Eye Disease Simulator

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Sponsor: Kellogg Eye Center

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Executive Summary

Communication problems between patients with eye diseases and others create issues with diagnosis and hinders discussion about the disease. Doctors find it difficult to solve issues without an accurate description of the patient's vision. Family members are often unable to understand the impact of the disease when given only a description of its effects. Current devices that exist are not suitable to fulfill the needs of the doctors and patients due to their lack of realism and customizability.

Our sponsor tasked us with creating a device that would help facilitate the description of common eye diseases, their progression, and treatment involved by simulating the disease through the use of augmented reality. This device should have a head mounted display and simulate the disease as accurately as possible. Our main priorities are the accuracy of the simulation, the customizability, and having the ability to layer different conditions. Enough of the patient's field of view should be covered to allow use of Humphrey's visual field test to give the simulation a real experience and show how the disease affects the patient's vision. It should be capable of simulating at least 5 grades of progression for any disease. A minimum of 2 different conditions should be able to be simulated at a time. Setting up and running a simulation should take at most 5 minutes. The device cost should be under under $150.

Our software currently has a usable interface that allows for the selection of a disease, filter template, and allows drawing of the affected areas. Additionally the device can layer multiple eye diseases, save and load simulations, and allows for a specific degree of vision to be chosen when drawn. Since our prototype uses a mobile augmented reality (AR) headset, no production for the physical portion is required.

Our device was validated through a modified glasses and helper grid technique where the user wears glasses that are modified to obscure parts of their vision, and uses a grid to create a simulation on the device. The created simulation and vision when wearing the glasses are compared. Patient verification was completed by William Sheahan, who has optic nerve damage in his right eye. Multiple rounds of testing the software and creating simulations took place to validate the design. Our device worked to simulate vision lost quite well, with William unable to differentiate between his real vision and the simulated vision. The confirmation of our testing proves that our design is viable. Our final design needs additional improvement but demonstrates that with the appropriate software and testing, eye diseases can be simulated to a high degree.

Our eye disease simulator meets all of our engineering specifications, but there is a lot of room for improvement. Our eye disease simulator is not as realistic or user friendly as it could be. We recommend the next iteration of the application be built without Unity, and allow Humphrey's test input methods like scanning. Also, using a platform other than mobile AR is recommended. Google Tango is an option, but we encourage research on other headsets since new ones are always being developed. Our device cannot currently simulate diseases that are not characterised by vision loss. Adding a swirling effect for Wet AMD or simulating cataracts could be more easily accomplished if the simulator was not built with Unity.

Contents

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Sam Christie is a senior Materials Science and Engineering student at the University of Michigan. He hopes to use his knowledge of materials to pursue a career in the aerospace industry, and is experienced with MATLAB and Python computing languages. He took interest in this project because it is an opportunity to work with and create AR/VR applications.

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Jeremy Drouillard is a senior Computer Science and Engineering student at the University of Michigan. He is interested in distributed systems and machine learning. Jeremy chose this project because he is excited by the possible applications of AR/VR technology.

Ronald Hobson

Ron Hobson is a dual degree student from Morehouse College. He is a senior studying physics and material science engineering at the University of Michigan. His passion for sustainable and environmental energy has moved him to experience amazing research and internship opportunities. Since he has been in school he has done research at Princeton University and traveled to France and Japan for other amazing research experiences. He has also worked part-time at Xalt Energy and Arconic. He has been able present his research on solar cells, microbial fuel cells, photonic crystals, and lithium ion batteries.

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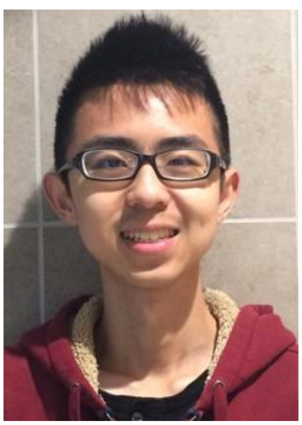
Xiaoer is a senior Materials Science & Engineering student at the University of Michigan, with another major in Electrical & Computer Engineering at Shanghai Jiao Tong University, China. She is interested in semiconductor materials and devices. She is doing research in OCM group, studying a new type of heterojunction comprising monolayer TMDC and organic semiconductors. She also has research experience in TEM characterization and blue OLED lifetime. She is good at C, C++, and MATLAB.

William “Bill” Sheahan

Bill Sheahan is a senior Mechanical Engineering student at the University of Michigan. His focus is in manufacturing processes and has interest in the automotive field. He has interned for Robert Bosch LLC in instrumentation and application for braking systems and Ford Motor Company in powertrain manufacturing focusing primarily on gears, manufacturing processes, and standards for quality control. He took a personal interest in the eye disease simulator project due to the fact that he was born with a cataract, had his left lens removed, has optic nerve damage in his right eye due to a viral infection, and has glaucoma.

