ANIMATED ADDITIVE MANUFACTURING

Designing Dynamic Exhibits with 3D Printing & Pixel Displays

Lakjith M. W.

2020

Figure I. 2D Parametric Eye

Animated Additive Manufacturing

Designing Dynamic Exhibits with 3D Printing & Pixel Displays

A ninety-point thesis submitted to the Victoria University of Wellington in partial fulfilment of the requirements for the degree of
Master of Design Innovation in Industrial Design
Victoria University of Wellington School of Design 2020

Lakjith Manapaya Weeratunge

Supervised by Ross Stevens

Abstract

Physical moving parts are prone to wear and tear. A pixel display can manifest complex motion and realistic images in full colour offering a form of tangibly while being less likely to suffer from wear and tear however, it remains restricted to 2D surfaces. The recent development in voxel-based printing (voxel = 3D pixel) allows multi-material and multi-colour 3D printing to transform images into physical objects. However, during the printing process the capacity to change the pixels colour and position in the future are lost, effectively fusing the digital information. The high demand for immersive experiences in video games, films, museums and interactive products are omnipresent. The combination of pixel display technology and multi material 3D printing is a potential avenue to create immersive experiences to feed this high demand.

Contents

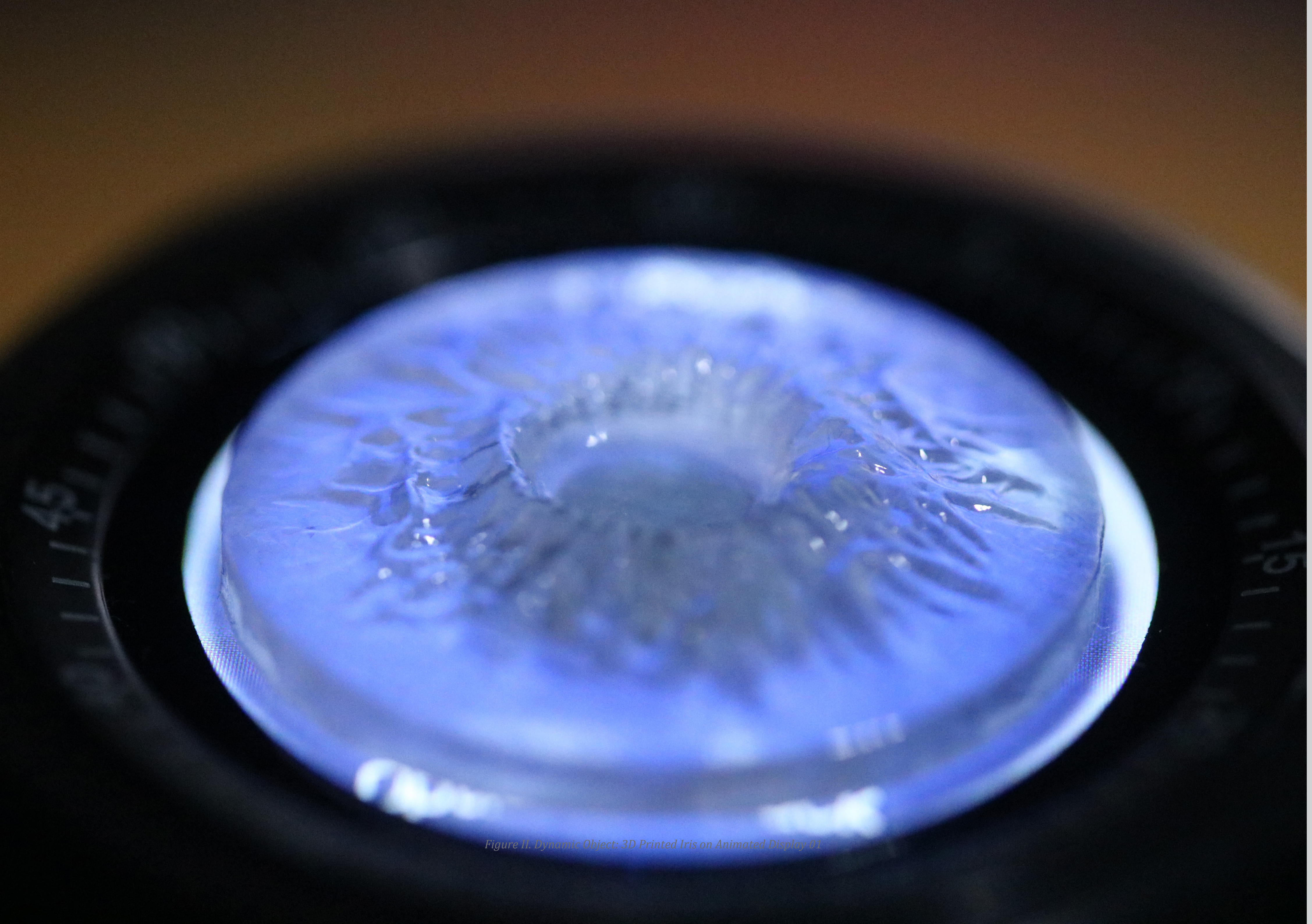


Figure II. Dynamic Object: 3D Printed Iris on Animated Display 01

Introduction

Physical props help the audience connect with story and concept by creating an immersive experience. Computer-generated imagery (CGI) is capable of creating extraordinary visual effects such as dynamic objects that can change form and colour. Developments in Virtual reality (VR) allow physical interaction with virtual objects that are usually behind the screen. In comparison, making encounters with physical props less exciting.

Immersive experiences are becoming a growing trend in the exhibition industry surpassing static 2D and 3D exhibits. New advancements in 3D printing technology such as voxel-based printing (3D printing at the pixel level) and additive manufacturing (AM) has allowed us to create life-like objects (Bader et al., 2018). Marrying digital displays which can introduce dynamic movement into static printed objects makes a powerful design element that can bring physical objects to life.

My research focuses on bringing together animation and 3D printing technology to create immersive objects for exhibits. I propose that this could be presented by embedding a digital screen onto the voxel-based print. While exhibitions focus on visitor centred experiences this research proposes that physical props have value in creating riveting experiences within these contexts; designing dynamic, digital objects with 3D printing has the potential to justify this proposal.

Aims and Objectives

Aims	Objectives	Methodes
Investigate the context for the combination of animation on a digital display and voxel-based printing to support experiences within the exhibition.	1a. Examine trends in exhibitions, current methods of incorporating and designing the use of printed and digital exhibits.	Literature Review
	1b. Analyse existing animatronic exhibits to define the qualities of the output.	Research Through Design
Develop prototypes that illustrate the relevance of screen embedded voxel prints to bring an immersive experience to exhibitions.	2a. Generate ideas for subject matter using existing exhibits and develop voxel printing techniques to merge the qualities of 3D printing and 2D digital technology.	
	2b. Design the exhibit in the context of a narrative, highlighting their immersive qualities.	Prototyping

Terminology

Computer-generated objects (CGO)
Objects that harness the power of computing with the tangibility and interactivity offered by the physical world.

Multi-material 3D printing (MMP)
The process of building physical objects from digital data in which material accumulates through a series of horizontal layers.
Rigid and flexible materials can be combined simultaneously within these objects.

Voxel-based printing (VBP)
Much like mmp is a process of building physical objects from digital data in which material accumulates through a series of horizontal layers 14 microns thick each layer is composed of voxels (3D pixels) consisting of individual colour and material data. And it usually is a complex process converting digital data into physical data.

Vero
Vero is a rigid acrylic-like material and consists of the main print colours CMYK, this material.

Digital Materials/Print Materials
The palette of materials available with Voxel Based printing, including Vero, Agilus and any blend of those materials. Digital materials can offer a range of flexibilities, opacities and colours.

Pixel
An individual area of usually coloured illumination on a display screen which is one of many from which an image is composed.

Dynamic Objects
Digital screens that are physically static but able to represent vivid and fluid imagery through the use of digital pixels.

Literature and Precedent Review

This section aims to review current literature and design precedents to create a foundation of research that can relate to a broader context of design and other relevant industries.

Firstly, it aims to understand the current landscape of exhibitions and museum exhibits to define a niche for computer generated objects with screens.

Secondly, it gains insight into the realms of dynamic digital screen technology and static 3D printing.

Thirdly, it investigates the opportunities into multi material printing and digital screen technology and analysis precedents that have creatively used the technology.

Animatronics

Modern museums are using new design to make learning more entertaining for visitors (Kotler & Kotler, 2000, p. 283). Museums are changing to become more relevant to the needs of society, transforming into visitor-centred, socially responsive educational spaces (Kotler, N. 2007, p. 418-419). Several factors have been found to enhance entertainment in educational exhibits. Rubin and Kozin (1984) found that personally significant, emotionally involved, consequential and surprising experiences were the most easily and vividly recalled memories.

This has led to animatronics being a popular avenue for museums and exhibitions. Animatronics are also capable of performing tasks that actors cannot do such as doing things precisely and repeatedly many times over which also includes performing them in dangerous and unpleasant environments. Moreover, they can animatronically bring life to objects that are typically inanimate. Due to this, they are also popular in the dark amusement industry for example, Haunted Houses that consist of horror tours. While animatronics are known to get the best jump scares when compared to human actors in the tours, some argue that animatronics need to work alongside actors as they are more in line with tools. They also believe that humans can relate to each other more than an inorganic machine could, and actively seek this in their tour experiences (Faupel, 2007).

Science museums have invested in animatronics due to its effective means to exhibit scientific methods and principles like explaining physics or the function of the human body. And natural history museums use animatronics to give life to exhibited animals, with dinosaurs being the prevalent choice (Papaioannou & Paschou, n.d.). Animatronic figures are often powered by pneumatics, hydraulics, or by electrical means, and can be implemented using both computer control and human control. Whilst animatronics has lower working costs than people there are several barriers to overcome when considering using animatronics. For example, it is made up of complex systems which consume large amounts of power, and for that reason, it is difficult to manufacture, handle and use (Kalnad, 2016, p. 1168). A study by Sue Dale Tunnicliffe (1999), found that animatronics in museums are captivating and exciting to students who are of age 4 to 11, while animatronics in zoos are not as appealing to some students. This ineffectiveness in zoos is likely due to the animatronics being overshadowed by the lifelike movements of living animals. In addition, animatronic models must also be well made and set within a meaningful context in order to be read and received well by the visitors. (Tunnicliffe, S. D. 2000).

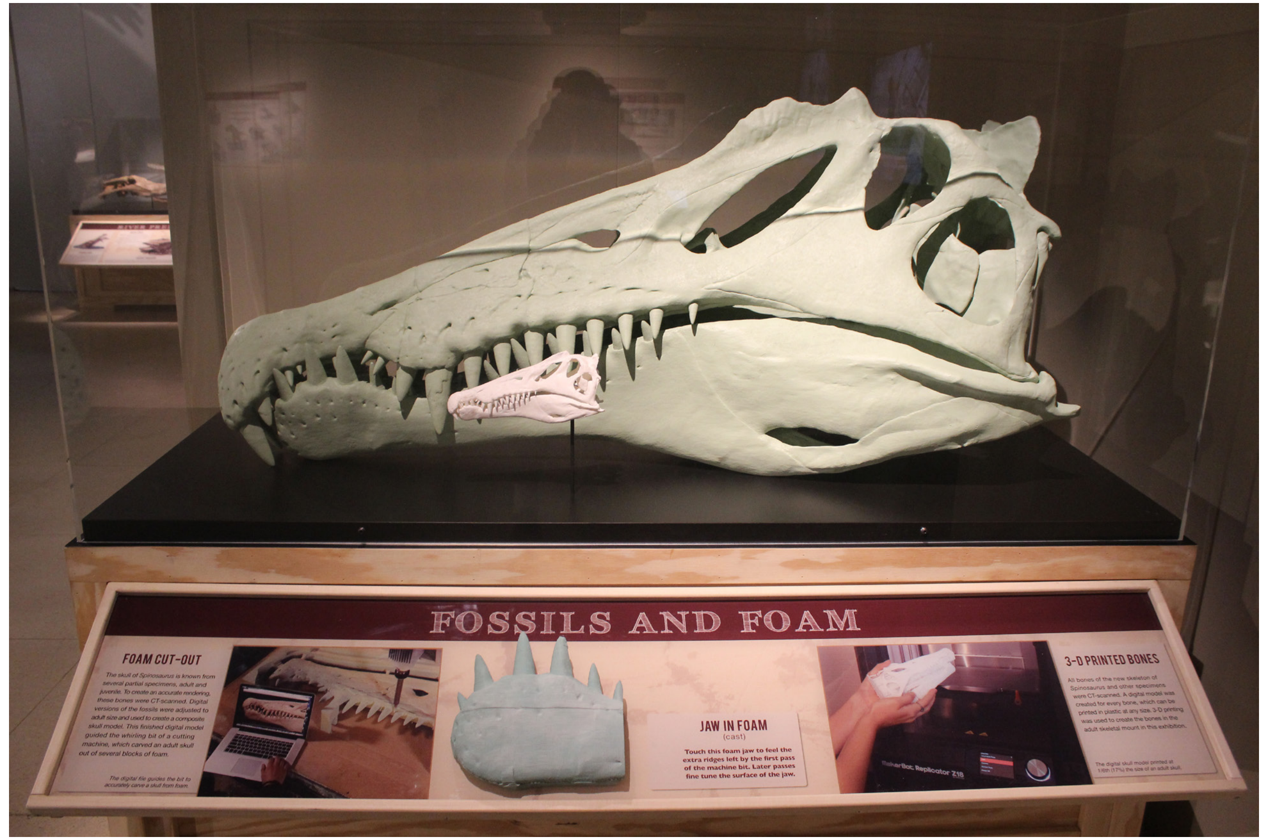
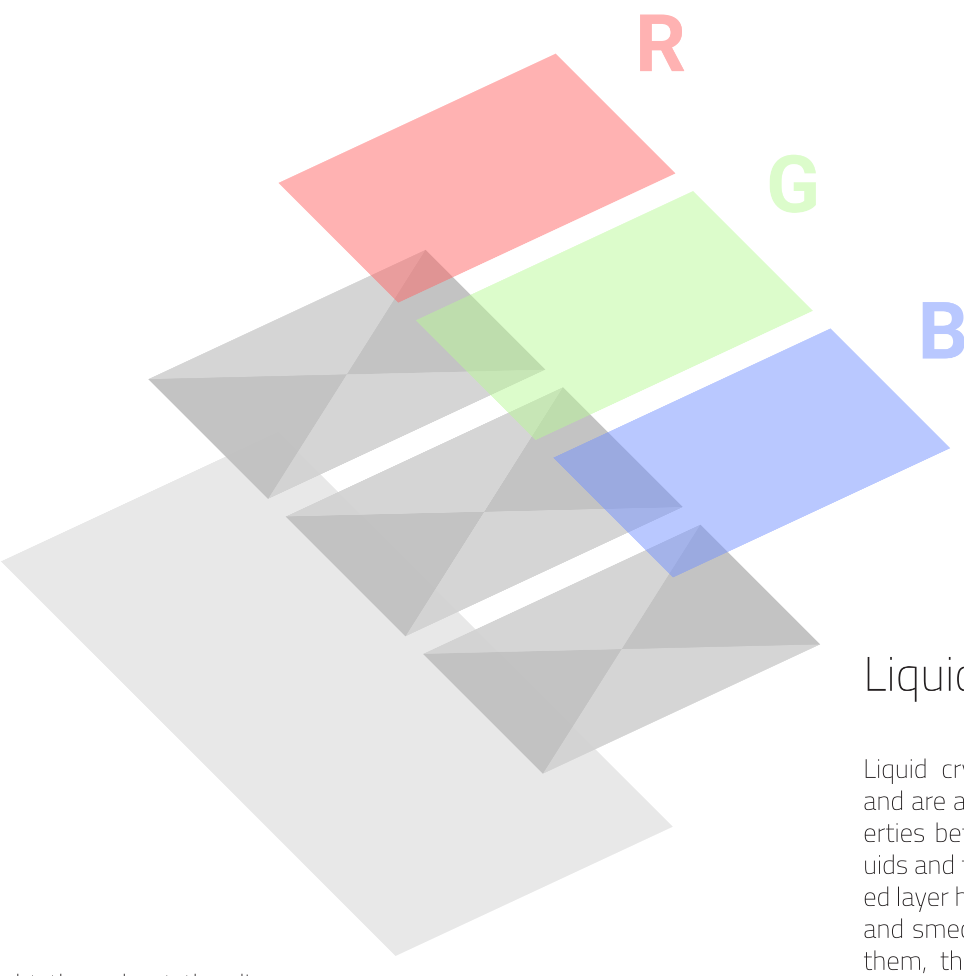


Figure 01. A typical 3-Dimensional fossil museum exhibit (USA, 2014)

Museums

Existing exhibitions of scientific cultural heritage mainly use one-way communication using sound and video, which has a limited ability to attract viewer's interest or to immerse them and is insufficient to promote understanding exhibits (Sanford, 2010). This has given rise to the combination of detailed 3D printed elements and visual effects leading to a more immersive experience that engages the viewers to actively participate in exhibits. Like 3D printed bronze mirror exhibit which allows all viewers to concurrently engage in exhibit. (Jo et al., 2019). This resurgence on the focus of providing more meaningful and memorable visits in museums has led to a method of achieving it through multisensory experiences like combining touch, sound and sight, encouraging museum visitors to explore an exhibition using a range of senses. However, Museums are facing challenges to provide permanent facilities for interaction with specimens for visitors in the exhibition space, as museums need to conserve the rare objects in their collections (Wilson et al., 2018).



Colour Filters

The light passed from the liquid crystal gates is then filtered into individual Red, Green and Blue colours, which make up the image.

Liquid Crystal Layer

Liquid crystals have a twisted structure and are a state of matter which has properties between those of conventional liquids and those of solid crystals, This twisted layer has two phases are called nematic and smectic, when you apply electricity to them, they straighten out blocking light, imagine it as a gate for the light where it is opened and closed respectively.

Back light

produces white light throughout the display.

Figure 02. A simplified diagram of a Liquid Crystal Displays pixel technology

Pixel Display Technology

Liquid-crystal displays (LCDs) are the most common type of display technology used today and make up essential elements in everyday life as they are the key components of TVs and monitors. LCDs also consume low amounts of energy which is why it is used in many general or wearable devices that have restrictions on its size and battery capacity (Manabe et al., 2016).

