Designing a Virtual Reality headset for amblyopic children

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To you, dear reader, I hope that you will enjoy reading this thesis.

Tim Elderhorst

Summary

Amblyopia, or lazy eye, is a condition where the visual system suppresses information from the patient's weaker eye, causing him to lose his stereovision. The condition is most prevalent in Western Europe, where it affects 3,67% of all children. **[1]** Amblyopia is often detected around the age of 4. It should be treated as soon as possible in order to ensure an effective treatment. If a child is not treated for amblyopia after the age of 8, this can cause lifelong vision problems. **[2] [3]**

Currently, the most common treatment for amblyopia is occlusion therapy, which requires the child to wear an eye-patch over his stronger eye. This method however causes the child to become acutely visually handicapped, diminishing the psycho-social wellbeing and quality of life of the children **[4] [5]**. Additionally, children are prone to tear off their eye-patches, diminishing the effectiveness and efficiency of the treatment.

Dichoptic training is a relatively new treatment for amblyopia, where patients play certain games or watch certain movies where the eyes are forced to work together. Dichoptic training forces the visual system to use visual information from both of the eyes, which stimulates and enhances the user's stereovision. **[6]** It has been proven that dichoptic training is more effective in treating amblyopia than the traditional method of occlusion therapy. **[7]**

Vedea Healthware BV is a Dutch start-up, dedicated to developing dichoptic training for children aged 4-10. **[8]** Vedea wants to deliver their dichoptic training by means of a VR headset, which allows children to be more immersed in their training than other methods, as it reduces stimuli from outside. A problem that Vedea discovered is that traditional VR devices are not suitable for children, mainly due to the large size and weight of these products. It was found that there is a gap in the current market for VR devices for children. Existing VR devices marketed towards children are in reality not different from regular VR devices for adults.

It was found that in order to make a VR device suitable for young children, it should meet the following three criteria: first of all, the fit of the mask should be less wide in order to fit the size of the child's head. Secondly, the product depth and weight should be low, in order to decrease the stress on the child's neck. This is because young children have more difficulty withstanding the forces on their necks than adults. Lastly, the ILD (inter lens distance) of the VR headset should match the IOD (interocular distance) of the child, which tends to be much lower than the ILD available in regular VR headsets. Failure to match the ILD to the child's IOD can result in headaches, eye-pain, nausea, double vision, unsharp vision and more problems. **[9]** An additional remark is that children may have more difficulty with finding the appropriate settings of the VR device than adults.

In order to make a VR headset suitable for amblyopes it has to be taken into consideration that amblyopes usually have underlying eye conditions. The most common ones are refractive errors such as myopia or hyperopia. Slight refraction errors can be solved by changing the lens depth. However, the best option is to let users wear contact lenses or prescriptionglasses inside the VR headset.

Another common condition among amblyopes is strabismus, which poses additional problems for using a VR headset. In order to make VR headsets suitable for strabismic users, a corrective prism should be incorporated into the VR headset. The strength of the corrective prism should correlate with the degree of deviation of the eye.

Lastly, for amblyopes it is vital that the ILD, IOD and ICD (inter camera distance) are equal. When there is a difference between the IOD and ILD or between the ICD and ILD, this causes optical distortion. While distortion should always be avoided in VR, it is extra important during dichoptic training, as it is hypothesized to decrease the effectiveness of the treatment. This is because amblyopes are already prone to discard the images coming from their weaker eye. Additional distortions such as warp and double vision will make it even more difficult for the user to make both of his eyes work together, which is hypothesized to decrease the effectivity of the dichoptic training.

A VR device was designed for Vedea, which meets the requirements that were set during the project. This product was produced by 3D printing, and will be used during Vedea's play tests and clinical trial. The Vedea VR device is 21% lighter than competitor products, and has a better mask fit. Furthermore, the Vedea VR device has a much lower ILD, and is therefore much more suitable for children with amblyopia. The product can be used in combination with prescription glasses, and it contains a click-on optical prism for strabismic users. In order to make the product viable for mass production, a redesign for injection molded parts is required.

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List of abbreviations

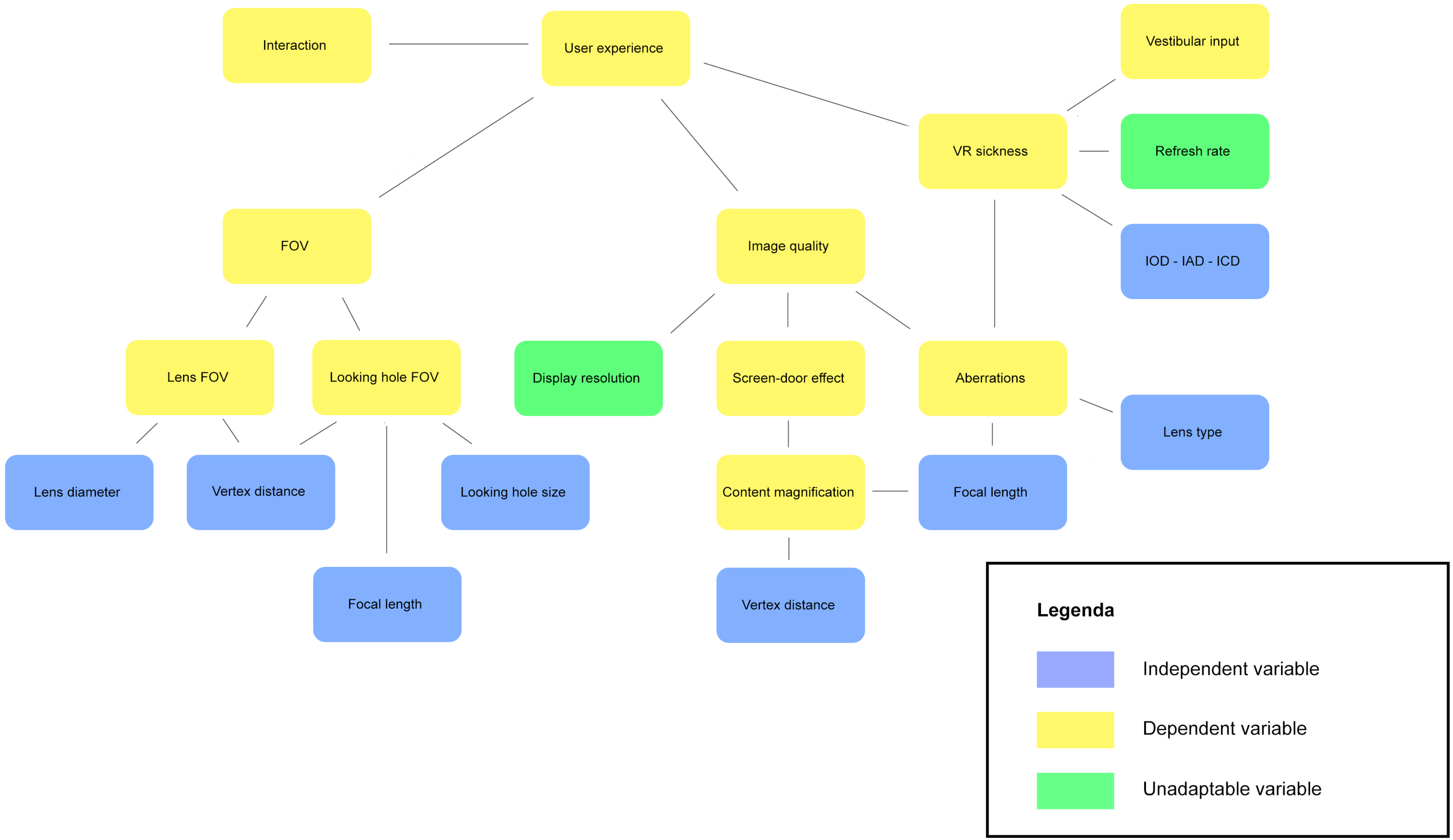
VR	Virtual Reality
AR	Augmented Reality
XR	Extended Reality
MR	Mixed Reality
IPD	Interpupillary distance
IOD	Interocular distance
ILD	Inter-lens distance
ICD	Inter camera distance
FOV	Field of view
Di	Image distance
Do	Object distance
f	Focal length
P	Lens strength
vx	Vertex distance
MVP	Minimum viable product
CAD	Computer Aided Design
3D	Three dimensional
DoF	Degrees of freedom
ppi	Pixels per inch
PPD	Pixels per degree

Influence Chart

Legenda

- Independent variable
- Dependent variable
- Unadaptable variable

User Experience Chart



Chapter 1

Introduction

1. Introduction

Every year, 2.45 million children worldwide are born with amblyopia, also known as lazy eye syndrome. The highest prevalence of amblyopia occurs in Western Europe, where it is estimated to affect 3.67% of all children. **[1]** Amblyopia is a condition where the visual system suppresses the visual information received by one of the eyes, which we call the lazy eye. Because this eye is not used, it will become underdeveloped, causing the patient to lose his stereoscopic vision. Amblyopia needs to be treated at a young age, preferably between the ages of 4 and 7. When children are older than 7 years old it becomes increasingly difficult to treat amblyopia. **[2] [3]**

The current treatment is called the occlusion method, which requires children to wear an eye-patch on their strong eye for several hours per day. The drawback of this method is that the child acutely becomes severely visually impaired. This causes serious repercussions for the children, ranging from bullying to children not wanting to play outside anymore. It has been shown in multiple studies that traditional methods such as eye-patching and atropine drops diminish the psycho-social wellbeing and quality of life of amblyopic children **[4] [5]**. Moreover, children who are being treated by occlusion therapy (eye-patching) sometimes tear off their eye-patches, which causes the treatment to be less effective and last longer than intended.

In the last few years, a new treatment method called dichoptic training was developed, which is more child-friendly than traditional treatment methods. Dichoptic training is a treatment method where the patient's stereovision is trained by forcing the eyes to work together. **[6]** The underlying principle of dichoptic training is that a different image is presented to the left and right eye. Because the user is presented with two distinct images, the user needs to use both eyes in order to interpret the visual stimuli. This can be done by playing certain games or watching certain videos where two distinct images are provided to both eyes. Research has shown that doing dichoptic training for 30 minutes per day has a more positive effect on treating amblyopia than wearing an eye-patch for several hours per day **[7]**.

Vedea Healthware BV is a Dutch medtech startup, dedicated to bringing dichoptic training for children to the market. **[8]** The company wants to do so by developing a platform, containing several dichoptic games and videos for children. The dichoptic training is supposed to be performed using a virtual reality (VR) headset. In order to provide the service as proposed by Vedea, a VR headset is needed. It was decided as a strategic decision by Vedea that a custom VR headset should be designed and developed for this specific situation. A custom headset can be tailored to the specific needs of the target group. Furthermore, a custom headset is favourable for the company, as it is cheaper in the long run and decreases the company's dependence on third party products. The goal of this research is to find out how a VR headset can be designed to fit amblyopic children aged 4-7.

1.1. Design assignment

The design assignment formulated in this thesis is to design a VR headset suitable for the use by 4-7 year old kids with amblyopia. For this assignment, Vedea is looking for a product that meets at least the following requirements:

- Children should be able to use the smartphone devices of one of their parents.
- Children should be able to comfortably wear the head mounted display for 30-60 minutes per day.
- The head mounted display should be customizable to head circumference.

1.2. Stakeholders

In order to set the right requirements for the product, it is important to define the most important stakeholders and their needs and desires.

The first and foremost stakeholder is Vedea Healthware BV. This company wants to develop dichoptic training for amblyopia patients using VR games. Vedea also gave the assignment to develop and produce the VR headset mentioned in this thesis.

The second stakeholder is Reddito BV. This company is the main stakeholder in Vedea Healthware BV, and was founded by Daniël Jansen. Daniël is in charge of the business development, marketing and sales of Vedea Healthware BV.

The third stakeholder is GainPlay Studio. This company is one of the three stakeholders in Vedea Healthware BV, and is responsible for the research and game development. The company was founded in 2014 by Teun Aalbers and Jan Jonk, and specializes in serious gaming.

The fourth stakeholder is Legio BV. This company is responsible for the platform and software development. The company was founded by Joel Wijngaarde.

Vedea Healthware BV and Vedea's stakeholders are interested in developing a treatment for amblyopic children. Vedea is trying to achieve this goal by offering dichoptic training on a VR headset. The VR headset in question will be a simple VR device, relying on the user's own smartphone. This type of VR device does not contain electronics, a custom display or an embedded system, which makes the device much cheaper and easier to produce than high-end VR devices like the Oculus Rift **[10]**. The added value of Vedea is a new treatment option for amblyopic children which is more effective and child-friendly than existing methods. Vedea wants to make this new method available to as many children as possible by starting in the Netherlands and spreading through Europe. In the process, Vedea is able to annually treat thousands of children in the Netherlands alone while growing the company. Financial resources will be obtained through a monthly subscription, which will be paid by the parents of the amblyopic children or their health insurance company. Vedea concerns itself with developing a software platform for VR games, the content of these VR games and a VR headset. The platform will be in the form of a smartphone application, in which the several VR games can be selected and played.

While the knowledge about developing a platform and the VR games is present in Vedea through its stakeholders Legio BV and GainPlay Studio, the same thing cannot be said about the development of the VR device. As Vedea has not yet brought any products to the market, Vedea does not have a regular cash flow and only limited financial resources. This position should be improved by bringing a first product to the market. Vedea will start this process by designing a minimum viable product (MVP) in terms of both platform, VR games and VR device. This MVP will function as a proof of concept for further investments, which should help Vedea to improve their financial position, allowing them to design better products and adding more value to their customers.

1.3. Boundaries

The focus of this thesis lies on the design process of the VR device which will be used for the MVP. The design of Vedea's platform and content library is also a part of the MVP, but will not be discussed in this thesis. In chapter 7 the company strategy will be explained, making use of a model consisting of three phases. The main focus of this thesis will be on phase 2, which is the design and development of the MVP. Phase 1 consists of the design and development of a prototype, which will be used during the playtests and clinical trial. While this process happened simultaneously with the design of the MVP, it will not be thoroughly explained in this thesis. Phase 3 concerns itself with the design of an improved product which should be brought to the market several years after the MVP. Although the design of this product will not happen until several years after the end of this thesis, some pointers will be given in this report about which features can be improved in the new product.

1.3.1. Deliverables

The following deliverables are expected to be completed by the end of this project:

- CAD models of all plastic parts
- A plan for the development or purchase of all additional parts (straps, cushion, lenses and closure)
- A prototype of the MVP for phase 1
- A detailed explanation of the variables that influence the product design
- A plan for the production of all plastic parts, including material and production method
- A plan for the use of the product
- A cost analysis of the complete product

1.4. Approach

During this project, a variation on the engineering design process will be used. The design method for this assignment will consist of the following aspects:

Research -> Design requirements -> Conceptual design -> Detailed design -> Prototyping/Production -> Testing

1. **Research**

The first phase consists of doing research into various subjects. In order to make a successful product, research should be done about the target group, optical science, amblyopia, the visual system, and many more subjects. The output from the research phase will be used as input for the design requirements.

2. **Design requirements**

A list of design requirements will be made based on the previous research, which gives the designer a set of constraints during the next phase. The conceptual designs made in the next phase have to satisfy the requirements as indicated in this phase in order to result in a satisfactory product.

3. **Conceptual design**

In this phase the designer will go through a creative process which is called ‘ideation’ or ‘conceptual design’. In this phase several concepts will be designed for a given problem. The best concept will be chosen, for which a satisfactory rationale will be given, and this concept will be worked out in detail.

4. **Detailed design**

In this phase the concept from the previous phase will be worked out in detail. This phase may include the use of calculations, or the use of 3D CAD (Computer Aided Design) modelling. The result of this phase is a detailed part/product design which is ready for production.

5. **Prototyping/Production**

In this phase the detailed part/product design will be produced. In early instances of this phase a prototype will be produced. If the prototype is satisfactory, this prototype will be tested.

6. **Testing**

The prototype made in the previous stage will be tested to see if it meets the requirements as stated in phase 2. If the prototype meets the requirements it is deemed a successful prototype.

The design method as seen above is not a linear process. Instead it is a cyclical process, where the product designer will go through every phase multiple times. Every time the result of a certain phase is unsatisfactory, the phase will be repeated or the designer will return to a previous phase. Every problem encountered during the assignment, both big and small problems, will trigger this design process. Additionally, multiple instances of this design process can occur simultaneously for different problems.

1.5. Competitor analysis

In the initial stages of this project it was found that some VR headsets for children already exist. However, upon further inspection it was found that these products in question are not much different from regular VR headsets for adults. The examined VR devices in question are the Destek **[11]** and the Heromask **[12]**. These devices are marketed towards children of 5-15 and 5-12 years old respectively. In chapter 11.3 will be explained why these products are not suitable for children of these age brackets.

During play tests by Vedea with children aged 4-7 it was found that the Destek and Heromask are too heavy, and the mask fit is too large for children of this age bracket. Furthermore, upon further inspection of these products it was found that the minimum inter-lens distance (ILD) of these products are 57 and 62 respectively. For children aged 4-7, these values are unsuitable in 99% and 100% of the cases respectively. In chapter 5 will be explained why ILD is important for this project.

To conclude, there is a gap in the market for VR headsets for children, and current VR devices aimed at children do not really fill this gap. In order to make the dichoptic training by Vedea available to young children (specifically children aged 4-7, but also older children), it is important that a VR headset for children will be developed.

Chapter 2

Amblyopia

2. Amblyopia

The analysis phase consists of research about several topics that are relevant to this assignment. Chapters 2-5 consist of research on various topics that are relevant for this design assignment. In order to design a product which will be used to treat amblyopia, it is necessary to first understand what amblyopia is (2.1), and how it is caused (2.2). Secondly, it will be discussed what dichoptic training is and how it can be used to treat amblyopia (2.3).