Bingxin Yu



Bingxin Yu is a senior undergraduate student from Material Science and Engineering Department in University of Michigan. He was born in China and studied there before entering college. During the undergraduate studies, he developed a strong base of knowledge and a wide scopes of topics, from thermodynamics and kinetics to quantum mechanics and polymers. He has done several researches in computational and biomedical area, including making custom GUI with RAPPTURE and developing shear bioreactor.

Background

People use all five of their senses to do daily tasks or enjoy entertainment. However, eye diseases hinder people's ability to perform tasks such as reading, driving, and cooking. Approximately 37 million Americans have some form of eye disease that disrupts their vision [National Eye Institute, 15]. They are diagnosed with one of four diseases: glaucoma, wet and dry age-related macular degeneration (AMD), diabetic retinopathy, and cataracts. These eye diseases can vary in severity and if left untreated, can result in permanent vision loss. It is difficult for the patient to accurately describe to doctors, peers, and loved ones how their condition affects their vision. There is a current need for a device that can accurately and quickly simulate what patients see, so that doctors can properly treat the patient, and so peers and loved ones can understand the challenges these patients go through on a daily basis.

Problem Description

Doctors, such as ophthalmologists, often face communication problems with their patients during diagnosis due to the patient's inability to accurately describe the problem. At the same time, doctors can have difficulty displaying the effects of the progression of a disease to a patient. This is very common with patients who suffer from eye diseases since sight is difficult to describe. These diseases can also display themselves in a variety of ways that are patient specific, with multiple factors which will affect the progression and the treatment of the ailment. If a device could be designed to accurately display what the patient sees to the doctor, and show the patient what effects treatment could have on their vision, then the treatment process could be made much effective and efficient.[Mian, 9]

Another issue facing the patient relates to their daily lives and loved ones. The patient may also have difficulty describing their vision to those around them such as loved ones. Both groups may not be able to fully understand the impact the disease may have on their life as it progresses or how the treatment will affect their vision. This tends to happen more often with younger patients, children are less likely to want to wear patches and take drops that will help future vision due to current discomfort [Shtein, 25]. Some diseases are not curable and have permanent effects such as loss of vision. In these cases patients may be unaware of the severity of their problem. In many cases, the treatment can only stop the progression but cannot bring back vision. Such permanent effects can have significant impact on the patient and others around them. The lack of ability for patients to describe what they see with their loved ones can drive a wedge between them. If a device can accurately show what the patient sees and how the disease will progress, families can have a much better understanding of what the patient goes through on a daily basis.

User Requirements & Engineering Specifications

The “customer” for the eye disease simulator is primarily doctors at the Kellogg Eye Center. From speaking with Dr. Mian, we have identified several user requirements. In this section we will introduce each user requirement, in order of importance, and explain the corresponding engineering specification.

Customizability

The most important user requirement is customizability [Mian, 9]. To the doctors, customizability means having control over how the disease is simulated. One could simulate glaucoma by cupping their hands around their eyes to force tunnel vision; however, this is not customizable. It is not possible to simulate glaucoma of different severity with this method. The doctors intend to use the simulator to show patients how their disease may progress. The progression may differ from patient to patient and this is why customizability is important.

As an engineering specification, customizability will be measured as the number of different representations of a single disease that can be simulated. We think this is a fitting measurement because it measures exactly how many unique inputs a doctor can give a disease simulation. We have decided the minimum number of representations for a given disease is five. Five is a reasonable minimum because it will allow the simulation to show three intermediate stages of the disease. This is important because diseases cannot be accurately represented with a fewer number of configurations. Take glaucoma for instance. Glaucoma progresses by slowly creating tunnel vision and eventually obstructing central vision [Haddrill, 16]. For a disease with such a long progression, it is important to have multiple intermediate stages in the simulation. That is why the number of configurations for a disease is a good measurement of customizability.

Layering

The next most important customer requirement is layering. Layering is the ability to combine multiple visual effects [Mian, 9]. To clarify, visual effects can be a disease, treatment, or additional filter like nearsightedness. If an eye disease simulator can layer, it is more useful to the doctors because it can be used to simulate a disease and, for example, how a treatment for that disease will affect the vision. Also, it is important to point out that layering is related to customizability. Clearly, layering increases the general ability for customization, but since layering includes combinations of whole visual effects it is markedly different.

Similar to customizability, layering will be measured as the number of effects that can be combined at once. This is a straightforward way to quantify the layering ability, since it measures how much layering is possible. Dr. Mian expressed great interest in being able to simulate a disease and a treatment. For this reason, two is the minimum number of layers.

Realism

Realism is the next more important customer requirement. Realism for our purposes means that the eye disease simulator accurately portrays what it is like to have the disease [Mian, 9]. This is important because the simulation's general purpose is to help the doctor explain how a disease will affect their vision. To quote Dr. Mian, "The more realistic, the better."

We will quantify realism as the percentage of the field of view the simulation occupies. This measurement really measures how immersive the simulation is. It seemed this metric captures what Dr. Mian and Lauro meant by realistic. For example, when discussing possible headsets we were told that an AR headset with a screen in only a portion of your vision would not be a good idea. Such a configuration would not convey what it is like to have the disease. Our group decided that the simulation should occupy enough of the field of view so that Humphrey's test results can be applied. The rationale is that the device would still simulate enough of the peripheral vision to allow diseases that affect peripherals to be realistically simulated because so much of our vision is peripheral [Goldstein, 14].

