Reality		Virtual Reality	
W	p	W	p
0.927	0.419	0.922	0.370

Table 7: Results of the Shapiro-Wilk test for normality of the Task Load Index score data for each system.

Vive Controller		Index Controller	
W	p	W	p
0.876	0.292	0.658	0.003

Table 8: Results of the Shapiro-Wilk test for normality of the NASA TLX score data for each VR controller.

5.1.2.2 Statistical Significance

There was a main significant difference of the system on the NASA TLX score ($t = -4.660$, $p < 0.001$). There was no significant difference of the controller type on the NASA TLX score ($t = -0.356$, $p = 0.740$).

5.1.2.3 Results

It was found that the NASA TLX score for the VR system ($M = 89.166$, $sd = 7.905$) was higher than the AR system ($M = 60.83$, $sd = 21.081$). With the data, it can be concluded that participants found that utilising the VR system was perceived as less strenuous regarding cognitive load than the AR system. The NASA TLX score for the Valve Index controller ($M = 90.000$, $sd = 7.569$) was higher than that of the HTC Vive ($M = 88.333$, $sd = 9.033$). With this data, it can be concluded that

utilising the Valve Index controller may be less strenuous regarding cognitive load than the HTC Vive controller.

5.1.3 *Task Difficulty and Completion Questionnaire*

Task difficulty and completion was recorded on five-point Likert scales, ranging from Strongly Disagree to Strongly Agree, and focused on studying the users' perception of how difficult they felt the tasks to be with each method of interaction. Specifically, users were asked how difficult it was to locate the VO within the VE, how difficult it was to pick up the VO, how difficult it was to move the VO, and how difficult it was to locate the landmarks within the floating eye, and the virtual patients. Questions related to the users' level of comfort with physically moving through the virtual environment were included to determine whether they were more comfortable with moving in AR or VR. The data are represented as the total number of users who responded with Disagreeing or Strongly Disagreeing.

5.1.3.1 *Paired T-test Preconditions*

There were no significant outliers in the AR/VR comparison data set for the Likert scale, although there was one significant outlier that was removed from the controller comparison data set. The Shapiro-Wilk test reported that the data did violate normality for the VR system, whereas the AR system did not (See Table 9), and that the data for the Valve Index controller violated normality, whereas data for the HTC Vive controller did not (See Table 10).

Augmented Reality		Virtual Reality	
W	p	W	p
0.885	0.149	0.826	0.030

Table 9: Results of the Shapiro-Wilk test for normality of the Likert score data for each system.

Vive Controller		Index Controller	
W	p	W	p
0.946	0.689	0.630	0.001

Table 10: Results of the Shapiro-Wilk test for normality of the Likert score data for each VR controller.

5.1.3.2 Statistical Significance

There was a main significant difference of the system on the Likert score ($t = 3.166$, $p = 0.011$), and no significant difference of the controller type on the Likert score ($t = -0.825$, $p = 0.456$).

5.1.3.3 Results

It was found that the Likert score for the AR system ($M = 13.30$, $sd = 4.473$) rated higher than the VR system ($M = 9.20$, $sd = 2.573$). With these data, it can be concluded that the participants perceived tasks in AR to be more difficult than in VR, even though the task was the same between the two systems. The Likert score data between the controller types indicated that participants perceived the tasks to be slightly more difficult with the Valve Index controllers ($M = 9.60$, $sd = 2.608$) than the HTC Vive controller ($M = 8.80$, $sd = 2.775$).

5.2 STAGE 2

Similarly to Stage 1, Stage 2 was a within-subjects study, where all eye examination solutions were examined by all participants and randomized to minimize carry-over effects. A one-way repeated measure ANOVA was employed to determine statistical significance within the data sets. However, in order to utilise this method of analysis, five pre-conditions must be fulfilled. Firstly, the dependent variable should be continuous, which is satisfied by each of the dependent variables in this study. Secondly, the independent variable should consist of at least two categorically-related group, which are the methods of fundus examination training in this instance. Thirdly, there should be no significant outliers in the related groups. Fourthly, the data should have a normal distribution, which is verified in the Shapiro-Wilk test of normality. Lastly, Mauchly's test of sphericity should indicate that the variance of differences within the data sets was not be violated.

5.2.1 *Quality Function Deployment Comparison*

The OcuLED program was compared to three alternate methods of fundus examination training; the set of three digital photographs, and two mobile AR apps. These methods were compared in order to determine which was preferred based on the the design requirements defined employing QFD. Each method was assessed through the use of a 5-point Likert scale, which ranged from "Strongly Disagree" to "Strongly Agree". The result represents the overall adherence score for each method.

5.2.1.1 *Requirement Importance Ratings*

The requirement rating scores that were obtained at the beginning of each testing session for Stage 2 were averaged and categorised based on the VO requirements.

Table 11: Rated Score Averages per Requirement.

	R1	R2	R3	R4	R5	R6	R7	R8	R9
Importance Score Avg.	4.15	4.2	3.9	4.25	3.8	4.6	4.65	4.3	4.1
Oculed Score Avg.	4	3.95	4.05	4.5	4.45	4.4	4.1	3.85	4
Photo Score Avg.	4.7	4.75	4.65	4.5	4.3	2.95	2	2.3	2.15
Styrofoam Head Score Avg.	4.45	4.15	3.7	3.8	3.95	4.25	4.1	3.9	3.65
OphApp Score Avg.	4.65	4.3	3.9	4.5	4	4.65	4.35	3.9	4

Based on the data collected from the participants, the customer requirement that is considered to be the “most important” is Requirement 7 (Tool Manipulation) with an averaged score of 4.67/5, while the “least important” is Requirement 5 (Multiple Viewer Experience) with an averaged score of 3.8/5. A HOQ was created for Oculed (See Appendix A.7), which provides a visualisation of how the program compares to its competitors regarding customer requirement compliance.

5.2.1.2 ANOVA Precondition Tests

There were no significant outliers in the data set for method comparison, and the Shapiro-Wilk test of normality indicates that the data did not violate normality for any of the methods (See Table 12). In addition, Mauchly’s test of sphericity indicated that the assumption of sphericity had not been violated ($W = 0.71$, $p = 0.31$).

Oculed		Digital Photograph		AR Styrofoam Head		OphApp	
W	p	W	p	W	p	W	p
0.963	0.601	0.936	0.198	0.938	0.224	0.912	0.127

Table 12: Results of the Shapiro-Wilk test of normality for method comparison.

5.2.1.3 *Statistic Significance*

There was a significant main effect of the training methods on the perceived on compliance, where $F(3,57) = 7.195$, $p < 0.0005$, $\eta_G^2 = 0.275$.

5.2.1.4 *Results*

Based on the data, it was found that the participants perceived Oculed's ($M = 4.14$, $sd = 0.43$) design to meet the customer requirements to a greater extent than the digital photograph method ($M = 3.58$, $sd = 0.68$) or the Styrofoam head alternative ($M = 3.99$, $sd = 0.50$). However, participants rated the OphApp solution ($M = 4.25$, $sd = 0.60$) slightly higher than Oculed in the same regard.

DISCUSSION

This chapter presents a discussion of the results obtained from Stages 1 and 2, and how they support or oppose the hypotheses.

6.1 STAGE 1

This section discusses the perceived usability, perceived cognitive load, and task completion associated with utilising the Microsoft HoloLens gesture system and the HTC VR controllers (i.e., the Vive and Index controllers).

6.1.1 *Usability*

The VR controllers were perceived more usable experience, it is believed that the technological background of the participants contributed to this. From study observations, the participants moved within the virtual eye fundus examination room more naturally, and operated the virtual ophthalmoscope with ease as they were able to move their arms and position the VR controllers at the right height and distance from the virtual patient. Furthermore, when gripping the virtual ophthalmoscope, the Valve Index controller was preferred as the finger tracking allows for a more natural interactions as it captures real grasping movements when the fingers flex. Furthermore, the controller provides haptic feedback to indicate a proper grip. The HTC Vive controller required users to use the grip buttons that resulted in a few tries as the buttons are pressed with the palm of your hand.

Although visual immersion was not formally evaluated, two participants commented that they enjoyed viewing the holograms through the headset, and felt

that it was easier to see the models through the HoloLens up close, in contrast to examining the models in VR. Upon further inquiry, the participants explained that it was very difficult for their eyes to fixate on the models through the screens of the VR headset when they were positioned in front of them.

As a result of the SUS analysis conducted on the Microsoft HoloLens gestures and the HTC Vive controller systems when performing a virtual eye fundus examination, in conjunction with the number of participants, **Hypothesis 2** cannot be supported as the hand gestures were perceived as difficult in comparison with the VR controllers. Furthermore, although no statistical significance was found between the VR controllers, the addition of finger tracking facilitated grasping the virtual ophthalmoscope.

6.1.2 *Cognitive Load*

The results analysis of the user-perceived cognitive load comparison shows that utilising physical controllers to interact with virtual elements has a lower perceived cognitive load than performing gestures. It is hypothesised that users regarded VR as a more desirable form of object manipulation because the actions that the user performs to pick up and move an object in VR are very similar to the way they would pick and move an object in real-life. Within VR, users are able to use their wrist, elbow, shoulder, and body position in conjunction with one another to adjust the VO's overall position and rotation on the x, y, and z-axes. However, object manipulation with the Microsoft HoloLens hand tracking is less robust on three accounts:

- Users are required to adjust the object's position and rotation separately, rather than simultaneously, in comparison to real-life, where a person is able

to move their hand through the combined use of their shoulder and elbow, and rotate their wrist.

- Users are only able to rotate the object on one axis (the y-axis), rather than all three concurrently, a feat that is accomplished in real-life through combined use of the wrist, and radial and ulna bones in the forearm.
- The gesture system allows users to only control the speed of the object's rotation for as long the gesture is held for, rather than adjusting the object's rotation based on the angle that the user's hand is at.
- Manipulating the VO with gestures appears to be more reliant on the headset's recognition of the user's hand and digits, rather than how the user moves.

In conclusion, gesture-based tasks are likely to be perceived as having a greater cognitive load due to the increased number of actions that are required in order to successfully manipulate an object to the same extent as manipulating an object with a controller. Similarly to usability, cognitive load was higher with the Microsoft HoloLens hand tracking system than with VR, therefore **Hypothesis 3** cannot be supported.

6.1.3 *Task Difficulty and Completion Questionnaire*

Altogether, participants rated the VR scenario as more favourable in comparison to its AR counterpart, with regards to picking up and moving the VO. Four participants stated that utilising the VR controllers to pick up and move the VO was easier in comparison to using the AR gesture system. One participant described the hand tracking in AR as spotty at best, and that the headset incorrectly recognised and registered hand gestures, while another participant noted that manipulating the VO was more challenging with gestures even under examiner instruction. In addition, rotating the VO was described as particularly frustrating, as all ten participants were unable to orient the VO in the direction they wanted.

