An Evaluation of the Impact of Macular Degeneration on Hazard Perception using Virtual Reality

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Declaration

I, Samuel Withers, declare that I am the sole author of this project; that all references cited have been consulted; that I have conducted all work of which this is a record, and that the finished work lies within the prescribed word limits.

This work has not previously been accepted as part of any other degree submission.

Signed Samuel Withers Date 31/01/2020

Form of Consent

I, Samuel Withers, hereby consent that my project, submitted in candidature for the MSc Software Engineering degree, if successful, may be made available for inter-library loan or photocopying (subject to the law of copyright), and that the title and abstract may be made available to outside organisations.

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Abstract

A virtual reality environment was created to simulate reacting to road hazards. Participants were instructed to react to hazards appearing in the environment as quickly as possible. These times were recorded, and the experiment repeated with a filter simulating macular degeneration turned on. The results were then compared to see whether macular degeneration has any impact on driving ability.

There was not enough statistically significant evidence to prove that this macular degeneration simulation influenced participants driving ability. The validity of this approach was discussed and found to have possible future application for determining the effect various eyesight conditions can have on driving ability in a safe environment.

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1 Introduction

1.1 Virtual Reality

Virtual reality (VR) is not a recent invention, in fact, there have been consumer versions of virtual reality headsets around since the Nintendo Virtual Boy back in 1995 [1]. However, in the last few years there has been a surge in the development of VR headsets and the technology has become more prevalent and affordable than ever. This is due to some of the limiting factors of VR being overcome. The main limiting factors in the past have been display resolution, refresh rate and tracking accuracy. VR is now at a stage where at the highest end we can have displays with high enough resolution that individual pixels cannot be seen, coupled with 120Hz refresh rate displays with tracking accuracy that can track a user's individual finger movements. Improvements like these have allowed VR to begin entering the mainstream markets which in turn means increasing numbers of software products being produced purely for VR.

The primary benefit of VR is that it can truly immerse a user in a different world to ours, whether that be a simulation of our world, or a fantasy world, the user can feel as though they are a part of it. This is useful as it means users can be placed in completely believable and immersive situations that otherwise would not be possible. This has many applications, one of which is allowing VR to be used for training people in situations that would normally be too dangerous for training to take place in them. For example, training store managers of what to do in a robbery situation [2] or training works how to operate dangerous machinery [3]

This makes VR a perfect candidate to conduct tests related to driving without having to put drivers on the road. VR can potentially be used to measure the effect that eyesight conditions will have on a person's driving ability. The benefit here is that it can be done in a true to life, immersive way, without endangering any road users.

1.2 Macular Degeneration

There are many people who are visually impaired yet undiagnosed [4], as many visual impairments develop gradually over time, meaning people will not go to an optician to get their eyesight checked as they have not noticed any perceivable deterioration in their eyesight. According to the National Eye Institute, in the USA in 2010, nearly 37 million adults have some form of vision impairment [5]. A significant percentage of these adults are likely undiagnosed.

Adults with undiagnosed eyesight conditions are likely to still hold a valid driving license, as most eyesight conditions develop later in life, likely after the person has secured their driving license. This means there are likely many drivers on the road with undiagnosed eyesight conditions [6]. These conditions may not be severe and may have no impact on their driving ability, however, in some cases there may be a significant impact on their driving ability, and they won't realise this until it's too late.

Macular Degeneration is a prime example of this, as it is a condition that typically develops later in life, and normally develops slowly. As it causes blurring of the central vision, it could easily have a significant impact on reaction times to stimuli in the centre of vision, therefore having an effect on driving ability [7].

If it were possible to determine the impact Macular Degeneration has on driving ability, then it would mean that it's possible to determine at which stage it becomes unsafe to drive with the condition. Also, modelling the condition allows drivers with perfect eyesight to better understand what other road users might be seeing and therefore be better informed to make better decisions whilst driving. One of the main constraints of VR currently is the field of view (FOV) being lower than that of the standard human vision. This makes MD a perfect starting point for investigating eyesight conditions with VR, as it affects the centre of the vision, simulating MD is not limited by the potential limitation of VR's FOV.

1.3 The Project

This project was designed as an investigation of the effect that eyesight conditions, specifically macular degeneration, can have on driving ability. This was to be done using a virtual reality environment to determine the effects MD may have without endangering any road users.

Determining the effect that eyesight conditions can have on driving is useful as it allows us to make better informed recommendations on who should and should not be allowed to obtain a driving license. This in turn allows the roads to be a safer place overall hopefully reducing the number of accidents cause by eyesight conditions affecting driving ability. A further benefit to this research is the potential to get a simulation of a relatively unknown eyesight condition into the hands of people who may have had no idea what it was. This raises awareness for the condition which is especially useful for macular degeneration as there are a number of people who have the condition but are undiagnosed.

1.4 The Hypothesis

The null hypothesis for this project is as follows;

Null: If a person's reaction time to hazards is measured twice, once with their vision unobstructed and again with their vision obstructed by a filter simulating macular degeneration, there will be no difference in the measured reaction times.

Therefore, the alternative hypothesis is as follows;

Alternative: If a person's reaction time to hazards is measured with their vision unobstructed and measured again with their vision obstructed by a filter simulating macular degeneration, their reaction time with be faster when their vision is unobstructed.

This set of hypotheses should allow us to gain insight into how significant macular degeneration is on driving ability in terms of reacting to hazards on the road.

2 Project Planning

In this section, the resources that were required for the project are listed and how they were used outlined. A Gantt chart was used for project planning and management, showing the proposed timescales for each of the tasks that was required to complete the project.

2.1 Resources Required

The following resources were required for the successful completion of the project.

- Oculus Rift CV1 headset – used for showing the virtual reality environment during the experiment.
- PC – used to create and power the virtual reality environment.
- Participants – needed to participate in the experiment.
- Unity game engine – used on the PC to create the virtual reality environment
- Books and papers on the subject area – to further research both Macular Degeneration and Virtual Reality

2.2 Gantt Chart

The Gantt chart was a very useful tool for planning on a high level all the tasks that needed to be undertaken and estimating the time frame for each task. This allowed a high-level planning strategy to ensure the project was completed within the given time limit.

The tasks were split into four main groups representing the main sections of work that were undertaken and an estimated time frame for each task was shown. The resources

needed, planning and difficulty of each task were considered when estimating the time needed for each task. The original Gantt chart for the project is shown below.

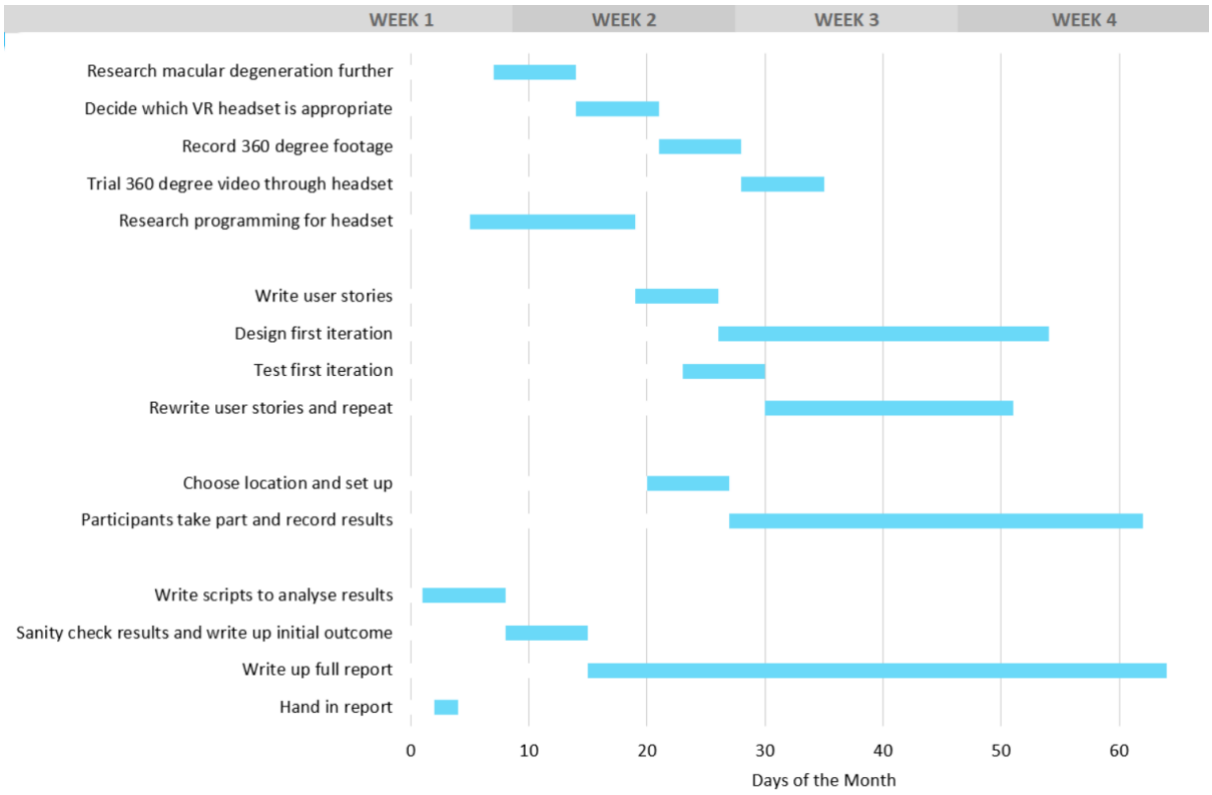


Figure 1: Gantt chart for the project

Some parts of the Gantt chart needed to be modified to reflect a deadline change and a change to the way the experiment would be conducted.

The list of tasks for the project was as follows

- Research Macular Degeneration further.
- Research VR headsets and choose the appropriate one for the project.
- Learn how to use Unity C#.
- Write user stories for development.
- Research literature around the topic and write a literature review.
- Design virtual reality environment for experiment.
- Choose location and participants for experiment.
- Perform experiment.
- Iterate and improve VR environment and experiment set up as needed.
- Perform second, improved experiment.
- Perform statistical analysis on results obtained.
- Write up findings from results.
- Write up full report.

