

# A digital workflow for 3D printed full-colour ocular prosthetics



Master Thesis

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Integrated Product Design  
Delft University of Technology

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## **Master Thesis**

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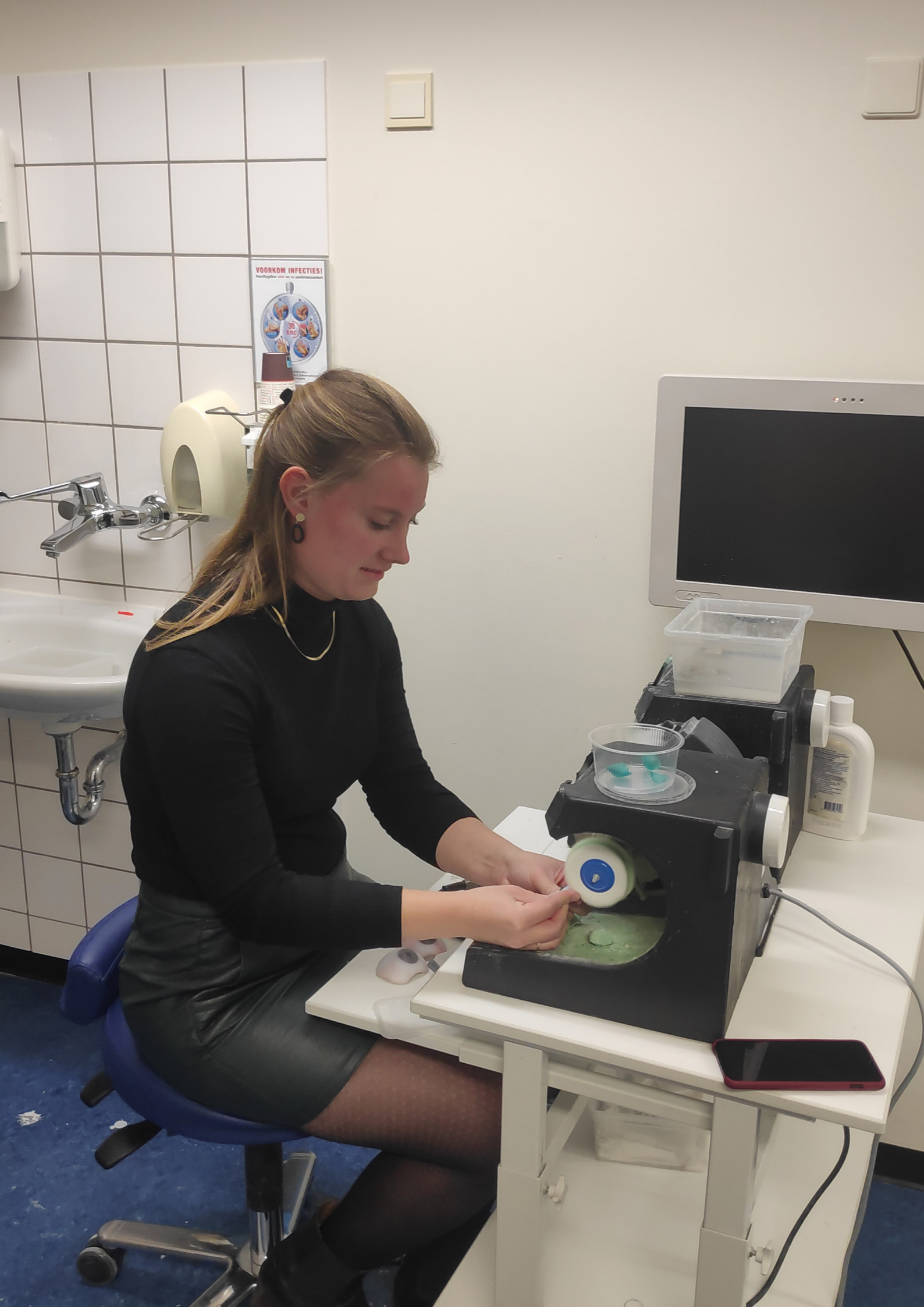
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# Preface

Dear reader,

In front of you is my thesis, the final deliverable of my graduation project for the master Integrated Product Design at TUDelft. This marks the end of my life as a student and the start of my life as a professional designer. For the past six months, I have explored how ocular prostheses can be produced with digital production techniques. I had the opportunity to work with a state-of-the-art full-colour 3D printer and to make multiple copies of my own eye. To reproduce one that is exactly the same was an exciting and complex challenge. I am happy and proud to share my final work with you, which I could not have done without a number of people.

First, I would like to thank the research team for Amsterdam UMC for providing me with this opportunity. It was an honour to be part of and to contribute to the field of ocular prosthetics. A special thanks to Jelmer for your trust in me and the freedom you gave me to make it my own.

Additionally, I would like to thank Willemijn, my chair, for her unstoppable enthusiasm and for providing constructive feedback. I appreciate that you took the time for me to give mini-lectures about colour and helped me with the targets. I would like to thank Zjenja, my mentor, for his technical perspective. I value your time and input during the Friday morning meetings. You encouraged me to learn more about the printer's 'black box' every time we met. Furthermore, Joris, thank you for teaching me how to work with the Stratasys J735 3D printer. It was a pleasure to have you as a sparring partner when the printing did not do what it was supposed to.

Finally, special thanks to my friends, boyfriend, roommates and family for their personal support during these months. You helped me either by giving feedback on my writing, being an eye model, or supporting me with ideas, encouragement or distractions. I could not have done it without you.

I really enjoyed working on this project, and I hope it can be a source of inspiration.

Enjoy reading.

- Ilse Calis

# Glossary

## **Blender**

Free and open source 3D computer graphics software interface for creating 3D models, animation, visual effects, rigging, and much more.

## **Bulbar conjunctiva**

A clear membrane of the eye which covers the outer surface of the eye

## **Capturing**

To record or take a picture of something using a camera

## **Contralateral eye**

The eye located on the opposite side of the body

## **Cornea**

The transparent outer covering of the eye

## **Displacement mapping**

An alternative computer graphics technique to create 3D geometry based on a texture- or height map

## **Gamut**

Range of realisable colours

## **Grasshopper**

A visual programming language and environment that runs within the Rhinoceros 3D CAD application

## **Limbus**

Transitional zone of the cornea and the sclera

## **Iris**

The coloured circular part of the eye that surrounds the pupil

## **LUT**

Lookup table

## **Ocular prosthesis**

A type of craniofacial prosthesis that replaces an absent natural eye

## **Ocularist**

Someone who specialises in the fabrication and fitting of ocular prostheses for people who have lost an eye or eyes due to trauma or illness

## **PCS**

Profile connection space, the standard colour space

## **PolyJet technology**

A 3D printing technology that builds parts by jetting thousands of photopolymer droplets and solidifying them with a UV light

## **Pupil**

The circular black area in the centre of an eye through which light enters

## **Refractive index**

An indication of the light-bending ability of an optical medium

## **Refractive power**

The degree to which an optical system converges or diverges light

## **Sclera**

The white layer that covers the outside of the eye

## **UV mapping**

The 3D modelling process of projecting a 2D image to a 3D model

## **Voxel**

Represents a value on a regular grid in three-dimensional space, 3D pixel

# Executive summary

Fabricating custom-made ocular prostheses is currently a highly-skilled, labour-intense and non-reproducible process performed by an ocularist. Custom-fit prostheses are made from acrylic using a plaster mould, the iris is hand-painted, and veins are mimicked by adding red embroidery threads. Digital production techniques provide opportunities to improve and automate this process. Therefore, this graduation project aims to research a possible digital workflow, including data capturing and calibration, modelling and 3D printing, for producing 3D-printed full-colour ocular prosthetics. The workflow should capture and reproduce the eye's appearance to create a life-like ocular prosthesis that resembles the patient's facial appearance as closely as possible.

Research into manual and digital production techniques results in a proposed digital workflow showing how a prosthesis can be produced. The workflow consists of five phases: collect, design, produce, post-process and finalise and shows how the patient and the ocularist are involved.

## **Data capturing and calibration**

The patient's eye colour data needs to be captured and calibrated to ensure accurate colour reproduction of the eye. The images can be calibrated by applying a colour profile made from a colour target to correct the camera error. The capturing research showed that photographing is a suitable technique to collect colour data for accurate colour reproduction if the eye and the colour target are shot under a controlled light condition. Multiple calibrated iris images were printed and compared to the participant's eye to review the capturing and calibration process.

## **Modelling**

The modelling research showed that a parametric model based on a computational design template is a suitable solution for adjusting the prosthesis model to a personalised shape. The template should automatically model the

inner parts of the prosthesis based on the outer shape and important parameters, such as the iris and pupil diameter. The first steps towards creating this computational design template are shown in this report by modelling a parametric iris disk.

## **3D Printing**

The full-colour 3D printing technology's capabilities were exploited to reproduce best the various features of a human eye, such as the sclera, blood vessels, pupil, cornea and iris. This investigation showed that mapping an eye image to the model does not always give the desired result and that different printing techniques are suitable for different eye parts. Alternative approaches, like contoning, sclera generator and 'dotting' and 'varying line deepness' techniques, are exploited and show promising results. However, a voxel-based printing technique is needed to combine and control these approaches, and current software lacks these possibilities.

Two experts and five users validated prostheses produced following the proposed digital workflow through an interview and by photographing them next to their eyes. All participants were impressed by the prosthesis and rated the total prosthesis as 'sufficient' or 'good'. Nonetheless, it remains a challenge to reproduce the exact iris colour, structure and veins. A voxel-based printing technique is recommended to have more control over these various aspects. More research is needed to explore the possibilities for controlling colour on a voxel level and to model a complete voxel-based prosthesis. The comparison between the manual and digital workflow showed that 3D printing results in significant time savings since over four hours of manual work could be replaced by 3D printing. 3D printing ocular prostheses make the workflow reproducible and faster, which leads to more accessible and affordable prostheses in the future.



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# 1 Introduction

This chapter provides an introduction to my graduation project about a digital workflow for 3D-printed full-colour ocular prosthetics.



# 1.1. Project introduction

In the Netherlands, roughly 20.000 people wear an ocular prosthesis as a result of losing their eye due to disease or trauma. An ocular prosthesis or artificial eye is a type of craniofacial prosthesis that replaces an absent natural eye. Ocular prostheses are essential means to improve the patient's quality of life by restoring the appearance of the face. It requires a lifelike prosthesis that matches the shape and colour of the contralateral ('real') eye. Although the patient will not be able to see with this eye, prosthetic eyes are used to resemble the patient's facial appearance as close as possible, see Figure 1.

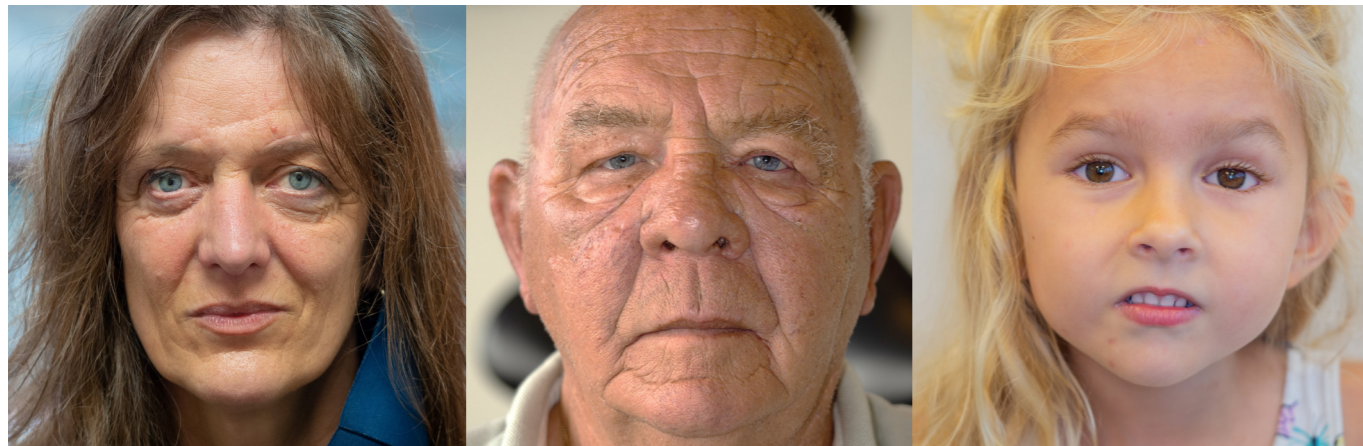


Figure 1. Patients with a prosthetic eye. Can you find the prosthetic eyes? images from [11]

Fabricating custom-made ocular prostheses is currently a highly-skilled, labour-intense and non-reproducible process performed by an ophthalmologist. These prostheses are often called 'glass eyes', although they are usually made of acrylic (polymethylmethacrylate). The most common approach to produce custom-fit prostheses is using a plaster mould based on an impression of the patient's eye socket [1]. Thereafter, the iris of the prosthesis is hand-painted by the ophthalmologist to match the patient's contralateral eye, and the veins of the eye are mimicked by adding red embroidery threads by hand.

New digital 3D production techniques provide opportunities to automate this process. For example, by 3D printing ocular prostheses, the workflow will be faster and reproducible, potentially leading to more accessible and affordable prostheses. Although ocular prostheses have been 3D printed successfully, iris colours are often manually added to the final prosthesis afterwards. Current challenges are obtaining an iris colour that matches the patient's contralateral eye and reproducing the fine details of the human iris with its pigmented and layered texture. As well as parametric modelling of custom-fit prostheses and properties such as biocompatibility and material longevity. Groot et al. [2] present a proof-of-concept of a 3D-printed ocular prosthesis with textured iris and sclera in one single print job, see Figure 2. This proof-of-concept was analysed and used as a starting

point for this project. This project was conducted in cooperation with Dyonne Hartong, Jelmer Remmers and Emiel Romein from Amsterdam University Medical Centers (Amsterdam UMC). They were involved in developing the proof-of-concept [2].

The proof-of-concept [2] shows one example of the printing technique, while in this graduation project, the complete digital workflow for making ocular prostheses, including capturing, modelling, and printing, was studied. The ultimate goal is a workflow that ensures accurate colour reproduction of the eye and is based on a (parametric) design template. In addition, the capabilities of the full-colour 3D printing technology were studied and exploited to reproduce best the various features of the human eye.



Figure 2. Final prosthesis of 'proof-of-concept' (a large and normal size version, and a large version of the textured iris). Image from [2]



## 1.2. Assignment

This project aims to research a possible digital workflow for 3D-printed full-colour ocular prosthetics. This workflow should capture and reproduce the eye's appearance to create life-like ocular prostheses that resemble the patient's facial appearance as closely as possible. This includes exploring digital options for capturing, modelling and 3D printing and comparing these with the current production workflow. To create lifelike results, investigating the iris structure, colour-matching, and the influence of layering and transparency of the cornea is needed. Also, the trade-off between quality and efficiency is explored by comparing the different production workflows. Finally, the fidelity level required for the end product is determined. A state-of-the-art full-colour 3D printer and a high-end professional camera are used during this project.

The scope of this project is shown in Figure 3. Capturing, modelling, printing and post-processing are researched and compared to the conventional production method. Researching the geometrics of the prostheses and properties such as biocompatibility, material longevity and dynamic deformation of the iris during pupillary response are considered outside this project's scope. The entire project brief can be found in Appendix A.

Parallel to this project, an other graduation project is done by J. Mulder to research a parametric model to define the shape of custom-fit prostheses [3]. The goal is that the approaches used in the projects are applicable to each other, and a combination will result in a complete workflow.

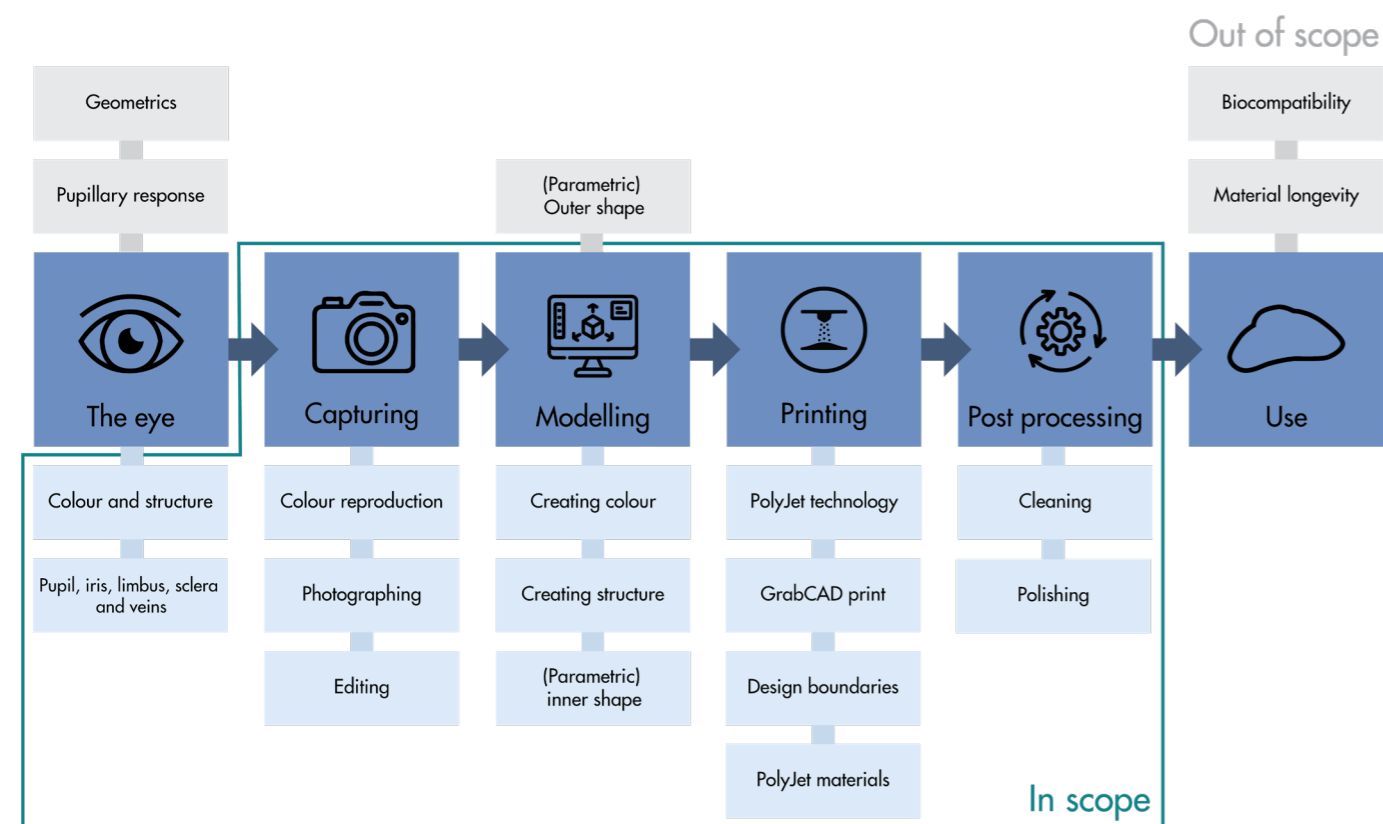


Figure 3. Scope of the graduation project

## 1.3. Research approach & reading guide

The approach of this project was based on Research through Design [4], which means research insights are generated by performing design practice. This process was highly iterative and often switched between theoretical and practical perspectives. Nevertheless, the research can be divided into three parts, capturing, modelling and printing.

This report has been divided into eight chapters. The first chapter, Introduction, is about understanding the problem and defining the research scope. Therefore, the current workflow of fabricating prostheses was analysed. Furthermore, the eye anatomy, visual eye structure, 3D printer technology and colour reproduction methods were studied and presented in visualisations. In the second chapter, related work is presented. A literature review was performed to benchmark technological innovations for producing ocular prosthetics, and the proof-of-concept [2] was evaluated.

First, the digital workflow and the four defined design drivers are presented in chapter three. Then the conducted research is shown following the capturing, modelling and printing steps. The research aims to answer the following research and design questions:

- Capturing (Chapter 4):
- Which (contextual) parameters and process steps are relevant for accurate colour reproduction?
  - How can the patient's eye colour data be captured and calibrated to ensure accurate colour reproduction?

Modelling (Chapter 5):

- Which (contextual) parameters and process steps are relevant for creating a parametric model of the prosthesis's inner parts?
- How can a parametric model, including colour and texture, be created based on a personalised outer shape of the prosthesis?

Printing (Chapter 6):

- How can the capabilities of full-colour 3D printing technology of the Stratasys J735 be exploited to reproduce best the various features of a human eye, such as sclera, blood vessels, pupil, cornea and iris?

Chapter seven contains the validation of prostheses produced following the proposed digital workflow. Four users and two experts are interviewed about their personalised 3D printed prosthesis to validate it against the design criteria. The report's final chapter reflects on the proposed digital workflow and the project. The proposed digital workflow is compared to the conventional workflow by reflecting on feasibility and efficiency. At last, this chapter reflects on the report in the form of a discussion and gives a conclusion and recommendations for further research.



# 1.4. The eye

A thorough understanding of the eye's anatomy is needed to reproduce its various features with the 3D printer at its best. Figure 4 explains the eye anatomy, including important visual elements such as the cornea, limbus, sclera, blood vessels, pupil and iris.

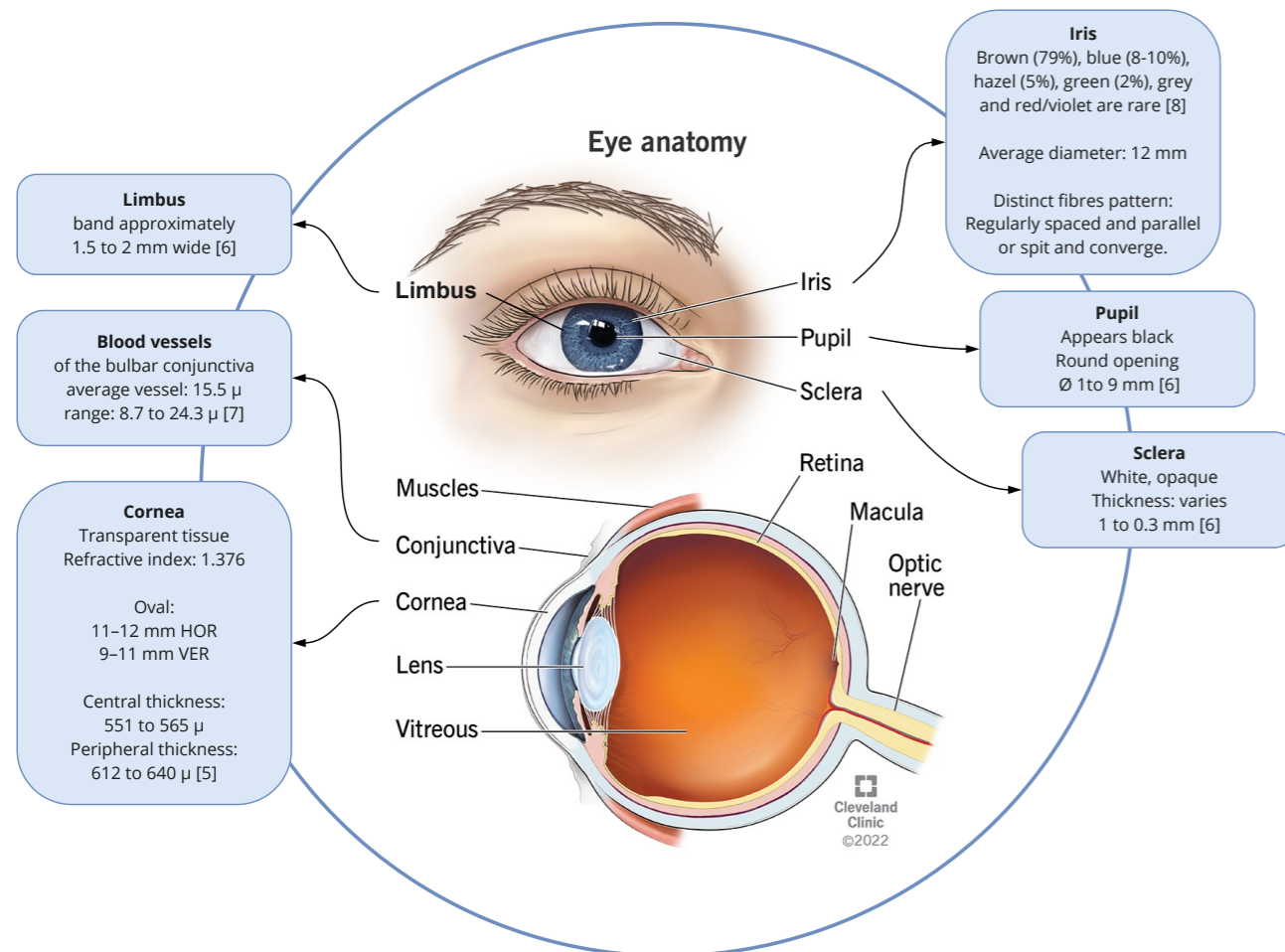
## Cornea

The cornea is a transparent layer made of water and collagen that extends over the iris. The primary purpose of the cornea is to protect the eye against infections. It is shaped as an horizontal oval, measuring 11-12 mm horizontally and 9-11 mm vertically [5]. With a refractive index of 1.376, which indicates the light-bending ability, and a refractive power of 40 to 44 diopter

(D), which shows to which degree the optical system converges light, the cornea accounts for approximately 70% of all refraction [5]. The corneal thickness gradually increases from the centre to the periphery, ranging from 551 to 640 microns [5].

## Limbus

The limbus is the transitional zone of the cornea to the sclera. The band is approximately 1.5 to 2 mm wide [6]. Some people have a darker band of colour visible since the stroma is thinnest at the limbus, where the underlying pigmented cells show through. The band is mostly sharper for young patients and for older patients more diffuse.



## Sclera

The sclera is the white part of the eye that surround the iris. It is made of collagen fibrils, with a varying thickness of 0.3 to 1 mm [6]. Due to the irregular arrangement of the fibril bundles, the sclera appears white. Other colours, like blue or yellow, may occur due to age or disease [6].

## Blood vessels

Blood vessels are visible in the bulbar conjunctiva, a thin transparent membrane covering the opaque white sclera. The veins in the conjunctiva provide essential nutrients to the eye. The blood vessel diameter in the conjunctiva range between 8.7 and 24.3 microns, with a mean value of 15.5 microns [7].

## Pupil

The pupil is the circular opening within the centre of the iris through which light passes before reaching the lens and focuses on the retina. It appears black since most of the light entering the eye does not escape. The pupil plays a vital role in our ability to see. The pupillary light reflex

controls the pupil's diameter in response to the intensity of light that falls on the retina. Thereby it assists in adaptation of vision to different levels of light and darkness. The pupil diameter can vary from 1 to 9 mm depending on the lighting conditions [6].

## Iris

The iris is the coloured area of the eye and is unique to every individual. The colours varies widely in humans. The most common eye colour in the world is brown (79%), followed by blue (8-10%), hazel (5%) and green (2%). Grey and red/violet-coloured eyes are rare [8]. The human iris colour is determined by two factors: the iris pigmentation and the way light is scattered from the iris [8]. The stroma, the front cell layers of the iris, are made from colourless collagen fibres. The back layer, the epithelium, contains dark-brown pigments. Every iris is unique with varying colours and patterns. This feature for instance enables reliable iris scans used for identification. Figure 5 shows an overview of the different iris characteristics.

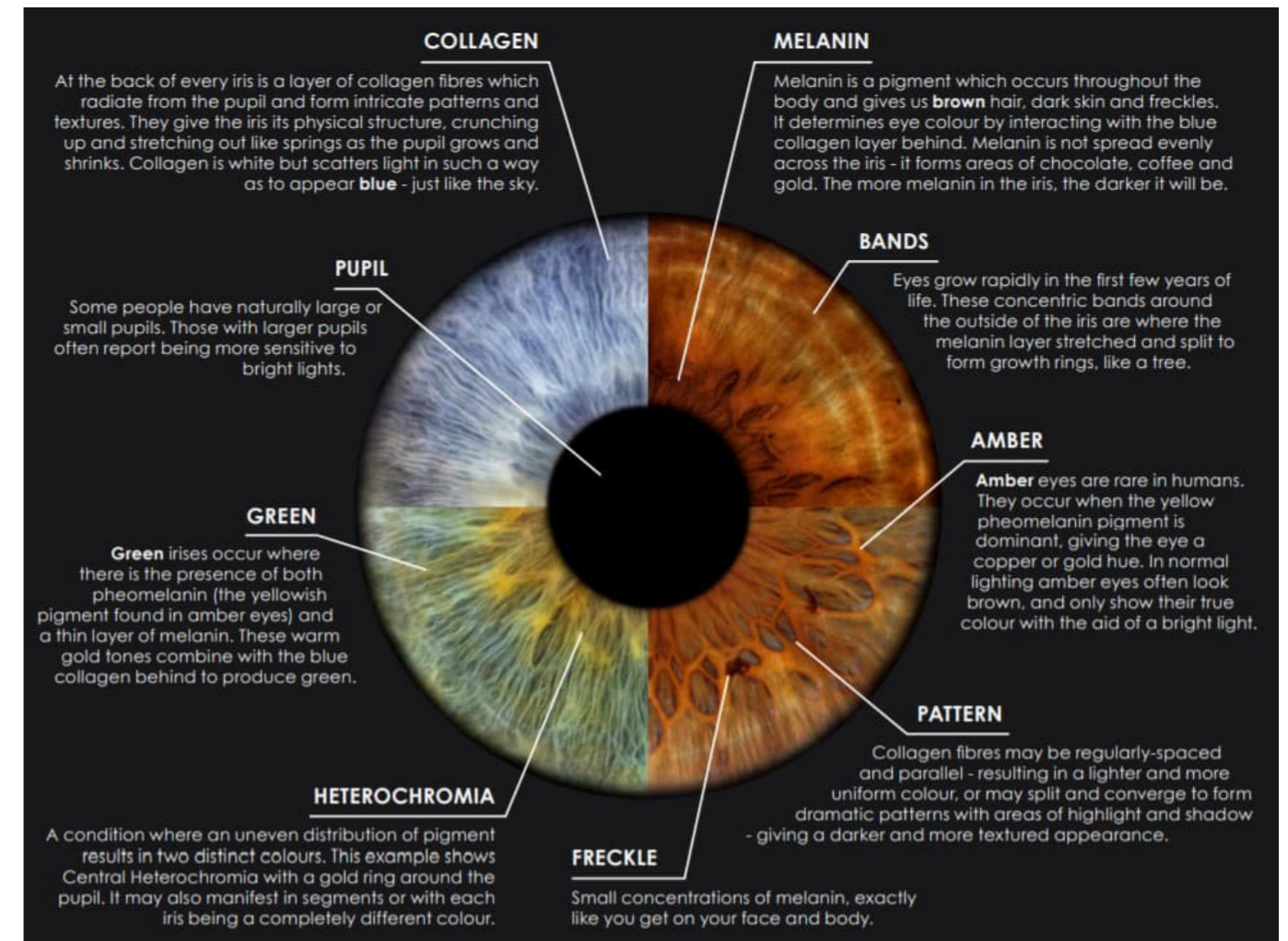


Figure 4. Eye anatomy. Image from [47]

Figure 5. Iris characteristics. Image from [48]

The iris colour is characterised by the presence of melanin in the stroma. Melanin determines the amount of pigment in the eye. Research from Wielgus and Sarna [9] shows that a brown iris contains the highest melanin concentration, whereas a blue iris only has a small amount, see Figure 6. The high concentration of melanin absorbs the majority of light, resulting in a dark brown hue. We perceive a blue iris due to Tyndall scattering [10] in the translucent stroma layer. The light passing through scatters in the stroma. Shorter wavelengths, the blue wavelengths, scatter to a greater extent, whereas longer wavelengths tend to pass through. For this reason, a blue iris is an example of structural colour, in contrast to a pigmented

colour. A hazel iris colour combines a moderate amount of melanin in the stroma and some light scattering, whereas a green iris is a combination of a small amount of melanin and scattering. A grey iris is similar to blue but contains excess collagen, which interferes with Tyndall scattering, preventing blue colour from appearing.

Every iris has a distinct pattern based on the collagen fibres, as shown in Figure 5. The collagen fibres may be regularly-spaced and parallel, resulting in a lighter and more even colour. Or the fibres split and converge to form patterns which create areas of highlight and shadow. This gives the iris a darker and more textured appearance.

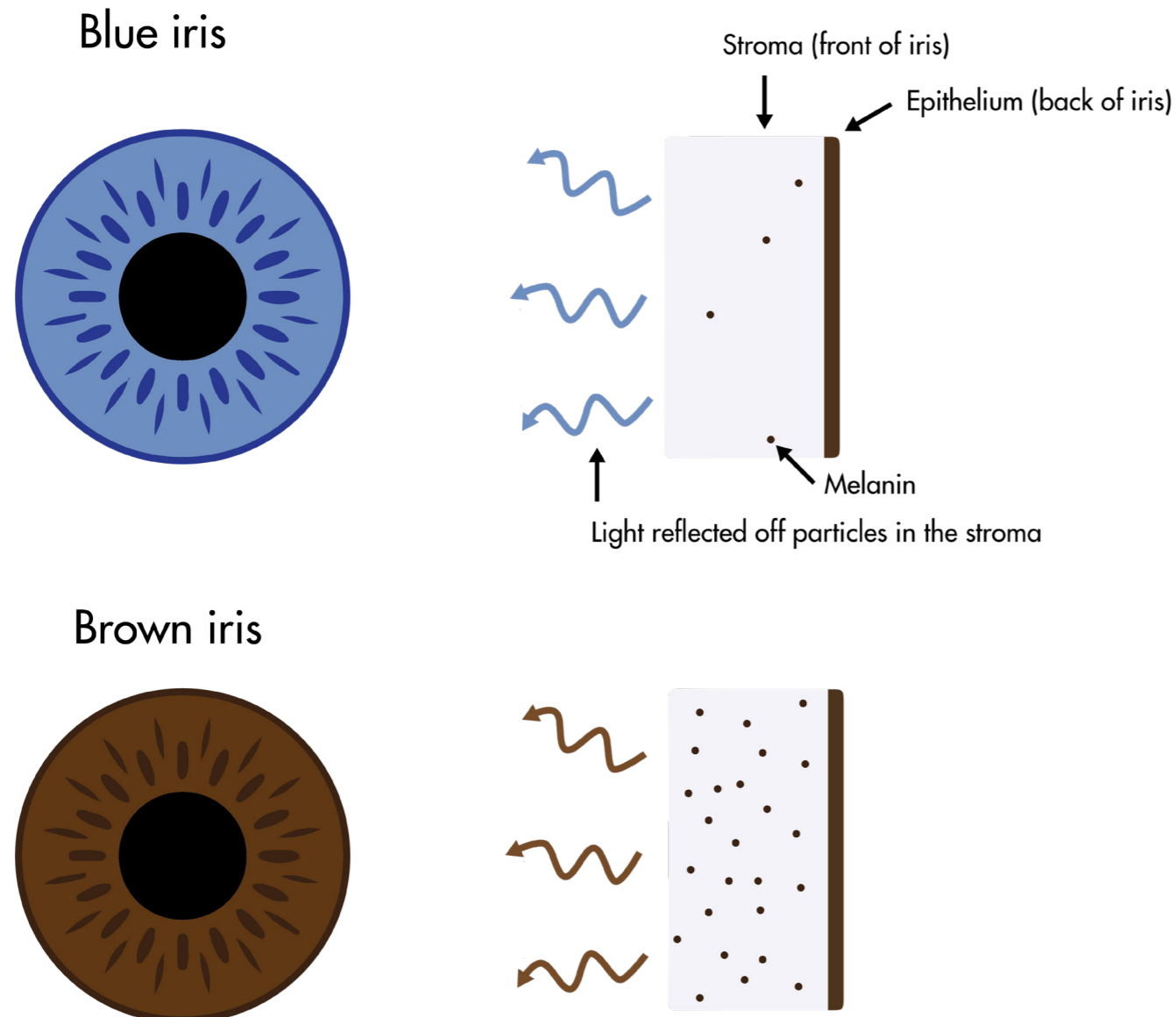


Figure 6. Iris colour characterised by the presence of melanin in the stroma

## 1.5. The eye vs ocular prosthesis

Figure 7 shows the eye's anatomy compared to a conventional prosthesis. The parts of the eye are reproduced in the prosthesis by using various techniques:

**1. Cornea**, is made by adding a layer of transparent polymethylmethacrylate (PMMA).

**2. Pupil**, is a painted black spot on top of the iris. Whereas the pupil's diameter can change size in our eye, it has a fixed size in the prosthesis.

**3. Iris**, the ocularist, paints the iris by hand to match the patient's contralateral eye colours.

**4. Limbus**, the ocularist paints the limbus as a darker band of colour and by gradually merging the iris colours to white on the iris edge.

**5. Sclera**, is made by pouring white PMMA into the plaster mould. This determines the prosthesis's shape largely. The ocularist paints a thin colour layer on top of the PMMA since most sclerae are not even white.

**6. Blood vessels**, are mimicked in the prosthesis by adding red embroidery thread.

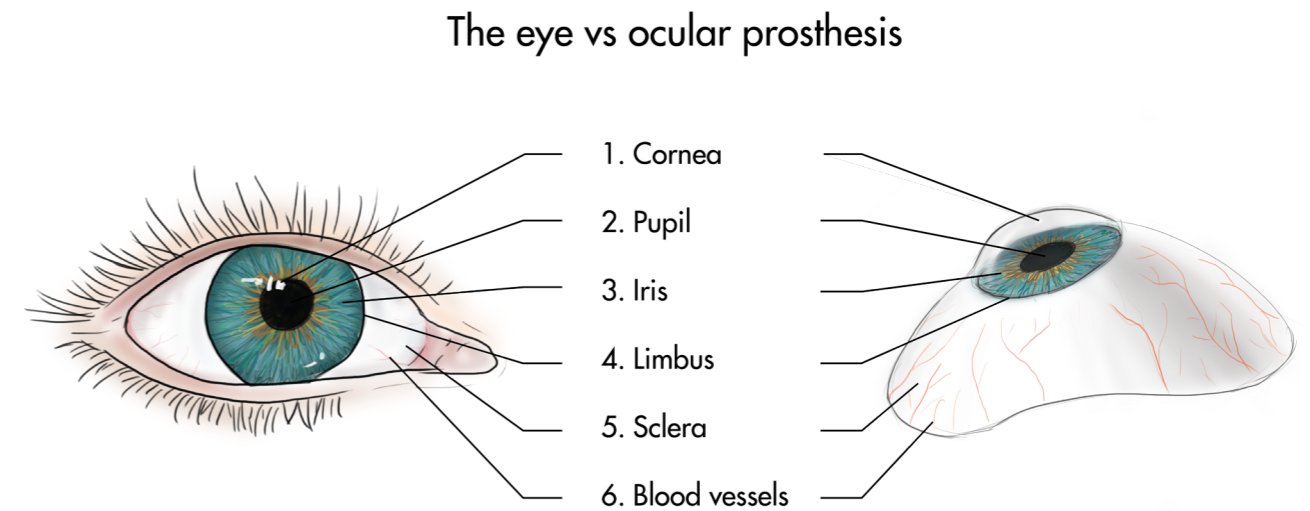


Figure 7. Anatomy of the eye compared to a conventional prosthesis



## 1.6. Conventional ocular prostheses

There are many ocular prostheses, varying in shape, stock produced or custom made, and different materials. Amsterdam UMC only makes custom acrylic prostheses since they treat patients with complex cases and varying reasons of losing their eye, see Figure 8. Amsterdam UMC is an expert centre for eye loss due to malignancies (cancer) or congenital abnormalities, like microphthalmia (born without one or both eyes) and anophthalmia (one or both eyes did not develop fully) [11]. Therefore, the prostheses made at Amsterdam UMC come in very different shapes, see Figure 9. As an example, a patient with anophthalmia requires a very thin prosthesis to fit in front of the undeveloped eye.