Figure 1 : girl with amblyopia

2.1. Amblyopia

Amblyopia, also known as “lazy eye syndrome”, is a condition in which the visual system is prioritizing the input from one eye, while discarding the information provided by the other eye. It develops when the brain and eye have trouble working together due to an underlying eye condition. As a result, the brain cannot fully understand the sight obtained from that eye, and chooses to ignore the visual input provided by that particular eye. Over time, the brain will rely more on the other eye, also called the stronger eye. This will cause the weaker eye, or lazy eye, to become underdeveloped. It is estimated that the worldwide prevalence of amblyopia is between 1 and 2%. **[13]** In European countries, the prevalence is estimated at 3 - 4 %. **[1]** Amblyopia is also the most common cause of vision loss for kids. The condition usually becomes apparent after the age of 4 **[14]**. When treated at an early age, kids will regain vision in their weak eye, although it will likely not restore the eye to its optimal state **[14]**. The older the child gets, the harder it becomes to treat amblyopia. When amblyopia goes untreated, children may develop lifelong vision problems. **[3]**

A common symptom of amblyopia is having difficulty perceiving depth. Children with amblyopia also tend to squeeze their eyes a lot, tilt their head, or close one eye when focusing on an object. In many cases amblyopia goes unnoticed, unless the child is diagnosed by a doctor. Therefore, it is important that all children get a vision screening at least once between the age of 3-5 **[3]**.

There are two existing treatments for amblyopia. The first treatment is using a stick-on eye-patch on the strong eye. This will force the children to use their weak eye, which will strengthen the bond between the weak eye and the brain. Some children need to wear the eye-patch for 2 hours a day, while other children need to wear it every waking moment. The second treatment consists of putting eye-drops of the drug atropine in the strong eye, on a daily basis. The eye-drops will blur the vision in the strong eye, forcing the child to use his/her weak eye. The disadvantages of the current methods are that they greatly reduce the children’s vision during their everyday life. This has a lot of negative influence on the child’s daily life, and it can cause them psychological harm. When amblyopic children wear an eye-patch over their strong eye or when they have received atropine, they become severely visually impaired. This causes them to avoid playing outside and it can also lead to bullying. Additionally, when using the first treatment option, children tend to tear off the eye-patches. This reduces the effectiveness of the method **[4] [5]**.

2.2. Causes of amblyopia

Amblyopia develops due to an abnormal visual experience during early life, which changes the pathway between the retina of the eye and the brain. This causes the weaker eye to receive fewer visual signals that can be transported to the brain. Over time, the ability of the eyes to work together decreases, which causes the brain to suppress or ignore the information provided by the weaker eye. **[3]**

Anything that blurs a child's vision or causes the eye to cross can cause the child to develop amblyopia. **[14]** The most frequent causes of amblyopia are the following:

- Difference in sharpness of vision between the eyes (refraction amblyopia due to anisometropia) is one of the most common causes of amblyopia. A significant difference in refraction of the eye, caused by myopia (near-sightedness), hyperopia (far-sightedness), or astigmatism (a problem in focusing due to irregularities in the cornea of the eye, also called a cylinder deviation), can cause amblyopia. Glasses and contact lenses are typically used to treat refractive issues.

- Muscle imbalance (strabismus amblyopia). The other most common cause of amblyopia is strabismus, a condition where an imbalance in the eye muscles appears in one or both of the eyes. This causes the eye to cross, resulting in diplopia (double vision), hindering the child's ability to focus on a certain point with both eyes. Strabismus amblyopia can cause one of the eyes to become amblyopic. An optical prism can be used to refract the light in order to temporarily treat strabismus. **[15] [16]** In order to permanently treat strabismus, eye-surgery is often used.

- Deprivation. A problem in one of the eyes, such as a cloudy area in the lens (cataract) can blur the vision in the eye. It requires early treatment to prevent permanent loss of vision. It is often the most severe type of amblyopia.

The prevalence of different causes of amblyopia differs per study and per ethnic group. **[17-20]** According to a study on Australian children, strabismus amblyopia plays a role in more than 50% of all amblyopia cases. **[17]** A study on Singaporean Chinese children reports that only 15% of amblyopia cases also suffer from strabismus. **[20]**

2.3. Dichoptic Training

According to a study on dichoptic training for adults with amblyopia **[6]**, dichoptic training is a promising treatment approach for amblyopia. Dichoptic training provides a simultaneous and separate stimulation of both eyes. The image displayed on the strong eye is decreased in contrast, therefore putting the eyesight of the strong eye at the same levels as that of the weaker one. Through the use of video games, the weaker eye will start to develop. The effect of dichoptic training on amblyopia patients has been researched in numerous studies. **[7] [21-23]**

According to Kelly et al. **[7]**, the use of dichoptic training for children proved to be more effective than the existing eye-patch option. Binocular games that rebalance contrast are mentioned as a promising additional feature.

The traditional treatments for amblyopia, being patching and atropine drops, focus solely on reducing the visual acuity of the strong eye. Reducing the visual acuity of the strong eye forces the visual system to rely on the weaker amblyopic eye, therefore strengthening the connection between the brain and the amblyopic eye. What these treatments do not offer is training the two eyes to work together. Patching therapy does not address the lack of binocular vision development, and might even weaken the strong eye **[24]**.

Figure 2: example of a dihcoptic training game

This is where dichoptic training appears to be the superior option, because it trains the two eyes to work together; something that is not trained with traditional amblyopia treatments such as patching or atropine drops. Another big advantage of dichoptic training over traditional methods is that it is a more child-friendly approach. Patching and atropine drops cause the child to be visually impaired for multiple hours a day, diminishing the psycho-social wellbeing and quality of life of the child **[4] [5]**. Dichoptic training only requires the children to play a game for 30 minutes per day, which is much more fun for the children and does not impair them in their daily life.

Dichoptic training does not necessarily include the use of VR (virtual reality) technology. In 2015, game company Ubisoft developed a dichoptic game for amblyopia patients called “Dig Rush” **[25]**. This game is supposed to be played on a tablet while wearing 3D glasses, with one blue and one red glass. The background of the game only makes use of black, white and grey tints, while the objects that the player can interact with are blue or red. Due to the 3D glasses, the player is able to only see certain objects with his left eye, and other objects with his right eye. In order to play the game, the player needs both of his eyes to work together, which helps them to develop their binocular vision.

While it is not necessary to perform dichoptic training using a VR device, it does offer some benefits. Because a VR device splits the image into distinct parts for the left and right eye, this makes it easier to manipulate the images that the left and right eye will see, which is necessary for dichoptic training. Another advantage of VR devices is that they are very immersive, and will therefore probably be better at keeping the user's attention on the training, which will help to make the training more effective. VR devices also have their disadvantages, namely that they are heavier than for example 3D glasses. This is especially a problem for children, as they have more trouble withstanding the weight of the VR device than an adult would. A paper on the use of VR in dichoptic training **[26]** states that VR is a promising medium for dichoptic training, but a comparative research between dichoptic training on VR and conventional media is still required. It also mentions the potential disadvantages of visual disturbances, dizziness and nausea, relating to the use of VR HMDs.

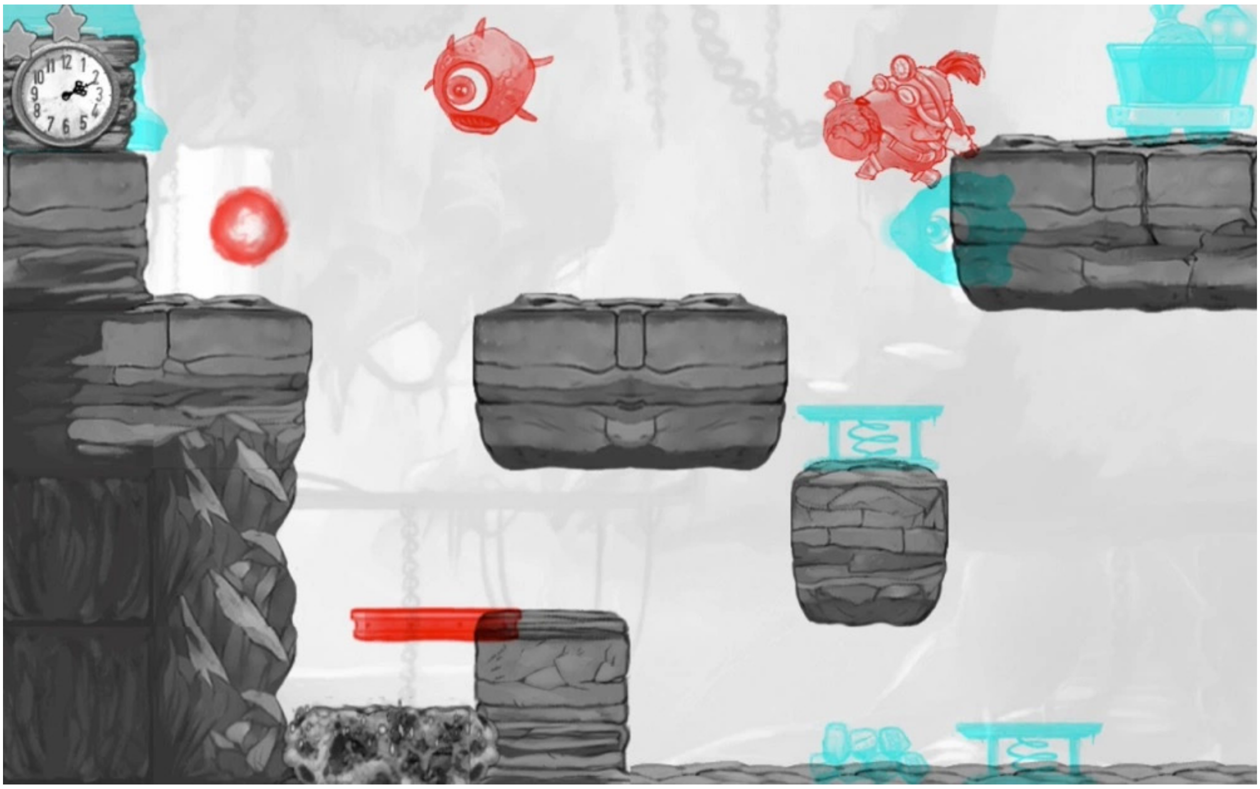


Figure 3: gameplay of Dig Rush, a dichoptic game using 3D coloured glasses

Chapter 3

Virtual Reality

3. Virtual Reality

Virtual Reality (VR) is a technology that will be used by Vedea as the medium for their dichoptic training. The first section will explain what VR is and how it works. Secondly will be explained how users can interact with VR (3.2) and how the user experience is constituted (3.3). It will then be explained how a VR headset works (3.4), and which components it contains (3.5). Lastly, this chapter will explain important aspects of the VR device in detail, being the field of view (3.6), tracking (3.7) and the display (3.8).

Figure 4: kid using a VR device

3.1. Introduction to VR

Virtual Reality (VR) is a technology that allows users to experience and interact with a virtual environment. Through VR, users experience a simulated world which can be similar to or different from the real world. When using VR, users are partly cut off from the real world, in order to experience the virtual world as if they were inside of the virtual world. VR can be used for several purposes, such as entertainment, education, medical treatment or in business settings. Usually when using VR, multiple of the user's senses are being stimulated. These are usually seeing and hearing, as they are the easiest and most valuable senses to simulate. In some cases the sense of touch is simulated through the use of haptic feedback systems such as haptic gloves or treadmills. There are instances where smell and taste are stimulated in VR, although most VR systems do not make use of this.

While other technologies such as non-VR video games and movies also contain simulated realities, they are not considered VR. The reason for this is that video games and movies do not replace the user's presence in the real world with a presence inside a virtual world. Instead, the technologies take up a place within the real world through artifacts such as display screens and loudspeakers.

VR is part of a family called extended reality (XR). **[27]** XR is a family of technologies whose function is to replace or add to the user's reality. Another subgroup of the XR family is augmented reality (AR), which is a technology that adds certain experiences to reality, without replacing it with a completely virtual reality. An example of AR is the game "Pokemón Go" **[28]**, where images of digital characters are displayed on the user's phone screen, as if they were present in the real world. A third subgroup of XR is mixed reality (MR), which is a combination of both VR and AR.
The way in which VR manifests itself does not always have to be the same. In most cases, the user uses a head-mounted display (HMD), also known as VR Goggles or a VR device. A head-mounted display is a sort of helmet containing a display screen. The content of the virtual world is displayed to the user through the display screen of the HMD. There can however also be VR systems that do not make use of HMDs, but instead use one or more large display screens in order to display the virtual world. Additionally, VR systems sometimes use sound or touch in order to stimulate the user beyond the optical part, although this is not a requirement for VR. The use of touch can for example be implemented in different ways, such as through haptic gloves or treadmills.

3.2. Interaction

In many VR systems, users can interact with the virtual world in a certain way. One of the most common means of interaction is one where the user can look around in the virtual world as if he was really there. This is done by means of a gyroscope, which is a device that tracks rotation. The use of a gyroscope allows the user to look around in the virtual world by means of rolling, pitching and yawing. A VR system that allows these three elements is called a 3 DoF (degrees of freedom) system. In some VR systems, the user can not only interact with the virtual world by rotating, but also by means of moving in a certain direction, which involves the use of a position tracker. Using a position tracker allows the user to move in certain directions, by means of strafing, elevating and surging. A VR system that allows both rotation and movement is called a 6 DoF system.

Figure 5: the six degrees of freedom in a VR application

There are other ways in which users can interact with a VR system. Some VR systems make use of controllers. In this case users can for example use a joystick to move around, and press buttons to perform certain actions. Other VR systems make use of a haptic feedback glove: a glove that tracks the movement of your hand and fingers, allows you to interact with the VR world by e.g. picking up objects, and provides the user with physical resistance when touching a virtual object. Some VR systems use a treadmill, which allows the user to walk around in the virtual world by actually walking in different directions. Interaction systems such as the treadmill and the haptic feedback glove give users a sensation that is very similar to the real world, while other interaction systems such as a controller offer simpler and less sophisticated ways to interact with the virtual world.

Figure 6-8: a haptic glove (left) a VR treadmill (middle) and a remote control (right)

3.3. User experience

While VR can be used for many different purposes, the goal of VR generally is to provide the user with an immersive experience. According to M. Slater, a good VR experience should be immersive, engaging and make the user feel present in the virtual world. **[29]** The combination of these variables is what is called user experience (UX). This chapter will explain in more detail the variables that contribute to a good user experience.

3.3.1. Immersiveness

Immersiveness is a term that is often misused to describe either presence or UX. What immersiveness actually describes is how well a VR system mimics the sensory experiences of the real world. Immersiveness relates to the form of the VR experience instead of the content. When watching a movie in a cinema with an IMAX screen and surround-sound, the immersiveness is much higher than when watching the same movie on your smartphone screen in the train. This has nothing to do with the content of the movie itself, nor is it a subjective experience of the user. Immersiveness is an objective property which can be measured. The immersiveness can e.g. be increased by having a higher field of view (FOV), a higher image resolution, or by having more possibilities for interaction with the VR device.

3.3.2. Fidelity

Where immersiveness refers to the form of the VR experience, fidelity refers to the content. Fidelity explains the level of detail of the content of the VR experience. This has nothing to do with the hardware product, but relates entirely to the software content, such as the movies or games that make up the VR experience. Similar to immersiveness, fidelity is an objective and measurable property which describes the simulated environment. In a book, fidelity could describe the level of detail in which the world and characters are described. For a movie, fidelity could e.g. refer to how lifelike the animations look. If you compare The Lion King (1994) to The Lion King (2019), you see that the 2019 version clearly has a higher fidelity. Having a higher fidelity however does not mean that the movie is better or more engaging than movies with lower fidelity. The level of fidelity is a choice of the developers, and the goal is not always to maximize fidelity.

Figure 9: comparison between the Lion King 2019 (left) and the Lion King 1994 (right)

3.3.3. Presence

Presence refers to the degree to which users feel present within the virtual environment. Similar to immersiveness, presence describes the form of the VR experience, and not the content itself. Contrary to immersiveness and fidelity, presence is a subjective experience of the user and not an objective property of the VR experience. Theoretically, having a higher immersiveness and fidelity increases the user's presence in the virtual environment. However, this is not always the case, as having higher immersiveness and fidelity will also increase the user's expectations of the VR experience. When these expectations are not met, the user's presence will be disrupted.

3.3.4. Engagement

Engagement, also known as interest or involvement, explains the user's cognitive reaction to the content of the VR experience. **[29]** When a user is very engaged with the content, he enters a state of extreme focus which is called the flow-state. When a user is not engaged, he will become bored and focus on things outside of the VR experience. Note that the level of engagement is not necessarily related to the immersiveness or fidelity. Someone can watch a badly animated movie on his smartphone screen in the train, and still be very engaged with the movie. Similarly, a movie with lower fidelity and immersiveness can be more engaging to a user than another movie with higher fidelity and immersiveness. However, in general having a higher immersiveness, fidelity and presence will increase the user's engagement. Engagement is a psychological and subjective process, relating to the content of the VR experience. It is therefore not an objective property of the VR experience.

3.3.5. Expectations

Being subjected to a certain VR experience will cause the user to develop certain expectations from this experience. If these expectations are not met, it will disrupt the user's presence and engagement with the content. Expectations can be seen as a barrier that connects immersiveness and fidelity (objective properties of the VR experience) to presence and engagement (psychological processes happening to the user). As mentioned before, having a higher fidelity and immersiveness will increase the expectations of the user. However, when these expectations are not met, this will have a negative effect on the user's presence and engagement.

3.3.6. Relation to each other

The relationship between immersiveness, fidelity, presence, engagement and expectations is complicated. While all of these factors influence each other, they are also in some ways independent of each other. A movie can have a low fidelity but still be very engaging. Or another movie can be very engaging, although the person watching it may not feel a strong sense of presence. Immersiveness and fidelity relate to objective characteristics of the virtual environment, while presence and engagement refer to the user's individual psychological state. At the same time, presence and immersiveness refer to the form of the VR experience, while engagement and fidelity refer to the content of the experience.

In order to design a great user experience, the goal should not always be to maximize all five parameters. Instead, it should be determined which factors are important for this particular project, and adjust the parameters accordingly. **[29]** In the case of Vedea's VR experience, the fidelity and immersiveness do not need to be high, and neither does the presence. The most important part of the Vedea method is that the engagement is high. This is however difficult to objectively measure, as engagement is a subjective reaction to other variables. The VR content should be engaging enough that users want to use the product on a daily basis for 30-60 minutes per day. If users are more engaged with the treatment, this means that the treatment will be more effective.