3 Research Methodology

In this section, the research methodology that has been followed is outlined and the philosophy, strategy and approaches behind the methodology discussed. The risks and limitations of the research will be discussed and steps that have be taken to prevent them presented. Finally, we will consider how the data was evaluated, collected and analysed through the research to determine whether the aim and objectives were achieved.

3.1 Philosophy

The first step was to decide on a research philosophy to follow. A research philosophy is important as it outlines a way in which data should be collected and analysed. The two major philosophies are positivist and interpretivist. As this research project attempted to quantify driving ability and compare results quantitively with others, the philosophy used will be positivism. Positivism is highly structured and is a system stating that research is based on information derived from sensory experience which can produce quantifiable data. This is a perfect fit for the experiment performed as the virtual reality experience produced a sensory experience that produced quantifiable results. If necessary, the quantifiable data could have been supplemented with qualitative data, however, conclusions could not be drawn from the qualitative data alone.

3.2 Approach

The next step after choosing an appropriate research philosophy was to identify an appropriate research approach. The two to choose from were inductive and deductive.

The deductive approach is typically paired with the positivism philosophy as it generally involves developing a hypothesis and then designing a research strategy to test that quantitative way. The inductive approach is typically paired with the interpretivist philosophy as it involves searching for patterns in the observations made during research. This means not starting out with a hypothesis to investigate and searching for patterns and meaning in the data during the process. This approach typically required a large time investment so is suitable for research where time constraints are not a large factor. As this research had a well-defined hypothesis to investigate and will be followed the positivism research philosophy, the approach chosen was deductive. We knew the exact amount of time allocated to perform the research project and deductive research allowed us to plan accordingly. The deductive approach is typically low risk as a hypothesis will generally be proven or disproven with very little room for middle ground, meaning the research was almost guaranteed an outcome in the defined time frame.

3.3 Strategy

Research strategies are important as they tell us how we are going to conduct our research and therefore how we are going to collect data. Here the strategies used during the project are outlined and discussed.

3.3.1 Experiment

The first strategy used was an experiment. This is because an experiment could be designed so that is investigated a single hypothesis with the goal of providing an answer with the results collected. The experiment was performed once (the pilot) and then refined and performed again for optimum results. The experiment designed allowed us to quantitatively say whether we can determine the impact macular degeneration has on driving ability.

3.3.2 Quantitative Research Strategy

The experiment outlined above was used to collect data. The data was statistically analysed to determine results and draw conclusions. In quantitative research, the researcher can change variables for the desired outcome

3.3.3 Software Development

Software development was a significant part of the project as a virtual reality environment needed to be created to perform the experiment. Systems to spawn objects and record reaction times also needed to be developed. Software development helped eliminate as much human error as possible from the experiment. The predominant software development technique and methodology used was feature driven development. The methodologies and techniques used are discussed in section 5.

3.4 Risks and Limitations

There is always inherent risk and limitation in any research. Certain steps were taken to minimise the risks and overcome limitations with this project. In this section the risks and limitations that were present are detailed and the steps taken to reduce them outlined.

3.4.1 Human Error

As both the developer of the software for the experiment, and the participants of the experiment are all human, some human error will inevitably creep into the project. The biggest source of error would have been people trying to predict when hazards were going to appear as opposed to truly reacting to the hazards appearing. To minimise this, the experiment was designed to keep the time between objects spawning suitably random that it could not be predicted. This is discussed further in section 5.

Another source of human error will simply be participants causing the reaction timer to be triggered by something other than a true reaction. Be that a double press, or simply a mistaken press. To combat this the experiment was closely monitored for anomalous results, and these detailed and removed when necessary. The experiment was also performed as many times as possible with as many different participants as possible so that if any anomalous results were not picked up, there would be a large enough data set that they would not skew the results.

3.4.2 Time

The most obvious constraint with any project is often time, and that is no exception for this project. There was a strict time deadline on this project. Proper time management techniques were practiced such as using Gantt Charts to plan out timeboxes for each task. This allowed for effective time management as it allowed a sensible view of all tasks that needed to be completed and how long each of them should take. The Gantt Chart helped in noticing when a task was taking longer or shorter than expected and was useful in adjusting timings accordingly to reflect how much of the time should be put into each task.

The deadline for the project was extended part way through the project allowing for more time to complete each remaining task. The Gantt chart used was updated to reflect this change.

3.4.3 Technology

The project required learning new technologies, the main two being Unity game engine and C# programming language. This could have been a limitation as learning these technologies to the level needed for this project could have taken a significant amount of time. This was mitigated by beginning to learn the technologies before the project began, allowing fewer resources to be consumed at the beginning of the project. When the project was planned, an appropriate amount of time was allocated to learning the technologies needed, this time was not a significant proportion of the project time due to the learning performed prior to the project. The project was also created using feature driven development, where the minimum viable product (MVP) was created first and more

complex features then added afterwards. This was done so that if a lack of knowledge or ability became a blocker, there would still be a working, viable project albeit with a few features missing. The use of feature driven development is discussed further in section 5.

4 Background research / Literature review

4.1 The human eye

In this section, the human eye is described and literature in respect of the subject reviewed. Eyesight conditions are outlined and examined and the literature around them reviewed.

4.1.1 How it works

The human eye is an organ within the skull of the human body. It allows humans to see the world around them through the visible spectrum of light. Light passes through the cornea at the front of the eye and is then focused onto the retina [8]. The iris is the coloured area of the eye around the pupil. It controls the amount of light entering the eye by expanding and contracting the pupil to let more or less light in respectively [9]. After passing through the iris, the light passes through the crystalline lens, which is the lens that focuses the light received onto the back of the eye. The focal point of a healthy eye should be directly on the retina, which is located at the back of the eye [10]. There is a single layer of cells in the back of the retina that absorb the light hitting it to prevent the light being reflected and allowing the retina to collect information from all of the light entering the eye. An interesting result of the light being absorbed is that the pupil appears black [8]. The retina then converts the light received into electrical signals that travel up the optic nerve to the brain. These signals are then interpreted by the brain and represented by the image we see [8].

4.1.2 Lenses

A lens is a curved transparent material used to either focus or disperse light through means of refraction. There are two types of lenses, simple and compound. A simple lens consists of a single layer of material, modifying the wavefront of the light once as it passes through the lens. A compound lens consists of multiple simple lenses used to modify the wavefront of the light multiple times as it passes through.

The modification of a wavefront, where light is deflected upon passing through a medium as it passes through the lens is called refraction. This happens due to parts of the wavefront entering the medium and slowing down, whilst other parts of the wavefront continue at the same speed, causing the light to 'bend'. Refraction can be used to our advantage to focus light at a specific point.

The lens in the eye is a simple lens, used to focus the light entering onto the retina. However, the cornea also refracts light to allow it to pass through the pupil. Therefore, the lenses in the eye can be thought of as a compound lens [8].

In a camera, in order to focus on an object at a specific distance, the lens is moved forwards and backwards relative to the recording surface of the camera. However, the lens in the human eye is interesting in that it can be varied in thickness by the muscles surrounding it to achieve the same affect [8].

Due to the curvature of the lens at the front of the eye, the image projected onto the retina is actually inverted. The brain later converts the signal, so the image we actually see is the correct orientation [10] [9].

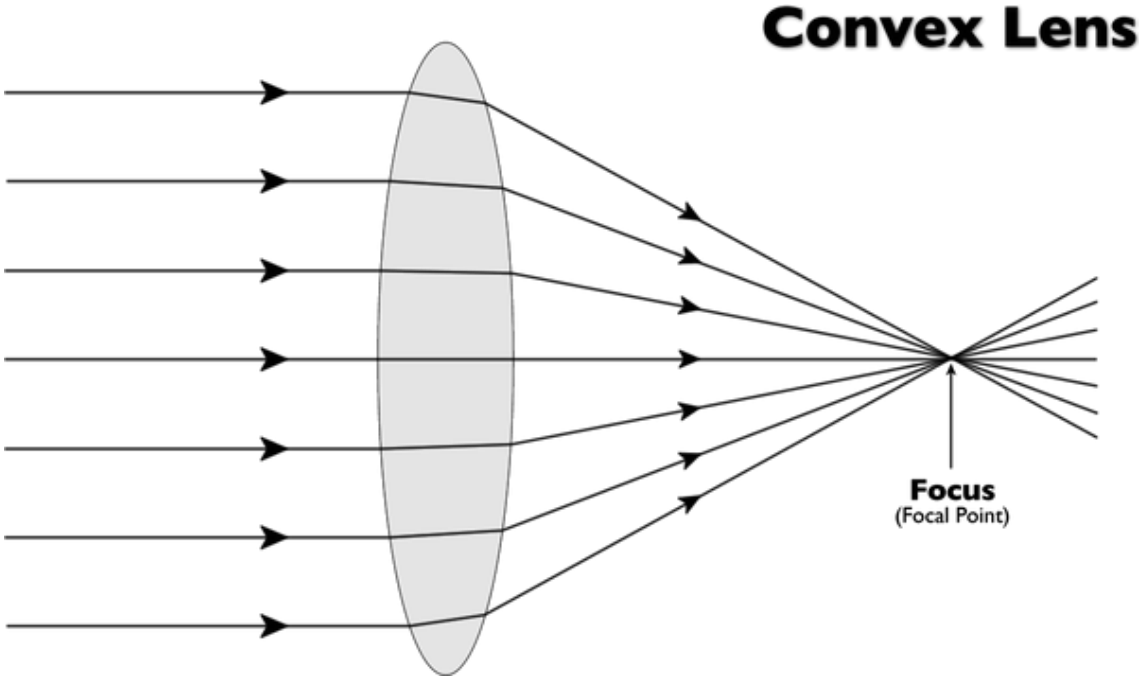
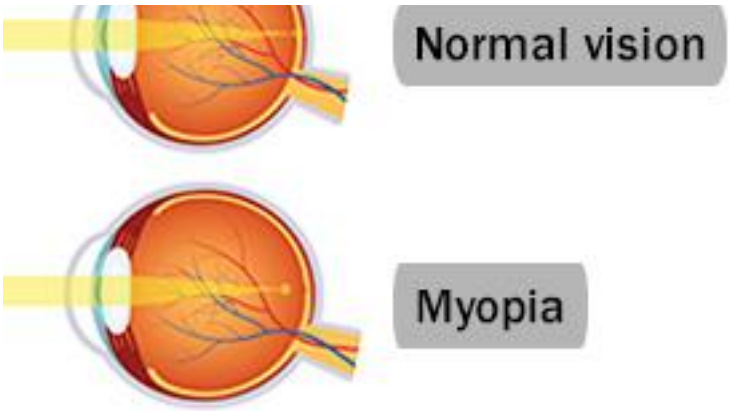


Figure 2: Light being refracted by a convex lens [36]

4.1.3 Shortsightedness (Myopia)

Short-sightedness, also known as Myopia, is a condition which causes objects near to a person to be in focus but objects far away to be blurry. This is caused by the lenses in the eye focusing the light in front of the retina instead of on it.