User Friendliness

The rest of the user requirements, including user friendliness, are secondary requirements. Dr. Mian described these as "long term goals" rather than a central part of the design [Mian, 9]. Despite this being a secondary requirement, it is still important that our solution is user friendly. User friendliness in this case means that it is easy for a doctor or patient to setup a simulation. User friendliness is important because an eye disease simulator that delivers on customizability, layering, and realism but fails to be user friendly will be unmarketable. The doctors will not use the product if it is inconvenient and takes a lot of time.

For the corresponding engineering specification, we will time how long it takes to set up an eye disease simulation. Time is a good metric because time is extremely valuable to the doctors using our product. The reason we use time rather than number of clicks is that some eye disease simulators could have a lengthy hardware setup procedure and we wanted to account for this. Additionally, we assume a simulator that can be set up in a brief amount of time is easy to use. The maximum setup time for any product will be five minutes. We settled on this amount of time because anything more could result in impatience from the doctor or patient and would feel tedious.

Availability

The last user requirement is availability. To our customer, availability is a combination of the ideas of cost-effectiveness and portability. Availability means that the product is easy to carry around, and it is easy for many patients or doctors to have. An available eye disease simulator is important, because if it is prohibitively expensive to produce or too unwieldy then fewer doctors and patients can use the simulator.

Our measure of availability is the cost to run a simulation on separate equipment. We focus more on the cost-effectiveness rather than portability intentionally. It is a foregone conclusion that the eye disease simulator will be a headset. We are assuming that nearly all headsets are portable. Secondly, cost-effectiveness is where the hardware differs significantly [Murphy, 21]. We want the cost of running on separate equipment to be no more than $150. This price range encompasses a good deal of AR equipment. Furthermore, hospitals will be more likely to adopt our product if it does not cost thousands of dollars like some AR equipment.

Concept Generation

In order to generate concepts for our eye disease simulator, we broke the project down into two parts. The first aspect is the device we use to display the simulation. The second is the method we use to create the simulation. We then explored which simulation methods and devices could be combined.

The main device categories were Mobile AR, lenses, AR for specific phones, stand-alone VR headsets, stand-alone AR headsets, and headsets that improve mobile AR. Aside from lenses, these categories cover essentially all the existing headsets on the market. Lenses would simply be using stickers or markers to distort the image as it passes through the glasses.

The main software categories are copying the Humphrey's test, approximating the Humphrey's test, performing a visual field test, and scanning the eye. Copying the Humphrey's test includes methods like scanning the outputs and also manually copying them. Approximating the Humphrey's test includes a method like drawing an approximation of the visual field. For a more detailed explanation of what we mean by performing the visual field test and scanning the eye, see appendix A.

Using the broad categories, we created the following table. Green indicates the software and hardware idea can be combined. Red indicates the ideas as incompatible.

Table 1. Generated concepts and their compatibility

		Software			
		Copy Humphrey's Test	Approximate Humphrey's Test	Perform Humphrey's Test	Scan the eye
Hardware	Mobile AR				
	Glasses				
	AR for a specific phone (Samsung Galaxy, HTC Vive, etc.)				
	Stand-alone VR Headset				
	Stand-alone AR Headset				
	Device that improves Mobile AR				

Concept Selection

When selecting concepts we used specific methods or products from the categories mentioned in the Concept Generation section. For the concept scoring, we selected devices that would score well from each category to show the pros and cons of the different types of devices. We tried to be inclusive of all of the categories, but some ideas like glasses and scanning the eye we did not seriously consider. Scanning the eye is just infeasible given the current state of AR technology and glasses are not customizable nor are they the solution the sponsor desires.

Headset Selection

After scoring, we chose Google Cardboard and the mobile AR platform for our headset. Its availability and lower cost help the patient access the simulation. Our only assumption with these types of headsets is that the patient owns a smartphone. In 2017, it is a safe to assume that most people have a smartphone since 68% of American own smartphones as of 2015 [Mediati, 32]. Devices like Google cardboard and other mobile AR headsets are affordable and work with most every phone [Google Cardboard, 30]. This allows the patient full control over comfort and cost when using the simulator app outside of the clinics. Using mobile VR/AR headsets also allowed us to use the Unity game engine to develop our simulator. However, with mobile AR, it was harder to implement eye tracking and some realism is lost because of the limited field of view. Testing with these devices was incredibly easy since a phone is our simulation medium, it can be easily removed, and the simulation can be calibrated.