3.4. VR device

VR headsets, also known as VR goggles or head-mounted displays (HMDs), are devices that allow people to enter a virtual world. A VR headset blocks the view of the real world, allowing users to become more immersed in the virtual world. In the virtual world, several contents can be displayed. This can consist of images, video, sound, interactive games or a combination of these aspects.

VR devices are the easiest and most common way to use VR technology. This is because it is relatively cheap and simple when compared to other methods, such as using large display screens all around the user. There are many different types of VR devices, which can vary greatly on price and quality. Take a look at the Google Cardboard **[30]** for example, which is a device that costs only 10 euros. The product is entirely made of cardboard, except for the lenses and head strap. The Google Cardboard makes use of the user’s smartphone, which will act as the display screen, embedded system and speakers of the VR device. On the other hand there are products like the HTC Vive **[31]**, with a custom screen, embedded system, controllers and high quality parts. Needless to say, the HTC Vive offers a much higher quality, but also at a much higher price (800 euros for the Vive Cosmos). Then there are the professional VR products, such as the Varjo-VR3 **[32]**, which offers a superior image resolution when compared to other VR products, but at a cost of more than 8.000 euros. Later on in this chapter there will be more information about the different specifications of a VR device, and how different VR devices compare to one another. However, first an explanation will be given about how a VR device works.

Figure 10: Google Cardboard (left) and figure 11: HTC Vive Cosmos (right)

3.5. How VR headsets work

The way in which a VR headset works is by splitting the visual input into two distinct parts. The left eye will look at a slightly different image than the right eye, due to the slightly different camera perspective in which the content is displayed. This small difference in perspective will create a false sense of depth in the VR world, simulating how our eyes would function in the real world. **[33]** As mentioned before, the VR device will split the image into two parts, while dividing the two halves with a small insert so that the left eye cannot see the right half of the display and vice versa.

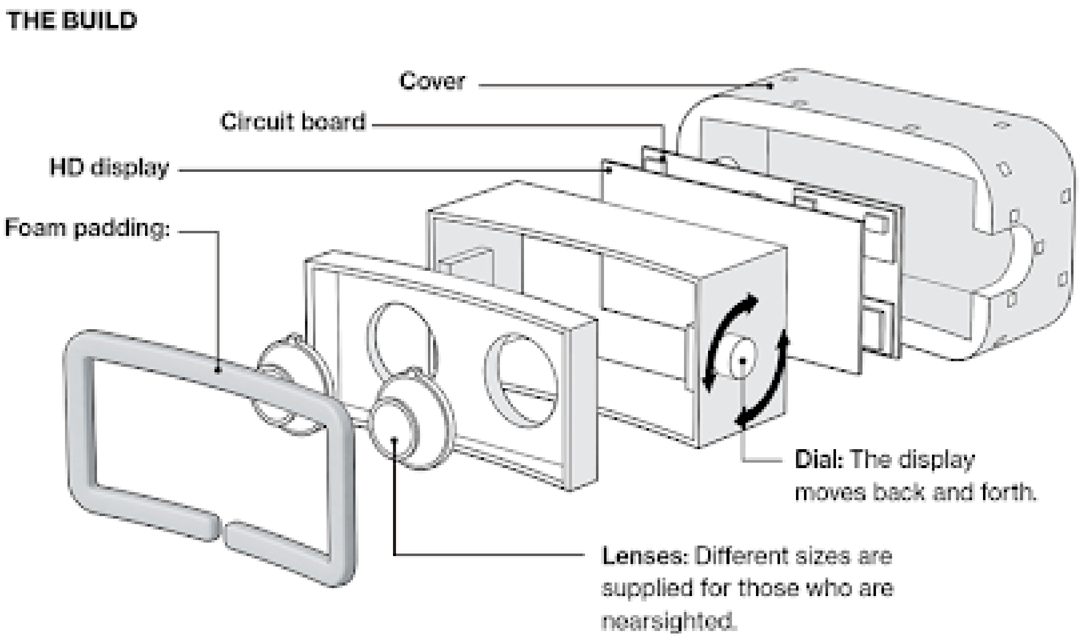


Figure 12: content of a VR HMD

Another important aspect of the VR device is the lens. Because the screen of the VR device is situated very close to the user's eyes, this will put a strain on the user's eyes and make it impossible for the user to focus on the image. **[34] [35]** In order to reduce the strain on the eyes and allow the user to see the image clearly, a pair of additional convex lenses should be added to the VR device. This will allow the ciliary muscles in the eyeballs to relax, while providing a sharp and magnified image to the user. In order to provide a sharp image, the placement of the lenses is crucial. More explanation about the lenses will be provided in the next chapters.

3.6. Field of View

An important term in VR is the field of view (FOV). FOV is important because it explains the degree to which people are able to see the virtual world through the VR device. A higher FOV will better approach the FOV of the real world, which will lead to a more immersive VR experience.

FOV explains the part of our view which is occupied by a certain object, in the case of VR this object is the display screen which displays the virtual world. In the real world, humans have a visual field of 200 to 220 degrees horizontally and 130 to 135 degrees vertically. **[36]** With regards to the horizontal visual field, the centermost 120 degrees make up our binocular view, which means that this is the part of the view which can be seen with both eyes. The parts of the view on the sides of the binocular view are called the temporal crescent, which can only be seen with one of the eyes. This is also called the monocular view.

Whenever we look at a certain object, this object takes up a certain part of our view. An object will have a large FOV when its size is large with respect to the distance between the observer and the object. The FOV of an object can be calculated with the following formula:

$$FOV = 2 \tan^{-1}(0.5 * width / eye\text{-}to\text{-}screen\ distance)$$

For example, when we look at a TV screen with a display size of 80 cm from a 2 meter distance, the diagonal FOV of the TV screen will be 22.6 degrees.

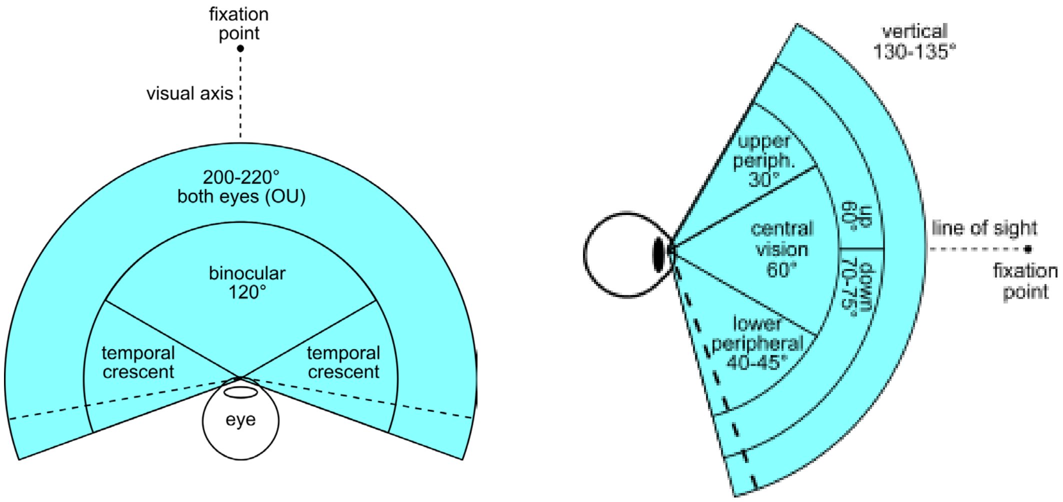


Figure 13: the horizontal (left) and vertical (right) human visual field.

In VR it is especially important to achieve a large FOV. When you are watching TV, you are looking at an object situated in the real world. In VR however, a virtual world is being simulated, which replaces your view of the real world. In order to create a realistic VR experience, the FOV of the virtual world must approach the visual field of the real world. In order to achieve this, the FOV should be significantly larger than that of a TV or smartphone for example. As it is not convenient to design a very large display (regarding weight and resources), the best option to achieve a high FOV is to place the display close to the user’s eyes. This also has its drawbacks however, as humans have trouble focusing on nearby objects. **[35]** This problem can however be solved by using optical tools called convex lenses. More information about convex lenses will be given in chapter 4.4.

3.7. Tracking

In order to make it possible for the user to look around and move in the virtual environment, VR devices make use of tracking. **[33]** There are two types of tracking, the first being head tracking (enabling the user to look around, by pitching, yawing and rolling) and the second being positional tracking (allowing the user to move, by strafing, surging and elevating). A distinction can be made between 3 DoF (degrees of freedom) and 6 DoF systems. The first one is the most simple variant, where the device only makes use of head tracking. This can be done by using a gyroscope. The latter makes use of both head tracking and positional tracking. This is a more advanced version of tracking which allows the user more opportunity to move in the virtual environment.

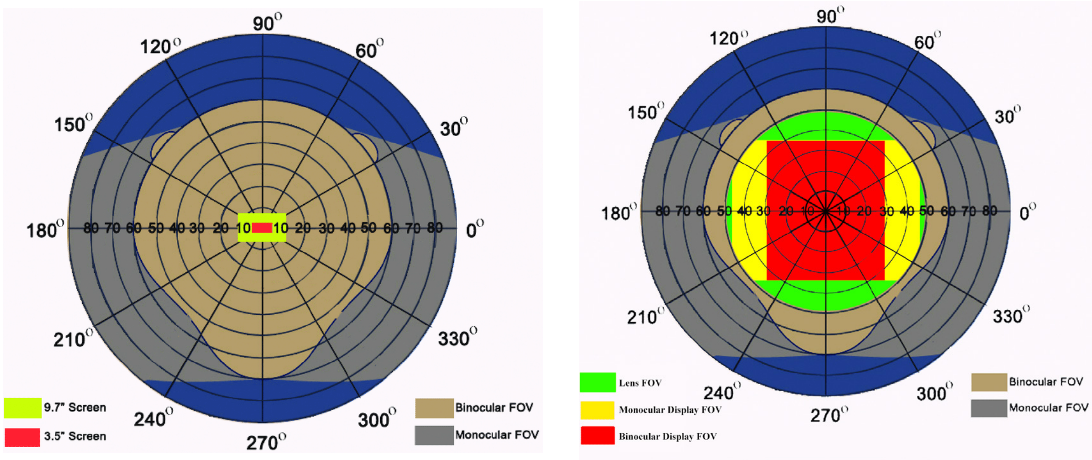


Figure 14: FOV of a tablet and phone (left) and FOV of a VR device (right), compared to the human visual field

There are two distinct ways to deliver positional tracking. This can happen either by inside-out tracking or outside-in tracking. Inside-out tracking is when a sensor inside the VR device tracks its surroundings in order to determine the user's relative position in the room. This can be done by having a camera scan certain markers in the room, or by simply scanning the features of the environment. Inside-out tracking does not necessarily have to be done using a camera. It can also be done using IR (infrared) sensors, or any other type of optical sensor.

Outside-in tracking is characterized by having sensors placed in the environment instead of in the VR device. In outside-in tracking, the position of the user is tracked by tracing the position of the VR device with regards to the sensors. It is common that the VR device contains markers on or in the device, which help the sensors to detect the device more easily. While all optical sensors can be used for outside-in tracking, the most common type are IR sensors.

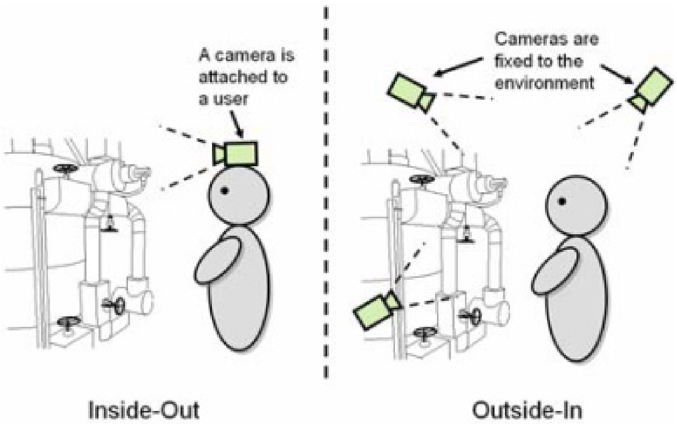


Figure 15: an example of inside-out and outside-in tracking

3.8. Display

The display is a vital part of any VR device, because it displays the content which forms the virtual environment for the user. This section will explain how displays can differ in different VR devices. Moreover, this section will explain the concepts of screen size, resolution and refresh rate, and how these variables affect the VR experience.

The display is the part of the VR device that displays the VR content to the user through the lenses. VR devices on the higher end of the spectrum usually contain custom made displays, while lower end devices usually rely on the user's smartphone as visual input. There are three important properties of the display: screen size, resolution and refresh rate. A high screen size, resolution and refresh rate are desirable qualities for a VR device, but they will also increase the price.

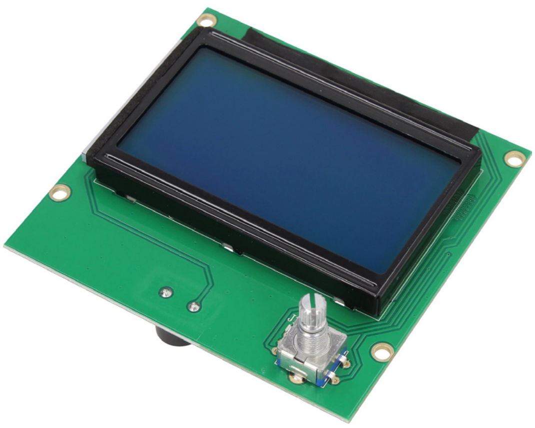


Figure 16: example of an LCD display screen (left) and figure 17: a display screen of an iPad (right)

3.8.1. Screen size

The screen size influences the FOV of the VR device. The larger the screen size, the higher the FOV can be. The FOV can however be limited by the size of the lens or the size of the looking hole. VR devices with a custom display usually have a higher FOV than devices that rely on the user's smartphone. The reason for this is that the latter devices need to have a small looking hole in order to be compatible with smaller phones.

3.8.2. Resolution

The resolution of the display screen is important in VR, even more than in other electronic devices. The goal of VR is to simulate the real world in a virtual environment. In order to do this realistically, the resolution of the virtual environment should approach the resolution of the real world. The highest resolution that the human eye can see is approximately 60 pixels per degree (PPD). When looking at a tv, laptop or smartphone, a 60 PPD resolution can easily be achieved. This is what is called high definition (HD) quality. In VR it is however much harder to achieve a high resolution. The main reason for this is that the display is located very close to the user's eyes and is subjected to additional magnification by the lenses, which results in a heavily magnified image. When looking at a flat screen, the part right in front of the user's eye will have a lower resolution than the parts that are located more towards the edges. The parts towards the edges will however not be well visible, due to the higher distortion of the lens towards the edges of the lens. A display screen with 400 pixels per inch (ppi) resolution would result in a resolution of approximately 12.5 PPD in front of the lens center when used in VR. This corresponds to a visual acuity of 20.8%. Current displays usually have a resolution of roughly 300 to 600 ppi. The former corresponds to a foveal vision of roughly 9.4 PPD, while the latter corresponds to roughly 18.8 PPD.

3.8.3. Refresh rate

The refresh rate of the display screen determines how fast the pixels on a screen that form the image are being refreshed. The refresh rate is expressed in Hertz (Hz) which means the number of times per second that the image changes. While refresh rate is important when playing regular video games, it is especially important in VR. Because the purpose of VR is to immerse the user in a virtual environment, a low refresh rate makes the user feel as if his eyes are not working correctly. Low refresh rates can lead to 'VR sickness', a condition that may result in nausea, headaches and disorientation. **[41]** The general consensus among VR users and designers is that 90 Hz is a good starting point for VR. Anything under 90 Hz can cause the problems mentioned above. [**41]**

Nowadays, display screens come in many different refresh rates, ranging from 30 to 144 Hz. Almost all smartphones nowadays have a standard setting of 60 Hz. However, in some cases it is possible to increase this rate to 90 or 120 Hz. If possible, the refresh rate should be set at the highest setting for the optimal VR experience. The downside of a high refresh rate is that it will deplete the battery faster, and it will require more GPU power. If possible, the refresh rate should be at least 90 Hz, as having a lower refresh rate can cause problems to the user.

3.9. Nuisances to user experience

In this section several effects will be explained which can cause nuisances to the user experience. The most common nuisances related to VR technology will be listed below. In this section will be explained how VR sickness, double vision and unsharp vision can be avoided when using a VR device.

3.9.1. VR sickness

Some users of VR devices experience feelings similar to motion sickness when using VR. There are several factors that may contribute to this feeling of sickness related to the use of VR.

- Low refresh rate (Hz)

Having a refresh rate below 90 Hz can cause nausea, headaches and disorientation to the user. **[37]** Refresh rate determines how many times the image input is refreshed. A low refresh rate will be noticeable by the user, and cause the user to notice the difference between the real world and the virtual world.

- The vergence-accommodation conflict.

This conflict is caused by the illusion of depth which is caused by VR. The difference between the visual input of both of the user’s eyes makes it seem like he is looking at objects at different distances from him, while in fact the user is looking at a screen, projected infinitely far away from him. When a certain object on the screen appears to be closer or farther away than the object the user is currently viewing, the user will instinctively accommodate. While accommodation is useful in the real world, in VR it causes users to lose their focus on the screen, as their eyes are no longer focused at infinity. The vergence-accommodation conflict applies to all current VR devices, and may cause nausea or eye-strain. **[38]**

- Mismatch between image input and vestibular input

Vestibular input coordinates movements of the eye, head and body, which affects our body’s balance, muscle tone, visual-spatial perception, auditory-language perception and emotional security. When a VR user senses a mismatch between the image input and the vestibular input, this can create a sense of uneasiness, dizziness, disorientation and nausea. This can for example happen when the user rotates his head, but his perception of the virtual world does not change accordingly **[39]**.

- Mismatch between the IOD and ILD

According to Regan and Price **[9]**, users with an IOD (interocular distance) smaller than the ILD (inter-lens distance) of the VR device will experience a range of problems, such as binocular stress, increased near-point convergence, fatigue, eye-pain, blurred vision, headaches and nausea. According to Kolasinski **[40]**, a mismatch between the IOD and ILD is one of the reasons that VR sickness can occur. More information about the IOD and ILD will be given in chapter 5.