Figure 8. Conventional prosthesis made from PMMA



Figure 9. Prostheses at Amsterdam UMC

In most cases, the eye must be removed before placing the prosthesis. Figure 10 shows how the enucleation and placing of the implant works at Amsterdam UMC. After removing the eye, the prosthesis is placed in front of the implant in the eye socket.

### Amsterdam UMC fabrication process

Figure 11 shows the fabrication process of ocular prostheses at Amsterdam UMC. Their process was compared to the traditional workflow described in the book 'Clinical Ocular Prosthetics' [1]. The outline of Amsterdam UMC's workflow corresponds to the conventional process, but it can be different in detail. Every oculist has their own unique way of making the prosthesis, and not much is documented about the differences.

### Situation after eye removal (enucleation)

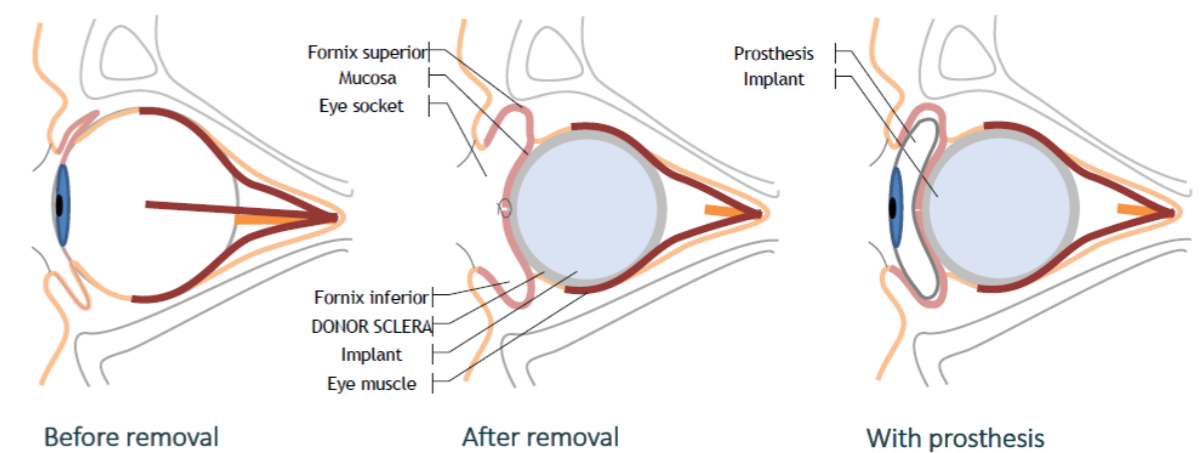


Figure 10. Enucleation, removal of the eye and placing of the implant. Image from [11]



### First consult

During the first consult, the ocularist takes an iris picture and collects all details and measurements of the eye. For example, the diameter of the pupil and iris are essential for making prostheses. In addition, the ocularist finds a colour sample matching the colours of the iris and sclera. To define the shape of the prosthesis, there are two approaches. Depending on the patient, the ocularist takes an impression from the eye socket or uses a reference model to find the perfect fit. The reference model is adjusted with wax and retried until the size and shape are correct.

### Processing

During the first processing step, the ocularist makes the iris/corneal unit. The high-resolution photograph of the patient's eye is adjusted digitally to the right size, and shadows are removed. The photo is printed and used as an underlayer by placing it on the right size premade iris disc and corneal button from PMMA. Later in the process, the ocularist will paint on top of the image to create the right colour and dept in the iris. This facilitates and accelerates the painting process because, traditionally, the whole iris is painted by the ocularist by hand [1].

### Intermediate fitting

If the ocularist chooses to take a socket impression, extra processing steps are necessary to create the right prosthesis shape. The impression is 3D scanned to create a 3D digital model. This model is digitally edited in Autodesk Meshmixer to the desired shape. The improved shape is 3D printed with a Stereolithography (SLA) printer and polished. Intermediate fitting with the patient is needed to review the new shape, mark the iris position and make proper adjustments. In a traditional process, a mould is made from the impression. Preheated ocular wax is poured into the mould to create a pattern. The anterior surface of the wax pattern is being trimmed to approximate the shape of the anticipated prosthesis. Then the wax pattern can be adjusted and retried with the patient until the shape is correct. Amsterdam UMC replaced the step of casting the impression and making a wax pattern with digital steps, resulting in a more adaptable process.

### Processing

During the second processing step, a plaster mould is made from the final shape model. After removing the shape model, the iris/corneal unit is placed into the mould. White PMMA is cast into the mould to create the prosthesis. When polymerisation is complete, the PMMA eye is removed from the mould, and the anterior surface of the prosthesis is cut back with an arbour band. The surface is cut back to create space for the transparent layer. A layer of paint is applied to the iris and sclera to make the right colour match and depth in the iris. Red cotton threads are placed to mimic the conjunctival veins of the patient. The PMMA eye is put back into the mould, and the paint is covered with a clear PMMA layer. To finish, the prosthesis is polished using pumice stone powder and a dental rag wheel. Blue and green eyes sometimes require an extra layer of paint, which leads to repeating the process from cutting back the anterior surface.

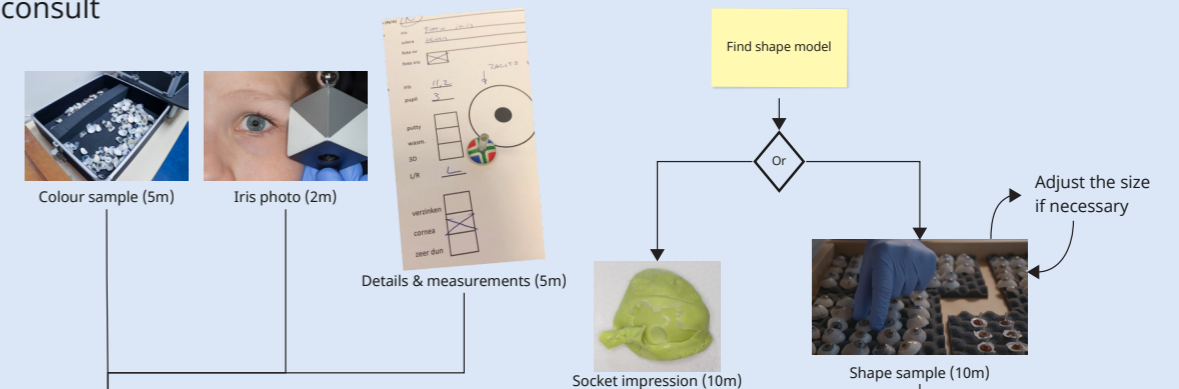
### Final consult

During the last consult, the completed prosthetic eye is placed into the patient's socket. If needed, minor size adjustments can be made by removing material and polishing again. After a month, the prosthesis is inspected. Figure 11 also shows the indicated time for each step during the process. The entire process takes over seven hours, including three and a half waiting hours in which the ocularist can do something else. It should be noted that the indication is a rough estimation from the ocularist at Amsterdam UMC. Since most prostheses are made in batches, it is hard to indicate a time for one prosthesis realistically.

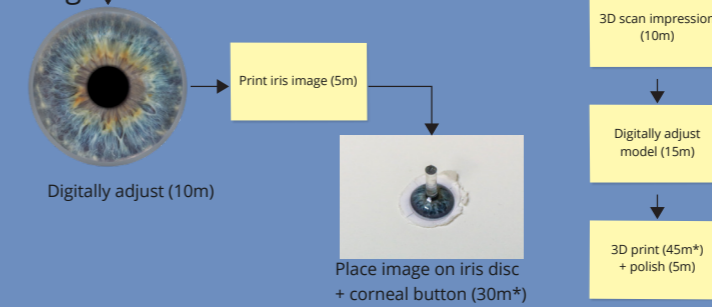
The prosthesis needs to be polished every year to prevent bacteria growth, potentially leading to infection. Every two years, a new prosthesis is recommended [11]. Our eye socket changes over time, resulting in the prosthesis non fitting properly anymore, potentially causing irritation. Young children growing need a more frequent change. The whole process needs to be repeated when changing the prosthesis since the number of manual steps makes it non-reproducible. The price of a prosthesis starts at €800 euros.

## Amsterdam UMC process

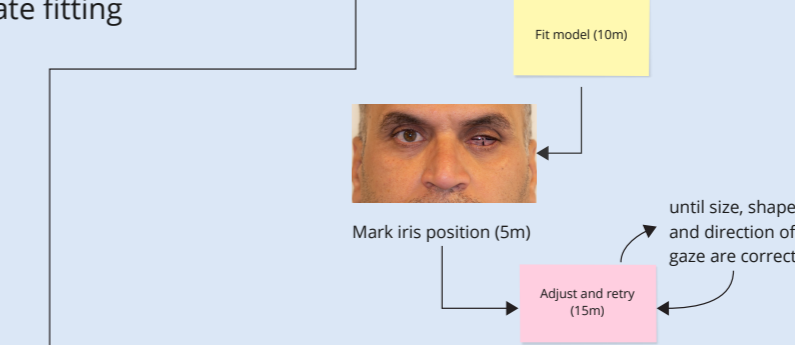
### First consult



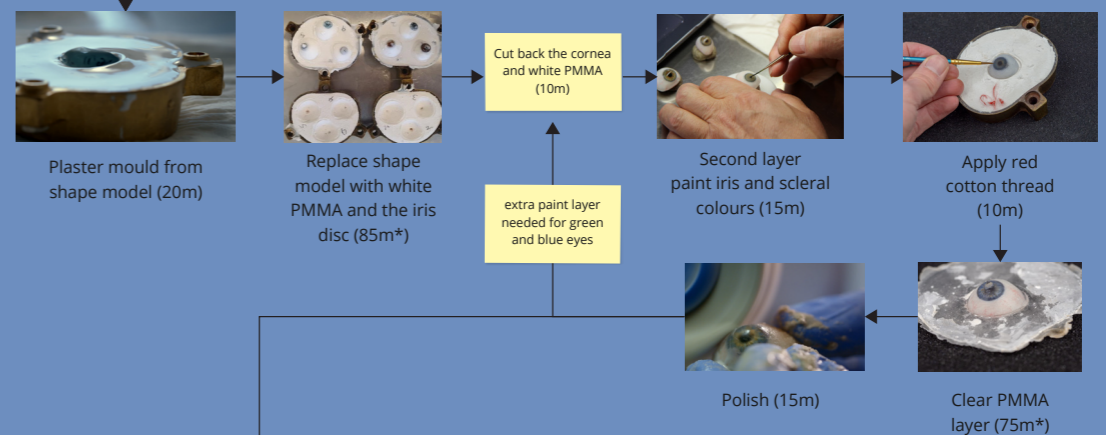
### Processing



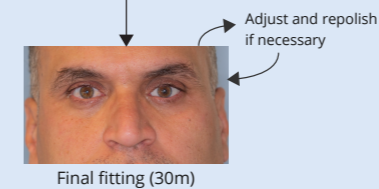
### Intermediate fitting



### Processing



### Final consult



\*Mostly waiting time

**Total workflow time (impression):**  
432 min, including 205 min waiting time

**Total workflow time (shape sample):**  
327 min, including 165 min waiting time

Figure 11. Prosthesis fabrication process at Amsterdam UMC. Image from [11]

# 1.7. Multi-material full-colour 3D printing

Material jetting is a powerful 3D printing technology that produces smooth and accurate parts. It is often called Inkjet 3D printing since the procedure is similar to 2D inkjet printing. To build 3D parts, it uses photopolymers that are jetted onto a build tray in tiny droplets and immediately cured with ultraviolet (UV) light. The print head consists of multiple small nozzles, which can extrude different materials allowing the production of multi-material parts.

Material jetting also allows for full-colour prints, making this printing technique interesting for 3D printing ocular prostheses. The Stratasys J735 3D Printer was used during this project. To reproduce the various features of the human eye, a thorough understanding of the 3D printing capabilities is needed. Figure 12 shows an illustration of the printer's operation. The printing carriage moves along the X-Y axis, consisting of 8 printing heads and two UV lamps. The build tray moves layer by layer in the Z-direction. To achieve a consistent layer height, the print heads extrude slightly more resin than necessary. A roller will run over the surface before curing, sweeping away any extra material.

### Printer specifications

The printer has a build size of 490 x 390 x 200 mm. It supports up to eight materials (6 base resins and two support material spots). The printer can reach a 27-micron resolution in high mix mode, resulting in 600 by 300 by 941 dpi (X by Y by Z). For full-model-size products, the accuracy is up to 200 microns [12]. GrabCAD Print is the supporting software for Stratasys 3D printers.

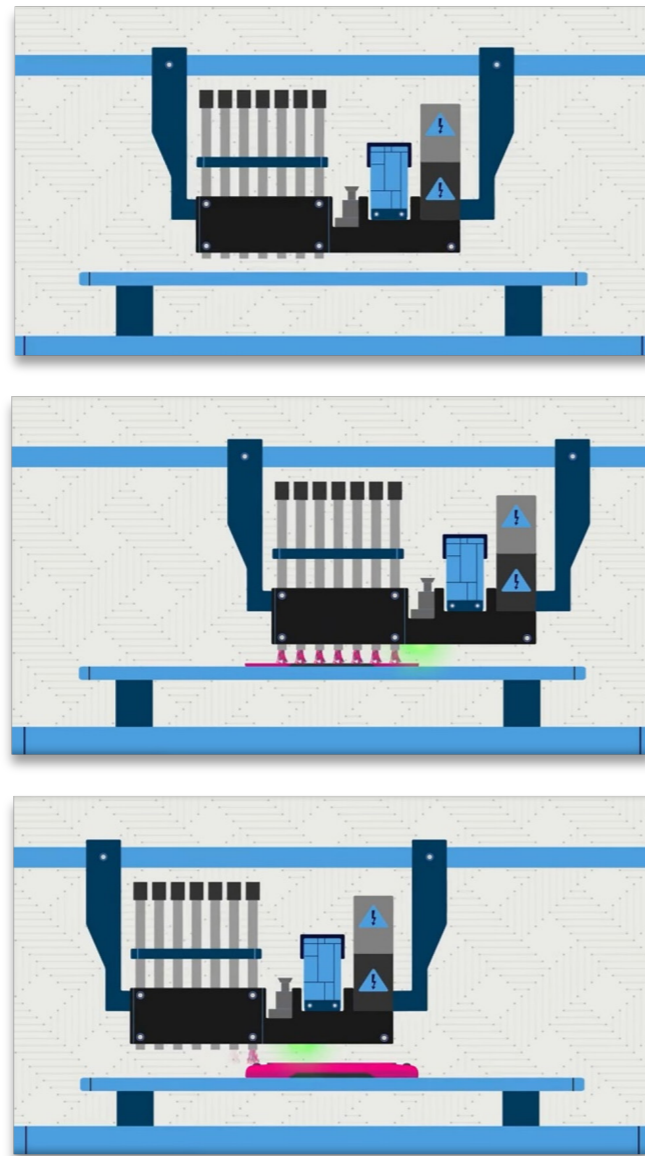


Figure 12. PolyJet technology. Image from [16]

### Materials

Appendix B presents an overview of all available materials for the Stratasys J735. For a full-colour print, all six resin spots are necessary. The samples made during this project were printed with the following materials: VeroCyan-V, VeroMagenta-V, VeroYellow-V, VeroClear, VeroBlackPlus and VeroPureWhite. The two support material spots were filled with SUP706.

Stratasys provides two types of support materials: SUP705 and SUP706. SUP705 is removable with a waterjet, while SUP706 is soluble [12]. The support material is printed simultaneously with the modelling material resulting in a fast print speed. Any geometry with an overhang needs support. GrabCAD placed the support material automatically where it is needed on downward-facing surfaces. Model surfaces with upward-facing surfaces will have a high gloss finish, whereas surfaces that have come into contact with the support material will have a matte appearance. To create a uniform matte finish, the part needs to be fully covered with support material. The support material is easily removed by hand or waterjet [13].

The Vero Vivid colour magenta, yellow and cyan are transparent, offering a wider colour gamut and smooth colour gradients [14]. However, printing these materials over a white core result in opaque colours. GrabCAD automatically applied the colours as a uniform 1 mm coating onto a white core [13].

Parts printed with VeroClear have a slightly yellow tint due to exposure to UV radiation. The yellow tint fades naturally over time but can be

accelerated by photobleaching. Photobleaching is the phenomenon when a fluorophore loses its fluorescence due to light induced damage. For maximum clarity, Stratasys advises printing the parts with a 'matte' surface and with the critical surface upwards [15].

The current materials used are not biocompatible. Only MED610 is a transparent, biocompatible material available for the Stratasys J735. The material is approved for permanent skin contact for up to 30 days [16].

### Texture printing

A full-colour model can be created by mapping a texture. Texture mapping is a method that applies an image to a 3D body by unwrapping the 3D object and applying the 2D texture to it. Models that contain a texture file, such as OBJ files, are printed with a 1-millimetre thick texture all around. The remaining internal core is printed white [17].

### Voxel printing

Since 3D printing technologies have improved due to machines capable of processing higher fidelity parts, multiple materials and complex hierarchical structures, it has become clear that the standard STL file format is insufficient to represent such features. Doubrovski et al. [18] present a multi-material bitmap printing method which can control the material composition on the voxel level. In bitmap printing, the part is represented by a stack of binary bitmap files which describe the printer's droplets. Each layer in the Z direction requires a separate bitmap written at the printer's resolution. Thereby it controls every drop of material jetted.



# 1.8. Colour reproduction

To ensure accurate colour reproduction, this section will discuss the theory behind the colour-matching process between the original (the eye) and the print (3D printed prosthesis). This process ensures that the 3D print will look as much like the original as possible.

Cameras, displays and printers are examples of colour capture and output devices. Each device has different colour capacities and ways of communicating colour [19], so they interpret and reproduce colour differently. International Color Consortium (ICC) created a colour management architecture that allows for the communication of colour across these devices [20]. Figure 13 shows the colour management workflow of this project.

An ICC profile describes the transformation from a device to the standard colour space, the profile connection space (PCS), defined by ICC. The PCS is based on a measurement system defined by CIE, the CIE XYZ values or CIELAB ( $L^*a^*b^*$ ). So, each ICC profile contains the transforms from source space to PCS or vice versa in the case of an output profile [19].

In practice, the camera has an RGB colour space which needs to be converted to the CMYKW colour space of the 3D printing. This step concerned obtaining two ICC profiles. First, RGB is converted to the PCS using the RGB profile, and then a second profile is required to map the PCS to CMYKW. These existing pipelines have

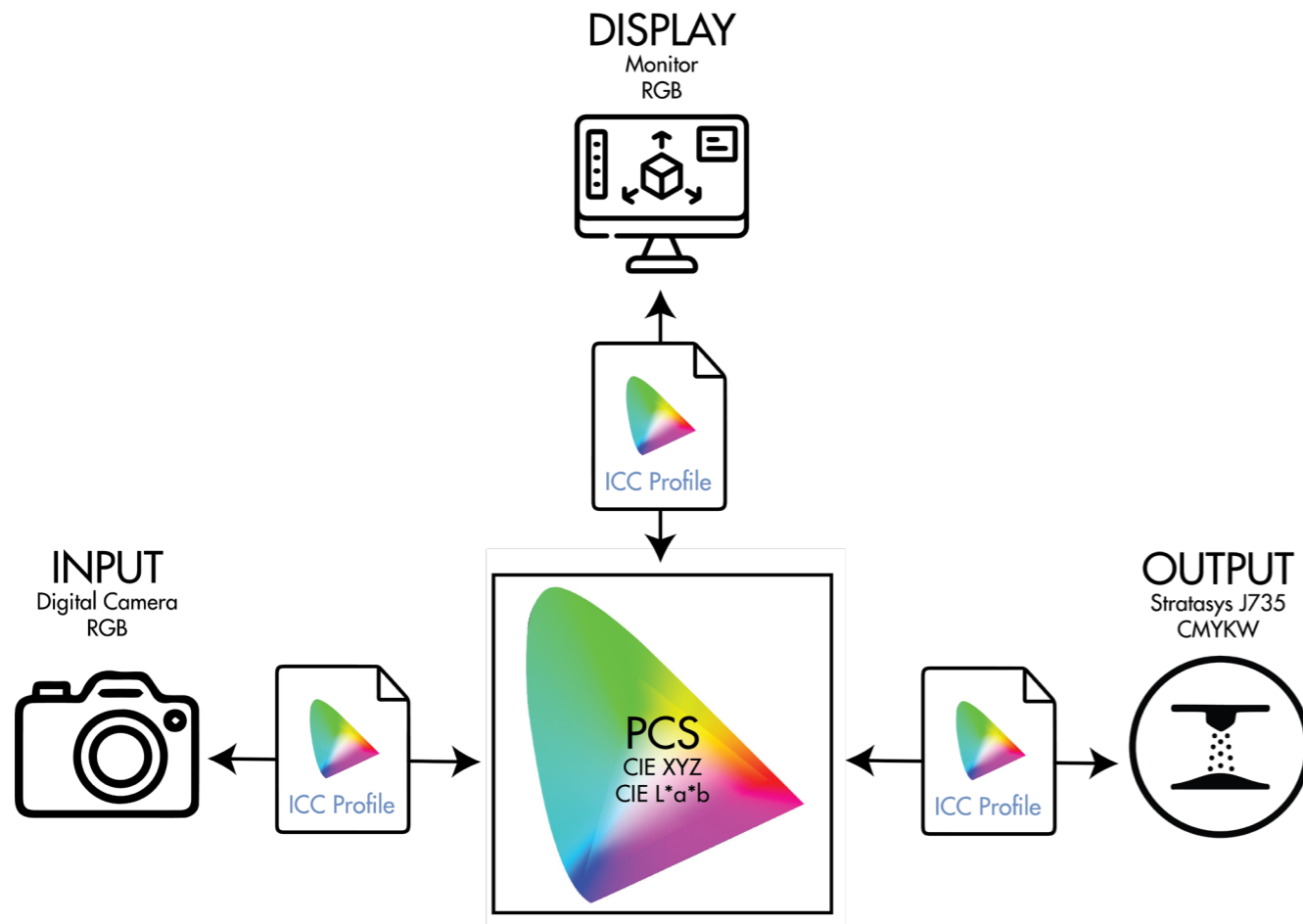


Figure 13. Colour management workflow

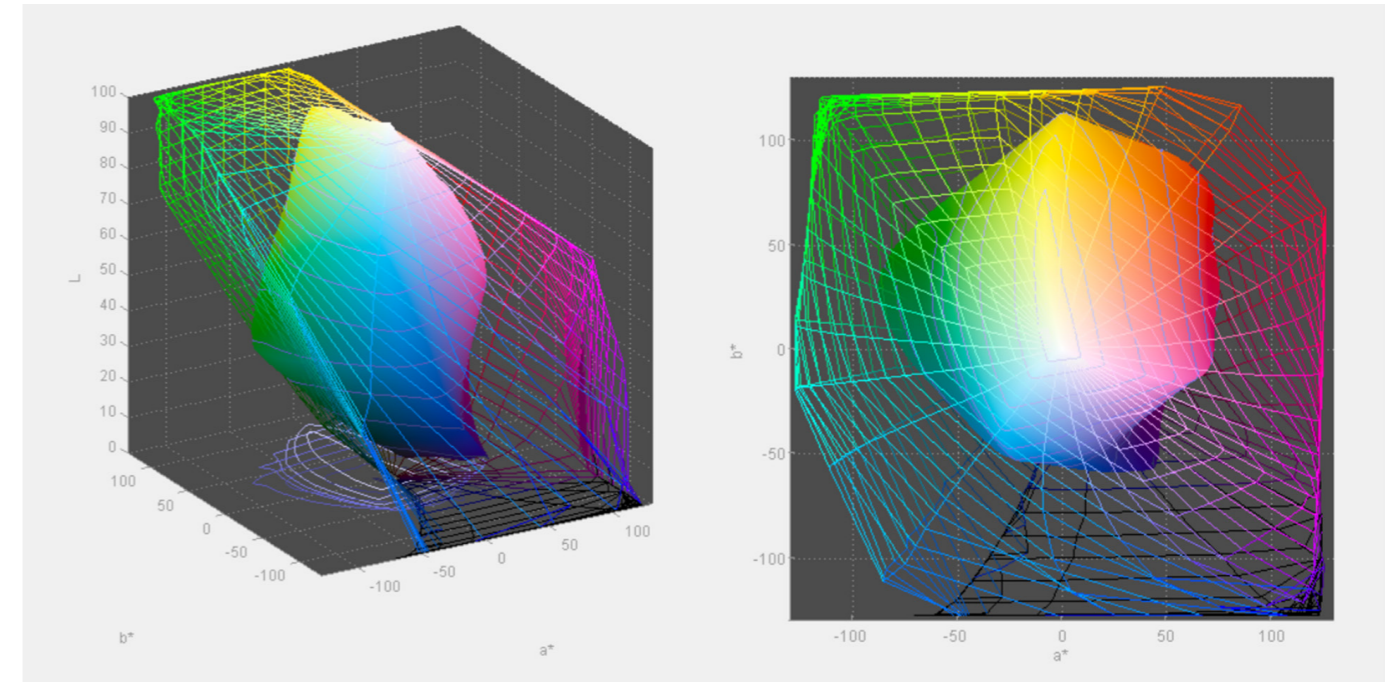


Figure 14. Camera gamut (wireframe) compared to printer gamut (solid), 3D and top view

been developed for 2D printing and are therefore not hundred per cent suitable for this purpose. However, (good) 3D printing colour management software is proprietary or lacking. The 3D printing profile also includes white as a printing material, which is different to 2D printing, where the substrate is white. Besides, the materials used are translucent.

Figure 14 shows the gamut of the Nikon D800E camera (wireframe) compared to the Stratasys J735 gamut (solid). It is clearly visible that the camera can capture a much more extensive colour space than the printer can print. For example, really saturated blues can be captured with the camera but not reproduced by the printer. This requires mapping the colours that lie outside the colour space into the printable colour range.

Each mapping is based on a rendering intent, which defines how the gamut of colours is modified. Four different rendering intents allow a choice between closest possible colour matching and remapping the entire colour range:

### Relative colorimetric

Shifts all the colours to the substrate's white. The printing disregards the source white. So printed white ( $RGB = 255, 255, 255$ ) will contain only white material.

### Absolute colorimetric

Tries to achieve objectively accurate colours regardless of the substrate's white by simulating the source white. The colours map accordingly. According to Stratasys, this is used for colour matching [21]. A downside of relative and absolute colorimetric is that it can lead to clipping. This means that colours that fall outside the gamut will all be mapped to the same colour on the outer boundary, which results in losing details.

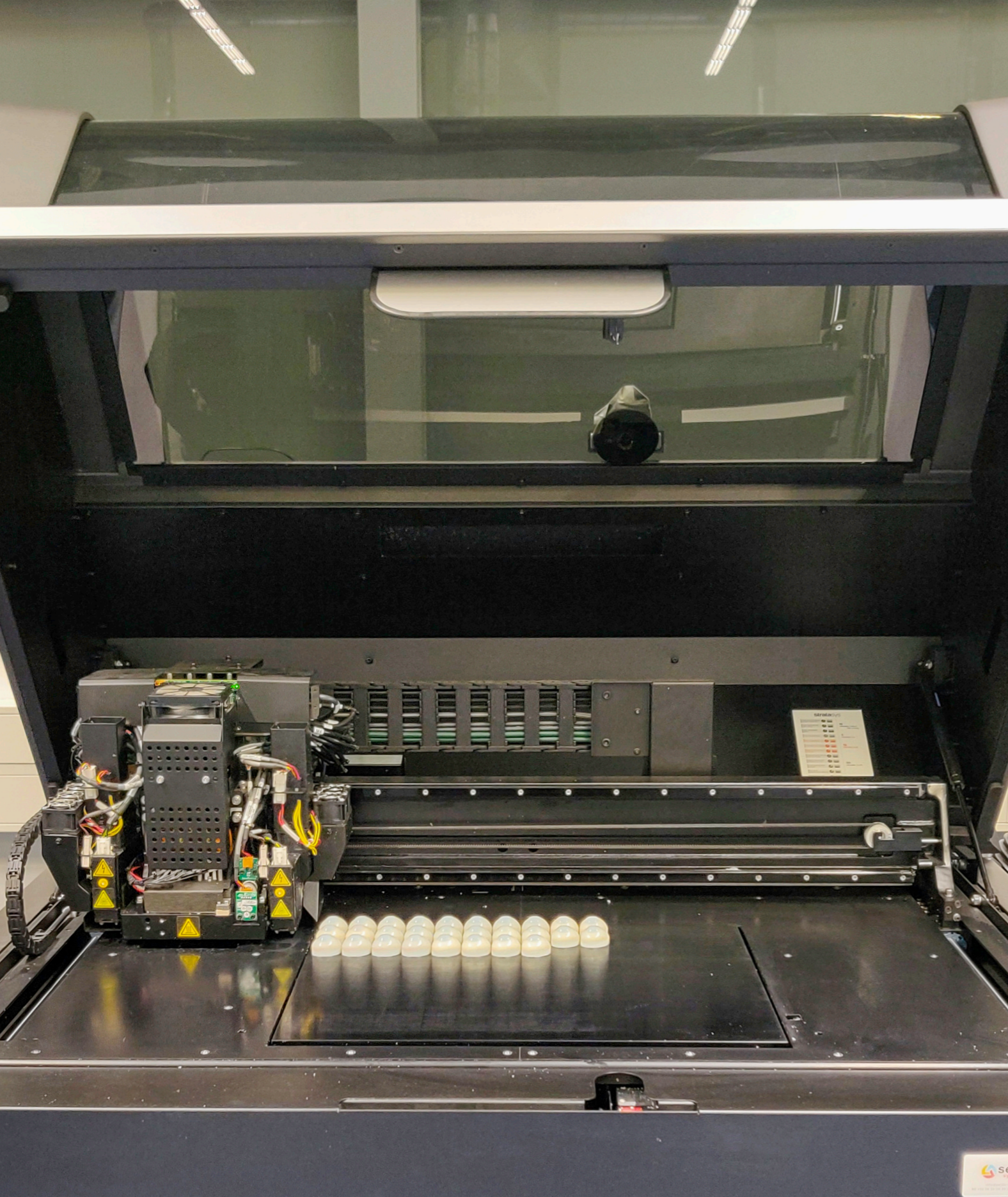
### Perceptual

The whole gamut of the image is compressed or expanded to fill the gamut of the destination device.

### Saturation

Makes colours more saturated, resulting in less accurate colours.





# 2 Related work

This chapter shows a literature review to benchmark technological innovations for producing ocular prosthetics, and the evaluated proof-of-concept [2].



# 2.1. 3D-printed ocular prostheses

Some key literature was identified via the proof-of-concept paper. Moreover, relevant literature was received from the team from Amsterdam UMC and searched using keywords like 'Ocular prosthetics' and '3D printing' and alternative keywords like 'Additive manufacturing', 'Eye' and 'Stratasys'. As the project focuses on capturing and reproducing the eye's appearance, innovations in capturing and producing the geometrics of the ocular prosthesis were not included in the literature review.

### Data capturing

Before reproducing the eye's appearance in the prosthesis, the visual aspect of the patient's eye needs to be captured. Zoltie et al. [22] present a digital photographic technique whereby pictures were taken of the patient's unaffected eye and combined into one final wide scleral view, see Figure 15. Figure 16 shows a colour diagnostics tool developed to apply the standardised dataset's colours objectively and consistently [23]. Disney [24] also described methods for digitally capturing ocular structures, including the white sclera, the transparent cornea and the coloured iris. The results are used for graphics applications in movies and video games.

### Fabrication

Many studies show different methods to innovate the production process of ocular prostheses. Figure 17 shows an overview of the methods and their pros and cons. A study of Walshaw et al. [25] describes a high-definition ocular prosthesis manufactured using a digital photograph of the eye. Nine eye positions are combined to create a broader scleral view. Finally, the image is printed on glue-based paper and placed on the acrylic shell. A similar approach was used to create an ocular portion of an orbital prosthesis [26]. Using a photograph of the patient's eye eliminates the need for hand painting. However, both prostheses lack iris structure and dept created by layering.

Alam et al. [27] and Beiruti et al. [28] show an innovative method to fabricate prostheses using rapid 3D printing. After 3D scanning and adjusting the impression of the patient's eye socket, the core is 3D printed using a Fused Deposition Modelling (FDM) printer. Nevertheless, all visual aspects are painted with traditional techniques on the 3D-printed core.

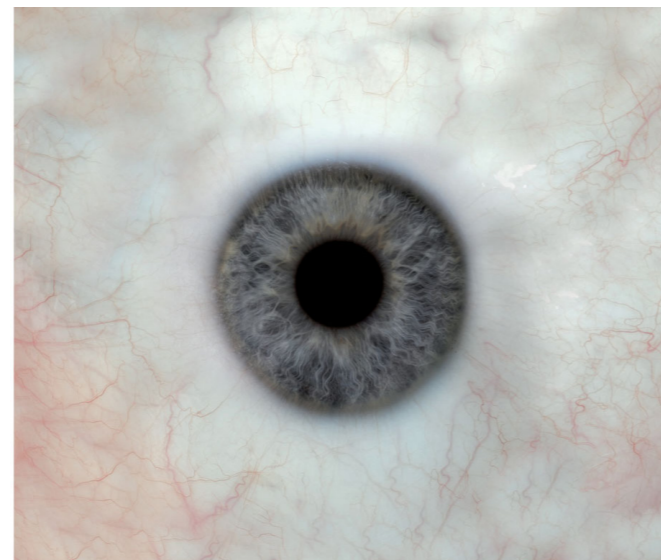


Figure 15. One wide scleral view. Image from [22]

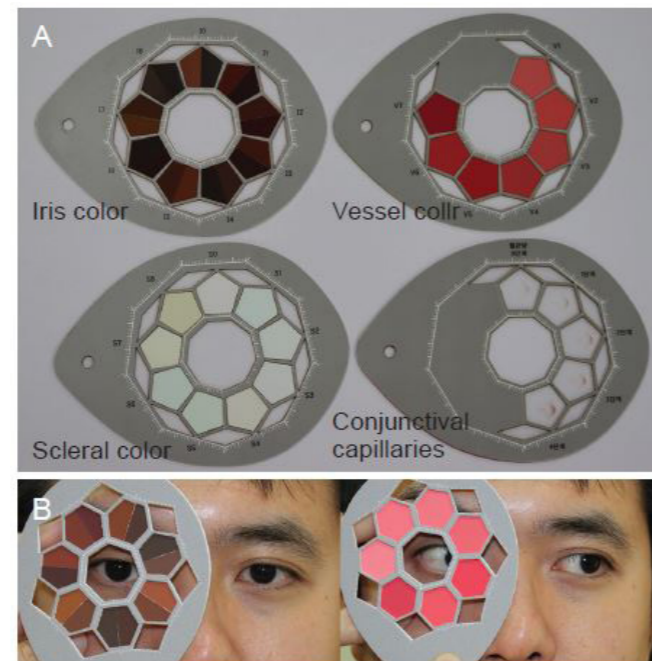


Figure 16. Colour diagnostics tool developed. Image from [23]

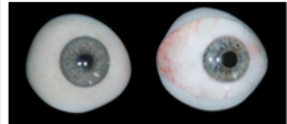
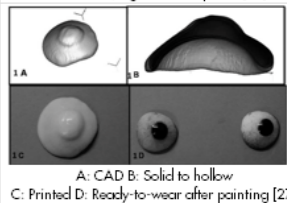
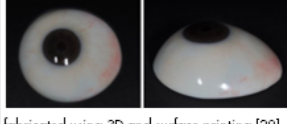



Who	Year	Reference	Process	New techniques	3D printer	Pros	Cons	
[25]	2018	Journal	Digital photograph printed on specialist glue-based paper placed on the acrylic shell	Photographing	-	High-detailed iris and sclera No painting needed	Lacking iris structure and dept Clear acrylic coating manual applied	 Left: Conventional, right: Printed photo [25]
[27]	2017	Journal	After 3D scanning and digitally adjusting the impression, the core is 3D printed. All visual aspects are painted on the 3D-printed core	3D scanning, CAD, 3D printing (FDM)	FDM	Faster production: 2,5 h instead of 10h More comfortable: 2.9g instead of 4,4 grams	Colour and clear acrylic applied with traditional techniques	 A: CAD B: Solid to hollow C: Printed D: Ready-to-wear after painting [27]
[28]	2019	Conference	A printed photograph is placed on the 3D printed core using sublimation technique	3D scanning, CAD, 3D printing, Photographing, Sublimation technique	DLP	Faster production High-detailed iris and sclera No painting needed	Lacking iris structure and dept Clear acrylic coating manual applied	 fabricated using 3D and surface printing [29]
[29]	2019	Scientific report	Full-colour 3D printed iris implanted in an original acrylate prosthesis	Photographing, 3D scanning, CAD, UV mapping, 3D printing,	Material Jetting	Faster production, less manual steps	Lacking iris structure and dept Veined cotton and acrylic coating manual applied	 Left: printed, Right: With surface treatment [30]
[30]	2020	Journal	Voxel 3D printing using existing digital effects technologies for film and display work	Houdini software, voxel 3D printing	Material Jetting	Iris and sclera colour, limbus transparency and vein weight can be controlled in an artistic manner.	Not based on patient data Proprietary software without explanation of the data or working	 3D printed prosthetic eyes at varying scales [31]
[2]	2021	Journal	Digital photograph applied by UV mapping and displacement mapping on average 3D model to create a full-colour and texture iris and sclera. Produced using a polyjet 3D printer	Photographing, CAD, UV mapping, Displacement mapping, 3D printing	Material Jetting	Full colour and texture prothese in one single print job Faster production	Average model Only biocompatible for 30 days	 Printed proof-of-concept [2]

Figure 17. Method comparison with pros and cons from literature

Research in [29] and [23] show a technique to fabricate customised ocular prosthesis with 3D printing and sublimation technique. Similar to the study by Alam et al. [27] and Beiruti et al. [28], the 3D model is based on a 3D scan of the impression. The visual aspects are captured by an picture of the eye and printed on the 3D printed core using a dye sublimation transfer technique. Sublimation printing is a printing technique that creates a graphic by using a heat press on a sheet of transfer paper with printed solidified inks. After being heated, the inks, which have now vaporised into gas, permeate the fibres of the 3D-printed core. This method produces a detailed image, but the prosthesis lacks iris structure and depth. In addition, the prosthesis needs to be manually coated with clear acrylic.

Research in [30] shows an ocular prosthesis with a 3D-printed iris, successfully printed with a PolyJet

printer (Stratasys J750). A high-quality photo of the iris is applied by UV mapping on the model to create a full-colour iris. Afterwards, the 3D-printed core was implanted in an original acrylate prosthesis. Also, this prosthesis lacks iris structure and depth, and the clear acrylic coating must be manually applied.

Robinson and Furneaux [31] present a workflow for voxel 3D printing to build largescale artificial eyes with the Stratasys J750. The artificial eyes are made with a proprietary 3D software programme called Houdini and are used as a case study for film and display work. The paper states that the voxel printing process allows them to create customised eyeballs, where aspects like the iris and sclera colour, limbus transparency and vein weight can be controlled in an artistic manner. However, the author gives no explanation of how the software works or which data is used.



## 2.2. Proof-of-concept evaluation

### Proof-of-concept

Only research of Groot et al. [2] shows a proof-of-concept of a full-colour 3D printed prosthesis with textured iris and sclera in one single print job, see Figure 2. The following workflow is used to create the prosthesis, see Figure 18. (A) First, a basic 3D prosthesis model was made, and a high-resolution photograph of the eyes was taken using a professional digital camera and a grey card. (B) Using Adobe Photoshop, this image was post-processed, including tweaking colours, changing the iris shape and covering missing parts. (C) A duplicate grayscale of the image was created in Adobe Photoshop. (D) Next, in Blender, a textured iris was created on the 3D model from the grayscale picture using the function 'displacement mapping'. This function displaced the points on the iris based on the corresponding pixel values of the grayscale image. In this way, darker shades represent the deeper parts of the iris, and lighter shades represent more protruding iris parts. (E) To create a coloured iris, the coloured version of the photograph was mapped onto this surface using Blender's "UVediting" tool. (F) Next, to produce realistic coloured veins, the procedure was repeated for the sclera. (G) The full-colour and textured iris and sclera were merged into one core. (H) The final render was made of the 3D model after combining the core with the transparent cornea. Finally, the model is produced using a PolyJet 3D printer (Stratasys J750), which resulted in the proof-of-concept of a single-print ocular prosthesis with a textured iris and sclera.