Among the ten participants, two reported fatigue while performing the gestures, although they declined an offer to take off the headset and rest. Five participants also reported that it was more difficult to locate and identify the landmarks within the floating eye in AR than it was to locate in VR. However, one participant felt it was still challenging to identify the landmarks in the floating eye with the VR controller as a result of contesting their own body movement against the hovering eye. There were no comments made by any of the participants regarding the use of the HTC Vive controller, although three participants commented that they liked the hand-strap of the Valve Index controller because it allowed them to relax their hand without worrying about holding onto the controller.

6.2 STAGE 2

This section discusses the results analysis of OcuLED to the use of digital photographs, the Styrofoam AR head, and the OphApp mobile AR app as ophthalmology training alternatives in relation of adherence towards the set of QFD customer requirements. In addition, this section also discusses the compliance of methods with respect to specific customer requirements.

6.2.1 QFD

The results analysis of QFD between OcuLED, the digital photographs, the Styrofoam AR head, and the OphApp mobile AR app indicates that users perceived the OcuLED method to adhere more closely to the virtual eye examination requirements than the digital photograph and Styrofoam AR head methods, and only marginally less than the OphApp method. Although these findings support **Hypothesis 1**, the results analysis encompasses a set of requirement compliance as a whole, rather than analysing and comparing the methods on a requirement-by-requirement basis.

Based on Table 11, the requirement that is considered to be the “most important” is Requirement 7 (Tool Manipulation) with a score average of 4.67/5. Although the Oculed score average for Requirement 7 is 4.1/5, the highest score average for Oculed is Requirement 5 (Multiple View Experience), which is ranked as the “least important” customer requirement. In comparison, the OphApp method - which was rated as the most compliant to customer requirements, had a score average of 4.35/5 for Requirement 7. In addition, the OphApp method scored higher than the Oculed method for nearly every requirement that had a importance score average over 4/5, most notably Affordability, Ease of Preparation, Eye Model Interactivity, and System Input Feedback. This suggests that future work on the Oculed program should be directed towards refining and further developing the components of the program that pertain to the aforementioned requirements, particularly the manipulation of the examination tool.

CONCLUSION

An investigation of previous and current methods of ophthalmoscopy training and education indicates that immersive technologies are becoming more widely adopted within the field of medicine as methods of practice. Developers for technology platforms, such as AR and VR, are able to replicate exceptional medical scenarios and conditions that would otherwise be difficult to train for. With respect to simulation for direct ophthalmoscopies, the need for improvement towards eye examination training has led to the development of numerous simulators and training programs.

This Master's thesis aimed at understanding the design, usability and cognitive load perceptions associated with virtualising the ophthalmoscopy examination with immersive technologies. Furthermore, this thesis also studied the usability, cognitive load, and task completion effects of hand gesture-tracking and VR controllers in a virtual eye fundus examination.

The thesis study was conducted in two stages. The first stage involved comparing and assessing the perceived cognitive load and usability for user interactions with the Microsoft HoloLens AR gesture system, and the HTC Vive VR system with physical controllers. In this stage, participants were tasked with manipulating a virtual ophthalmoscope in order to examine the fundi of three virtual patients. Participants were able to maneuver the ophthalmoscope through the use of the Microsoft HoloLens' gesture system, and the HTC Vive's controllers. The second stage was focused on understanding how the proposed virtual eye fundus scenario, Oculed, compared to a set of high-resolution digital photographs, the Styrofoam AR head app, and the OphApp mobile AR app in terms of design requirements set by a content expert. In this stage, participants were asked to rank the design

requirements based on how important they believed they would be to potential consumers, and to evaluate each method based on how closely they felt it complied with each stipulation.

The primary research question of, **“What are the design, usability and cognitive load perceptions associated with virtualising the ophthalmoscopy examination with immersive technologies?”**, was divided into three smaller, more specific questions.

The first derivative question is, **“How does the OcuLED program compare to the digital photograph, Styrofoam AR head, and OphApp applications of fundus examination training regarding compliance with the QFD customer requirements?”**. It was hypothesised that the proposed VR program would be rated higher than the other methods of examination training for compliance with the customer requirements. The data analysis of Stage 2 reveals that although the OcuLED method was given a higher requirement compliance rating than the photograph and Styrofoam AR head methods, only three out of the nine requirement category score averages were met or exceeded.

The second question derivative is, **“How does hand gesture-tracking operation of the virtual ophthalmoscope compare to the VR controllers, which employ buttons, trackpad, and finger-tracking in terms of usability?”**. Although gesture-based actions were hypothesised to be perceived as more usable than VR controller interactions, the data analysis of Stage 1 indicates that physical VR controllers are regarded as a more practical and functional choice for virtual interactions. It was noted that participants experienced great difficulty with utilising the gesture system, where inaccurate gesture recognition and registration induced frustration. In addition, controllers provided haptic feedback to the participants, indicating success with picking up or interacting with a virtual object.

The final question derivative is, “**How does the hand gesture-tracking operation of the virtual ophthalmoscope compare to the VR controllers, which employ buttons, trackpad, and finger-tracking in terms of perceived cognitive load for task completion?**”. It was hypothesised that gesture-based actions would be perceived as having a lower cognitive load than VR controller interactions. However, the data analysis shows that user interaction via gesture systems presents a higher cognitive load than interaction through physical controllers. It is possible that the perceived cognitive load is greater due to the fact that virtual object manipulation with gestures requires object translation and rotation to be performed as two consecutive user actions akin to left-mouse clicks. In comparison, VR controllers allow for the simultaneous translation and rotation of a virtual object because the controller-based movements are reliant on the user’s arms movements.

Based on the answers to the second and third derivative questions, it can be concluded that while AR systems demonstrate a unique way of presenting content to users, it is more difficult to utilise the gesture system for object interaction than VR. The results of the study have shown that users may also perceive tasks to be more difficult in AR than in VR, even if the tasks are the same between the two systems, and therefore may also pose a greater cognitive load on the user. In addition, the VR system appears to be more robust and further developed than the AR system, which may contribute to its ease of use. These conclusions can be used in conjunction with the score averages of the design requirements to improve the design of the Oculed program as a potential method of ophthalmoscopy practice.

7.1 RECOMMENDATIONS

Studies that focus on the perceived usability and cognitive load of Oculed in its intended VR form would allow for the gathering of important data that can further improve Oculed. In addition, further investigations that expand upon establishing

design parameters, such as those from the QFD, can be conducted to create a framework in which future simulators and programs can be built upon.

7.2 CONTRIBUTION

This thesis has highlighted desirable design parameters that can provide insight on features to consider for future development of similar simulators and programs. In addition, the research from this thesis has allowed for a better understanding of user input devices and the associated effects on the virtualisation of the direct ophthalmoscopy.

7.3 FUTURE WORK

Given the results and feedback from Stages 1 and 2, the OcuLED program can be refined and improved upon such that the program better adheres to design elements and requirements that are regarded as desirable amongst potential consumers. In this case, adjustments can be made to the functionality of the virtual ophthalmoscope to allow for a more detailed inspection of the fundus, as well as additional means to interact with the eye model. Furthermore, development towards supplementary 3D-printed peripherals can be conducted to enhance user experience and increase the realism of the virtual procedure. Another component of the program that can be improved upon is the anatomic accuracy of the fundus. Further detailing of the fundus will provide users with the opportunity to locate anatomic landmarks within three-dimensional, spherical space, rather than on a two-dimensional plane.

A

APPENDIX A: STUDY MATERIAL

A.1 CONSENT FORM

Title of Research Study: A Mixed Reality Training Scenario for Fundoscopy Training

You are invited to participate in a research study entitled “A Mixed Reality Training Scenario for Fundoscopy Training”. This study has been reviewed by the Ontario Tech University Research Ethics Board REB#15526 and originally approved on 7 November 2019. This study will take 20 minutes. Please read this consent form carefully, and feel free to ask the Researcher any questions that you might have about the study. If you have any questions about your rights as a participant in this study, please contact the Research Ethics Office at 905 721 8668 ext. 3693 or researchethics@uoit.ca.

Researcher(s):

Alvaro Joffre Uribe Quevedo PhD, Lead Investigator: alvaro.quevedo@uoit.ca - (905)-721-8668 x2615

Michael Chan, Student Lead: michael.chan4@ontariotechu.net - (647)-938-1258

Departmental and Institutional affiliation(s): Faculty of Business and Information Technology

Purpose and Procedure:

This research aims to gather general usability and engagement perceptions for a mixed reality scenario designed for the purposes of basic procedural training in direct fundoscopic examinations.

Please inform the researchers if you need any assistance and remember that you can withdraw at any point during the study before submitting the usability and engagement questionnaire.

At the beginning of the experiment, you will i) complete this consent form, which will take two minutes, ii) receive a five minute introduction to the augmented reality headset and the virtual reality headset, as well as the virtual reality controllers and a brief tutorial on the augmented reality gestures, and iii) be reminded about the withdrawal process. After the introduction, you will be assigned a platform, where you will follow the on-screen instructions.

This study focuses on gauging your experience when interacting with elements of augmented reality and virtual reality environments using hand gestures and traditional VR controllers. After receiving the designated platform, you will be handed the headset, where the screen’s prompts will guide you through the interactions. This process can take 5-10 minutes depending on the headset that is assigned to you. For example, hand-tracking interactions may take longer due to hand gesture detection. Once all the prompts on the screen have been followed through to completion, you will be seated in front of a laptop with an electronic usability, Task Load Index, and engagement questionnaire. The questionnaire completion will take between five to ten minutes.

Potential Benefits:

Simulators and serious games have been used for the purposes of education and training in many fields, including medicine, where students and trainees are provided with the opportunity to learn and practice examinations within a safe learning environment. Learners, as well as instructors, are able to adjust various parameters and learning objectives based on individual learning needs without the need for additional lab equipment or supplements. Through the use of mobile platforms, such as phones and tablets, augmented reality allows for more accessible learning, as well as an additional method for learners to better visualise concepts within a 3D environment.

Potential Risk or Discomforts:

You may experience fatigue by wearing the augmented reality and virtual reality headsets, and performing the hand gestures necessary to complete the interaction and navigation tasks. If you feel any fatigue, or other discomfort as a result of gesticulation or other technologies, please inform the researchers and choose whether you would like to take a break or withdraw.

Confidentiality and Data Storage:

All data will be collected through a digital questionnaire associated with a participant ID and not any identifiable information from you. The questionnaire will not ask for any information that holds the expectation of privacy as it focuses on usability and engagement perception. Data collected and consent forms will be kept confidential by Alvaro Uribe Quevedo on a university-owned hard drive, stored in his office, within a secured cabinet, which is unavailable for persons outside of graduate program. Data will also be stored on separate encrypted Cloud storage locations and will not be available to persons outside of the research team. The questionnaire data will be retained indefinitely and will be stored on Google Drive.

Right to Withdraw:

Your participation is voluntary, and you can answer only those questions that you are comfortable with answering. The information that is collected will be held in strict confidence and discussed only with the research team. You have the option to withdraw from the study at any time during the experiment and have your data destroyed. Please note that the withdrawal deadline is immediately before the questionnaire has been submitted. After submission it will be impossible to link the data back to you for removal as it is recorded anonymously. You are not required to give a reason for withdrawing from the study.