3.9.2. Double vision

Double vision is caused when the distance between the lenses (ILD) does not match the in-game distance between the camera’s (ICD). According to Regan and Price **[9]**, double vision can also occur when the user’s IOD (interocular distance) is smaller than the ILD of the lenses. For an optimal experience, the ILD and ICD should be equal to the user’s IOD for non-strabismic users. The IOD is the distance between the centers of the user’s eyes, which is a physical characteristic of each individual user. More information about the IOD, ILD and ICD is given in chapter 5.

3.9.3. Unsharp vision

The primary cause of unsharp vision in VR is when the depth positioning of the lenses is incorrect. Placing the lens too close to the display will make the virtual image appear more nearby, resulting in eye-strain and in extreme cases unsharp vision. Placing the lens too far away from the display will cause the image to form in front of the retina, resulting in an unsharp vision. In order to achieve sharp vision without eye-strain, the user needs to find his own ‘sweet spot’. This is the spot where the image forms on the user’s retina, without the user needing to flex the ciliary muscles in the eye.

Another cause of unsharp images in VR is spherical aberration of the lenses. Spherical aberration causes the light rays to bend differently when they enter the lens further away from the optical center of the lens. Due to spherical aberration, light rays passing through the edge of the lens will have a shorter focal length than light rays passing through the center. As a result, the user may be able to see sharp images through the center of the lens, but not through the edges of the lens. Spherical aberration can be limited by choosing lenses that limit spherical aberration for VR applications. This will be further discussed in chapter 4.6. Another way in which spherical aberration can be limited is by choosing lenses with fewer lens strength. This however creates other unwanted outcomes, being that the size and weight of the product will increase, resulting in an increased strain on the user’s neck.

Chapter 4

Optics

4. Optics

Before we can understand how a VR device works, we must first understand the workings of the human visual system. In the first section will be explained how the human visual system works, and how it allows us to see objects (4.1). Afterwards, it will be explained what accommodation is, how it allows us to focus on certain objects (4.2), and why it is important in VR (4.3). The following sections focus on lenses (4.4), why the placement of the lens is important (4.5) and which optical aberrations occur in lenses (4.6).

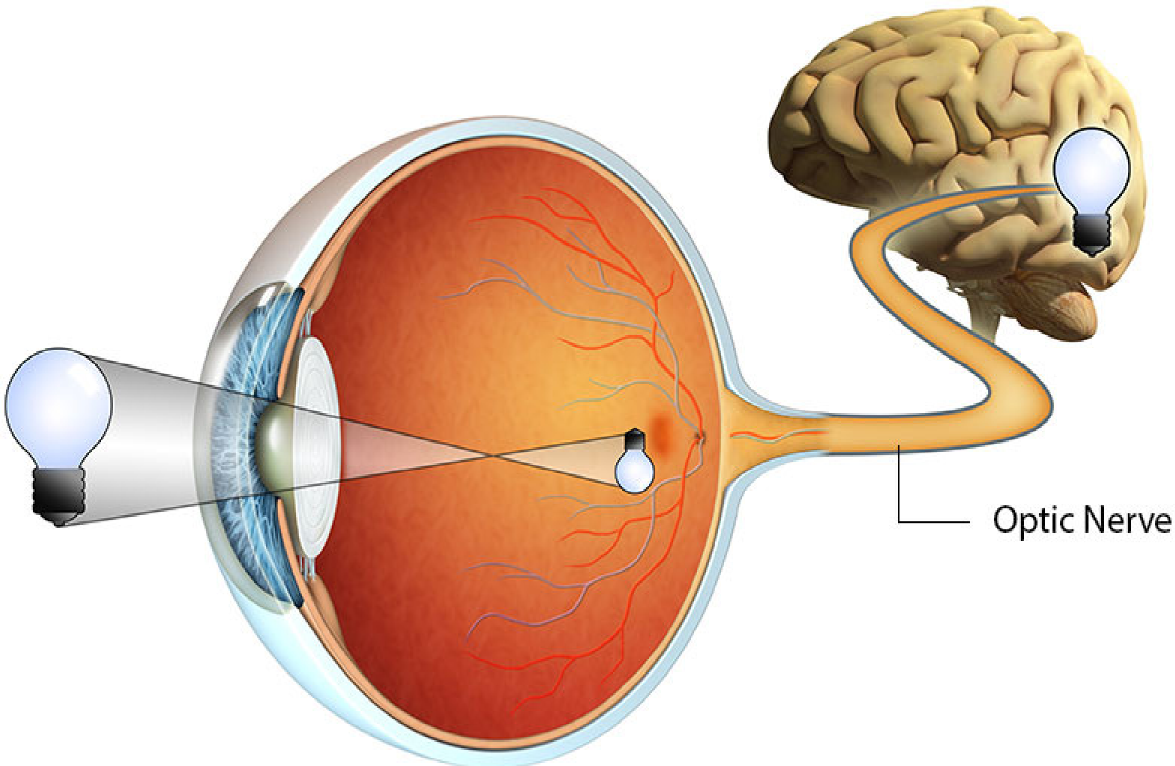


Figure 18: schematic drawing of the optic nerve

4.1. Our visual system

Our visual system consists of the eyes, along with some parts of the central nervous system. The eyes register visual information in the form of light, and this information is processed in the brain by the visual cortex. A neural pathway connects the eyes with the visual cortex, and allows the information to transport from the retina to the brain. **[41]**

Our eyes are the organs of the visual system that enable us to see visual details. The eyes can see objects when light is reflected by the object into the eye, through the cornea, pupil and eye lens onto the retina. The eye lens converges the incoming light rays, and converges them into a single point called the image point. If the image point is situated at the retina, this results in sharp vision. If the image point is located before or behind the retina, this results in blurred vision. The eye lens has the ability to become more and less convex, thereby changing the focal length of the lens. This process is called accommodation, and is necessary for us to change our focus from near to far away objects. **[41] [42]**

Accommodation happens unconsciously, therefore people are usually unaware that their lenses are constantly changing in strength. **[41]** The closer that an object is located to the eye, the more the lens has to bulge in order to place the image point on the retina. When an object is far away, the ciliary muscles in the eye stretch, increasing the focal length of the lens. When an object is nearby, the ciliary muscles in the eye compress, causing the focal length of the lens to decrease. **[41] [42]**

The retina is made up of rods and cones, which convert the light into electrical impulses which are sent to the brain. The cones allow us to see colours, and are used especially during the day. The rods are very sensitive to light, and allow us to see light in dark environments. The space on the retina which is placed directly behind the pupil and lens is called the yellow spot. This spot contains the highest concentration of cones, and is therefore able to see the highest quality of vision. This type of vision is called foveal vision or central vision, and makes up 1.5-2 degrees of our total vision. **[36]** The vision which is located outside of the fovea is called peripheral vision. This type of vision is significantly less sharp than the foveal vision, due to the low concentration of rods and cones outside of the yellow spot. Although the resolution of the peripheral vision is very low, this type of vision is still useful for seeing fast movements or general shapes and colours, which draw the attention of the fovea.

4.2. Focus

Focusing on a certain object requires more than simply seeing the light rays coming from that object. The only way to see a clear image is to bring the image into focus. This is done by converging the light rays coming from a point on an object into a single point, and placing this point on the retina. This point is called a focus point, or image point. Every object is made up of a multitude of points, and in order to focus on the object all these points should be converted to image points and placed on the retina. Light rays naturally diverge when coming from an object, and they converge after leaving the lens of the eye. The distance between the eye and the object determines the distance between the eye lens and the image point. When an object is far away from the eye, the resulting image point will be close to the eye lens. When an object is nearby, the resulting image point will be further away from the eye lens. As mentioned earlier, we can only focus on an object when the image points associated with that object are placed exactly on the retina. If the image points are placed in front of or behind the retina, the resulting image will be vague. **[41]** In the figure below it can be seen that for a certain lens strength, only objects at a specific distance can be put into focus.

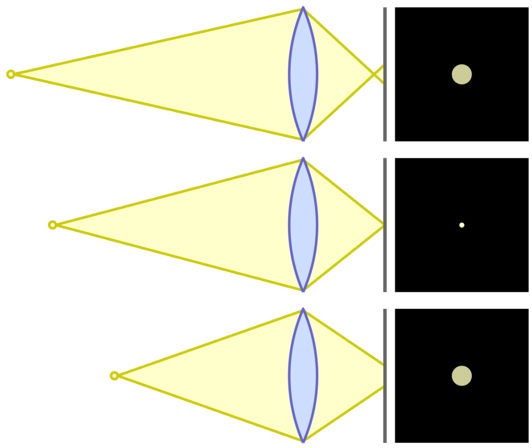


Figure 19: the focus of light rays with different object distances.

Luckily, our eyes are able to change the strength of the eye lens, which allows us to focus on objects at different distances. In a relaxed state, our eye lenses are very strong, containing a lens strength of 60 diopters. This strength is needed to converge horizontal light rays into an image point in only several centimeters. When the ciliary muscles contract, the eye lens can gain an additional strength of up to 16 diopters in a process called accommodation **[35]**.

Accommodation happens unconsciously, and allows us to focus on more nearby objects as well as far away objects **[35] [41]**. Focusing on faraway objects is the least difficult for our eyes, as our eyes can focus on objects infinitely far away when our ciliary muscles are in a relaxed state. Focusing on nearby objects requires more effort of the ciliary muscles. There is also a limit on which distances can still be focused on. This limit is called the near point. For a young child, this near point is situated between 5 and 10 cm away from the eyes. The distance to the near point however increases over time, because we lose the accommodative power of the eyes. **[41]** If a person has a near point 20 cm away from his eye, he will not be able to clearly see objects that are more nearby than 20 cm. It is possible to see an object at 20 cm or further away from the eye. It should be noted that looking at nearby objects requires more effort from the ciliary muscles than looking at faraway objects. **[35]**

4.3. Implications of accommodation in VR

The process of accommodation needs to be taken into account in order to design a pleasant VR experience. In the previous section it was established that it is most pleasant for the eyes to look at faraway objects instead of nearby ones. **[35]** In order to have this optimal experience, the image which is displayed to the user should be displayed infinitely far away. The problem however is that in VR devices the display is located very close to the user's eyes, which makes it impossible for the user to focus on the image, and can even cause several negative effects such as eye-pain and headache **[43]**. Luckily, there are optical tools which can be used to display the image further away than the object actually is. These tools are called convex or converging lenses, and they will be explained in the next section.

4.4. Lenses

This section will explain what lenses are, and how they can be used to create a better VR experience. Secondly, it will be explained why the placement of the lenses is important. Lastly, it will be explained what optical aberration is, how it affects the image, and how aberrations can be minimized.

In chapter 3 it was explained that a high FOV is necessary in order to have a better VR experience. The best way to achieve this is by placing the display screen very close to the eyes. In this chapter it was explained that people, even young children, have trouble focusing on nearby objects. **[35] [41]** Luckily, there are optical instruments that can help us to focus on nearby objects, called converging (convex) lenses. Convex lenses are lenses made of a transparent material (such as glass or certain plastics), which have a curved surface and a thick center. Lenses that are convex on one side and flat on the other are called plano-convex lenses. Lenses that are convex on both sides are called biconvex lenses. For VR purposes, it is better to use plano-convex lenses, best-form lenses or aspheric lenses (more about this will be explained in chapter 9.2.3). If the convex side of the plano-convex lens is facing the display screen, it will result in minimal aberrations. If the convex side is facing the user however, it will result in more aberrations than when using a biconvex lens. **[44]**

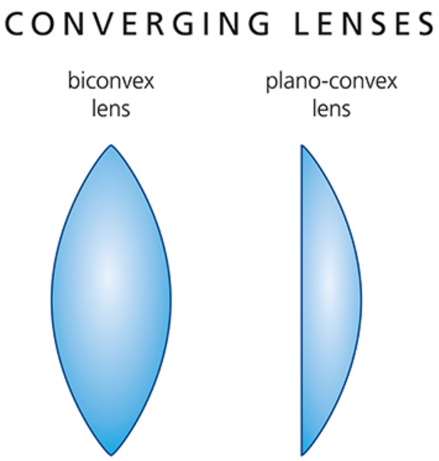


Figure 20: equi-biconvex (left) and plano-convex (right) lens

Convex lenses are optical instruments, which are used to make objects appear farther away. **[42]** Convex lenses are also used in glasses for people with hyperopia (farsightedness). People with farsightedness have trouble focusing on nearby objects due to an irregularity in their eyeball or eye lens. **[41]** The convex lenses in their glasses make all objects in the real world appear further away. The same principle applies in a VR device: the lenses allow the user to look at a display only several centimeters away, and it appears as if the display is much larger and much farther away. This allows the user to focus on the screen without exhausting the ciliary muscles in their eyes. The lenses also have an additional function of magnifying the display, which helps to further increase the FOV of the display.

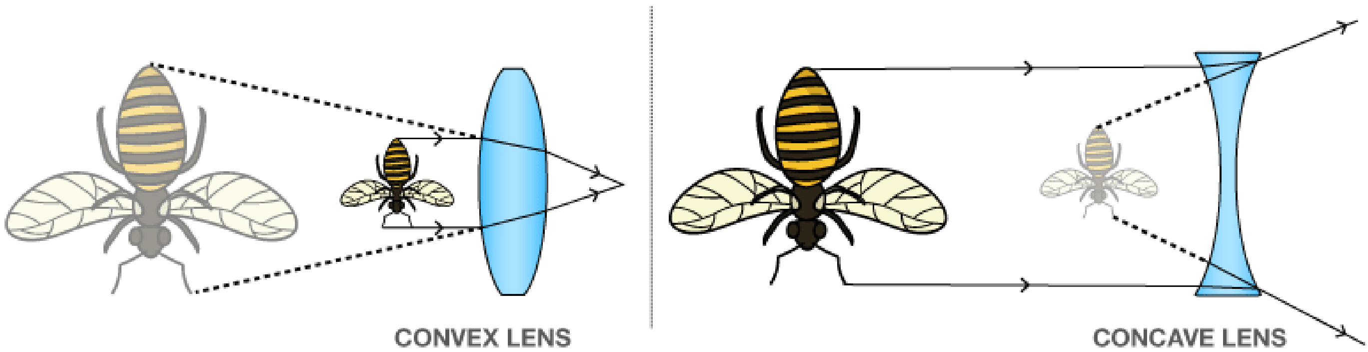


Figure 21: schematic drawing of a convex and concave lens

4.5. Lens placement

In order to provide a sharp image in a VR application, the placement of the lenses is crucial. In a VR application, a convex lens is used in order to magnify the image, similar to the use of a magnifying glass. When using a magnifier, the user is looking at a virtual image of an object. This virtual image should be farther away from the eye, and appear magnified. **[42]** The distance to the virtual image, also known as the image distance (d_i), depends on the strength of the lens and the object distance (the distance between the lens and the object the user is looking at, also known as d_o). In the ideal situation, the virtual image is placed infinitely far away from the eye. This can be done by placing the object (in this case the display screen) exactly at the focal point of the lens. The focal point is a point located at the focal length (f) of the lens. **[42]** The focal length of the lens is a physical property of the lens, depending on the curvature of the lens surfaces. The focal length is inversely proportional to the lens strength. When the object (or in this case the display) is placed at the focal point, the image of the screen will be placed at infinity, which allows the user to look at the image without flexing the ciliary muscles of the eye. This is the ideal viewing position for people without refractive errors. **[41]**

When the object distance is smaller than the focal length, the image distance will be larger than the object distance but smaller than infinity. Depending on the focal length and object distance, the image distance can be far away or nearby. If the object distance is much smaller than the focal length, the image distance will be relatively small. As a result, the user may still be unable to see the virtual image sharply, even though the virtual image is further away from the eye. Alternatively, the user may be able to see the image sharply, although this will require significant effort from the ciliary muscles. If the object distance approaches the focal length, the image distance will be relatively high, which allows the user to see the image sharply and with minimal effort of the ciliary muscles.

The third situation is that the object distance is larger than the focal length. This is the worst situation, as it guarantees an unsharp image for the user. The reason for this is that the lens converges the light rays so much that the real image is not displayed on the retina but in front of it. The eye lens has a minimum strength of around 60 diopters, and can therefore not further relieve the lens strength to place the real image on the retina. The larger the object distance is when compared to the focal length, the more unsharp the image will be.

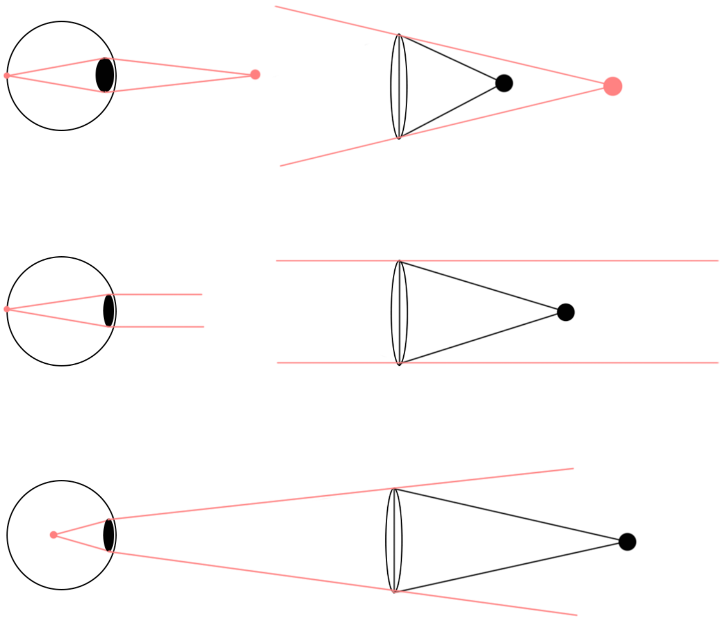


Figure 22: the optics of a magnifier when d_o < f (top), d_o = f (middle), and d_o > f (bottom)

For most users, the ideal viewing position would be when the display is placed exactly at the focal length of the lens. However, in some cases certain users may benefit from placing the display slightly in front of or behind the focal length. This happens for example when users suffer from myopia or hyperopia respectively. **[42]** The most important takeaway for this project is that the focal length of the lens should match the object distance (the distance between the lens and display).