To conclude, multiple studies have shown possibilities for 3D printed ocular prosthesis, but only Groot et al.'s [2] study shows a prosthesis made in one single print job. This proof-of-concept was used as a starting point for this project. An evaluation of this proof-of-concept can be found in chapter 2.2.

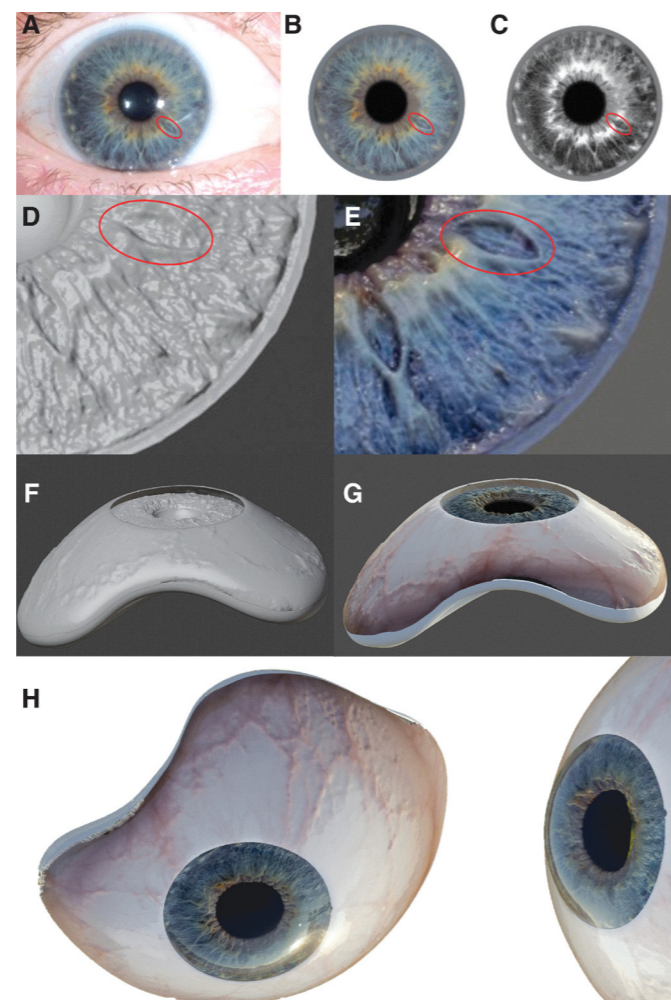


Figure 18. 3D design workflow proof-of-concept. Image from [2]

The proof-of-concept [2] made by Amsterdam UMC was printed using the Stratasys J735 at the faculty of Industrial design Engineering of TU Delft, see Figure 19. Figure 20 shows an evaluation of the proof-of-concept compared to a traditional prosthesis. The iris colour is evaluated based on the advice of the ophthalmologist since it was impossible to compare it to the contralateral eye.



Figure 19. 3D printed proof-of-concept next to a conventional prosthesis – a PMMA cast, with hand painting and red threads to simulate blood veins.

The transparent cornea of the 3D printed prosthesis has a yellow tone due to printing glossy. This yellow tone disappears over time. The iris is more detailed than the painted one, and a 3D structure is visible when looking closely. The iris is slightly convex, which makes it much more realistic than the flat painted iris in the conventional prosthesis. The sclera is not white. It has a dark red/brown tone, especially closer

to the edge. The blood vessels are blurred and too thick compared to the thin cotton threads. The blurred vessels also contribute to the sclera's dark red/brown colour. The iris colour is slightly too blue, according to the paper's author [2]. The colour of the pupil is not correct since it is more dark grey than black. The limbus is visible and has the right colour, but the transition from the ring to the white sclera can be smoother.

	Traditional prosthesis				Proof-of-concept			
	--	-	+	++	--	-	+	++
Cornea								
Iris details								
Sclera colour								
Blood vessels								
Iris structure								
Iris colour								
Pupil								
Limbus								

Figure 20. Proof-of-concept evaluation

# 3 Digital workflow & design drivers

The proposed digital workflow and the four defined design drivers are presented in this chapter.



All research insights come together in four design drivers for the workflow, see Figure 21. The first design driver, realistic appearance, means that the outcome of the production workflow, the prosthesis, should have a realistic appearance. The prosthesis should restore the appearance of the face, and the colour should match the contralateral eye. Secondly, patient participation should be a pleasant experience, meaning a straightforward and painless process since most patients are still traumatised by losing their eye. The goal is also to keep the number of consults as low as possible. For an efficient workflow, the aim is to automate the process steps to make the workflow as efficient as possible. The product should also be fabricated in a single print of the 3D printer. Lastly, the process should be reproducible by collecting patients' eye data and using digital production techniques. This saves times since a new prosthesis, which is needed every two years, could be easily printed again after minor digital changes have been applied. A full list of product requirements and wishes can be found in Appendix C.

Figure 22 shows the proposed workflow to make an ocular prosthesis with digital production techniques. This workflow shows how the ocularist, the patient and the data streams are involved and consists of five phases: collect, design, produce, post-process and finalise. Chapters 4, 5 and 6 dive deeper into the research done for the capturing, modelling and printing steps. Icons in the workflow steps show how the steps are linked to these chapters.

**Collect**

During the intake, the ocularist collects all data needed to produce the prosthesis. This includes taking photos of the patient's eye, writing down the details and measurements of the eye and finding a shape model. There are two ways to

find the shape model. The ocularist takes an impression of the patient's eye socket or tries to find a fitting shape sample from the sample box. If needed, the sample is adjusted with wax until it fits perfectly.

**Design**

The shape sample can directly be 3D scanned to create a 3D model of the external shape. The shape of the impression is not in line with the form of a prosthesis. After scanning the impression, the exterior shape of the prosthesis is modelled based on the computation design template. The ocularist prints the new shape with an SLA printer and fits the model during the intermediated fitting.

After defining the external shape, the internal shape is modelled based on the computation design template. This template automatically generates the inner parts of the prosthesis based on the outer shape. This is explained further in chapter 5. The ocularist edits the captured photos of the collect phase and applies these to the 3D model. After creating a 3D structure, the design of the model is finished.

**Produce**

The model is produced using a PolyJet 3D printer. Before printing, the ocularist carefully defines the materials and specific GrabCAD settings.

**Post-process**

During post-processing the 3D-printed prosthesis is cleaned by removing the support material. The ocularist polishes the prosthesis using pumice stone powder and a dental rag wheel, according to standard procedures in ocularist practices.

**Finalise**

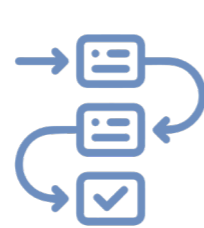
During the last consult the final prosthesis is fitted.



Realistic appearance



Pleasant experience



Efficient workflow



Reproducible

Figure 21. Four design drivers

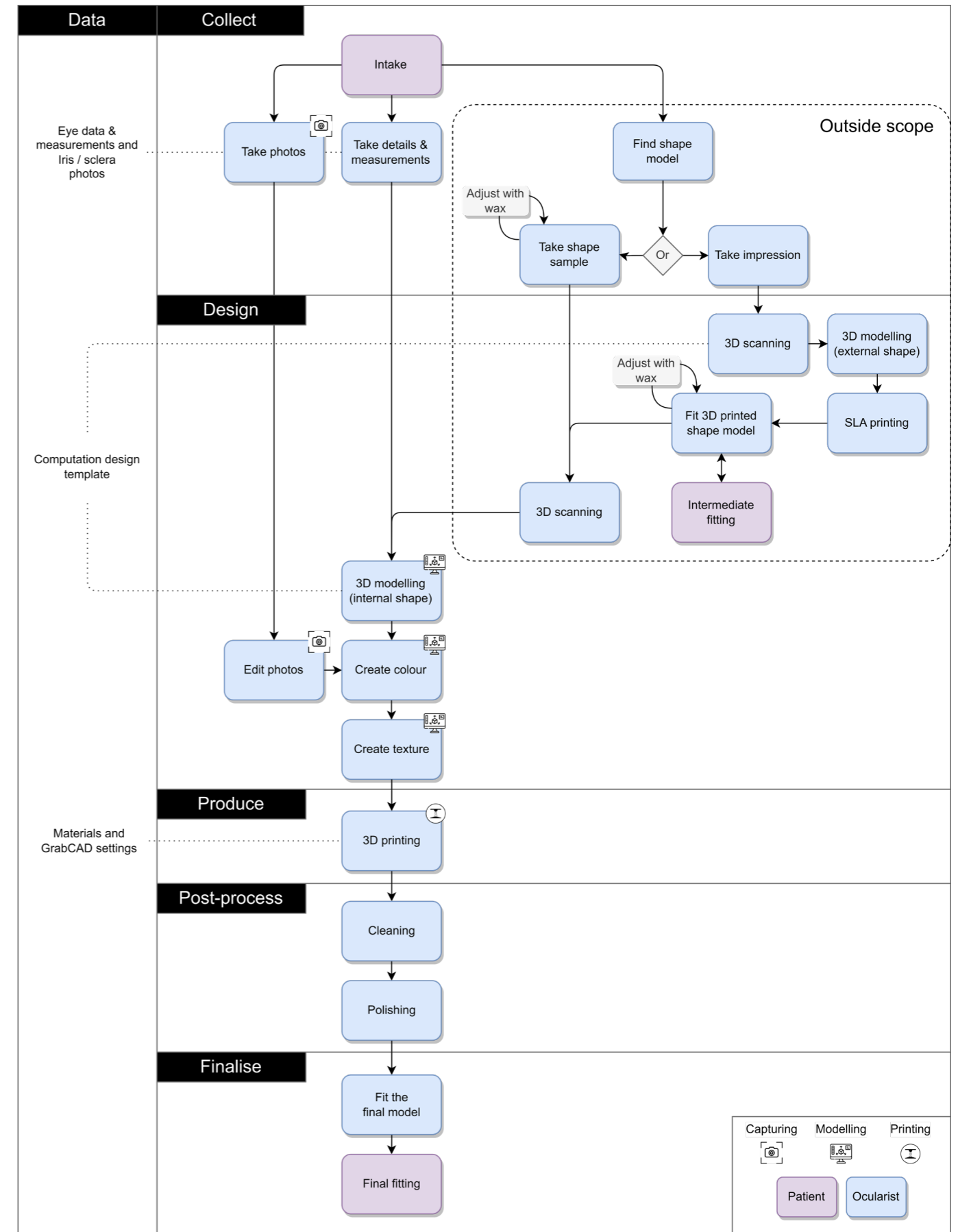


Figure 22. The proposed digital workflow





# 4 Capturing

Which (contextual) parameters and process steps are relevant for accurate colour reproduction?  
And how can the patient's eye colour data be captured and calibrated to ensure accurate colour reproduction?



# 4.1. Data capturing

*'It all begins with the camera. If it doesn't capture accurate colour, how can you expect realistic reproduction?' – X-Rite [32]*

As explained in chapter 1.8, different cameras capture colour differently since different lenses have different colour characteristics. To capture accurate colour, a custom profile must be created based on the raw output from the camera in the specific shooting condition. Before making the profile, these specific shooting conditions need to be defined and controlled. As a starting point, online research was done to learn from

professional photographers who make iris photos. All learnings can be found in appendix D. Most photographers illuminate the eye from the side to create shadows in the iris and make the structure more visible. This way of illuminating results in aesthetically pleasing images, but the shadows in the iris are not desired when capturing for colour reproduction, see Figure 23.



Figure 23. illuminating the eye from the side

Figure 24 shows an overview of essential elements to consider while photographing the eye. Four photography setup concepts were created by combining these elements and explored during the project. Two elements were eliminated based on to the online research. Photographing with daylight since it is a varying and uncontrollable light source, as well as using ring lights because that results in a ring shaped catch light in the iris. The overview shows two ideas to minimise glare in the photos. These ideas can be explored in the future if glare is a problem.

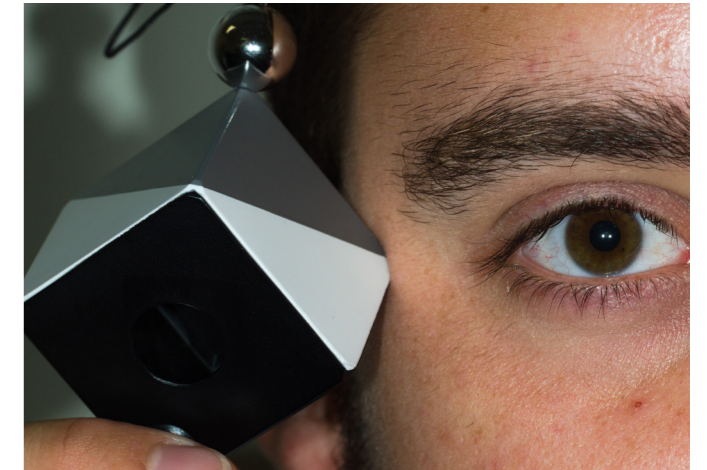


Figure 25. DataColor Spyder Cube

### Ocularist setup

Figure 26 shows the four tested photography setups and their results. The first setup is similar to the approach of the ocularist. It was tested at AUMC while taking photos from the research team and patients. The Olympus STF-8 Macro flash overruled the ambient light from the room

and produced two catch lights that fell into the pupil. The ocularist initially chose to photograph by hand since it makes the setup portable. A DataColor Spyder Cube was used to correct the white balance, see Figure 25.

Environment	Room light 	Dark room 	Day light 		
Lighting	2 Flashes next to lens 	Camera flash 	Softbox 	External flash 	Ring light 
Stabilize head	Unsupported 	Headrest 			
Color correction	DataColor Spyder Cube 	X-Rite ColorChecker passport 	ISa ColorGauge 		
Minimize glare	Semi-transparent mirror 	Polarizing filter 			
					<ul style="list-style-type: none"> <li><span style="color: blue;">●</span> Ocularist setup</li> <li><span style="color: purple;">●</span> Camera flash setup</li> <li><span style="color: teal;">●</span> Soft box setup</li> <li><span style="color: orange;">●</span> External flash setup</li> </ul>

Figure 24. Essential elements for photographing



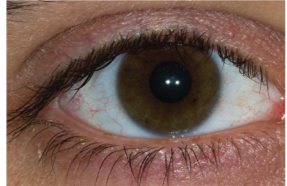
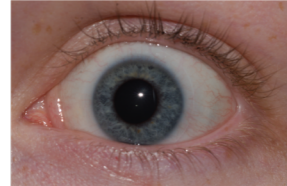
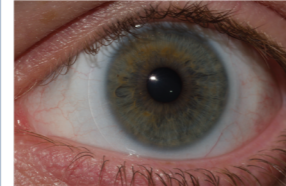

	○ Ocularist	● Camera flash	● Soft box	● External flash
<b>Setup</b>	<ul style="list-style-type: none"> <li>Room light</li> <li>2 flashes next to the lens</li> <li>Unsupported head</li> <li>By hand</li> <li>DataColor Spyder Cube</li> </ul>	<ul style="list-style-type: none"> <li>Dark room</li> <li>Camera flash</li> <li>Headrest</li> <li>Camera tripod</li> <li>ColorChecker Passport</li> </ul>	<ul style="list-style-type: none"> <li>Dark room</li> <li>Camera flash + 2 softboxes</li> <li>Headrest</li> <li>Camera tripod</li> <li>ColorChecker Passport</li> </ul>	<ul style="list-style-type: none"> <li>Dark room</li> <li>External flash</li> <li>Headrest</li> <li>Camera tripod</li> <li>ColorChecker Passport</li> </ul>
<b>Camera settings</b>	Olympus E-M10 Mark II with macro lens 60mm f/2.8 and Olympus STF-8 Macro flash, settings ISO100 f/13 1/160 s, RAW export, 4608 · 3456px	Nikon D800E with PC-E Micro NIKKOR lens 85mm f/2.8D, settings ISO100 f/13 1/160s, RAW export, 7360 · 4912px	Nikon D800E with PC-E Micro NIKKOR lens 85mm f/2.8D, settings ISO100 f/13 1/160s, RAW export, 7360 · 4912px	Canon 800D with EF 50mm f/1.2 and Canon Speedlite 430EX III-RT mounted on top, setting ISO100 f/5.6 1/160s, RAW export, 6016 · 4012px
<b>Results</b>	 <ul style="list-style-type: none"> <li>The flash produces two catch lights that fall into the pupil</li> <li>Flash overruled the ambient light from the room</li> </ul>	 <ul style="list-style-type: none"> <li>Pupil is too big</li> </ul>	 <ul style="list-style-type: none"> <li>The continuous light of the softboxes makes the pupil small and iris big</li> <li>The flash overruled the light of the softboxes, resulting in one catch light in the pupil</li> </ul>	 <ul style="list-style-type: none"> <li>Light not from the front, but more from above since the external flash is on top of camera</li> <li>Resulting in a catch light in the iris</li> <li>and more shadows from the lashes</li> </ul>

Figure 26. Photography setups results

### Camera flash setup

The Camera flash setup was tested in a dark room with black-painted walls to prevent reflections. A camera tripod and headrest were used to ensure the distances stayed the same. The setup had a controlled continuous light source by only using the camera flash, which on the other hand, results in a big pupil while photographing. Another disadvantage is that the setup is not portable. The ColorChecker Passport was used. Compared to the DataColor Spyder Cube this target can also correct the colours.

### Softbox setup

The softbox setup concept is similar to the camera flash setup, only two soft boxes were added. The continuous light of the soft boxes makes the pupil small and the iris big. Figure 27 shows photos of the setup. To prevent a catch light from the soft boxes, they must be placed just behind the camera flash. The camera flash is strong enough to overrule the light of the soft boxes, resulting in only one catch light in the pupil, see Figure 28 and Figure 29.

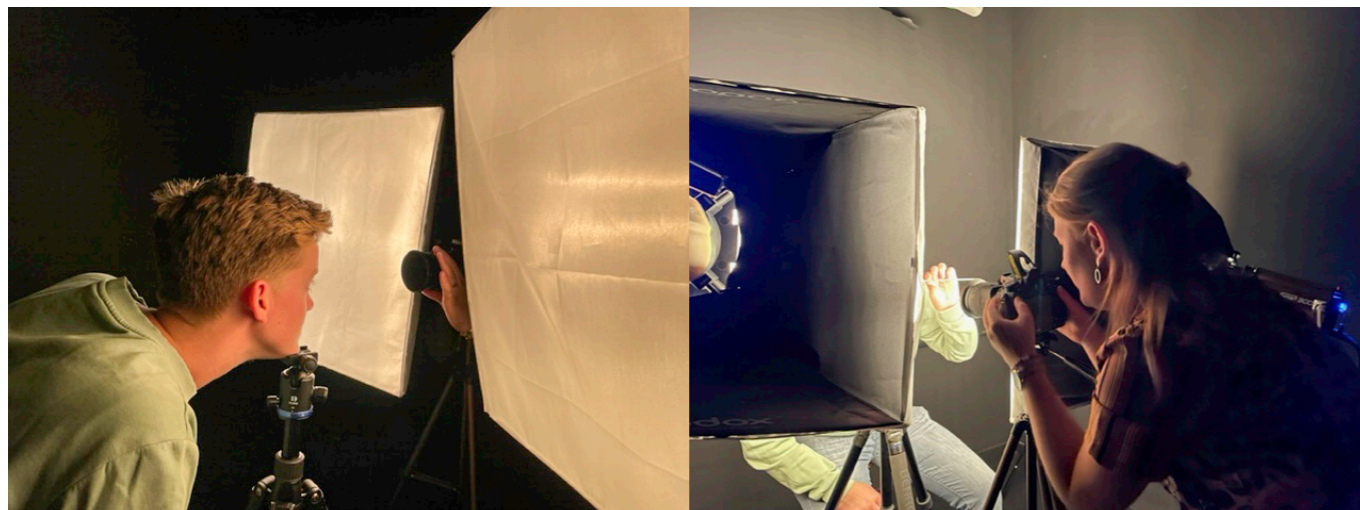


Figure 27. Photos of the softbox setup (front and back view)

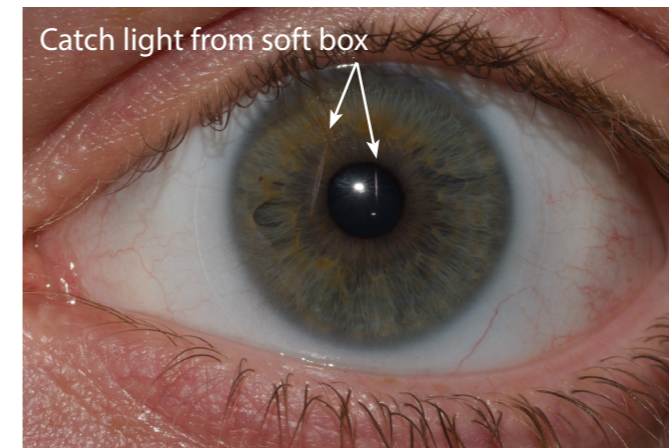


Figure 28. Soft box in front of camera flash

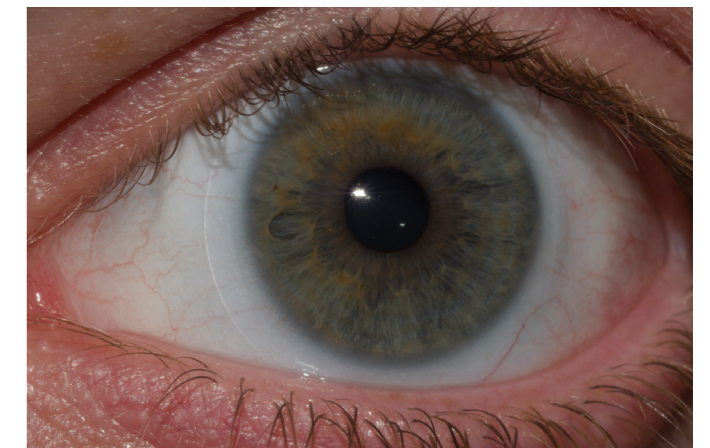


Figure 29. Soft box behind camera flash

### External flash setup

This concept shows a setup where an external flash is used instead of the camera flash. For this experiment, the Canon 800D with EF 50mm f/1.2 was used with a Canon Speedlite 430EX III-RT mounted on top of the camera. Therefore the light comes slightly from above instead of from the front, resulting in a catch light in the iris and more shadow on the sclera from the lashes.

### Conclusion

After testing the different setups, it can be concluded that a photo studio is preferred to control the light conditions. The softbox setup concept includes this controlled light condition, with fixed distances from a tripod and the headrest. Once the photo studio is set up correctly, only one profile of this condition is needed for all photographs.

A portable camera with an intense flash is a suitable solution for a patient who can not be photographed at the studio's location. It should be noticed that a new camera profile needs to be made for this specific photograph. Figure 30 shows all do's and don'ts for photographing the eye collected during this research.

**Do**

- Use a professional digital camera with a macro lens
- Set white balance in the camera before shooting
- Use a colour checker target
- Build your own photo studio
- Dark room with black walls
- 2 soft boxes next to the camera
- Use front lighting (2 flashes next to the lens or camera flash)
- Make a headrest for the patient
- Ask the patient to make big eyes or spread them open with your fingers.

**Don't**

- Illuminate the eye from the side
- Photograph in room light or daylight
- Photograph from the hand

Figure 30. Do's and don'ts for photographing the eye



## 4.2. Colour calibration

Custom camera profiles are a must for any photographer who relies on consistent, accurate colour. A custom profile must be created based on the raw output from the camera in the specific shooting condition. Before making the profile, it is essential to set the White Balance in the camera to eliminate unrealistic colour cast. A custom white balance was set in-camera by shooting the White Balance Target of the X-Rite ColorChecker Passport.

### Physical reference colour targets

A custom camera profile can be made by shooting a physical reference target. This project used two different targets: the X-Rite ColorChecker Passport and the ISa ColorGauge,

see Figure 31. The X-Rite ColorChecker Passport consists of 24 matte patches and comes with free, user-friendly software to make the profiles. The software provides creating DNG, Dual illuminant DNG and ICC profiles and has a plug-in for Adobe Lightroom and Photoshop. On the other hand, the size of the ColorChecker Passport is relatively large compared to the eye. This makes it hard to photograph the eye and target simultaneously. The ISa ColorGauge Micro target consists of 30 patches, and the overall size is 35 mm x 41.3 mm. It can be used with the open-source ArgyllCMS software, which can analyse, plot results and detect problem patches. Both targets were tested, and this section explains their workflows and results.



Figure 31. ColorChecker Passport and ISa ColorGauge Micro Target

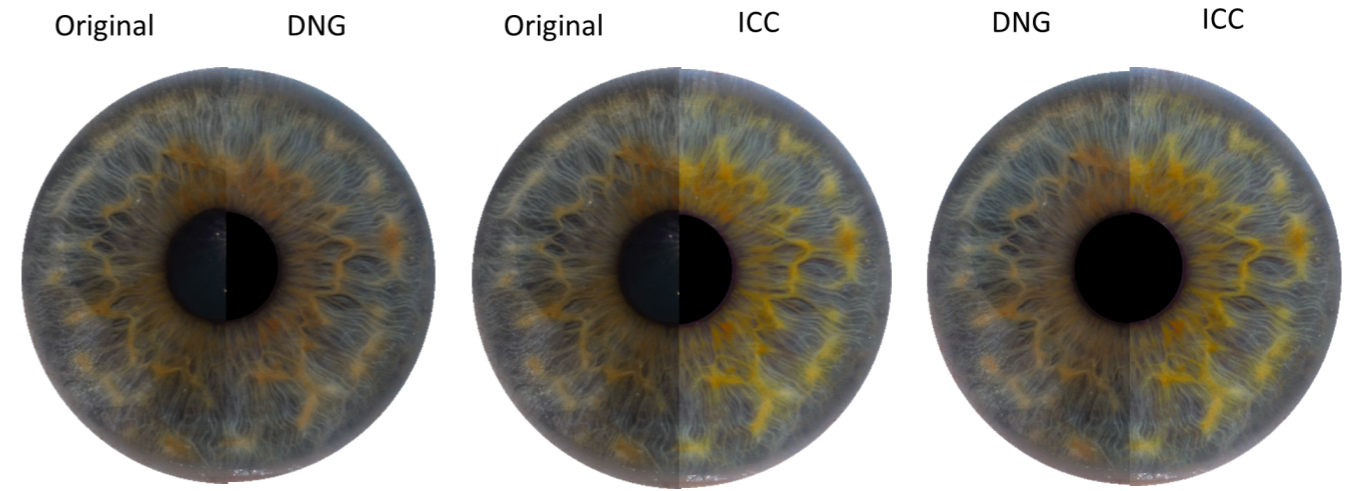


Figure 32. DNG and ICC profile applied to an iris foto

### DNG, Dual-illuminant DNG and ICC profiles

In the early days, all raw converters used ICC profiles. At that time, Adobe was unhappy with the functionality offered by ICC profiles, so they introduced a new camera profile format 'Digital Negative' (DNG) [33]. Unlike ICC profiles, an advantage of DNG profiles is that it supports Dual-illuminants. A Dual-illuminant allows for the creation of an all-round profile that may be used in several light conditions, like tungsten and daylight. Within this project, a dual-illuminant is not needed since only the specific light condition of the photo studio needs to be captured. As Torger notes: 'DNG profiles are more well-defined, and the conversion pipeline is more intuitive' [33]. For example, Adobe Lightroom provides batch photo editing but only supports DNG profiles.

### ColorChecker Passport DNG and ICC profiles

Appendix E shows how a DNG and ICC profile can be made with ColorChecker Camera Calibration software based on a photo of the ColorChecker Passport target. Figure 32 shows the differences between a custom DNG, custom ICC profile and

the original image (standard camera profile applied). The ICC profile lifted the yellow/orange colours and made them brighter than in the DNG profile. To evaluate the profiles, a printed version was compared to the eye in the original lighting conditions. Figure 33 shows the 3D printed versions of the iris with DNG and ICC profile applied, and Figure 34 and Figure 35 show the printed versions next to the eye. Colour differences between the profiles were hardly visible due to the amount of detail and the scale. Therefore, it can not be concluded that one approach would be better than the other.

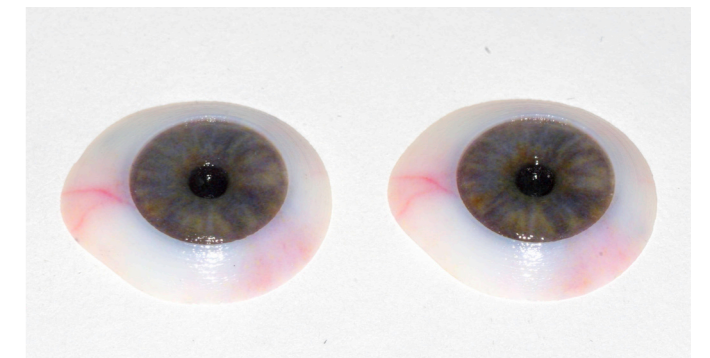


Figure 33. 3D printed iris with profile applied (left: DNG, right: ICC)

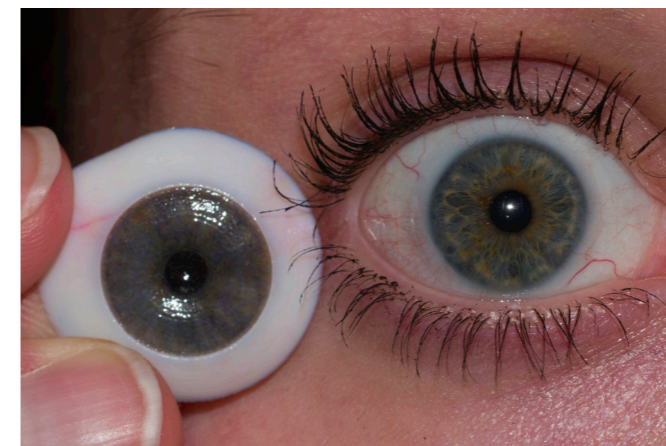


Figure 34. DNG profile iris compared to eye



Figure 35. ICC profile iris compared to eye



### ISA ColorGauge Micro

To make a profile of the ISA ColorGauge, the open-source ArgyllCMS software was used. ArgyllCMS is an ICC-compatible colour management system that supports accurate ICC profile creation for cameras. It is a command line terminal-only environment, which makes it less user-friendly than the ColorChecker Camera Calibration software.

ArgyllCMS 'scanin' tool locates the patch values in a photo of the target [34]. The 'scanin' tool needs two files to scan the patch values. First, a template (.cht) describes the chart's features and how the patches are labelled. The second file (.cie) contains the chart's CIE values for each labelled patch. Both files were set up for this project and can be found in Appendix F, together with colourimetry data of the ISA ColourGauge Micro provided by ISA [35]. Appendix G describes how a profile from the ISA ColorGauge can be made with the ArgyllCMS and DCamProf software. The software is very error sensitive. Therefore it is essential to shoot the target correctly. The target should be photographed straight from the front, and the four white corner markings must be visible, see Figure 36 for an example.

The ISA ColorGauge comes in glossy and matte versions. The glossy version gives errors while running the software or very high deviation, see Appendix H. This results from glare on the image since the target is illuminated from the front. Appendix I describes the results of the matte ISA ColorGauge. While running, the software provides results about the deviation in CIE values of the scanned patches, the delta E value (DE value). In this case, the 'scanin' results of the target photo had an average DE of 4.39, and the worst patch is B04 (DE 11.80).



Figure 36. Photo of ISA ColorGauge target

### Conclusion

The ColorChecker Passport and ISA ColorGauge are both suitable for making a profile. Which to choose will depend on the photography goal and the photographer's preferences. The ColorChecker Passport comes with intuitive software which is easy to understand. The target is relatively large to fit next to the eye, resulting in lower-resolution eye images. But the target can be photographed separately from the eye if the light conditions and distance to the target do not change. Despite the software being intuitive, it should be noted that it does not provide information on how the profile is made and what the deviations are.

The ISA ColourGauge is recommended if more control is desired while making profiles. It takes some time to understand the ArgyllCMS software, but clear documentation is provided. On the other hand, it can analyse and plot results and detect problem patches. The ISA ColourGauge is small enough to fit into the photo next to the eye, resulting in high-resolution images.

For accurate colour reproduction, it is relevant to shoot the eye and the colour target in a controlled light condition. Preferably in the same shot, but otherwise, all conditions must be identical. The patient's eye colour data can be captured by photographing in a studio with controlled conditions and calibrated by applying the custom-made profile based on a colour target.

# 5 Modelling

Which (contextual) parameters and process steps are relevant for creating a parametric model of the prosthesis's inner parts? And how can a parametric model, including colour and texture, be created based on a personalised outer shape of the prosthesis?

### Research model

As shown in chapter 3, the ultimate goal is a fabrication workflow based on a (parametric) design template to create a custom-shaped patient prosthesis. Defining a personalised outer shape of the prosthesis was considered outside this project scope, therefore all samples modelled for colour and texture research were based on a mesh of a generic prosthesis. The mesh was created by 3D scanning a generic-shaped prosthesis and was provided by the ocularist, together with the Blender file of the proof-of-concept. Blender was used during this research to create full-colour and textured models. By defining two vertex groups (iris and sclera) on the mesh, Blender allowed two textures to be mapped on one watertight mesh, which was needed for printing. Although meshes are very suitable for applying textures and rendering, it has limitations when describing the shape.

### Mesh vs NURBS

In a polygon mesh, the surface is represented by many triangles. It is impossible to make a perfectly smooth curve because triangles are always calculated as a straight line between points. A high number of polygons can be perceived as smooth, but it also results in large file sizes. CAD surface models are usually created using NURBS surfaces (shorthand for Non-Uniform Rational B-splines). NURBS is a mathematical formulation representing the geometry of curves, circles, arcs, and surfaces in 3D space. A few control points define the curves, and an algorithm calculates the curve based on the control points that joins two points in a system. NURBS models have smooth surfaces and are infinitely scalable without loss of surface quality. The file size is small since all the data contained are mathematical points, making it easy to read by the printer's slicing software. The downside of this mathematical way of describing a model is that it becomes more

difficult to calculate, which makes it unsuited for applications where render times need to be fast, like in animation. It is also not possible to UV unwrap a NURBS object, making it less suitable when needing textures.

### Computation design template

As shown in the workflow in chapter 3, modelling the inner parts of the prosthesis is also based on the computation design template. The ultimate goal is a template that automatically generates the prosthesis's inner parts based on the outer shape. Figure 37 shows how the operation of this computation design template is envisioned. The starting point is a NURBS model of the outer shape. The inner shape is defined by subtracting the average thickness of the cornea (0,5 mm) from the outer shape. After determining the gaze direction, a cut-off of the size of the iris' diameter is made to create an anterior chamber. The coloured and greyscale versions of the sclera photograph (.png) are mapped onto this surface to create a full-colour and textures sclera. Parallel to the modelling steps, an iris disk is made based on the input parameters iris and pupil diameter. The mapping process is repeated for the iris to produce realistic colour and texture. Next, the parametric iris disk is combined with the sclera model to create one core. In the last step, the core is combined with the outer shape, which is the shape of the cornea, to make the final full-coloured and textured model.

A small part of the computation design template was developed in Grasshopper. The script shows a parametric iris disk, which can change shape by adjusting the input sliders, see Figure 38. The iris disk is modelled by defining points linked to the input sliders. Lines are created between these points and revolved into a surface. Appendix J shows all details of the grasshopper script, including the clusters 'Create points' and 'Create lines between points'.

## Ocular prosthetic parametric model

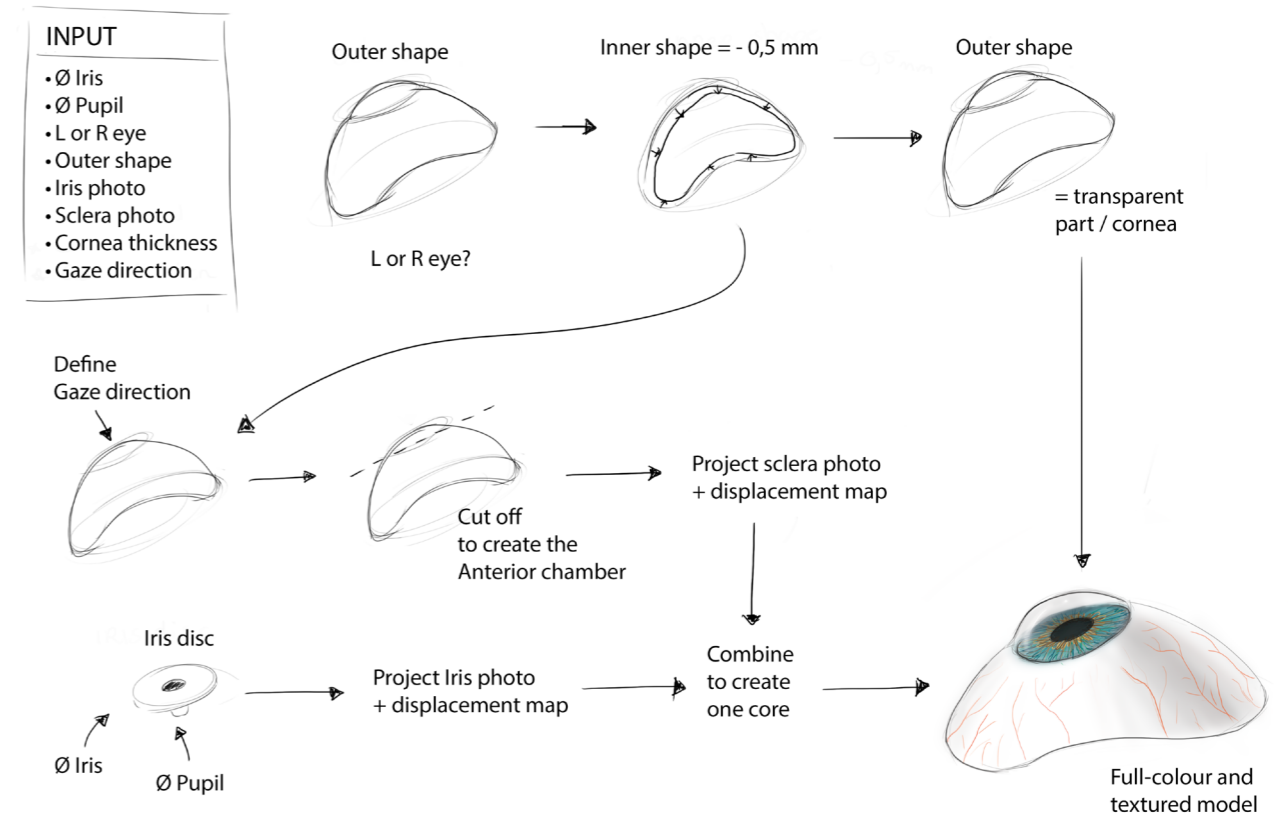


Figure 37. Envisioned working of the computation design template to design the inner part of the prosthesis.