Conflict of Interest:

This study will have no impact on any courses you have taken, are taking, or will be taking where the researchers are instructors. Please remember that your participation is voluntary and you can withdraw at any point during the study without consequences. This study focuses on gathering usability, task load, and engagement perceptions that will be used to improve the design of virtual and augmented reality interactions for virtual eye fundus examination.

Debriefing and Dissemination of Results:

After participation, you have the option to ask the researchers any additional questions you may have about the study. You can email the Principal Investigator, Dr. Uribe Quevedo should you want a copy of your results.

Participant Concerns and Reporting:

If you have any questions concerning the research study or experience any discomfort related to the study, please contact the researchers Alvaro Joffre Uribe Quevedo at 905-721-8668 x2615 or

alvaro.quevedo@uoit.ca, or Michael Chan at 647-938-1258 or michael.chan4@ontariotechu.net.

Any questions regarding your rights as a participant, complaints or adverse events may be addressed to Research Ethics Board through the Research Ethics Office – researchethics@uoit.ca or 905.721.8668 x. 3693.

By consenting, you do not waive any rights to legal recourse in the event of research-related harm.

Consent to Participate:

- I have read the consent form and understand the study being described;
- I have had an opportunity to ask questions and my questions have been answered. I am free to ask questions about the study in the future;
- I freely consent to participate in the research study, understanding that I may discontinue participation at any time without penalty. A copy of this Consent Form has been made available to me.

A.2 WELCOME SCRIPT

Welcome Script

Good day, thank you very much for taking the time to participate in this study! As previously mentioned briefly in the recruitment post, this research is focused on user interaction systems with augmented reality (AR) and virtual reality (VR). You will be completing a few simple tasks through the use of simple gestures, traditional VR controllers, and a 3D-printed peripheral that is designed to mirror a real-life examination tool.

HoloLens Explanation

This is the Microsoft HoloLens, an augmented reality head-mounted display that projects virtual objects into the real world. Users are able to see and interact with these virtual elements through the use of hand gestures. The primary gesture is called the “grab” gesture, and can be performed by pointing at your target, and tapping your thumb with your index finger. This gesture is primarily used for selecting objects (much like left-clicking with a mouse), and can also allow you to move and rotate the model if you hold the gesture and move your hand.

Virtual Reality Component

During the study, you will also have the opportunity to use a VR headset with traditional VR controllers, and a custom-built peripheral that allows you to perform the same interactions as the gesticulation system (selection, translation, and rotation). These interactions will be used for dragging and dropping objects, as well as performing basic rotation tasks. The program will present some audio-visual cues to help you focus on the task. Many components for the program, primarily UI elements such as buttons, and the main 3D model, are interactive. If you are feeling any fatigue as a result of wearing the headset, you may ask a member of the research team to remove the headset, and take a break.

If you experience any problems, or have further questions, please do not hesitate to let the research team know!

A.3 SYSTEM USABILITY SCALE

Usability Questionnaire

*Required

I think that I would like to use this system frequently. *

	1	2	3	4	5	
Strongly Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Strongly Agree

I found the system unnecessarily complex. *

	1	2	3	4	5	
Strongly Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Strongly Agree

I thought the system was easy to use. *

	1	2	3	4	5	
Strongly Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Strongly Agree

I think that I would need the support of a technical person to be able to use this system. *

	1	2	3	4	5	
Strongly Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Strongly Agree

I found the various functions in this system were well integrated.

*

	1	2	3	4	5	
--	---	---	---	---	---	--



Strongly Disagree Strongly Agree

I thought there was too much inconsistency in this system. *

1 2 3 4 5

Strongly Disagree Strongly Agree

I would imagine that most people would learn to use this system very quickly. *

1 2 3 4 5

Strongly Disagree Strongly Agree

I felt very confident using the system. *

1 2 3 4 5

Strongly Disagree Strongly Agree

I needed to learn a lot of things before I could get going with this system. *

1 2 3 4 5

Strongly Disagree Strongly Agree



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A.4 LIKERT SCALE

Usability Likert Scale

*Required

1. It was difficult to locate the virtual fundoscope within the scene. *

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Strongly Agree

2. It was difficult to pick up and move the virtual fundoscope. *

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Strongly Agree

3. I felt uncomfortable with moving around the virtual environment. *

Mark only one oval.

	1	2	3	4	5	
Strong Disagreeely	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Strongly Agree

4. I found it difficult to locate the landmarks within the large, floating eye. *

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Strongly Agree

A.5 TASK LOAD INDEX

Usability Questionnaire

*Required

Task Load Index

Mental Demand

How mentally demanding was the task? *

	1	2	3	4	5	
Very Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very High

Physical Demand

How physically demanding was the task? *

	1	2	3	4	5	
Very Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very High

Temporal Demand

How hurried or rushed was the pace of the task? *

	1	2	3	4	5	
Very Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very High



Performance

How successful were you in accomplishing what you were asked to do? *

	1	2	3	4	5	
Failure	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Perfect

Effort

How hard did you have to work to accomplish your level of performance? *

	1	2	3	4	5	
Very Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very High

Frustration

How insecure, discouraged, irritated, stressed, and annoyed were you? *

	1	2	3	4	5	
Very Low	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very High



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A.6 CUSTOMER REQUIREMENT EVALUATION

Customer Requirement Rating

Please rate each customer requirement in terms of importance.

***Required**

1. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

2. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

3. Running multiple instances simultaneously (the method can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

4. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

5. Multiple viewer experience (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

6. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

7. Tool manipulation (the method allows users to manipulate a virtual and/or physical examination tool) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

8. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

9. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

10. Are there any other customer requirements that you can think of?

Customer Requirement Evaluation for the
Oculed Program

Please rate how you felt the Oculed method prioritised the
customer requirements.

11. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

12. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

13. Running multiple instances simultaneously (the model can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

14. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

15. Multiple people can see through it (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

16. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

17. Virtual Tool Manipulation (the method allows users to manipulate a virtual examination tool) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

18. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

19. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

Customer Requirement Evaluation for the Digital Photograph Method

Please rate how you felt the digital photograph method prioritised the customer requirements.

20. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

21. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

22. Running multiple instances simultaneously (the model can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

23. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

24. Multiple people can see through it (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

25. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

26. Virtual Tool Manipulation (the method allows users to manipulate a virtual examination tool) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

27. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

28. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

Customer Requirement Evaluation for the
AR Styrofoam Head Method

Please rate how you felt the AR Styrofoam Head method
prioritised the customer requirements.

29. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

30. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

31. Running multiple instances simultaneously (the model can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

32. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

33. Multiple people can see through it (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

34. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

35. Virtual Tool Manipulation (the method allows users to manipulate a virtual examination tool) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

36. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

37. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

Customer Requirement Evaluation for
the OphApp Method

Please rate how you felt the OphApp method prioritised the
customer requirements.

38. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

39. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

40. Running multiple instances simultaneously (the model can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

41. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

42. Multiple people can see through it (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

43. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

44. Virtual Tool Manipulation (the method allows users to manipulate a virtual examination tool) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

45. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

46. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

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A.7 QFD HOQ

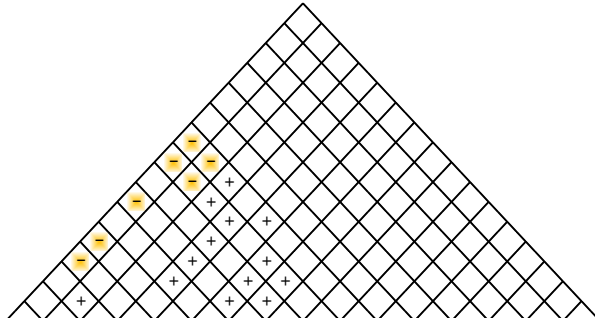
QFD: House of Quality

Project:
Revision:
Date:

Correlations	
Positive	+
Negative	-
No Correlation	.

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Row #	Weight Chart	Relative Weight	Customer Importance	Maximum Relationship	Customer Requirements (Explicit and Implicit)	Column #																Customer Competitive Assessment					Row #																			
						1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	0	1	2	3	4		5																		
1	■	11%	4.15	9	Affordability (the method is affordable)	●	○	●	●	●	●	●	▽	●	●																											4	4.7	4.5	4.7	1
2	■	11%	4.2	9	Easy to set up (method is easy to set up)	○	●	○	○	●	●	●	▽	●	●																											4	4.8	4.2	4.3	2
3	■	10%	3.9	9	Running multiple instances simultaneously (the model can be run in multiple instances)	▽	○	●	▽	○	▽	▽	▽	○	○																											4.1	4.7	3.7	3.9	3
4	■	11%	4.25	9	High-fidelity eye model (the method makes use of a high-fidelity eye model)	○	▽	▽	●	▽	●	▽	○	●	○																											4.5	4.5	3.8	4.5	4
5	■	10%	3.8	9	Multiple people can see through it (the method allows for multiple viewers)	○	●	▽	▽	●	▽	▽	▽	○	○																											4.5	4.3	4	4	5
6	■	12%	4.6	9	Eye model interactivity (the method allows the user to interact with the eye)	●	○	▽	○	▽	●	▽	○	○	○																										4.4	3	4.3	4.7	6	
7	■	12%	4.65	9	Virtual Tool Manipulation (the method allows users to manipulate a virtual examination tool)	○	●	▽	●	▽	○	●	○	●	●																										4.1	2	4.1	4.4	7	
8	■	11%	4.3	9	Input Feedback (the method allows for feedback based on user input)	▽	○	▽	○	●	●	▽	●	●	●																										3.9	2.3	3.9	3.9	8	
9	■	11%	4.1	9	VR Modes (the method has the capacity for immersive and non-immersive VR)	●	●	○	●	●	○	○	▽	●	●																										4	2.2	3.7	4	9	
10																																									10					
11																																									11					
12																																									12					
13																																									13					
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15																																									15					
16																																									16					



A.8 THANK-YOU SCRIPT

Thank You Script

You've just reached the end of the study, thank you so much for participating! If you have any questions or comments, please feel free to email us (information found in your copy of the consent form).

Have an amazing day!

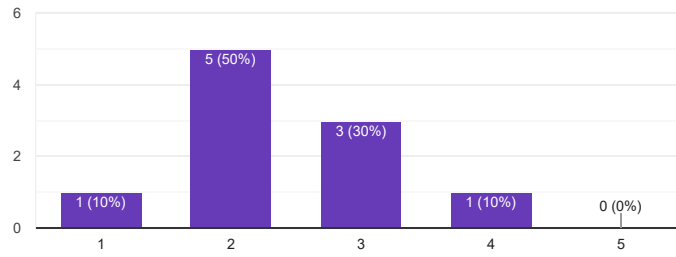
A.9 AUGMENTED REALITY - MICROSOFT HOLOLENS STUDY RESULTS

Post-Test Survey for AR

10 responses

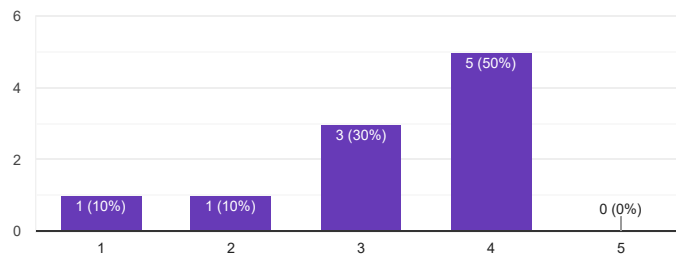
I think that I would like to use this system frequently.