4.6. Aberrations

Although lenses and other optical instruments can help us to see better, they also decrease the optical quality of the image in the process. Even simple instruments such as glass windows do not offer complete optical quality, as a part of the light is reflected on the surfaces of the material. This is why lenses used in VR headsets often contain an anti-reflection (AR) coating.

Because lenses are complex optical instruments, they introduce several problems which lower the optical performance of the lens. These imperfections in the image are called aberrations. The most important aberrations regarding VR devices are spherical aberration, chromatic aberration and distortion. Note that there are more optical aberrations than the ones described above (such as tilt, coma and astigmatism), but these do not apply in this particular system.

4.6.1. Spherical aberration

Spherical aberration is arguably the most important aberration when it comes to VR devices. Spherical aberration is an aberration that occurs in spherical lenses, because spherical lenses do not have the necessary surface curvature to create a perfect lens. Regular spherical lenses are made in a way which is easy to produce, but this does not lead to a perfect lens. Due to the spherical shape of the lens surfaces, the light rays that enter the lens on the edges are refracted more strongly than the light rays entering the lens towards the center. **[42]** As a result, the focal point of the light rays at the edge of the lens will be shorter than the focal point of the light rays at the center of the lens. This means that when the user of a VR device can see clearly through the center of the lens, the image at the edges of the lens will be unfocused and vice versa. The most notable effect of spherical aberration is an unfocused image towards the edges of the lens.

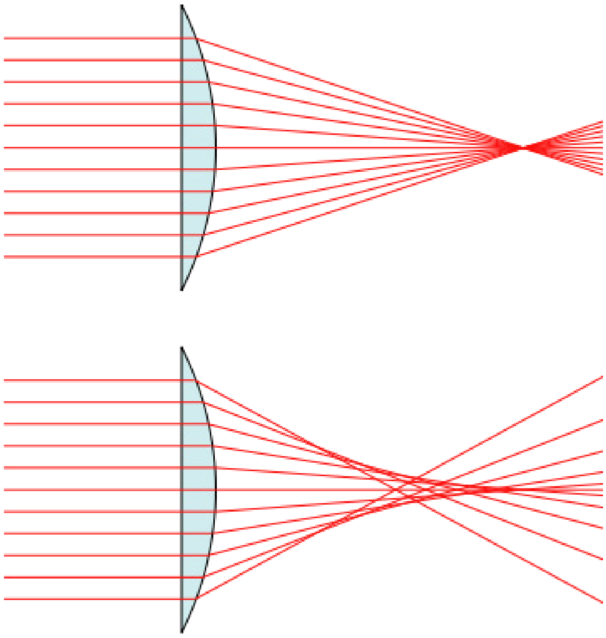


Figure 23: an ideal lens (top) and an actual spherical lens (bottom)

There are several ways to decrease the spherical aberration of a lens. The best way is to use an aspheric lens. Aspheric lenses are lenses that are designed and produced in a certain way, where the surfaces are not spherical but rather have a complex shape. The shape of the lens is designed in such a way that the focal point of all light rays will be the same, therefore effectively diminishing the spherical aberration at a certain image distance. The shape of an aspherical lens can be determined by taking a Cartesian oval (as determined by Descartes), and revolving this shape along the optical axis. The resulting shape is however quite complex, and difficult to manufacture. As a result, aspherical lenses are more expensive than spherical lenses. Ano ther way to decrease the spherical aberration is by choosing a suitable spherical lens. For VR purposes, best-form and plano-convex lenses are the most suitable, as these types of lenses are optimal for the collimation of a point source (which is the function that the lenses fulfill in the case of a VR headset). More information about different lens types will be given in chapter 9.2.3. The final way to reduce spherical aberration is by reducing the strength of the lens. This however has other negative implications for the design of the VR device.

4.6.2. Chromatic aberration

Chromatic aberration is a type of aberration that occurs in optical devices such as lenses or prisms. The reason for chromatic aberration is that different wavelengths of light are refracted at different angles. As a result, different colours will be refracted differently when coming from the same light ray. **[42]** A single ray of light will therefore be dispersed into a larger ray, where the individual colours are split up. Similar to spherical aberration, chromatic aberration occurs more profoundly in stronger lenses. Chromatic aberration however is easier to solve, through the use of an achromatic doublet. An achromatic doublet combines a convex and a concave lens, each with different indices of refraction and different degrees of colour dispersion. When combined, the amount of chromatic aberration can be set to zero. As an added benefit, achromatic doublets also reduce the amount of spherical aberration in any given lens.

Even though chromatic aberration can be solved relatively easily, oftentimes this is not done in VR devices. The reason for this is that achromatic doublets are heavier and more expensive than regular convex lenses. Furthermore, while the effect of chromatic aberration exists in VR devices, the effect is not that profound and does not interfere with the user experience that much. For this reason, it should be determined by the product designers if an achromatic doublet is worthwhile or not for any given project.

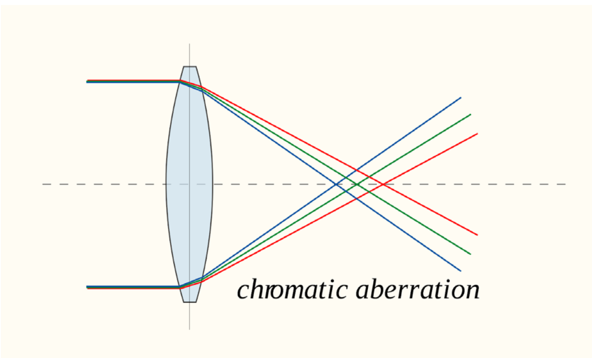


Figure 24: the effect of chromatic aberration in a convex lens

4.6.3. Distortion

Distortion is a form of optical aberration which appears in lenses, in which the straight lines of an image become curved. Distortion arises due to the fact that the same lens produces different magnification for different axial distances. **[42]** Similar to spherical and chromatic aberration, the distortion effect will be most profound at the edges of a lens, and the least profound at the center of the lens. The most common types of distortion are barrel distortion, pincushion distortion and handlebar distortion.

The type of distortion that occurs in an optical system depends on the placement of the aperture stop. The aperture is the smallest hole through which the light rays can pass through. In the case of VR, the aperture stop is the pupil of the eye. If the aperture stop is located before the lens, it will result in pincushion distortion. If the aperture stop is located behind the lens, it will result in barrel distortion. **[42]** In some systems a combination of barrel and pincushion distortion can occur due to having multiple lenses. The most common type of alternate distortion is handlebar distortion. Handlebar distortion occurs when there is barrel distortion in the middle and pincushion distortion at the edges of the lens. In the case of VR, the optical system consists of two lenses (the convex lens and eye lens) which are located behind the aperture stop (the aperture stop being the user's pupil). Therefore, the distortion in this system is pincushion distortion.

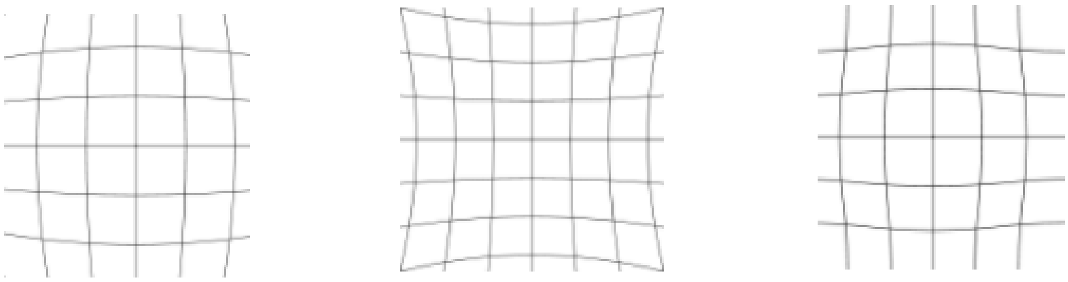


Figure 25: barrel distortion (left), pincushion distortion (middle) and handlebar distortion (right)

Distortion is a geometric aberration. This means that contrary to other types of aberration, no optical information is lost due to distortion. The only thing that happens due to distortion is that certain parts of the image are more magnified than other parts. This effect can be corrected in the software by applying the inverse distortion as what is created by the lens, so that the total distortion of the image becomes zero. Although the distortion can be completely eliminated in theory, in practice this is usually not the case due to the complex nature of the lens. Another way to decrease distortion is by choosing a lens with a high focal length, as weaker lenses will produce fewer aberrations. The best lens for decreasing aberrations in VR is an aspheric lens, although these lenses are very difficult to design and produce. Other lens types with low aberrations when used in VR are best-form lenses and plano-convex lenses.

Chapter 5

Interocular Distance

5. Interocular Distance

In this section will be explained what interocular distance (IOD), inter-lens distance (ILD) and inter-camera distance (ICD) are, and why these terms are often wrongly mistaken for interpupillary distance (IPD). It will be explained what the relationship between these values should be in order to create an optimal VR experience. It will also be explained which values are common for IOD, and how this affects a VR device designed for young children.

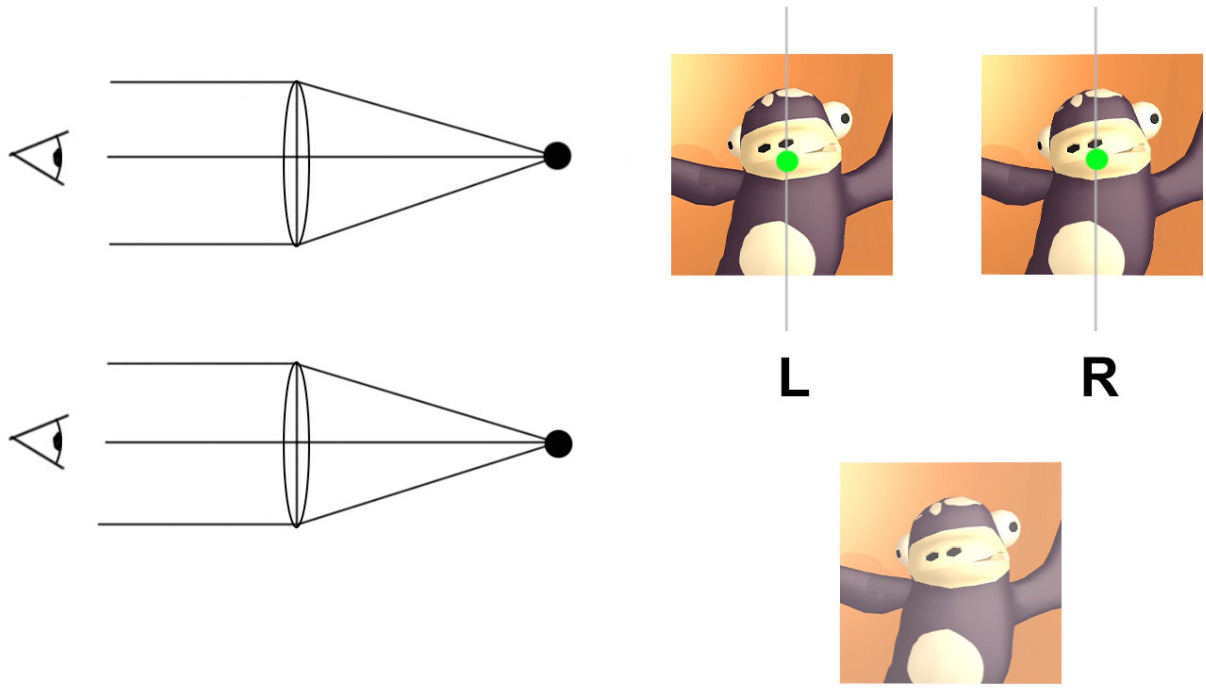


Figure 26: schematic drawing showing the relation between IOD, ILD and ICD

Another important term with regards to VR is the interocular distance (IOD), meaning the distance between the user's eyes. This term is often misnamed as the interpupillary distance (IPD), but these are not the same due to the fact that the distance between your pupils changes depending on where your eyes are focusing. The IOD is a physical property of a person, which varies for different people. **[45]**

The second term which is affiliated to IOD is the distance between the two lenses, which is called the inter-lens distance (ILD). The last term which is of importance in VR is ICD (inter-camera distance). This term refers to the distance between the two cameras in the virtual world.

When using VR, the user is in fact looking at two distinct images that largely overlap. **[33]** The reason why ILD is important is because it determines the image that the user is seeing. Because of the type and position of the lens, the light rays coming from the pixels of the display screen are being collimated. Collimated light means that the light rays coming from a light source are parallel to each other. **[42]** The only variables that affect the horizontal position of the image are the ILD and ICD. For an optimal VR experience, the ILD and ICD should have exactly the same value. If the ILD and ICD do not match, the user will experience double vision, because the images projected onto the left and right eye do not match. This is not only irritating to the user, but also counterproductive to treating amblyopia, as the goal of dichoptic training is to improve stereo vision. **[6]** One way to solve the issue is to allow the lenses to be moved in horizontal direction, which allows for an adjustable ILD. In order to avoid double vision, the ILD should be equal to the ICD.

Furthermore, the ILD (and therefore also the ICD) should be equal to the user's IOD for users without strabismus. The reason for this is that the part in the middle of the convex lens allows for the highest quality image. If the lens axis is not in line with the user's pupil, the displayed image will be slightly distorted, caused by aberration of the lens. Moreover, a mismatch between the IOD and ILD causes the images to be warped. The angular deviation of warp can be calculated using the following formula:

$$\text{Warp (degrees)} = \tan^{-1}\left((ILD - IOD) / 2 * d_o \right)$$

In this formula 'd_o' stands for the object distance, which is equal to the focal length of the lenses in most cases. To make things worse, the images seen by the left and right eye will warp in opposite directions, which makes it harder to focus on the image. Furthermore, Regan and Price **[9]** hypothesized that if the user has an IOD smaller than the ILD, the user may experience all sorts of problems, such as headache, eye-pain, blurred vision, double vision and nausea. These symptoms worsen when the difference between IOD and ILD becomes larger, as well as the image distortion.

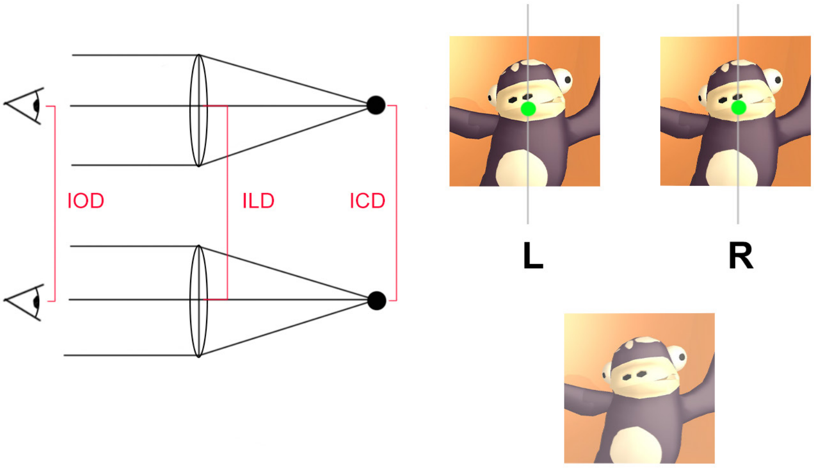


Figure 27: the image displayed when IOD = ILD = ICD.