Figure 3: Light being focussed on the retina for normal vision vs in front of the retina for myopia



Approximately 1 in 3 people in the United Kingdom suffer with short-sightedness and it is becoming more common each year [11]. The treatment for short-sightedness is typically a provision of prescription lenses to compensate for the lenses in the eyes and to re-focus the light onto the retina. These will normally either be glasses or contact lenses.

Laser eye surgery is an alternative, less common treatment, due to its invasiveness. It is a relatively recent treatment that is becoming more popular, cheaper and safer. Laser eye surgery works by re-shaping the cornea (the lens at the front of the eye) so that, in combination with the crystalline lens, light is properly focused onto the retina. Laser eye

surgery is typically a permanent fix for short-sightedness; however, some patients may need further corrective surgery in future [12].

4.1.4 Macular Degeneration

Macular degeneration (MD), also known as age related macular degeneration (AMD), is a condition affecting eyesight which can result in impairment in the centre of vision. The condition is most common in people aged 60 or over. However, factors such as family history, genetics and smoking can play a role in the development of the condition [13]. The condition accounts for 8.7% of blindness worldwide and is the leading cause of serious vision loss amongst elderly individuals [14]. People with the condition can experience slight blurring or distortion in the centre of their vision at an early stage, with this progressing to vision loss in the central vision as the disease progresses.

The macula is a small part of the retina at the back of the eye. It is a small patch about 5mm across responsible for all of our central vision and a large part of colour vision. The macula has a higher concentration of photoreceptor cells than the rest of the retina, photoreceptors being cells that detect light and send electrical signals to the brain based on the light detected. As it is responsible for all central vision, macular degeneration causes blind spots in the centre of vision but not the extremities. In the UK alone macular degeneration affects over 600,000 people. 6.2 million are affected worldwide [15].

MD can cause everyday activities such as reading, recognising faces and driving to become difficult. MD is typically diagnosed by an optometrist performing an eye exam. The severity is categorised into early, intermediate and late types depending on the severity of the damage. The current approach to diagnose and determine the severity of MD is to have the subject look at an Amsler grid (a grid with dots in specific places on it, designed for identifying MD) and describe what they can see at certain points on the grid. Some lines appear wavy and black spots may be seen. The doctor conducting the test analyses the results and uses these to determine whether the subject has MD and the severity and type of the condition.

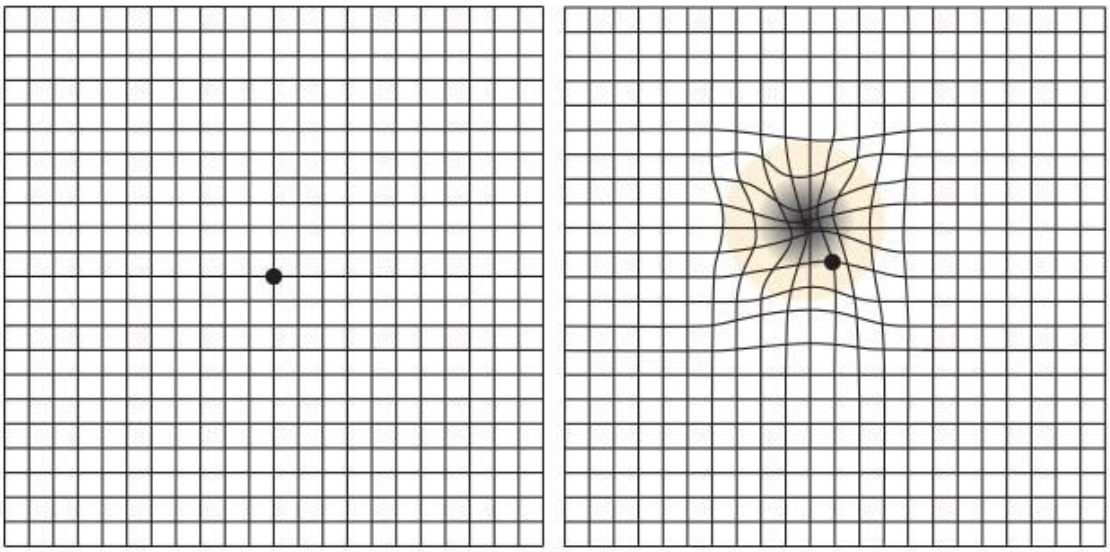


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Figure 4: Amsler grid as seen with perfect vision (left) and how it may look with an advanced stage of MD (right) [42]

4.1.5 Wet and Dry Macular Degeneration

Macular Degeneration typically manifests itself in one of two forms; “wet” or “dry”. Most cases, 85 to 90 percent of them in fact, are dry MD. Dry MD causes a more gradual degradation of eyesight as the blood vessels in the eye do not leak during its development; hence ‘dry’. There are few symptoms at the early stages of dry MD, with people noticing those symptoms later in the development of the condition, sometimes not until they have had the condition for years.

Wet MD, on the other hand, progresses slightly more quickly and is severe in its onset. Wet MD is caused by the blood vessels in the eye leaking below the macular, causing damage to the centre of the vision. This can cause permanent vision loss and eye damage. It is possible for dry MD to progress into wet MD.

4.1.6 Treatment for Macular Degeneration

At present, there is no cure for macular degeneration. However, there are treatments that may slow the disease and stop severe loss of vision. These treatments include anti-angiogenic drugs. Drugs that are injected into the eye to stop new blood vessels from forming and block the blood vessels from leaking, making dry macular degeneration less likely to progress into wet macular degeneration [16]. Laser eye surgery is another option for treatment. A laser is used to destroy abnormal blood vessels that are causing macular degeneration [16]. Another treatment is taking supplements containing vitamin C and E, zinc and copper as research has shown the risk of vision loss can be lowered with these supplements [14].

Cures for macular degeneration have been researched. A team of scientists has investigated the feasibility of transplanting retinal pigment epithelial cells gathered from stem cells into a patient with macular degeneration. However, the research was not conclusive as to whether this treatment was completely effective or not and more research is being done into this avenue [17]

4.2 Virtual Reality

4.2.1 What is VR?

Virtual Reality (VR) essentially means 'near-reality'. In terms of technology, VR is a specific type of reality emulation. VR technologies typically use a headset with video and audio to simulate a three-dimensional environment which can be moved through and interacted with. However, some go further and provide forms of haptic feedback to add to the immersion factor [18] [19].

The origin of the concept of a VR headset is often thought to be Stanley Weinbaum's 'Pygmalions Spectacles', a science fiction book from 1935. In the book, the main character wears a pair of goggles that transport him to a fictional world [20].

The first physical VR machine was introduced in 1962 and called 'Sensorama'. Sensorama was a device used to simulate a motorcycle ride through New York. It used a combination of colour display, fans, odour emitters, stereo sound and a motion chair to achieve this effect. Sensorama was introduced by Morton Heilig and is considered the earliest VR system. Nowadays it is thought that the machine was ahead of its time but at the time its advanced nature ultimately lead to its commercial failure [21]. Heilig details many potential uses for the machine in his patent application, including helping students train to fly a jet before stepping into one. Unfortunately, investors were not interested and Sensorama failed to secure enough investment for development to continue [22].

In recent years, VR technology has reduced in price enough that it is now a more wide-spread, consumer technology. Typical consumer uses of VR are for gaming and video consumption, whilst corporate uses range from education to medical. With

continuing advances in the technology and the use cases for it ever growing, the future of VR in the consumer and enterprise spaces looks bright.

4.2.2 How it works

There are many small variations in how headsets work. Therefore, for this section, the Oculus Rift and Samsung Gear VR headsets will be used as examples, as these two systems provide the best outline for the basis of the technology.

4.2.2.1 Oculus Rift

The Oculus Rift is a PC based VR headset that was released on March 28th, 2016 [23]. The headset features two displays, one per eye, with a resolution of 1080x1200 each. The Rift achieves stereoscopic 3D by feeding a slightly different image to each display, one for the left eye and one for the right and, resultantly, each eye sees the virtual world from a slightly different vantage point. Seeing these different images allows the brain to perceive depth in the images, meaning we feel as though things are further away or closer, making a stereoscopic 3D effect which is almost identical to that experienced in real life.

The Rift has sensors in the headset to track head movement, and also infra-red lights on the front and sides which are picked up by the external sensors. This allows the headset to be tracked in 3D space, allowing what is called six-degrees-of-freedom (6DoF) movement. This means that headset positional changes moving forward/backward, up/down and left/right, and orientation change through yaw, pitch and roll can be detected. The headset can, thus, be tracked in all three dimensions of movement and all three axis of rotation. This tracking means the movements the headset performs in the

real world are tracked perfectly and translated into the same movements in the virtual world.

The time from the movement being performed in the real world to being processed and the display signal for that movement sent to the headset screens, is less than 2ms. This ultra-low latency is what allows VR to work, as the latency is low enough that the human body doesn't detect it. If the latency is too high, this often causes motion sickness for the user due to a disconnect between what their body feels and what they see; almost the exact opposite of how seasickness works.