10 responses



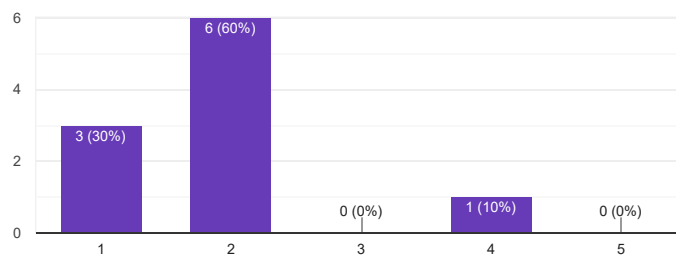
I found the system unnecessarily complex.

10 responses



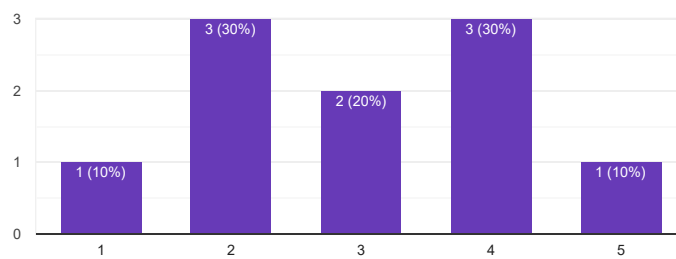
I thought the system was easy to use.

10 responses



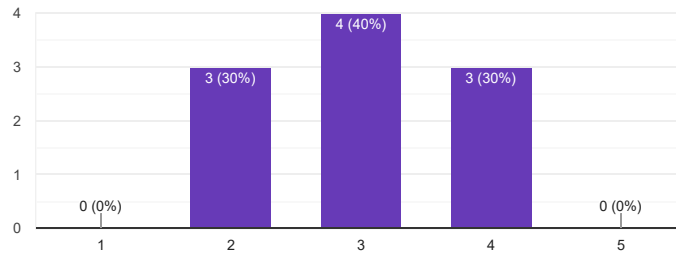
I think that I would need the support of a technical person to be able to use this system.

10 responses



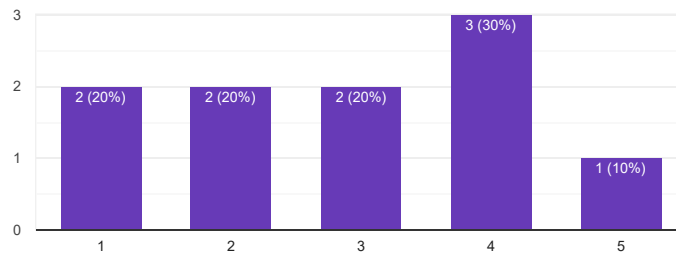
I found the various functions in this system were well integrated.

10 responses



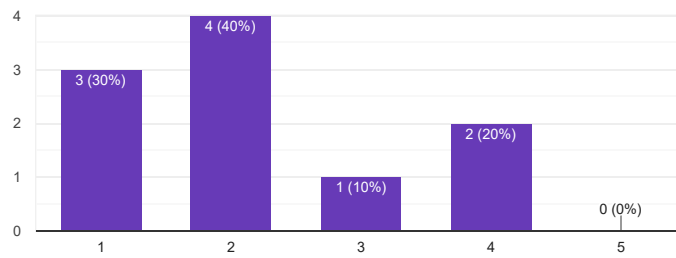
I thought there was too much inconsistency in this system.

10 responses



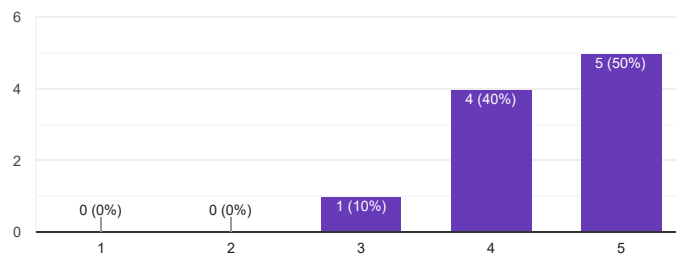
I would imagine that most people would learn to use this system very quickly.

10 responses



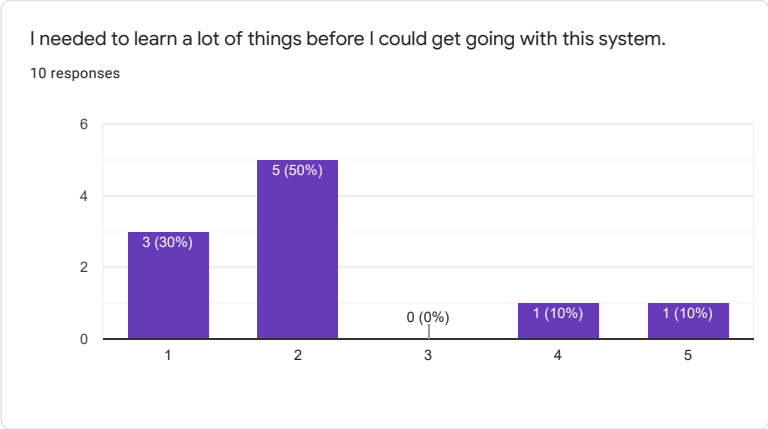
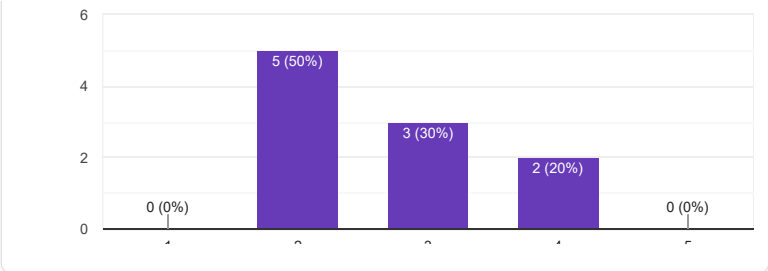
I found the system very cumbersome to use.

10 responses

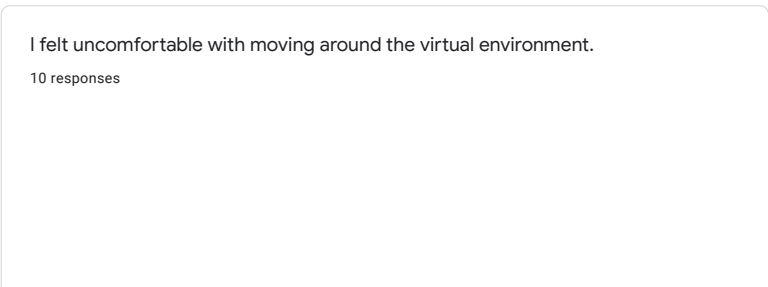
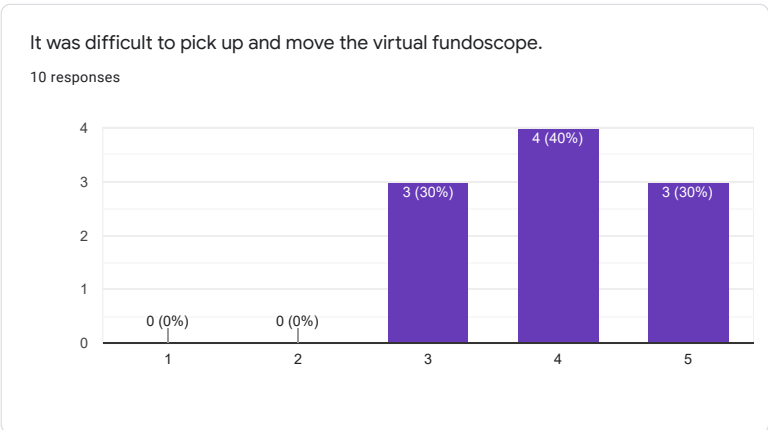
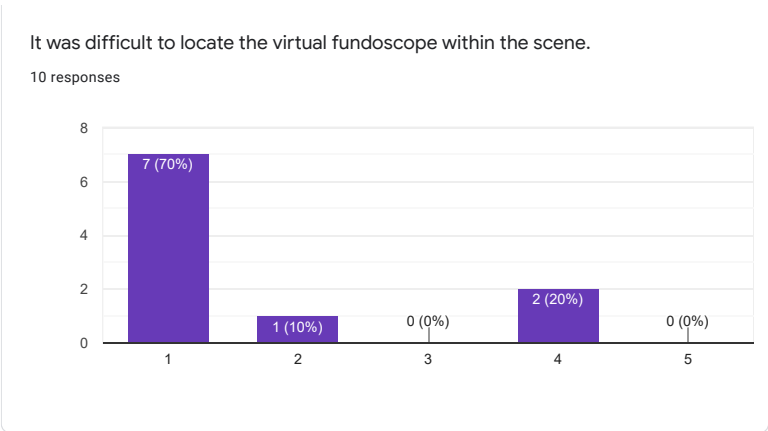