LCD consists of many different branches of technology. LCDs based on the Twisted Nematic (TN) mode are the most common flat panel displays. TN LCDs contain a small number of matrix segments. Lower matrix segments mean the density of the pixels are lower, and for that reason cannot be applied for displays with high detailed content such as a Television screen. Later, a similar technology called the Thin Film Transistor (TFT) LCDs was discovered, this technology allowed the utilization of larger segments enabling larger pixel densities and higher resolutions. This increase in performance of TFT LCDs did not have drawbacks as the TFT panels kept the advantages from the TN LCDs such as low weight, low space requirement and low power consumption. As the TFT LCD technology was refined it was soon replacing the analogue cathode ray tube (CRT) Display which was mainly used in desktop monitors and televisions. To achieve this, better viewing angles, contrast and colour shift, was improved. Which was possible by the introduction of optical compensation films. This was later realised in LCD technologies such as In-Plane Switching (IPS) and the vertically aligned (VA) mode at the end of the 1990s. Which finally replaced the remaining CRT monitors. (Pauluth & Tarumi, 2004).

Liquid crystal display (LCD) panels are thinner and lighter than Cathode ray tube (CRT) units for similar display sizes. LCD panels also offer higher image quality and are available in much larger sizes. (Cho et al., 2016)

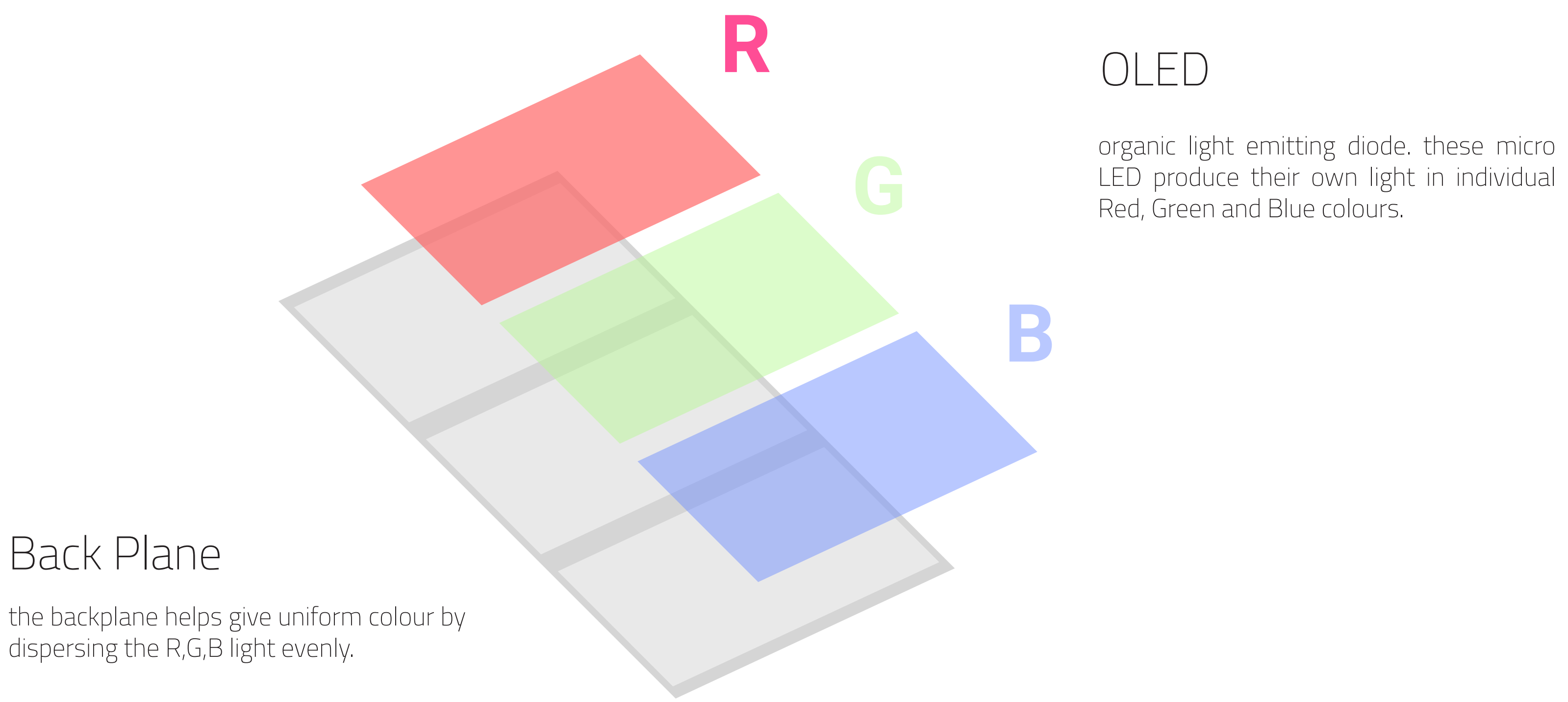


Figure 03. A simplified diagram of a OLED pixel technology

OLED/AMOLED

The organic light-emitting diode (OLED) is an emerging technology for emissive displays. Colour image on AMOLED (Active Matrix Organic Light Emitting Diode) is constructed by three layers of pixel values including the red, green, and blue subpixels, and how bright or dim the colours correlate directly with the electricity power. AMOLED Displays when compared to LCDs have higher contrast ratio and offer significantly lower power consumption due to their ability to turn off individual pixels known as true black pixels, but this depends entirely on the displayed content as high luminance level can affect the power efficiency (Chondro et al., 2018).

Applications

Recently true AMOLED flexible displays have been developed and used in curved mobile phones. Technology can now achieve full-screen high definition imaging using an innovative pixel arrangement that allows for better manufacturing of flexible, curved full high definition AMOLED displays (Thomas Industrial Network 2018). The advantage for this technology is that digital pixel information can now inhabit more than just the conventional 2D space such as a flat screen tv, this means that digital experiences can be more immersive than before and inspire future technologies.

Figure 04. An interactive display. Jacklee. (2016)

Pixel Display in Exhibition

The new advancements in displays have given rise to avant-garde methods of use, in particular, the use of digital media in museums exhibitions and has made it more convenient than analogue equipment like animatronics. It not only allows exhibitions to be played automatically in a loop but also replay at will or in reverse motion, which means that exhibitions are now capable of conveying information repeatedly accurately without wearing out. Digital technologies like pixel displays provide non-invasive and non-destructive methods to examine exhibits like mummies or animals. (Wagner, K, 2017 p. 169 - 172). They also allow small, oversized or fragile items which were not previously possible to be displayed, be viewed and manipulated in the virtual world without fear of damage. (Gelfand, A. 2013). This technology is becoming more attractive as studies show that visitors spend more time on at hands-on exhibits and any other (Macdonald, S, 2007, p. 149–162) Studies also indicate a significantly higher average of attention times for observing dynamic content as compared to static content and are emerging an efficient method for providing optimized information through attractive multimedia content. They are found in airports, hotels, universities, retail stores and various outdoor public spaces (Ravnik & Solina, 2013).

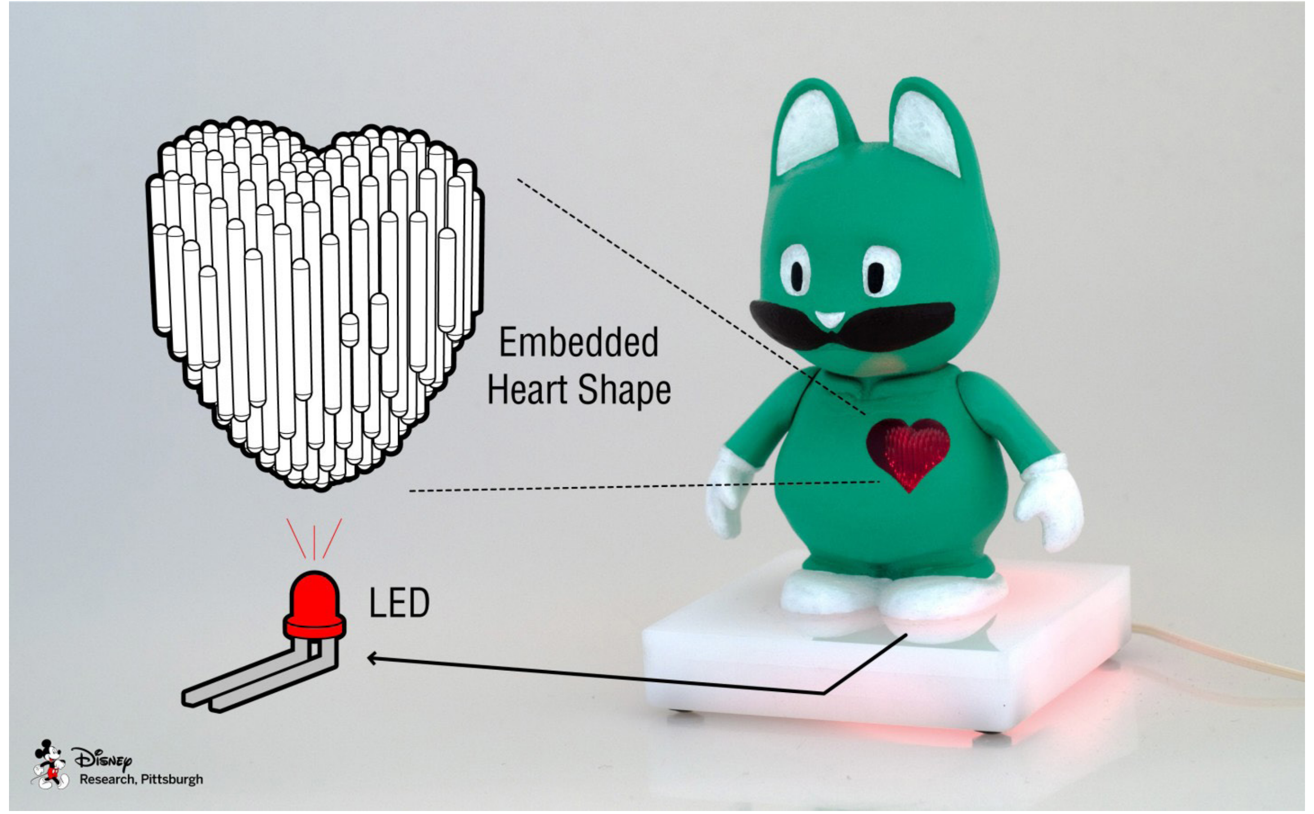


Figure 05. Example of Disney's 3D printed optics using clear resin (Disney Research Develops 3D Printed Optics, 2012)

The first project is called Papillon (printed optics) and it is a technology for designing highly expressive animated eyes for interactive characters, robots, and toys. The goal is to create light pipes using clear additive manufacturing (AM) materials to bounce a light projection up to a specific surface, similar to how a fibre optic cable works, which allows for the differing surfaces to show different displays without requiring a screen. In the Papillon project they are focusing on eyes that are designed as a bundle of optical fibres guiding images projected from a pixel display to the surface which would be the character's eye. (Brockmeyer et al., 2013). The second project is to create reactive toys by touch sensitivity. These would work through disrupting the energy flowing through it. This concept would not only be used for interactive toys but also allow for better refined controllers (Matisons, 2014). The second project is to create reactive toys by touch sensitivity. These would work through disrupting the energy flowing through it. This concept would not only be used for interactive toys but also allow for better refined controllers. (Matisons, 2014).

Disney Research labs have also created virtual capture systems to digitize the human eye with unprecedented levels of detail. In the paper, they mentioned that shape of the human eye "has so far been mostly approximated in our community with gross simplifications." These simplifications are the cause of less expressive and believable CGI characters. They have accomplished this by first separating the data of the captured eye into three main parts, the surrounding white sclera, outer transparent cornea and the inner iris. Secondly, they captured the eye in from 11 poses through the first image set and then another set with different pupil dilations. The capturing process takes roughly ten minutes to complete from which the images are used to construct a 3D mesh in a software. The corneal shape of the eye can be defined by the LED lights in the scene and multiple views of the refracted iris, the iris is reconstructed using a novel multi-view stereo capture system. By doing this they were able to capture the nuances of the eyes of the participants clearly and precisely than thought possible (Berard et al., 2014.).

As we enter the new age of virtual reality and 3D media, highly expressive and lifelike avatars are becoming essential requirements in the medium. Although Disney's research proves to be a huge step forward the process as a long way to go as it is not yet something that can be called practical as the method takes a long-time, careful calibration and expertise with sensitive equipment.

This research seeks to advance this new practice of combining the pixel display to make physical props and how it can bring dynamic movement. In response to new content appearing in museums, this thesis employs a speculative design approach to inform the creation of subject matter. This ensures the design output is relevant to its potential application. The subject matter centres on how the combination of two pre-existing technologies can create vivid and efficient design

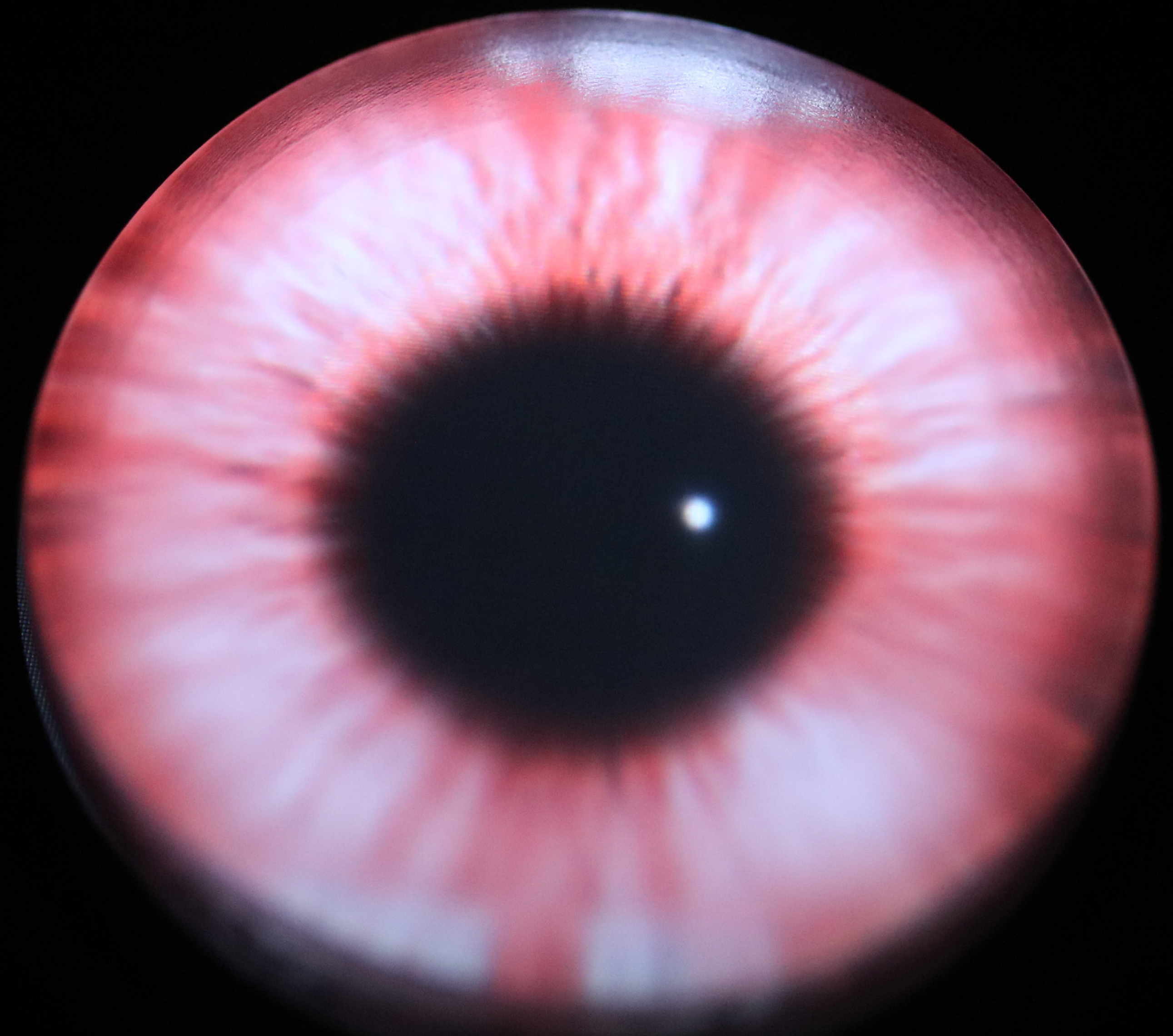


Figure III. Dynamic Object: 3D Printed Lens on Animated Display 01

Multilateral 3D printing / Voxel printing

Additive Manufacturing is a collection of digital production technologies also known as three-dimensional (3D) Printing. Although there are a wide variety of principles in adding material, all AM technologies share in common the ability to fabricate objects directly from 3D model data by adding material layer upon layer (Doubrovski et al., 2015). Recent 3D printing advancements have purged many design limitations and given rise to Avant-garde methods of design creativity. Multilateral 3D printing And Voxel-based where two or more materials can be fused together to build up the object (Wong, K, V & Hernandez, A, 2012), and specifically in voxel-based printing each build layer can be printed down to 14 microns (GrabCAD, 2020). While there are many different methods of 3D printing, this research focuses on the application of Voxel-based printing using PolyJet technology.

In the process of PolyJet printing, the jet head slides back and forth along the x-axis similar to a line printer, depositing a single super thin layer of photopolymer material. After building each layer, Ultraviolet bulbs alongside the jetting bridge emit Ultraviolet light, immediately curing and hardening of each layer (Singh, R. 2011). Acrylic-based resins and rubber-like polymers, known as Vero and Agilus30 respectively and can be printed simultaneously to create composite materials, colour is added through Vero material which is composed of Cyan Magenta Yellow and Key (CMYK). This research uses the Stratasys J750, referred to as the J750 in this thesis.

For designed objects to be printed using voxels, the object or the collection of a data set, needs to be encased in a hull. This hull can be a rectangular box or any containment such as a detailed boundary representation of the enclosed shape.

Then with the relative x,y and z dimension of the hull, with the resolution of the 3D printer bed, determines the number of layers the printer will fabricate for the given model. Finally, in the printing process, each layer's internal material information sourced from the given data set is computed, and any area in the layer that is not occupied by the data but is inside the approximating hull is translated as transparent, which will then be filled with support material depending on the design (Bader et al., 2018). Design processes and software are discussed further in section.

Voxel based printing is still in its early stages of development as a tool used by designers. And few examples focus on the combination of digital displays and voxel-based prints.

Figure 06. Gallipoli The Scale of Our War (Libraries, 2015)

Figure 07. (Smaug 2016)

Exhibits: Existing Designs

Smaug :
In 2014, The Weta Workshop unveiled Smaug the Magnificent at the Wellington Airport. The display was composed of Smaug's head resting on rocks the exhibits was made to look like his head was sticking out a large deep cave wear the rest of body would be, the whole display consisted of fourteen parts including an animatronic eye and eyelid, the display took about four months with forty Weta staff members to create (NZ Herald, 2014). Although the Smaug shows some organic movement it is apparent that its eye movement is slow and clunky, and is displayed in a manner to show one side of his face, showing the one eye, this is due the physical limitations of animatronics and temporary displays where cost and material choices are divvied. However, if it were to use a pixel display it could negate the physical limitation and address dynamic movement through digital means efficiently replicating realistic organic movement which this research addresses.