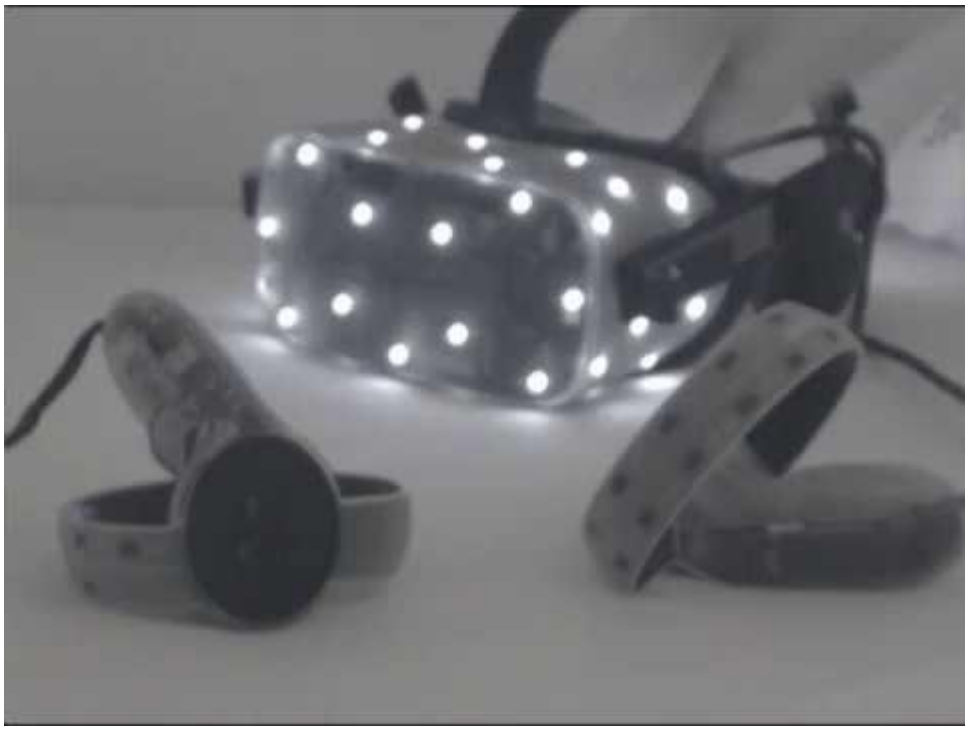

Figure 5: The Oculus Rift headset and controller under infra-red light, showing the infra-red LED's on both [39].

The controllers are tracked in a very similar way to the headset, with infra-red LED's being tracked in 3D space by the external sensors, allowing hand presence in the virtual

world. The buttons on the controller are placed in such a way grabbing object in virtual reality feels as natural as possible.

The Oculus Rift is powered by a PC and is connected using a USB 3.0 cable and an HDMI cable to allow for data transfer between the PC and the headset.

4.2.2.2 Samsung Gear VR

The Samsung Gear VR is a very different type of VR headset to the Oculus Rift. Instead of being powered by a PC, the Gear VR contains no screens and uses a mobile device as its screen instead. The headset consists of a strap to secure it to the head, a touchpad and buttons on the side of the headset, and a slot to place a mobile device into in the front. In between the mobile device and the user's eyes are a set of lenses, which are used to morph the image shown on the device screen into a VR image for your eyes to see.

The approximate field of view of the headset is 101 degrees (this changes marginally depending on the device that is used) and the refresh rate is 60Hz, as this is the refresh rate of all the devices that are compatible with the headset.

A special application must be installed on the mobile device to play Gear VR applications. This application is made by Oculus, the creators of the Oculus Rift headset, and acts as a launcher for all Gear VR applications. Once running the application, the device screen shows two images which morph into one 3D image when viewed through the headset lenses.

Figure 6: Gear VR content on the phone outside of the headset [40].

Some applications on Gear VR are simply made to be watched. Others can be controlled by the controls on the headset. There is a wireless controller that can be paired with Gear VR which is used for controlling more complex applications such as games.

Gear VR cannot provide the same 6DoF movement as the Oculus Rift; instead providing 3DoF movement. 3DoF is where the headset only tracks rotational motion, pitch, yaw and roll and cannot track your positional movement in 3D space.

The advantages of Gear VR are that is does not require any external sensors or a PC to power it, meaning it can be set up and started quickly. This has meant a large adoption of Gear VR for educational uses and even in places like theme parks, where it is used to 'VR enhance' rides. In Alton Towers, it is used in conjunction with a roller coaster called Galactica, where the VR experience in the headset starts at the same time as the ride moves, simulating a ride through space.

4.2.3 Types of headsets

There are two mainstream variations in VR headsets, tethered and un-tethered. Tethered headsets are typically the more powerful of the two as they connect to a PC via an HDMI/Display Port cable and are powered by the PC. However, they have the limitation of having to run a cable from the headset to the PC, restricting the user's movement, and possibly their immersion, due to the cable presence almost always being felt. However, there are certain set-ups that can mitigate this, as shown below.

Figure 7: HTC Vive headset using ceiling mounted cables to overcome the majority of the movement and immersion restrictions offered by tethered headsets

A large advantage of tethered headsets over un-tethered is that they allow for six-degrees-of-freedom, or 6dof, movement. This means that the users real world movements translate

into the VR scene. For example, if the user walks forwards in real space, they will walk forward in the VR space.

Examples of consumer tethered headsets are the HTC Vive, Oculus Rift and the Valve Index.

An un-tethered headset is usually powered by a mobile device inserted into the front of the headset running special software. The lenses in the headset focus the user's vision onto the phone screen. An un-tethered headset can offer the user the immersion of having no trailing cables and no restrictions on movement. However, the real-world movement can only be translated into three-degrees-of-freedom, or 3dof, in the virtual space, meaning the user cannot walk throughout the VR space without the use of an external controller for movement. Un-tethered headsets will use less demanding software applications than tethered headsets, due to being powered by a mobile device as opposed to a PC. Examples of un-tethered headsets are the Samsung Gear VR [24] and the Google Cardboard [25].

There is an outlier within the un-tethered headset bracket: The Oculus Quest. This is a headset that attempts to provide the full 6dof tethered headset experience without the need for a PC or any cables. The headset is powered by equipment contained within the headset itself, specifically a Snapdragon 835 mobile processor [26] [27]. The headset uses the inside-out tracking method to allow the headset to operate using 6dof movement and it lets the user to have hand presence within applications via controllers also tracked using the inside-out tracking [27] [26].

4.2.4 Applications of VR

Whilst VR is still a somewhat niche technology on the consumer side, it has been adopted for multiple uses on the corporate side of things. The applications of VR are far and wide, from gaming to medical training, and are still being explored as VR is a young industry.

4.2.4.1 Training

VR technologies have been adopted by multiple companies to be used as training tools; often to simulate a situation that would be too dangerous or too difficult to set up the correct circumstances for a real-life test.

In 2018, Verizon hired a company called Strivr to develop training scenarios depicting heist scenarios in their stores in VR. There are dozens of robberies at gunpoint each year in Verizon stores, so the company wanted an immersive experience to train store managers how to behave in such a situation, in a way that was easily accessible to many stores across the USA [19]. Lou Tedrick, the Vice President of Verizon's global learning division, said "We thought VR would be a good use case because it would help the muscle memory of what it had felt like to be robbed. You want to be able to feel it in a safe environment and be able to talk about it". Since late 2018, around 1500 Verizon managers have used the VR training experience created by Strivr and Verizon are planning on having a VR trained manager present in every one of their stores across the USA [19].

Another use case was explored by a group of computer scientists and electrical engineers in the University of Sibiu in early 2019. They conducted an experiment to investigate whether VR could be used to augment the training cycle of employees, instead

of replacing it [28]. The experiment involved two groups of 10 participants attempting to build a multi-layered Lego car. This is a similar training exercise to ones used to train engineers on a production line. The first group was given 5 attempts to build the car, with feedback being given by other users between the attempts. The second group interacted first with a VR training system, simulating the building of the Lego car, before moving on to the real-world scenario. An AI algorithm was responsible for feedback during the VR training phase, giving hints to those who make mistakes and helping them build the car faster [28].

Of the first group, only 6 managed to build the car in under a minute (after 5 attempts) with a fastest time of 49.3 seconds. Of the second group however, 8 people managed to build the car in under a minute after 7 attempts in VR and 5 attempts in the real-life situation. The fastest time from the second group was 42.1 seconds [28].

They drew the conclusion that the VR environment allows a gradual training process to prepare participants for the main task. The VR stage required minimum human input once users were able to operate the VR by themselves, allowing for less human input overall. However, this research is not yet complete. The researchers have said that the initial experiment "showed promising results" however "the research will continue with the plan to extend the current training scenarios" exploring augmented reality, identifying a medical use case, and performing another testing session with far more participants (100+) [28].

4.2.4.2 Entertainment

VR, currently, is most widely known and used for entertainment purposes, with video games and television/movies making up the main form of media consumed on VR devices. Games such a Beat Saber, a rhythm game in which the player slices blocks with lightsabers, have broken into mainstream media with millions of sales and views on platforms such as YouTube.

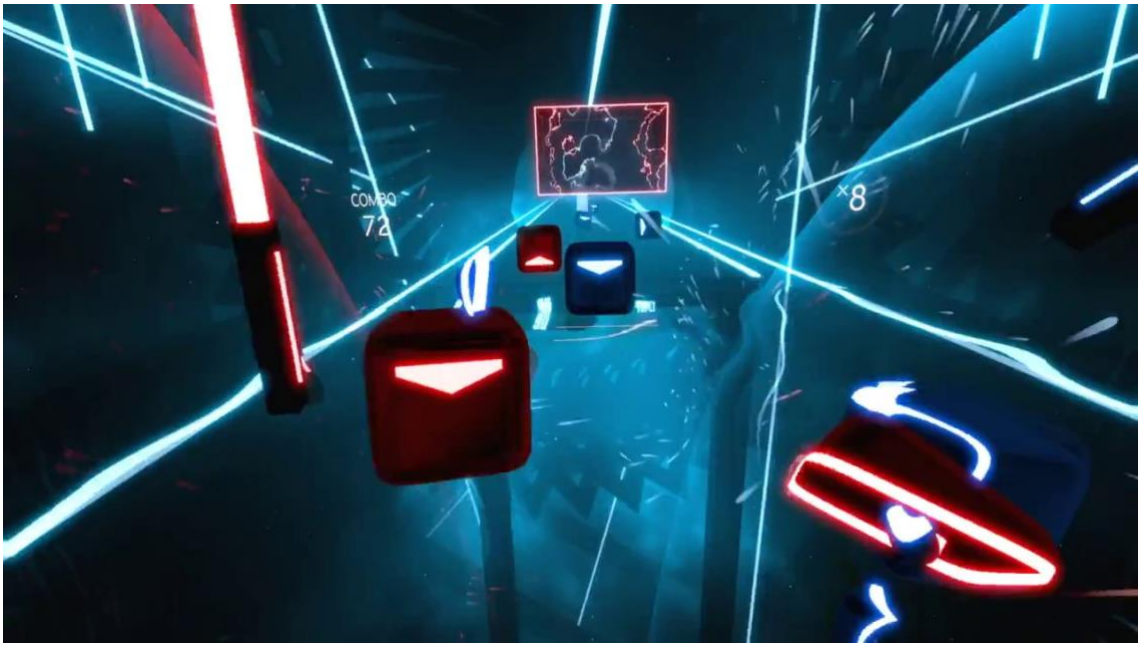

Figure 8: Beat Saber VR game

4.2.4.3 Education

The finding of information has been revolutionised in the internet age we now live in. Search engines make it easier and quicker than ever to find information on almost any topic, and books are being digitalised so they can be more widely distributed. However, the internet has not yet really revolutionised the way in which we learn. Learning is still typically done by information comprehension and fact retention.