Taking all the above into consideration, we created the following chart to compare the merits of different software concepts. The scoring method for AR capability was binary, 0 and 1 meaning not capable and capable, respectively. We consider Mobile AR the benchmark. A zero score means that the concept is equal to the benchmark. The numbers one, three, and six indicate how significantly better or worse the concept is compared to the benchmark. We weighted the top AR capability as six times more important and realism as two times more important than the tertiary. The equation for calculating the total score for different headset is listed below, and the results are shown in Table 2.

$$\text{Total score} = 6*\text{AR capable} + 2*\text{realism} + \text{availability} + \text{eye tracking}$$

Table 2. Concept scoring system for headset selection

Headset	AR Capable	Realism	Availability	Eye Tracking	Total Score
Mobile AR (Google Cardboard)	1	0	0	0	**6**
Microsoft Hololens	1	-3	-3	6	**3**
Oculus Rift	0	3	-1	0	**5**
Galaxy VR	0	0	-1	0	**-1**
Project Star VR	0	6	-6	6	**12**
SEER	1	3	-6	0	**6**

Our scoring resulted in a Project Star VR winning, followed by Mobile AR and SEER. However, Project Star VR is not available to the everyday consumer and is not AR capable. Because of this, we will not use it for our project. Additionally, despite SEER’s superior field of view, we will also not be using it because it is not available [SEER, 31]. In fact, they just started shipping the headsets to their Kickstarters. As a result, we have decided to use Google Cardboard as our headset.

Software Selection

There are multiple factors that influenced our software selection. Of the engineering specifications, we ranked customizability, layering, and realism equally as the most important. User-friendliness was given secondary weighting. We also did not consider availability when selecting the software concept because availability is only impacted by the hardware. Outside of the engineering specifications, we also considered how complex the software would be to implement. We refer to this as software simplicity. This is an important consideration because the bulk of this project was software, and this was a team that does not have much experience when it comes to developing software. A difficult to implement software concept would jeopardize our ability to deliver a functional eye disease simulator in the a timely manner. For this reason, we also gave software simplicity top priority.

Taking all the above into consideration, we created the following chart to compare the merits of different software concepts. We consider manually inputting the numerical results of the Humphrey’s test the benchmark. A zero score means that the concept is equal to the benchmark. The numbers one, three, and six indicate how significantly better or worse the concept is compared to the benchmark. We weighted the top priority metrics as three times more important than the secondary. The equation for calculating the total score is listed below, and the results are shown in Table 3.

Total score = 3*(customizability + layering + realism + software simplicity) + user-friendliness

Table 3. Concept scoring system for software selection

Software Concept	Customizability	Layering	Realism	Software Simplicity	User-friendliness	Total Score
Manually Inputting Humphrey's Test	0	0	0	0	0	**0**
Drawing the Humphrey's Test	0	0	-1	0	6	**3**
Scanning the Humphrey's Test - pdf	0	0	3	-3	1	**1**
Scanning the Humphrey's Test - img	0	0	3	-6	6	**-3**
Performing a Visual Field Test	0	0	6	-6	3	**3**
Using a slider to adjust severity of disease	-6	0	-1	3	6	**-6**

The two concepts that scored the highest are the drawing of the Humphrey's test and actually performing the Humphrey's test with the eye disease simulator. Despite performing a visual field test scoring well, we felt that its poor score on complexity could not be ignored. Additionally, performing the visual field test was "well outside the original scope" according to Dr. Mian [Mian, 9]. Consequently, we have decided to go with the drawing method because it was generally equivalent to the benchmark in the primary objectives but was an improvement in user-friendliness because it is not as tedious. It is worth pointing out that drawing the Humphrey's test is not as accurate as scanning or transcribing the results, because the operator of the eye disease simulator will have to approximate the results of the test. However, this is still better than not using the Humphrey's test results at all.

Before moving on to the next section, we would like to further explain why we didn't go with the scanning method, since Lauro expressed interest in this method during our presentation. The main benefit of scanning the results is that once the results are scanned, the eye disease simulator could use the entire output in its simulation. No other method, except for performing the test, accomplishes this. However, in order to be able to extract all the information from the results, we would have to build a pdf or image scanner. Building a pdf scanner would be simplest of the two, but it would not be as user-friendly to upload the results to the eye disease simulator. Image scanning is a more complicated problem but it would be as simple as taking a picture of the results. The benefits of scanning simply did not warrant its complexity.

Concept Description

After down selecting headset and software concepts from our list of possible designs, we've decided to use the Mobile AR design that incorporates the user drawing the Humphrey's Visual

Field Test on their mobile device. Although approximately 66% of Americans own a smartphone [Mediati, 32], it would be easier for the hospital to provide a smartphone so that there would be one readily available to all patients. The purpose for using Mobile AR is so patients can feel comfortable using the device at home to demonstrate to family and friends how they view the world through their own eyes. Google Cardboard, one example of a Mobile AR headset, is readily available on the market and affordable. There are nicer headsets designed for Mobile AR as well, giving the patient and hospital flexibility to choose the headset that is right for them. Lastly, while testing the validity of our software, it will be easier to calibrate using our testing method because of the single component that is the smartphone rather than other headsets mentioned earlier in this report.