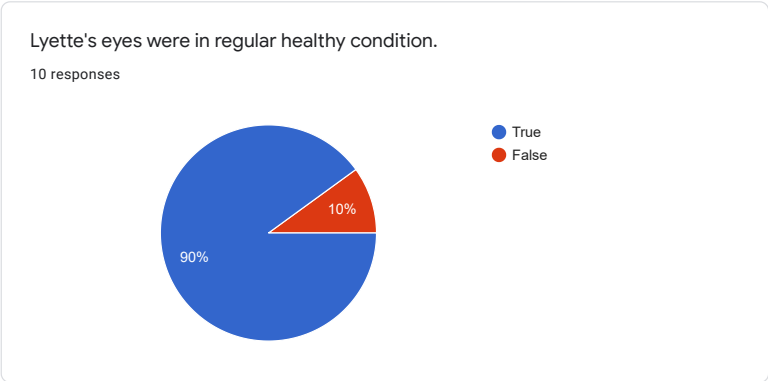
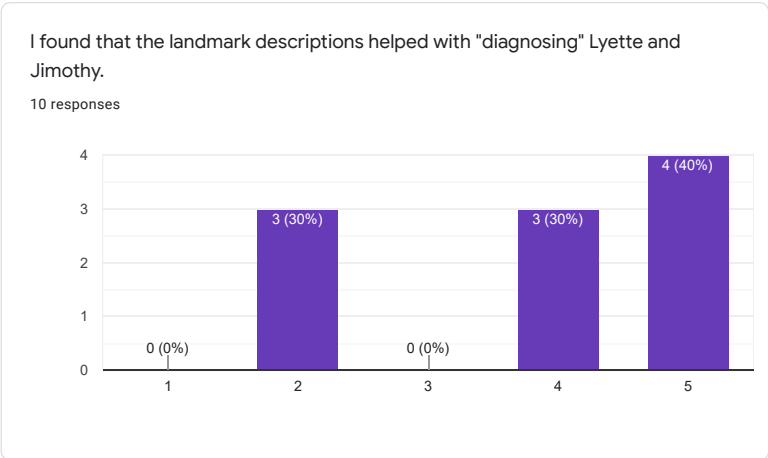
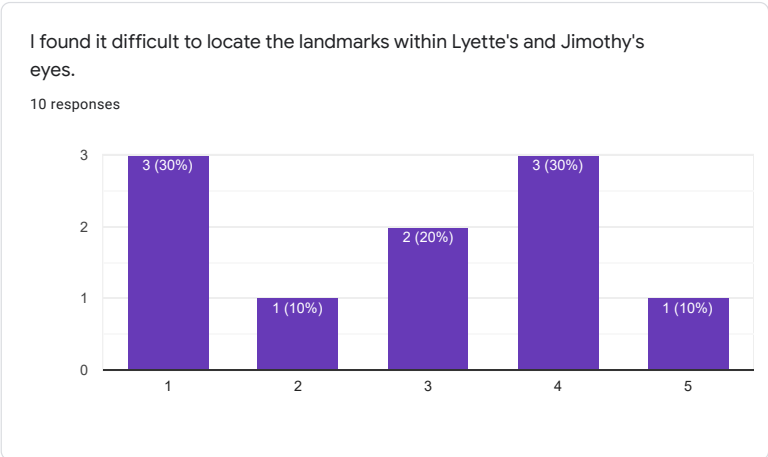
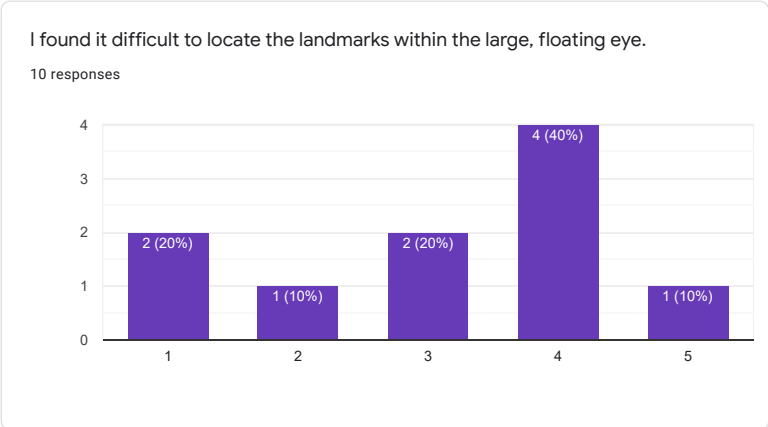
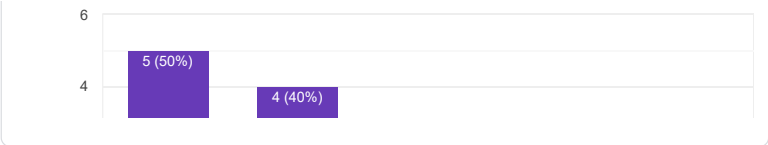
I felt very confident using the system.

10 responses



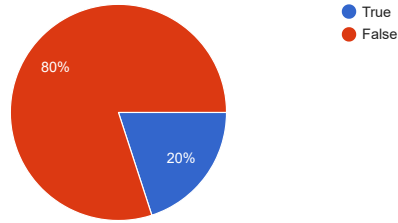
Additional Usability





Jimothy's eyes were in regular healthy condition.

10 responses



Additional Feedback:

6 responses

joystick scrolling bad, drag rotation would be much better

I stopped before checking their eyes because it was making my eyes hurt.

When turning the scope a small movement will make it spin 180 degrees. Using the hololense (even under instruction) is somewhat more difficult to control because of the hand gestures required. Once I got the hang of the controls after a few mins the game was easier to control, but there is a learning curve on how to do the hand gestures properly which does not affect the game's mechanics but just the overall use of the hololense

Voice command to rotate the tool won't work

Hand tracking was spotty at best, had to keep resetting my hand so that it would pick up the gestures. It would also think that I made hand gestures that I hadn't made so I was constantly in the menu rather than in the application.

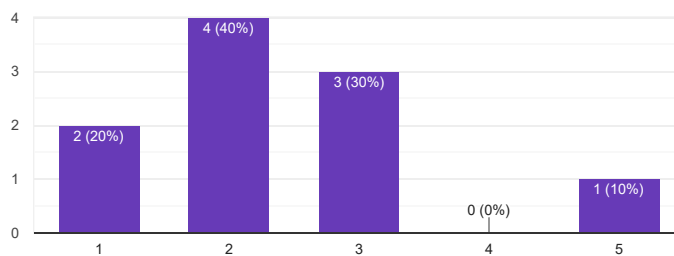
Hololens hurts eyes significantly more than VR does, but it was easier to diagnose the

Task Load Index

Mental Demand

How mentally demanding was the task?

10 responses



Physical Demand

How physically demanding was the task?

10 responses

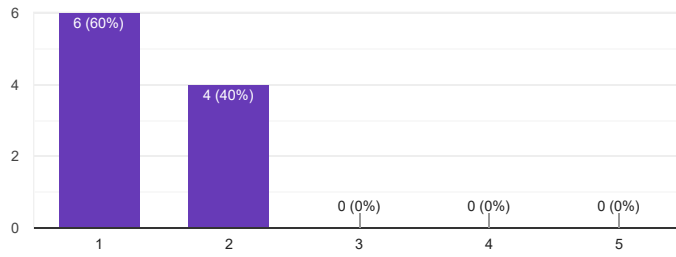
3

3 (30%)

Temporal Demand

How hurried or rushed was the pace of the task?

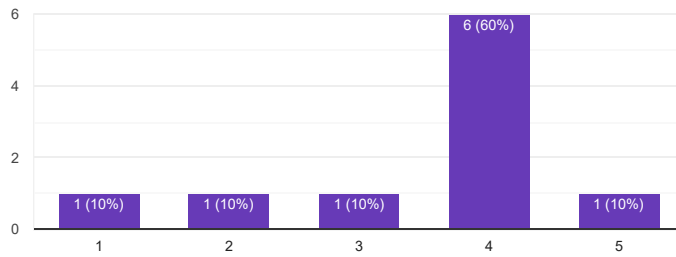
10 responses



Performance

How successful were you in accomplishing what you were asked to do?

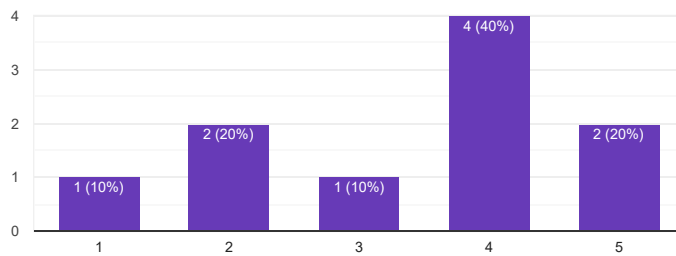
10 responses



Effort

How hard did you have to work to accomplish your level of performance

10 responses



Frustration

How insecure, discouraged, irritated, stressed, and annoyed were you?

10 responses

4

4 (40%)

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Google Forms

A.10 VIRTUAL REALITY - HTC VIVE AND INDEX STUDY RESULTS

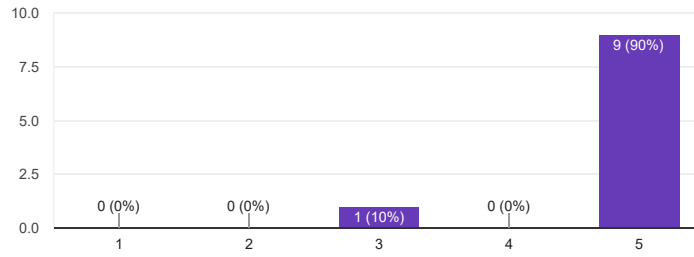
Post-Test Surveys for VR

10 responses

I think that I would like to use this system frequently.

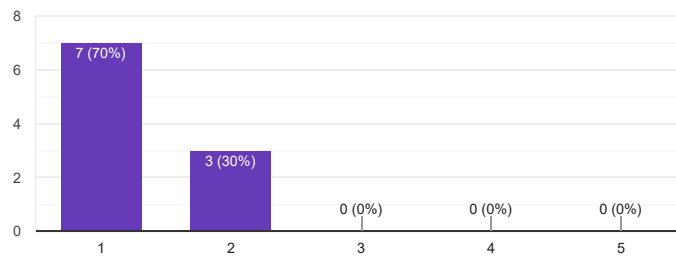


10 responses



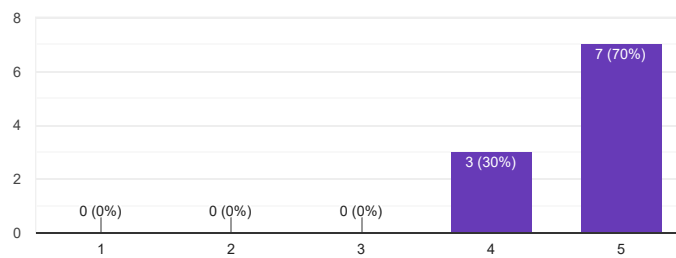
I found the system unnecessarily complex.

10 responses



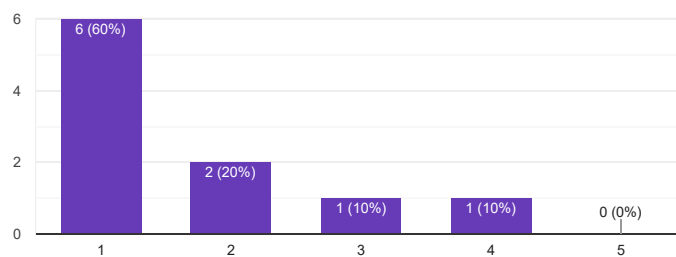
I thought the system was easy to use.

10 responses



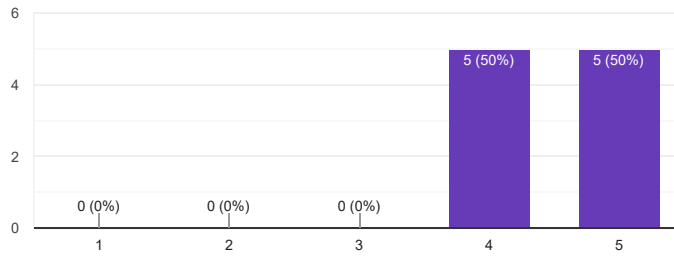
I think that I would need the support of a technical person to be able to use this system.

10 responses



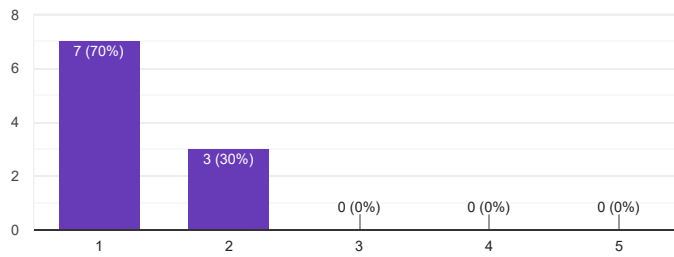
I found the various functions in this system were well integrated.