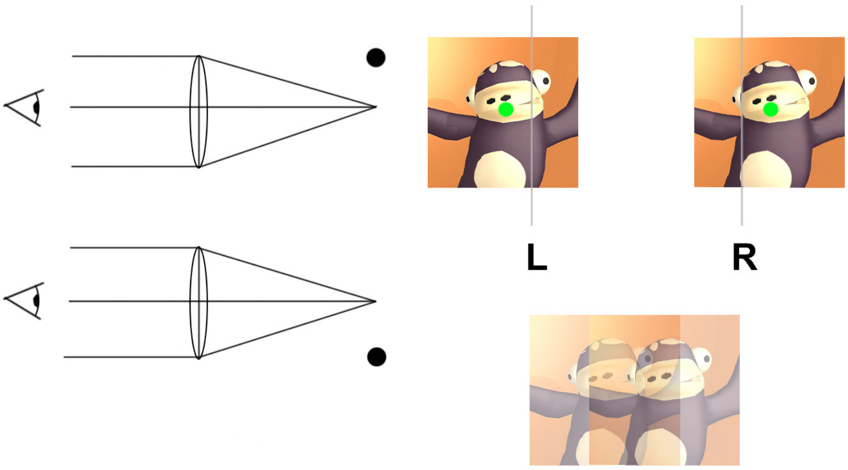


Figure 28: the image displayed when IOD = ILD with a deviating ICD

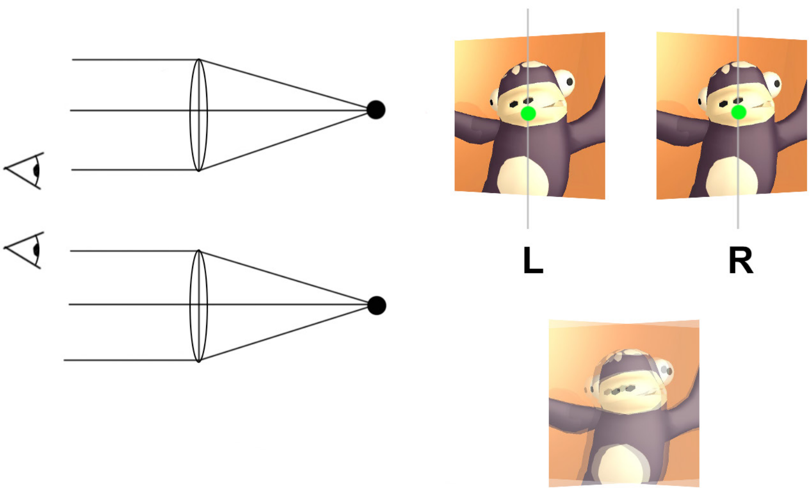
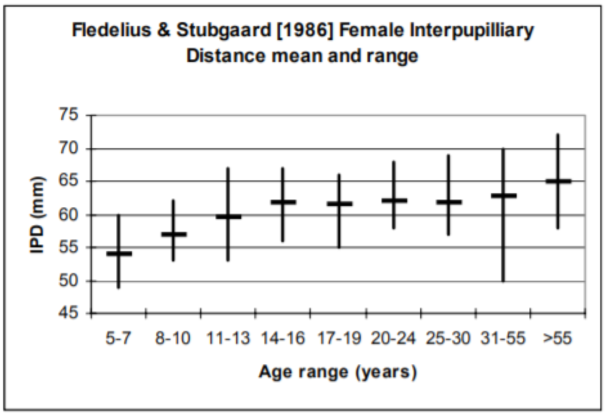


Figure 29: the image displayed when ILD = ICD with a deviating IOD

The average adult has an IOD of 63 mm (62 for women, 64 for men) **[46]**. However, children have a smaller IOD because their heads are not fully developed yet. The target group for this product consists of children aged 4-7. According to several studies, the IOD of this group usually ranges from 40 to 62 mm, with an average of 53 mm. The problem for this age group is that there are no VR devices available that take into account people with a low IOD. Even products that are specifically marketed for children are in reality not suitable for them due to their high ILD settings. During the analysis phase research was done about two VR devices marketed towards children of age 5 and older, which had a minimum IPD of 57 and 62 mm respectively. Children aged 4-7 can still use these products as long as the ILD matches the ICD, but they will experience more optical distortion due to the mismatch between the ILD and their IOD. Furthermore, there is a risk that the children will experience physical discomfort as described by Regan and Price. **[9]**



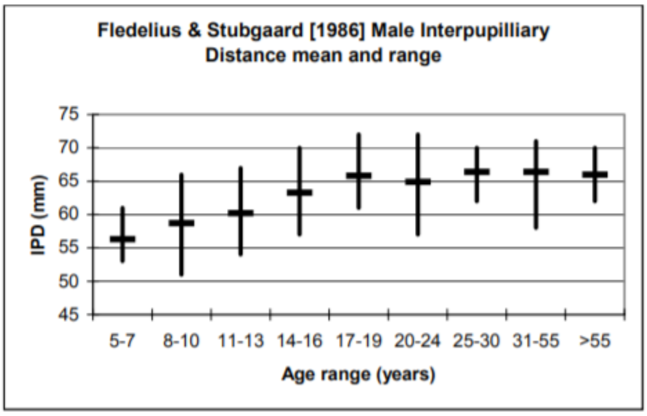


Figure 30: female (left) and male (right) IPD per age group

In order to make VR experiences possible for children aged 4-7 it is of utmost importance that the ILD of the product matches the ICD of the software. For an optimal experience, the ILD and ICD should also match the user's IOD. This can be achieved by allowing a low ILD setting on the product, and manually choosing an ICD that fits within the IOD range of the users. While the mean IOD for this age range is 53 mm **[55]**, the minimum ILD should be lower in order for the product to be inclusive for people with lower IODs.

Chapter 6

Additional Research

6. Additional Research

This chapter focuses on additional research which is of importance for the design of the VR device. First it will be explained how the weight of the product influences the user (6.1). In the second section (6.2) will be explained how the product can be optimized for strabismic users, a notable subgroup of the amblyopic children.

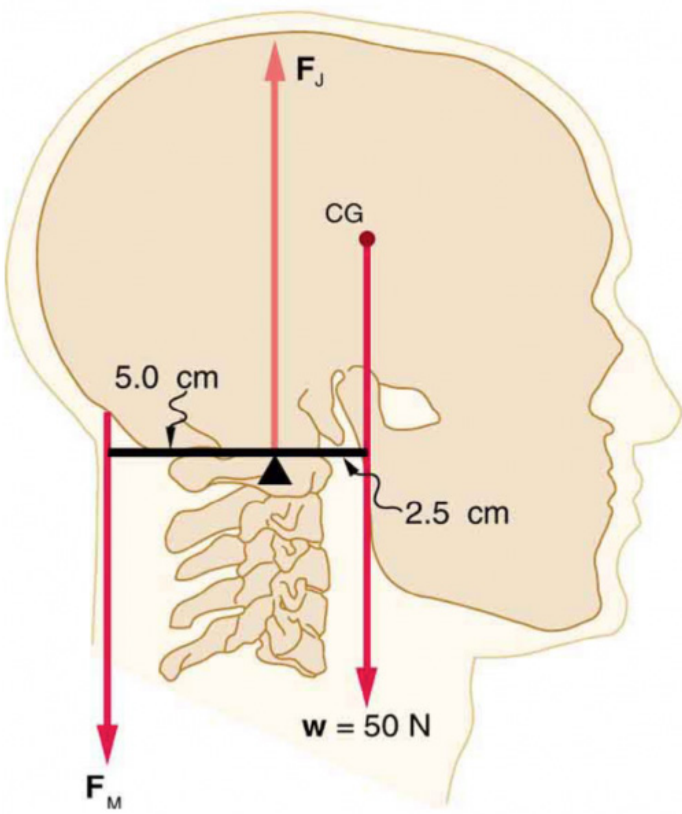


Figure 31: forces on the atlanto-occipital joint

6.1. Forces on the head

The following section will explain the forces that are inflicted on the head when using a VR device. There will also be explained how a counterweight can be used, how it affects the moment of inertia, and why it may or may not be a good addition to a VR device. This section will first explain the forces on the head in a static situation, and later describe the forces on the head in a dynamic situation.

The weight of the VR device exerts a force on the muscles in the neck, as well as the bones of the cervical spine. The gravity force exerted on the VR device causes a forward moment, rotating the head forward. The head is connected to the cervical spine at the atlanto-occipital joint, which is the joint responsible for allowing us to nod ‘yes’. **[47-49]** The center of gravity of the head is located 2.5 centimeters posterior to and 2.5 centimeters above the atlanto-occipital joint. **[50]** In a normal situation, the mass of the head causes a forward moment, which is countered by a backward moment caused by the muscles in the neck. The splenius capitis, splenius cervicis and the trapezius exert a downward force on the back of the head, causing a backward moment. **[47] [49]** The cervical spine exerts an upward force on the atlanto-occipital joint, allowing the head to stay in place.

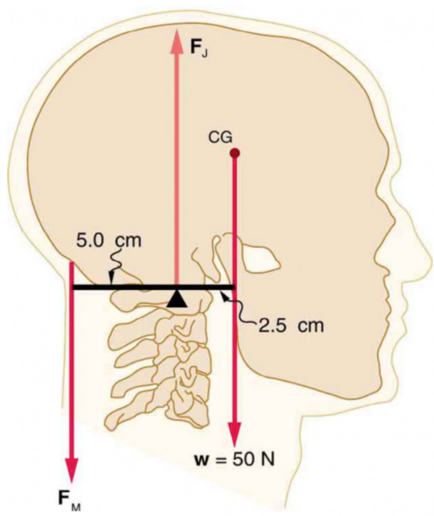


Figure 32: forces on the atlanto-occipital joint

According to Huelke **[51]**, 80% of the average human brain weight is achieved at 3 years of age, and 90% at 5-8 years of age. As the human head weighs approximately 5 kg, the head weight of 4-7 year old children is estimated to be 4.5 kg. The forces exerted on the head in an unloaded case can be seen in the table below:

	Force (N)	Arm (m)	Moment (Nm)
Mass head	45	0.025	1.125
Pulling force neck muscles	22.5	-0.05	-1.125
Pushing force cervical spine	67.5	0	0

When adding the mass of the VR device, estimated to be approximately 0.3 kg for the VR device and 0.2 kg for the smartphone, the force on the neck muscles and the cervical spine will increase:

	Force (N)	Arm (m)	Moment (Nm)
Mass head	45	0.025	1.125
Pulling force neck muscles	37.1	-0.05	-1.855
Pushing force cervical spine	87.1	0	0
Mass smartphone	2	0.17	0.34
Mass VR device	3	0.13	0.39

The force on the neck muscles increases by 14.6 N, a 65% increase, and the force on the cervical spine increases by 19.6 N, a 29% increase. By adding a counterweight, the neck muscles and the spine can partly be relieved:

	Force (N)	Arm (m)	Moment (Nm)
Mass head	45	0.025	1.125
Pulling force neck muscles	22.7	-0.05	-1.135
Pushing force cervical spine	78.7	0	0
Mass smartphone	2	0.17	0.34
Mass VR device	3	0.13	0.39
Counterweight	6	-0.12	-0.72

When a 600 gram counterweight with an arm of -12 cm is added, the force on the neck muscles will decrease to its usual state (unloaded case). The force on the cervical spine will decrease 8.4 N, but will still be 11.2 N higher than in an unloaded case. It can be concluded that in an upright position, a counterweight will have a positive effect on the user. When the user turns his head forwards or backwards, this will have little effect on the moment, as the arm of both the VR device and the counterweight will become smaller. When looking down slightly, the arm of the head mass will become slightly larger, although this would also be the case in an unloaded situation.

It should be noted that it is advisable that users maintain an upright position at all times when using the VR device with a counterweight. When leaning forward and looking at the floor, this will cause a moment around the lower part of the cervical spine, which can be damaging to the user’s neck.

6.1.1. Head movement

When using the VR device, the user is able to perform different movements that influence his camera angle and position in the virtual world. Low-end VR devices contain a gyroscope that allows the user to move in three degrees of freedom, being rolling, pitching and yawing. High-end VR devices also contain additional sensors which track the relative position of the user in the real world. This allows the user to move in three additional degrees of freedom, being elevating, strafing and surging.

The MVP will rely on the user's smartphone, and uses the gyroscope embedded in the smartphone to achieve three degrees of freedom: rolling, pitching and yawing. Pitching and yawing are especially interesting for the user, as they allow the user to change his perspective of the virtual world.

The rolling motion is performed by lateral flexion of the head around the uncovertebral joints, also called cervical side-bending. **[48]** The muscles involved in this motion are the longus capitis and the rectus capitis. The pitching motion is performed by cervical flexion and extension. Involved muscles are the splenius and the trapezium, and the joint allowing this movement is the atlanto-occipital joint. The yawing motion is performed by cervical rotation around the atlanto-axial joint. The muscles involved in this movement are the sternocleidomastoideus, upper trapezius and the splenius. **[49]**

All of the three motions are slightly impeded by the mass of the VR device, especially pitching and yawing. The mass and arm of the VR device and a possible counterweight increase the moment of inertia of the user's head. An increased moment of inertia causes the user to require more force in order to make the same head movement with the same acceleration. As an example, the effects of the VR device and a possible counterweight on the user's ability to perform the yawing motion will be calculated. The total moment of inertia during the yawing motion is found by adding the moment of inertia of the head, the VR device and the counterweight. For simplification, it is assumed that the head is a point mass, rotating around the axis of rotation being the atlanto-axial joint. The formula for moment of inertia is the following:

$$I = 0.5m * r^2$$

M being the mass of the head and r being the distance between the head's center of gravity and the point of origin. This relates to the following equation:

$$I = 0.5 * 4.5\ kg * (2.5\ cm)2$$
$$I = 14.1\ kg*cm2$$

The moment of inertia of the VR device is as follows:

$$I = 0.5 * 0.2\ kg * (17\ cm)^2 + 0.5 * 0.3\ kg * (13\ cm)^2$$
$$I = 28.9 + 25.35$$
$$I = 54.3\ kg*cm^2$$

The moment of inertia of the possible counterweight is as follows:

$$I = 0.5 * 0.6\ kg * (12\ cm)^2$$
$$I = 43.2\ kg*cm^2$$

The total moments of inertia in an unloaded situation, a situation with a VR device, and a situation with a VR device and counterweight are given in the table below:

	Total moment of inertia (kg*cm^2)
Unloaded situation	14.1
Situation with VR device	68.4
Situation with VR device and counterweight	111.6

It can be seen that the moment of inertia during the yawing motion increases significantly when using a VR device, and even more when using a counterweight. The equation above was repeated for the pitching motion:

	Total moment of inertia (kg*cm^2)
Unloaded situation	32
Situation with VR device	93.8
Situation with VR device and counterweight	144.5

It can be seen that the situation regarding pitching is similar to the situation regarding the yawing motion. It can be concluded that adding a counterweight helps to decrease the static forces on the neck muscles and cervical spine, but increases the forces needed to perform the yawing and pitching motions. As a result, adding a counterweight will make it harder for users to look around in the virtual world, even though the static forces on the neck are reduced.

6.2. Strabismic users

In this section will be explained how strabismus, one of the most common causes of amblyopia, affects the VR experience when using a HMD. It will also be explained which steps can be taken so that strabismic users can also use the VR device.

In the beginning of this chapter it was explained that one of the most common causes of amblyopia is strabismus. **[17-19]** For this reason, a significant portion of Vedea's target group will consist of strabismic children. The exact percentage of amblyopic children with underlying strabismus ranges from 15% to over 50%, but it appears to be most common in caucasian children. **[17-20]**

The problem with strabismus is that it makes it difficult or even impossible to use the Vedea treatment without additional aid. When a non-strabismic person uses a VR device, the lenses are placed right in front of their eyes. This way, the user can look straight ahead and see a part of the display through the lenses. For a strabismic person, one or both of the eyes cross in or out. The strabismic eye will therefore not be able to see the display in front of the eye. Instead, the strabismic eye will focus on a spot next to the display. First of all, this makes it impossible for the user to completely see the intended part of the virtual environment. Secondly, this will hinder the treatment, as it does not discourage the visual system to suppress the image seen through the weaker eye.

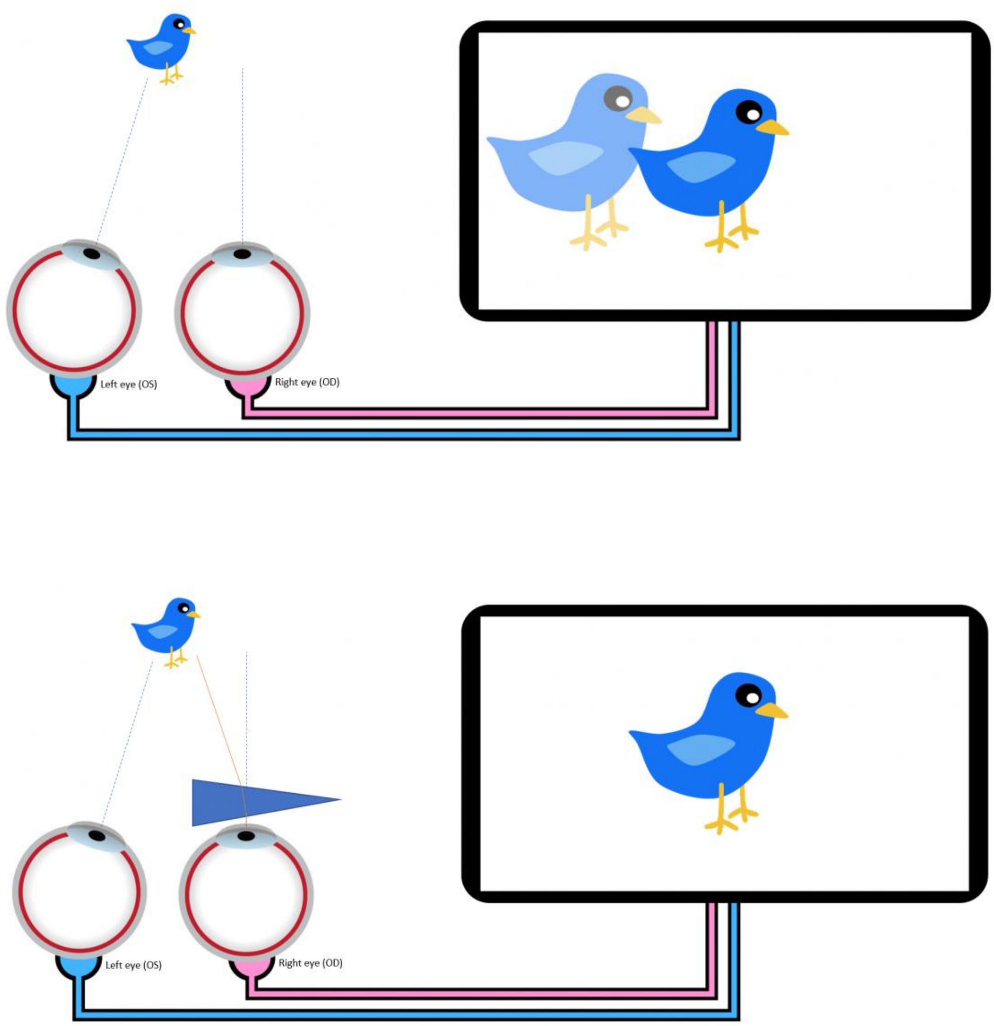


Figure 33: a strabismic (exotropic) person looking at a bird without (top) and with (bottom) a corrective prism

Luckily, there are optical instruments which can help strabismic users to successfully use a VR device. These optical instruments are called optical prisms **[42]**, and their function is to refract the light coming from the display in such a way that it matches the angular deviation of the strabismic eye. As a result, strabismic users are able to use a VR device with almost the same quality as non-strabismic users can. To do this, a prism should be used that matches the deviation of the eye. For this reason, people with varying degrees of strabismus will require a different prism strength. The prism will be placed between the strabismic eye and the lens of the VR device. The optical prism of choice is Fresnel prism foil. This is a transparent film with layers of very small prisms on one side. This prism foil can be placed on the lens, or it can be placed on a thin piece of transparent material. The strength and direction of the prisms depends on the user. In order to design a good solution for each individual user, collaboration with their orthoptist is recommended.