Virtual reality can be used to change the way that education content is delivered, allowing people to experience content as opposed to simply reading, seeing or hearing it. VR can give a person a better sense of place, making them truly feel as though they are in a new world. A science lab can be scaled down into an experience on a VR headset; this can put a person in a situation where they can try experiments in a lab without any fear of the real-world impact of it going wrong. Doctors can learn the basics behind surgeries with the hand presence that VR can provide, without any expensive equipment needed and without any fear of the real world impacts of it going wrong. Both cases would necessarily be supplemented by real life training further down the line.

In 2017, a study was conducted on breast cancer patients undergoing radiation therapy to see whether virtual reality could be used to increase knowledge of the treatment and create a more positive experience for the patients. There was a control group who underwent the standard pre-radiotherapy education and a VERT (Virtual Environment for Radiotherapy Training) group who underwent a VERT-based session outlining the treatment they would be receiving and how it worked. It was found that the VERT groups scores on the knowledge of the radiation therapy were statistically significantly higher than those of the group who underwent the standard education; at all points throughout

the treatment; and that the anxiety levels of the VERT group were perhaps lower throughout (though more research is needed to confirm this point) [29].

4.3 Engines

In this section, the use and operation of game development engines will be outlined

4.3.1 What is a game engine?

A game engine is a piece of software that is designed to allow game creators to build games quickly and effectively. Essentially putting all the tools a game developer could need in one place, such as the ability to import art assets, assemble assets into a scene, add lighting/camera effects and add logic to game objects. In general, a game engine will include these main components:

- Main game program
- Rendering engine
- Audio engine
- Physics engine
- Artificial Intelligence

Some engines may have more components and others less, but these five components will normally be included in some way. An engine is a piece of software designed to help a developer create a game as quickly and easily as possible by providing as many of the functions the developer may need as easily as possible.

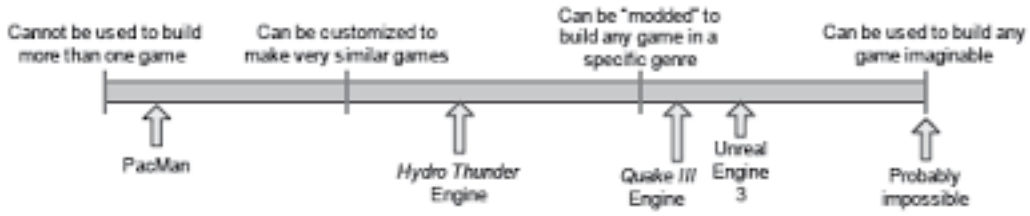

Figure 9: Game engine reusability gamut

The above image shows examples of what can be perceived as a game engine and what cannot. The defining criteria for what a game engine is seems to be software that can be used to create almost any type of game but may be better suited to a particular type eg. First person shooter, driving game etc. There is not a black and white definition of exactly what constitutes a game engine and what doesn't, however the above is a good way to define a game engine.

4.3.2 Unity

The Unity game engine was the engine chosen for this project. Unity was launched in 2005 and, to begin with, the engine was exclusively for Mac OS development. Since then, the engine has been extended to support over 25 platforms making it one of the most platform agnostic game engines. Unity is free for any person to use, which makes it a widely accessible engine. There is a paid version of Unity, however this is only required if annual turnover of the business using Unity is greater than $100,000 a year (and then a monthly fee is needed). However, for the use case of this project, Unity is an entirely free engine to use.

The engine offers the ability to create games, in both 2D and 3D, of any genre. Scripting for Unity is done with the C# language. Unity provides excellent virtual reality support, with built in support for every major VR headset and several minor ones. The Oculus Rift CV1 is supported natively by Unity, with an API that includes controller tracking and hand presence as well as headset tracking and world scaling. When VR is enabled in Unity, the standard main camera is overridden with a camera that tracks the movement of the headset. The Oculus Rift headset supports the Unity editor mode, meaning the edits to the environment can be checked out directly within the headset itself, saving large amounts of time on play testing.

5 Development

In this section the development process followed during the software development stage of the project will be outline. The technology and design decisions that were made discussed and justified.

5.1 Feature Driven Development

The project was designed using feature driven development (FDD). Feature driven development is an iterative and incremental agile approach to software development. FDD involves five different steps, these are:

- Develop overall model
- Build feature list
- Plan by feature
- Design by feature
- Build by feature

During this project a further step was added which was to work out the minimum viable product (MVP) that was needed for the project to be successful. The features needed for the MVP were then prioritised over others so if there was a blocker to software development later in the process the project would still be a success.

5.2 Design of Environment

The environment was designed to be plain with a simple colour palette to ensure no distractions from the experiment whilst it was being performed. The car model used was the “sports vehicle black” model from the “Marcos Shults Sports Car” pack [30]. This was used because it had a spacious environment inside the model to put the camera in so the participant would be placed in the car in virtual reality, and because it had collision built in on the wheels, saving time during the development process. It was also chosen due to the large size of the windscreen, allowing no obscuring of the participants view during the experiment.

Figure 10: The car used for the experiment viewed from the outside

The car was placed a long road created from prefabricated objects from the City Voxel Pack [31]. This pack was chosen because of its simple, clear design and because the shape

was simple to stitch together with multiple prefabricated objects (prefabs) to make larger prefabs of my own.

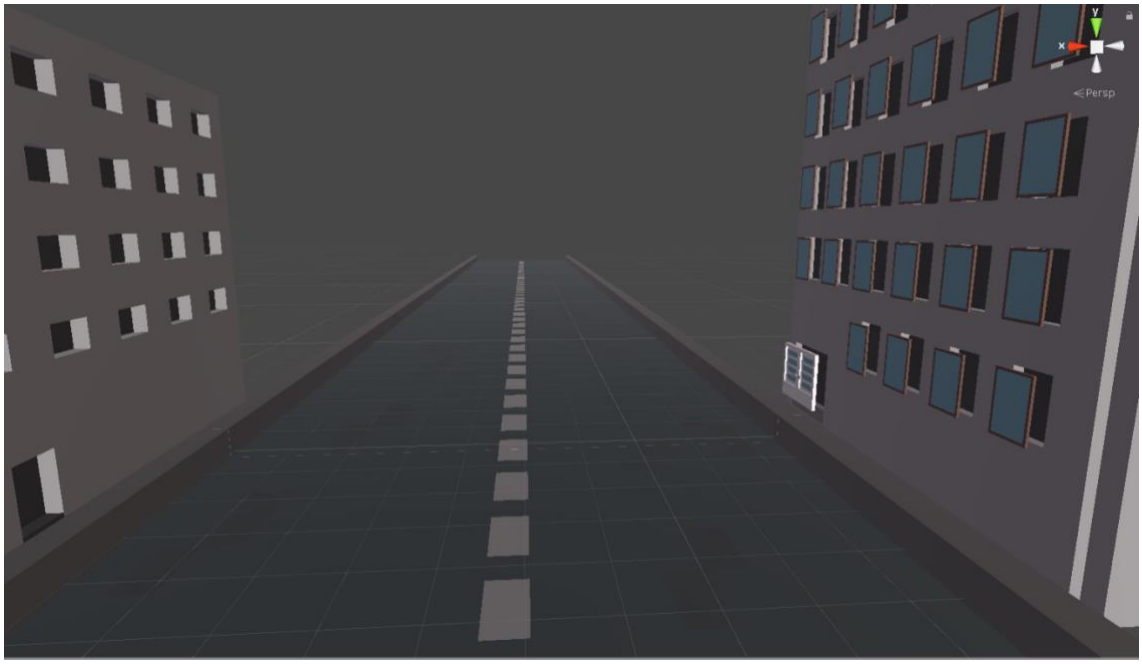

Figure 11: Part of the road the car was placed on in the environment

Buildings were placed either side of the road to add a sense of immersion and simply to make the environment looks less empty. The buildings used were also from the City Voxel Pack [31]

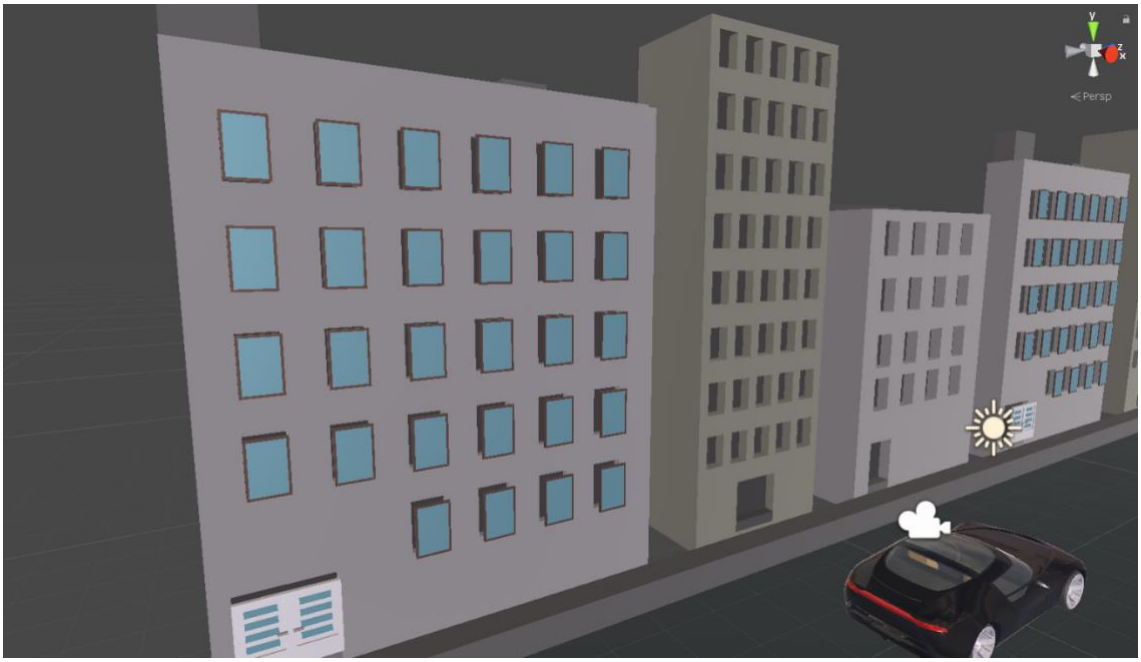

Figure 12: Some of the buildings used in the environment

A skybox was added to the environment again to add to the immersion but also to add realistic lighting and sun glare when the participant looked directly at the sun, therefore simulating a real environment much more closely than having flat lighting. A sunset skybox was used from the HDR skies pack [32] as it was high enough resolution to look photorealistic through the headset, again adding to the immersion of the scene.