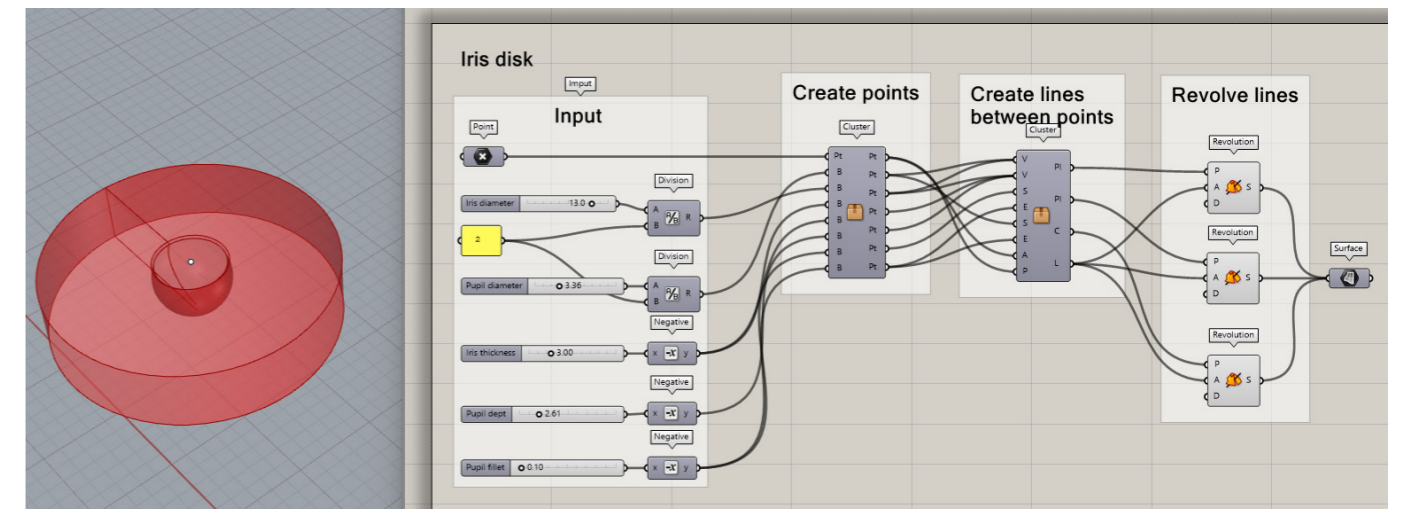


Figure 38. Parametric iris disc in Grasshopper



### Creating colour

Full-colour models were created by mapping the coloured version of the photograph onto the surface using the function 'UVediting' in Blender. This function unwrapped the 3D object and applied the 2D texture to it, in this case, the photograph. UV mapping was used to create a coloured iris and sclera, see Figure 39. Appendix K explains how the coloured iris and sclera was edited before applying.

In Grasshopper colour can be projected onto the model using the function 'Image sampler'. A NURBS model can not be unwrapped, so before UV wrapping the model must be translated into a mesh.

### Creating texture

The function 'displacement mapping' in Blender is used to create a 3D texture. This function displaces points of the surface according to the values of the duplicate grayscale image of the photograph. In this way, darker pixels represent the deeper parts of the iris, and lighter pixels present the more protruding parts. Appendix K shows how the grayscale image was created in Photoshop. The image needs to have enough contrast for the result to be visible, which can be achieved by editing levels in Photoshop. Figure 40 shows the prosthesis with 0.0, 0.3 and 0.5 displacement maps.

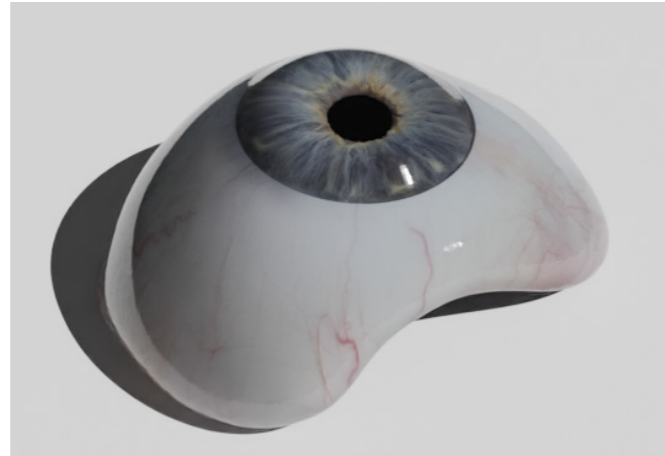


Figure 39. Render of prosthesis with coloured iris and sclera

A 3D texture can be achieved in Grasshopper by displacing the control points based on the image in the 'image sampler', this is shown in Appendix J.

### Conclusion

The Blender model is suitable for creating models with different colours and textures. Therefore it was used for modelling most of the 3D prints during this research. Nevertheless, the model is based on a generic shape and is challenging to change. A parametric model is a suitable solution to model the inner parts based on a personalised outer shape. The basis for a parametric model is a computational design template. Important parameters for this template are the iris and pupil diameter, the left or right eye, the outer shape, the iris and sclera photos, cornea thickness and the gaze direction. Relevant process steps are creating the inner shape, the anterior chamber, the iris disk, a coloured and textured iris and sclera, and combining them into one full-colour model. Figure 37 shows how the operation of this computation design template is envisioned, and the first steps towards making are shown in Grasshopper.

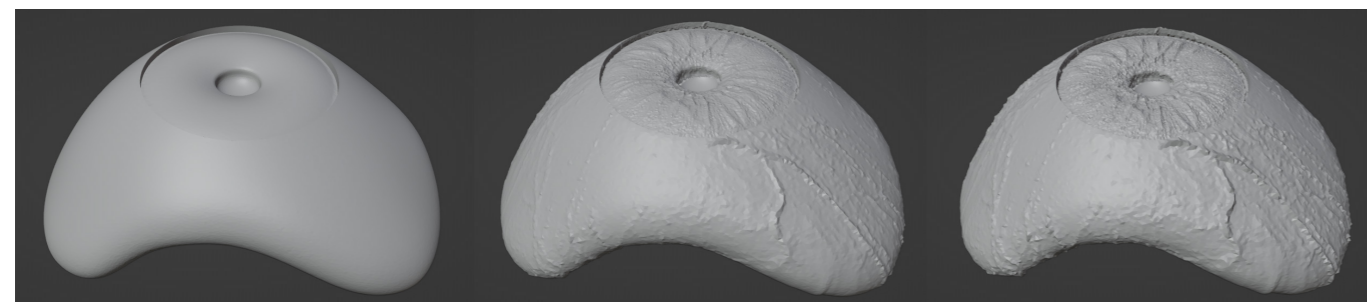


Figure 40. Prostheses with 0.0, 0.3 and 0.5 displacement map

# 6 Printing

How can the capabilities of full-colour 3D printing technology of the Stratasys J735 be exploited to reproduce best the various features of a human eye, such as sclera, blood vessels, pupil, cornea and iris?



### Contoning technique for sclera

To mimic the sclera, an even off-white surface is desired. Figure 42 shows printed sclera samples based on the colours of the colour diagnostic tool developed by Hyun [36]. The individual colour dots are clearly visible on the off-white sclera samples, see Figure 41.



Figure 41. Microscope photo sclera sample

Research from Babaei et al. [37] showed an interesting technique for 3D printing colours using a layering approach. Compared to halftoning, which was used before, the contoning technique creates colour by combining ink layers with various thicknesses on top of each other, Figure 43.



Figure 42. 3D printed sclera colour samples

A sample was made to test this technique, see Figure 44. The sample consists of three layers of VeroYellow-V on top of 69 layers VeroPureWhite (approximately 2mm) covered with ten steps of 10 layers VeroPureWhite (10 to 100 layers). Since the build-up of the sample needs to be rather precise, bitmap printing was used to control the material composition on the voxel level. The sample was made with the MATLAB-based Bitmap Slicing Program developed by Doubrovski et al. [18], which is explained in Appendix L.

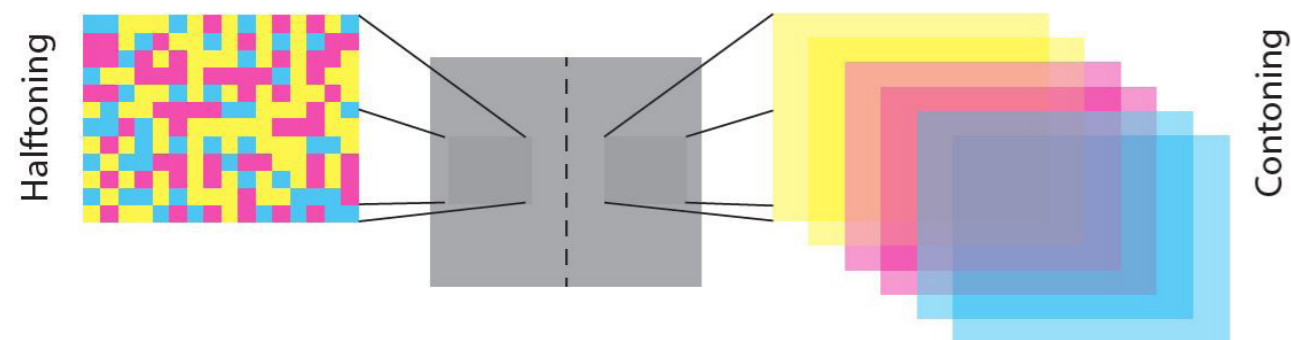


Figure 43. Halftoning and contoning technique, image from [37]

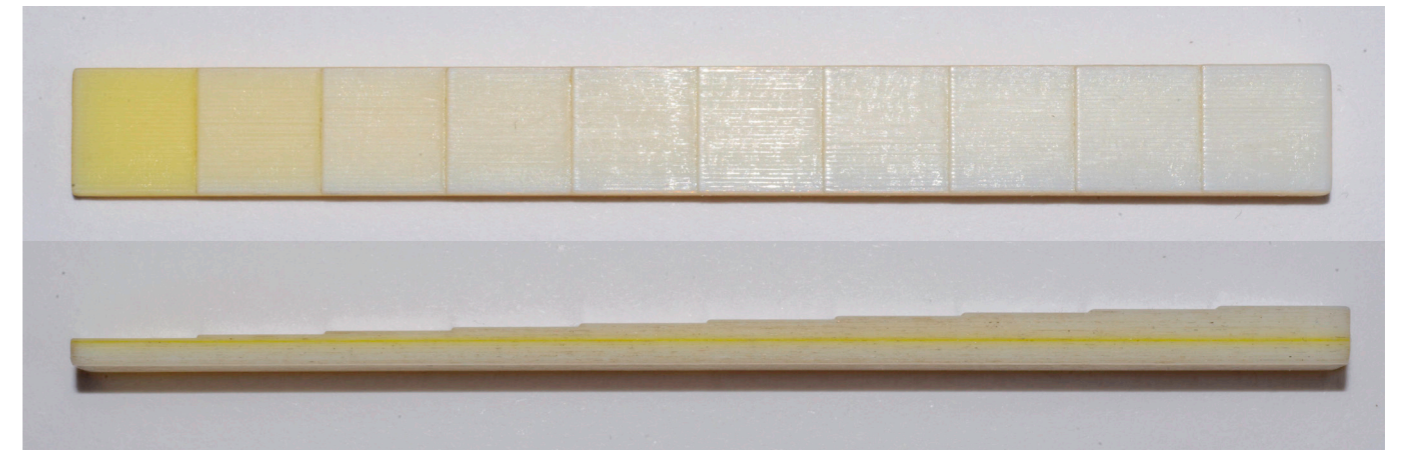


Figure 44. Contoning sample, ten steps of 10 layers VeroPureWhite (Top and side view, 10 to 100 layers, left to right)

All steps of the samples show an even colour. Steps 2 and 3 show an even off-white colour, while step 1 is too yellow, and step 4 is almost entirely white. Contoning is a promising technique to create even off-white surfaces in a prosthesis, but more research is needed to explore the layer's placement, layer thickness and the influence of varying colours.

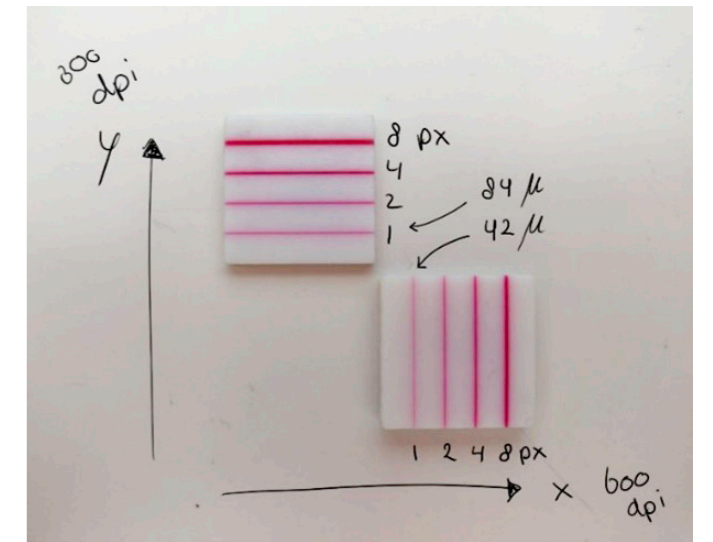


Figure 45. Printer's resolution samples in X and Y

### Dotting and varying line deepness technique for blood vessels

An average blood vessel is  $15,5\mu$  thick. The printer's resolution is 600 dpi x by 300 dpi y by 941 dpi z, resulting in a voxel of  $42\mu$  by  $84\mu$  by  $27\mu$  (X by Y by Z). To mimic blood vessels, VeroMagenta-V lines of 1, 2, 4 and 8 pixels are printed in a VeroPureWhite block; see Figure 45 and Figure 46.



Figure 46. Mimic blood vessels by magenta lines of 1 pixel

The lines on the samples are thicker than desired and show a significant blur of detail and bleeding effect, see Figure 47. The resins used in the Stratasys J735 are inherently translucent and therefore show significant sub-surface scattering. As Elek et al. point out: 'The resulting light diffusion leads to over-blurring and potential color bleeding when printing spatially-varying color textures. This translucent 'crosstalk' between surface points also strongly depends on the internal structure of the volume surrounding each surface point' [38]



Figure 47. Bleeding effect



A sample with red-coloured vessels was made by mixing 75% VeroMagenta-V with 25% VeroYellow-V. Unfortunately, the VeroMagenta-V is not strong enough to match the vessels' red colour, see Figure 48. This colour should be achieved by mixing more colours.



Figure 48. Vessels red coloured samples

In Blender, a high-quality eye image was mapped on a sample of 22x30x2 mm and printed, see Figure 49 and Figure 50. Figure 50 shows a significant blur of detail. Most blood vessels disappeared and became blurry pink.

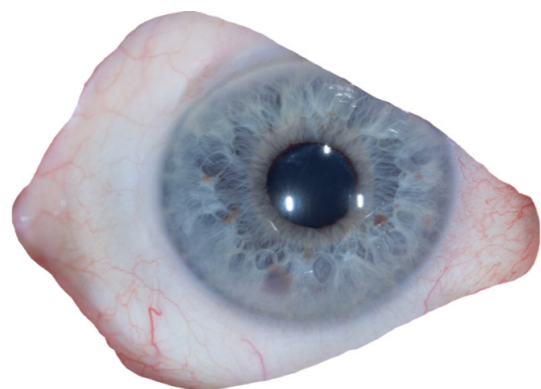


Figure 49. High quality eye image

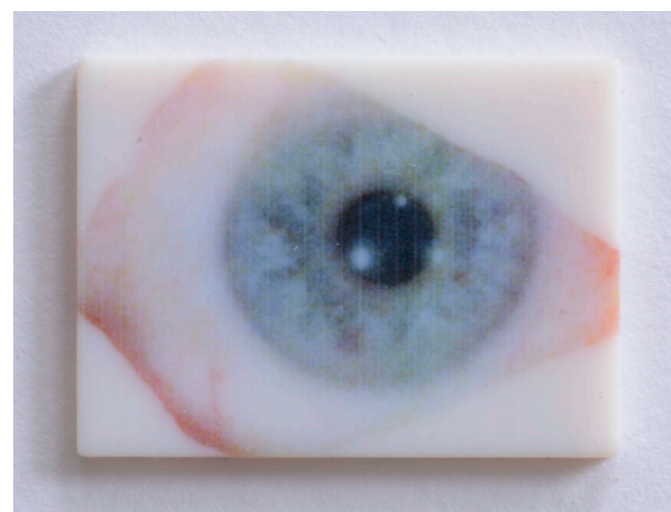


Figure 50. High quality image printed sample

Based on the proof-of-concept (chapter 2.2.) and the examples shown in this chapter, it can be concluded that just mapping an image of the sclera on the prosthesis does not give the desired result. Most blood vessels of the image disappear and show a significant blur of detail due to the printer's resolution and surface scattering.

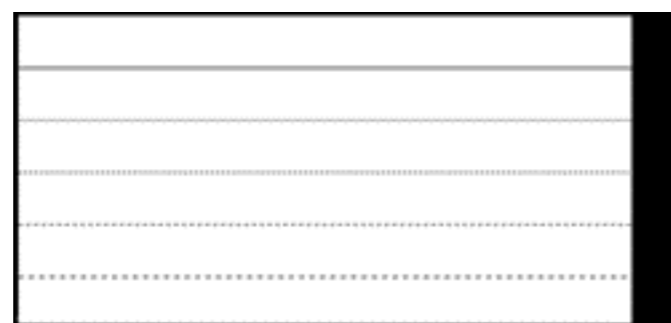


Figure 51. Bitmap png. of dotting lines sample

Two techniques were explored to create thinner lines mimicking blood vessels. First 'dotting' was explored. The sample includes one continuously line of 1 pixel compared to four different dotting lines of 1 pixel. The dotting lines varying in white spacing between the dots, see Figure 51 for the Bitmap. Figure 52 shows the printed result. The second and third lines look thinner but still continuously. At the fourth and fifth lines, individual dots start to appear.



Figure 52. Dotting lines sample (top line is continuously)

For 'varying line deepness', the second technique, the lines vary in z-direction deepness (perpendicular to the surface). The first line is one pixel thick, the second two pixels, the third three and so on, see Figure 53. Less deep lines also result in thinner lines and less bleeding.



Figure 53. Sample with variation in line deepness (1 to 5 pixels deep, left to right)

### Generated sclera including blood vessels

As shown in appendix K, merging different sclera images in photoshop is a manual and time-intensive process. Additionally, printing the sclera based on a photo does not give the desired result. A suitable solution could be a script automatically generating a sclera with veins. Figure 54 shows how this envisioned script could work. The script will be based on different sclera colours, veins colours and amounts of veins. The script should be combined with a voxel-based printing technique to be able to play with varying lines' thicknesses.

### Sclera generator

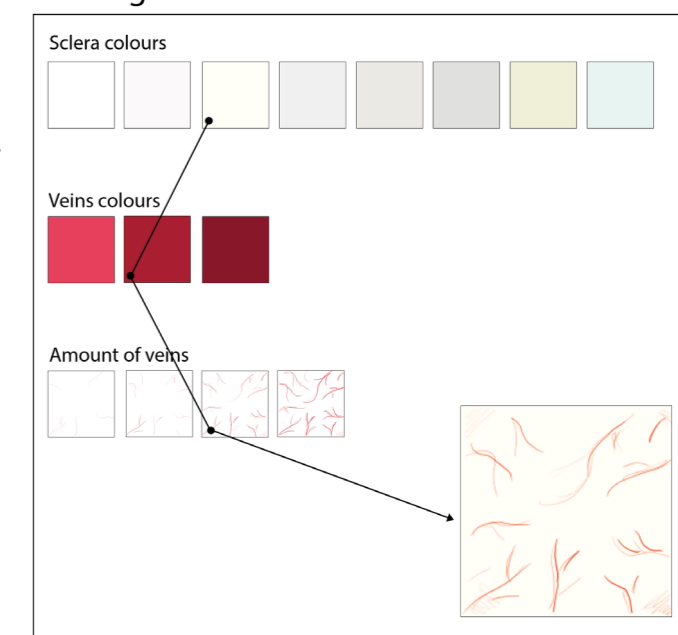


Figure 54. Sclera generator

To test if a generated sclera could work, samples were printed with a generated sclera image. In Photoshop, the images were made by tracing the veins from the photo with a line thickness corresponding with the 600 dpi printing resolution. Figure 55 shows the photo used as an underlayer. Three iterations of the traced images and their printed results are shown in Figure 56. With this approach, it remains a challenge to determine the right line thickness and colour to create a realistic appearance.



Figure 55. Sclera photo used as underlayer



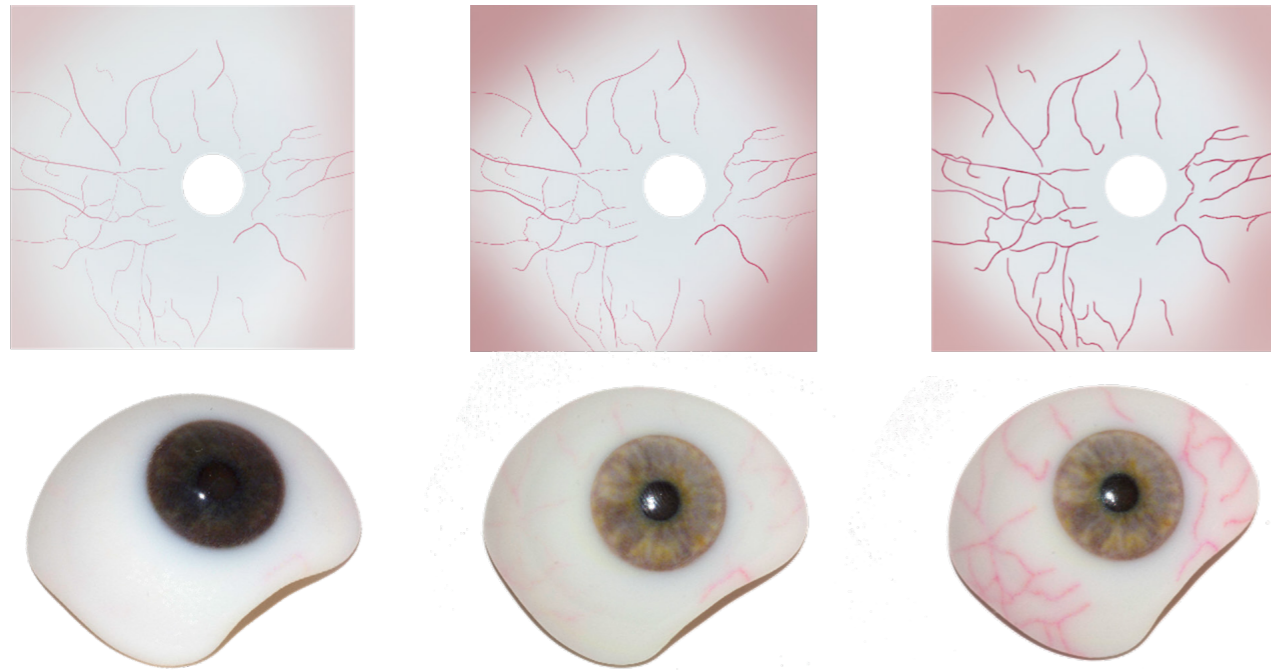


Figure 56. Three traced sclera iterations with printed result

### Layer thickness for pupil

The pupil in the proof-of-concept was not appearing black, suggesting that the layer of black ink was too thin. A sample was made to test at which layer thickness the VeroBlackPlus becomes opaque. Figure 57 shows the sample consisting of steps of 0.1mm on a 1 mm layer VeroPureWhite. From 0.6 mm, the VeroBlackPlus appears opaque, but Stratasys advises at least a layer thickness of 1 mm to get opaque colour.

In addition to the material being black, the pupil in the prosthesis also appears black due to its shape. The pupil is a circular opening with a spherical hole, which appears black since most of the light entering does not escape. Some prostheses need to be very thin, resulting in not enough space for the black layer or the spherical hole. A possible solution could be to stop the printer during printing and manually place a thin black implant.



Figure 57. Black layer thickness sample, ten steps of 10 layers VeroBlackPlus (10 to 100 layers, left to right)

### Colour matching and textured iris

Different high resolution iris images were printed on a sample with the average iris diameter (12 mm) to test if the fine details of the irises can be reproducible, see Figure 58. Figure 59 shows one of the original iris images and Figure 60 shows the corresponding printed result under the microscope. The iris appears too green, and the grey/blue colour seems missing. Furthermore, the limbus appears absent, the sample shows a significant blur of detail, and most of the iris pattern disappeared. It should be noted that the model is a single iris disk. The surrounding sclera, cornea and convex-shaped iris disk contribute a lot to the realism of the prosthesis.



Figure 59. Original iris image



Figure 58. Five iris samples



Figure 60. Iris sample under the microscope

Different iris samples were printed for three participants to test if a matching iris colour could be obtained, see Figure 61. The prints were based on iris images, which were calibrated with two different profiles and edited with an exposure of 1, 2 or 3. All prints were compared to the original eye under the same light conditions as the original photo. To make the samples more realistic, they consist of the top slice of the prosthesis model, including the iris, pupil and a little bit of the sclera. Appendix M shows all results of the samples compared to the eye. In general, the colour match of all three participants was largely accurate, but the lack of detail and iris structure resulted in a mismatched look, see Figure 62.

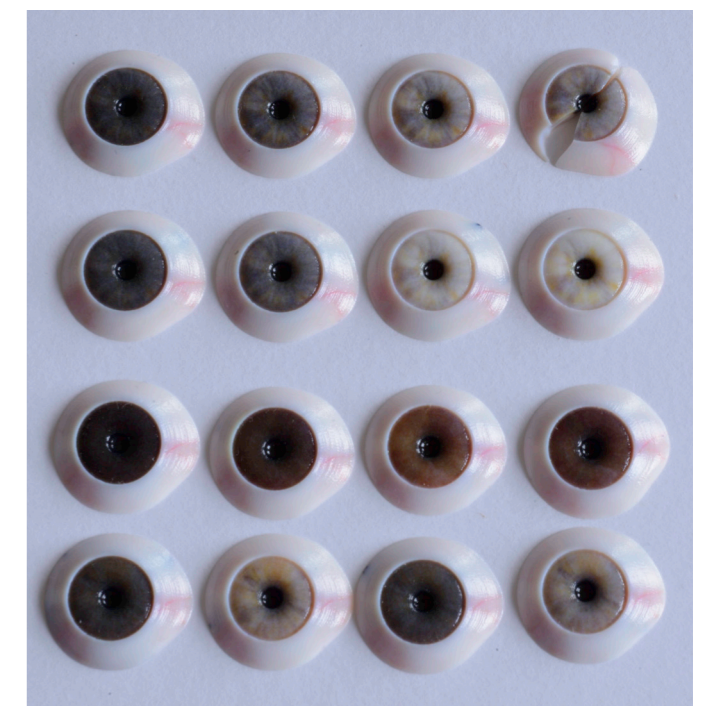


Figure 61. Overview of all iris colour samples



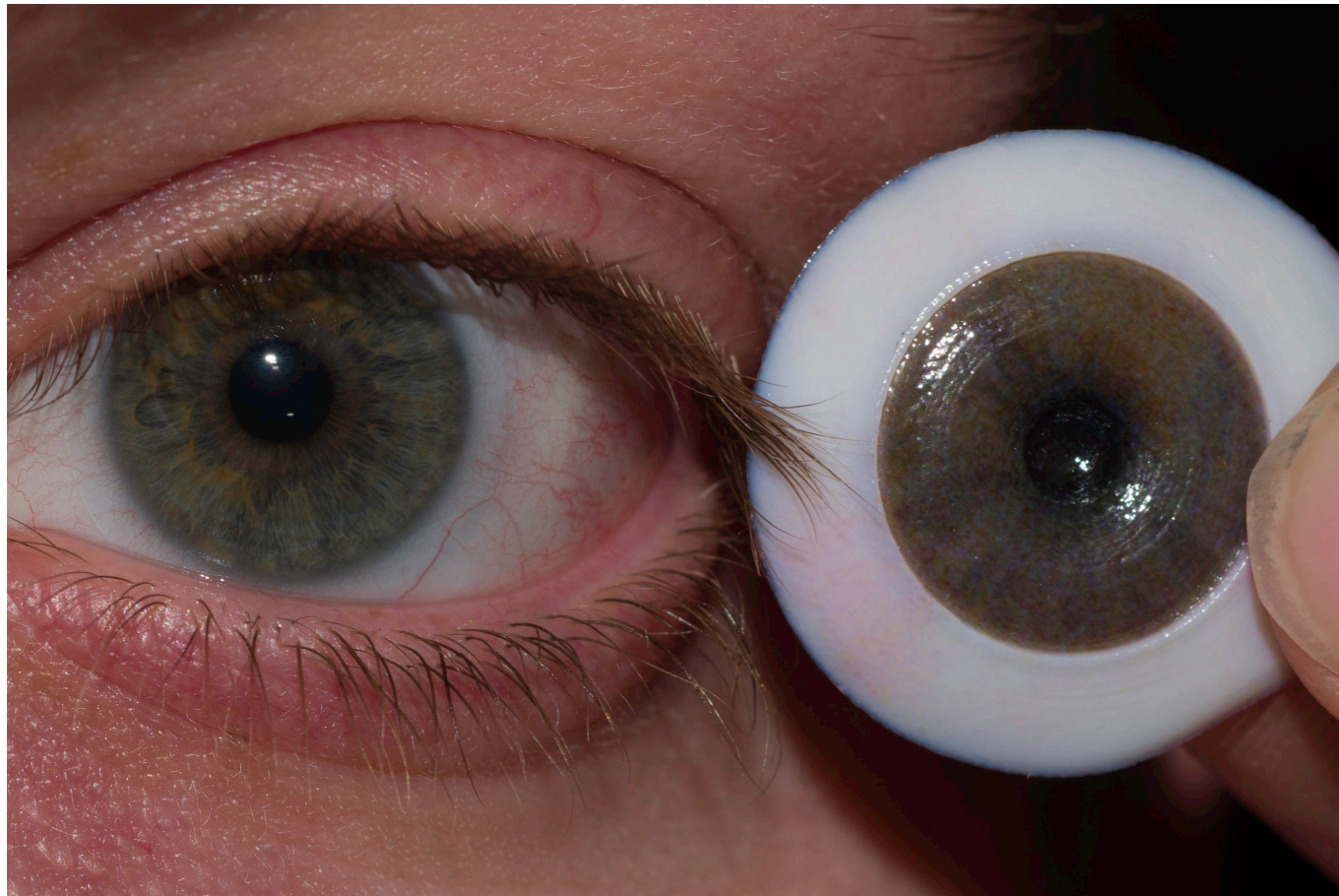


Figure 62. Original iris compared to printed iris

In addition, more irises were printed to test if certain editing parameter could influence the colour of the iris, and the printability and visibility of the fine details in the human iris. The following parameters were changed while editing the iris image in Photoshop: exposure, resolution, saturation, cyan, limbus and sharpen filter.

**Exposure**

For this particular eye, the printed iris was too dark, see Figure 63. A reason could be that more light was needed during photographing. The original image is edited with an exposure of 1, resulting in a slightly too light iris compared to the eye, see Figure 64. In general, the blue/green colour seems missing. But the iris with an exposure of 1 shows more yellow/orange colours, and the contrast between the colours is more extensive, making the texture more visible.

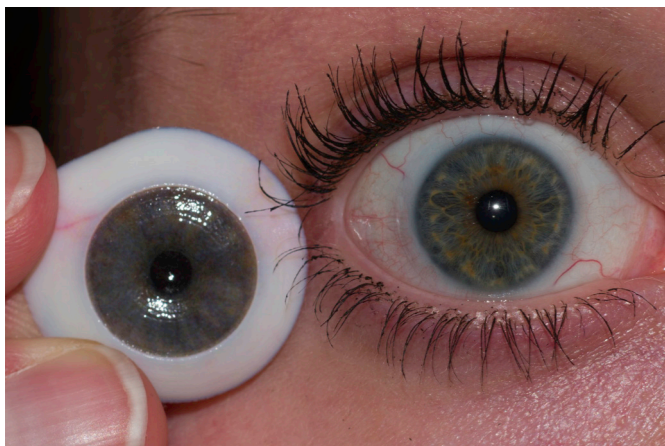


Figure 63. Sample with original iris photo compared to the eye.



Figure 64. Sample with iris exposure 1 photo compared to the eye.

**Resolution**

All photos were made with a high-end professional camera (7360 by 4912 px). This results in images with a much higher resolution than the printer's resolution of 600 dpi. Figure 65 shows that downscaling the resolution in advance does not influence the print's colour.

**Saturation**

The increase in saturation made the yellow/orange colours more prominent and the contrast between the colours is more extensive, making the texture more visible. Blue/green colours still seem missing, see figure 65.

**Cyan**

For this particular eye, adding extra cyan improved the iris colour to match the eye, see Figure 65.

**Limbus**

A limbus was manually added in Photoshop by adding a gradient circle from the dark iris colour to white. After printing this difference was not visible compared to the original, see Figure 65.

**Sharpen filter**

The sharpen filter in Photoshop makes the transitions sharper, resulting in a more prominent structure. Unfortunately, after printing, this is not visible, see Figure 65.



Figure 65. Iris colour comparison between the original iris and a low resolution, saturated, cyan, limbus, and sharpen filter edited iris. eye.



As explained in chapter 1.8, the camera can capture a much more extensive colour space than the printer can print. It could be possible that the printer can not reproduce specific colours that exist in the eye. The iris colours of all seven participants in this research were plotted in the gamut of the 3D printer. Figure 66 shows all iris images, and Figure 67 shows the gamut. Two white colours and some dark brown and black colours lay outside the gamut. All other colours of these specific irises fell within the gamut and should be reproducible by the printer.



Figure 66. Irises which were plotted in the gamut

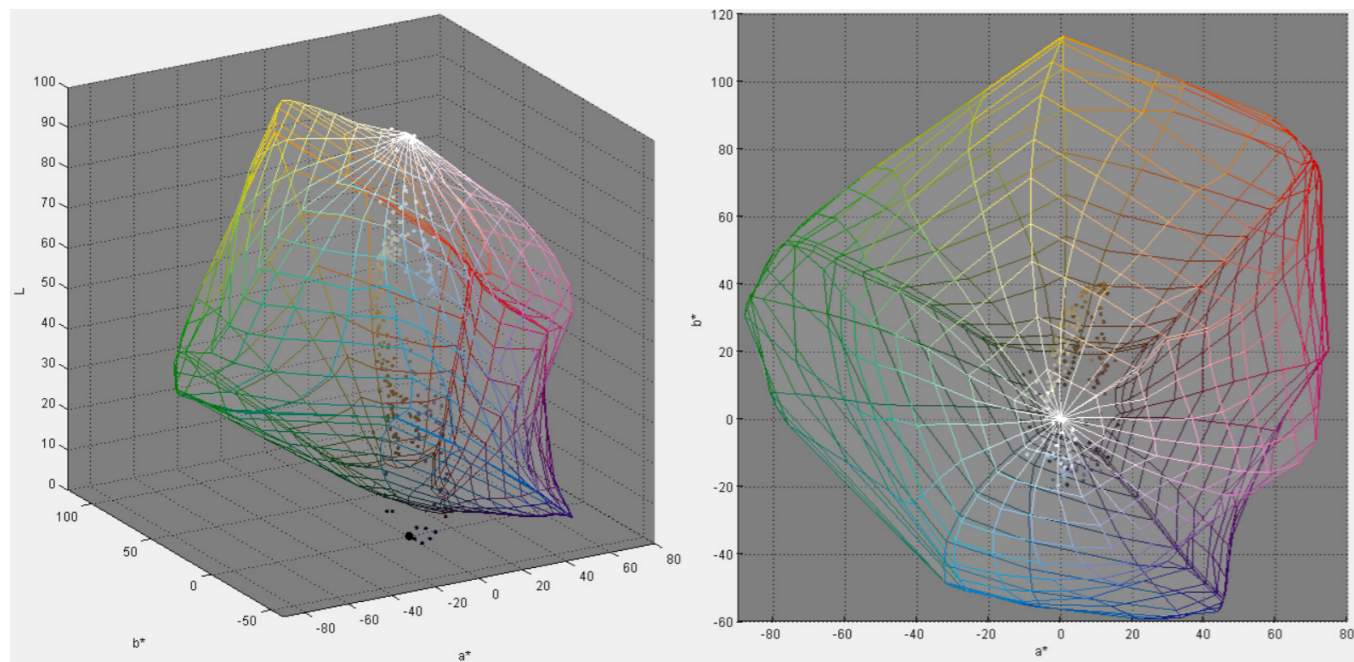


Figure 67. Iris colours plotted in the 3D printers gamut. (3D and top view)

To investigate how the 3D printer prints certain colours, a photograph of the ColorChecker Passport was printed, see Figure 68. The colours of the 3D printed version (3D P) were compared to the original ColorChecker Passport (CCP) by photographing them in the same lighting conditions. Figure 69 shows the colour comparison. All 3D printed colours are less saturated, but the colour tone looks similar. The yellow colours are greyish and not so bright. In addition, it is clearly visible that the 3D printed red hues are magenta based since red is more a very dark magenta than red.



Figure 68. 3D printed ColorChecker Passport vs the original

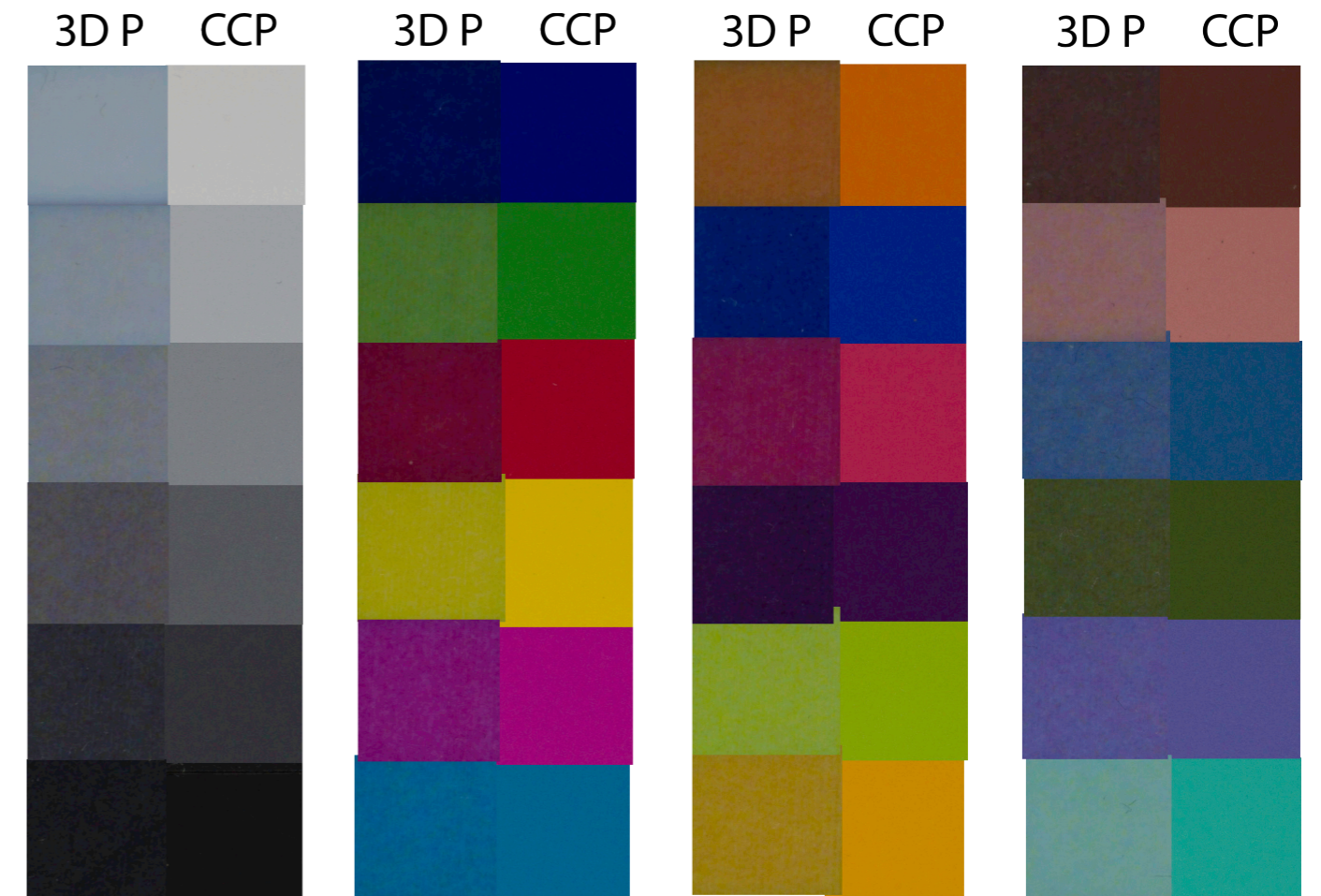


Figure 69. Colour comparison between 3D printed (3D P) and original ColorChecker Passport (CCP)



## Conclusion

Different printing techniques were explored and compared to reproduce the different features of an eye optimally. For the sclera, the contouring technique is a possible improvement to create an even off-white sclera colour. Mapping an image of the sclera, including blood vessels, on the prosthesis does not give the desired result since most blood vessels disappeared and showed a significant blur of detail due to the printer's resolution and surface scattering. Another opportunity to improve the sclera could be a script automatically generating a sclera with veins. The script should be combined with a voxel-based printing method to implement the 'dotting' or 'varying line deepness' technique to create thin and sharp veins. To optimise the reproduction of the pupil, it can be best printed as a 1 mm thick black layer shaped like a spherical hole. The iris can be printed using a mapped photograph to ensure accurate colour

reproduction, but the structure and details were missing. Changing the exposure, saturation and amount of cyan proved to make the structure more visible for this specific iris. Further investigation is needed to test whether these methods also apply to other irises.