Gallipoli The Scale of Our War :
Another Weta Workshop exhibit is found in the Te Papa museum has captured an extraordinary moment; the human exhibits are scaled 2.4 times human size. The giant sculptures are brought to life using technologies such as 3D maps and projections, miniatures, models, dioramas, and a range of interactive experiences (Gallipoli, 2015). Even though these sculptures are lifelike they still lack any engagement with the viewer which takes away from the immersive experience, the use of animatronics here much like Smaug would grant an immersive experience but would be too demanding and complicated to fit in each sculpture that consists of two eyes each.

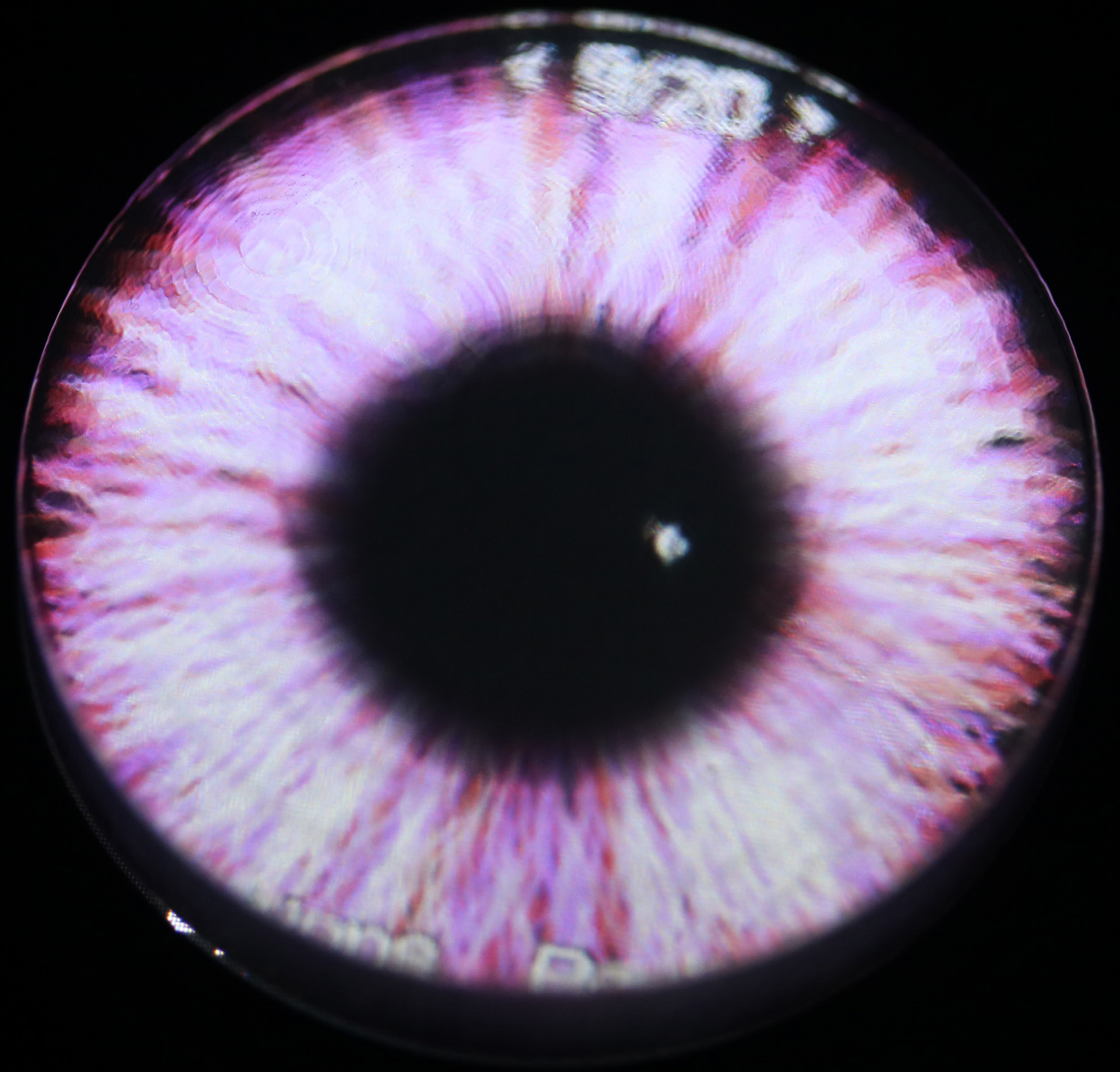


Figure IV. Dynamic Object: 3D Printed Clear Lens on Animated Display 02

EYES

Studies have shown when conveying emotion through prototypical facial expressions, eye expression is the most vital component of expressing and identifying genuine emotion (Calvo & Fernández-Martín, 2013). Pupillary contractions can be influenced by illusions of light intensity, even when the physical luminance is unchanged (Laeng & Endestad, 2012, P 2163-2164).

Slit EYE

Slit-eyes in animals are found as either vertical or horizontal pupils. Vertical slits are better for estimating object distance and distances along the ground, allowing them to make finer depth discriminations suited for a predator stalking its prey however horizontal slits are better for seeing objects on the horizon, perfect for prey seeing an approaching predator and deciding which way to flee. (Banks et al., 2015)
Vertical pupils are perceived as more threatening and cause a phenomenon known as "the evil eye effect". Humans have a long evolutionary history of rivalry with snakes and generated one of the most important evolutionary pressures on the primates' visual systems which evolved to rapidly detect snakes for survival in the wild, snakes were the first real predator of the primates and primates' visual areas had to evolve. (Isbell. 2006) humans could have a disposition to quickly associate vertical pupils with threat as a result (Alper et al., 2019). This is why we perceive vertical eyes as evil.

Infant EYE

Eyes play a crucial role in emotion regulation and synchrony between infant and mother, findings showed that mutual eye gaze between infants and mothers would be associated with an increase in positive affect during the face-to-face interactions.

EYE Contact

Direct eye contact has shown to activate a part of the brain called the right anterior cingulate, a region known to be involved in complex social tasks. Direct eye gaze with more appealing faces have shown activates the right and left ventral striatum, this location is where you find dopamine receptors and strongly associated with reward and reward prediction.

EYE Attraction

Despite the fact of eye colour being perceived as making eyes more attractive, it does not play a role in the attractiveness of eye areas and the iridal colour is not a criterion for decision making.

EYE Colour

In an experiment inspired by Van Dillen (2011) participants learned to associate eye colour of blue-eyed and brown-eyed with a personality, being more extraverted or introverted versus a physical category indicating whether the target's irises absorbed long or short frequency light. They used these associations in a subsequent speeded categorisation task of blue-eyed and brown-eyed faces displaying various emotional expressions (Dillen et al., 2015).

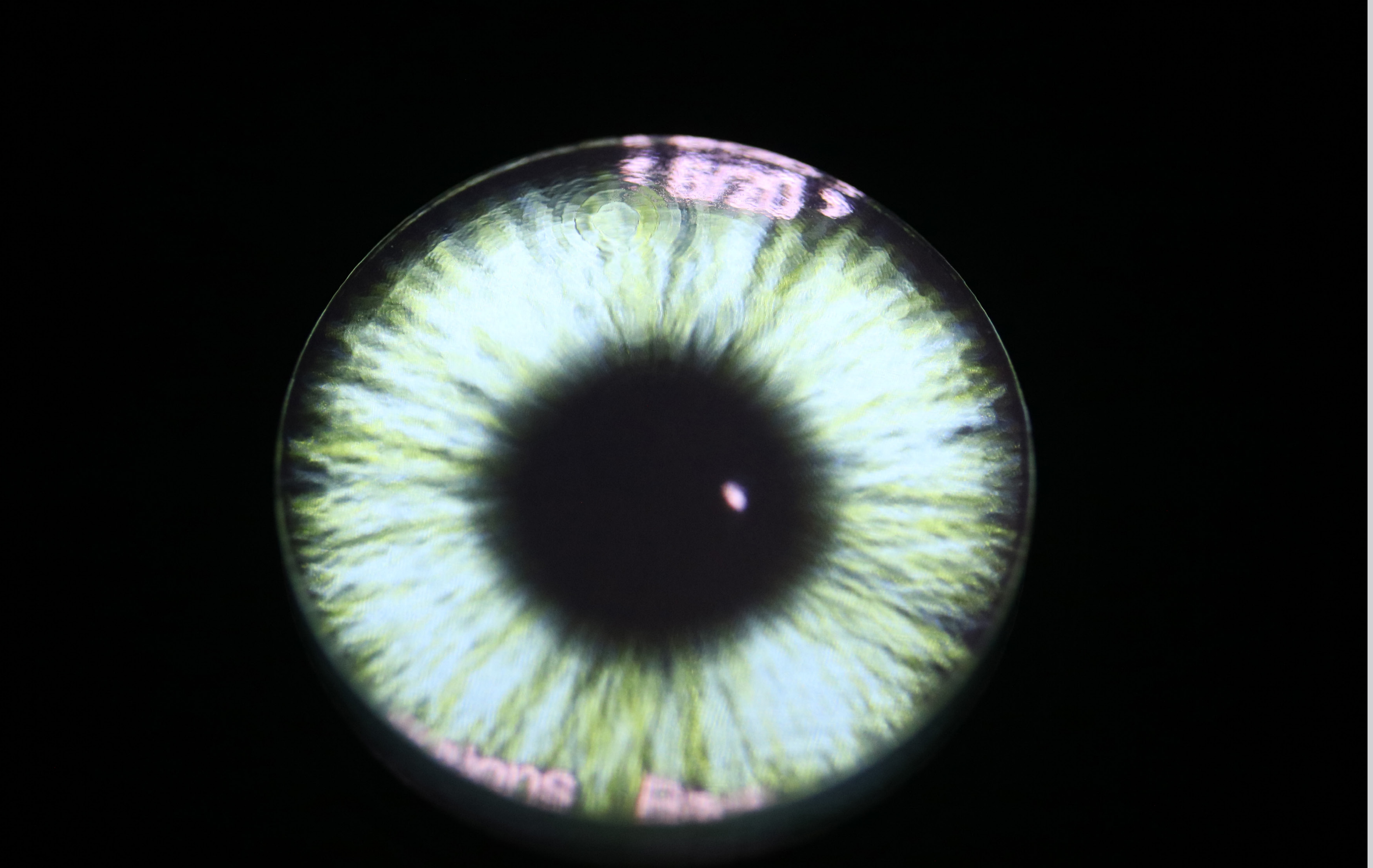


Figure V. Dynamic Object: 3D Printed Clear Lens on Animated Display 03

The evolution of eyes is very likely to proceed in stages. Firstly, there were simple eyespots (early Cambrian period, 570 to 500 million years ago), with a small number of receptors in an open cup of screening pigment. Eyespots would distinguish light from dark but could not represent complex light patterns. Invagination of this eyespot into a pit would add the capacity to detect the direction of incident light. Addition of receptors may then have led to a chambered eye, whereas duplication of an existing pit may have led to a compound eye.

Simple vs Advanced

Adding an optical system that could increase light collection and produce an image would later dramatically increase the usefulness of an eye. Whereas, primitive eyes can provide information about light intensity and direction, advanced eyes deliver more sophisticated information about wavelength, contrast, and polarization of light.

Lenses

Simple eyes do not have pupils or even lenses, so they can provide only coarse information about the distribution of light in the environment. Lenses allow the eyes to collect and concentrate light, which leads to increased sensitivity and allows information contained by that light to be spatially resolved. Advanced eyes collect light through an aperture and focus it with a lens onto photoreceptor cells.

The Vertebrate lens

The vertebrate eye lens is a highly specialized organ whose sole function is to carry out proper refraction of incident light beams in order to ensure visual acuity. The organ, which is completely devoid of blood vessels, gets its nourishment from the surrounding fluid, called the aqueous humor. The lens is generated from ectodermal cells, and is composed of this cell type in its various differentiated forms. The outer epithelial monolayer contains.

Devolution of EYES

Many cave-dwelling animals adapt to their environment through the degeneration of eyesight or even complete eye loss (Koch, L. 2018)
Loss of eyes is one of the most common morphological features of cave-adapted animals, including many fish species. Blind cave morphs of Astyanax mexicanus called the blind cave tetra evolved from surface fish during a few million years of isolation in dark Mexican caves.

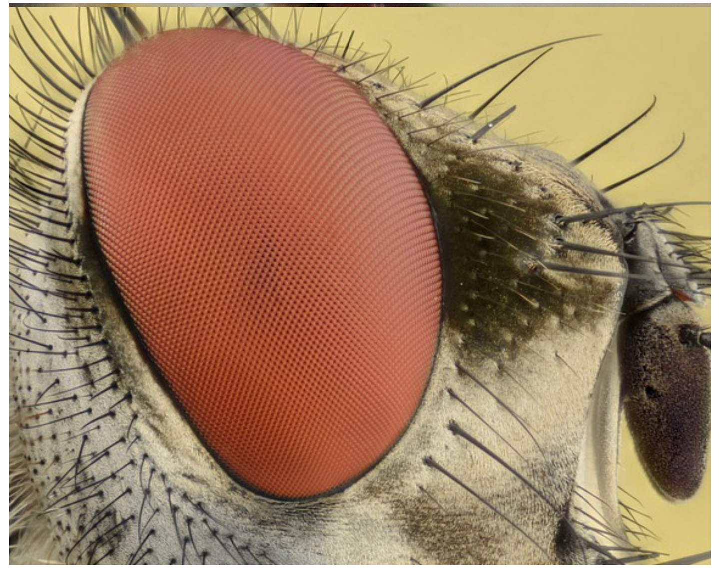


Figure 08. Example of a compound Eye

Figure 09. Example of a Chambered Eye (Hillewaert, 2008)

"Both evolution and technology have to obey the same set of physical rules. Image-forming lenses, for example, have to be made using the principle of refraction by a transparent high refractive index material, whether the lens evolved in an octopus or fish, or was designed by Leitz or Nikon." (Land & Nilsson, 2012).

EYE Size

The size of the eye is a fundamental factor determining visual performance. Therefore, a larger eye housing a larger pupil allows more photons into the eye allowing for better sight. In the animal kingdom eyes range in size from below 1 mm diameter in smaller species to the soccer-ball-sized eyes of giant squid. In vertebrates, whales have the largest eyes. The diameters in the blue whale, humpback whale, and sperm whale reach 109 mm, 61 mm, and 55 mm, respectively. Eye size plays a fundamental factor when it comes to visual performance. With a larger eye (that can house a larger pupil), diffraction blurring is reduced, and the higher flux of photons allows for smaller contrasts to be detected. But large eyes in animals are energy expensive to build and maintain (Nilsson et al., 2012).

All animals detect light using specialized cells called photoreceptors, of which there are two main kinds: ciliary and rhabdomeric. Crustaceans and their relatives, including insects, have rhabdomeric photoreceptors; while animals with backbones, including humans, have ciliary photoreceptors (Verasztó et al., 2018).

Compound EYE

The compound eyes are found in all arthropods and individual ommatidia can contain pigment cells, cone cells or secreted lenses (Callaerts et al., 2006).

Chambered eyes

All vertebrates have chambered eyes with lenses (Fernald, R. D. 2004). The chambered or camera-like eyes in which an image falls onto a two-dimensional array of photoreceptors.

Both chambered eyes and compound eyes form images using shadows, refraction or reflection.

Figure 10. Mantis Shrimp macro (Austria, 2010)

Mantis shrimp:

According to the Colour and Vision exhibition at London's Natural History Museum. The multicoloured mantis shrimp has the most sophisticated vision in the animal kingdom. These astonishing eyes of the shrimp contain 16 visual pigments, as compared with just three in humans and a mere two in dogs. They can sense several kinds of polarised light. This enables the mantis shrimp to locate food, to avoid predators, and also to communicate with potential rivals and mates with dazzling reflected displays of polarised and other light. (Robinson, A. 2016).

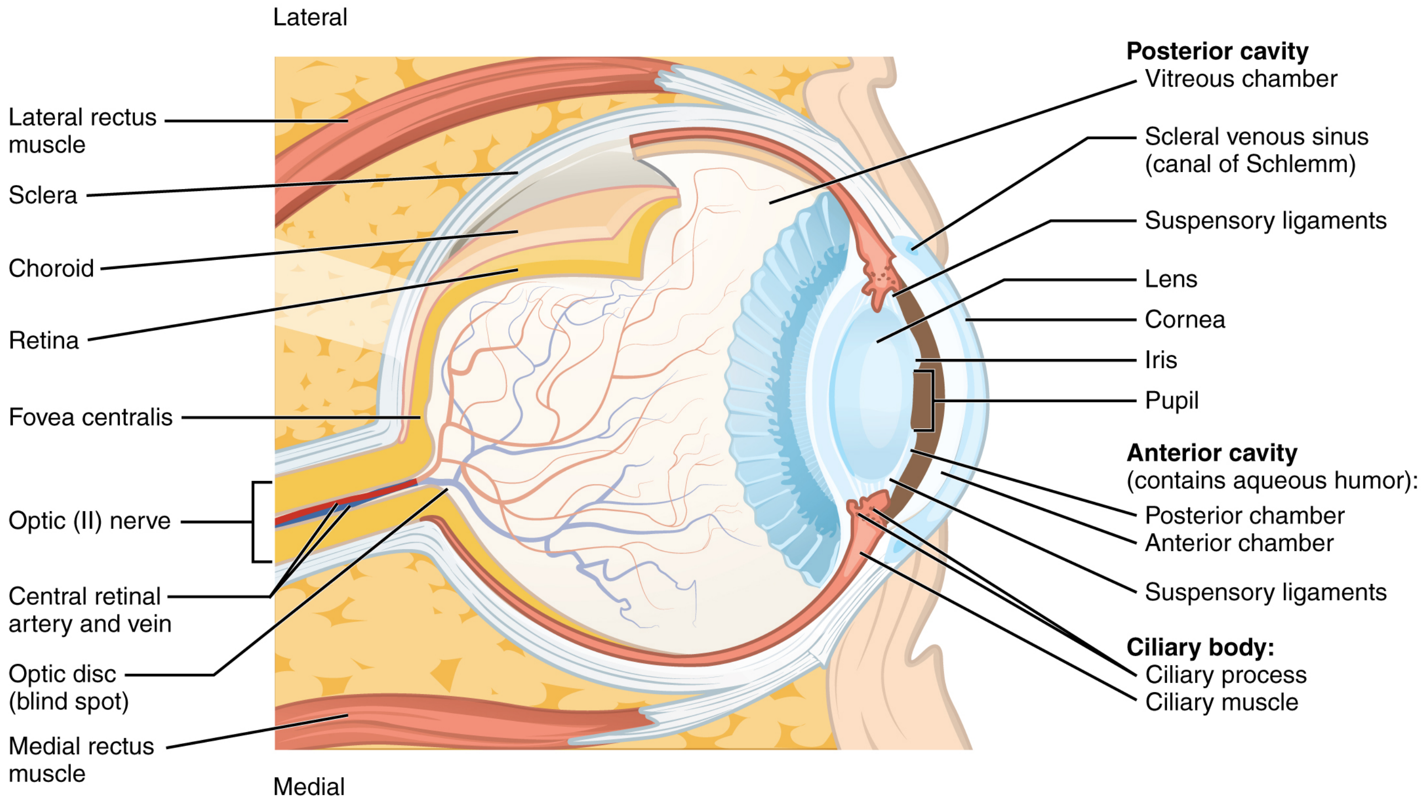


Figure 11. Illustration of the human eye with anatomy labelled. College, O. (2013).