The overall design was then a car on a straight road stretching out the horizon. The road was sandwiched between several buildings of varying shapes and heights and the whole scene takes place at dusk whilst the sun's setting.

5.3 Pilot Experiment Design

The pilot experiment was designed entirely with randomness in mind. The design was to have a hazard appear randomly in front of the car and for the participant to react to the hazard as quickly as they could once it appeared. The hazard chosen for the pilot experiment was a yellow coin approximately the height of the car in size. The hazard was set to spawn in a specified area in front of the car, an example of which is shown in the below image.

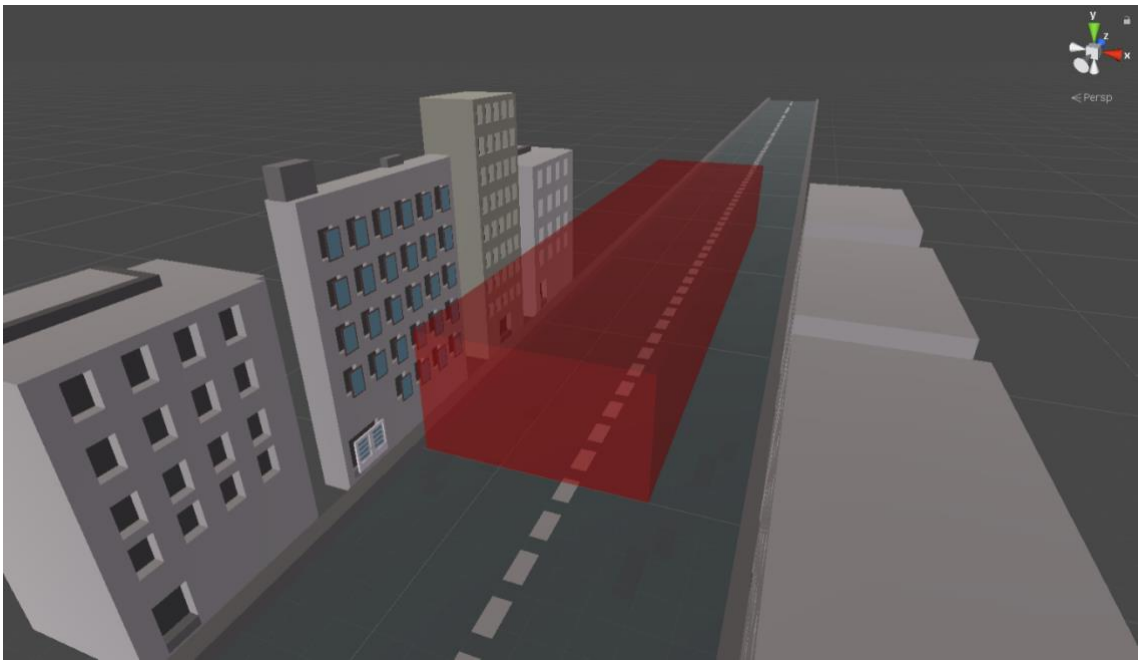

Figure 13: The area in which the pickup could spawn

The spawn time was set to be random between five and fifteen seconds after the previous hazard had disappeared, with the very first spawning randomly between five and fifteen seconds after starting the program. When a hazard spawned a timer would start that would be stopped by pressing the space bar on the keyboard. This was used to

measure participants reaction times to the hazards. The test was set to run for two minutes with the reaction time to each hazard appearing measured. The participant would react to however many hazards appeared during the two minutes and the average reaction time calculated afterwards.

5.4 Final Experiment Design

The pilot experiment was refined and improved upon for the final experiment. It was designed in a way to keep the test consistent amongst all participants but still random enough that the participants were truly reacting to the hazards appearing and were not able to predict them. 13 items were spawned in for each participant during each test and the spawn times for the hazards were fixed at times between 5 and 15 seconds. Two sets of spawn times and locations were made so that when the macular degeneration filter was applied the hazard spawn times and locations were still unpredictable.

5.5 Macular Degeneration Filter

The test was run twice for each participant, once where the vision of the participant was unobstructed, and once again where the participants vision was obstructed by a filter to simulate macular degeneration.

The filter was designed using a standard vignette filter, which is a filter that darkens the edges of a screen to cause the centre of an image to be the focus, or simply for artistic effect.

Figure 14: A standard vignette filter on a white screen [41]

This is the opposite of what is needed for a macular degeneration filter, so the pixel values of the vignette filter were simply reversed, causing a pitch-black dot in the centre of the image.

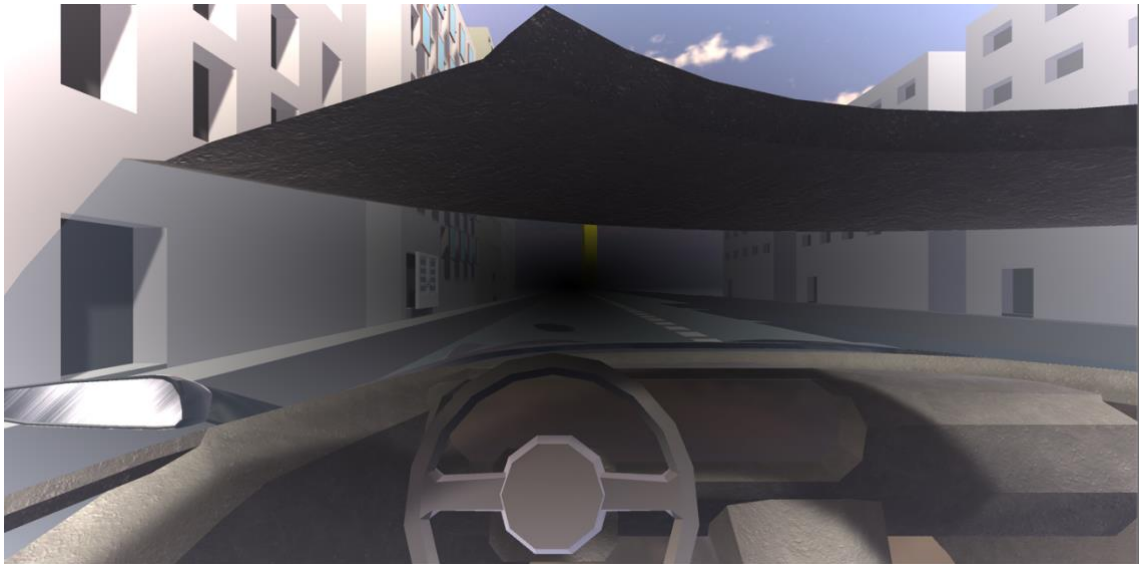

Figure 16: Macular degeneration filter used on the project (reverse vignette filter)

Figure 15: Test environment without any filter applied

It should be noted that this only simulated one very specific way in which macular degeneration might manifest itself in someone's eyesight.

The code used to produce this filter uses a modified version of a vignette filter script [33]

5.6 Reaction Timer

The reaction timer was designed using a C# script for Unity. The reaction timer was one of the few components that remained the same throughout the pilot and final experiment. The timer would start when the program started and would reset to zero every time and object spawned. Upon the space bar being pressed, the timer would output the current time to the console, therefore giving the reaction time.

5.7 Coin spawner

The coin spawner was designed using a C# script for Unity. Two vector3 variables were used to set the centre and size of the area in which the coins could spawn. These variables allowed a box to be place in 3D space, and the coins could only spawn within this area. The specific values of this were changed between the pilot and final experiment however the method to create the spawn box remained the same throughout.

The coin object was a prefabricated object taken from Unities built in 'standard assets' prefabs folder [34]. The prefabs that were to be spawned could be added to a list within the Unity editor, and the code would then randomly select a prefab from the list when an object was called to be spawned. As the coin was the only object in the list throughout, it

was the only object that was spawned, the code was designed this way with future development in mind.

During the pilot experiment, a spawn point within the confines of the spawn cube was randomly selected. Once the cube was spawned it would remain on screen for two seconds before the destroy method was called. During the final experiment, the spawn points were manually set within the code so that they would be the same for all participants.

The spawn timer is where the pilot and final experiment differed greatly. During the pilot, a time between 2 and 8 seconds was randomly assigned after the previous object de-spawned, the next object would spawn after that amount of time had elapsed. During the final experiment, the spawn timers were manually set within the code.

6 Experimental Methods

6.1 Method

The VR headset used for the experiment was the Oculus Rift CV1 (consumer version 1). This headset was chosen to its ease of use and compatibility with multiple different pieces of software, including the game engine used. The game engine used was Unity due to the ease of its VR integration and the ability to use C# as the language for scripting. The Oculus Rift headset was connected to a PC running the Unity software with the VR scene in Unity running on it.

Before each use, the headset and keyboard were cleaned with anti-bacterial wipes to ensure a hygienic set up for each participant, this is especially important for the headset as it sits near to each users' eyes.