Figure 70 shows how it would be envisioned if all printing techniques were combined into one prosthesis. To reproduce the various aspects sclera, blood vessels, pupil, cornea and iris, the model must be controlled on the voxel level. Partly this could be achieved by using the multi-material bitmap printing method. However, the current software available lacks the possibility to model a complete voxel-based prosthesis and to control the various aspects. In addition, more research is needed to explore the possibilities of translating a coloured image to a voxel-based model.

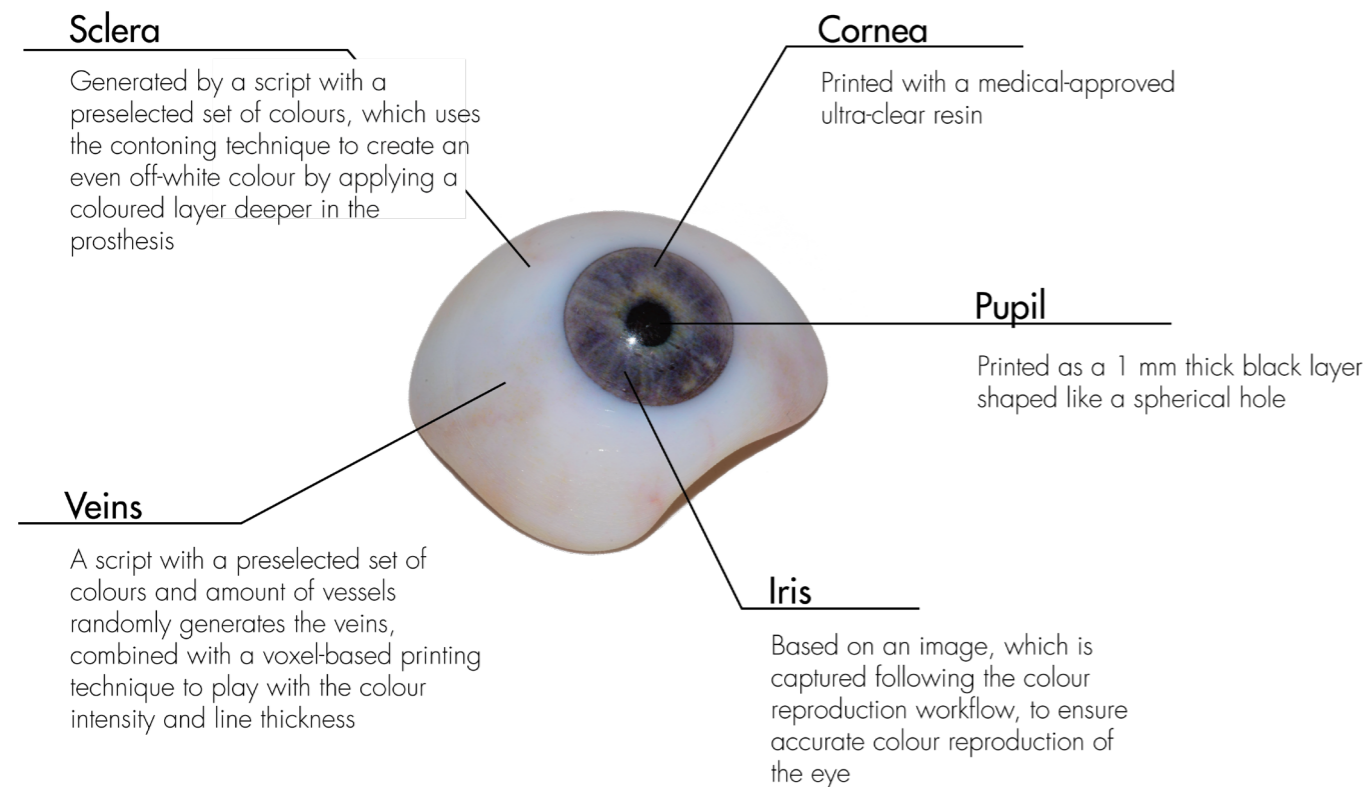


Figure 70. Visualisation of all printing techniques combined into one prosthesis



# Validation

This chapter describes the validation of the prostheses produced following the proposed digital workflow.



Prostheses produced following the proposed digital workflow were validated by a user test, in which two experts of Amsterdam UMC and five users participated. Photos of the participant's iris and sclera were taken and mapped onto the 3D model in Blender. For every participant, four prostheses were printed; one with a 3D structure (0.3 displacement), one without, one with an edited iris with an exposure of 0.5 and one with an exposure of 1.0. Six of the seven participants were interviewed about their personalised 3D-printed prostheses to validate them against

the design criteria. In addition, the prostheses of all seven participants were photographed next to the original eye in the same light condition as the original photo. Appendix N shows all edited images used and the pictures of the results. Appendix O presents the interview questions with the answers of the six participants.

Figure 71 shows an overview of the most relevant results of the user tests. Note that E1, for example, resembles expert 1, and P1 resembles participant 1, etc.

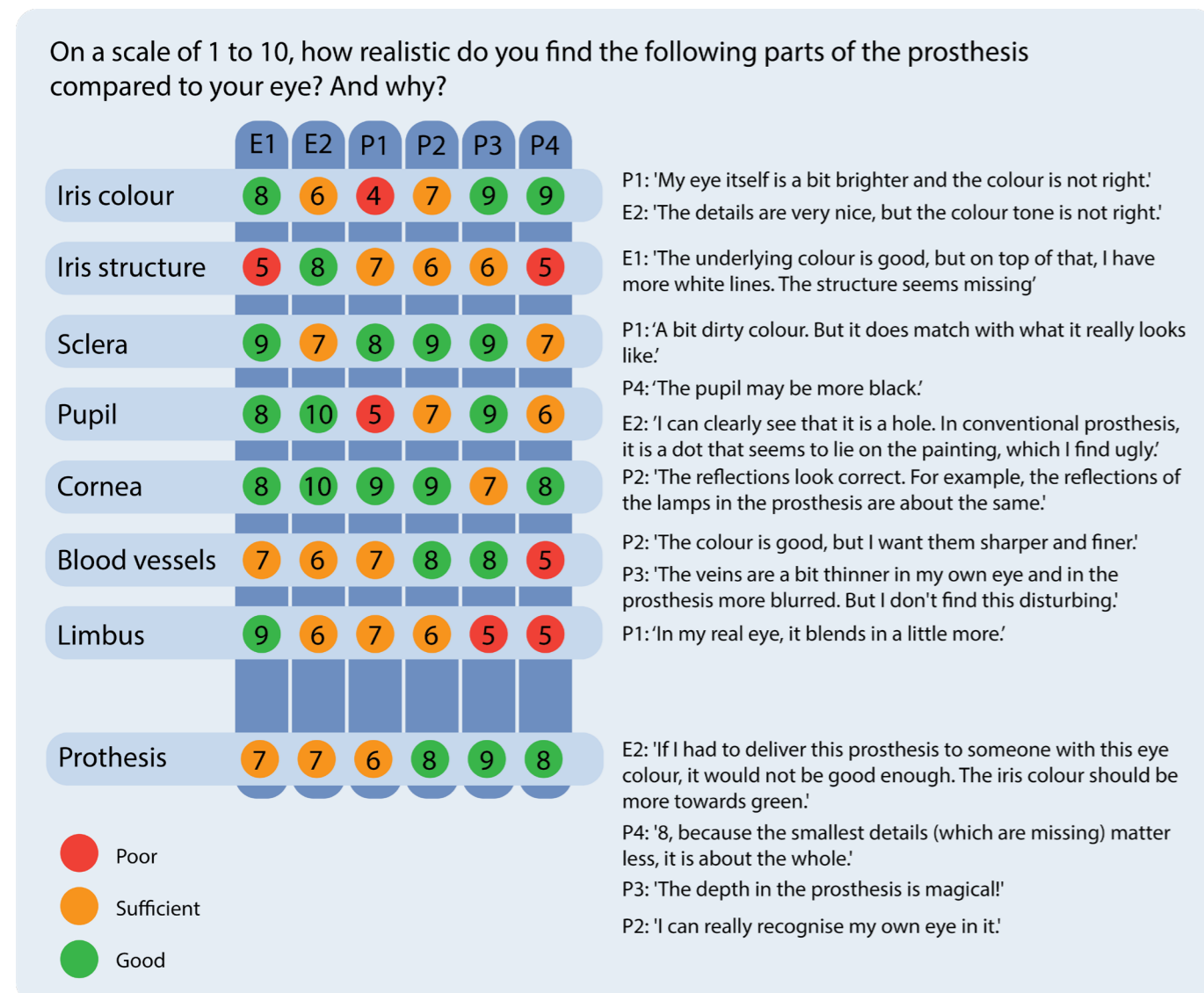


Figure 71. Overview of the most relevant results of the user test interviews.

All participants, including the two experts, were impressed by the prosthesis and rated the total prosthesis as 'sufficient' or 'good'. Nonetheless, it remains a challenge to reproduce the correct iris colour and structure. The colour tone was right for most participants, but the detailed pattern seems missing. Three of the six participants preferred the prosthesis with an exposure of 0,5. An example is shown in Figure 72. A slightly lighter iris also contributes to making the structure more visible.

All participants were satisfied with the sclera colour, the cornea shape and the glossiness of the prosthesis. For most participants, the pupil may be more intensive black, but the experts found it sufficient. All participants indicated that the blood vessels were blurry compared to their eyes. Most would like to have them finer and shaper but were satisfied with the current result. Reproducing a realistic limbus was also challenging. Some participants missed the darker-coloured ring, but others found the transition to the white sclera not smooth enough. The limbus was too sharp.

All participants were asked to choose the most realistic prosthesis between one with a 3D structure and one without, without knowing the difference. In one prosthesis, a displacement map was applied of 0.3 on the iris and sclera. Unfortunately, the results were hardly visible. Two participants could not indicate a difference between the prostheses. One participant chose the one without structure since the transition from the iris to the pupil was sharper. The other three participants chose the one with a 3D structure but were unable to explain this difference. E1 and P1 chose the one with structure since the lighter colours stand out more, making the colour texture more visible. This is actually the result of the 3D structure. The lighter colours are located a little higher, making them more prominent. After explaining the difference, no one could see the 3D structure. Although the difference could have been more pronounced, it is debatable whether the 3D structure adds something to the realism of the prosthesis.



Figure 72. Prosthesis comparison of original and exposure 0.5





# 8

## Conclusion

The chapter reflects on the project in the form of a discussion and gives a conclusion and recommendations for further research.



# 8.1. Manual vs digital workflow

Figure 73 shows the manual workflow next to the proposed digital workflow. The workflows were simplified by leaving out the steps of finding a shape model and making a 3D model of the outer shape. These steps are considered outside the scope's project and cannot be fairly compared. The manual workflow includes a time indication per step. It should be noted that the indication is a rough estimation from the ocularist at Amsterdam UMC. Since most prostheses are made in batches, it is hard to indicate a time for one prosthesis realistically.

The actions of the ocularist during the first consults are relatively similar in both workflows. In the digital workflow, extra photos of the sclera are needed, which also results in extra editing work during the processing step. The editing approach used within this project was manual work and, therefore, time-consuming. Since the editing steps are relatively simple, this could be outsourced or automated.

A computational design template that automatically generates the prosthesis's inner parts based on the outer shape will significantly improve efficiency. The ocularist only needs to provide all input files, and the software can automatically generate the 3D model, which is ready to print. Although chapter 5 shows the first steps towards this template, developing the software will be challenging and time-consuming. Within this project, all prostheses created with the digital workflow were based on an average-shaped prosthesis. Making the workflow applicable to custom-shaped prostheses will remain a challenge, together with automating the modelling process.

The digital workflow consists of fewer production steps than the conventional methods, see Figure 73. 3D printing the prostheses can replace all the manual steps from 'Print iris image' to 'Clear PMMA layer', which takes over 4 hours, resulting in significant time savings. In an optimised process, the Stratasys J735's building tray is full with 110 prostheses, resulting in a total printing time of 11,5 hours (6,5 minutes per prosthesis). In addition, 'printing time' can be used to do other work.

Moreover, the steps of the digital workflow are reproducible, meaning if digital patient data is saved, it would always be possible to go one step back in the process. If something goes wrong in the conventional production, like a speck of dust ends up in the prosthesis during production, the prosthesis is rejected and must be made again. Sometimes a part can be redone by sending it away and pouring plastic into the mould again. In contrast, the digital workflow supports returning to the modelling phase, changing and printing again. Moreover, since every two years, a new prosthesis is recommended, the last model could be changed digitally and printed with the digital workflow.

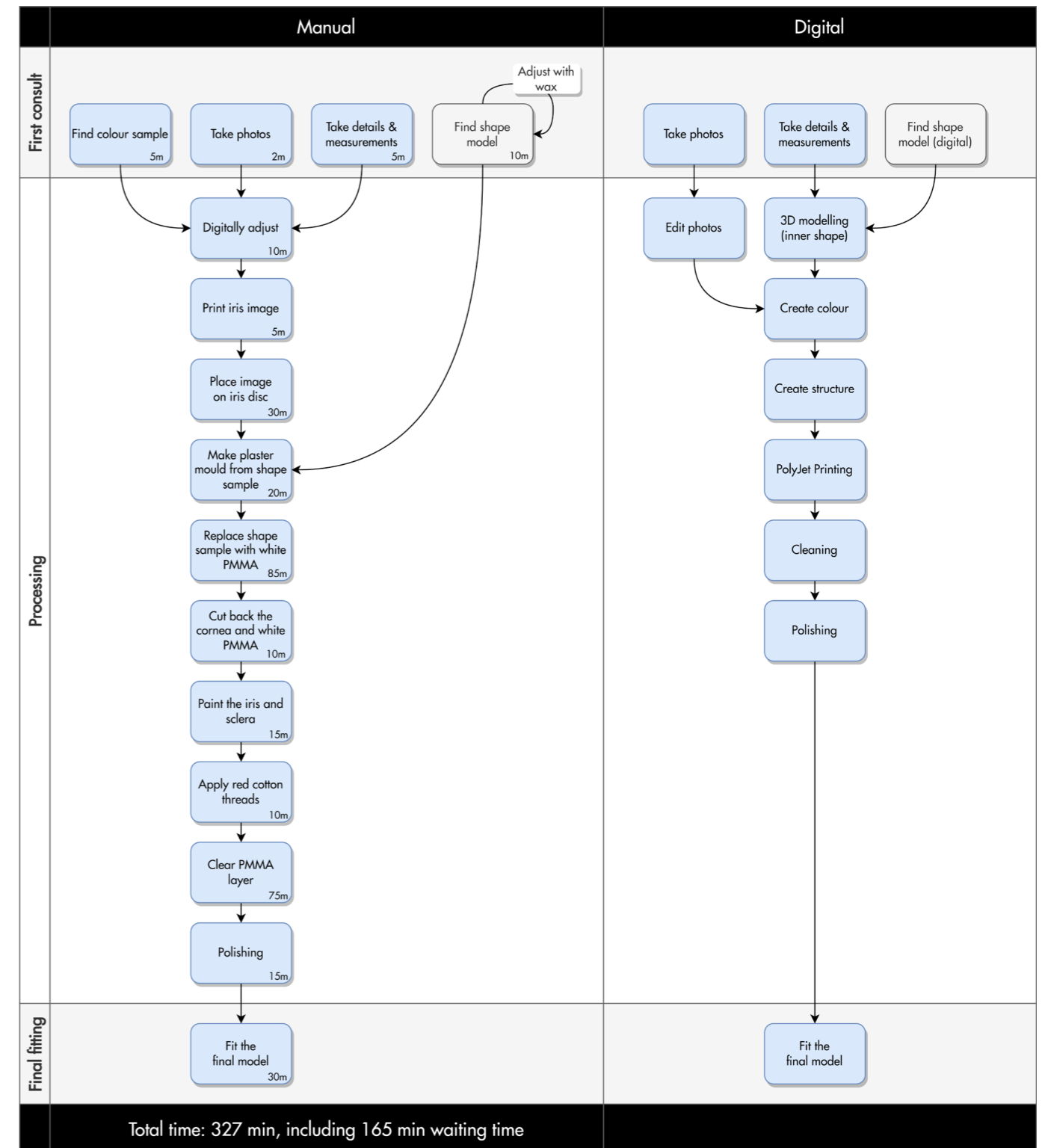


Figure 73. Manual workflow next to digital workflow



## 8.2. Conclusion

This graduation project was started on the observation that fabricating custom-made ocular prostheses is currently a highly-skilled, labour-intensive and non-reproducible process performed by an ophthalmologist. Digital production techniques provide opportunities to improve this process.

Research into the conventional and digital production techniques resulted in the proposed digital workflow. This workflow shows how a prosthesis can be produced with digital production techniques and consists of five phases: collect, design, produce, post-process and finalise. It also shows how the patient and ophthalmologist are involved and shows the data stream.

The capturing research showed that photographing is a suitable technique to collect colour data for accurate colour reproduction if the eye and the colour target are shot in a controlled light condition. A controlled light condition means a camera studio with fixed distances, a camera flash next to the lens, two soft boxes, a headrest and a target for capturing realistic colour. A single colour profile is needed for this setup based on the target, which makes editing quick.

The modelling research showed that for adjusting the prosthesis model to a personalised shape, a parametric model based on a computational design template in Grasshopper is a suitable solution. The first steps towards creating this computational design template are shown in this report, including important parameters needed.

The investigation of alternative approaches to (re) produce best the various features of the human eye showed that different printing techniques are suitable for different parts of the eye. The iris can be printed using a mapped photograph to ensure accurate colour reproduction. Printing the sclera based on a photo does not give the desired

result since most blood vessels disappear. A script that automatically generates different sclera with veins would be a more suitable solution. The script should be combined with a voxel-based printing technique to implement contouring and play with varying lines' thicknesses. Finally, a visualisation was made of how a future printed prosthesis would look like if all techniques were combined into one. However, the current software available lacks the possibility to model a complete voxel-based prosthesis and to control the various aspects.

Prostheses produced following the digital workflow have been validated by two experts of Amsterdam UMC and five users by interviewing and photographing the results. All participants were impressed by the prosthesis and rated the total prosthesis as 'sufficient' or 'good'. Nonetheless, it remains a challenge to reproduce the correct iris colour and structure. Even though all participants indicated that the blood vessels were blurry compared to their eyes, most were satisfied with the current result.

The comparison between the manual and digital workflow showed that 3D printing the prosthesis can replace seven manual steps, which take over four hours, resulting in significant time savings. In an optimised process, the printer can print 110 prostheses in 11,5 hours, and 'printing time' can be used to do other work. Moreover, the digital workflow is reproducible, which supports returning to the modelling phase, changing and printing again.

The development of this digital workflow adds valuable knowledge to the future production of 3D-printed ocular prostheses, which has several benefits over the conventional method. 3D printing ocular prostheses make the workflow reproducible and faster, which leads to more accessible and affordable prostheses in the future. With the recommendations of chapter 8.3 in mind, the proposed workflow can become a very interesting and feasible option for ophthalmologists that want to integrate new technologies into the production process of ocular prostheses.



Figure 74. A 3D printed prosthesis produced following the proposed workflow



## 8.3. Discussion and recommendations

Based on the conclusions from chapter 8.2, there are recommendations regarding further development of 3D printed ocular prostheses.

### Capturing

Most tools (monitor and 3D printer) used in this project were not calibrated properly. Besides, the spectra of the light sources used (flash and soft boxes) are also unknown. It is recommended to calibrate all tools to ensure accurate colour reproduction. In addition, build a photo studio with controlled light conditions and measure the light sources' spectra to understand the light conditions before making the profiles.

### Modelling

Further develop the computational design template, which can create the inner parts of the prosthesis based on a personalised outer shape and applies colour and texture. In the future, this template could be combined with a template that creates a personalised outer shape based on a scan of the impression or a reference model. It is recommended to work with a NURBS-based model since NURBS models have smooth surfaces and are infinitely scalable without losing surface quality. In addition, the file sizes are small, making it easy to read by the printer's software. Nevertheless, more research is needed to explore the possibilities of projecting textures on a NURBS model since UV wrapping is currently impossible.

With the current image mapping technique, there is no control over the colour and thickness of the blood vessels. If more control by reproducing blood vessels is desirable, developing a script that automatically generates a sclera with veins is recommended. For this, it is important to define different sclera colours, vessel colours and vessel amounts. The script should be voxel-based to use the contouring technique and play with varying line thicknesses.

### Printing

Our eye includes structural colours, which makes comparing the colour difficult since it depends on the light conditions. It is therefore suggested to test the colour reproduction workflow with a physical colour target first (for example, a conventional prosthesis or an item that has colours that often appear in the eye). This will make it easier to compare the result and validate the accuracy of the workflow.

The seven participants used in this project do not represent all iris colours existing. As a follow-up study, it would be interesting to plot the iris colours of a larger target group into the 3D printed gamut to explore if the printer can reproduce the colours.

Materials in the printer are often changed since the printer is also used for other research purposes at the faculty. To change, one material is flushed with the new material. Sometimes old material remains behind, which could result in minor colour deviation. Besides, the materials used are inherently translucent, resulting in significant sub-surface scattering. Therefore it is recommended to explore printing the prostheses with opaque materials. This could potentially result in sharper details and a darker pupil.

Some parts of the printing software are a 'black box'. For example, the software behind the translation from an RGB image to the CMYK dots printed by the Stratasys J735 is unknown. It is recommended to use voxel-based printing to control this. More research is needed to explore the possibilities for controlling colour on a voxel level and to model a complete voxel-based prosthesis while having control over the various aspects of the eye.

### Validation

During the user test, the participants were asked to evaluate the prostheses compared to their eyes. The test was a close-up comparison in front of the mirror. Thereby, the prosthesis was not placed in an eye socket making it less realistic. Based on this user test, it can not be concluded whether the prostheses 'fidelity' level would be good enough for a patient. Users indicated that the resolution of the prosthesis is much lower than the eye, while the current hand-painted prosthesis also does not have a

high resolution. Clinical trials with patients will show how 3D-printed prostheses are validated compared to conventional prostheses. Before a clinical application is possible, properties such as biocompatibility and material longevity, which were considered outside this project's scope, will need further investigation.



Figure 75. A collection of 3D printed prostheses within this project



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# Appendix A: Project brief



## Personal Project Brief - IDE Master Graduation

A digital workflow for 3D printed full-colour ocular prosthetics project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 02 - 05 - 2022 end date 28 - 10 - 2022

### INTRODUCTION \*\*

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

In the Netherlands, roughly 20.000 people wear an ocular prosthetic as a result of losing their eye due to disease or accident. An ocular prosthetic or artificial eye is a type of craniofacial prosthesis that replaces an absent natural eye. Ocular prostheses are important means to improve the patients' quality of life by restoring the appearance of the face. It requires a lifelike prosthesis that matches the shape and colour of the contralateral eye. Although the patient won't be able to see with this eye, prosthetic eyes are used to resemble the patient's facial appearance as close as possible.

Fabricating custom-made ocular prosthetics is currently a highly-skilled, labour-intensive and nonreproducible process performed by an ocularist. Most prosthetics are made of acrylic (PMMA) in a plaster mould based on an impression of the patient's eye socket. Furthermore, the iris of the prosthetic is hand-painted by the ocularist to match the patient's contralateral eye and the veins of the eye are mimicked by adding red embroidery threads by hand.

New digital 3D production techniques provide opportunities to improve this current nonreproducible and labour-intensive process. Research from Groot et al. (2021) presents a proof-of-concept that incorporates 3D scanning, digital modelling and 3D printing to digitise the process of making ocular prosthetics. The following step is to improve this workflow, which will include better capturing and reproducing of the eye's appearance.

Starting points for possible improvements are:

- researching possible methods for creating a full-fledged digital workflow, including capturing, digital modelling and 3D printing.
- researching an appropriate workflow for the stakeholders
- researching the possibilities for creating lifelike results, including iris structure, exact colour-matching, the influence of layering and transparency of the cornea.

Opportunities such as biocompatibility, material longevity and dynamic deformation of the iris during pupillary response are considered outside the scope of this project. Current limitations are the possibilities of the Stratasys J735 and the cameras used for capturing.

This project will be conducted in cooperation with Dyonne Hartong and Jelmer Remmers from Amsterdam University Medical Centers. They have developed the proof-of-concept previously described.

Groot, A. L., Remmers, J. S., & Hartong, D. T. (2021). Three-Dimensional Computer-Aided Design of a Full-Color Ocular Prosthesis with Textured Iris and Sclera Manufactured in One Single Print Job. *3D Printing and Additive Manufacturing*, 8(6), 343–348. <https://doi.org/10.1089/3dp.2021.0048>

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IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30

Page 3 of 7

Initials & Name IL. Calis Student number 4450736

Title of Project A digital workflow for 3D printed full-colour ocular prosthetics



introduction (continued): space for images



image / figure 1: Final prosthesis of 'proof-of-concept' (Groot et al., 2021).

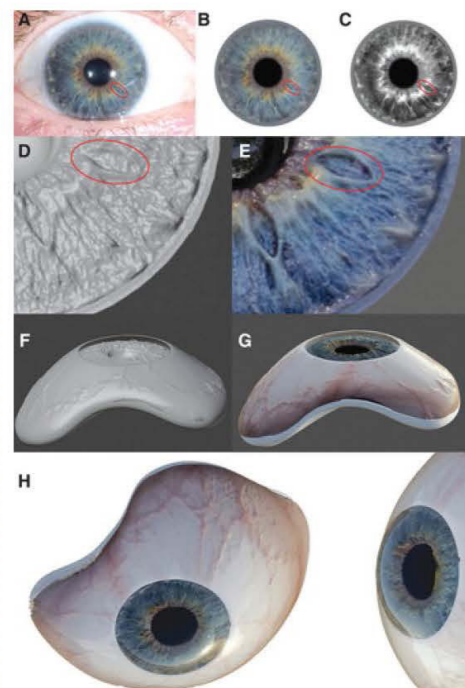


image / figure 2: Workflow to create 'proof-of-concept' (Groot et al., 2021).

**PROBLEM DEFINITION \*\***

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Problem statement

The fabrication of ocular prosthetics is currently a highly-skilled, labour-intense and nonreproducible process. 3D printing ocular prosthetics makes the workflow reproducible and faster, which leads to more accessible and affordable prosthetics.

Focus and solution space

The project focuses on optimizing the workflow, including capturing and reproducing the eye's appearance, for making ocular prosthetics. This includes researching digital options for capturing, modelling and 3D printing and comparing these with the current workflow. To create lifelike results research into the iris structure, colour-matching, and the influence of layering and transparency of the cornea is needed. Researching the geometrics of the ocular prosthetic is not included in this project. By comparing the different workflows I will research the trade-off between quality and efficiency and try to answer which level of 'fidelity' is needed for the end product.

**ASSIGNMENT \*\***

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... . In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

In this assignment, I will be researching how to optimize a full-fledged digital workflow, including capturing, digital modelling and 3D printing, for making ocular prosthetics. The goal is to capture and reproduce the eye's appearance to create life-like ocular prosthetics that resemble the patient's facial appearance as close as possible.

During the project, my activities will be:

- literature research
- understanding the current workflow of making ocular prosthetics through observing and desk research
- understanding the stakeholders and context through observing and interviewing
- researching possibilities for capturing, digital modelling and 3D printing
- research how to validate the exact colour-matching of the prosthetic to the contralateral eye
- researching the possibilities for creating lifelike results, including iris structure, exact colour-matching, the influence of layering and transparency of the cornea

- design a way to capture the appearance of the patient's contralateral eye
- reproducing the eye's appearance using the Stratasys J735
- generating valuable concept direction for creating a lifelike ocular prosthetic
- design samples, prototypes and iterations for the prosthetics

- validating the workflow with an ocularist and users
- validating the prototypes with an ocularist and users

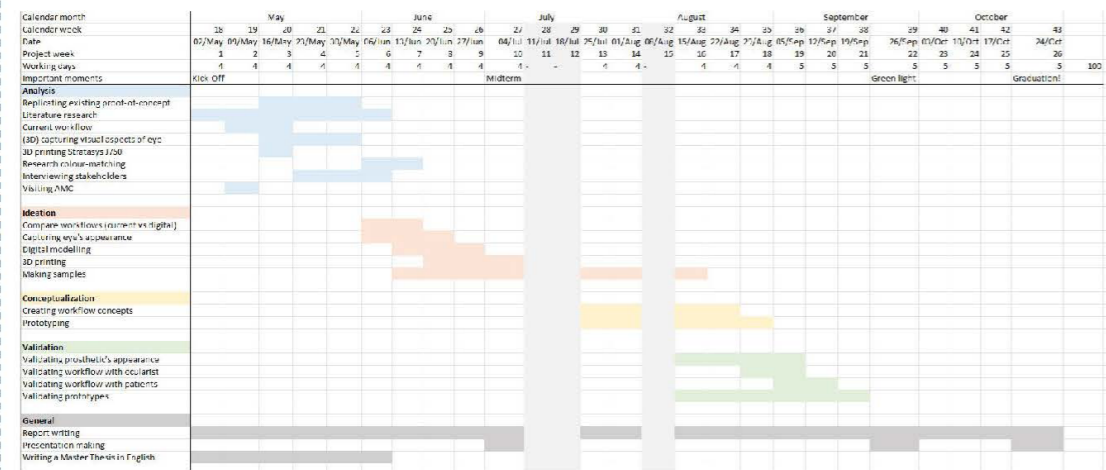
The final result will be a life-like ocular prosthetic prototype made with a digital workflow.



**PLANNING AND APPROACH \*\***

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 2 - 5 - 2022 end date 28 - 10 - 2022



In the analyse phase, I will explore the topic through literature research, observing and interviewing stakeholders. Also a replica of the 'proof of concept' will be made. During ideation, the current and digital workflow will be compared and new ideas will be generated for capturing and reproducing the eye's appearance. Simple tests and samples will be made to validate assumptions and possible methods.

During conceptualization, different concepts of the workflow will be created and tested by extensive prototyping. In the validation phase, the prototypes and workflow will be validated with the stakeholders.

During the first 10 weeks, 5 weekly hours will be dedicated to TA work. Another 4 hours will be dedicated to the course 'Writing a Master Thesis in English'. Therefore it is decided to work 4 days a week on the graduation project. After the summer holiday, I will switch to 5 days a week.

**MOTIVATION AND PERSONAL AMBITIONS**

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... . Stick to no more than five ambitions.

I've chosen this project as my graduation project since I've always had an interest in 3D printing. Even more, I like to design user-centred or medical products because I want to design for a better life by creating more value for the user. This project is a combination of both my interests.

Last year I followed the course 'Digital Materials'. Now as a teaching assistant for the course I have learned how to design for and work with the Stratasys J735. Within this project, I want to broaden my competencies with multi-material 3D printing.

During the first 10 weeks, I am following the course 'Writing a Master Thesis in English'. I want to improve my academic writing skills during this project. After the course, I want to focus on showing my learnings in my midterm report and final thesis.

- Personal learning ambitions:
- Individually conducting and managing such a large project
  - Broadening my competencies with multi-material 3D printing
  - Improving my academic writing

**FINAL COMMENTS**

In case your project brief needs final comments, please add any information you think is relevant.



# Appendix B: Materials overview

Figure 76 shows all materials available for PolyJet printers of Stratasys. The crossed out materials are not available for the Stratasys J735.

## PolyJet Material Families

### Basic

- ~~VeroWhitePlus™~~
- VeroBlackPlus™
- ~~DraftGrey™~~
- VeroBlue™
- VeroGrey™
- RGD720™

### Design

- Vero PureWhite™
- Vero Colors  
Cyan / Magenta / Yellow
- Vero Vivid Colors  
CyanV / MagentaV / YellowV
- VeroClear™
- VeroUltraClear™
- VeroFlex™  
White / Black / Clear  
Cyan / Magenta / Yellow  
CyanV / MagentaV / YellowV
- VeroUltra™  
White / Black
- ~~VeroUltraClearS~~
- ~~Vero™ ContactClear~~

### Functional

- Digital ABS Plus™ Ivory
- ~~Rigur™~~
- DurusWhite™
- ~~High Temperature RGD525™~~
- Agilus30™ Clear
- Agilus30™ Black
- Agilus30™ White
- Agilus30™ Colors
- Cyan/Magenta/Yellow
- ~~Elastico™ Black~~
- ~~Elastico™ Clear~~
- TangoPlus™
- TangoBlackPlus™
- ~~TangoBlack™~~
- ~~TangoGray™~~

### Medical

- ~~TissueMatrix™~~
- ~~BoneMatrix™~~
- GelMatrix™
- MED610™
- MED615RGD™
- MED Digital ABS™
- Hearing Aids Clear FC630™
- ~~Hearing Aids Rose Clear FC655™~~

### Dental

- MED610™
- ~~VeroClaze™ MED620~~
- ~~MED626FLX™~~
- VeroDentPlus™ MED690
- ~~VeroDent™ MED670~~

### Support

- SUP705™
- SUP705B™
- SUP706B™
- ~~SUP707™~~
- ~~SUP716™~~
- ~~WSS™ 150~~
- GelMatrix™



Figure 76. Materials available for the Stratasys J735, image from [16]

# Appendix C: List of Requirements

## Performance

- The product should mimic the appearance of the human eye
- The product should be customisable to match the contralateral eye of the patient
- The product should conform to the unique contours of the orbital socket of the patient
- The product should be biocompatible

## Workflow

- The workflow should consist of digital production steps
- The workflow should be reproducible

## Capturing

- The eye should be captured in a controlled light condition
- The eye and target should be captured in the same light condition
- The target should consist of matte colour patches
- The eye images should be calibrated with a custom made profile of a colour target

## Modelling

- The modelling approach should create the inner parts of the prosthesis based on a personalised outer shape

## Printing

- The product should be printed with a full-colour 3D printer

## Fabrication

- The product should be fabricated in a single print
- The design of the product should be done by the ophthalmologist

## Finalising

- The prosthesis should be polished according to standard procedures in ophthalmologist practices.

## End-of-life

- The product should last for at least two years

## Wishes

- The workflow should be automated
- The digital twin of the product should be based on a computational design template



## Appendix D: Data capturing - Online photographing research

Online research is done to learn from professional photographers who make iris photos. Important learnings are categorised on camera settings, camera lens, lighting, stabilisation and tools. The sources are varying from videos, websites or blogs.

### Camera settings

- Fast shutter speed, 1/1000s is ideally. Large field of depth F11-16. High resolution 24MP. F7.1, 1/100s ISO 400 [39]
- Reduce the aperture on your camera to achieve a shallower depth of field. Use a fast shutter speed to eliminate blurriness. Lower your ISO value to prevent digital grain [40]
- 1/125, F11 ISO100 [41]
- Manual, 1/50sec, take many images, f/2.8, ISO100 [42]

### Camera lens

- Uses a 1:1 macro lens, 24 MP, APS-C [43]
- Use a circular polarising filter – cut out glare and avoid reflections (CPL filter). Add also one to the Speedlight [44]
- No macro lens? Use a close-up filter, extension tubes or refused adapters. [44]
- Use a DCR-250 lens to double the magnification: 2:1 magnification [39]
- Marco lens or extension tubes [40]
- 1:1 or extension tube [45]

### Lighting

- Side light (no ring light or front). Or use a camera flash from the side/back [43]
- Use a regular speed light from the side. Positioned the light around 110 degrees from the eye and 70 degrees from the camera to get the best results. [44]
- Ring light – Does not work. Side light - More dept at 45 degrees. Camera flash with light from the side [39]
- Produce a catch light with a continuous light source [40]
- Different eyes require a different amount of light. Use a strobe or flashlight. Room with ambient light. Light to the side creates more detail. [41]
- Camera flash from the side. Use an offset flash, also from the side, and tape the top to create a minor light source [45]

### Stabilization

- Use a box to stabilise the head [43]
- Try to stabilise the head [39]
- Tripod or handhold and take lots of pictures [41]

### Tools

- Specialized Eyemazy Photobox, makes iris photos to print on canvas [46]
- Flip the screen of the camera to photograph your eye [45]
- Developed an iris photo tool. Make an iris photo tool and place a flashlight on the side [42]

## Appendix E: Colour calibration - Making an ICC and DNG profile with ColorChecker Camera Calibration

ColorChecker Camera Calibration software is easy to use by following the instructions on the left side, see Figure 77.

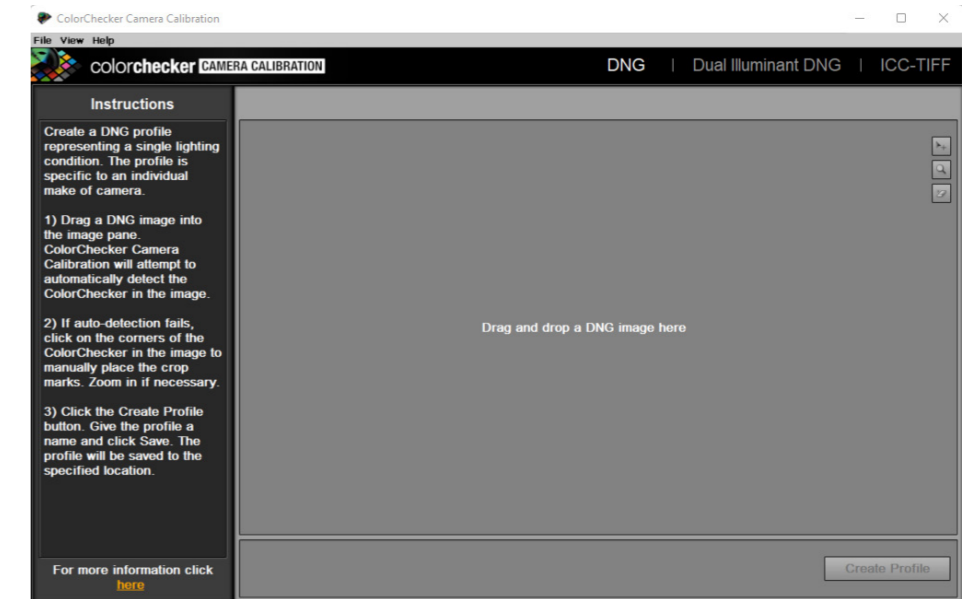


Figure 77. ColorChecker Camera Calibration software

The workflow for making a DNG is different from the workflow for making a ICC.

#### DCP workflow:

1. Export the reference image to DNG (Camera Raw).
2. Load in ColorChecker software.
3. Create DCP.
4. Open the raw image in Photoshop. Camera Raw automatically opens.
5. Apply profile in Camera Raw
6. Click open to open the image in Photoshop.
7. Start editing.
8. While exporting make sure to 'Embed Color Profile'.

#### ICC workflow:

1. Export the reference image to linear Tiff (DCRaw or RawTherapee).
  - a. (Tiff becomes very dark!)
2. Load in ColorChecker software.
3. Create ICC.
4. Open the raw image in Photoshop. Camera Raw automatically opens.
5. Chose standard camera profile.
6. Click open to open the image in Photoshop.
7. Overrule the standard camera profile, by applying the ICC profile: Edit > Assign profile.
8. Start editing.
9. While exporting make sure to 'Embed Color Profile'.