Combining the headset design with a software that meet our design requirements was chosen from the list of methods discussed earlier in the Software Concepts. After down selecting, we've decided that the "Draw Affected Area" method on a smartphone would be the best viable method for the user to represent what a patient would visualize. Users will draw the graphs of the Humphrey's test results with their finger. This is significantly less complex than performing the visual field test with a smart phone. Drawing the Humphrey's test had a better user friendly interface and further increased the user's comfortability to use the software outside of the hospital. Although, drawing the Humphrey's test graphs would result in varying representations rather than scanning the patient's test, this method was less complex than scanning the Humphrey's test results. This required a significant amount of time to develop, not to mention that the Humphrey's test results are not in a standardized format.

Final Design

We delivered a final working prototype. The prototype is a simulator for central vision loss. We completely delivered on the concept we selected. The prototype will be able to validate the final design, because, while it is not perfect, it is functional. A video demonstration can be found here: https://www.youtube.com/watch?v=_UxAIawMaf4

This is the screen a user would draw the Humphrey's test on.

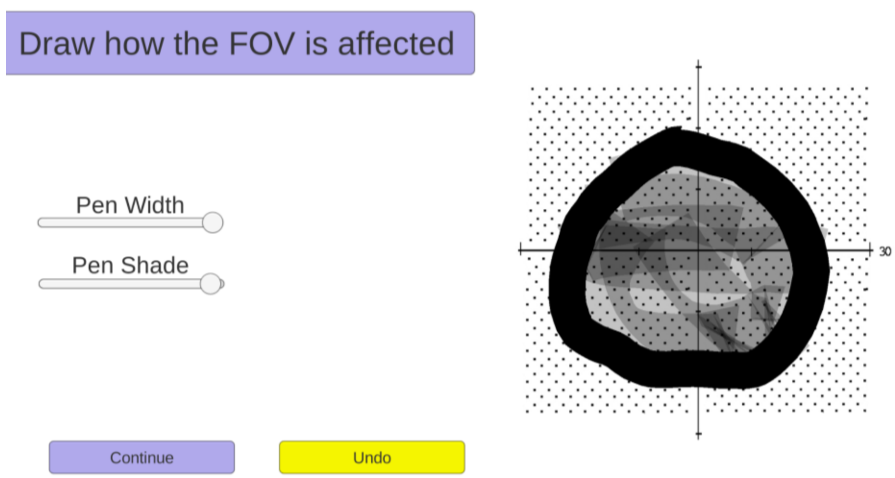


Figure 1. User interface for drawing impact field

As you can see, this user drew a circle with some central vision loss. Simulating this drawing looks like this.

Figure 2. Simulation of the visual field

Here you can see how the drawing is scaled to obstruct the vision of the left eye. The user cannot see through the black ring and they can only barely see through the gray transparent area within the black ring.

This prototype validated that we can accurately simulate central vision loss. We accomplished this by using the markers and glasses test and also having Bill verify that he can simulate his vision. We could not validate if we can accurately simulate diseases affecting peripheral vision nor can we validate simulations of diseases that are not characterized by this simple vision loss such as Wet AMD.

Manufacturing Plan

Since our project is solely software we will focus on how we developed it in this section. We laid out what our software would like from a theoretical perspective as seen below in figure 3. We used this during software development as a roadmap.

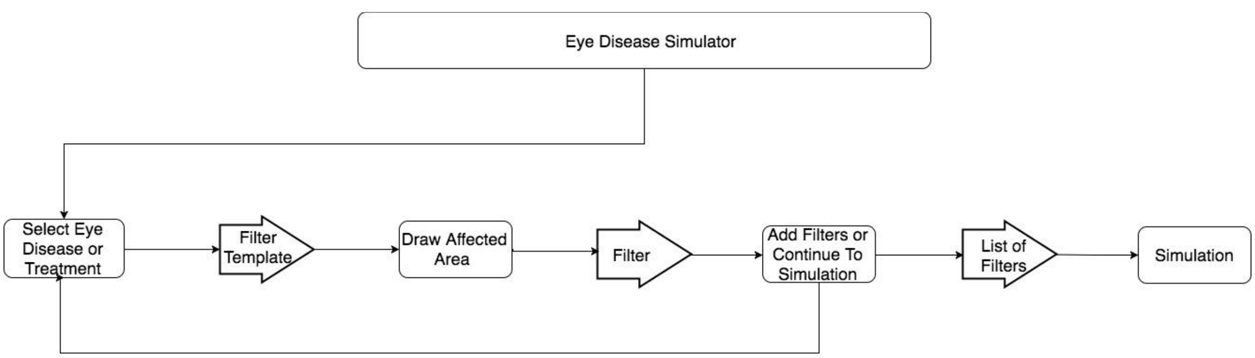


Figure 3. High-level Abstraction of Software

The smaller software modules were completed from left to right. This is a natural approach to software development as opposed to working on the parts individually and then figuring out how to staple them back together. Also, it allowed us to easily gauge our progress. As stated before, we used Unity to develop the eye disease simulator. It is free to develop with Unity. However, Unity and Vuforia, one of the libraries we used, both have fees if we ever monetize our eye disease simulator [Unity, Vuforia; 41, 42]. The main reasons we used Unity is because the amount of resources available for Unity and because Unity allowed us to build our product for iPhones and Androids simultaneously.