The participant was then instructed on how to adjust the various straps on the headset to achieve the optimum fit, as a good fit is essential to clear image quality from the headset. They were given several minutes to adjust the headset and move themselves around in the virtual space until they were comfortable, in the right place in virtual reality and to once again check the fit of the headset.

The participant was instructed to press the space bar as soon as they saw an object appear on screen to allow the system to record their reaction time to the object. All objects were placed in such a way they would appear in front of the car in VR, so no objects would be missed due to looking in the incorrect direction, for example, looking out the windscreen when the object appears behind the car.

A demo approximately one minute in length was then played to the participant, allowing them time to get used to reacting to the hazards that appear on screen and preparing them for the actual test. The results from this demo period were not recorded.

The real test was the begun after informing the participant it would take approximately two minutes. The reaction time to each hazard was automatically recorded by the system throughout the two minutes. After the two minutes the macular degeneration filter was turned on and the experiment repeated. The reaction times from each half of the experiment were then transferred to an Excel spreadsheet for comparison and analysis.

During the pilot experiment the placement of the object and the time at which they would spawn in was generated randomly within a range of given parameters. However, for the second, improved experiment the spawn placement and times were fixed so the experiment was identical for each participant.

6.2 Results Analysis

6.2.1 Result calculations

The results of the experiment produced two distinct data sets that could be compared. One was the reaction times without the MD filter, and one was the results with the MD filter. Microsoft Excel was used as the analysis tool for the data sets as it allows quick and easy calculations on large data sets.

The average reaction time of each participants was first calculated, with and without the filter. The average reaction time was calculated using

$$\overline{x} = \frac{\sum x}{n} \tag{1}$$

Where $\sum x$ is the sum of all the reaction times and n is the number of reaction times. The difference between these two averages was then calculated by subtracting the average without the MD filter from the average with the MD filter. This was done to see if each participant was faster or slower with the MD filter activated and by what amount each participant was faster or slower. If the value was positive the average reaction time was faster without the MD filter, if the value was negative the average reaction time was faster with the MD filter. The standard deviation of each set of reaction times was calculated as well. Standard deviation was calculated using

$$\sigma = \sqrt{\frac{\sum(x - \overline{x})^2}{n}} \tag{2}$$

where σ is the standard deviation, x is a reaction time value, $\overline{x}$ is the average reaction time for that participant and n is again the number of reaction times. This was done to see whether the MD filter had any effect on how consistent each participants results were.

The average of the averages of each data set was also calculated, along with the standard deviation of those averages. This was done to see and overall value of whether the reaction time was quicker with or without the MD filter and to see how consistent the results of each data set were.

6.2.2 Hypothesis testing

An F-test was used on the data sets of the averages to determine whether the variances of the two sets were equal.

We then used a t-test to see whether there is a statistic difference in the two results obtained. This allows us to say whether the results are statistically significant or not. Due to the nature of the null hypothesis stating that there will be "no difference in the measured reaction times" we will be using the two-tailed test. A two-tailed test is designed to evaluate whether there is an increase or a decrease in sets of results. In this case, the two-tailed test cannot tell us if one result is statistically significantly higher or lower than another, but it can tell us if the results are statistically significantly different from one another. The test was performed at significance levels of $\alpha = 0.01$, $\alpha = 0.05$ and $\alpha = 0.10$ so we can seat what levels of significance we can reject the null hypothesis at.

7 Results

The experiment was conducted with 14 participants, meaning 28 sets of results. 14 without the macular degeneration filter and 14 with.

7.1 Non-statistical results

7.1.1 Averages

Each run of the experiment produced 12 reaction times, which were averaged out to a single time for each participant. The average of these averages was then calculated allowing us to obtain an average reaction time without the MD filter and an average time with the MD filter.

The average reaction time without the MD filter was found to be 374±11ms. The average time with the MD filter was found to be 402±11ms.

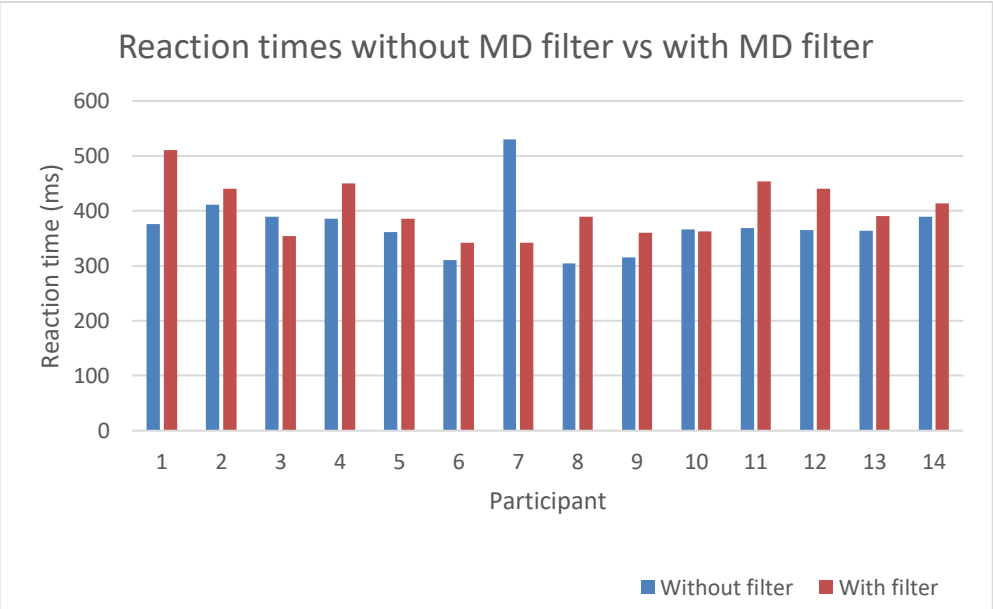

Figure 17: Graph of each participants average reaction times

7.1.2 Difference

For each participant it was calculated whether the reaction times were faster with the MD filter or without it. There were found to be 11 participants who were faster without the MD filter meaning there were 3 participants who were faster with the MD filter on. On average the times with the MD filter on were 28ms slower than those without the MD filter on.

7.1.3 Standard Deviation

The standard deviation tells us on average how far from the mean we can expect a result to deviate. The average standard deviation without the MD filter was 75±11ms and the average standard deviation with the MD filter was 64±11ms.

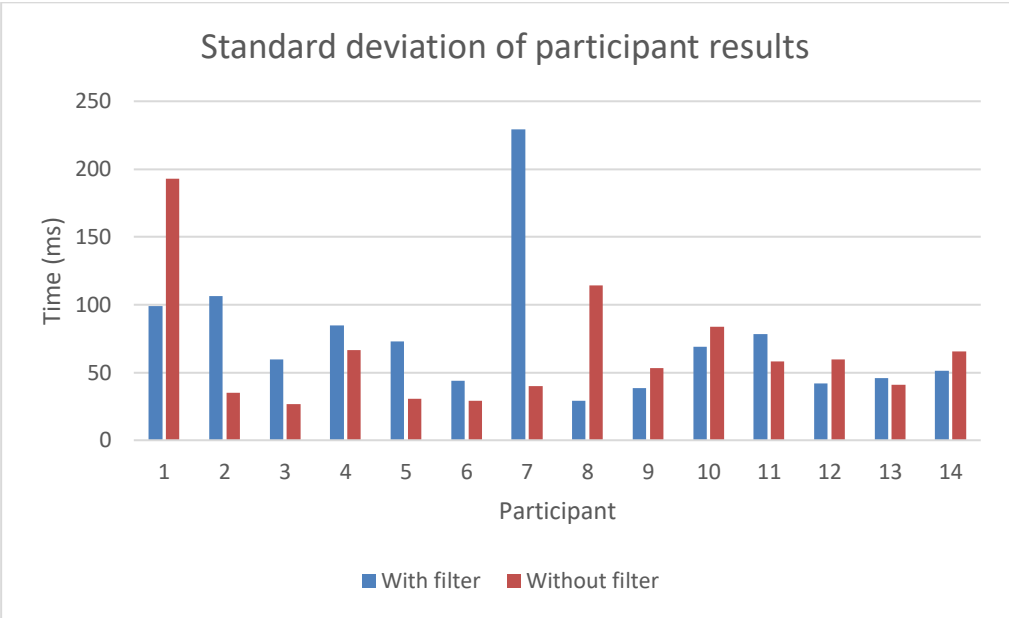

Figure 18: Standard deviation of each participants result set

7.2 Statistical Significance

7.2.1 F-Test

An F-Test was performed to see whether the variances of the two data sets are equal or unequal. The variance of the data set without the MD filter was 3030 and the variance of the data set with the MD filter was 2545. As these variances differ, we can perform the two-tailed t test assuming unequal variances.

7.2.2 T-test

A two tailed t-test was performed at the significance levels of $\alpha = 0.01$, $\alpha = 0.05$ and $\alpha = 0.10$.

At the significance level of $\alpha = 0.01$, t Stat = -1.42 and the critical t value is 2.78. At the significance level of $\alpha = 0.05$, t Stat = -1.42 and the critical t value is 2.06 and at $\alpha = 0.10$, t Stat = -1.42 and the critical t value is 1.71.

8 Discussion

8.1 Average, Standard deviation and difference

The average and standard deviation values we obtained from the data have not been analysed in such a way we can determine statistical significance from them. However, it is still worth discussing the results and what they may mean.

8.1.1 Mean

The average reaction time without the MD filter was found to be 374±11ms. The average time with the MD filter was found to be 402±11ms.

Even with the uncertainties there is still a difference, albeit small, between the two reaction times. The difference is 28ms. At a speed of 70mph (motorway speed limit), this amount of time translates to approximately a car length by the time an average vehicle has come to a stop. This is a very small amount over stopping distances from 70mph.

8.1.2 Standard deviation

The average standard deviation of the reaction times without the MD filter was found to be 75±11ms and with the MD filter it was found to be 64±11ms. This is interesting because the common thought is that when the vision is obstructed in some way the reaction times would be more spread out as opposed to closer together. The difference between the standard deviations is very small, 11ms to be exact, when uncertainties are taken into account these values overlap. This essentially means the average amount we can expect a result to deviate from the mean remains constant.

8.2 F and T test

The F test was performed on both sets of data, the data without the MD filter had a variance of 3030 and the data with the MD filter had a variance of 2545. This gives us an F value of 1.19 which means the variances are unequal.