Lastly, the angular deviation of the strabismic eye will also cause a lateral deviation, the direction being the same direction as the angular eye deviation. In order to provide a clear image, the convex lens should be displaced in the direction and magnitude of this deviation. The deviation can be calculated by the following equation:

$$\text{Lateral deviation} = vx \tan(y)$$

In this equation vx stands for the vertex distance (the distance between the eye lens and the prism), and ‘y’ stands for the angular deviation in degrees. If the lateral deviation is 4 mm to the left, this means that the convex lens should also be placed 4 mm to the left. Strabismic users will have different ILD settings than non-strabismic users. Non-strabismic users with an IOD of 50 mm will also require an ILD and ICD of 50 mm. A strabismic user with an IOD of 50 mm and his left eye crossing out with a lateral deviation of 4 mm will require an ILD and ICD of 54 mm. Similarly, if his eye was crossing in with the same deviation, he would require an ILD and ICD of 46 mm. While this would not cause problems for average users, it may cause problems for users with a high angular deviation that are at the high or low end of the available IPD range of the product.

Because the ICD should ideally be equal to the IOD plus or minus the lateral deviation, there should be a possibility to enter the user’s IOD as well as his angular eye deviation for both eyes into the Vedea software. This information should be used to determine the ICD in the Vedea smartphone application. For the MVP however, a simpler approach will be used where the information about the user’s IOD will be stored in QR codes that will be connected to the user’s smartphone. For strabismic users there should be paid extra attention to the choice of ICD, because it should match the user’s IOD plus or minus the lateral deviation, and not merely the user’s IOD.

6.3. Conclusion

In chapter 2 some background information was given about amblyopia and its causes. Secondly, more information was given about dichoptic training and how this can be used to treat amblyopia. Chapter 3 explained VR and the various aspects that are of importance in this design assignment. Chapter 4 explained how the human visual system works, and explained how lenses are used in a VR device. Chapter 5 explained how the user’s IOD, the device’s ILD and the ICD of the content interact with each other. Finally, in chapter 6 some additional research topics were discussed such as the forces on the user’s head, which additional steps are needed for strabismic users.

Many aspects that were discussed in these chapters will come back in later chapters, and will be used to make informed choices during the design process. Things like the FOV, IPD and image distance will play an important role in the rest of the design process. In the next chapters the design process will be explained, which builds largely on the knowledge explained in this chapter. However, the product which will be designed for Vedea will also have to fit the company, as well as the various stakeholders involved. In order to design the optimal product for Vedea in this situation, it is necessary to take into account Vedea’s company strategy. This strategy will be explained in the next chapter.

Chapter 7

Product Strategy

7. Product Strategy

In this chapter the product strategy of Vedea Healthware BV will be examined. The product strategy in combination with the analysis from the previous chapters will result in a formulation of design requirements for the VR device. These requirements will be used during the concept ideation phase.

Figure 34: content of a Vedea game

The product strategy of Vedea Healthware BV consists of three components. The first is the software platform, containing the content library, a user interface and a set of algorithms. The second component is the content library itself, consisting of several VR games and small movies. The last one is the hardware, consisting of a VR device on which the platform and content can be accessed. This thesis is primarily focused on the design and development of the hardware, but it is important to understand that the platform and content also play an important role in the complete product.

As a recent startup, Vedea Healthware BV does not have many resources for the development of its product, and relies heavily on financial support from third parties. In order to overcome this financial barrier, it is the mission of Vedea to minimize its product-to-market time, as well as the development cost of its first product. For this reason it is the ambition of Vedea to realize a minimum viable product (MVP) to bring to the market. The MVP is a product that contains the minimum functions necessary to provide dichoptic training to the target group, being amblyopic children aged 4-7. In order to create an MVP, this product will contain only the necessary functions. In addition, it is desired that the MVP requires minimal upfront investment. Before such a product can be brought to the market, the product will need to be subject to play tests with the target group, as well as go through a clinical trial. Therefore, the first phase of the Vedea product strategy will be to complete the play tests and clinical trial. After finishing the first phase, new opportunities will hopefully open up for additional investments. Additional investments will allow the company to move on to the second phase, which is the production of the MVP, and bringing it to the market. Bringing a first product to the market will allow the company to receive a stream of profit, which can be used to finance improved products. The third phase will consist of the design, development and marketing of an improved product, which has a higher quality than the MVP.

7.1. Phase 1: Play tests & clinical trial

The first phase commenced in early 2021 and will take place until approximately the end of 2021. First of all, a set of play tests will be done using amblyopic children aged 4-7. The children will play with the product, consisting of the hardware product and a series of VR games. During the play tests, it will become apparent if the product is liked by the target group or not, and whether there are mistakes in the design of the product (both hardware and software).

The second step is a clinical trial, where amblyopic children aged 4-7 will perform the dichoptic training for a longer period of time. During the clinical trial it will be assessed whether the dichoptic training as it is provided by Vedea is an effective treatment for amblyopia. If the clinical trial is successful, it will unlock new possibilities with regards to further investment, as it is a proof of concept that the Vedea method is a satisfactory treatment method. If the clinical trial is unsuccessful, this means that there is a factor in the hardware or software that is inhibiting the effectiveness of the treatment. The effectiveness of dichoptic training for amblyopia treatment has been well documented, therefore an unsuccessful clinical trial would indicate that the dichoptic training was not properly reproduced by the company.

7.1.1. Requirements

In order to execute the play tests and clinical trials, 50 hardware products are required. Furthermore, the software and game library have to be partly finished. The hardware that will be used for phase 1 will be a slight simplification of the MVP of phase 2. Due to the low volume of production, the only suitable production method for the hardware is 3D printing. As a result the products for phase 1 will be slightly different than the MVP, due to a different production method.

Figure 35: a photo of the phase 1 prototype in progress in April 2021.

7.2. Phase 2: The Minimum Viable Product

If the play tests and clinical trial from phase 1 are successful, this will prove the validity of the Vedea treatment method. This validity will hopefully unlock new possibilities with regards to further investment, which will aid the company in the production and marketing of the MVP. Vedea's plan is to launch the MVP between January 1st 2022 and December 31st 2022. In the first two years, the company aims to produce 6000 - 7000 products. In the third year, this number should be brought up to 20.000 products. This scale of production requires the company to produce 250 - 300 products per month during the first two years, and up to 600 products per month in the third year. This requires Vedea to make an MVP that is suitable for mass production. In order for the MVP to be eligible for mass production, it should be slightly different from the product used in phase 1. For the plastic parts, injection molding will be used as this production process is more suitable for the high volume that Vedea wants to achieve.

Upwards of 650 products, injection molding is more economical than 3D printing. It is however preferable to start injection molding sooner than that, because the fixed costs of injection molding are an investment for the future, whereas 3D printing has very high variable costs.

When the part design of the MVP is completely finished, a series of molds can be made for the injection molding process. The purchase of the molds will be a significant investment, but the material cost of injection molding will be very low. A rough cost estimate was made of 40.000 euros for the molds and 10 eurocents per product for the material cost of the plastic parts.

Due to the limited resources of the company, the MVP will be a relatively simple product which should require limited investments with regards to the product development. It was chosen as a strategic decision by the company to make an MVP that uses the smartphone of the user as input for the VR device. Using a smartphone as input relieves the need for an embedded system, including a custom display. As an embedded system requires multiple parts that are relatively expensive and difficult to produce, this would increase the cost of the product significantly for people that already own a smartphone. A basic smartphone-based VR device such as the Destek costs approximately 40 euros, while a low-end non smartphone-based product such as the PlayStation VR or Oculus Go will cost around 200 euros. This is a price increase of 400%. As you can see, a smartphone-based VR device can be much cheaper than non smartphone-based VR. The price of the smartphone however is not taken into account for this price.

Relying on the user's smartphone comes with its own disadvantages. In the use phase, children will need to rely on the smartphone of one of the parents, as these children will likely not have a smartphone of their own. Doing so would inhibit the original smartphone owner from using his phone for 30-60 minutes per day. Additionally, notifications on the smartphone may disrupt the dichoptic training of the user. Furthermore, there are product technical limitations which stem from the choice of using a smartphone as input. Because there are large variations in the size of smartphones, a looking hole should be chosen that fits small phones. Doing so results in a lower FOV than necessary for the majority of the smartphones. Similarly, the type of smartphone used can lead to a low resolution or refresh rate. Because certain qualities like the resolution and the refresh rate depend on the user's phone, Vedea will have no influence on those properties of the product. Choosing to rely on the user's smartphone limits the company in choosing a desired display size, display resolution and refresh rate. Because all of these factors influence the immersiveness of the VR device, this means that the immersion that the VR device provides will vary based on the smartphone that is used. This will also affect the level of presence that users will experience when using the VR device.

7.3. Phase 3: The long term product

While the MVP will be the company's entry into the market, it will not be the most high quality product. Vedea will use the profit it makes during the first few years to develop a more advanced product, which will be called the long term product. Because the operations of Vedea are already running thanks to the MVP, this allows more time, resources and complexity for the development of the long term product. This allows Vedea to develop a more expensive product, as long as this relates to a higher quality product. This chapter will list the aspects that will remain the same between the two products, as well as the aspects that can be improved in the long term product.

7.3.1. Similarities

The following aspects will not change from the MVP to the long term product:

- Focal length

The focal length does not significantly influence the price of the product, therefore an ideal focal length can already be achieved in the MVP. The focal length influences the magnification of the image, and therefore also the viewing window. The focal length also influences the product weight, force on the user’s neck and the optical aberrations of the lenses.

- Object distance

The object distance determines the image distance, together with the focal length. In order to achieve a pleasant viewing experience for the average user, the object distance should be equal to the focal length, placing the image distance at infinity. Therefore, the object distance is completely dependent on the focal length of the lenses.

- Product depth

The product depth is mainly determined by the object distance, which is completely dependent on the focal length. The product depth largely influences the product weight.

- Image distance

The image distance is determined by the focal length and the object distance. In order to achieve a pleasant viewing experience the object distance should be equal to the focal length. Therefore, the image distance is completely dependent on the focal length.

- Vertex distance

In order to increase the FOV and the viewing window, the vertex distance should be minimized. However, the vertex distance should be large enough to accommodate users with prescription glasses.

- Content magnification

The content magnification relates to how much the content is magnified due to the lenses. The content magnification is equal to (1 + vertex distance/focal length). The content magnification is therefore dependent on the focal length and the vertex distance.

- Eye-to-screen distance

The eye-to-screen distance is determined only by the object distance and the vertex distance. Therefore, the eye-to-screen distance is influenced by the vertex distance and focal length of the lenses.

- Lens diameter

An appropriate lens diameter can be chosen for the MVP. The product designers are however limited by the availability of stock lenses.

- ILD

The minimum ILD depends on the lens diameter. The maximum ILD can be decided upon by the product designers.

- Viewing window

The viewing window determines the part of the display that can be seen through the lenses. The viewing window depends on the focal length, lens diameter and vertex distance. The viewing window will likely not change between the MVP and the long term product.

7.3.2. Room for improvement

There are several things that could be improved in the long term product. Having more financial resources allows Vedea to implement several things that are hard to implement in the MVP.

- High quality custom lenses

In order to get the best quality display, achromatic or aspheric lenses should be used, or even a combination of them. Aspherical lenses can be used to limit the spherical aberration. Achromatic lenses can be used to limit the chromatic aberration, while partly decreasing the spherical aberrations. A combination of achromatic aspherical lenses would diminish both the spherical and chromatic aberrations. The use of an aspherical or achromatic lens would however add extra weight to the lenses. This weight can be reduced by making use of a Fresnel lens, although this would partly decrease the quality of the image by adding the so-called ‘god rays’ to the image.

While achromatic convex lenses are sold as commodities these days, an aspheric achromatic biconvex Fresnel lens is very rare, and would most probably require a custom lens and mould design. Aspheric lenses are difficult to design and produce, and therefore expensive.

- Embedded system and custom display

Replacing the smartphone with an embedded system and a custom display has a number of advantages. First of all, children no longer need to use their parents’ smartphones in order to use the product. Giving away their smartphone for 30-60 minutes per day can be a nuisance to the parents of the amblyopic child. Secondly, a VR device with an embedded system could offer a better quality in terms of FOV, display resolution and refresh rate than the MVP, depending on the used parts.

- FOV

When using a VR device with an eye-to-screen distance of 70 mm, a lens diameter of 40 mm and a vertex distance of 25 mm, and a content magnification of 1.56, the viewing window will be a circle with a diameter of 72 mm. A part of the circle will get lost, due to the fact that the dividing wall between the two parts of the screen takes up a part of the view. Additionally, the looking hole at the back of the VR device is deliberately made smaller than necessary for most smartphones, in order to accommodate for the smaller smartphones. Using a custom display allows for a larger looking hole. Additionally, larger lenses can be used to increase the FOV even further.

While the MVP allows for a FOV of approximately 77 x 71 degrees, a custom display could increase this to 77 x 77 degrees. The most effective way to increase the FOV however would be to decrease the vertex distance to 15 mm, resulting in a potential FOV of 106 x 106 degrees. This would however make the product unsuitable for users with prescription glasses.

- Display resolution

The 50% most popular phones in the Netherlands in 2019 have a resolution of 326 to 576 ppi. **[52]** Most iPhones have a resolution of 326 ppi, while Samsung phones usually have a higher resolution. An average resolution of 400 ppi is not bad for VR standards. Combined with a horizontal FOV of 67 degrees per eye, this would amount to a resolution of 14.3 PPD. While this is by no means a low quality resolution for VR standards, it could be improved when using a custom display. Improving the resolution of the display from 400 to 500 ppi with the same FOV would increase the resolution from 14.3 to 17.9 PPD. This is an increase from 23.8% to 29.8% visual acuity.

Another advantage of a custom display is that it creates a more uniform product. When using a smartphone as the input for the VR display, some users may have a 500 ppi smartphone, while others have a smartphone resolution of 300 ppi or less. This means that some users will have a lower resolution, and therefore may have poorer results in their treatment.

- Refresh rate

Refresh rate plays an important role in making the VR environment feel realistic. Having a refresh rate below 90 Hz can cause nausea, headache and disorientation. **[37]** For smartphones, the standard refresh rate is set at 60 Hz, which is not enough to have a problem free experience. However, some smartphones offer the possibility to change the refresh rate to 90 or even 120 Hz. While this option is sufficient, it can lead to other use-related problems. For example, users may forget to switch their refresh rate back to 60 Hz after doing the VR treatment, which will cause their phone battery to deplete faster during everyday use. Alternatively, switching the refresh rate before and after each VR session can be a nuisance to the user. Having a custom display screen can mitigate these problems. A display can be chosen with a standard refresh rate setting of 90 to 144 Hz. This way, the refresh rate will always be sufficient, and the user does not have to change the settings of the VR device everyday.

- Additional degrees of freedom

The MVP is a simple product, relying on the gyroscope of the user's smartphone to realise three degrees of freedom. In the long-term product, additional sensors can be placed on the product to track the user's relative position. Doing so allows the user to move in six degrees of freedom instead of three. Adding three additional degrees of freedom adds more realism to the user experience. Additionally, it allows for extra ways in which users can interact with the virtual world, thereby increasing their immersion into the virtual world, which increases the effectiveness of the amblyopia treatment.

Furthermore, the addition of three additional degrees of freedom allows Vedea more opportunities with regards to its content design. Additional degrees of freedom allow new movements to the user of the VR device, which can be incorporated into the content of Vedea's games and videos. Vedea will be able to create games with additional features, therefore allowing more creative freedom to Vedea's game designers and developers. As a result, the addition of more degrees of freedom allows for the design of more games, as well as more possibilities within those games. As a result, the addition of more degrees of freedom could increase both the quantity and quality of Vedea's game content.

Transitioning from a 3 DoF system to a 6 DoF system requires additional sensors, in the form of either an inside-out or outside-in tracking system. The sensors used in these systems are optical sensors, usually in the form of infrared sensors or camera sensors scanning for stickers or features in the environment.

- Additional ways of interaction

While it is already the intention of Vedea to implement a remote controller in the MVP, additional ways of interacting with the virtual world would open up new possibilities for the creation of game content. While haptic gloves and VR treadmills would not be necessary, simpler ways of interaction such as a motion controller could be a suitable option for Vedea.

Chapter 8

Design Requirements

8. Design Requirements

Chapter 2 to 6 consisted of background information which is necessary for the design of the VR device. Chapter 7 consisted of the company strategy with regards to the development of the VR device. In this chapter the design requirements for the VR device will be described, based on the information of the previous chapters. These design requirements will be used as input for the product design and development, and will also be used to evaluate the final product.

Figure 36: a child using a VR device

8.1. List of requirements

The following requirements are goals that were set before the start of the project:

- Parents should be able to use their own smartphone devices.
- Children should be able to comfortably wear the head mounted display for 30-60 minutes per day.
- The head mounted display should be customizable to head circumference.

The following requirements are additional requirements for the MVP based on the analysis and product strategy:

- The maximum production costs of the product are €40,-
- The product is compatible with the majority of contemporary smartphones.
- The lens depth is adjustable.
- The ILD is adjustable.
- The focal length of the lenses does not exceed 60 mm.
- The product is compatible with children aged 4-7.
- The product is compatible with users with refraction errors.
- The product is compatible with strabismic users.
- The product is compatible with users with an IPD between 47 and 62 mm.
- The image distance can be set to infinity.
- The ICD matches the ILD of the lenses.
- The maximum weight of the product is 300 grams.
- The VR device does not cause physical discomfort, eye-strain or nausea.

The following aspects are wishes for the product:

- The refresh rate is at least 90 Hz.
- The ICD and ILD match the user's IOD.
- The resolution is at least 9 PPD (15% visual acuity)
- The VR device has a horizontal FOV of at least 70 degrees.

8.2. Practical design guidelines

The previous chapters have presented some research into different topics, such as optics, biology, amblyopia and VR technology. Based on this information, some lessons can be learned to aid in the design of a VR headset. In this chapter a quick overview of these lessons will be given, along with a quick explanation of each guideline. The guidelines below can be used as a “cheat sheet” for developers of VR devices, although this one is specifically created for Vedea.

- The focal length should be approximately 45 - 60 mm.

A lower focal length allows for a smaller product size due to less product depth, resulting in less weight and a lower force on the neck. A higher focal length causes thinner and lighter lenses, and reduces the spherical aberrations of the lens. Furthermore, a higher focal length increases the object distance range for which the product is usable. This larger range allows the users to find their sweet spot more accurately.

A focal length lower than 45 mm would increase the aberrations of the lenses. Moreover, the viewing window would become smaller than ideal when using a focal length lower than 45 mm.