The only other parts that were needed are the headsets. There are different types of AR headsets ranging from $10 with Google Cardboard to fancier headsets costing $10 or $20 more. The hospital would like nicer headsets, but we already have Knox Cardboard for our own purposes.

Parameter Analysis

Software does not have dimensions, parts, or materials so in this section we will instead explain the decision making process for major software decisions. The biggest problem we faced creating the eye disease simulator was figuring out how to translate drawings into simulations. In order to map the drawing onto the simulation, the software normalizes the drawing to be on a unit scale. Then, the unit drawing is translated in front of the proper eye and scaled to fill the eye. The line width is scaled by the average of the X-scale and Y-scale. These translated drawings simply obscure the original camera image. The reason this work is done upfront rather than during the simulation is so the simulation does not need to constantly compute the position of the lines. If our simulator needed to perform computations while simulating, this could result in a much slower, less smooth simulation. Another important decision we had to make was how lines would be drawn, specifically what should be the color and transparency of the lines. We originally had the user draw lines that were black or some shade of gray. However, we decided to use black lines with adjustable transparency. This decision made sense to us since it would be clearer to users what the lines represent. Given the nature of our project, there were not many other implementation decisions to make. Instead, we just implemented our original design plan.

Validation Plan

Our validation plan tested that our device accurately and realistically simulates a user's inputs. This was performed through the use of modified glasses and helper grids. Multiple glasses are modified to obscure various parts of the wearer's vision such as blurriness and dark spots. The wearer then looks at the helper grid. The helper grid gives the wearer a clear sense of what part of their vision is obscured. The wearer then recreates what they see on the poster in the application by drawing it. They then take off the glasses and view the simulation. They can then compare how their vision was obscured with the glasses on and with the simulator on. More detailed instructions can be seen below.

We will not be validating any other aspects of our device, or performing any other tests due to the nature of our project. Our engineering specifications regarding customizability, layering, and user friendliness are all also validated with this test. When using the device it can be seen that there are 2 sliders, one for pen width and one for pen shade, that the user can use to alter the pen while they draw. Any number of layers or filters can be added to each eye, and the simulations take at most 2 minutes to create and run. Our other specification of availability, or simply cost, depends on whether the user wants to purchase a low-end headset like Google cardboard, or a more expensive, higher-end one.

Helper Grid Testing for Verification

This is a step by step guide for how to test the functionality and accuracy of the device for the at home testing.

1. The user will wear modified glasses. These glasses will be marked up so that the visual field is changed.
2. The user will close one eye and hold a helper grid approximately 12 inches from their face. They will center the grid so that their focal point will be the center of the grid.
3. The user will maintain focus on the center of the grid and note the number of grid lines they can see without moving their eyes in both the horizontal and vertical directions. This will be the edge of their visual field.
4. The user will note gaps in the grid from the modified vision from the glasses.
5. The simulation will mimic the grid and the user will, to the best of their ability, copy the vision loss they experienced to the grid in the app.
6. The user will repeat the steps while closing the other eye.

This process is how a patient would use the device and helper grids during the at home tests without the modified lenses. The comparison between the modified glasses and the simulation will help the verification of the device.

Patient Verification

Patient verification can be used before and after introduction into the clinical setting. The at home tests can be used to monitor day to day visual fields and help with communication between friends and family. These tests are very approximate given the inaccuracy of these types of visual field tests and should only be used for education and not as a diagnostic tool. The clinical testing can be used to validate the device in its early stages and later be used as a tool to facilitate doctor-patient interactions. These tests are more accurate because they use more accurate visual field tests.

While receiving feedback from patients who have eye diseases would be extremely beneficial, there are lengthy protocols involved with having patients participating in projects like ours. There is not enough time left in the semester to get approval for and get patient feedback, but if this project is continued by a different team at a later date then it is certainly a possibility.

At home testing

This is a step by step guide for how to use the simulation for the at home testing.

1. The patient or user will close one eye and hold a helper grid approximately 12 inches from their face. They will center the grid so that their focal point will be the center of the grid.
2. Then they will maintain focus on the center of the grid and note the number of grid lines they can see without moving their eyes in both the horizontal and vertical directions. This will be the edge of their visual field.
3. They will then note gaps or visual impairment in the grid.
4. The app will mimic the grid and the patient or user will, to the best of their ability, copy the vision loss or impairment they experience to the in the app grid.
5. The patient or user will then repeat the steps while closing the other eye.

These at home tests are difficult because asking someone to draw what they cannot see can be challenging. Other types of symptoms, such as distortion, are also very difficult to depict through these tests. These tests should be approximations and only used as educational purposes or for communication not diagnosis.

Clinical testing and verification

This is a guide for how to use the simulation would be used for clinical testing.

The doctor will use the results from a visual field test to draw the patient's visual field through the in app prompting. The patient will then use the simulation app and give verbal or written feedback regarding how accurate the simulation captures their visual field. This process can be performed with other hospital staff and verified by a doctor to allow for less time wasted in calibration.