The two tailed t test was then performed at three significance levels; $\alpha = 0.01$, $\alpha = 0.05$ and $\alpha = 0.10$. The t Stat value for all was -1.42. In order to be able to reject the null hypothesis this value must be less than the negative of the critical t value.

The t stat value in all cases is greater than the negative of the critical t value. The critical t values are 2.78 for $\alpha = 0.01$, 2.06 for $\alpha = 0.05$ and 1.71 for $\alpha = 0.10$.

This means that we do not reject the null hypothesis which states "If a person's reaction time to hazards is measured twice, once with their vision unobstructed and again with their vision obstructed by a filter simulating macular degeneration, there will be no difference in the measured reaction times." There is not enough statistically significant evidence against the null hypothesis in favour of the alternate hypothesis, therefore we cannot reject the null hypothesis.

8.3 Uncertainties

There was one uncertainty present throughout this project. Due to the refresh rate of the project in unity, the reaction timer would only update on a screen refresh. This means that due to the Oculus Rift CV1's refresh rate of 90Hz, the timer would only update every 11.1 milliseconds. This means that if a participant pressed the space bar (timer trigger key) 1ms after a frame refresh, then the timer would not stop until 10ms later. These are

very small amounts of time but do have a noticeable effect on the results. When this is considered for both sets of results (with and without the MD filter) this uncertainty can mean a result of 400ms and a result of 380ms could actually have been the space bar pressed at 391ms and 390ms respectively. This was considered when displaying the data and drawing conclusions from it.

9 Conclusions

9.1 Difference in reaction times

The reaction times of the two data sets do differ, but not in a statistically significant way. This means that we cannot conclusively say whether the macular degeneration filter had any difference on the reaction times of the participants involved. There are several plausible reasons for this outcome.

Chiefly, the environment the participant was placed in was static. This had several implications, the main one being that the participant was reacting instinctively to a change in the environment as opposed to reacting to a specific hazard. This is very different to driving in real life, where there are constant distractions such as other cars, buildings, pedestrians and the environment itself moving past. This means a driver must register a hazard as something different to the standard environment around them, leading to a very different type of reaction to a change in a static environment.

9.2 Validity of experiment

In conclusion, this experimental set up cannot statistically disprove the null hypothesis and therefore cannot conclusively tell us whether macular degeneration has an appreciable impact on driving ability. The average reaction times with the macular degeneration filter on were slower than those with the filter off, however the difference between them was very small, again likely due to the static design of the environment.

There is validity in the approach taken in this project, further research would be required with an improved virtual reality environment. The experiment could be modified

in future with a moving environment and varying filters to simulate multiple eyesight conditions.

With slightly different set ups this method could be used to simulate eyesight conditions such as myopia, cataracts etc. Virtual reality is the best technology to simulate these eyesight conditions to determine the impact they could have on driving ability in a safe environment. This project provides a basis for future work on simulating eyesight conditions in a safe environment.

10 Reflection

10.1 Future Work

This project has a vast scope for future work and applications. In this section, the potential improvements and different directions the project could take are outlined and discussed.

10.1.1 Software Improvements

10.1.1.1 Moving Environment

If this project were to be repeated in future, the single most effective change that could be made would be to create a moving environment. This would mean having the car move along the road (or the road move underneath the car) with the environment passing by to the sides. The hazards would then appear in the far distance (possibly appearing out of some fog).

This would be an excellent improvement as it would allow for the same distractions we can get whilst driving in real life. This includes things like looking at buildings or trees passing by. During the experiment in this project, the participant was likely reacting to a change in the static environment, rather than seeing the hazard and then confirming consciously that it is the hazard. This would make the experiment truer to life, likely producing more accurate results when compared to real life. Of course, this is simply speculation, it is not possible to confirm this without doing the experiment in real life also.

10.1.1.2 Control of the Car

A further improvement on top of the moving environment would be to have the participant control the movement of the car. This would be very difficult to implement as the triggers for the hazards would most likely not be consistent due to different participants driving differently from one another. However, if this was able to be implemented, it would provide the truest to life experience possible with a virtual reality environment. Of course, this could be further enhanced by hardware like a steering wheel to control the car and a simulator to reproduce the experience of the car moving for the participant.

10.1.1.3 Hazards

The experiment could be further improved by having less obvious hazards. Instead of having a brightly coloured coin, have one that is a similar colour to the rest of the environment. These results could then be compared with those produced by the brightly coloured coin to see what difference the colour of the hazard makes.

The hazards could be replaced with driving related ones such as barriers and people in the road. This would once again, create a truer to life experience than what is currently provided.

10.1.1.4 Reaction Timer

The reaction timer in the software for the experiment was tied directly to the refresh rate the software was running at, which was 90Hz. This led to an 11ms uncertainty on each result taken. If the timer was redesigned to be tied to CPU cycles instead of the refresh rate of the software, this would lead to significantly more updates per second effectively reducing the uncertainty of the reaction time to 0ms. This would obviously be

a large improvement meaning greater confidence in the results and any conclusions drawn from then.

10.1.2 Hardware Improvements

10.1.2.1 Headset

The experiment could be repeated using different headsets with higher field of views. The biggest difference would come from a headset with a higher refresh rate, such as the Valve Index which has a maximum refresh rate of 144Hz. A higher refresh rate would reduce the uncertainties of the experiment, a refresh rate of 144Hz would reduce the uncertainty for each result from 11ms to 7ms which is approximately a 30% reduction. This would allow for greater confidence in each result allowing for more accurate data analysis and greater statistical confidence in any conclusions drawn from the results.

10.1.2.2 Eye tracking

Whilst instructed not to, some participants instinctually found themselves trying to look 'over' the macular degeneration filter in VR as this allowed them to see more effectively. This obviously cannot happen in real macular degeneration as any dark spots will follow your eyes wherever they move.

Eye tracking hardware could be implemented to stop this and improve the macular degeneration simulation as the dark spots in VR could be programmed to follow the gaze of the participant wearing the headset.

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12 Appendix

	Participant														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Reaction times w/o MD	673	317	317	351	585	274	368	306	328	518	362	325	303	469	
	357	368	340	424	323	279	1209	284	291	319	425	390	317	335	
	340	369	325	335	330	280	357	257	302	280	330	402	402	457	
	381	735	346	290	313	302	301	274	264	275	320	391	413	369	
	413	324	369	329	302	391	544	281	313	430	335	313	357	302	
	346	469	390	616	368	268	656	369	402	325	446	313	290	379	
	268	391	457	446	368	302	564	330	268	368	582	368	335	424	
	346	402	524	446	334	302	524	298	345	413	380	446	351	446	
	336	424	402	379	369	302	559	302	302	413	320	413	446	391	
	290	335	358	346	391	408	335	302	358	313	310	358	358	419	
	424	419	457	358	302	335	469	313	279	335	297	324	408	340	
	335	380	391	313	357	279	480	335	325	413	313	334	380	346	Overall averages
Average	376	411	390	386	362	310	531	304	315	367	368	365	363	390	374
StDev	99	106	60	84	73	44	229	29	38	69	78	42	46	51	75
Reaction times w MD	1083	440	417	418	362	350	396	329	362	462	415	440	329	380	
	608	402	346	392	418	330	313	346	330	351	400	424	346	558	
	424	468	330	469	413	370	436	350	379	257	456	396	417	502	
	429	490	370	558	391	358	324	302	413	347	552	525	368	407	
	446	457	357	402	346	380	313	286	346	302	471	346	424	335	
	646	429	391	563	368	391	329	335	480	590	480	396	446	391	
	351	370	341	395	318	313	313	370	302	341	451	413	407	468	
	428	428	313	407	396	341	329	390	302	385	380	491	380	407	
	357	424	335	391	391	295	313	458	303	324	391	446	469	329	
	468	491	347	525	414	302	313	303	313	368	555	380	357	346	
	391	413	346	502	424	346	391	491	380	324	502	563	357	418	
	491	468	357	380	380	324	335	713	413	306	392	458	380	428	Overall Averages
Average	510	440	354	450	385	342	342	389	360	363	454	440	390	414	402
StDev	193	35	27	67	31	29	40	114	53	84	58	60	41	65	64
Diff between average	134	29	-36	64	23	32	-188	85	46	-4	85	75	27	24	28

Figure 19: Raw data obtained from the final experiment

Name	Cameron	Matthew	Meirion	Alex	Ben	Steve	Phil	Grant	Geraint	Jane	Elliot	
	Times without MD (ms)											
	368	324	462	473	473	357	339	389	413	424	324	
	479	335	443	513	423	435	296	324	391	490	346	
	423	313	379	402	379	357	379	407	335	436	356	
	391	335	390	413	335	302	412	346	374	537	334	
	357	391	413	468	380	313	290	429	357	585	356	
	324	323	315	448	357	359	457	323	480	552	380	
	335	361	291	313	379	435	290	319	379	713	302	
	336	324	296	368	379	312	392	379	324	468	308	
	435		335	413	368	313	274	313	469	412	334	
				346	363	402	256	289	391	581	413	
					310	312	301	302	329	467	368	
					346	270		413		568	313	
						302		557		646	290	
										435		Overall averages
Average	383	338	369	416	374	344	335	368	386	522	340	380
StDev	53	26	63	62	42	53	65	73	52	90	35	56
Range	155	78	171	200	163	165	201	268	156	301	123	180
	Times with MD (ms)											
	328	558	384	395	400	428	418	351	434	534	411	
	413	379	724	413	435	357	509	812	468	523	347	
	346	379	368	445	446	335	368	402	387	534	363	
	313	307	368	868	390	290	302	380	357	523	291	
	357	352	346	646	346	313	323	502	358	435	449	
	579	346	468	568	335	390	324	691	357	609	302	
	401	379	446	379	346	352	335	690	379	479	435	
	341	312	356	476	324	402	335	485	413		399	
	335	446	413	468	335	352	280	446	401		313	
	340	424	434	334	415	324	333	413	396		335	
	402	446	368	524	447	291		513			457	
			391	735	428			480			430	
											313	Overall averages
Average	378	393	422	521	387	349	353	514	395	520	373	419
StDev	75	72	102	159	47	44	66	143	36	54	60	78
Range	266	251	378	534	123	138	229	461	111	174	166	257

Figure 20: Results of the pilot experiment