Anatomy of the EYE

The eye is a nearly spherical fluid-filled elastic shell with an anterior (corneal) bulge. The compartments of the eye comprise the corneo-scleral covering, the vascular bed, the vitreous, the lens, the iris, the retina, and the anterior and posterior chambers filled with aqueous humour. The eyeball itself occupies only about 20% of the volume of the eye socket, the remaining space being filled with muscles and ligaments, blood vessels, nerves and fatty tissue. In man, the external diameter of the eye globe is about 24 millimetres (mm), giving an external volume of about 7,000 microliters (μL). The thickness of the eye's covering - the cornea in front and the sclera behind - varies between 0.3 and 1. 3 mm, so that the internal volume of the eye is approximately 6,000 μL

This table gives approximate comparative information for human, cat, and rabbit eyes.

	Human	Cat	Rabbit
Eye diameter	24mm	21mm	16mm
Eye volume (external)	7,000 μL	5,000 μL	2,000 μL
Eye volume (internal)	6,000 μL	4,000 μL	1,500 μL
Anterior chamber volume	180-280 μL	300-690 μL	285 μL
Posterior chamber volume	60 μL		57 μL"

Collins, R., & van der Werff, T. J. (1980). Introduction. In R. Collins & T. J. van der Werff (Eds.), Mathematical Models of the Dynamics of the Human Eye (pp. 1–7). Springer. https://doi.org/10.1007/978-3-642-50153-1_1

Design Process

Software Used

GrabCad Print:
Used to organise and assign files to 3D print

Adobe After Effects:
Used to animate 2D images to be used in the pixel display.

Blender:
Design and create 3D animations and models to be 3D printed.

Bounding Box Software - Materialize:
Used to convert images file to height map/bitmap files

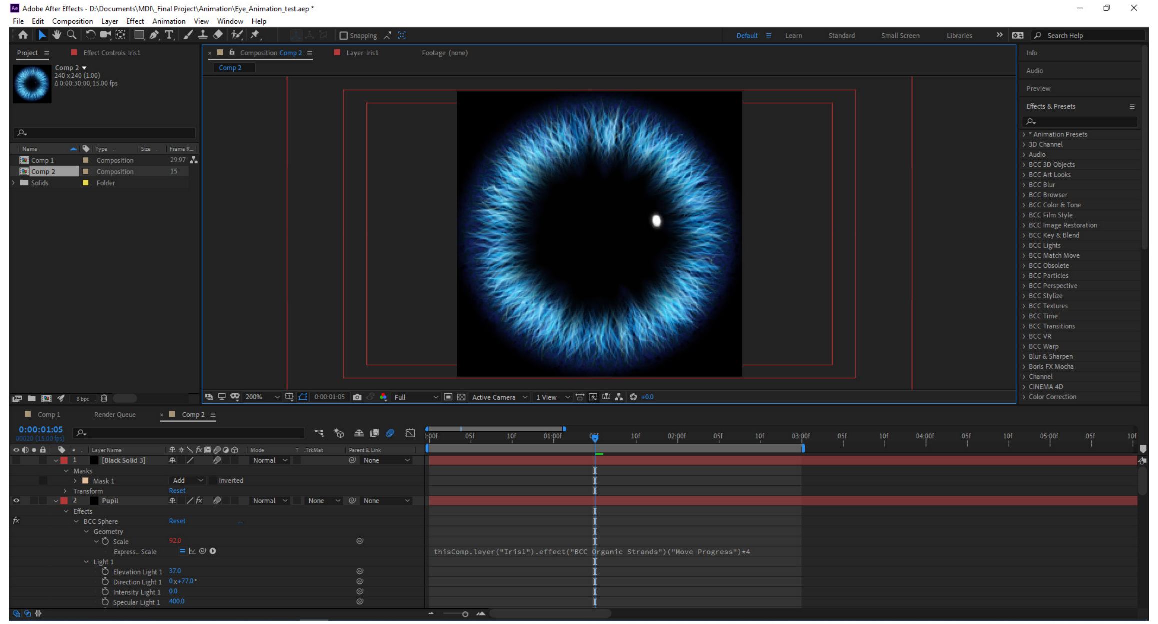
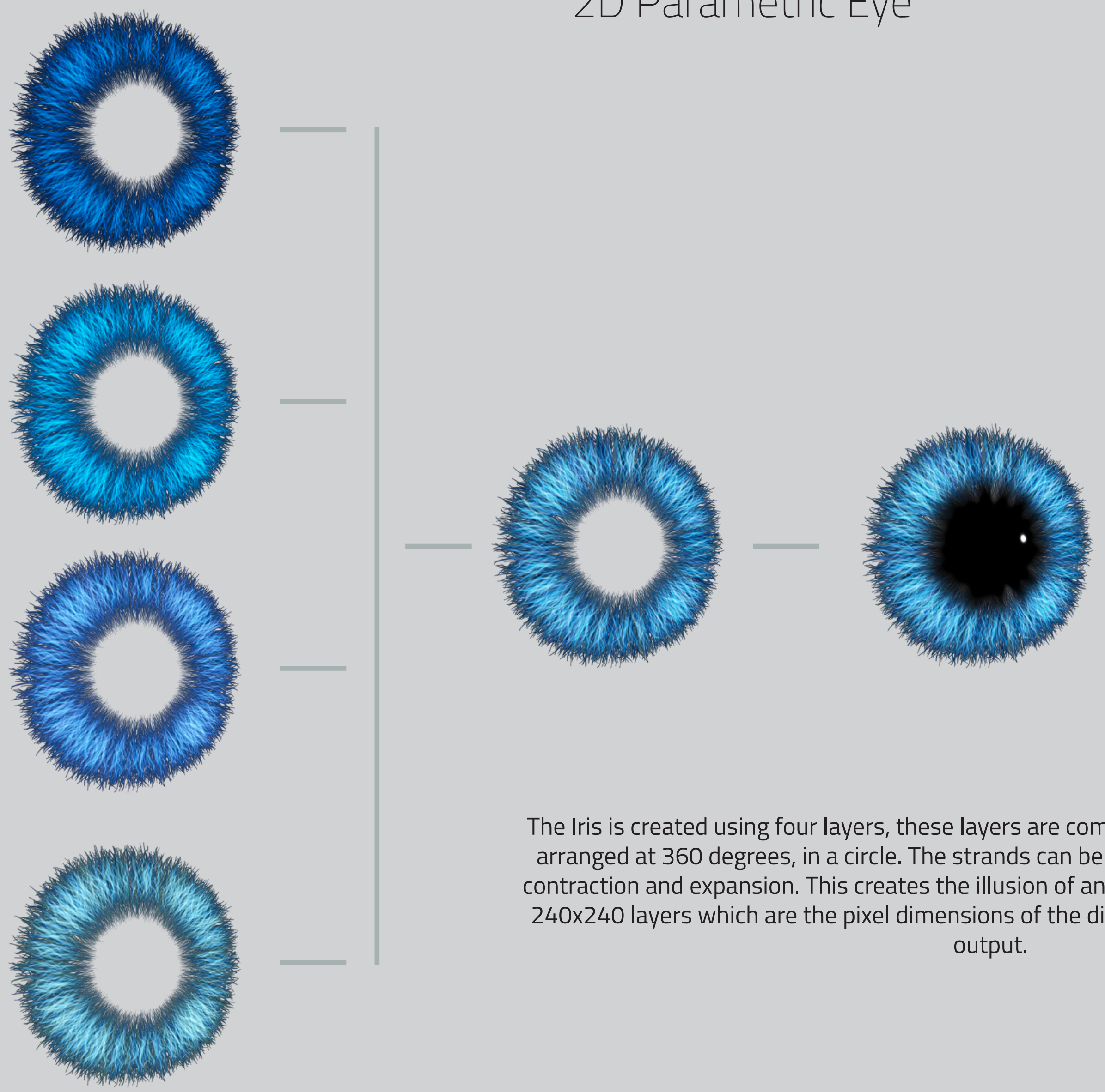


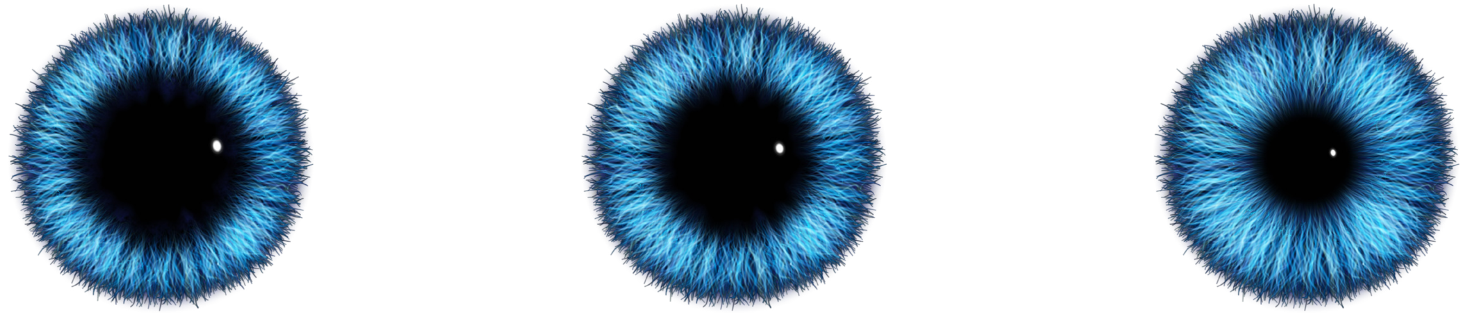
Figure 12. 2D Paramentic Eye in Adobe After Effects - Screenshot

2D Parametric Eye



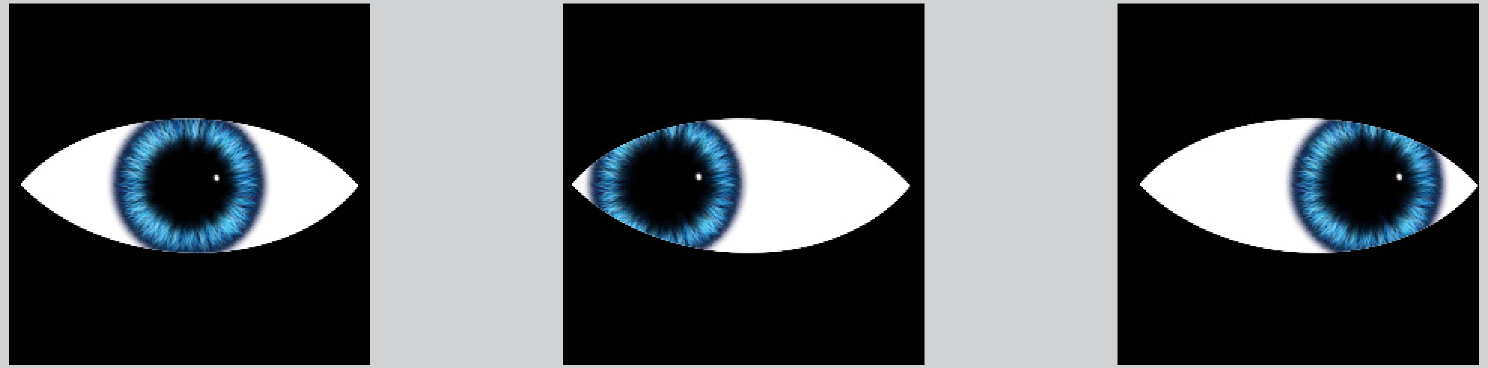
The Iris is created using four layers, these layers are composed of individual linked strands arranged at 360 degrees, in a circle. The strands can be adjusted in length mimicking the contraction and expansion. This creates the illusion of an eye. The layers are also created in 240x240 layers which are the pixel dimensions of the digital pixel display used in the final output.

Figure 13. Iris layers



The first animation was a dilation of the pupil (Figure. 13). This design was created to emulate realistic eye movement in 2D space whilst still enabling it to change to any colour within the RGB (Red, Green, Blue) value.
However, movement of the pupil was difficult to accurately replicate as each strand which made up the iris had to stretch or contract based on the direction of movement.

Figure 14. Aftereffects 2D Iris Animation Transition



The Iris animation was then taken and animated in another composition to replicate eye movement.
Although the animation was successful the immersive presence was lost.