This process will work best with symptoms such as blurred vision or vision loss where a patient can confirm that the portions that the doctor has modified are not too large and are in the correct place within the visual field.

Results

Our device was validated through the above techniques. Patient verification was completed by William Sheahan. Multiple rounds of testing the software and creating simulations took place to validate the design. Our device worked to simulate vision loss quite well. Once we had a working prototype program and headset the testing became easier. The continued testing also proved that there is a learning curve to how to use the program that affects how well the simulation is drawn and displayed. There are aspects of the software we used that made the simulation less realistic than projected, but overall it worked well. The confirmation of our testing proves that our design is viable. Our final design needs additional improvement but demonstrates that with the appropriate software and testing, eye diseases can be simulated to a high degree.

Discussion

We are pleased with how our eye disease simulator turned out, but with any project, there are some things we would have done differently and things that can be improved upon. In this section, we will first critique our project and then enumerate possible future improvements.

Design Critique

There are many strengths to our final product. The main strength of our design is that it definitely meets all our engineering specifications. This is a huge positive because it shows we can translate user requirements into a final product. The simulations have also been verified as realistic. Additionally, our app caused many users to have ah-ha moments at the design fair. When we showed people Bill's vision and asked them to close their left eye (the good eye), they were shocked by how severely diminished his right eye's vision is. Many children even asked Bill incredulously, "Is this what you see?" This is a positive because it allowed a patient (Bill) to be understood like he never has before.

Our design of course is not perfect and there are some obvious weaknesses. First, the simulator can only simulate vision loss. This makes our design less useful for a lot of patients. Also, the drawing mechanic for the simulator is not perfect. For instance, when users are drawing transparent lines and the lines overlap, the overlap area will be less transparent than either line. This makes drawing smooth, accurate simulations difficult. Another major weakness is scaling the drawings to fully occupy an eye. Using Vuforia, it is next to impossible to determine at runtime the dimensions of the viewport for each eye. This forced us to hack in a manual scaling number to make the simulations scale properly. Related to the scaling issue, our device isn't perfectly compatible with different phones. If we used a different phone, the drawings wouldn't scale properly if the screen sizes were sufficiently different. This would require users to calibrate simulations to their phone. The last key weakness is that the field of view for mobile AR is not extremely wide. While it does meet our engineering specification for realistic, it could be much wider.

Recommendations

We have a number of recommendations for anyone working on this product in the future. First, we recommend not using Unity and instead developing the app in Java (if you're building for Android). We cannot recommend continued use of Unity because it contributes to a lot of our design's weaknesses. Unity does not have a built in method for drawing, and the components we used to add the ability to draw cause the overlapping issue. Vuforia, Unity's AR system, does not give the developer much control over the image being displayed to the user. This limits developers to only simulating vision loss and the simulator should definitely simulate different visual defects like swirling for wet AMD. Vuforia also does not provide a method for determining the viewport sizes which makes it impossible to automatically scale simulations properly. The eye disease simulator could also be improved by adding easier ways to input the Humphrey's test results, such as scanning the results. To address the field of view of the simulation, we would recommend exploring other headset options. As time passes, better headsets will become available, but as of now we would recommend using Google Tango, Google's mobile AR platform. Google Tango is different from normal mobile AR because the platform requires multiple cameras. This increases the field of view to 180 degrees[Feist, 43]. A critical suggestion we would make is to refocus the scope of this project solely on increasing patient adherence to prescriptions by increasing patient's understanding of their own disease. This is a big enough problem on its own. Roughly 50% of patients with a chronic disease do not adhere to their treatment plans and roughly 15% of healthcare costs are attributed to patient non-adherence[Brown, 44;Egan, 45]. Including increasing others' understanding of the patient, competes with increasing patient adherence. For example, if we focused solely on increasing patient adherence, we likely would not have developed a plain mobile AR simulator since cost would be less important. The last suggestion we would make is actually study the effects of the eye disease simulator. This should be what the next group works towards no matter what. A study could validate our hypothesis that patient adherence will increase when doctor's show them their disease progression in the eye disease simulator. If the hypothesis is disproven, then at least we would know the eye disease simulator is not the solution to this problem.

Summary

Our eye disease simulator meets all of our engineering specifications but there is a lot of room for improvement. Namely, our eye disease simulator is not as realistic or user friendly as it could be. To improve user friendliness, we recommend the next iteration of the application be built without Unity. Also, user friendliness could be improved by allowing more Humphrey's test input methods like scanning. To improve realism, we recommend using a platform other than mobile AR. We suggest Google Tango but encourage research on other headsets, since new ones are always coming out. Another important issue is that our eye disease simulator cannot simulate diseases that are not characterised by simple vision loss. Adding a swirling effect for wet AMD or simulating cataracts could be more easily accomplished if the simulator was not built with Unity since the AR system does not give us much control over the simulated sight.