# Appendix F: Colour calibration - Chart & Reference files

## ISAColorGaugeCHT:

BOXES 31  
 F \_\_ 0.0 0.0 43.2 0.0 43.2 36.9 0.0 36.9  
 D ALL ALL \_\_ 43.2 36.9 0.0 0.0 0.0 0.0  
 X A F 1 5 6.3 6.3 2.7 2.7 6.3 6.3

BOX\_SHRINK 5.2

REF\_ROTATION 0.0

XLIST 7  
 2.70 1.0 1.0  
 9.00 1.0 1.0  
 15.30 1.0 1.0  
 21.60 1.0 1.0  
 27.90 1.0 1.0  
 34.20 1.0 1.0  
 40.50 1.0 1.0

YLIST 6  
 2.70 1.0 1.0  
 9.00 1.0 1.0  
 15.30 1.0 1.0  
 21.60 1.0 1.0  
 27.90 1.0 1.0  
 34.20 1.0 1.0

## EXPECTED LAB 30

A1 38.76 13.81 14.69  
 A2 50.86 -27.78 -27.68  
 A3 52.85 49.90 -12.86  
 A4 82.02 3.28 78.75  
 A5 43.48 50.74 29.13  
 B1 65.15 19.21 17.92  
 B2 95.34 -0.90 1.90  
 B3 72.17 -1.05 -0.04  
 B4 28.60 -1.09 0.07  
 B5 55.60 -38.46 32.19  
 C1 49.61 -4.20 -21.33  
 C2 92.09 -0.92 1.46  
 C3 62.32 -1.10 -0.01  
 C4 17.97 0.04 0.09  
 C5 29.51 13.42 -47.69  
 D1 43.54 -12.89 22.66  
 D2 86.92 -1.12 0.97  
 D3 49.61 -1.29 -0.10  
 D4 9.50 0.45 0.25

D5 72.10 19.51 67.85  
 E1 55.52 8.78 -24.31  
 E2 82.37 -1.12 0.56  
 E3 38.89 -0.23 -0.48  
 E4 4.33 0.32 -0.47  
 E5 72.50 -22.92 56.08  
 F1 70.42 -32.39 -0.48  
 F2 63.13 35.43 57.84  
 F3 40.08 10.25 -44.77  
 F4 51.75 47.36 16.93  
 F5 30.32 22.13 -19.02

## ISA ColorGaugeCIE:

CTI3  
 DESCRIPTOR "ISaColorGauge"  
 ORIGINATOR "Ilse Calis"  
 CREATED "Sep 19. 2022"

KEYWORD "SAMPLE\_LOC"  
 NUMBER\_OF\_FIELDS 4  
 BEGIN\_DATA\_FORMAT  
 SAMPLE\_LOC LAB\_L LAB\_A LAB\_B  
 END\_DATA\_FORMAT

NUMBER\_OF\_SETS 30

BEGIN\_DATA  
 A1 38.76 13.81 14.69  
 A2 50.86 -27.78 -27.68  
 A3 52.85 49.90 -12.86  
 A4 82.02 3.28 78.75  
 A5 43.48 50.74 29.13  
 B1 65.15 19.21 17.92  
 B2 95.34 -0.90 1.90  
 B3 72.17 -1.05 -0.04  
 B4 28.60 -1.09 0.07  
 B5 55.60 -38.46 32.19  
 C1 49.61 -4.20 -21.33  
 C2 92.09 -0.92 1.46  
 C3 62.32 -1.10 -0.01  
 C4 17.97 0.04 0.09  
 C5 29.51 13.42 -47.69  
 D1 43.54 -12.89 22.66  
 D2 86.92 -1.12 0.97  
 D3 49.61 -1.29 -0.10  
 D4 9.50 0.45 0.25  
 D5 72.10 19.51 67.85  
 E1 55.52 8.78 -24.31  
 E2 82.37 -1.12 0.56  
 E3 38.89 -0.23 -0.48  
 E4 4.33 0.32 -0.47  
 E5 72.50 -22.92 56.08  
 F1 70.42 -32.39 -0.48  
 F2 63.13 35.43 57.84  
 F3 40.08 10.25 -44.77  
 F4 51.75 47.36 16.93  
 F5 30.32 22.13 -19.02  
 END\_DATA



## The Colorimetry Data provided by ISa [35]

The RGB calculations for a given Color space condition were calculated from formulas at <http://www.brucelindbloom.com/> RGB values for other color spaces can be calculated by visiting the above URL.

There can always be inter-batch variations. The values listed below should be considered nominal for the batch provided to ISa by X-Rite Corp. For critical color calculations the user should perform their own optical measurements of the colorimetric values or contact us (info@imagescienceassociates.com) for individual target calibrations. The count values shown in RED below are considered out-of-gamut for the particular color space listed. All L\*a\*b\* values are for D50 Illuminant, 2 degree observer. Bradford adaption used for selected color spaces



Patch #	Average (n=50)						St. Dev. (n=50)			Adobe RGB (1998)			sRGB			ProPhoto			eciv2			Status T density
	L*	a*	b*	L*	a*	b*	R	G	B	R	G	B	R	G	B	R	G	B				
	1	38.76	13.81	14.69	0.08	0.12	0.18	109	83	71	109	83	71	83	69	55	116	91	76			
30	30.32	22.13	-19.02	0.34	0.99	0.46	86	61	100	94	58	102	68	49	79	93	61	108				

Patch #	Average (n=50)						St. Dev. (n=50)			Adobe RGB (1998)			sRGB			ProPhoto			eciv2			Status T density
	L*	a*	b*	L*	a*	b*	R	G	B	R	G	B	R	G	B	R	G	B				
	1	38.76	13.81	14.69	0.08	0.12	0.18	109	83	71	118	83	68	83	69	55	116	91	76			
30	30.32	22.13	-19.02	0.34	0.99	0.46	86	61	100	94	58	102	68	49	79	93	61	108				

## Appendix G: Colour calibration - Making a DNG profile with ArgyllCMS and DCamProf

ArgyllCMS 'scanin' tool locates the patch values in a photo of the target [34]. The 'scanin' tool needs two files to be able to scan the patch values. First, a template (.cht) that describes the features of the chart and how the patches are labelled. The second file (.cie) contains the CIE values for each labelled patch in the chart. Both files were setup for this project and can be found in Appendix F, together with colorimetry data of the ISa ColourGauge Micro provide by ISa [35].

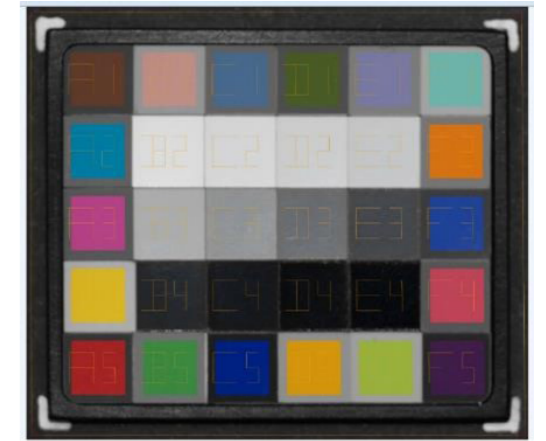


Figure 78. Diagnostic output (diag)

Figure 79 shows the step by step approach. The 'scanin' tool creates a .ti3 data file. This file includes the CIE test values and the corresponding RGB scanner values [34]. It also produces a diagnostic output (diag) which can be check to see if the chart has been correctly recognized, see Figure 78 for an example. The DNG was made with the DCamProf software. This profile is known as 'DCP', DNG camera profiles.

Read patches:

1. Open the raw photo in RawTherapee
2. Crop and rotate image
3. Save as linear Tiff (16-bits) named 'ISaTest' in right folder: C:\Users\NAME
4. Run:

```
scanin -v -p -dipn ISaTest.tif ISaColorGaugeCht.cht ISaColorGaugeCIE.cie
```

5. Now TI3 file is created

Make CDP:

6. Place TI3 in right folder: C:\DCamProf
7. Run:

```
cd "C:\DCamProf"
```

```
dcamprof.exe
```

```
dcamprof make-profile -i D50 -C ISaTest.ti3 ISaTest.json
```

```
dcamprof make-dcp -n "NIKON D800E" -d "ISaTest" -t acr -g adobergb-strong ISaTest.json ISaTest.dcp
```

8. Now DCP file is created
9. Place DCP profile in correct adobe folder:
  - a. C:\Users\NAME\AppData\Roaming\Adobe\CameraRaw\CameraProfiles
10. Open the raw photo in Photoshop. Camera Raw automatically opens.
11. Apply the profile in Camera Raw
12. Click open to open the image in Photoshop.
13. Start editing.
14. While exporting make sure to 'Embed Color Profile'.

Figure 79. Step by step approach to make a DNG profile from the ISa ColorGauge



## Appendix H: Colour calibration - Results glossy ISa ColorGauge

Glossy version of the ISa ColorGauge gives errors while running the software or very high DE values. This is a result of glare on the image, since the target is illuminated from the front, see Figure 80 and Figure 81.

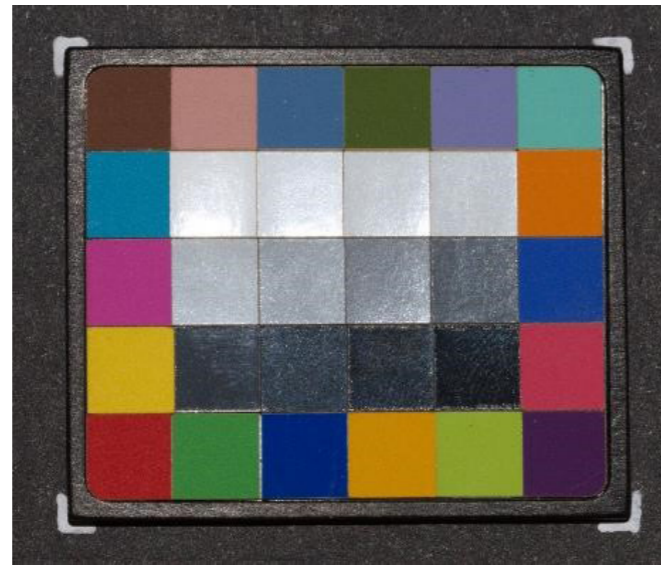


Figure 80. ISa ColorGauge with glare

```
C:\Users\ilse>scanin -v -p -dipn cc24.tif ColorChecker.cht cc24_ref.cie
Input file 'cc24.tif': w=2708, h=1849, d = 3, bpp = 16
Data input file 'cc24_ref.cie'
Data output file 'cc24.ti3'
Chart reference file 'ColorChecker.cht'
Creating diagnostic tiff file 'diag.tif'
About to allocate scanrd_object
Verbosity = 2, flags = 0x62a01
About to read input tiff file and discover groups
adivval = 0.394026
About to calculate edge lines
728 useful edges out of 45181
About to calculate perspective correction
Perspective correction factors = -0.000005 -0.000004 1353.999986 924.500000
About to calculate rotation
Mean angle = 2.639348
Standard deviation = 12.611243
Robust mean angle = 0.320489 from 631 lines
About to calculate feature information
About to read reference feature information
Read of chart reference file succeeded
About to match features
Checking xx
Checking yy
Checking xy
Checking yx
Checking xix
Checking yiy
Checking xiy
Checking yix
Axis matches for each possible orientation:
 0: xx = 0.140972, yy = 0.165076, xx.sc = 0.120347, yy.sc = 0.119066
 90: xiy = 0.104055, yx = 0.158736, xiy.sc = 0.232345, yx.sc = 0.120347
180: xix = 0.138932, yiy = 0.168363, xix.sc = 0.119678, yiy.sc = 0.121571
270: xy = 0.102047, yix = 0.159511, xy.sc = 0.232345, yix.sc = 0.120116
r0 = 0.214768, r90 = 0.098311, r180 = 0.214884, r270 = 0.097894
bcc = 0.214884, wcc = 0.097894
There are 0 candidate rotations:
About to write diag file
scanin: Error - Scanin failed with code 0x3, Pattern match wasn't good enough
```

Figure 81. Error - Scanin failed due to glare

## Appendix I: Colour calibration - Results matte ISa ColorGauge

The reference image is converted to a linear tiff, see Figure 82 and Figure 83.

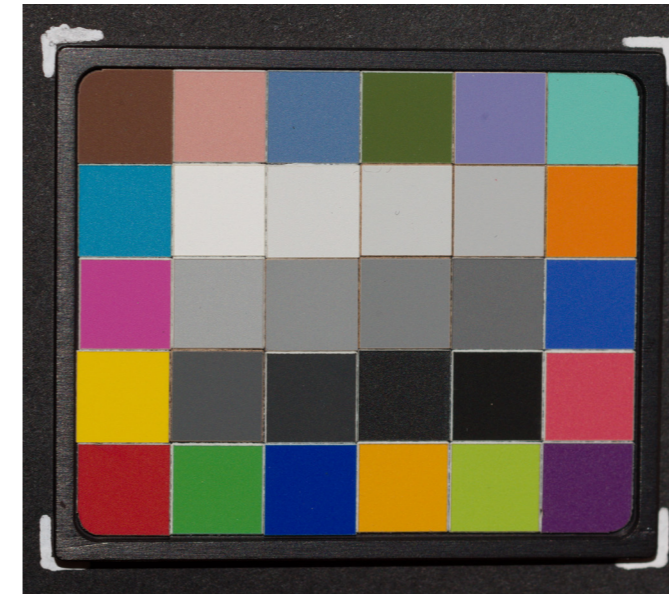


Figure 82. Reference image

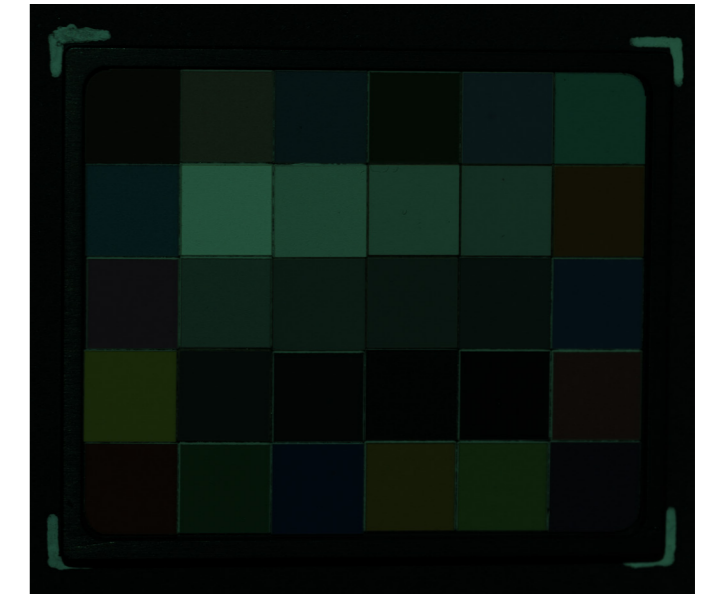


Figure 83. Linear Tiff reference image

The result of the diag is shown in Figure 84.



Figure 84. Diag result



**Result:**

C:\DCamProf>dcamprof make-profile -i D50 -C target3-11.ti3 target3-11.json

Reading target...

Warning: large dynamic range difference detected. Likely glare issue.

Camera G on darkest patch(es) is 498.7% lighter compared to observer Y.  
Y dynamic range is 7.53 stops, G dynamic range is 4.95 stops, difference 2.58 stops. A small difference is normal, while a large indicates that there is glare.

Generating values for the calibration illuminant D50...

Warning: auto-selected neutral patch (C02) is not the lightest, as the lightest patch is considerably off-white. That is if you later use the target for white balancing you should use the indicated patch instead of the lightest.

The most neutral patch (C02) differs 2.07 DE from actual neutral, transforming target reference XYZ values to match, using CAT02.

Automatic LUT relaxation weights assigned.

Making camera profile...

Finding a camera raw RGB to CIE XYZ matrix for calibration illuminant D50...

Warning: whitest (most neutral) patch in target (C02) differs DE 2.07 from calibration illuminant, matrix precision may suffer.

Inverting to get ColorMatrix:

```
{  
  "ColorMatrix1": [  
    [ 0.694322, -0.175791, -0.061605 ],  
    [ -0.604375, 1.338164, 0.299293 ],  
    [ -0.146469, 0.183523, 0.866973 ]  
  ]  
}
```

Matrix patch match average DE 4.23, DE LCh 3.62 1.07 0.82

median DE 3.00, DE LCh 2.54 1.14 0.66  
p90 DE 11.23, DE LCh 11.20 2.27 2.22  
max DE 11.80, DE LCh 11.76 2.50 3.09

ColorMatrix optimal white balance for target: 0.441794,1,0.755915 (m2.2635,1,1.3229)

Finding a camera raw RGB to CIE XYZ matrix for connection space illuminant D50...

```
{  
  "LUTMatrix1": [  
    [ 0.643896, 0.130411, 0.189912 ],  
    [ 0.321447, 0.620130, 0.058423 ],  
    [ 0.001562, 0.072401, 0.751239 ]  
  ]  
}
```

LUTMatrix optimal white balance for target: 0.440085,1,0.741626 (m2.27229,1,1.34839)

Matrix patch match average DE 6.69, DE LCh 4.58 3.30 1.92

median DE 7.42, DE LCh 3.32 3.54 1.64  
p90 DE 11.31, DE LCh 11.29 7.23 4.84  
max DE 11.94, DE LCh 11.91 8.90 4.99

Finding a camera raw RGB to CIE XYZ matrix for connection space illuminant D50...

Y row limit set to -0.2.

Applying white-balance to get ForwardMatrix:

```
{  
  "ForwardMatrix1": [  
    [ 0.737435, 0.118666, 0.108118 ],  
    [ 0.333694, 0.770287, -0.103982 ],
```

```
[ 0.068812, -0.208455, 0.964845 ]
```

```
]
```

```
}
```

ForwardMatrix optimal white balance for target: 0.440085,1,0.741626 (m2.27229,1,1.34839)

Matrix patch match average DE 4.50, DE LCh 3.90 1.18 0.89

median DE 3.32, DE LCh 2.94 1.35 0.74  
p90 DE 11.27, DE LCh 11.23 2.42 2.38  
max DE 11.87, DE LCh 11.80 2.62 3.22

Making 2.5D chromaticity-addressed lookup table for XYZ correction...

10.00% of the patches was put in a chromaticity group due to nearby neighbor.

40.00% of the patches was removed due to being nearby the whitepoint.

Largest chromaticity group contains 2 patches. Patch count reduced from 30 to 15. Note that patch matching cannot reach 100% when chromaticity groups are formed, as the LUT matches the average within a group.

Lightness axis is disabled. Since lightness affects chroma, the LUT chroma control points are recalculated to better match the uncorrected lightness.

A residual error of up to about 0.2 DE is expected.

Relaxing LUT stretch with up to 3.52 DE. Iterating over 15 patches...

Lightness correction is disabled.

Average DE for the 15 tested patches increased to 3.50 after LUT relax.

33.33% could do without LUT correction.

Native LUT patch match average DE 4.39, DE LCh 3.88 1.01 0.67

median DE 3.10, DE LCh 2.94 0.98 0.77  
p90 DE 11.27, DE LCh 11.23 2.52 1.38  
max DE 11.87, DE LCh 11.80 2.88 1.61

5 worst patches for Overall DE:

B04 RGB 0.057 0.133 0.102 XYZref 0.055 0.057 0.048 XYZcam 0.126 0.131 0.114 sRGB #424444  
#636568 DE 11.87 DE LCh +11.80 +0.60 +1.12 (gray 30%)

E03 RGB 0.084 0.194 0.147 XYZref 0.103 0.107 0.091 XYZcam 0.185 0.192 0.165 sRGB #5B5B5D  
#77797B DE 11.32 DE LCh +11.31 +0.17 -0.53 (gray 40%)

D04 RGB 0.021 0.048 0.037 XYZref 0.010 0.011 0.009 XYZcam 0.047 0.048 0.041 sRGB #1B1A1A  
#3D3D3F DE 11.27 DE LCh +11.23 +0.19 -0.89 (gray 10%)

E04 RGB 0.015 0.032 0.024 XYZref 0.005 0.005 0.004 XYZcam 0.032 0.033 0.027 sRGB #0F0E10  
#333232 DE 10.80 DE LCh +10.77 -0.10 -0.77 (black)

C04 RGB 0.030 0.071 0.055 XYZref 0.025 0.025 0.021 XYZcam 0.067 0.070 0.061 sRGB #2C2B2C  
#494B4D DE 10.17 DE LCh +10.07 +1.01 -1.04 (gray 20%)

5 worst patches for Lightness DE:

B04 RGB 0.057 0.133 0.102 XYZref 0.055 0.057 0.048 XYZcam 0.126 0.131 0.114 sRGB #424444  
#636568 DE 11.87 DE LCh +11.80 +0.60 +1.12 (gray 30%)

E03 RGB 0.084 0.194 0.147 XYZref 0.103 0.107 0.091 XYZcam 0.185 0.192 0.165 sRGB #5B5B5D  
#77797B DE 11.32 DE LCh +11.31 +0.17 -0.53 (gray 40%)

D04 RGB 0.021 0.048 0.037 XYZref 0.010 0.011 0.009 XYZcam 0.047 0.048 0.041 sRGB #1B1A1A  
#3D3D3F DE 11.27 DE LCh +11.23 +0.19 -0.89 (gray 10%)

E04 RGB 0.015 0.032 0.024 XYZref 0.005 0.005 0.004 XYZcam 0.032 0.033 0.027 sRGB #0F0E10  
#333232 DE 10.80 DE LCh +10.77 -0.10 -0.77 (black)

C04 RGB 0.030 0.071 0.055 XYZref 0.025 0.025 0.021 XYZcam 0.067 0.070 0.061 sRGB #2C2B2C  
#494B4D DE 10.17 DE LCh +10.07 +1.01 -1.04 (gray 20%)

5 worst patches for Chroma DE:

A04 RGB 0.308 0.492 0.116 XYZref 0.601 0.607 0.078 XYZcam 0.593 0.600 0.112 sRGB #F7C625  
#F3C549 DE 2.91 DE LCh -0.25 -2.88 -0.27 (light strong yellow)

E05 RGB 0.166 0.414 0.134 XYZref 0.359 0.446 0.096 XYZcam 0.348 0.426 0.116 sRGB #A9BB46  
#A5B656 DE 2.85 DE LCh -1.02 -2.53 +0.81 (light yellow-green)

D05 RGB 0.261 0.328 0.084 XYZref 0.495 0.441 0.063 XYZcam 0.489 0.441 0.088 sRGB #EFA12C  
#EAA245 DE 2.65 DE LCh +0.01 -2.52 -0.81 (light strong orange)



A03 RGB 0.179 0.183 0.206 XYZref 0.325 0.211 0.242 XYZcam 0.352 0.248 0.258 sRGB #C45897  
 #C7699B DE 4.48 DE LCh +3.64 -2.45 +0.93 (purple-red)  
 B05 RGB 0.065 0.253 0.102 XYZref 0.154 0.236 0.081 XYZcam 0.155 0.230 0.091 sRGB #4D954C  
 #509253 DE 2.02 DE LCh -0.58 -1.75 +0.82 (yellow-green)

5 worst patches for Hue DE:

F02 RGB 0.236 0.215 0.065 XYZref 0.415 0.319 0.052 XYZcam 0.433 0.336 0.069 sRGB #E77D30  
 #E9813F DE 2.34 DE LCh +1.11 -1.29 -1.61 (strong orange)

A05 RGB 0.126 0.074 0.041 XYZref 0.225 0.136 0.042 XYZcam 0.232 0.147 0.056 sRGB #B8393A  
 #B84345 DE 2.58 DE LCh +1.49 -1.56 -1.41 (red)

A02 RGB 0.069 0.317 0.326 XYZref 0.139 0.193 0.310 XYZcam 0.195 0.251 0.374 sRGB #0095B4  
 #0098BA DE 6.30 DE LCh +5.94 -1.55 +1.38 (blue)

C05 RGB 0.028 0.106 0.185 XYZref 0.072 0.061 0.213 XYZcam 0.087 0.077 0.225 sRGB #004592  
 #1A4D95 DE 3.10 DE LCh +2.94 -1.49 -1.38 (dark purple-blue)

F03 RGB 0.055 0.184 0.264 XYZref 0.126 0.114 0.301 XYZcam 0.156 0.147 0.331 sRGB #2E5DAA  
 #416AB1 DE 4.58 DE LCh +4.51 -1.42 -1.29 (dark purple-blue)

5 best patches for Overall DE:

C02 RGB 0.358 0.814 0.604 XYZref 0.785 0.814 0.672 XYZcam 0.785 0.814 0.672 sRGB #E8E8E8  
 #E8E8E8 DE 0.00 DE LCh +0.00 +0.00 +0.00 (white)

D02 RGB 0.305 0.696 0.518 XYZref 0.677 0.703 0.584 XYZcam 0.668 0.695 0.577 sRGB #D9DADB  
 #D8D9D9 DE 0.30 DE LCh -0.26 -0.03 -0.14 (gray 90%)

B03 RGB 0.189 0.437 0.329 XYZref 0.425 0.442 0.374 XYZcam 0.416 0.433 0.367 sRGB #AFB1B3  
 #ADB0B2 DE 0.51 DE LCh -0.43 +0.19 -0.19 (gray 70%)

C03 RGB 0.142 0.329 0.249 XYZref 0.298 0.310 0.262 XYZcam 0.313 0.326 0.278 sRGB #959798  
 #989B9D DE 1.21 DE LCh +1.13 +0.43 +0.06 (gray 60%)

D01 RGB 0.056 0.141 0.065 XYZref 0.113 0.136 0.054 XYZcam 0.119 0.141 0.063 sRGB #5F6C41  
 #616D48 DE 1.53 DE LCh +0.73 -1.30 +0.35 (yellow-green)

Writing output to "target3-11.json"...

Complete!

C:\DCamProf>dcamprof make-dcp -n "NIKON D800E" -d "target3-11" -t acr -g adobergb-strong  
 target3-11.json target3-11.dcp

Generating 2.5D HueSatMap with 90x30 = 2700 entries...done!

The tone curve's contrast value is 1.30 (=> auto chroma scaling value 1.121)

Generating 3D LookTable with 90x30x30 = 81000 entries for the neutral tone reproduction operator...

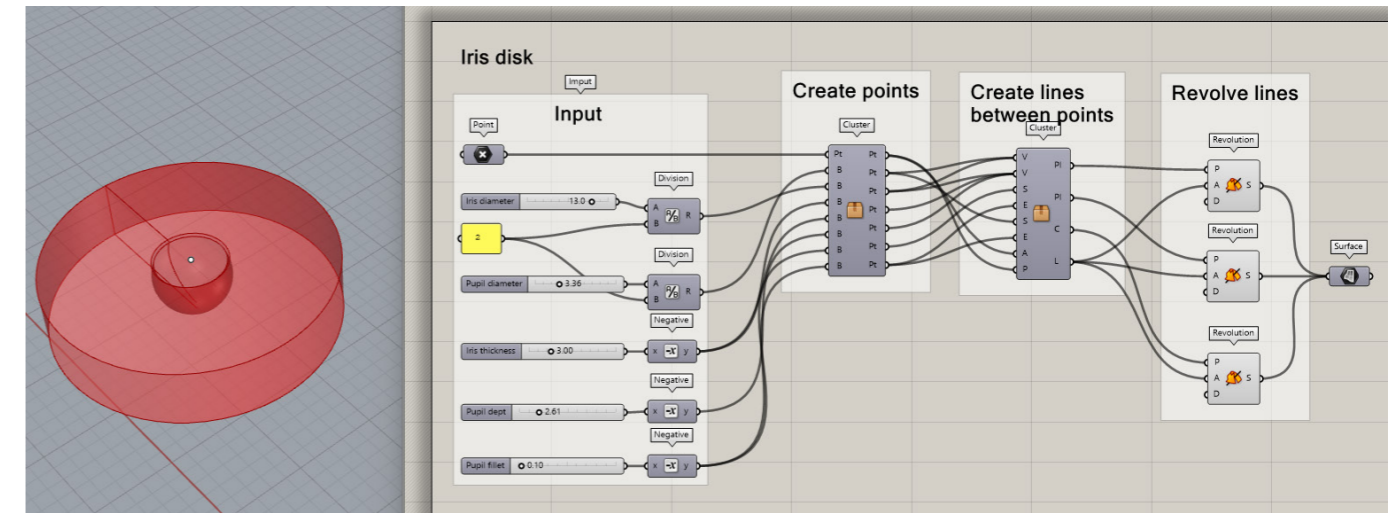
0%..10%..20%..30%..40%..50%..60%..70%..80%..90%..100%

Writing output to "target3-11.dcp"...

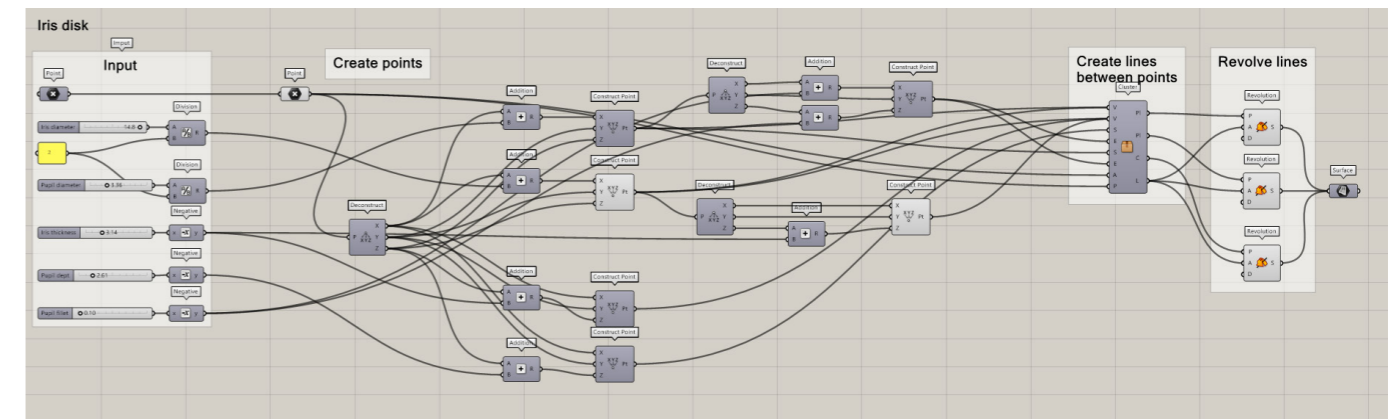
Complete!

# Appendix J: Modelling - Parametric 3D model

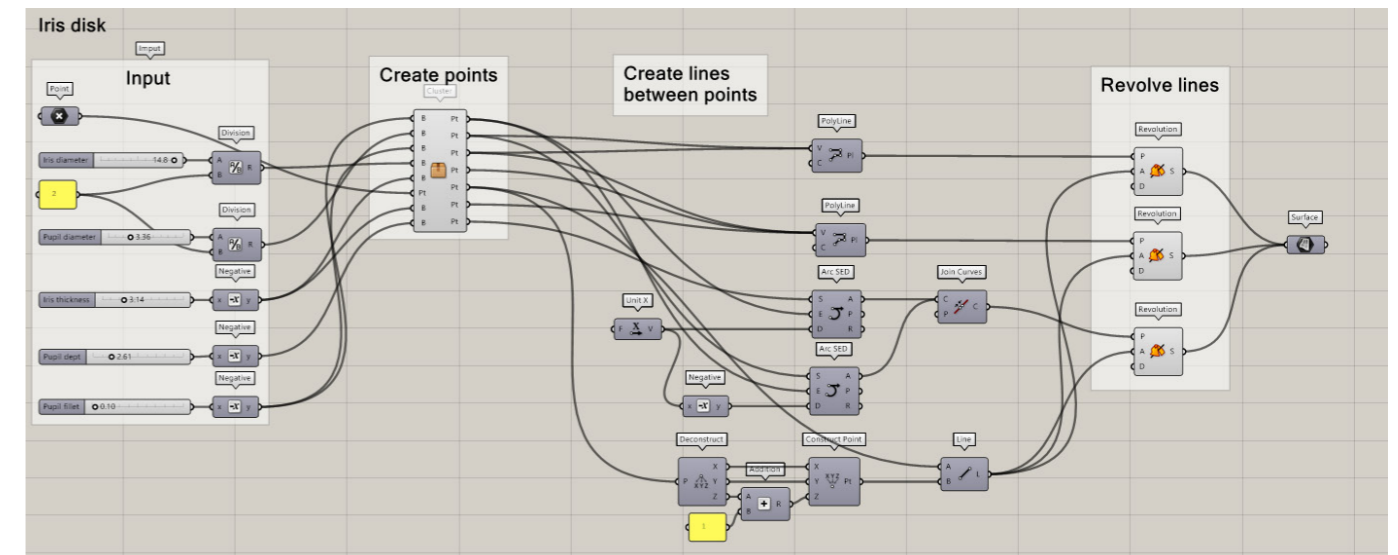
Parametric Iris disk:



Cluster 1: Create points

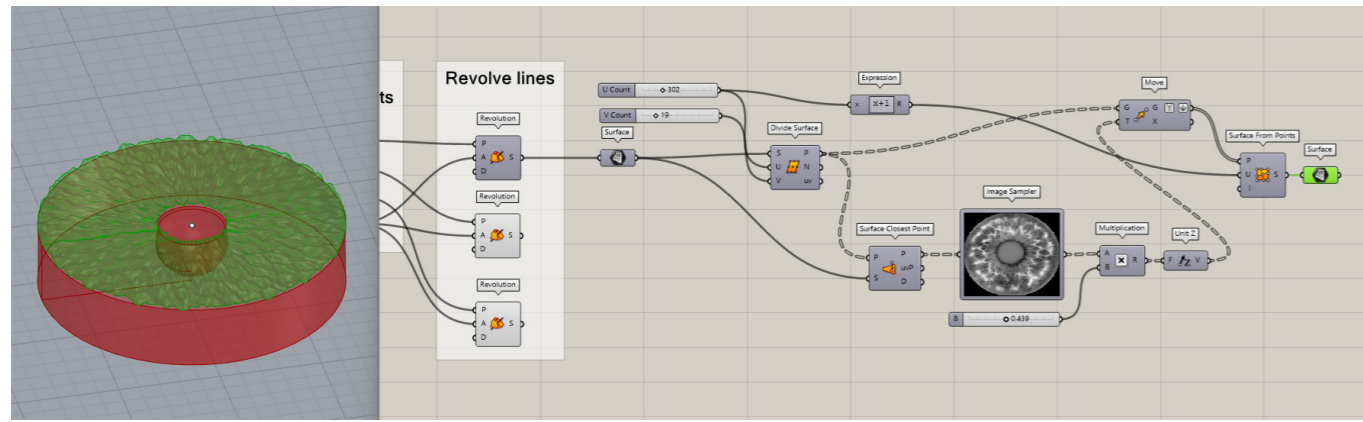


Cluster 2: Create lines between points





Displaced surface based on the image in the 'Image sampler':



## Appendix K: Modelling – Photoshop editing iris and sclera images

### Coloured iris image:

1. Open the photo and apply a custom profile
2. Cut out the iris by applying a mask
3. 'Warp' the iris to the correct shape if necessary
4. Remove the reflections
5. Add a black pupil
6. Use the 'sharpen' filter to make the pattern more visible
7. Add limbus ring
8. Image size to 600 dpi (printers resolution)
9. Export 'png', sure to 'Embed Color Profile'.

Original



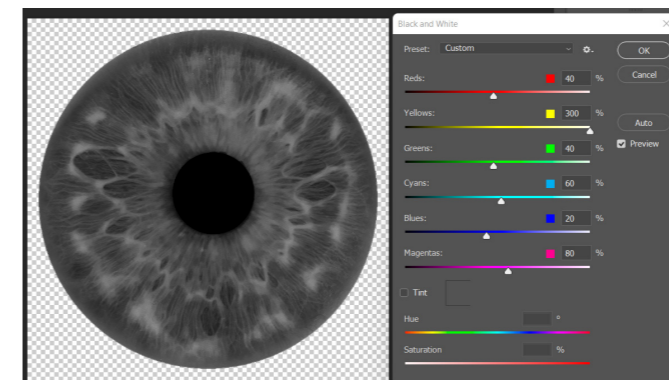
Edited



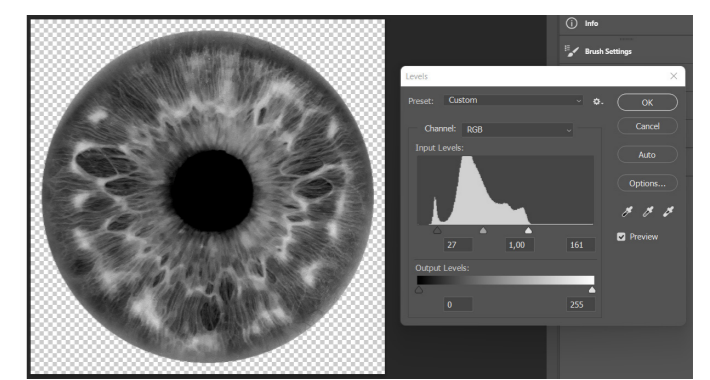
### Greyscale duplicate:

1. Image > adjustments > black & white
2. Make the yellow colours white
3. Image > adjustments > level
4. Change the levels to create contrast

Adjust > Black & white



Adjust > Level



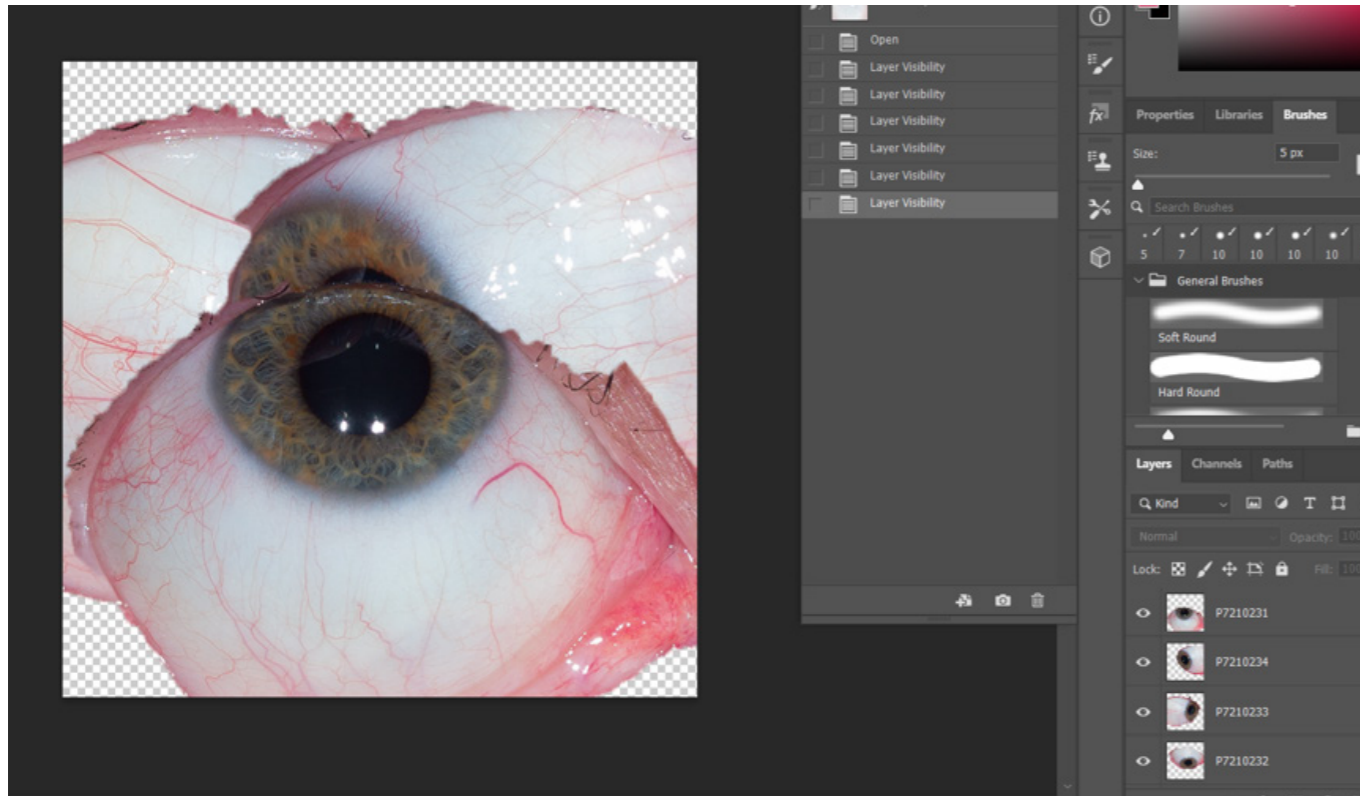


### Coloured sclera image:

1. Open the four sclera photos and apply the custom profile
2. Cut out the sclera parts by applying a mask
3. Place in the correct order
4. 'Warp' every sclera to the correct shape
5. Remove the reflections
6. Merge the edges into one sclera
7. Export 'png', sure to 'Embed Color Profile'.