Figure 15. Animation test with eyelids

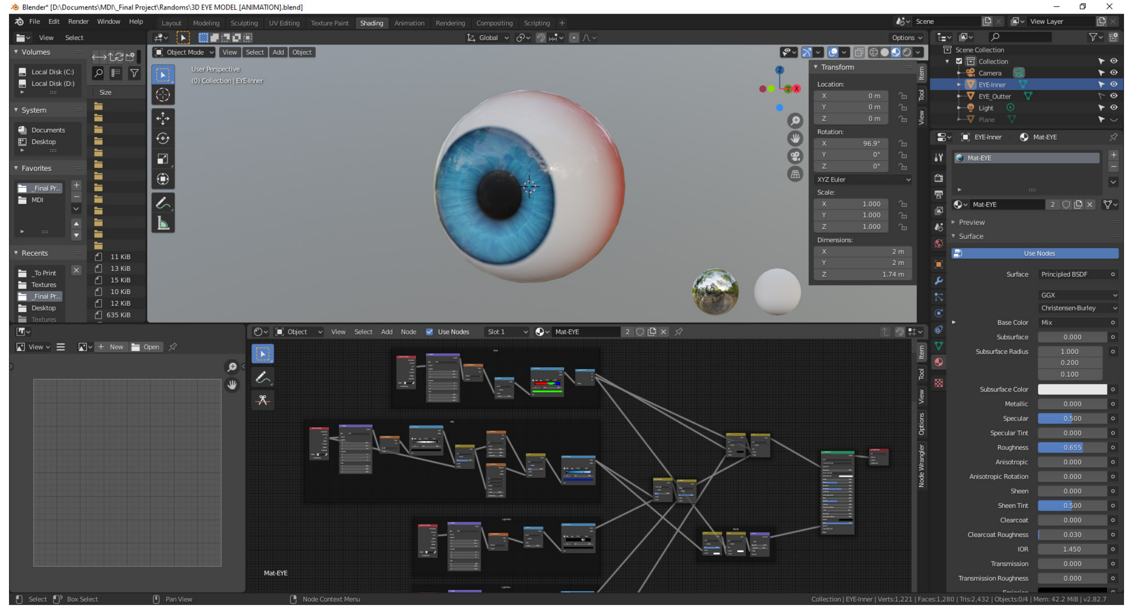


Figure 16. Blender 3D Parametric Eye Model - Screenshot

3D Parametric Eye

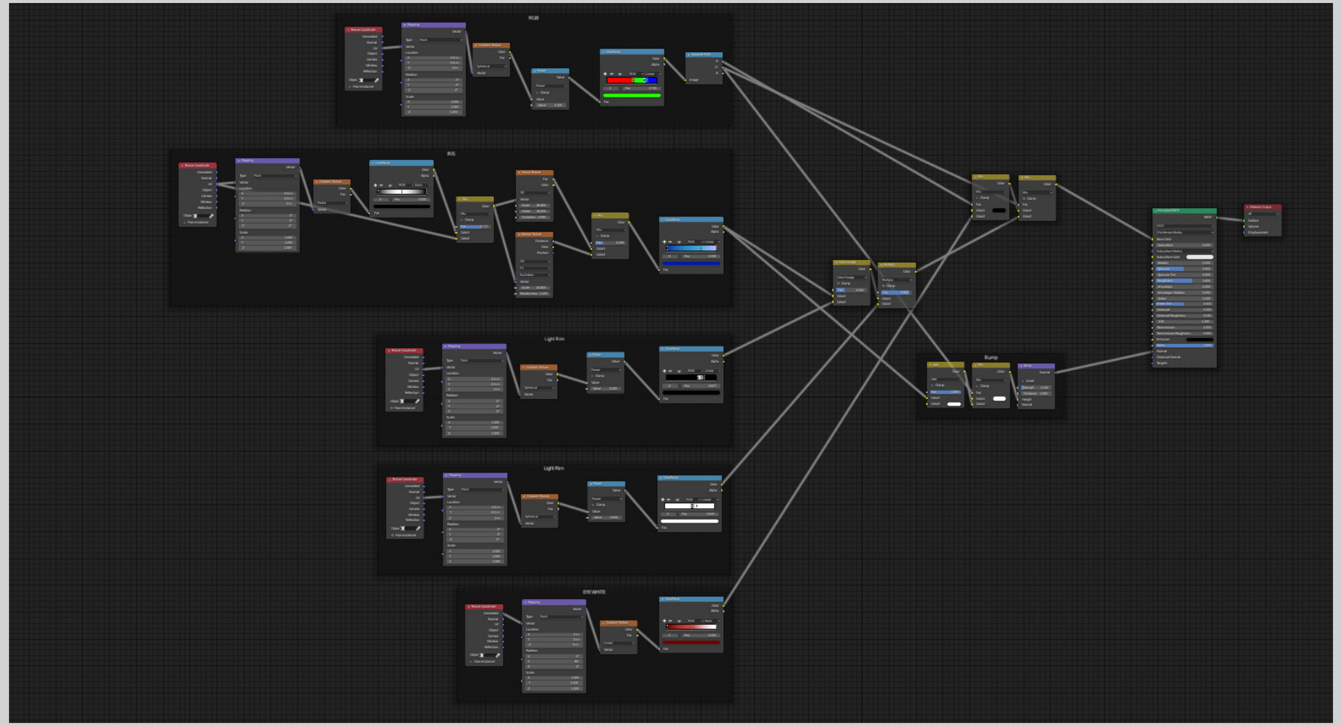


Figure 17. Blender 3D Eye Node Definitive - Screenshot

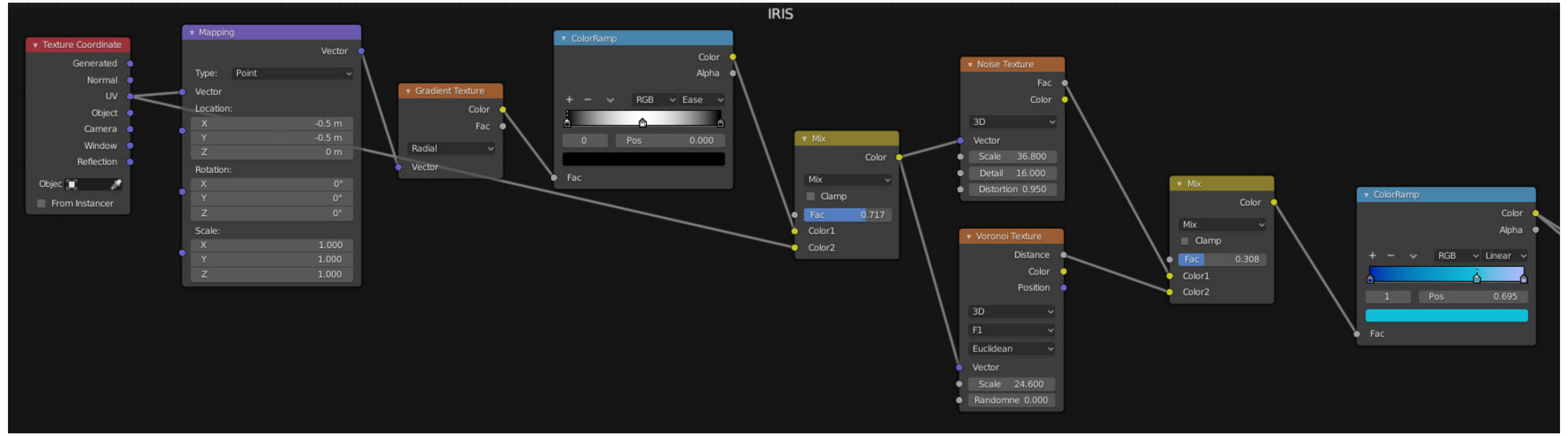
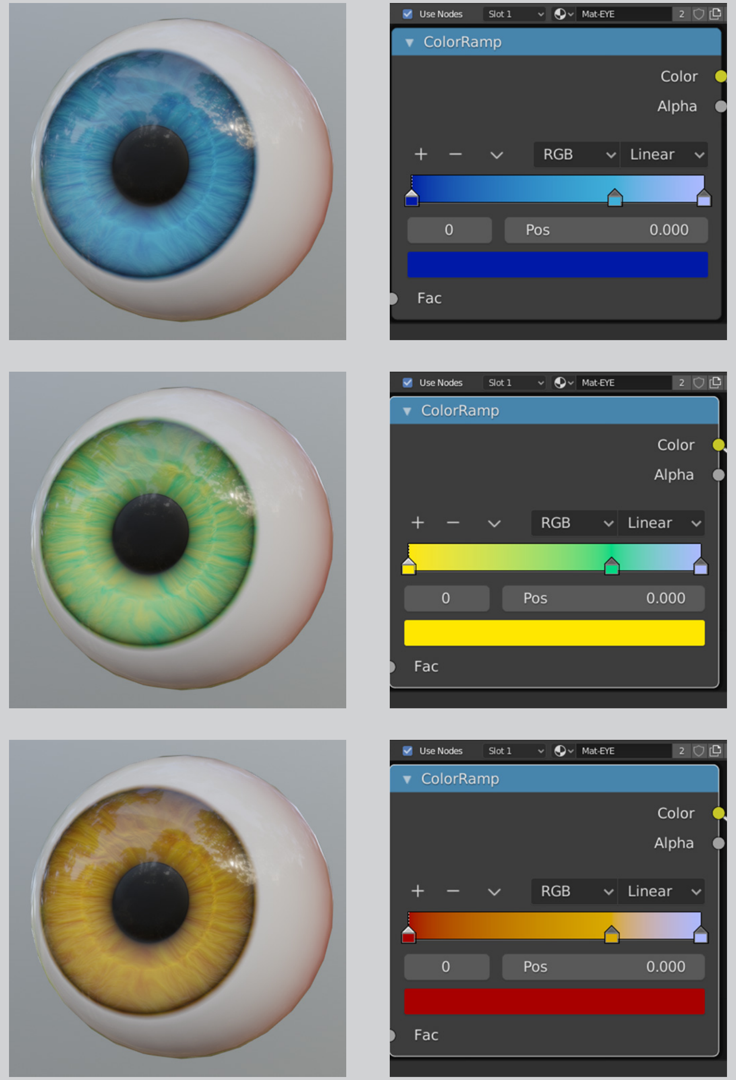


Figure 18. Figure 10. Nodes for colour - Screenshot



This node allows the user to change the colour of the 3D eye, between 3 sets of parameters of colour, and can be cho-sen from any RGB value, which has 16777216 x 3 possible colour combinations.

Figure 19.

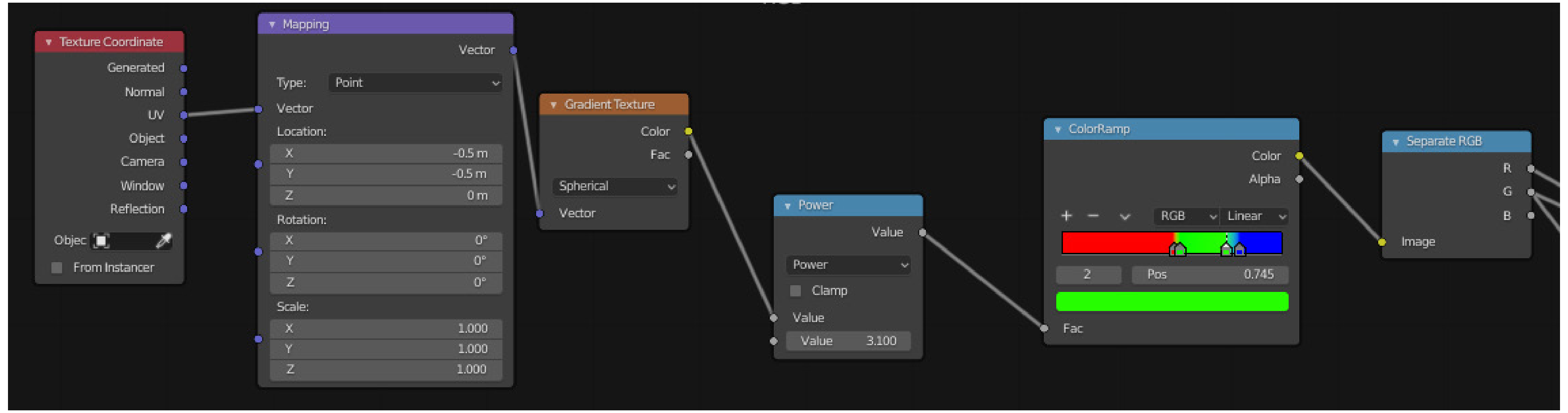
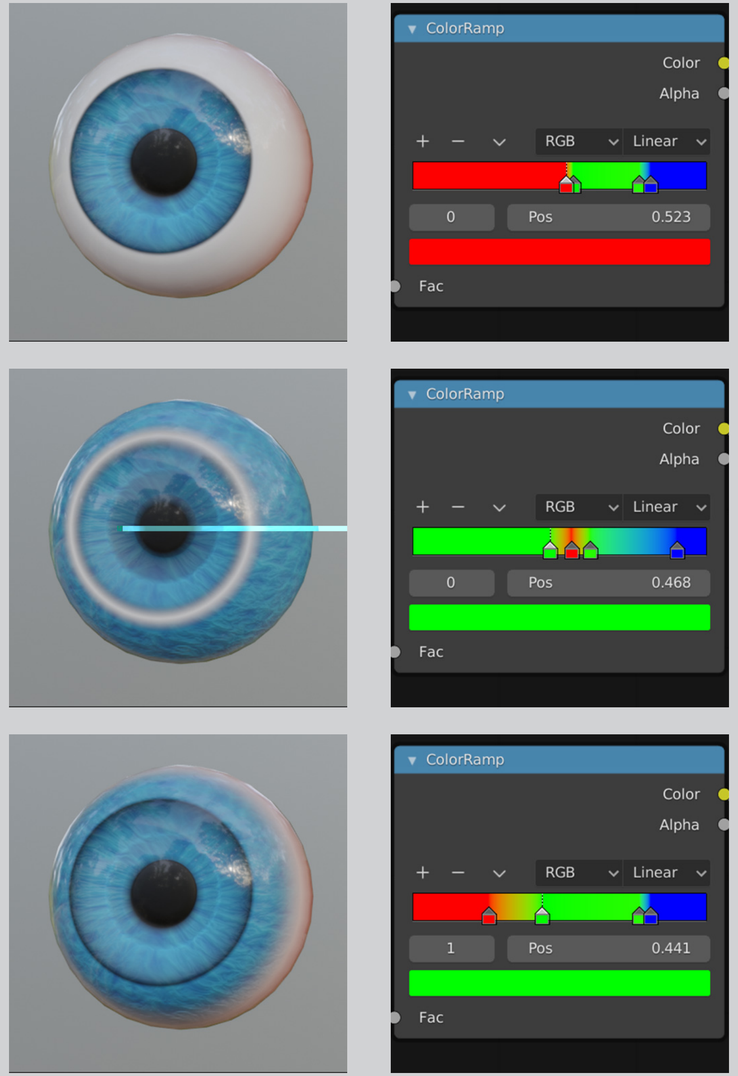


Figure 20. Nodes for Masking eye segments in blender



The sclera, iris and pupil are segmented into a colours Red, Green and Blue values, This ensures that when the model changes the segment can be adjusted accordingly.

Figure 21. Parametric eye with relative nodes adjusted to demonstrate masking segments

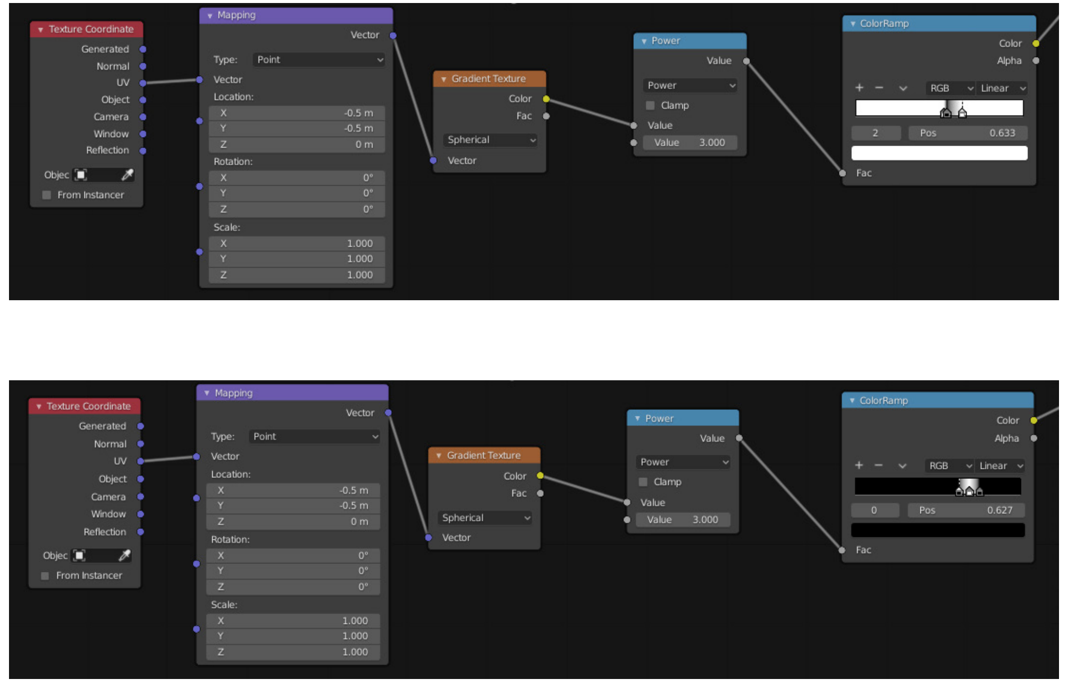


Figure 22. Nodes for inner and outter bands in the parametric eye

These nodes control the rings that give detail and depth to the iris such that if eye size were to change the detail will remain the same. demonstrated in the figures are the white and black rings exaggerated.

Figure 23. parametric Iris rings inner and outter.

Figure 24. Basic blueprint for custom display system

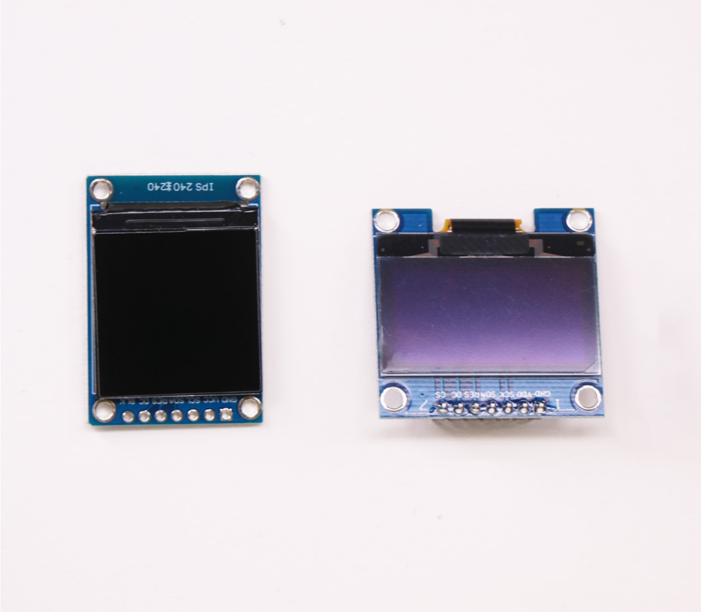


Figure 25. Small LCD and AMOLED displays

Initial Ideas

While my initial idea was to build and use my own display system capable of receiving data through wifi and sd memory card, through the use of an Arduino board. It proved to be more unwieldy and a greater task than previously thought. The figure shows the initial basic concept for the system and the two LCD and AMOLED displays purchased.

Figure 26. Smartwatch disassembled

Smart Watch.

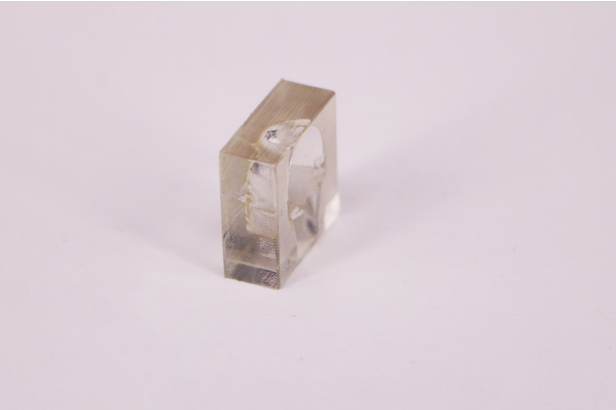
Smartwatches are a compact device with an easy to use operating system with and features such as Bluetooth connectivity and a loudspeaker. This smartwatch also has a circular cropped display which is well suited for the animations of the eye, see figure 26. The smartwatch was purchased from AliExpress for $9 each. And a total of 4 of them were purchased as backup watches in case the delicate componentry was damaged or malfunctioned. See figure for the cracked touch screen as I was disassembling the componentry.

Smart Phone.

The smartphone used as a personal device, Huawei p10 plus. The device was used to playback animation footage as this was fine for high-quality video playback, given that it has a high pixel density of 540 PPI. Even though the smartwatch display was preferred because it is more compact and affordable, which makes it a better device to test and prototype on.

Problems/Issues

Due to the fact that this smartwatch has an underpowered processor, it is difficult to play video files such as mp4, avi or webm. The solution was to convert my animation footage into simple GIFs (Graphics Interchange Format) as there are light image files and far less taxing on the device. Despite this, converting the files into Gifs meant that some quality and higher frame rates for smoother animation playback was hindered. The Smartwatch user interface was also an aesthetic issue as there was no possibility of hiding them while the animation was playing.



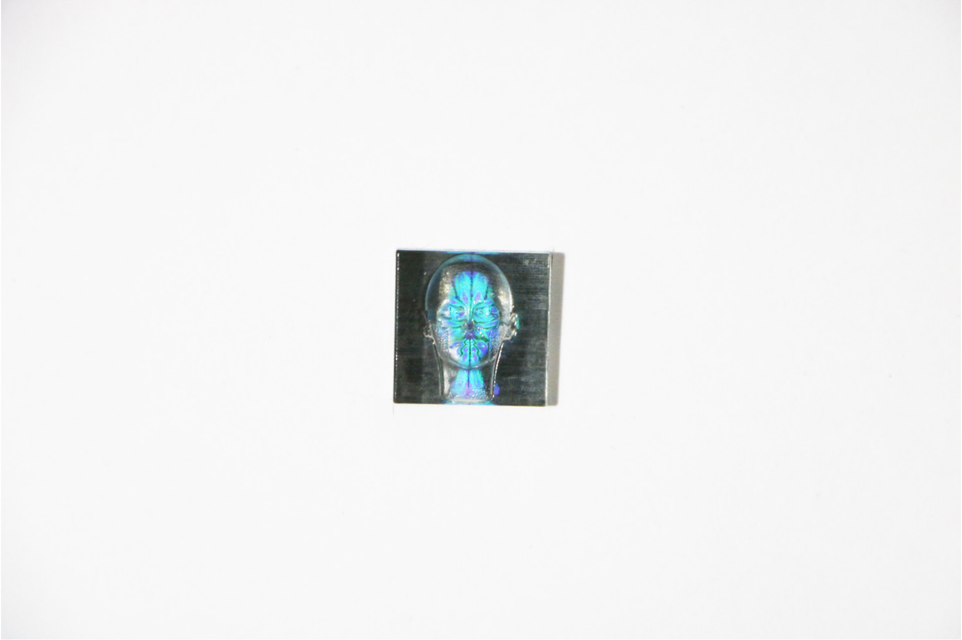


Figure 27. Initial prints of a hollow face using Vero clear
Figure 27a. Hollow face print with dynamic animation

First Prototype

The initial prototype was based on an optical illusion called The Hollow-Face illusion in which the perception of an inverted or concave face appears as a normal or convex face. This face will appear to look in a single direction, at the viewer and can appear to track a moving viewer, even when looking at extreme angles. This test was done because of how this optical illusion is capable of showing fluid motion from static objects through the use of illusions. And it was also one of the first stages into using Stratasys j750, learning the 3D printing process.