There are also two important big picture issues and corresponding recommendations. First, this eye disease simulator's scope is too large. We tried to solve two problems: making it easier for patients to explain to others how their disease affects their vision and also increasing patient adherence by increasing their understanding of their own disease. These are two separate problems and their solutions do not perfectly overlap. We recommend that future eye disease simulators only be built to increase patient adherence since it could have a larger impact. With that being said, we don't know if our simulator actually increases patient adherence. This must be formally studied to justify building a complete simulator.

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Appendix

Appendix A - Bill of Materials

Our device was designed with the idea that the patients and doctors could use their own smartphones. Under this assumption the only thing the user has to buy is a headset to use. This allows the user to control the price and comfort level of the device. Our software would be accessible from the android store. The software we used for development, Unity and Vuforia, were free downloads.

Table A-1. The bill of materials

Item	Quantity	Source	Addtional Cost
Phone	1	Team	N/A
Headset	1	Knox	$8.00
Unity	1	Unity	$0.00
Vuforia	1	Vuforia	$0.00
Clear lens glasses	2	Ragstock	$9.98
Helper grid	1	Google search	$0.00
Black Expo Markers	2	Walgreens	$2.99

*An android smartphone was provided by Jeremy Drouillard

Appendix B - Relevant Patents & IP Assignment

The patent WO 2015198023 A1: Ocular simulation tool is invented by Luke Anderson, and is published on Dec 30, 2015[Anderson, 3]. This patent is owned by Swansea Medical Apps Limited. The abstract of this patent is: The invention provides a medical training system comprising software arranged to reconfigure a virtual face or portion thereof in response to a user's movement in free space and in accordance with one or more symptoms relating to a predetermined ocular condition. The system further comprises motion sensing means arranged to detect the user's movement made in free space. Therefore, the user's gestures can be used to input commands via a hands-free input interface. The invention simulates one or more ocular conditions which are displayed on a screen. The user e.g. medical student is able to interact with the system via a variety of input means including movement in free space so as to produce a response on the virtual patient's face, the response being symptomatic of one or more ocular conditions. For example, the eyes may track the user's finger in a particular manner. The invention also provides a simulation tool for training users in respect of a corrective procedure, such as laser surgery.

The key claims that we think are most relevant to our project are:

- Software arranged to reconfigure a virtual face or portion thereof in response to a user's movement in free space and in accordance with one or more symptoms relating to a predetermined ocular condition;

- A display device for displaying the virtual face or portion thereof;
- Being able to determine whether the user has correctly diagnosed the ocular condition by comparing the user's inputted diagnosis with a stored record of the predetermined ocular condition;
- Enabling the user to simulate performance of a corrective procedure.

The first claim is important since we will also generate a software that can simulate the eye diseases, and we also planned to simulate more than one symptoms. The second claim stands out because of the display device for displaying, because we also have a display device (the screen of a smart phone and the headset). The third one is related to one of the challenges that we wanted to solve -- confirmation of simulation, because it is important to enable our simulator to check whether the simulated visual field is similar, or the same as what the patients are actually seeing. The last claim is also crucial, since we can try to add the corrective methods in our simulator to make it more versatile.

Our eye disease simulator expands upon this learning tool by teaching the patient how their vision may change over time. We simulate more specific visual fields based on the user inputs, to make our device more customizable. The uniqueness of each simulation can give the users better understanding on the visual field of a specific patient. The eye disease simulator can be marketed to the public, and can provide a bridge between the doctors and the patients by helping to understand the effects of both the eye disease and eye disease treatment, while the Ocular Simulation is only an educational tool for medical students.

The patent US5737056A: Method for simulation of visual disabilities is invented by Neil F. Martin, Terese W. Robinson, and Howard N. Robinson [Martin, 18]. It is published on Apr 07, 1998, and its owner is Maryland Patent Holdings LLC. The abstract of this patent is: “The disclosed invention is directed to lenses to be worn with eyeglasses. The light transmission or field of vision of the lenses has been so modified as to produce visual distortions simulating various eye conditions and particularly simulated possible postoperative visual distortions and anomalies. Various modifications to conventional eyeglasses are disclosed.”

The key claim that is mostly related to our eye disease simulator is: A method for obtaining informed consent from a patient prior to ophthalmologic surgery comprising fitting over eyeglasses worn by said patient a lens or lenses whose field of vision has been modified to simulate a visual anomaly which may occur as a result of said surgery and then obtaining informed consent from said patient.

This claim shows that this patent is aimed at providing the patients with the postoperative visual distortion simulation to build the informed consent from them prior to surgery, which is the same with one of the functions of our project, because we also want to use this simulator to let the patients know what their visual field would be if they did not follow the doctor’s advice and did not receive proper treatments.

Our device uses a different method to achieve the eye disease simulation. it simulates the visual fields by applying different filters after the camera, while this patent uses several different contact lenses to modify the light transmission in order to generate visual distortion. Therefore, it is more convenient to use, and the quality of visual fields it generates can be improved significantly, because they are more realistic and specific.

Appendix C - Safety Report

Our application can be used by a variety of android smartphones and AR headsets. Safety requirements and regulations should be followed according to the devices used. Use only in a safe environment.

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