Merging different sclera images in photoshop is a manual process, which takes time and some practise.

Sclera images in correct order:



Final combined sclera image:

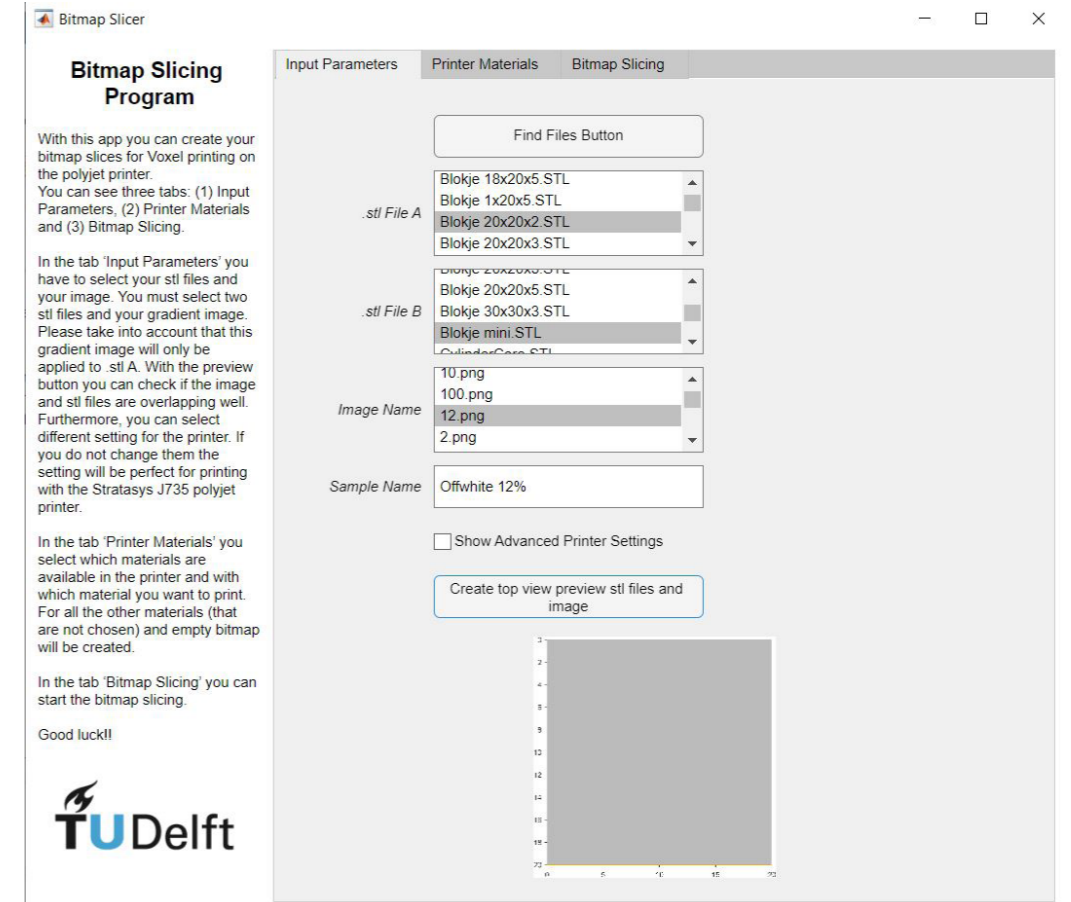


## Appendix L: Printing - Bitmap sample making

This appendix shows an example of how a sample can be made using the Matlab BitmapSlicer tool developed by Doubrovski et al. [18].

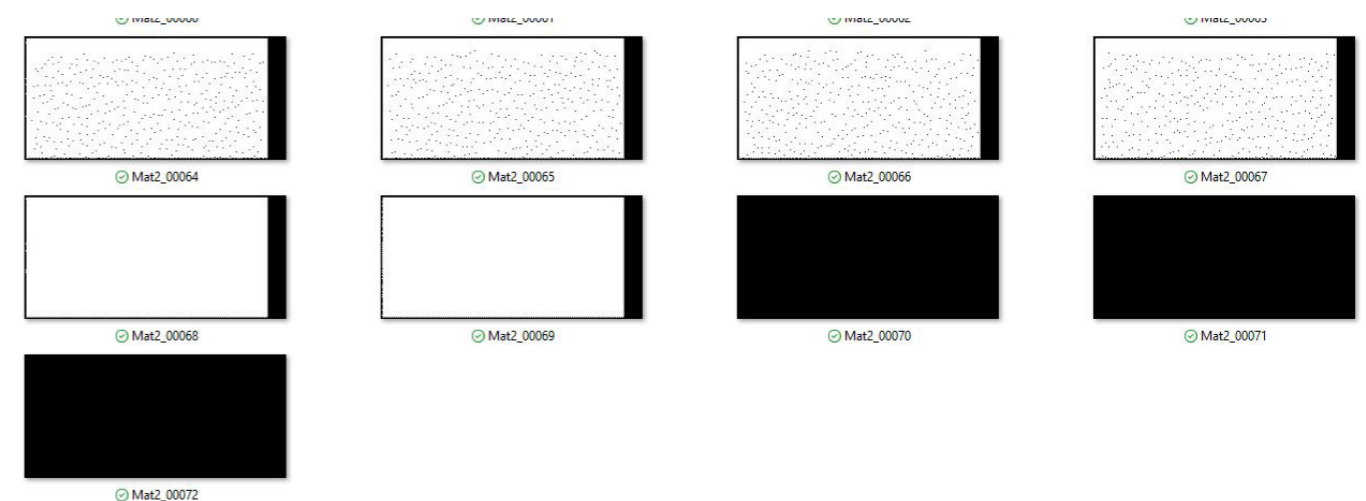
The sample creating is a block of light yellow (12%) covered with a few layer of pure white. An STL of a 20x20x2 mm block is combined with a negligible small STL. A 12% grey png. is projected on the STL., creating a file with 12% yellow and 88% white voxels.

Bitmap slicing tool:



Manually, the first and second layers (png) are changed to white voxels in Photoshop to create the samples.

Png. files:

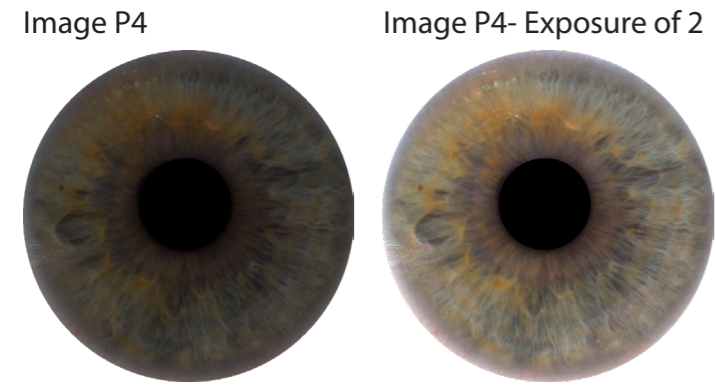




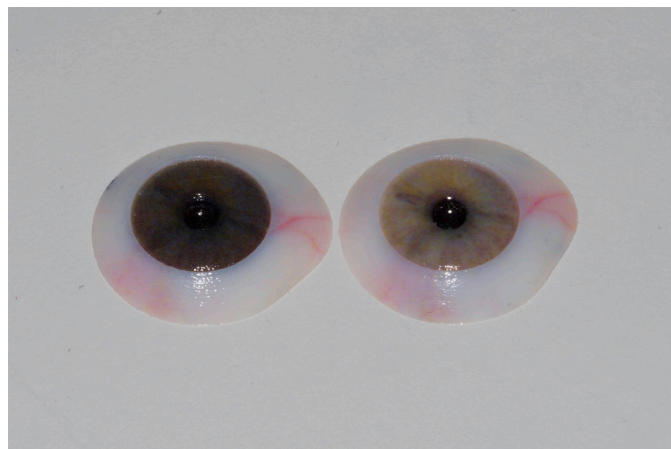
# Appendix M: Printing – Results Iris colour sample

3 users participated: P2, P4 and P5

## Participant 4

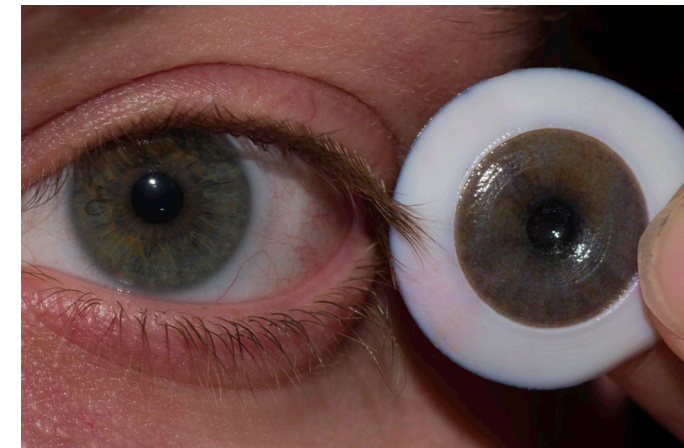


3D printed result (P4 original left, exposure 2 right)

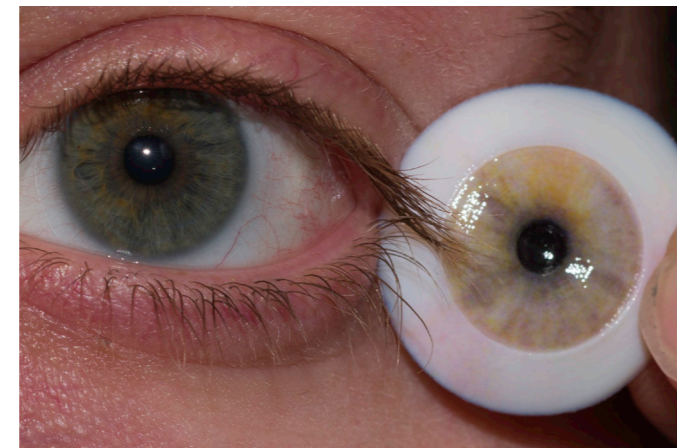


Comparison to eye:

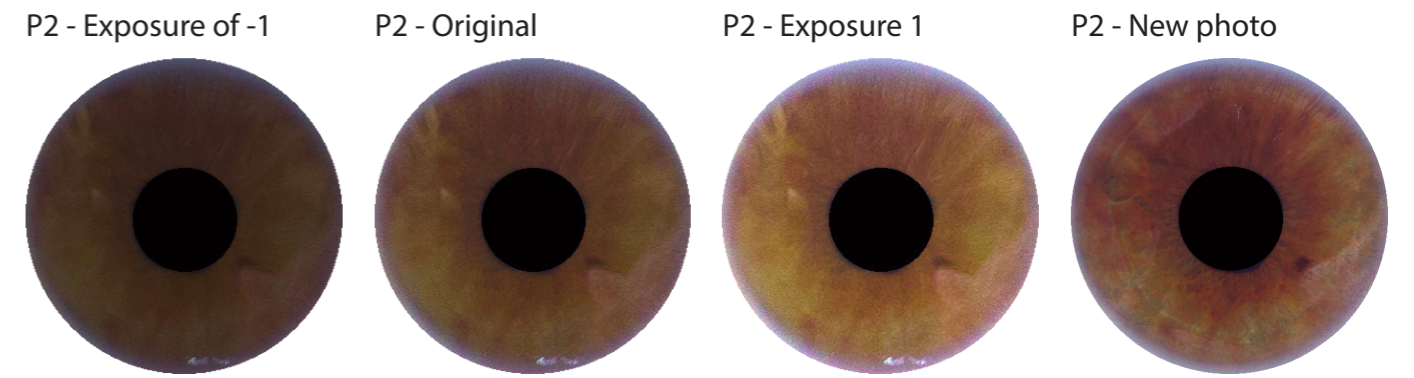
Original



Exposure 2

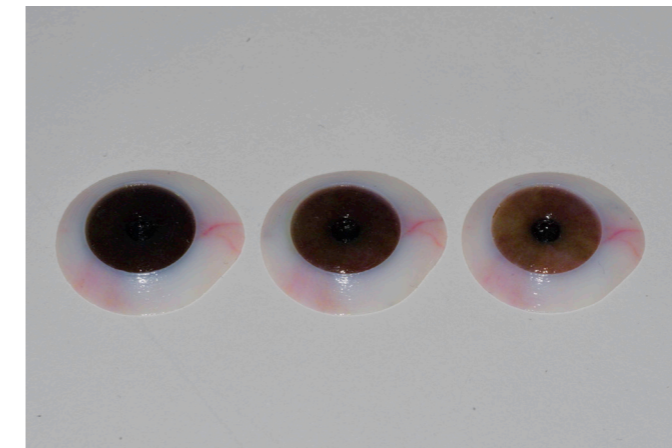


## Participant 2

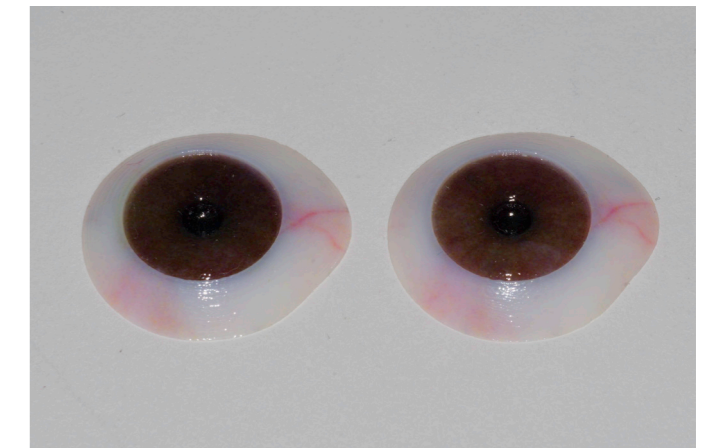


3D printed results:

Expo -1 - original - Expo 1 (left to right)

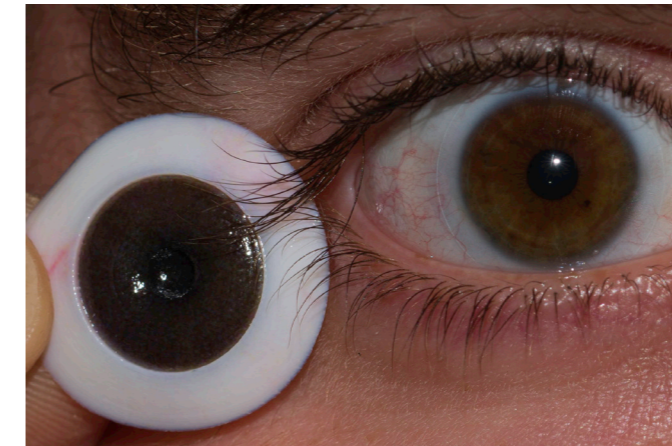


Original - New photo



Comparison to eye:

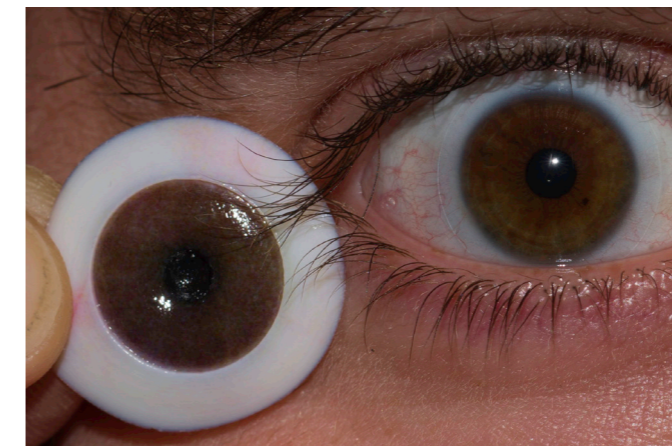
P2 exposure -1



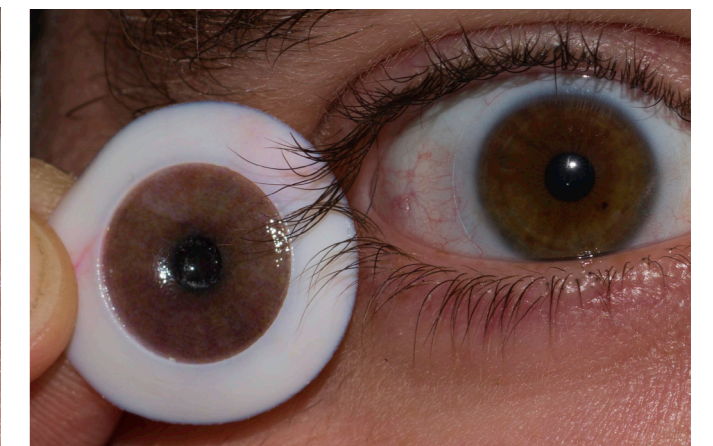
P2 exposure 1



P2 original



P2 new photo





**Participant 5**

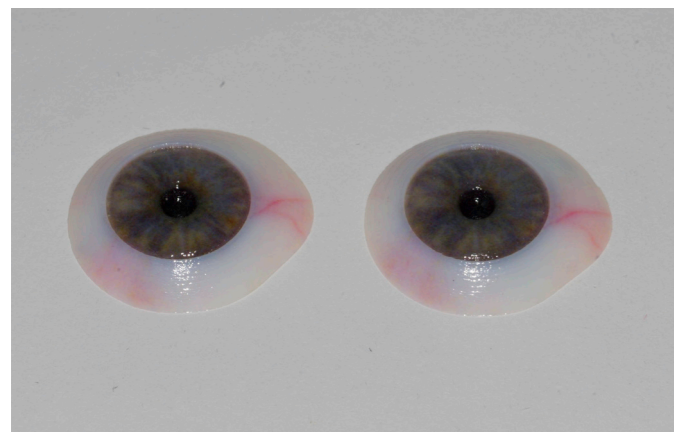
P5 - ICC



P5 - DNG



3D printed results:  
ICC - DNG (left to right)

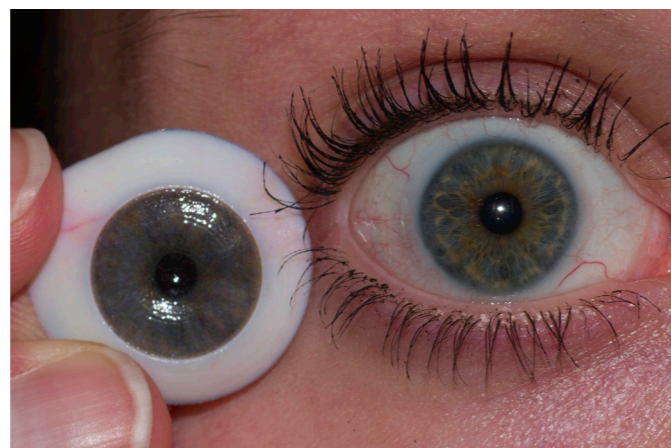


Comparison to eye:

P5 ICC



P5 DNG



P5 - ICC Original



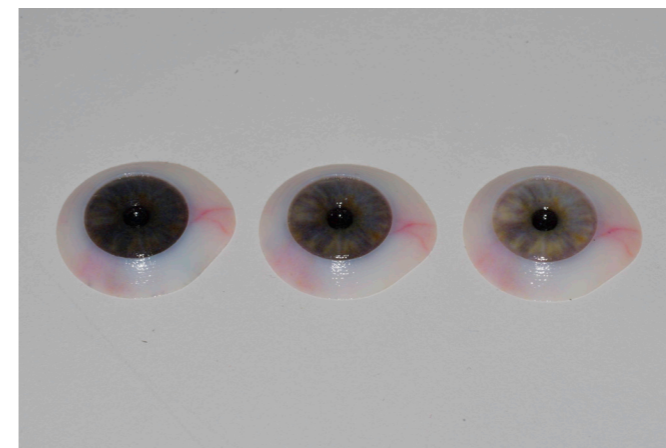
P5 - ICC exposure 1



P5 - ICC exposure 2

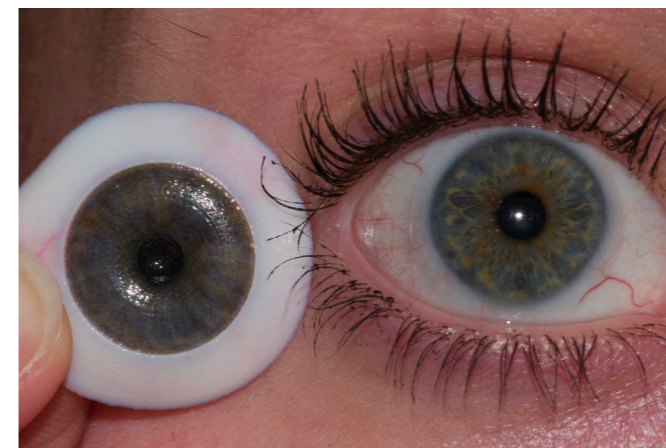


3D printed results:  
ICC Original - Expo 1 - Expo 2 (left to right)

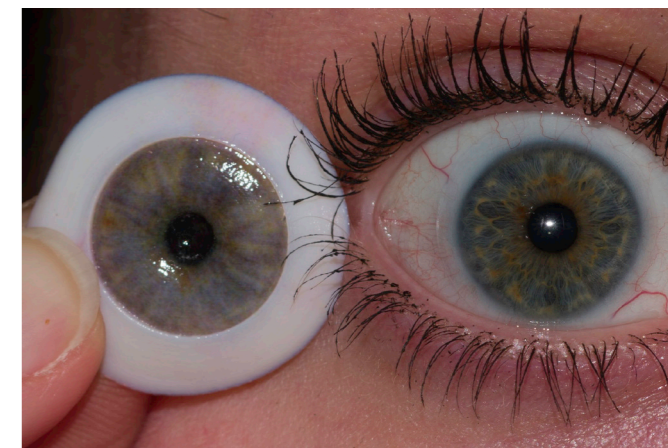


Comparison to eye:

P5 ICC - Original



P5 ICC - Exposure 1



P5 ICC - Exposure 2



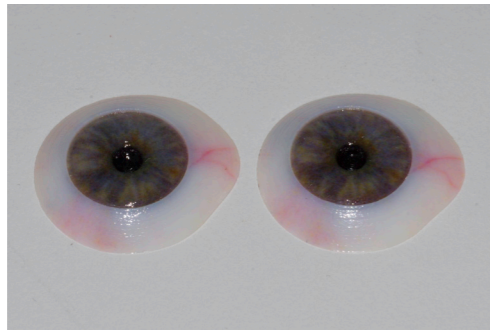


**P5 ICC - Lower Resolution, Limbus, Saturated, Cyan and Sharpen filter**

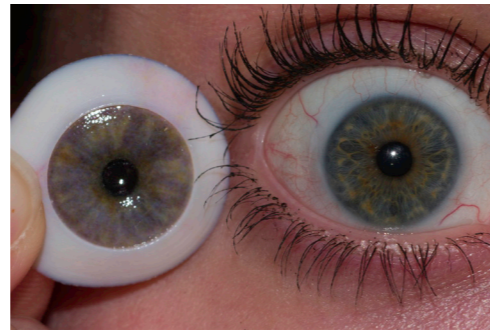
Lower Resolution



Original - LowRes



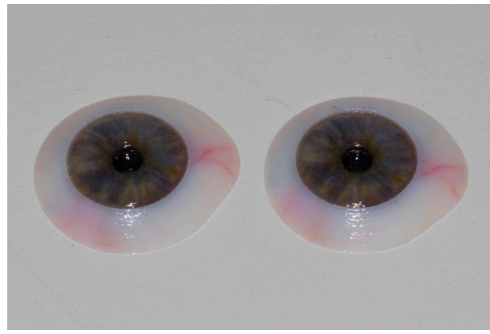
LowRes to eye



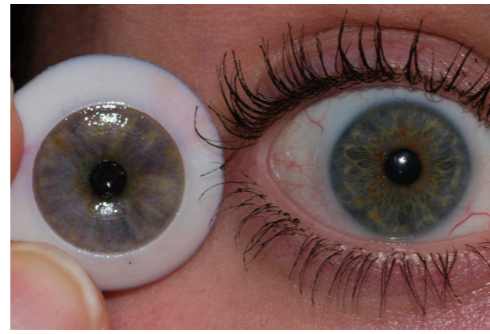
Limbus



Original - Limbus



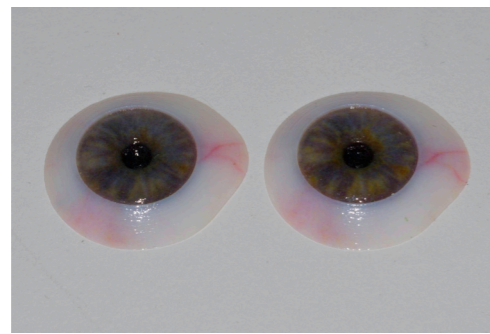
Limbus to eye



Saturated



Original - Saturated



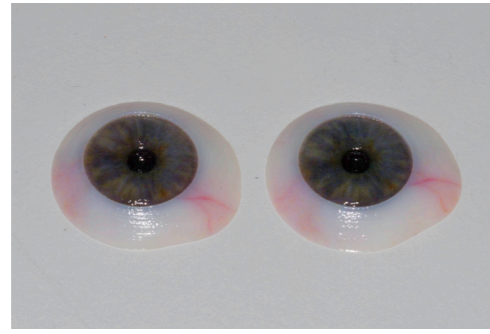
Saturated to eye



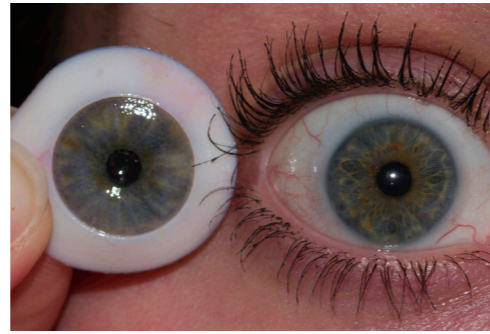
Cyan



Original - Cyan



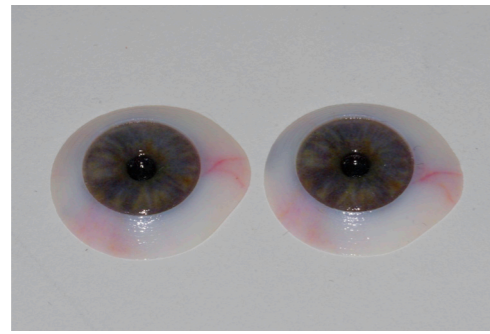
Cyan to eye



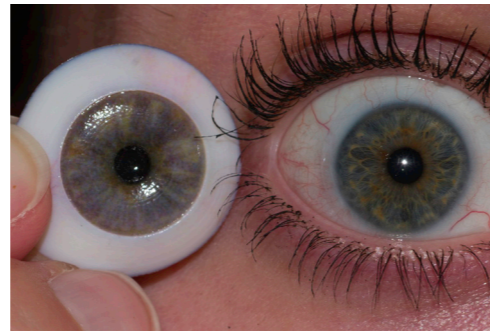
Sharpen filter



Original - Sharpen filter



Sharpen filter to eye



# Appendix N: Validation – Results user test (photos)

**2 experts and 5 users participated: E1, E2 and P1, P2, P3, P4 and P5**

This appendix shows first the iris comparison between the 3D printed eye and the natural eye. Then, the sclera is compared.

Image of the seven different prostheses made for the participants:





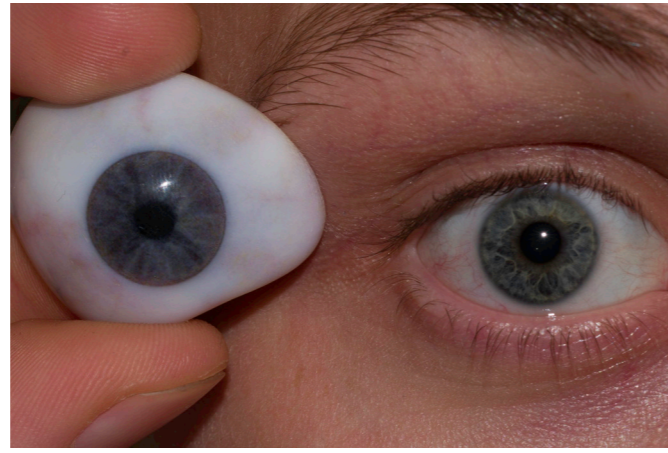
**Expert 1**

E1 Original

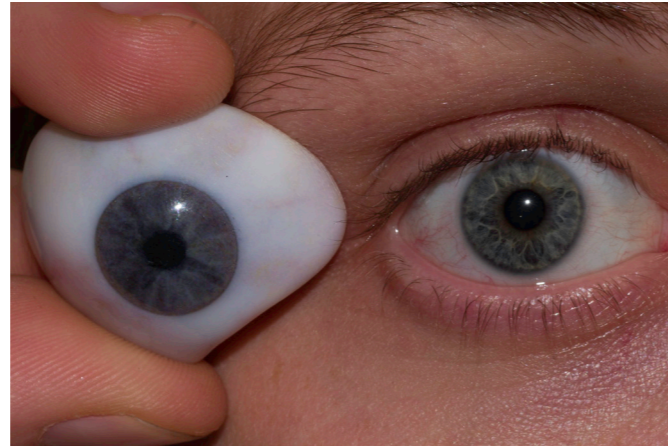
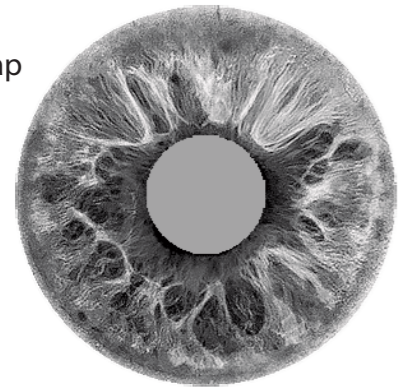
Image or displacement map image



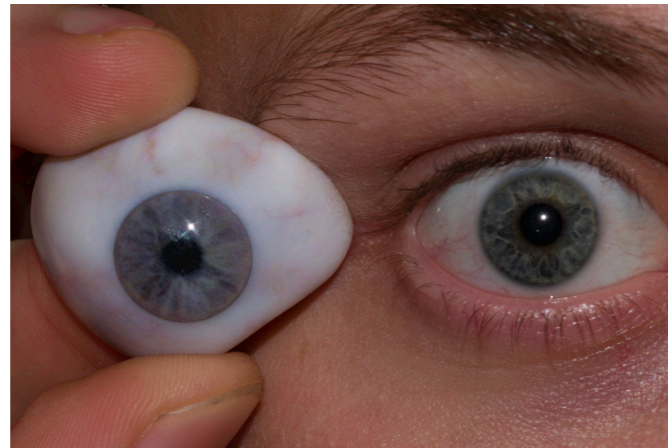
Compared to the eye:



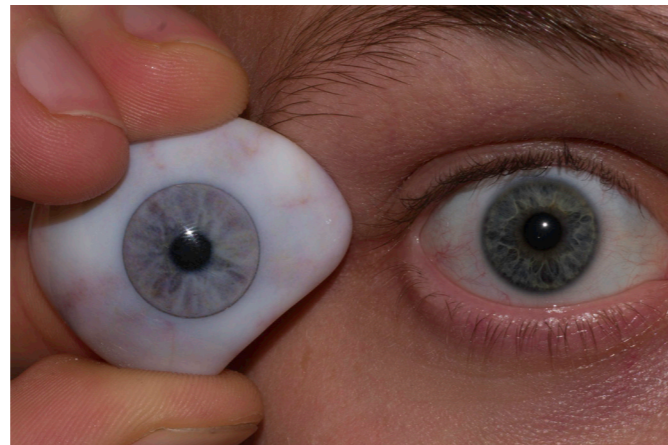
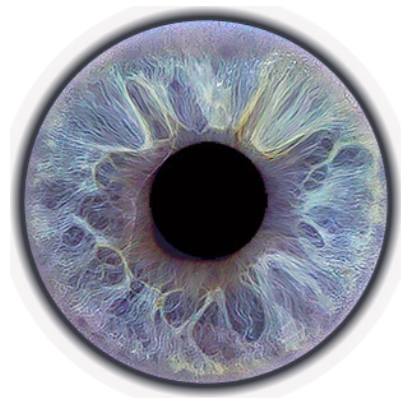
E1 Original +  
3D structure of a  
displacement map  
of 0.3



E1 Exposure of 0.5



E1 Exposure of 1



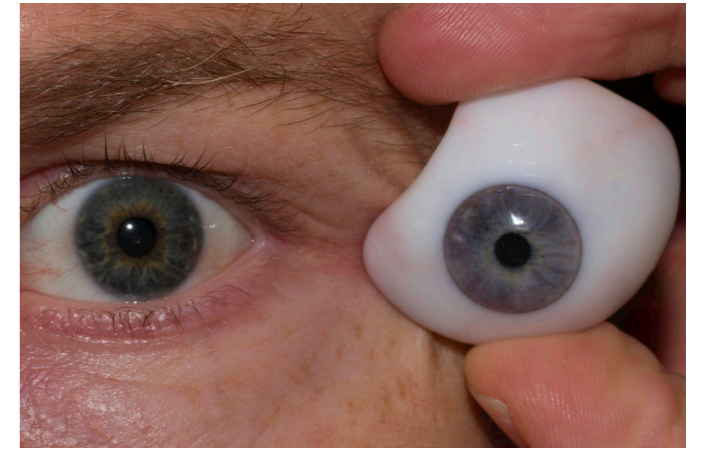
**Expert 2**

E2 Original

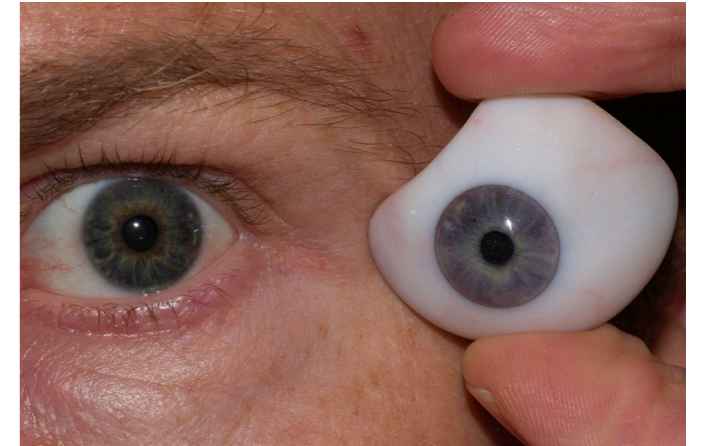
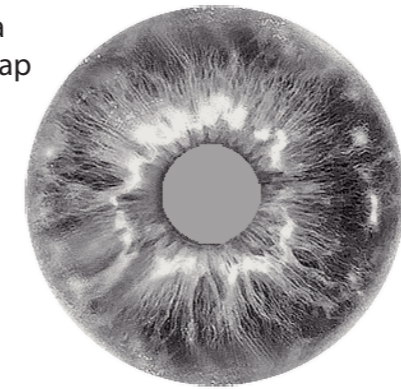
Image or displacement map image



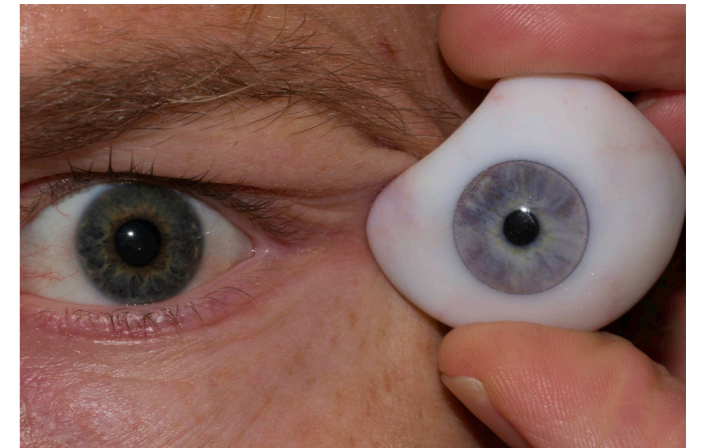
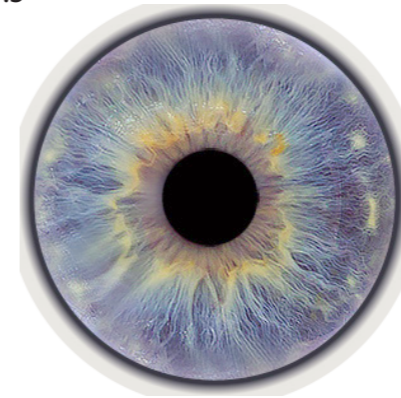
Compared to the eye:



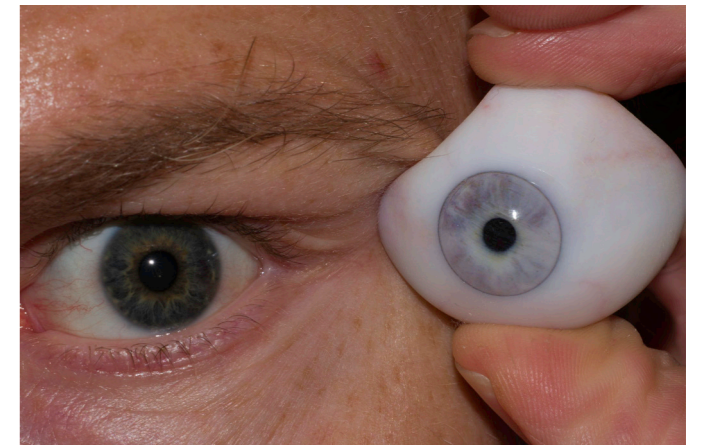
E1 Original +  
3D structure of a  
displacement map  
of 0.3