10 responses



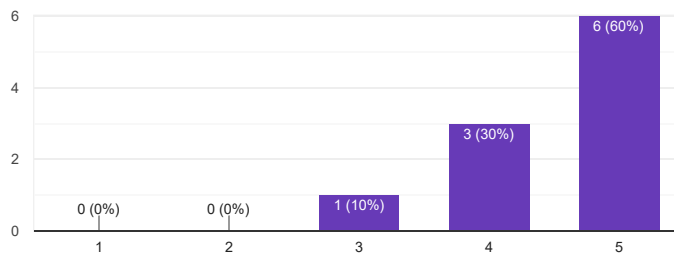
I thought there was too much inconsistency in this system.

10 responses



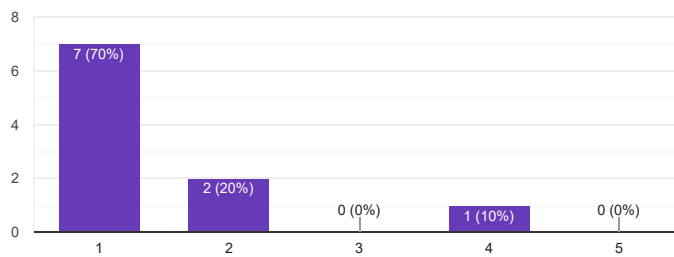
I would imagine that most people would learn to use this system very quickly.

10 responses



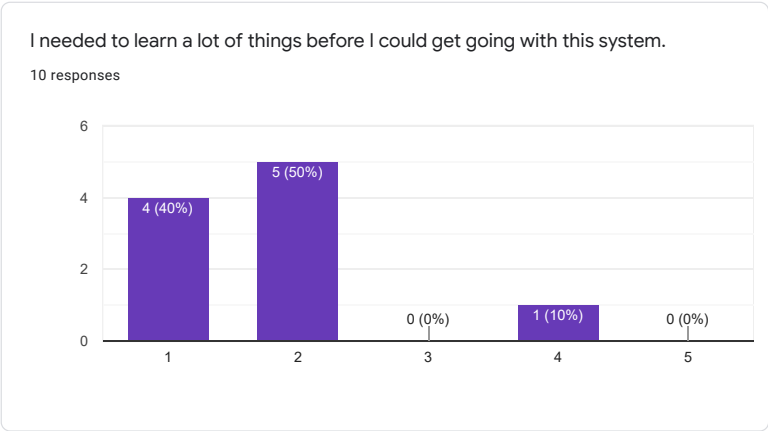
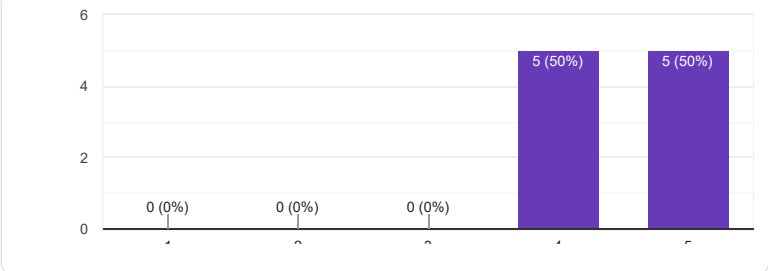
I found the system very cumbersome to use.

10 responses

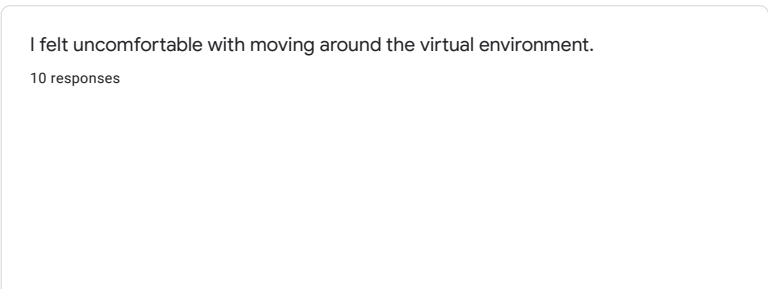
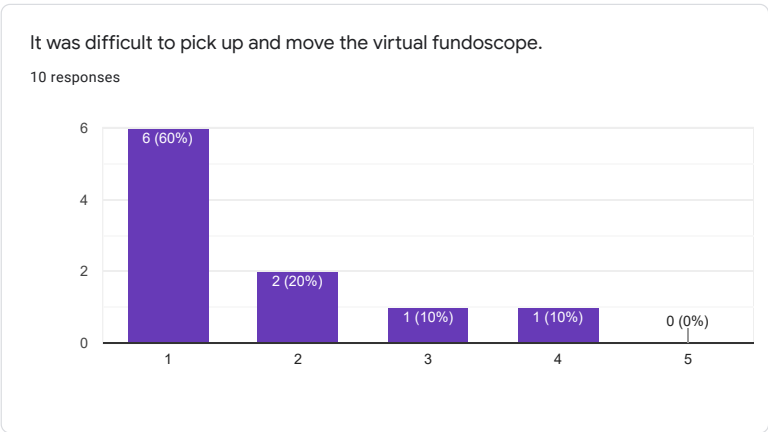
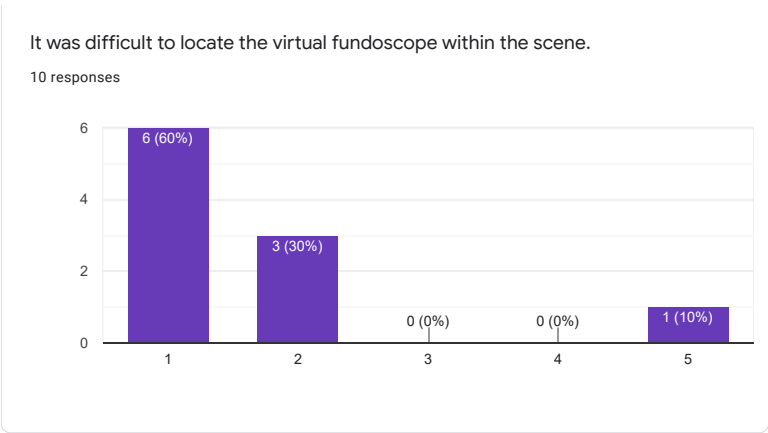


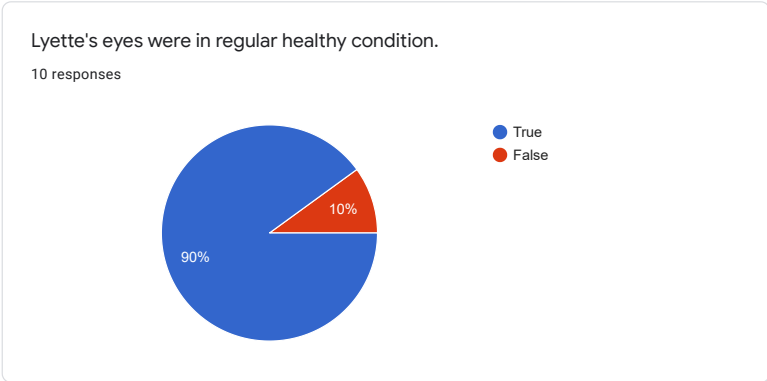
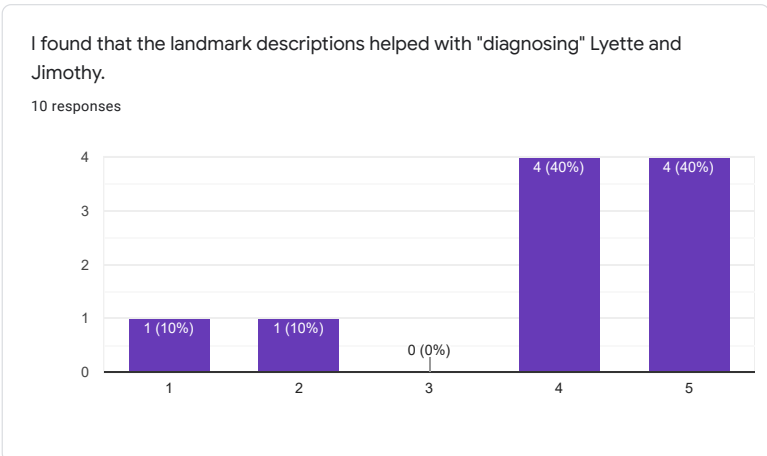
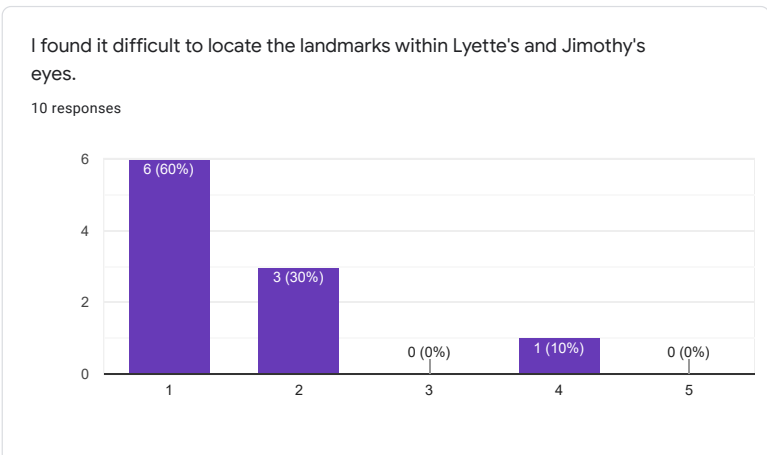
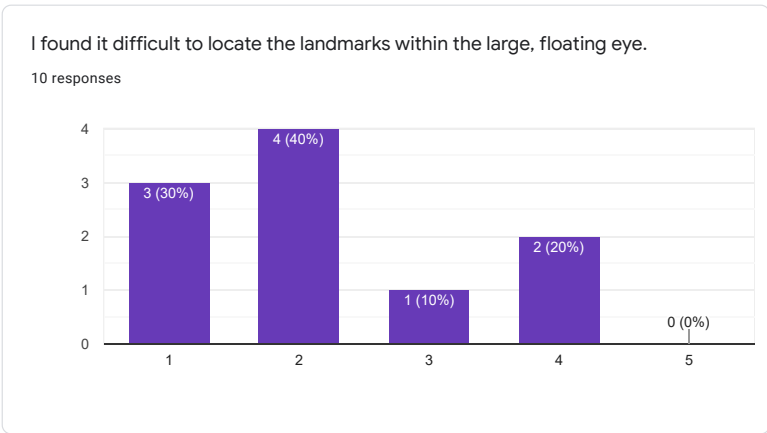
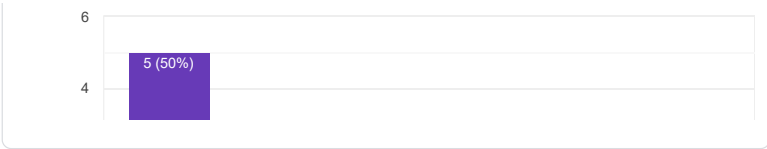
I felt very confident using the system.