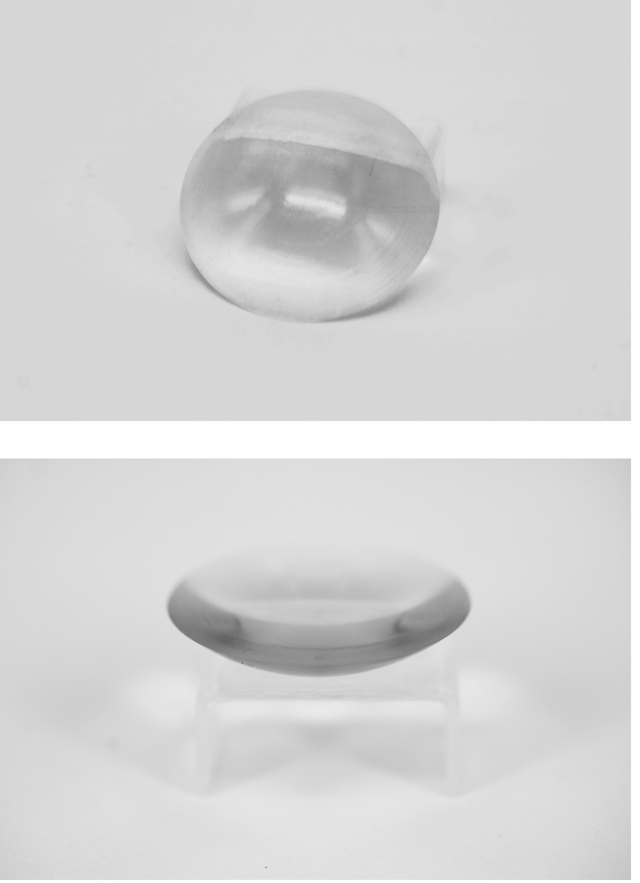


Figure 28. Printed lens with flat base

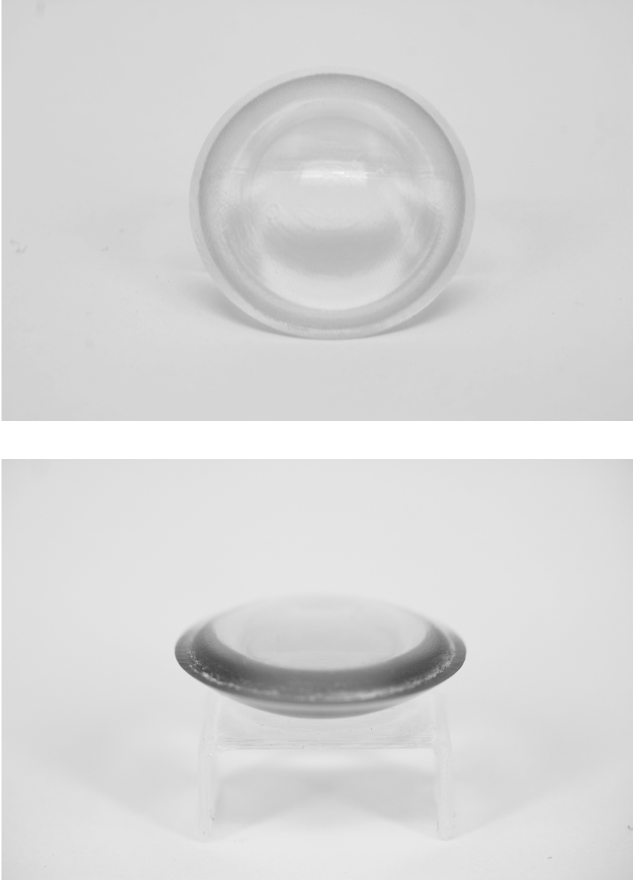


Figure 29. Printed lens with concaved ring base

Lenses

Inspired by lenses in magnifying glasses. Lenses with different concave rings embedded into the bottom of the lens were designed in Blender and 3D printed using Vero clear material in the J750 printer. These rings were designed to investigate how it would magnify the eye animation from the display, specifically the iris.

Figure 30. Failed lens print

Some lenses printed with the convex rings were thin towards the outer edge and were difficult to clean and maintain, as they were too fragile the edge would easily fracture and compart.

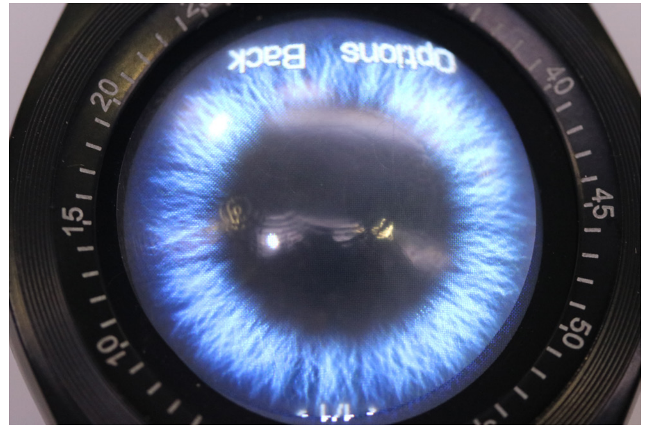


Figure 31. Printed lens with flat base on smartwatch display

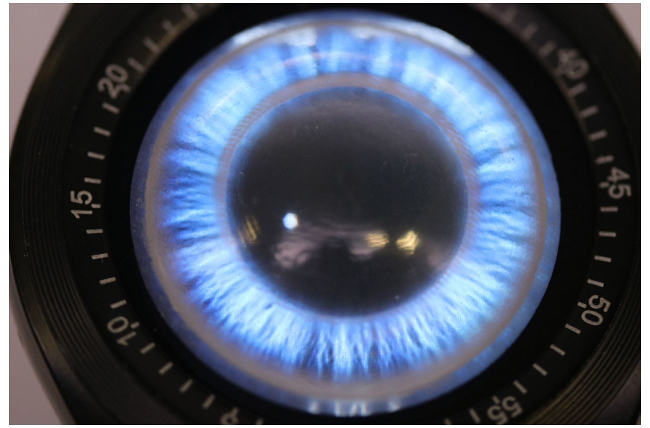


Figure 32. Printed lens with concave ring base on smartwatch display

Seen in figures to the right is a normal flat lens compared to concave lens respectively, set on top the digital watch display. In the concave lens it is clearly visible that the iris detail is magnified in comparison to the convex lens. However, detail is lost as magnification blurs the iris strands together.

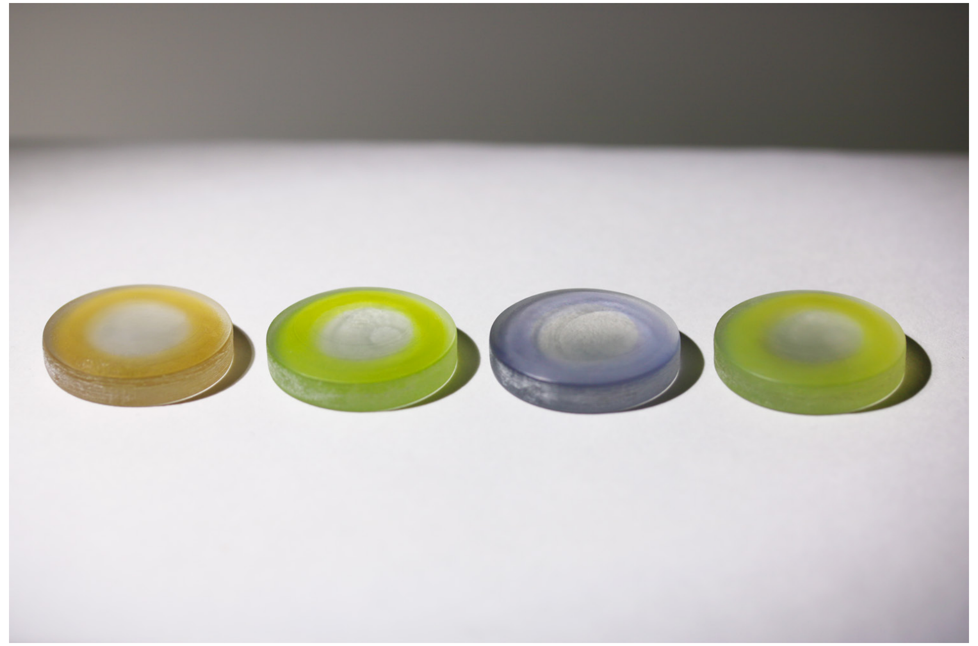


Figure 33. Printed lenses with coloured rings

Coloured Rings

Investigation into colour was conducted through the implementation of flat coloured rings embedded into the clear lens.

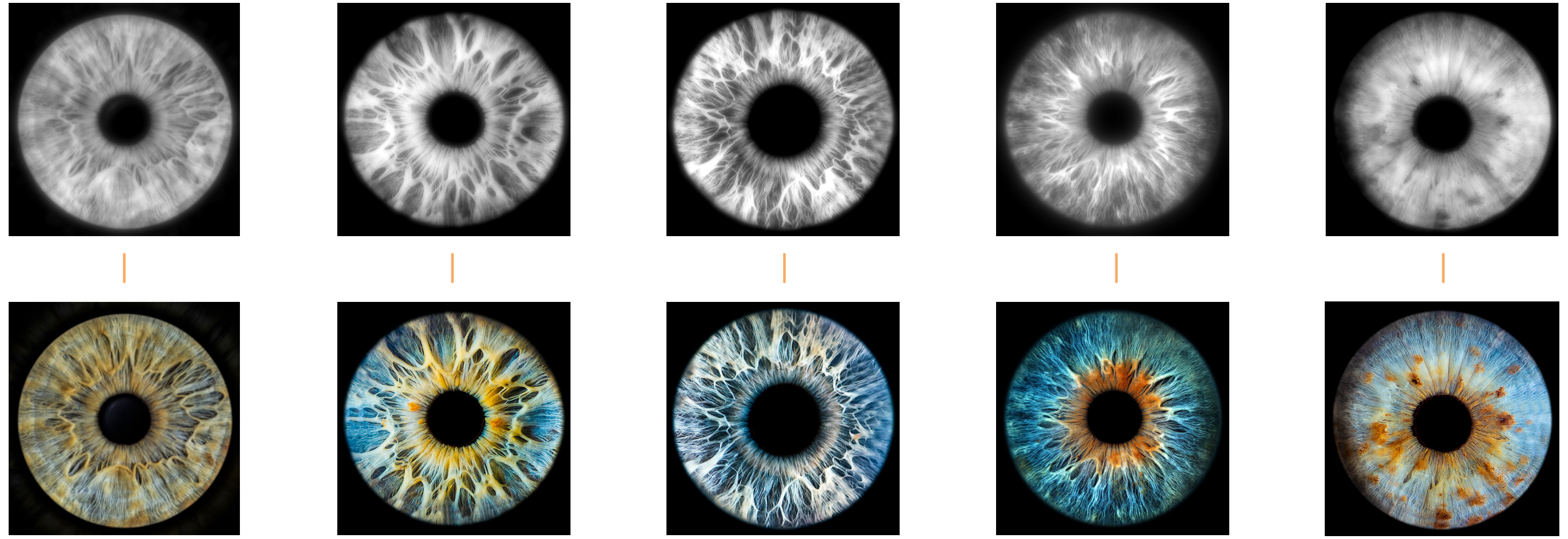


Figure 34. Bitmap files converted from Iris high-resolution images
Figure 35. High-resolution Iris images from theirisphoto

3D Iris

The iris images were designed impart using high definition iris images obtained from website theirisphoto (Irisphoto2, n.d.).

These images were reconstructed into height maps in the bitmap (BMP) image format by utilizing Materialize (Bounding Box Software - Materialize, n.d.). These files are similar to a black and white image but also contain information for each pixel such as surface elevation data for computer generated modelling software.

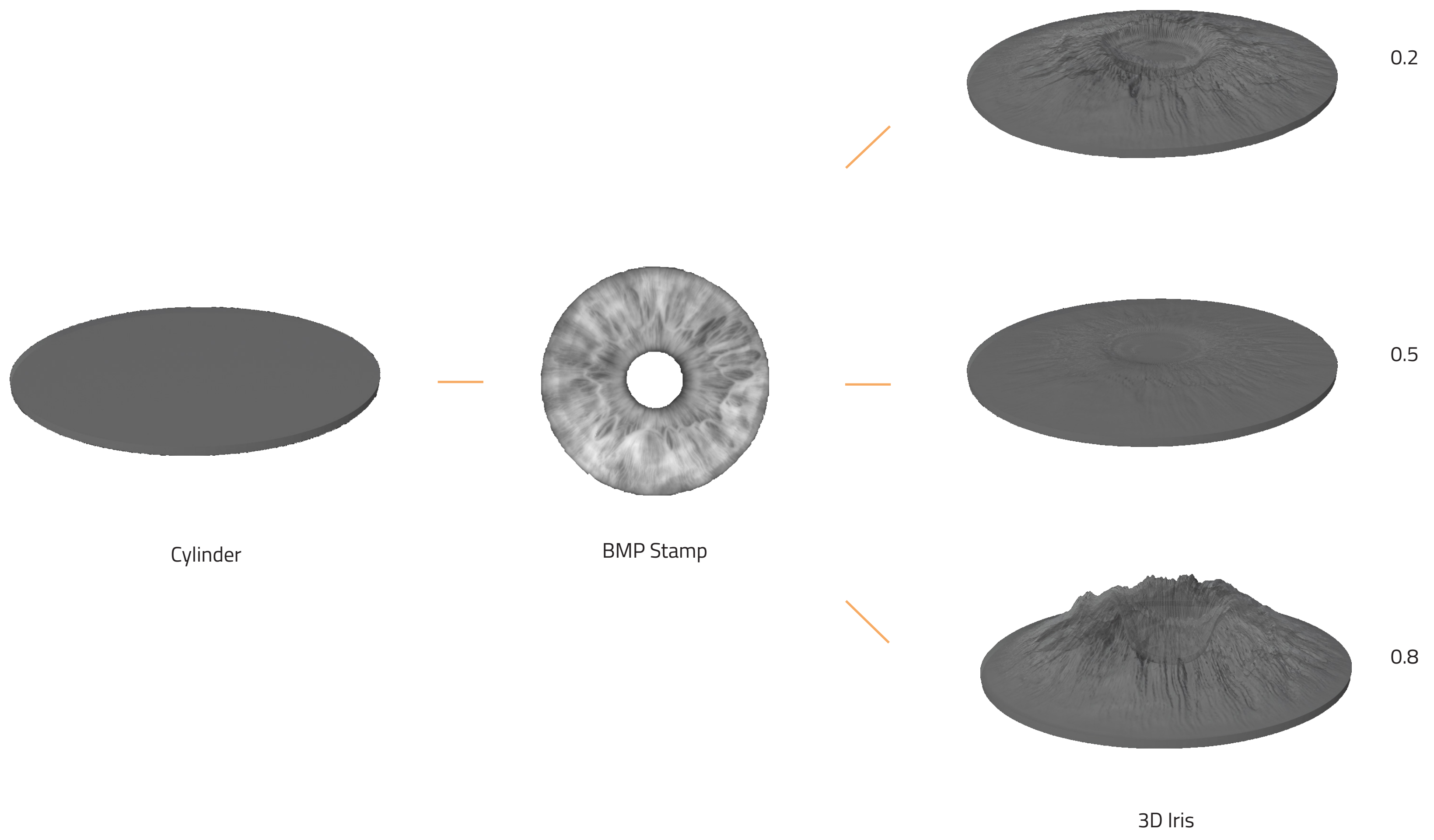


Figure 36. Simplified diagram of the 3D Iris design process

The BMP files were then used to create brushes in Blender, similar to an embossing stamp process. The brush was stamped onto a flat surface of a coin-shaped cylinder. Typically, a cylinder or any closed surface object is necessary in order to 3D print as the printing process requires an object with volume. Height strength of each stamp could also be adjusted to fit the shape of the lenses.

Figure 37. Printed 3D Iris in matte and glossy

Next clear three-dimensional irises were designed and printed to investigate if the effect of the iris animation is nuanced by 3D print.

They were also printed in the two coating styles the j750 printer provided. in, Matte and Glossy, respectively. Glossy coats were preferred as they were observed to be more transparent than Matte coats.

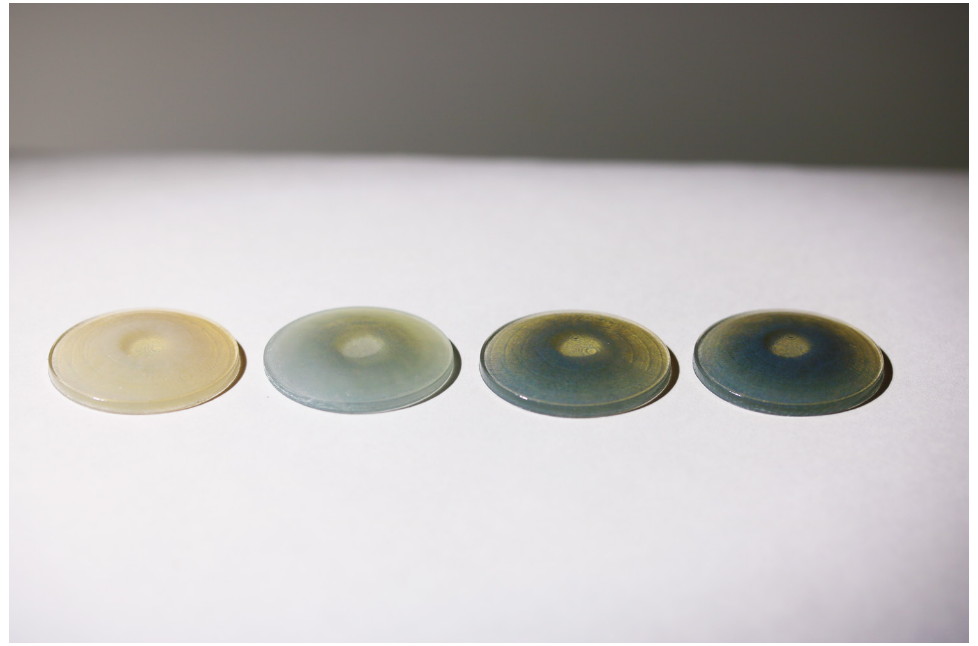


Figure 38. Multi-material 3D Printed lenses with 3D embedded Irises in tinted greyscale values, white to black.