E2 Exposure of 0.5



E2 Exposure of 1

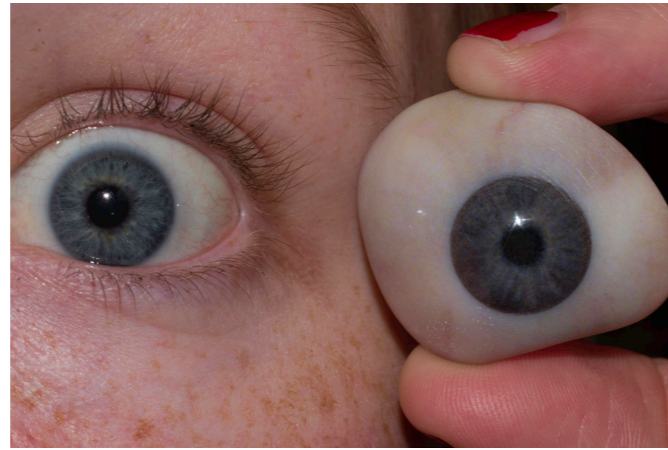




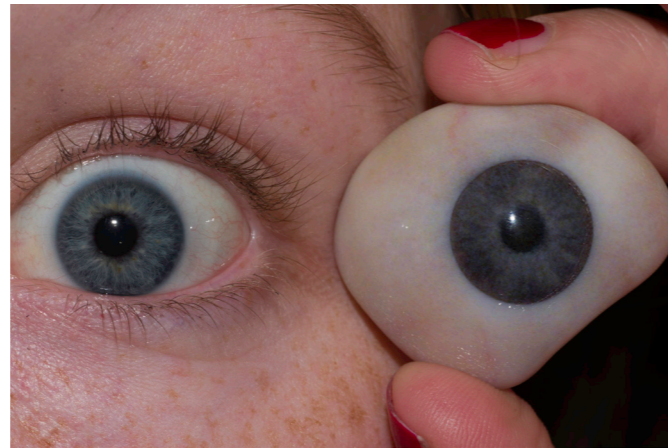
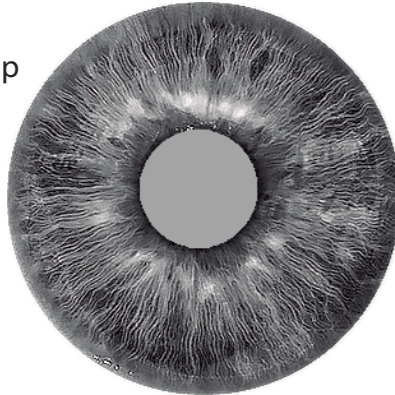
**Participant 1**

Image or displacement map image Compared to the eye:

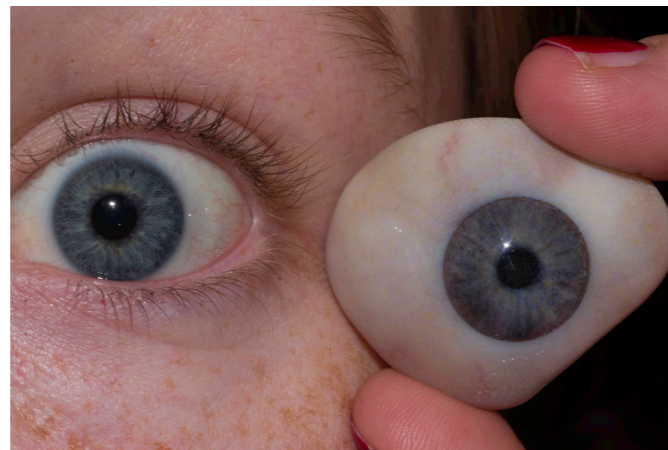
P1 Original



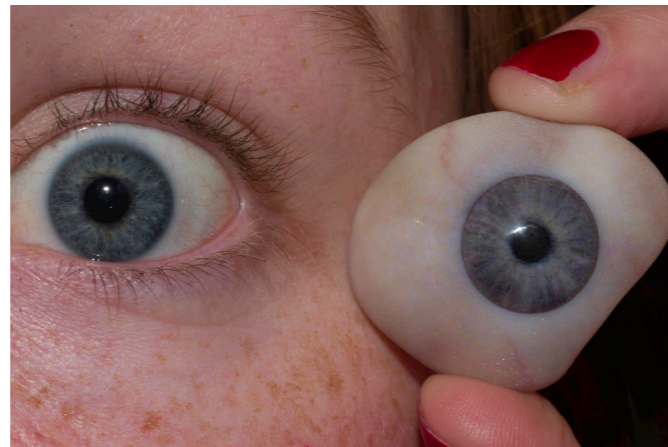
P1 Original +  
3D structure of a  
displacement map  
of 0.3



P1 Exposure of 0.5



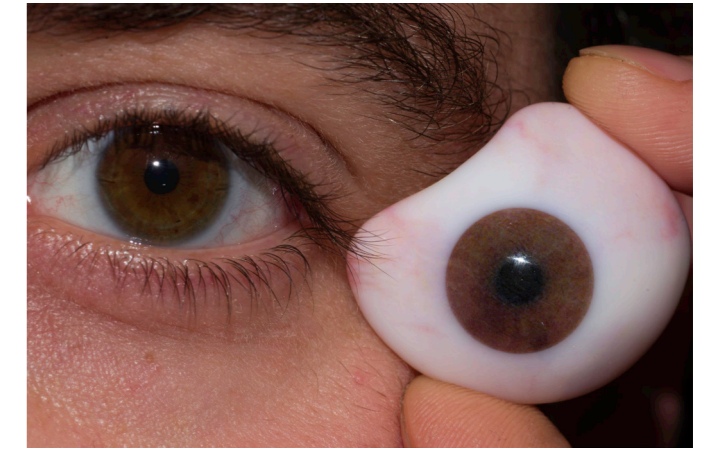
P1 Exposure of 1



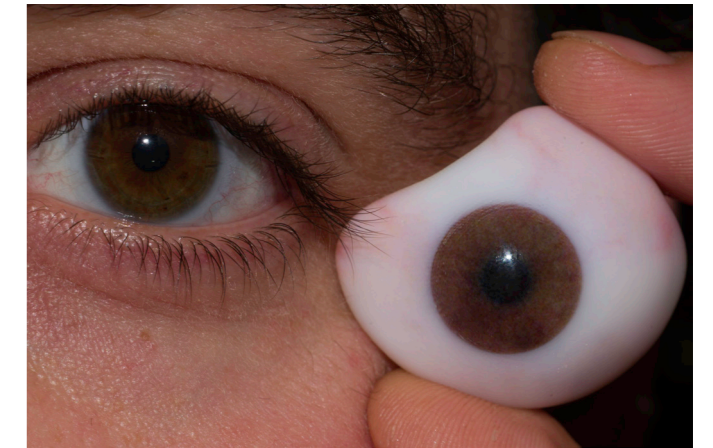
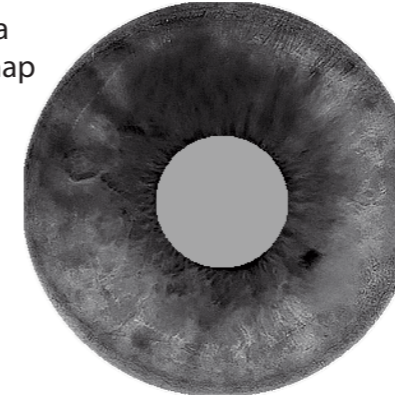
**Participant 2**

Image or displacement map image Compared to the eye:

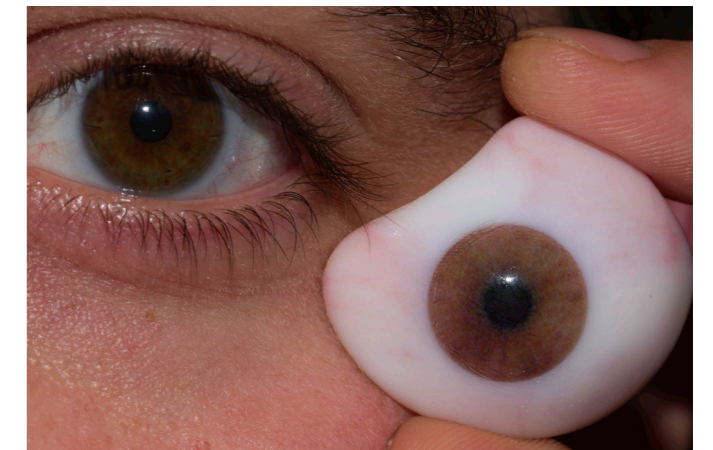
P2 Original



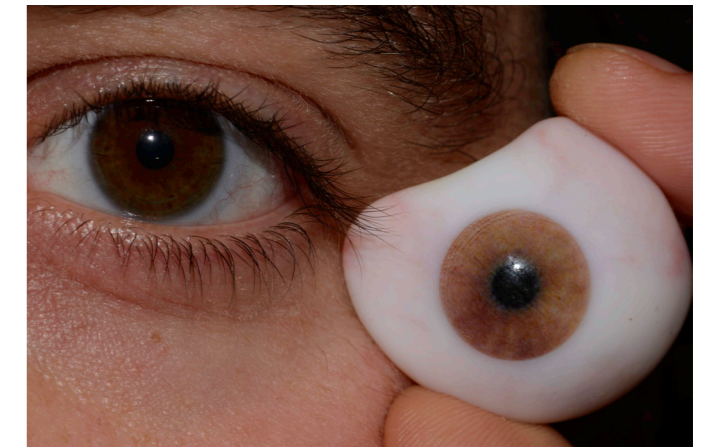
P2 Original +  
3D structure of a  
displacement map  
of 0.3



P2 Exposure of 0.5



P2 Exposure of 1

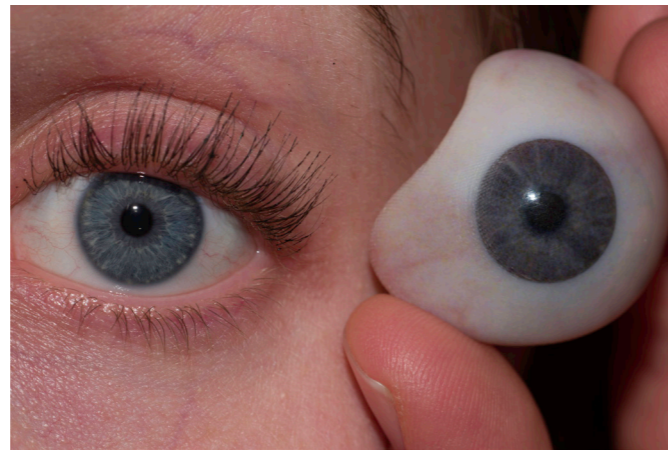




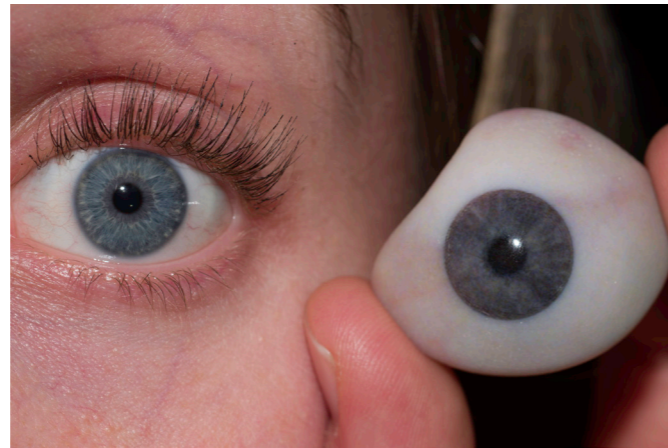
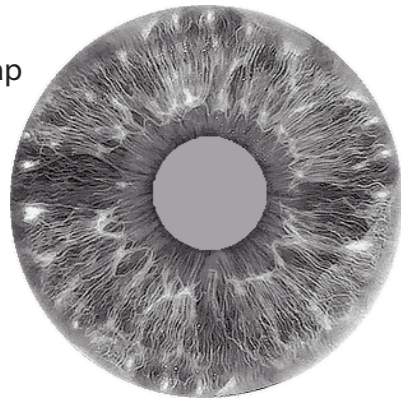
**Participant 3**

Image or displacement map image Compared to the eye:

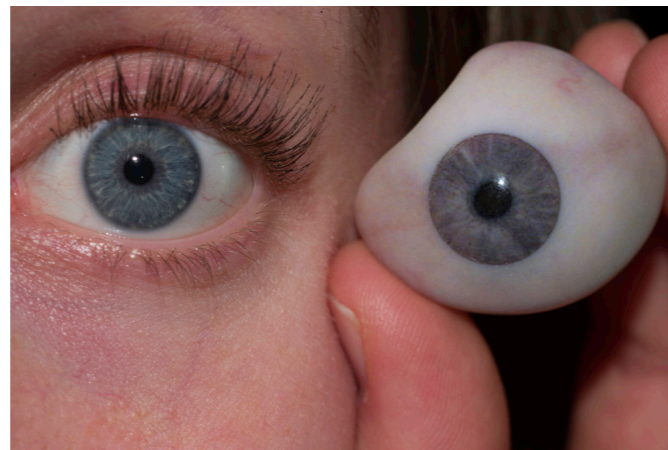
P3 Original



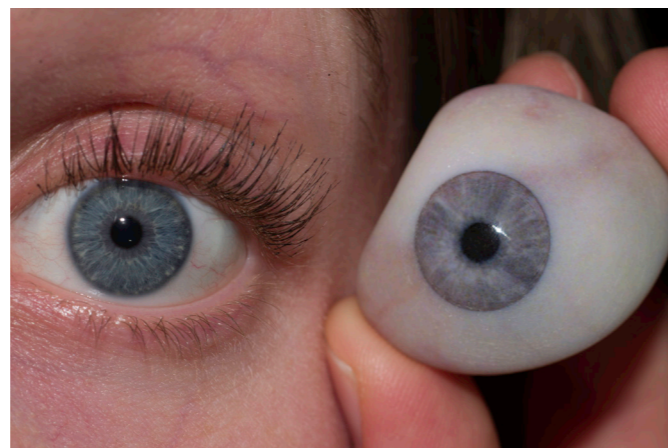
P3 Original +  
3D structure of a  
displacement map  
of 0.3



P3 Exposure of 0.5



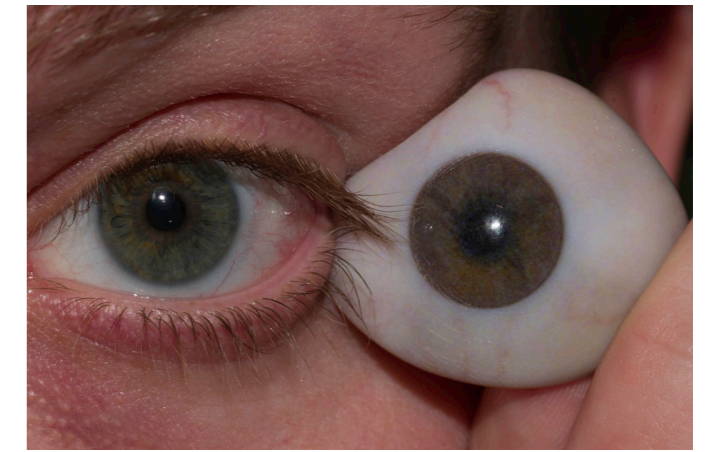
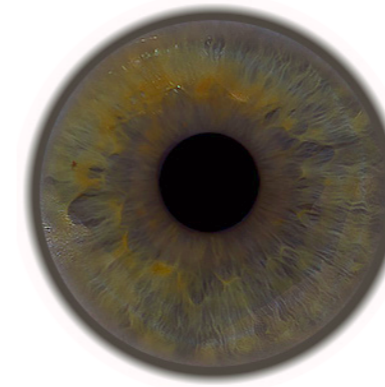
P3 Exposure of 1



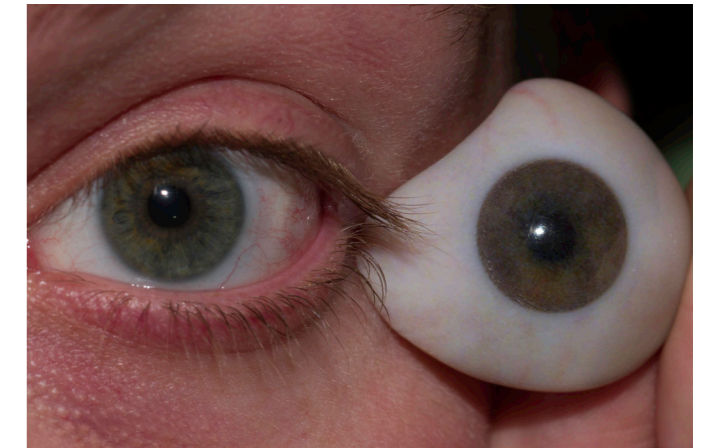
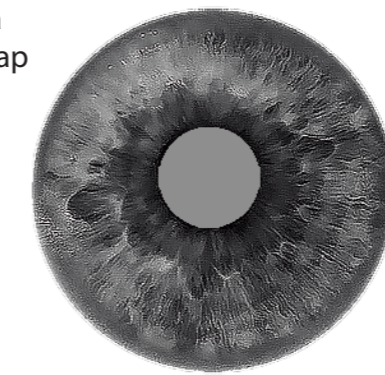
**Participant 4**

Image or displacement map image Compared to the eye:

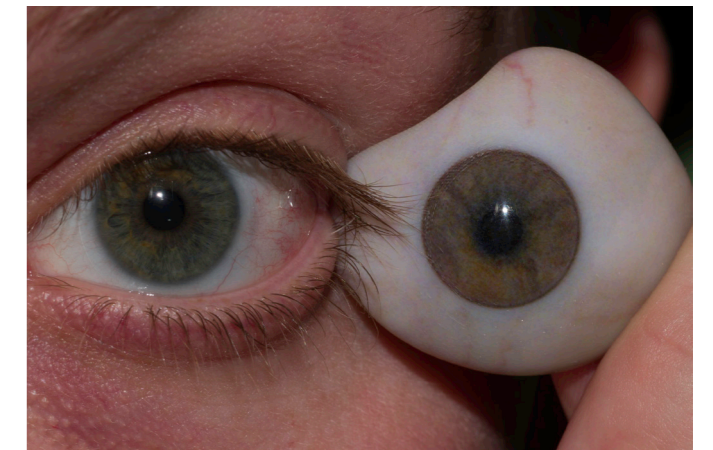
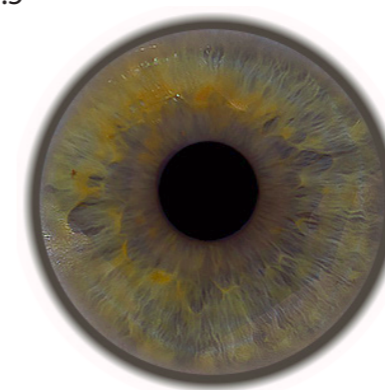
P4 Original



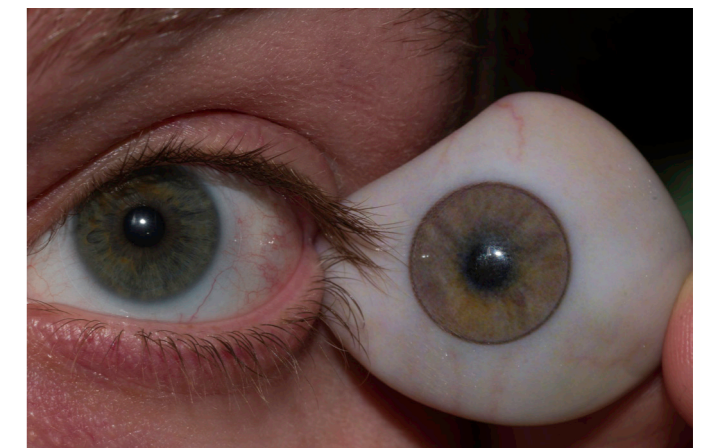
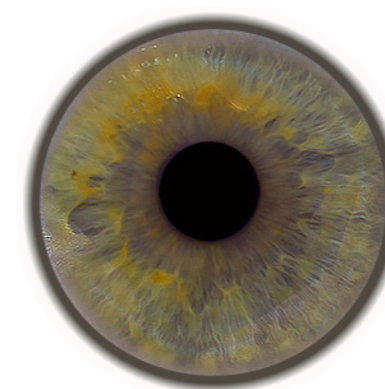
P4 Original +  
3D structure of a  
displacement map  
of 0.3



P4 Exposure of 0.5



P4 Exposure of 1

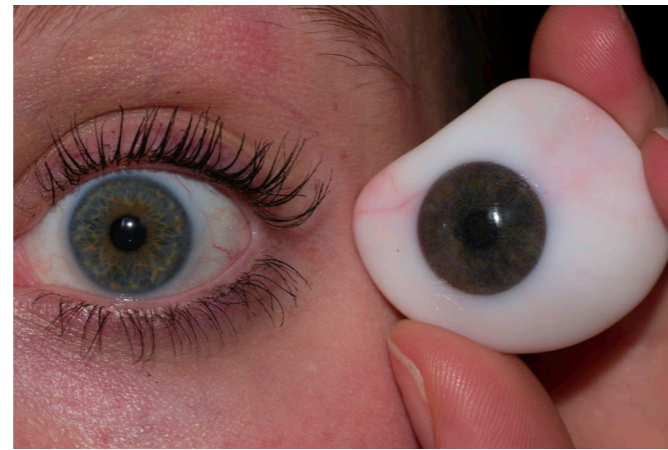




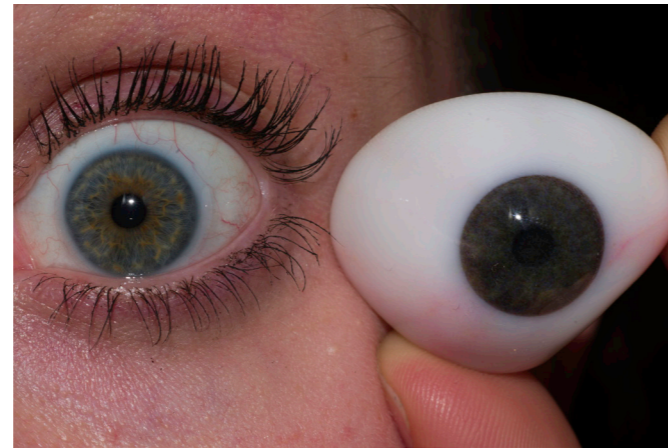
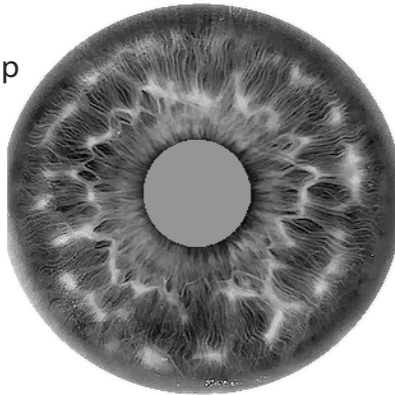
**Participant 5**

Image or displacement map image Compared to the eye:

P5 Original



P5 Original +  
3D structure of a  
displacement map  
of 0.3



P5 Exposure of 0.5



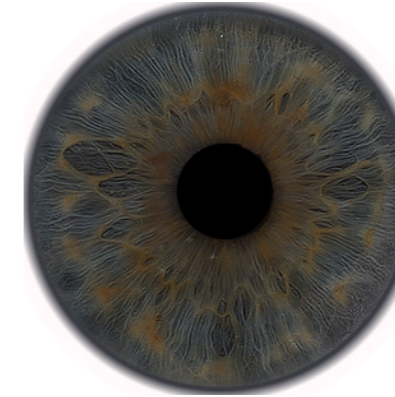
P5 Exposure of 1



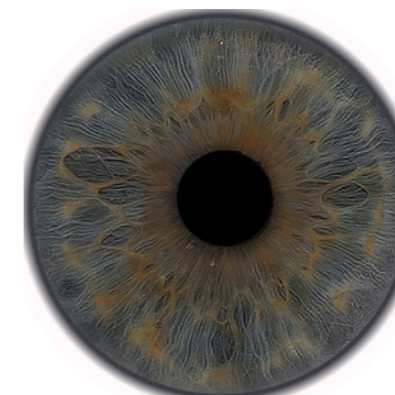
**Participant 5**

Image or displacement map image Compared to the eye:

P5 New photo  
Edited with the  
ISA ColorGauge



P5 New photo  
Exposure of 0.5



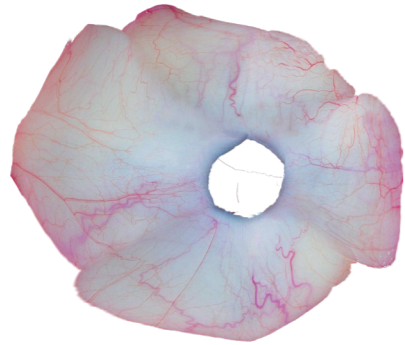


**Sclera comparison**

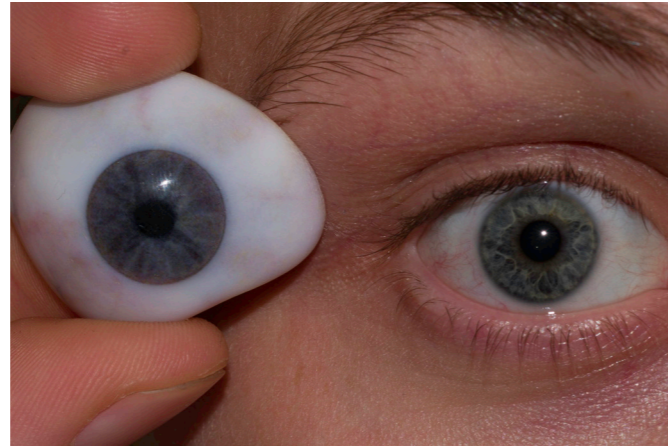
**Expert 1**

E1 Original

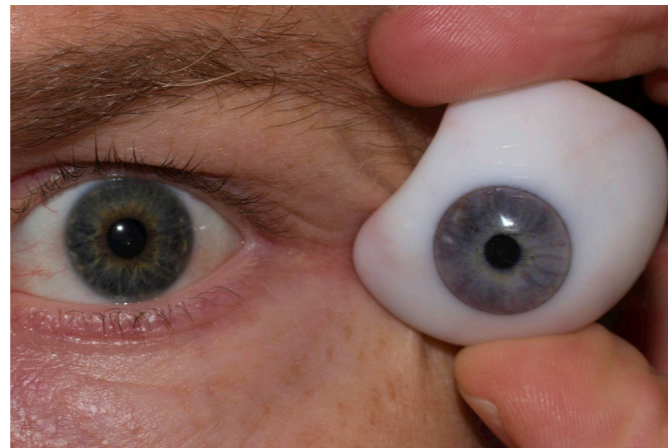
Sclera image



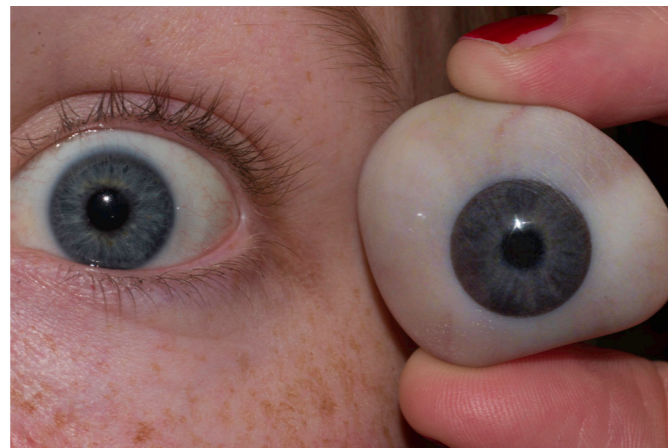
Compared to the eye:



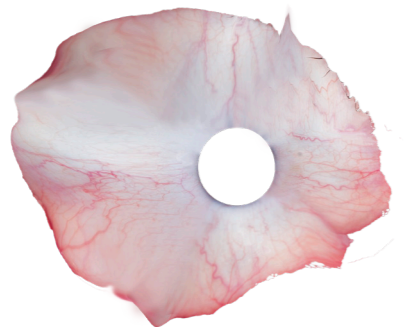
E2 Original



P1 Original



P2 Original

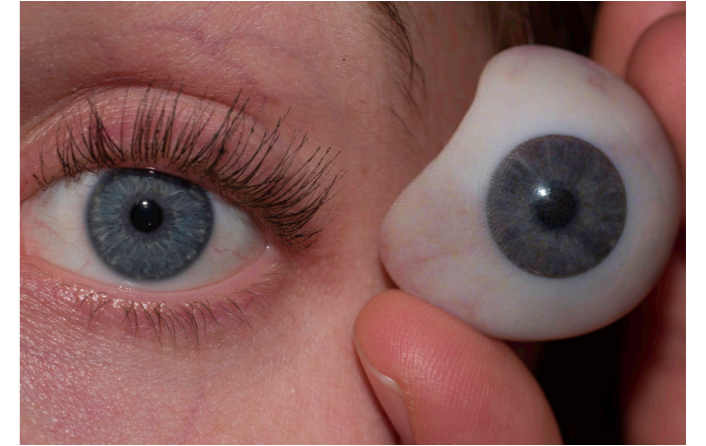


P3 Original

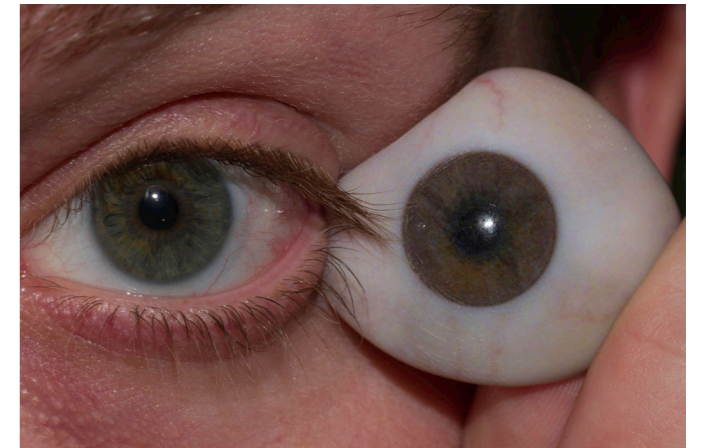
Sclera image



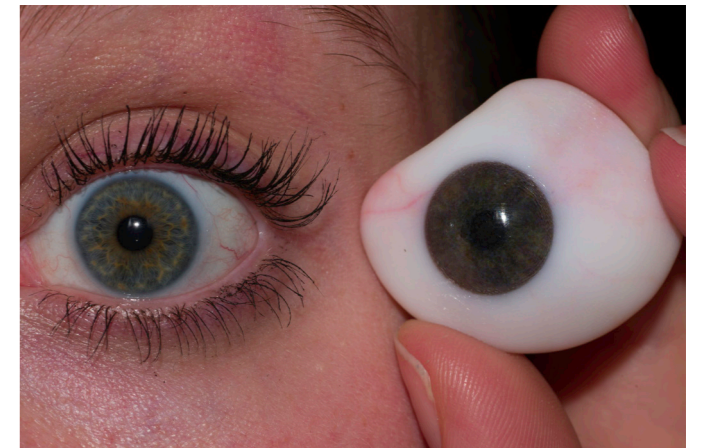
Compared to the eye:



P4 Original



P5 Original





# Appendix O: Validation – Interview questions and results

## Interview questions:

>> Give the user the personal prosthesis + mirror

Interview questions:

- What is your first impression of the prosthesis?
- On a scale of 1 to 10, how realistic do you find the following parts of the prosthesis compared to your eye? And why?

- o Iris colour
- o (Iris structure)
- o Sclera
- o Pupil
- o Cornea
- o Sclera
- o Blood vessels
- o Limbus (transition between pupil and sclera)

- On a scale of 1 to 10, how realistic do you find the total prosthesis? And why?

>> Give the user prosthesis 2 (the one without a 3D structure in the iris)

>> Without telling the user the difference, ask

- Which prosthesis do you find most realistic? And why?

>> If the iris colour doesn't match, give the user a prosthesis with a higher exposure

>> Photograph the user holding the four prostheses next to their eye.

## Expert 1 (E1)

>> Give the user the personal prosthesis + mirror

Interview questions:

- What is your first impression of the prosthesis?

The underlying colour is good, but on top of that, I have more white lines. The prosthesis doesn't really represent the white lines

On a scale of 1 to 10, how realistic do you find the following parts of the prosthesis compared to your eye? And why?

- Iris colour  
8, good.
- Iris structure  
5, Structure seems missing
- Sclera colour  
9, could have been a little darker
- Pupil (hold your finger behind the pupil)  
8, Good, slightly less black
- Cornea  
8, difficult to see, but the cornea is very clear
- Blood vessels

7, the blood vessels are blurred, in the real eye, they are sharper.

- Limbus (transition between pupil and sclera)

9, On the prosthesis, the limbus is sharper.

- On a scale of 1 to 10, how realistic do you find the total prosthesis? And why?

7, the iris structure is less visible.

>> Give the user prosthesis 2 (the one without a 3D structure in the iris)

>> Without telling the user the difference, ask

- Which prosthesis do you find most realistic? And why?

0.3 chosen (one with 3D structure)

The lighter colours stand out more. The Colour texture is more visible. White is more in the foreground.

I don't see the structure, but the lighter parts stand out more. It has more colour texture.

>> If the iris colour doesn't match, give the user a prosthesis with a higher exposure

Not needed

>> Photograph the user holding the four prostheses next to their eye.

## Expert 2 (E2)

>> Give the user the personal prosthesis + mirror

Interview questions:

- What is your first impression of the prosthesis?

Good polishing. Lighting up the area around the pupil was successful.

On a scale of 1 to 10, how realistic do you find the following parts of the prosthesis compared to your eye? And why?

- Iris colour

6, My eye is greener, while this one is too blue/grey

If I had to deliver this prosthesis to someone with this eye colour, it would not be good enough. The iris colour should be more towards green. The details are very nice, but the colour tone is not right.

- Iris structure

8, details are very nice

- Sclera colour

7, could be a bit yellower

- Pupil (hold your finger behind the pupil)

10, I can clearly see that it is a hole. In conventional prosthesis, it is a dot that seems to lie on the painting, which I find ugly.

- Cornea

10, just good

- Blood vessels

6, more veins are needed, and in reality, they are sharper.

- Limbus (transition between pupil and sclera)

6, it could be softer

- On a scale of 1 to 10, how realistic do you find the total prosthesis? And why?

7, For a real prosthesis, a number of aspects are still missing, in particular, the sclera and the transition from the iris to the sclera. But it's a really nice eye. This one is a bit bland, the iris can have a bit more sparkle.

>> Give the user prosthesis 2 (the one without a 3D structure in the iris)



>> Without telling the user the difference, ask

- Which prosthesis do you find most realistic? And why?

I don't see the difference, the structure is not visible. The difference is too fine.

But guess was good anyway

>> If the iris colour doesn't match, give the user a prosthesis with a higher exposure

Not needed

>> Photograph the user holding the four prostheses next to their eye.

### Participant 1 (P1)

>> Give the user the personal prosthesis + mirror

Interview questions:

- What is your first impression of the prosthesis?

I find it great that you really see the layers and depth in the prosthesis. But I expected it to be bluer.

On a scale of 1 to 10, how realistic do you find the following parts of the prosthesis compared to your eye? And why?

- Iris colour

4, it is more grey

- Iris structure

7, by the 0,5 (more exposure) the structure is more visible.

- Sclera colour

8, a bit dirty colour. But it does match with what it really looks like

- Pupil (hold your finger behind the pupil)

5, the size of the pupil is okay, and it forms nicely to the inside. I was expecting it to be a bit darker, more black. That you can see the hole makes it less real.

- Cornea

9, beautiful. Shiny look

- Blood vessels

7, they are light. I like the vague one. Maybe want to see a slightly brighter line

- Limbus (transition between pupil and sclera)

7. that I like it here. In my real eye, it blends in a little more

- On a scale of 1 to 10, how realistic do you find the total prosthesis? And why?

6, I think my eye itself is a bit brighter, and the colour is not right.

>> Give the user prosthesis 2 (the one without a 3D structure in the iris)

>> Without telling the user the difference, ask

- Which prosthesis do you find most realistic? And why?

Choose the one with a structure. The general iris look seems to be just a little more correct.

Can not explain the difference

The colour of the iris is better. Limbus appears sharper, More realistic feeling.

The structure is the same, but the colour contrast is better.

>> If the iris colour doesn't match, give the user a prosthesis with a higher exposure

0.5 – is better! But still missing the blue colour

1 – too light

>> Photograph the user holding the four prostheses next to their eye.

### Participant 2 (P2)

>> Give the user the personal prosthesis + mirror

Interview questions:

- What is your first impression of the prosthesis?

Shine good, good white. Veins could be finer.

On a scale of 1 to 10, how realistic do you find the following parts of the prosthesis compared to your eye? And why?

- Iris colour

7, my eye is a little lighter

- Iris structure

7, not much structure, by 0,5 (more exposure), there's more colour difference visible.

- Sclera colour

9, good. Maybe my own sclera is a bit more yellow. this one is just white

- Pupil (hold your finger behind the pupil)

7, can be darker, and the transition from brown to black is vague. I miss the clear edge.

- Cornea

9, The reflections look correct. For example, the reflections of the lamps in the prosthesis are about the same. Good shine.

- Blood vessels

8, the colour is good, but I want them sharper and finer

- Limbus (transition between pupil and sclera)

6, my limbus is much darker. In my eye is, the limbus bigger and more clearly visual. The limbus on the prosthesis is more blended

On a scale of 1 to 10, how realistic do you find the prosthesis? And why?

8, much better than the proof-of-concept. The veins are not so fine, but the sclera colour is very good. I can really recognise my own eye in it.

>> Give the user prosthesis 2 (the one without a 3D structure in the iris)

>> Without telling the user the difference, ask

- Which prosthesis do you find most realistic? And why?

Choose the one without structure by following my feeling. Hard to see the difference.

The one without texture has a sharper pupil. Due to the texture the pupil blend more with the iris.

>> If the iris colour doesn't match, give the user a prosthesis with a higher exposure

0,5 – the colour is better! But don't miss the dark brown limbus/edge - there's also more colour difference seeing.

>> Photograph the user holding the four prostheses next to their eye.

### Participant 3 (P3)

>> Give the user the personal prosthesis + mirror

Interview questions:

- What is your first impression of the prosthesis?

Awesome! Cool, really close to the real thing

The Colour is cool. Towards the middle, what lighter. In my eye, the outside ring is darker, in the prosthesis, this is more gradual.

On a scale of 1 to 10, how realistic do you find the following parts of the prosthesis compared to your



eye? And why?

- Iris colour

9, My inside is lighter, and the outside darker. The gradient should start later.

- Iris structure

6, but the resolution is also higher in my eye than in de prosthesis. Less lines visible

- Sclera colour

9, colour is a good match

- Pupil (hold your finger behind the pupil)

9, the dept is the prosthesis is magical.

- Cornea

7, duller in the prosthesis than by myself, but the resolution is also higher in my eye than in de prosthesis.

- Blood vessels

8, the veins are a bit thinner in my own eye. In the prosthesis more blurred. But I don't find this disturbing.

- Limbus (transition between pupil and sclera)

5, Less contrast than in my own eye.

- On a scale of 1 to 10, how realistic do you find the prosthesis? And why?

8,5

>> Give the user prosthesis 2 (the one without a 3D structure in the iris)

>> Without telling the user the difference, ask

- Which prosthesis do you find most realistic? And why?

they really look a lot alike. I don't see a difference. Can not choose.

0,3 looks a little darker

>> If the iris colour doesn't match, give the user a prosthesis with a higher exposure

0,5 – too light

>> Photograph the user holding the four prostheses next to their eye.

#### Participant 4 (P4)

>> Give the user the personal prosthesis + mirror

Interview questions:

- What is your first impression of the prosthesis?

Beautiful

On a scale of 1 to 10, how realistic do you find the following parts of the prosthesis compared to your eye? And why?

- Iris colour

Side note: I'm colourblind, so I find it hard to give a valuable estimation

9, colour looks the same

- Iris structure

5, structure not really visible

- Sclera colour

7, also good, but I see some brown spots. Maybe I have them to, but my eyelid covers them.

- Pupil (hold your finger behind the pupil)

6, may be blacker

- Cornea

8, good

- Blood vessels

5, the veins are a bit blurry and not complete. The small ones are missing.

- Limbus (transition between pupil and sclera)

5, It is a strong line, with is not in line with my eye. The coloured circle is missing / darker in my eye.

- On a scale of 1 to 10, how realistic do you find the prosthesis? And why?

8, because the smallest details (which are missing) matter less, it is about the whole.

>> Give the user prosthesis 2 (the one without a 3D structure in the iris)

>> Without telling the user the difference, ask

- Which prosthesis do you find most realistic? And why?

This one is less well polished (one without structure)

Other than that, I don't see any difference

>> If the iris colour doesn't match, give the user a prosthesis with a higher exposure

0,5. Is better

1 too light

>> Photograph the user holding the four prostheses next to their eye.