10 responses



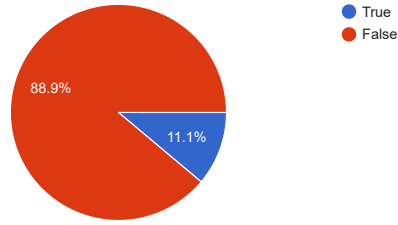
Likert Usability Scale





Jimothy's eyes were in regular healthy condition.

9 responses



Additional Feedback:

4 responses

jittery contorller

There was some difficulty in reading the text associated with the landmarks in the large eye.

Jimothy needs to take better care of his eyes.

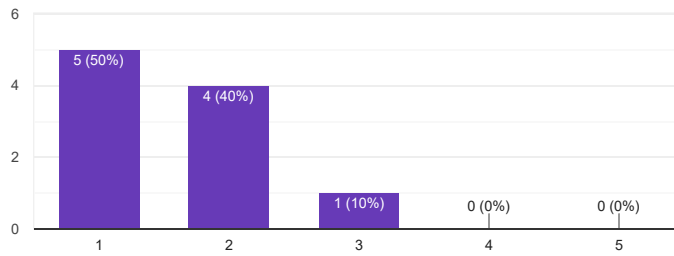
Jimothy had a red background when it said healthy was blue/green. Stood out immediately. Character models should be moved more within the play area to avoid real world barriers. Eyeball hovering up and down makes it hard to read the internal text. Everything was laid out nicely and in a logical flow.

Task Load Index

Mental Demand

How mentally demanding was the task?

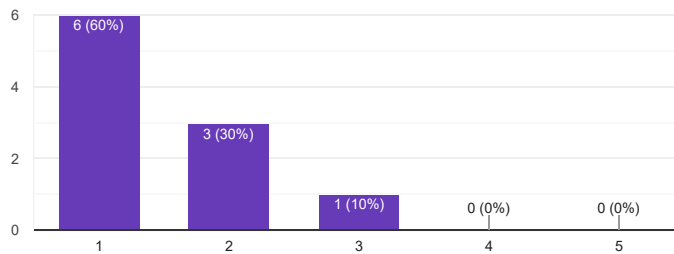
10 responses



Physical Demand

How physically demanding was the task?

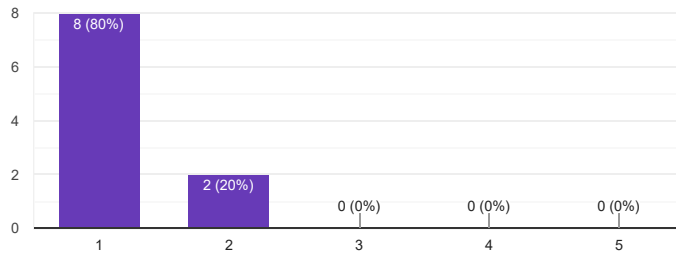
10 responses



Temporal Demand

How hurried or rushed was the pace of the task?

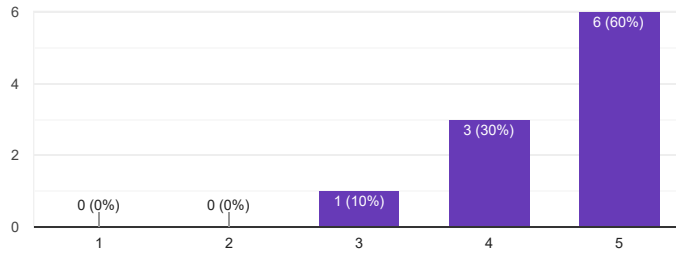
10 responses



Performance

How successful were you in accomplishing what you were asked to do?

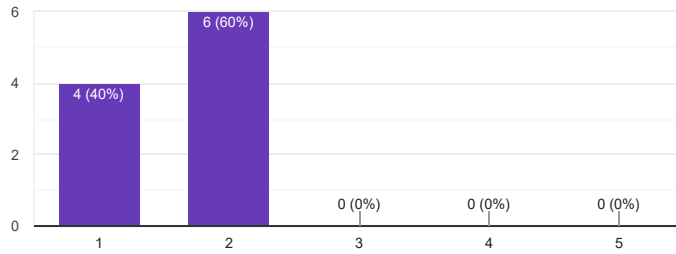
10 responses



Effort

How hard did you have to work to accomplish your level of performance

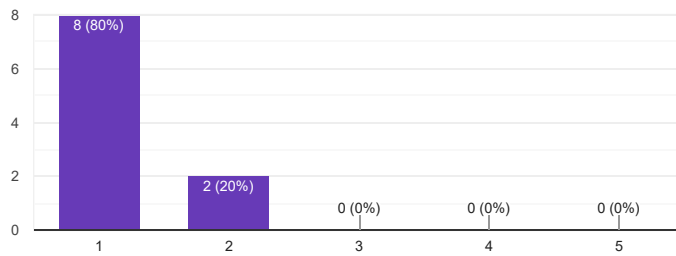
10 responses



Frustration

How insecure, discouraged, irritated, stressed, and annoyed were you?

10 responses



A.11 QFD REQUIREMENT EVALUATION STUDY RESULTS

Customer Requirement Rating

Please rate each customer requirement in terms of importance.

***Required**

1. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

2. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

3. Running multiple instances simultaneously (the method can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

4. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

5. Multiple viewer experience (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

6. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

7. Tool manipulation (the method allows users to manipulate a virtual and/or physical examination tool) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

8. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

9. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Not Important	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Most Important

10. Are there any other customer requirements that you can think of?

Customer Requirement Evaluation for the Oculed Program

Please rate how you felt the Oculed method prioritised the customer requirements.

11. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

12. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

13. Running multiple instances simultaneously (the model can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

14. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

15. Multiple people can see through it (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

16. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

17. Virtual Tool Manipulation (the method allows users to manipulate a virtual examination tool) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

18. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

19. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

Customer Requirement Evaluation for the Digital Photograph Method

Please rate how you felt the digital photograph method prioritised the customer requirements.

20. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

21. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

22. Running multiple instances simultaneously (the model can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

23. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

24. Multiple people can see through it (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

25. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

26. Virtual Tool Manipulation (the method allows users to manipulate a virtual examination tool) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

27. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

28. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

Customer Requirement Evaluation for the
AR Styrofoam Head Method

Please rate how you felt the AR Styrofoam Head method
prioritised the customer requirements.

29. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

30. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

31. Running multiple instances simultaneously (the model can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

32. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

33. Multiple people can see through it (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

34. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

35. Virtual Tool Manipulation (the method allows users to manipulate a virtual examination tool) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

36. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

37. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

Customer Requirement Evaluation for
the OphApp Method

Please rate how you felt the OphApp method prioritised the
customer requirements.

38. Affordability (the method is affordable) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

39. Easy to set up (method is easy to set up) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

40. Running multiple instances simultaneously (the model can be run in multiple instances) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

41. High-fidelity eye model (the method makes use of a high-fidelity eye model) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

42. Multiple people can see through it (the method allows for multiple viewers) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

43. Eye model interactivity (the method allows the user to interact with the eye) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

44. Virtual Tool Manipulation (the method allows users to manipulate a virtual examination tool) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

45. Input Feedback (the method allows for feedback based on user input) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

46. VR Modes (the method has the capacity for immersive and non-immersive VR) *

Mark only one oval.

	1	2	3	4	5	
Low Priority	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Priority

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Google Forms

APPENDIX B: STUDY RESULTS

B.1 BOXPLOTS

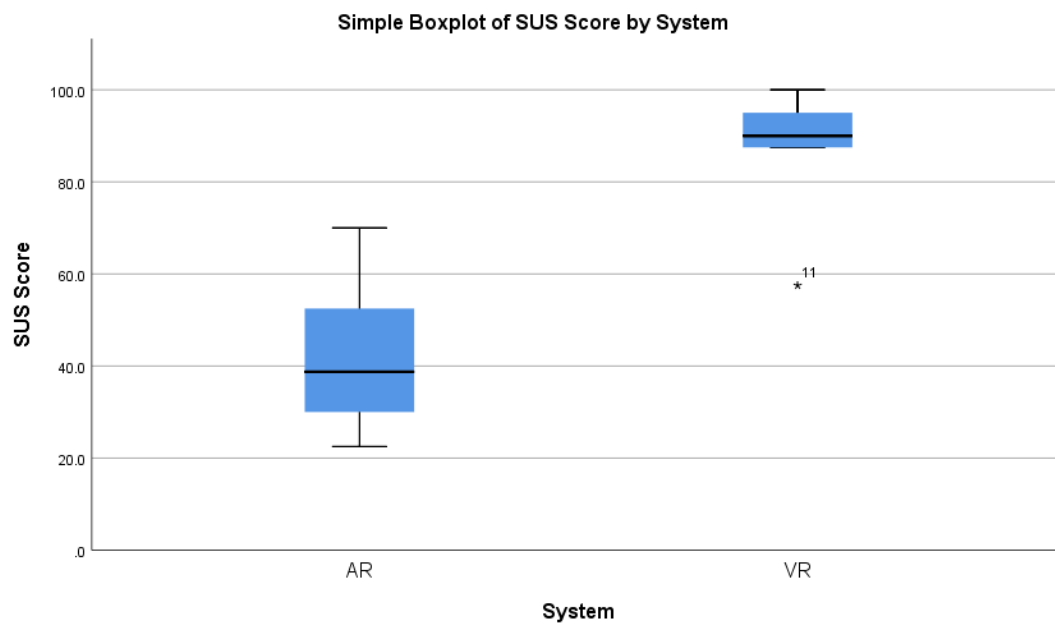


Figure 17: Box plot of SUS scores for each system. Significant outliers are shown, but were removed from data set during analysis.