The 3D Iris models were then printed utilizing the j750's multi-material printing in various grayscale colours. Seeing that printing a clear iris and a clear lens would make it invisible. This was also done to discover which values would suit the animation.

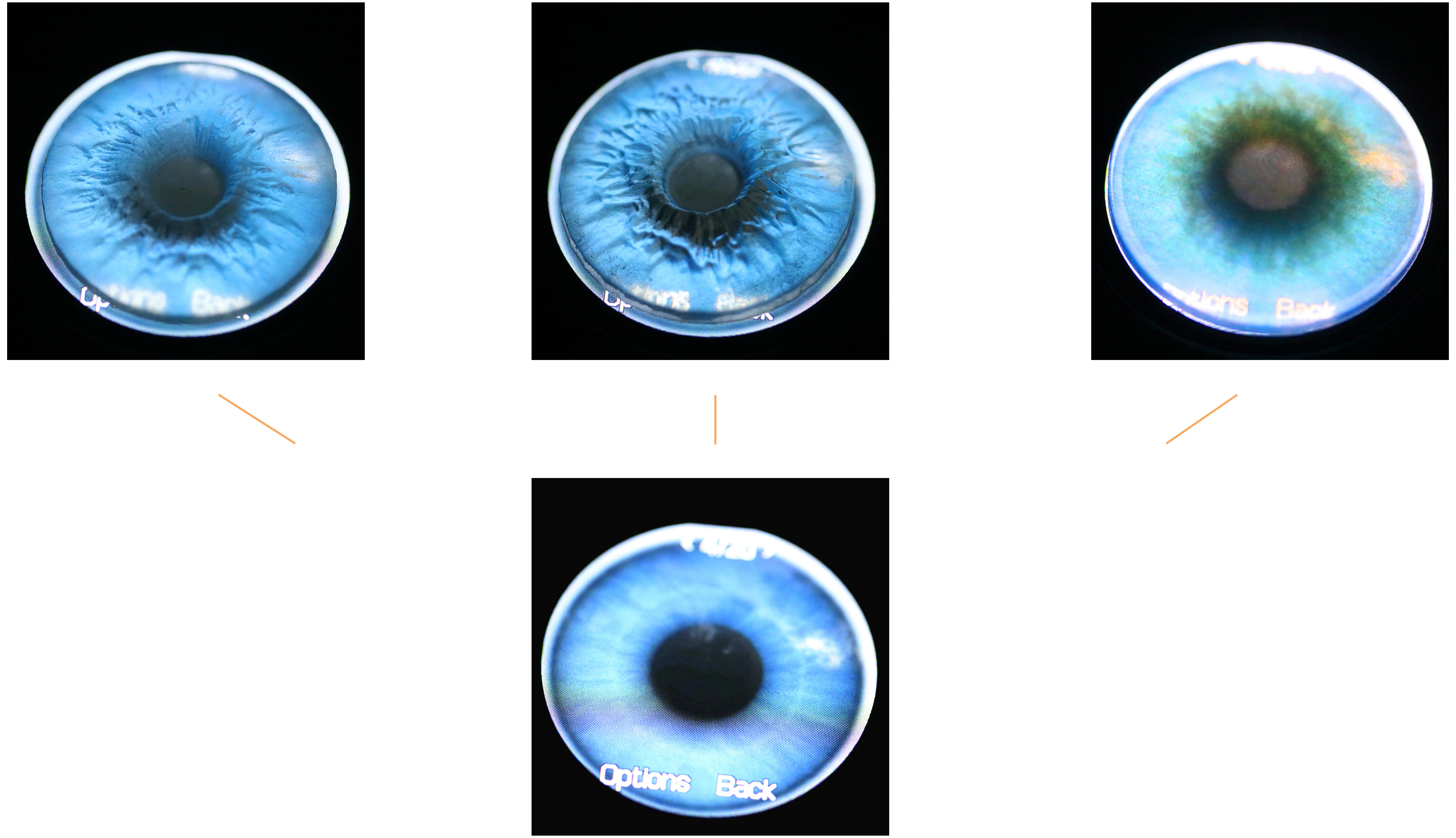
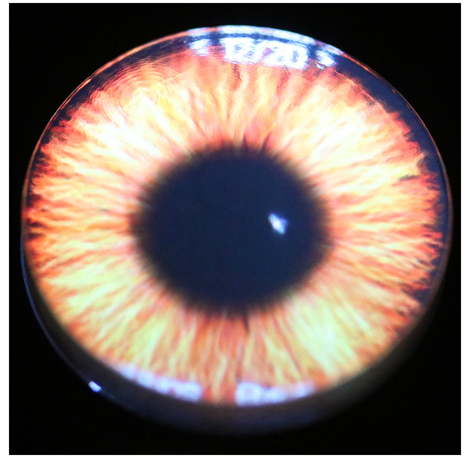
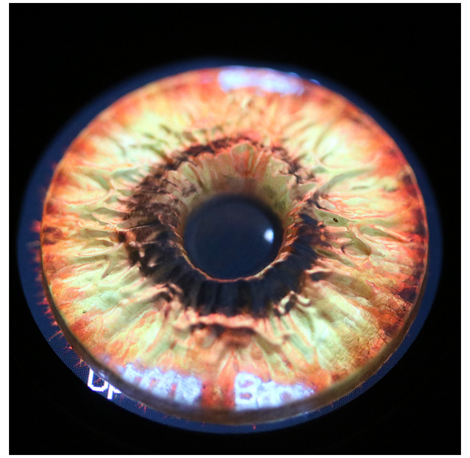
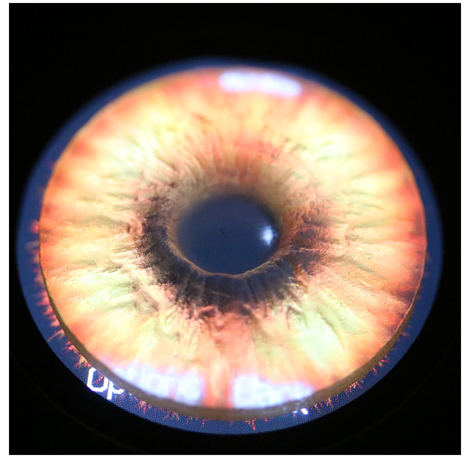


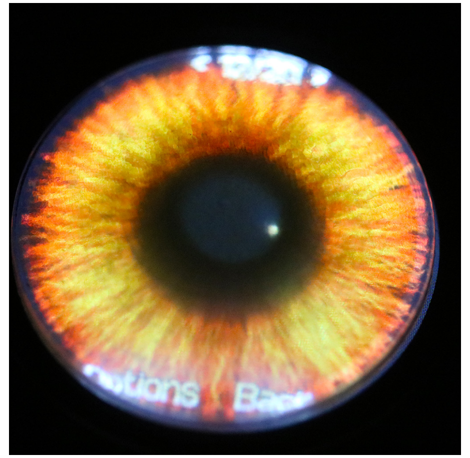
Figure 39a. Printed 3D Iris in Vero Matte on, Figure 39b. Printed 3D Iris in Vero Glossy, Figure 39c Printed 3D tinted Iris in embedded Lens
Figure 39. 3D parametric Iris animation in Smartwatch display

The 3D iris prints were placed on top of the smartwatch display, where the animation was played. As seen from the figures 38a, 38b and 38c, the lens and animation in tandem compliments each other, creating a captivating additional layer for the medium.









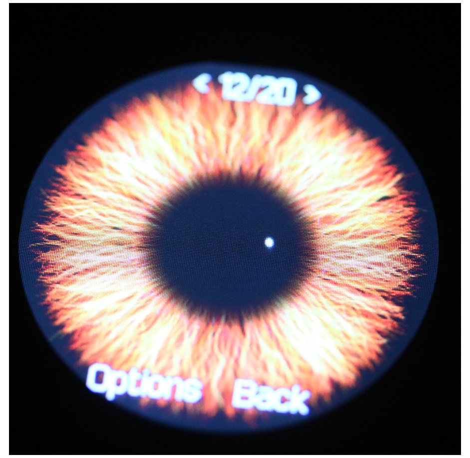


Figure 40a. Printed 3D Iris in Vero Matte on, Figure 40b. Printed 3D Iris in Vero Glossy, Figure 40c Printed 3D tinted Iris in embedded Lens
Figure 40. 2D parametric Iris animation in Smartwatch display

More examples are seen in figures, 40a, 40b and 40c. These are created using the 2D parametric eye design in Adobe AfterEffects. These 3D multi-material prints showcase additional levels of detail and quality that cannot be bought out by animation from the display.

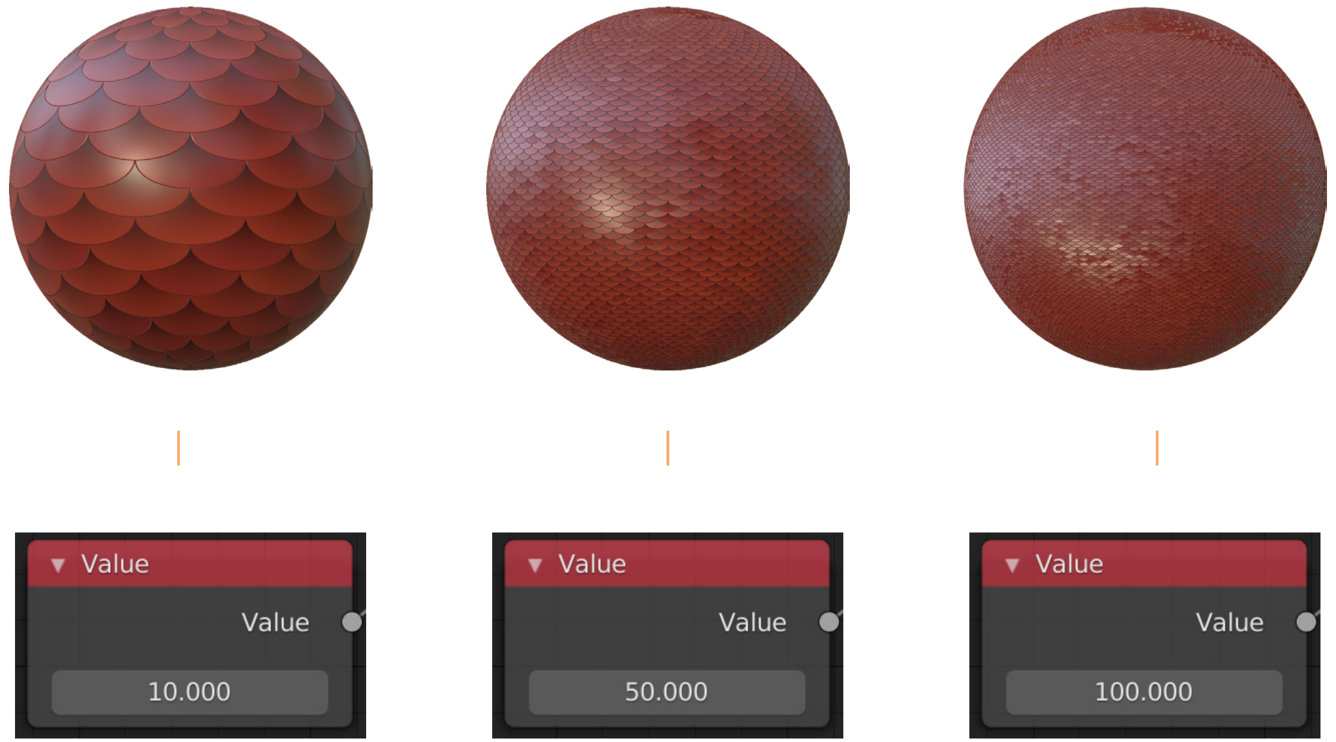
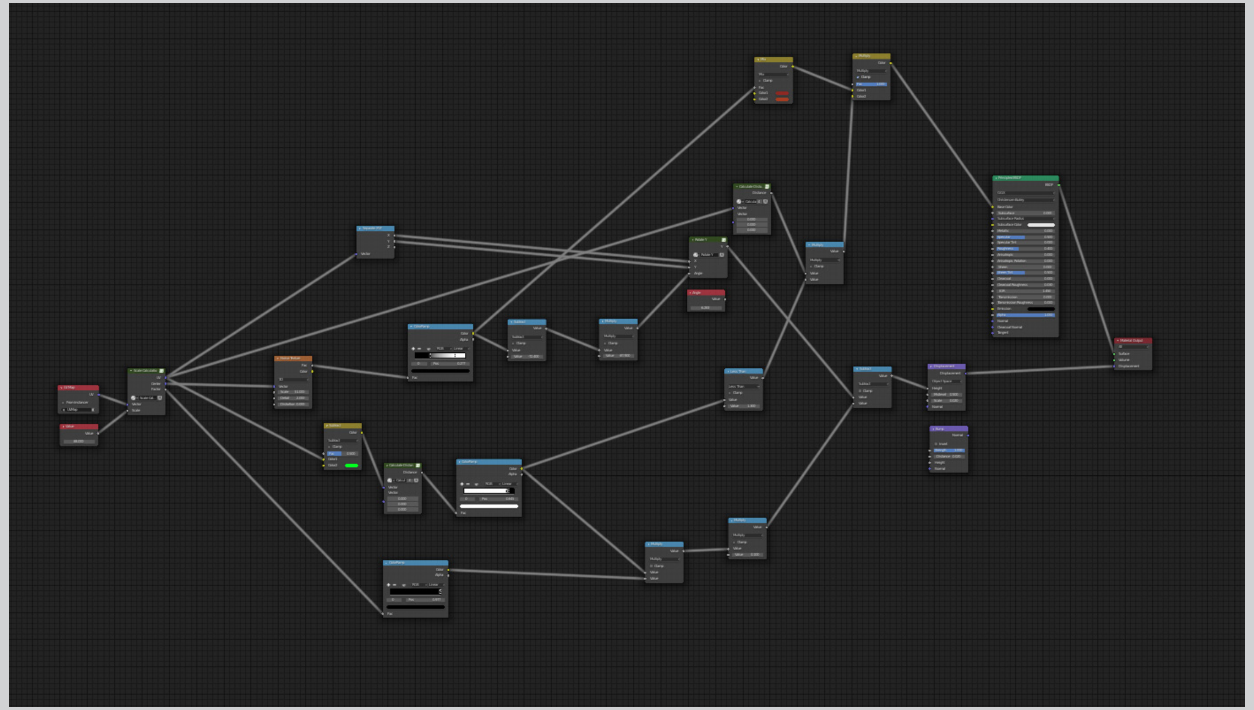


Figure 41. Parametric dragon scales, density/size nodes adjusted to 10, 50 & 100

Voxel Printing



For voxel-printed objects to showcase colour and detail, parametric scales were built using Blender nodes to mimic dragon scales. The adjustable parameters are, size/density and colour. This node set was designed so that it could be applied to any surface model such as a complex model of a dragon.

Figure 41 a. Blender nodes used to create parametric dragon scales - Screenshot

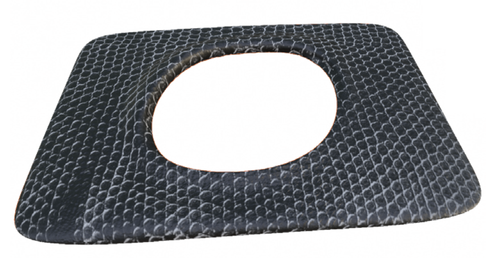


Figure 42. Designed eyelid section of a dragon with parametric skin, rendered in blender, for Voxel-based printing.

Figure 42. Voxel-based printed result.

Succeeding the lens project. Another printing process known as voxel-based printing was explored with the use of the J750 printer. The design concept was to create a housing that would serve as a narrative piece for the dynamic object, the lens and animation from the display.

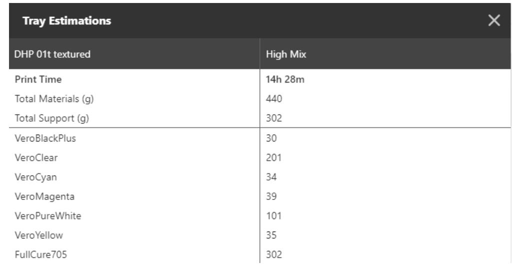
Having said that after many tests using the voxel-based printing method it was found to be a failure, please see figures for more details.

Figure 43. Modelled d ragon head for narrative and housing components. Designed in blender.

Design Output

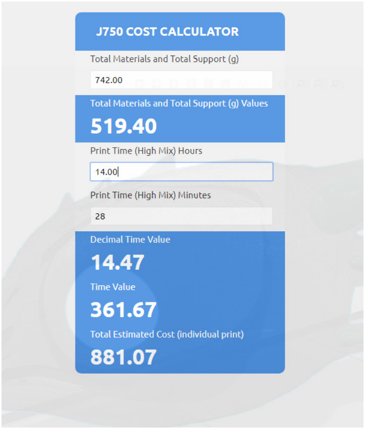
Inspired by animations such as Jane and the Dragon (2005) and the How to Train Your Dragon (2010) a detailed dragon head model was designed in Blender from the ground up. This model was intended to be complementary to the 3D printed lens and display componentry, in order to manifest and contextualise the design output. It was initially designed as a cross-section to enable the componentry to be accessed easily.

Figure 43a. Design inspiration moodboard used for the dragon head



Tray Estimations

DHP 01t textured	High Mix
Print Time	14h 28m
Total Materials (g)	440
Total Support (g)	302
VeroBlackPlus	30
VeroClear	201
VeroCyan	34
VeroMagenta	39
VeroPureWhite	101
VeroYellow	35
FullCure705	302



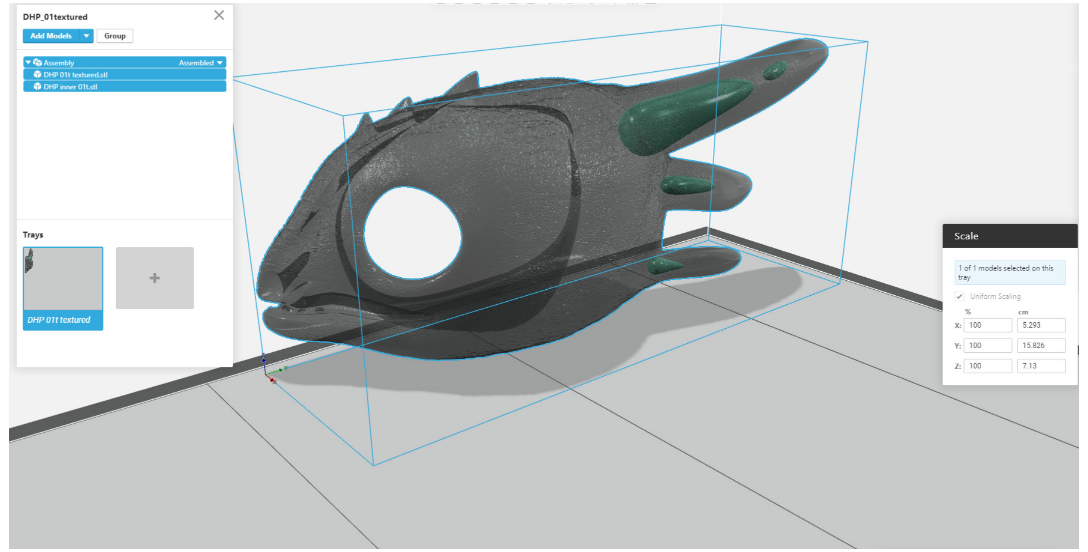


Figure 44. estimated time to print - Screenshot Figure 44a. estimated cost - Screenshot
Figure 44b. Dragon head in Grabcad, ready to print - Screenshot.