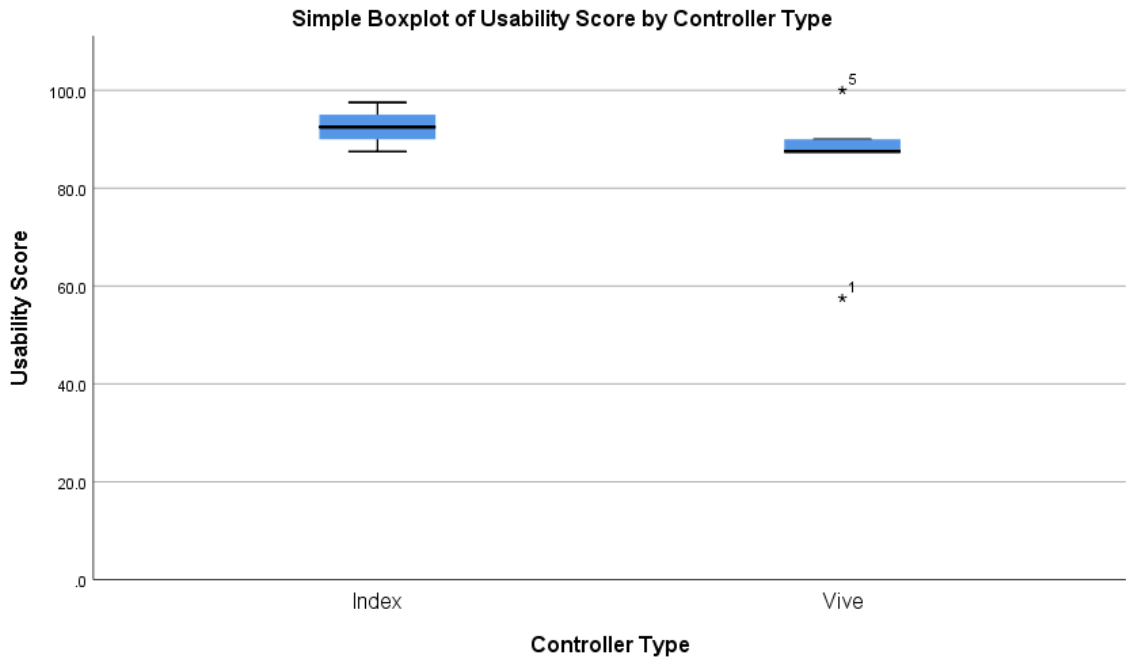


Figure 18: Box plot of SUS scores for each controller. Significant outliers are shown, but were removed from data set during analysis.

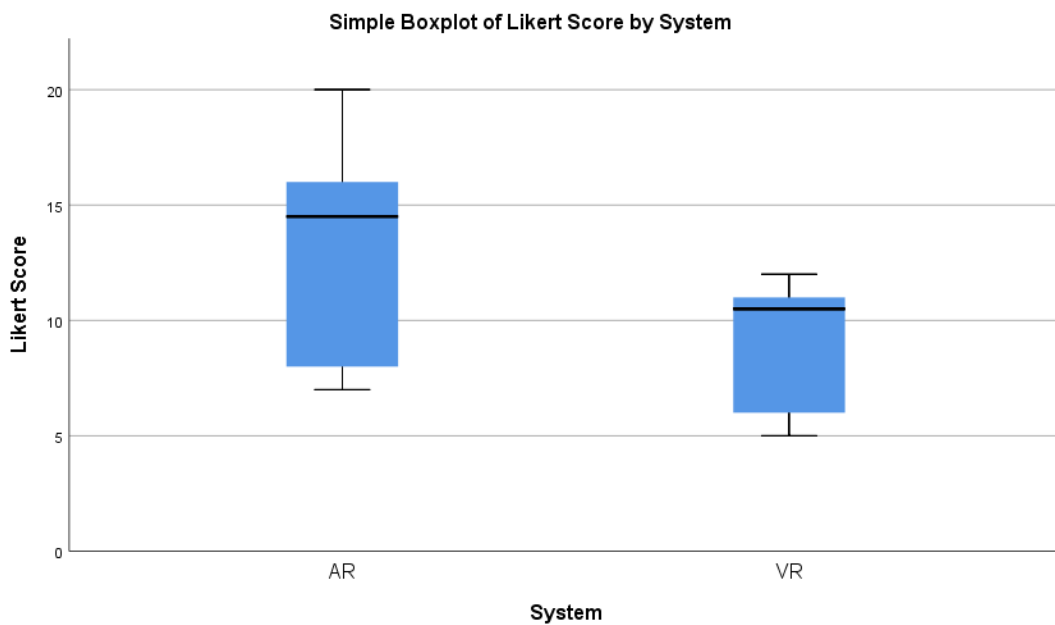


Figure 19: Box plot of Likert scores for each system. Significant outliers are shown, but were removed from data set during analysis.

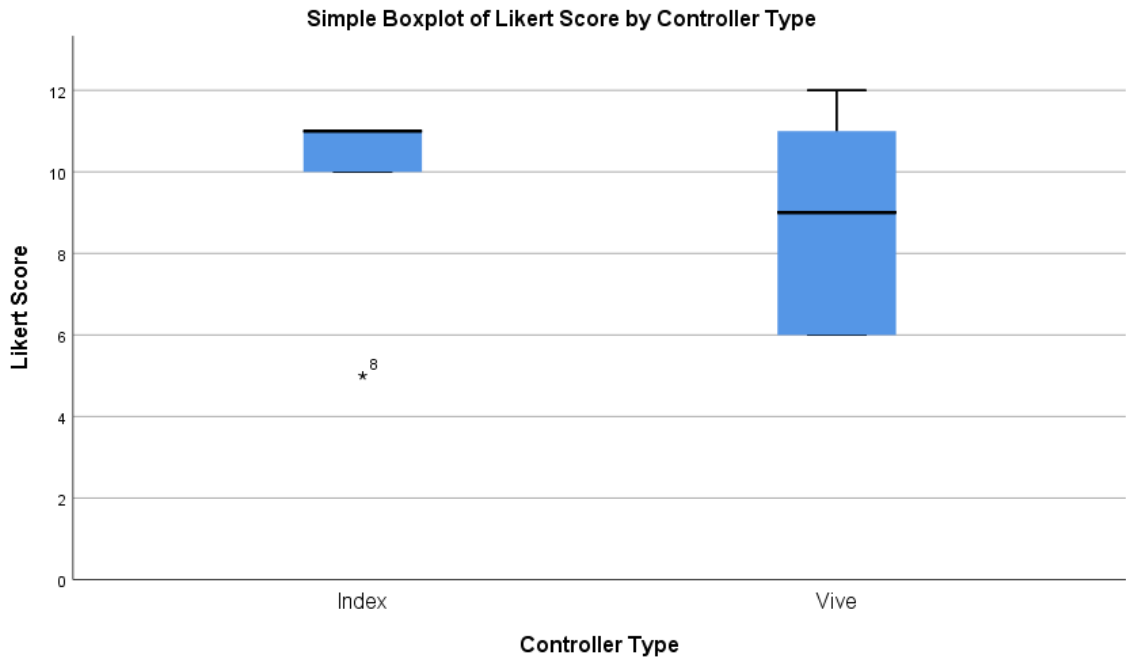


Figure 20: Box plot of Likert scores for each controller. Significant outliers are shown, but were removed from data set during analysis.

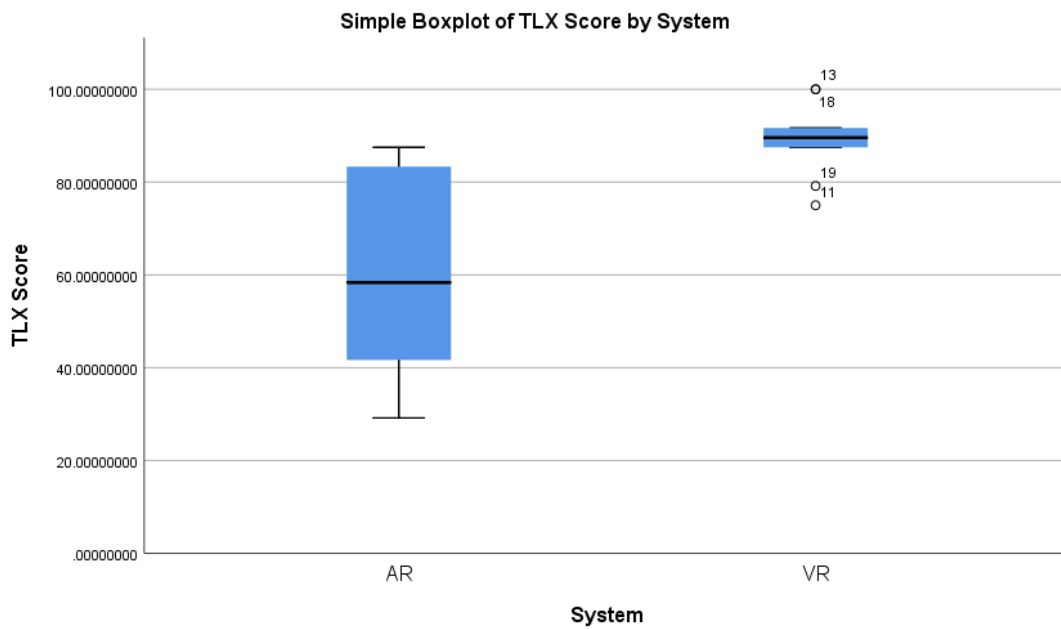


Figure 21: Box plot of TLX scores for each system. Significant outliers are shown, but were removed from data set during analysis.

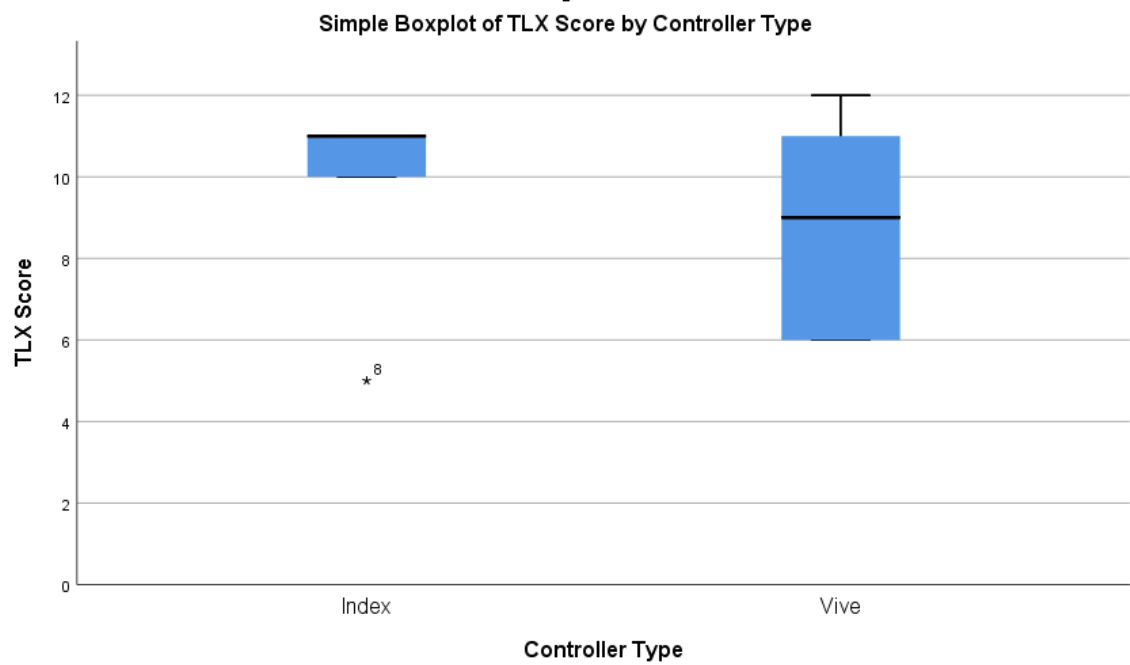


Figure 22: Box plot of TLX scores for each controller. Significant outliers are shown, but were removed from data set during analysis.

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