However, this proved to be a costly and time-consuming avenue as the estimated cost to print this model would be 881 NZD with a total build time of 14 hours. For these reasons, the path was abandoned.

Figure 45. Dragon head wall plaque side and back view

The solution came in a Dragon wall plaque. This served as the new narrative piece for the design output, which would house the lens and display with animation to complete a contextualized dynamic object for exhibition.

Figure 46. Components removed from the dragon wall plaque

Figure 47. tools used to remove the components and cut out the eye

Figure 48. Design Output 01

Figure 49. Design Output 02

Figure VI. Dynamic Object: 3D Printed Clear Lens on Animated Display 03

Final Evaluation and Conclusion

Whilst Disney research is experimenting with display and printing technology, their focus is on objects that sit on top of displays, which has restrictions by design. This research reveals a novel approach to designing dynamic objects with 3D multi material-printing. The work also demonstrates how immersive dynamic movement can easily be produced, which is something that is difficult to achieve with animatronics. The research bridges the gap between the dynamic digital and physical, that is static 3D printing.

To conclude, a successful immersive exhibit exists through the use of multimedia and clear narrative, as humans respond and recall those experiences better. This research seeks to explore how multi-material 3D printing can be used in conjunction with dynamic displays to design Animated Additive Manufacturing objects to advance immersive exhibits. The design output showcases the potential for dynamic objects to create compelling exhibits and in some instances replace older analogue technology such as animatronics.

For future applications it could be shifted to personally tailored user experience for an exhibition, for example wirelessly uploading viewers' own eye colour to display through a phone. Although in this research, attempts at voxel-based printing were unsuccessful, voxel-based multi property printing has been used in industry, such as WetaWorkshop realistic prosthetic eyeballs (Wellington, 2019). And with the emerging new display technologies such as flexible displays they offer the potential to follow the shape of a 3D object, the ability to contour with organic shapes meaning less distance between the display and the object's surface. Due to this, less environmental waste will be produced, and cause cheaper manufacturing as they become more common and mass produced meaning they could be equipped with more products.

We could see implementation flexible displays being integrated into the layers during the printing process.

Animated Additive Manufacturing presents a novel approach to the way dynamic objects are designed and experienced. Thrusting this research to new and exciting possibilities in the future of designing immersive exhibits.

References

Doubrovski, E. L., Tsai, E. Y., Dikovsky, D., Geraedts, J. M. P., Herr, H., & Oxman, N. (2015). Voxel-based fabrication through material property mapping: A design method for bitmap printing. *Computer-Aided Design*, *60*, 3–13. https://doi.org/10.1016/j.cad.2014.05.010

Bader, C., Kolb, D., Weaver, J. C., Sharma, S., Hosny, A., Costa, J., & Oxman, N. (2018). Making data matter: Voxel printing for the digital fabrication of data across scales and domains. *Science Advances*, *4*(5), eaas8652. https://doi.org/10.1126/sciadv.aas8652

USA, R. S. from O. (2014). *Taken at the National Geographic Museum Spinosaurus Exhibit.* Fossils and Foam. https://commons.wikimedia.org/wiki/File:3D_printed_Spinosaurus_skulls.jpg

Jacklee. (2016). *English: An interactive display on Level 2 of the City Hall Wing of the National Gallery Singapore.* Own work. https://commons.wikimedia.org/wiki/File:Interactive_display,_City_Hall_Wing,_National_Gallery_Singapore_-_20160101.jpg#filehistory

College, O. (2013). *English: Illustration from Anatomy & Physiology, Connexions Web site. http://cnx.org/content/col11496/1.6/, Jun 19, 2013.* Anatomy & Physiology, Connexions Web site. http://cnx.org/content/col11496/1.6/, Jun 19, 2013. https://commons.wikimedia.org/wiki/File:1413_Structure_of_the_Eye.jpg

Libraries, C. C. (2015). *Rikihana Carkeek* [Photo]. https://www.flickr.com/photos/christchurchcitylibraries/23083380982/

Disney researchers design 3D Printed curved display to eliminate distortion (video). (n.d.). 3ders.Org. Retrieved 2 June 2020, from http://www.3ders.org/articles/20131008-disney-researchers-design-3d-printed-curved-display-to-eliminate-distortion.html

Libraries, C. C. (2015). *Rikihana Carkeek* [Photo]. https://www.flickr.com/photos/christchurchcitylibraries/23083380982/

Like_the_Grand_Canyon. (2016). *Smaug* [Photo]. https://www.flickr.com/photos/like_the_grand_canyon/24566989335/

Austria, prilfish from V. (2010). *Mantis Shrimp macro—Odontodactylus scyllarus*. Mantis Shrimp macro - Odontodactylus scyllarus. https://commons.wikimedia.org/wiki/File:Mantis_shrimp_(Odontodactylus_scyllarus).jpg

Gallipoli: The Scale of Our War. (2015, December 21). Museum of New Zealand Te Papa Tongarewa, Wellington, NZ. https://www.tepapa.govt.nz/visit/exhibitions/gallipoli-scale-our-war

Alper, S., Us, E. O., & Tasman, D. R. (2019). The evil eye effect: Vertical pupils are perceived as more threatening. *Cognition and Emotion*, *33*(6), 1249–1260. https://doi.org/10.1080/02699931.2018.1550741

Banks, M. S., Sprague, W. W., Schmoll, J., Parnell, J. A. Q., & Love, G. D. (2015). Why do animal eyes have pupils of different shapes? *Science Advances*, *1*(7), e1500391. https://doi.org/10.1126/sciadv.1500391

Calvo, M. G., & Fernández-Martín, A. (2013). Can the eyes reveal a person's emotions? Biasing role of the mouth expression. *Motivation and Emotion*, *37*(1), 202–211. https://doi.org/10.1007/s11031-012-9298-1

Laeng, B., & Endestad, T. (2012). Bright illusions reduce the eye's pupil. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(6), 2162–2167. JSTOR.

Isbell, L. A. (2006). Snakes as agents of evolutionary change in primate brains. *Journal of Human Evolution*, *51*(1), 1–35. https://doi.org/10.1016/j.jhevol.2005.12.012

MacLean, P. C., Rynes, K. N., Aragón, C., Caprihan, A., Phillips, J. P., & Lowe, J. R. (2014). Mother–infant mutual eye gaze supports emotion regulation in infancy during the Still-Face paradigm. *Infant Behavior and Development*, *37*(4), 512–522. https://doi.org/10.1016/j.infbeh.2014.06.008

Kampe, K. K. W., Frith, C. D., Dolan, R. J., & Frith, U. (2001). Direct eye contact with attractive faces activates brain areas associated with 'reward' and 'reward expectation'. *NeuroImage*, *13*(6, Supplement), 425. https://doi.org/10.1016/S1053-8119(01)91768-9

Dillen, L. F. van, Harris, L. T., Dijk, W. W. van, & Rotteveel, M. (2015). Looking with different eyes: The psychological meaning of categorisation goals moderates facial reactivity to facial expressions. *Cognition and Emotion*, *29*(8), 1382–1400. https://doi.org/10.1080/02699931.2014.982514

Papaioannou, G., & Paschou, S. (n.d.). *Papaioannou, G. & Paschou, S. (2015), Human Animatronics in Museum Experience: Casa Parlante - The Living Museum, Corfu, Greece. Presentation at VAMCT 2015, Delphoi, Greece [23-26 September 2015]*. Retrieved 1 July 2020, from https://www.academia.edu/20686283/Papaioannou_G._and_Paschou_S._2015_Human_Animatronics_in_Museum_Experience_Casa_Parlante_-_The_Living_Museum_Corfu_Greece._Presentation_at_VAMCT_2015_Delphoi_Greece_23-26_September_2015_

Kotler, N., & Kotler, P. (2000). Can Museums be All Things to All People?: Missions, Goals, and Marketing's Role. *Museum Management and Curatorship*, *18*(3), 271–287. https://doi.org/10.1080/09647770000301803

Kotler, N. (2007, May 11). *New Ways of Experiencing Culture: The Role of Museums and Marketing Implications: Museum Management and Curatorship: Vol 19, No 4*. https://www-tandfonline-com.helicon.vuw.ac.nz/doi/abs/10.1080/09647770100801904

Faupel, D. (2007). Animatronics vs. Actors. *Tourist Attractions and Parks*, *37*(4), 178.

Rubin, D. C., & Kozin, M. (1984). Vivid memories. *Cognition*, *16*(1), 81–95. https://doi.org/10.1016/0010-0277(84)90037-4

Kalnad, C. (2016). Review on Animatronics. *Imperial Journal of Interdisciplinary Research (IJIR).* http://www.onlinejournal.in/IJIRV2I9/183.pdf

Tunnicliffe, S. D. (1999). It's the way you tell it! What conversations of elementary school groups tell us about the effectiveness of animatronic animal exhibits. *Journal of Elementary Science Education*, *11*(1), 23–37. https://doi.org/10.1007/BF03173788

Tunnicliffe, S. D. (2000). Conversations of family and primary school groups at robotic dinosaur exhibits in a museum: What do they talk about? *International Journal of Science Education*, *22*(7), 739–754. https://doi.org/10.1080/095006900050044071

Chondro, P., Chang, C.-H., Ruan, S.-J., & Shen, C.-A. (2018). Advanced Multimedia Power-Saving Method Using a Dynamic Pixel Dimmer on AMOLED Displays. *IEEE Transactions on Circuits and Systems for Video Technology*, *28*(9), 2200–2209. https://doi.org/10.1109/TCSVT.2017.2723600

Manabe, H., Date, M., Takada, H., & Inamura, H. (2016). Techniques to Reduce Driving Energy of 1-Pixel Displays. *IEEE Transactions on Industry Applications*, *52*(3), 2638–2647. https://doi.org/10.1109/TIA.2016.2531621

Pauluth, D., & Tarumi, K. (2004). Advanced liquid crystals for television. *Journal of Materials Chemistry*, *14*(8), 1219–1227. https://doi.org/10.1039/B400135B

Hillewaert, H. (2008). Nautilus pompilius L. 1758. Own work. https://commons.wikimedia.org/wiki/File:Nautilus_pompilius_(head).jpg

New True FHD AMOLED Display Uses Innovative Pixel Arrangement. (2018, June 2). *Product News Network*. Gale General OneFile. http://link.gale.com/apps/doc/A541291876/ITOF?u=vuw&sid=zotero&xid=8e96e27f

Wagner, K. (2017). The mummy and the medical gaze: Digital visualisations in the British Museum's exhibition Ancient lives, new discoveries. *Museum Management and Curatorship*, *32*(2), 160–175. https://doi.org/10.1080/09647775.2016.1273131

Gelfand, A. (2013). If We Build It (and Promote It) They Will Come: History of Analog and Digital Exhibits in Archival Repositories. *Journal of Archival Organization*, *11*(1–2), 49–82. https://doi.org/10.1080/15332748.2013.882160

Macdonald, S. (2007). Interconnecting: Museum visiting and exhibition design. *CoDesign*, *3*(sup1), 149–162. https://doi.org/10.1080/15710880701311502

Ravnik, R., & Solina, F. (2013). Interactive and Audience Adaptive Digital Signage Using Real-Time Computer Vision. *International Journal of Advanced Robotic Systems; London*, *10*(2). http://dx.doi.org.helicon.vuw.ac.nz/10.5772/55516

Screven, C.G. (2000). Information design in informal settings: Museums and other public spaces. In R.E. Jacobson (Ed.), Information Design (p. 131–192). Cambridge, MA: MIT Press.

Brockmeyer, E., Poupyrev, I., Mahler, M., Dauner, J., & Krahe, J. (2013). PAPILLON: Expressive eyes for interactive characters. *ACM SIGGRAPH 2013 Emerging Technologies on - SIGGRAPH '13*, 1–1. https://doi.org/10.1145/2503368.2503380

Matisons, M. (2014, December 9). *3D Printing Technology Helps Disney Research Design Realistic Human Eye Model*. 3DPrint.Com | The Voice of 3D Printing / Additive Manufacturing. https://3dprint.com/29400/disney-research-3d-eye-study/

Berard, P., Bradley, D., Nitti, M., Beeler, T., & Gross, M. (n.d.). High-Quality Capture of Eyes. *Disney Research Zurich*. Retrieved 30 August 2020, from https://www.researchgate.net/publication/286245792_High-Quality_Capture_of_Eyes/citations

Jo, Y. H., Kim, J., Cho, N. C., Lee, C. H., Yun, Y. H., & Kwon, D. K. (2019). A STUDY ON PLANNING AND PLATFORM FOR INTERACTIVE EXHIBITION OF SCIENTIFIC CULTURAL HERITAGE. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2-W15*, 605–607. https://doi.org/10.5194/isprs-archives-XLII-2-W15-605-2019

Wong, K. V., & Hernandez, A. (2012, August 16). *A Review of Additive Manufacturing* [Review Article]. ISRN Mechanical Engineering; Hindawi. https://doi.org/10.5402/2012/208760

Guide to Voxel Printing—GrabCAD Help Center. (n.d.). Retrieved 12 July 2020, from https://help.grabcad.com/article/230-guide-to-voxel-printing?locale=en

Singh, R. (2010). Three-dimensional printing for casting applications: A state of art review and future perspectives, Advanced Materials Research, (p 83-86).

Singh, R. (2011). Process capability study of polyjet printing for plastic components. *Journal of Mechanical Science and Technology*, *25*(4), 1011–1015. https://doi.org/10.1007/s12206-011-0203-8

Bader, C., Kolb, D., Weaver, J. C., Sharma, S., Hosny, A., Costa, J., & Oxman, N. (2018). Making data matter: Voxel printing for the digital fabrication of data across scales and domains. *Science Advances*, *4*(5), eaas8652. https://doi.org/10.1126/sciadv.aas8652

Smaug unveiled at Wellington airport. (2014, November 6). *NZ Herald*. https://www.nzherald.co.nz/entertainment/news/article.cfm?c_id=1501119&objectid=11354295

Gallipoli: The Scale of Our War. (2015, December 21). Museum of New Zealand Te Papa Tongarewa, Wellington, NZ. https://www.tepapa.govt.nz/visit/exhibitions/gallipoli-scale-our-war

Gore, A. V., Tomins, K. A., Iben, J., Ma, L., Castranova, D., Davis, A. E., Parkhurst, A., Jeffery, W. R., & Weinstein, B. M. (2018). An epigenetic mechanism for cavefish eye degeneration. *Nature Ecology & Evolution*, *2*(7), 1155–1160. https://doi.org/10.1038/s41559-018-0569-4

Land, M. F., & Nilsson, D.-E. (2012). *Animal Eyes*. Oxford University Press, Incorporated. http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=886475

Callaerts, P., Clements, J., Francis, C., & Hens, K. (2006). Pax6 and eye development in Arthropoda. *Arthropod Structure & Development*, *35*(4), 379–391. https://doi.org/10.1016/j.asd.2006.09.002

Wilson, P. F., Stott, J., Warnett, J. M., Attridge, A., Smith, M. P., & Williams, M. A. (2018). Museum visitor preference for the physical properties of 3D printed replicas. *Journal of Cultural Heritage*, *32*, 176–185. https://doi.org/10.1016/j.culher.2018.02.002

Sanford, C. W. (2010). Evaluating Family Interactions to Inform Exhibit Design: Comparing Three Different Learning Behaviors in a Museum Setting. *Visitor Studies*, *13*(1), 67–89. https://doi.org/10.1080/10645571003618782

Bloemendal, H. (1977). The vertebrate eye lens. *Science*, *197*(4299), 127–138. https://doi.org/10.1126/science.877544

Koch, L. (2018). All eyes on rapid adaptive evolution. *Nature Reviews Genetics*, *19*(8), 472–472. https://doi.org/10.1038/s41576-018-0027-9

Gore, A. V., Tomins, K. A., Iben, J., Ma, L., Castranova, D., Davis, A. E., Parkhurst, A., Jeffery, W. R., & Weinstein, B. M. (2018). An epigenetic mechanism for cavefish eye degeneration. *Nature Ecology & Evolution*, *2*(7), 1155–1160. https://doi.org/10.1038/s41559-018-0569-4

NILSSON, D.-E. (2013). Eye evolution and its functional basis. *Visual Neuroscience*, *30*(1–2), 5–20. https://doi.org/10.1017/S0952523813000035

Robinson, A. (2016). Eyes that surprise. *The Lancet*, *388*(10045), 650. https://doi.org/10.1016/S0140-6736(16)31281-8

Land, M. F., & Nilsson, D.-E. (2012). *Animal Eyes*. Oxford University Press, Incorporated. http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=886475

Nilsson, D.-E., Warrant, E. J., Johnsen, S., Hanlon, R., & Shashar, N. (2012). A Unique Advantage for Giant Eyes in Giant Squid. *Current Biology*, *22*(8), 683–688. https://doi.org/10.1016/j.cub.2012.02.031

Verasztó, C., Gühmann, M., Jia, H., Rajan, V. B. V., Bezares-Calderón, L. A., Piñeiro-Lopez, C., Randel, N., Shahidi, R., Michiels, N. K., Yokoyama, S., Tessmar-Raible, K., & Jékely, G. (2018). Ciliary and rhabdomeric photoreceptor-cell circuits form a spectral depth gauge in marine zooplankton. *ELife*, *7*, e36440. https://doi.org/10.7554/eLife.36440

Disney Research develops 3D printed optics. (2012, October 5). New Atlas. https://newatlas.com/disney-research-3d-printed-optics/24435/

Wellington, V. U. of. (2019, September 11). *Eyes on the prize*. Victoria University of Wellington; Victoria University of Wellington. https://www.wgtn.ac.nz/news/victorious/2019/spring-2019/eyes-on-the-prize