- The lens diameter should range from 30 to 45 mm.

A small lens diameter reduces the weight of the lenses. A large diameter increases the FOV up to a certain point, but the edges will be increasingly distorted due to spherical aberration. It is not necessary to have a lens diameter much higher than 37 mm, as the FOV is constrained by the looking hole.

- A plano-convex lens is more suitable for VR devices than an equi-biconvex lens.

When there is a significant difference between the object distance and image distance, a plano-convex lens will produce less aberrations than an equi-biconvex lens. **[45]** In this case it is very important that the convex face of the lens faces the display screen. If the convex face of the lens faces the user it will result in more aberrations than an equi-biconvex lens.

- For increased image quality, achromatic or aspherical lenses can be used.

Achromatic lenses reduce the chromatic aberration (and to some extent the spherical aberration), but come at double the weight and double the cost of an achromatic lens.
Aspherical lenses reduce the spherical aberration, making the image much sharper. However, aspherical lenses are difficult to design and produce, and come at a higher weight and price.
If weight is an issue, use Fresnel lenses.

Fresnel lenses greatly reduce the weight of the lenses. This option should however only be selected if the weight is important, as Fresnel lenses will reduce the image quality by adding “god rays”. Fresnel lenses are especially useful in combination with aspherical or achromatic lenses. It is however unsure if Fresnel lenses are suitable for dichoptic training.

- Lens depth should be adjustable.

The light rays coming from a certain point converge to a point of focus, or image point, which should be placed exactly at the retina. Changing the position of the lens will change the depth position of the image point, allowing the user to place this point exactly at the retina. When the image point is placed exactly at the retina, the image will be focused, causing a sharp image. For most people an image distance at infinity places the image point at the retina. **[43]** However, for some users the image point will be in front of or behind the retina, which requires them to place the lens slightly to the front or back.

- For users without refractive errors, the object distance should be set equal to the focal length of the lens.

If the object distance is equal to the focal length of the lens, the resulting image distance will be set to infinity. Having the image distance at infinity is the ideal setting for most users, unless they have a refraction error such as myopia or hyperopia. **[43]**

- The ILD should be adjustable, independently for both lenses.

For regular users it is more user-friendly to adjust the IPD by changing the position of both lenses at the same time using one knob. However, for strabismic users it is necessary to change the position of each lens independently, as the use of a prism (which is necessary for strabismic users) requires the lens in front of the strabismic eye to be placed slightly more to the left or right.

- The ideal ILD range for children aged 4-7 is 40 - 62 mm.

Nearly 100% of children aged 4-7 have an IOD between 40 and 62 mm. **[15]** Allowing for an IOD below 40 mm is not necessary as IODs below 45 mm rarely occur in this age group. Allowing for an IOD above 62 mm will make the product more suitable for children older than 7, especially children older than 10.

- The ILD should match the ICD of the content.

If the ILD and ICD do not match, this will result in double vision. Ideally, the ILD and ICD should also match the user's IOD. If the IOD is higher or lower than the ILD it will result in optical warp distortion. It is unsure how much this will affect the effectiveness of the dichoptic training.

- The product should be approximately 8.7% less wide than regular VR devices.

Children's heads grow in size while they get older. For this product, only the width of the head is important to take into account, as the head height hardly changes after age 6. The average 6 year old has a head width of 8.7% smaller than that of an adult. **[20]** If necessary, multiple sizes can be made for the facemask in order to ensure a perfect fit for all users.

Chapter 9

Conceptual Design

9. Conceptual Design

Several requirements, wishes and guidelines were made in the previous chapter, in order to form a basis for the conceptual design process. These requirements, wishes and guidelines were informed by thorough analysis of the underlying concepts, as well as the company strategy of Vedea. This chapter will explain the conceptual design process. Designing the ideal product for this particular scenario depends on several factors. First of all, the product requires the right balance of several factors. Increasing the value of certain factors will decrease the value of others. Secondly, a physical product should be made, consisting of several parts. The part design should be optimized in order to ensure a product that works smoothly.

Figure 37: influence chart of the product, mapping how different variables affect each other

9.1. Variable design

In the initial stages of the conceptual design, an influence chart was made to map out the different variables of the product. The influence chart and user experience chart can be seen on page 10 and 11 of the report.

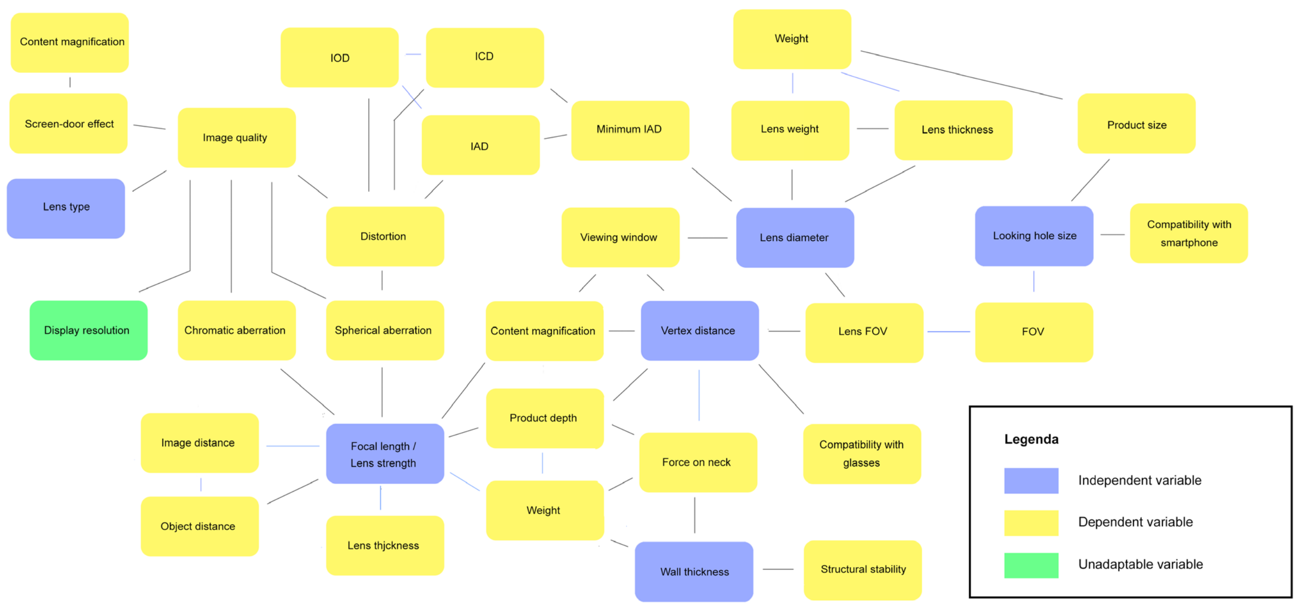


Figure 38: influence chart of the product, mapping how different variables affect each other

Variables that can be chosen by the product designer are shown in blue. Variables whose values result from other variables are shown in yellow. Finally, values that cannot be influenced by the product designer (in this case the values belonging to the user's smartphone) are shown in green. The variables shown in blue are especially important in the design of the product, because these values can be chosen by the designer and because they influence the outcome of the product. For example, increasing the focal length of the lenses will allow for a better image quality due to lower aberrations and lower content magnification, but it will also lead to more weight. In the next subchapter will be explained how certain variables such as focal length affect the product.

9.1.1. Factor model

In a later stage of the project a factor model was made, in which all of the relevant properties relating to the product were mapped out. It was found that changing certain parameters will have an effect on other factors. After mapping out all the properties which relate to the product, the properties were divided into two categories: properties for which the value depends on other properties, and properties for which the value can be chosen by the product designer. The properties for which the value can be chosen were singled out and put into a new document.

Parameter	Goal	Explanation
Focal length (f)	45 - 60 mm	A stronger lens decreases the product depth, but also increases the aberrations and makes it more difficult to find the user's sweet spot. Furthermore, it increases the content magnification, leading to more zoom and causing a higher screen-door effect.
Vertex distance (vx)	10 - 25 mm	The vertex distance should be as small as the user can tolerate in order to increase the FOV. However, a too small vertex distance causes the product to be incompatible with users that are wearing glasses, or in extreme cases the lenses will stick out and touch the users' eyes or eyelids.
Lens diameter (ld)	34 - 42 mm, depending on the looking hole size	Increasing the lens diameter can lead to a higher FOV, but only if the looking hole size is sufficiently large. Increasing the lens diameter also increases the minimum ILD, causing the product to be less suitable for young children with low IODs.
Wall thickness	Minimize up to a certain value	Increasing the wall thickness causes the structural stability of the product to increase, but it also increases the weight of the product and therefore the forces on the user's neck.
Counterweight (m)	Find ideal value	A counterweight decreases the static stress on the neck, but also makes it more difficult for the user to look around in the virtual world.
Looking hole	Maximize up to a certain value	A larger looking hole can increase the FOV if the lens diameter is sufficiently large. However, it also causes smaller smartphones to no longer be compatible with the product.

Figure 38: factor model of the product, mapping the independent product variables

The colour of the parameter indicates its importance in the design of this product. Red indicates that the parameter is very important. Yellow indicates that it is somewhat important, and green indicates that it is not very important.

Focal length
The focal length of the lenses is an important factor of the product, which influences many other variables such as the product depth, weight and content magnification. A stronger lens would allow the product to be smaller in depth, which would reduce the weight of the product. More importantly though, a shorter product reduces the arm on the weight of the product, leading to less forces on the user's neck. Increasing the lens strength however also has many disadvantages. It would increase the weight and thickness of the lenses, as well as increase the spherical aberration and distortion of the lenses. Stronger lenses increase the magnification of the

content, causing the product to zoom in on the display more. This causes a higher degree of the screen-door effect, where the optical quality of the image decreases due to the user being able to see the individual pixels of the screen better. It would also be more difficult for users to find their sweet spot with regards to focus. Roughly speaking, a stronger lens decreases the optical quality of the image, but also makes the product feel lighter. Because the focal length of the lenses influences so many aspects of the product, it is advisable to test the product using lenses with varying degrees of strength, in order to find out what is the ideal setting. Common focal lengths seen in VR devices range from 45 to 62 mm. For this product a focal length of 45 mm was chosen, which is on the low end.

Vertex distance
The vertex distance should be minimized up to a certain point. Reducing the vertex distance will increase the FOV of the product, but having a too low vertex distance will cause the lenses to protrude into the user’s eyes or eyelids. Having a low vertex distance will also make the product less compatible with users who are wearing glasses, as the product will leave little space between the user’s eyes and the lenses of the product.

Lens diameter
The lens diameter increases the FOV up to a certain point, depending on the size of the looking hole. However, increasing the lens diameter also increases the lens thickness and lens weight, and increases the minimum ILD of the product. Especially when using strong lenses with a low focal length, the FOV should be large in order to accommodate for the high amount of zoom. The lens diameter does not have to be very large in order to achieve a competitive FOV. A lens diameter of 34 mm will be sufficient to achieve the same FOV as competitor products. However, a lens diameter of at least 38 is optimal for this product in order to not waste the potential FOV caused by the size of the looking hole. For the prototype, lenses with a diameter of 42 mm were chosen as this is a standard size for lenses which are readily available.

Wall thickness
Increasing the wall thickness increases the structural stability of the product, but it also increases the weight, and therefore the forces on the user’s neck. Weight is already seen as an important factor in HMD (head mounted display) design, but it is even more important when designing a HMD for young children. There are many things that influence the weight of the product, including e.g. the weight of the lenses, size of the product, material density and wall thickness. The most effective ways to decrease the weight of the product are to decrease the material density and wall thickness, however each of these factors causes the product to be more fragile. This is especially risky for a children’s product, as young children are less careful when interacting with fragile objects than adults. For this product it was chosen to sacrifice a bit of stability in order to make the product lighter. The reason for this is that a heavier product will be less compatible with younger children. A uniform wall thickness of 2 mm was chosen for the outer parts of the product.

Counterweight
The counterweight can be used as an addition to the VR device, but it is unsure if this will be an improvement to the product. Adding a counterweight would reduce the static stress on the user’s neck, but it would also increase the moment of inertia during the yawing and pitching motion. This would make it harder for the user to look around in the virtual world. For this product it was chosen to not implement a counterweight, as it would make it more difficult for the user to look around in the virtual world. As can be seen in chapter 2.9.1. the moment of inertia

becomes up to two times as large when using a counterweight of 600 grams. This was deemed a too great sacrifice in order to decrease the static forces on the neck.

Looking hole size
For the looking hole a size of 118 x 55 mm was chosen. This number is low enough in order to be compatible with all of the smartphones featured in the list of top 50% smartphones in the Netherlands in 2019 **[53]**, but also high enough to have a competitive FOV when compared to similar products. Increasing the looking hole size beyond this value would make the product less compatible with smaller smartphones, but it would also require the product to be larger. The reason for this is that the machinery inside the product should be moved to the outside in order to make room for the looking hole.

9.2. Lens Design

The design of the lenses is a vital part of the product, as much of the product's requirements are tied to the lenses. The purpose of the lenses in a VR device is to collimate the light of the point source, in this case the point sources being the individual pixels of the display screen. Collimating the light of the pixels allows users to focus on the display without needing to flex the ciliary muscles in the eye. However, lenses also come with added disadvantages, such as an added weight, added cost, and optical distortion in the form of aberrations. In this subchapter the various lens properties will be explained.

9.2.1. Focal length

The focal length is arguably the most important property of any lens, as it determines the strength of the lens. The strength of a lens can be given by the following formula:

$$P = 1 / f$$

In this formula P is the power of the lens and f is the focal length. A shorter focal length equals a stronger lens. Because the purpose of the lens is to collimate a point source, the object distance (being the distance between the lens and the display) needs to be equal to the focal length. If the object distance and focal length are equal, the image distance will be set to infinity, effectively collimating the light from the display. As a result, the focal length will determine the distance between the lens and the display, which effectively determines the product depth. A stronger lens will require a smaller product, which causes less stress on the user's neck. However, stronger lenses also add more weight to the product, and cause more optical aberrations.

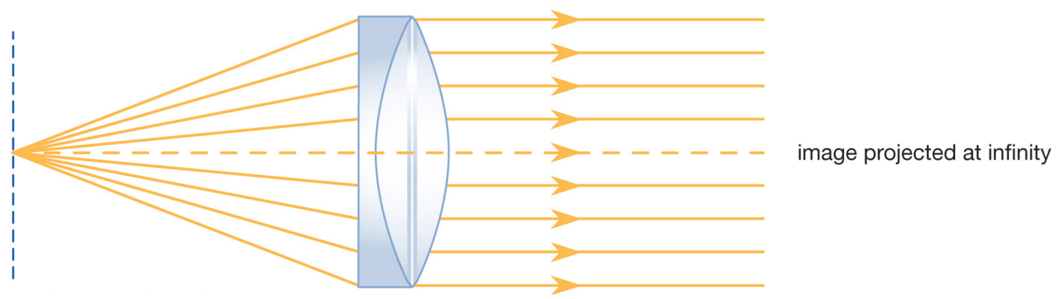


Figure 39: a lens used as a beam collimator, collimating a point source

Most VR devices use lenses with a focal length between 45 and 62 mm. Focal lengths longer than 62 are not advised, because they cause the VR device to be deep, which causes more stress on the neck. Focal lengths under 45 mm may be possible, but they do cause more aberrations and weight. For this product, a focal length of 45 mm was chosen.

9.2.2. Lens diameter

The lens diameter is an important aspect of the lens because it largely determines the FOV of the VR device, as well as the weight of the lens. The weight of the lens increases exponentially when the lens diameter increases. However, it is also important to achieve a high FOV, as this increases the user's presence in the virtual environment. The relationship between the FOV and the lens diameter is given in the following formula:

$$FOV = 2 \tan^{-1}(0.5\ ld / vx)$$

In this formula 'ld' stands for the lens diameter and 'vx' for the vertex distance.

Another disadvantage of a high lens diameter is that it increases the minimum ILD (distance between the lenses). Other VR devices usually have lens diameters between 25 and 42 mm. In this product, a lens diameter of 42 mm was chosen. This is a relatively high lens diameter, which allows for a high FOV.

9.2.3. Lens type

Even when the basic properties are known, there are still many different types of lenses to choose from. First of all, lenses can be divided into convex and concave lenses. Convex lenses are used among other things to create a virtual image that is further away than the object, while concave lenses are used to create a virtual image that is more nearby. In this case a convex lens is required.

There are many different types of convex lenses, such as biconvex, plano-convex, best-form and aspheric lenses. In the case of using lenses for a VR headset, the purpose of the lens is to collimate a point source. The best lens for collimation is an aspheric lens, because it minimizes the spherical aberration that occurs in regular spherical lenses. However, aspheric lenses are very difficult to design and produce, due to the very specific curvature of the lens.

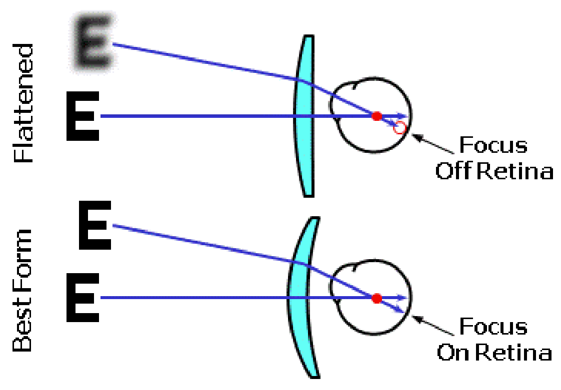


Figure 40: the difference in optical outcome between a regular convex lens and a bestform lens

An alternative to aspheric lenses are spherical lenses. Equiconvex lenses (symmetrical biconvex lenses) are not advised for collimating a point source, as they produce significant spherical aberration if the conjugate ratio is too high. The conjugate ratio is the ratio between the image distance and the object distance, which is infinite for this case. Usually plano-convex lenses are used for collimation, because these lenses work best in the case of an infinite conjugate ratio. **[44]** These are lenses where one side is curved and the other side is flat.

An even better alternative to plano-convex lenses is called a best-form lens. Best-form lenses are biconvex lenses, but the curvature of both faces of the lens follows a specific ratio for which the spherical aberration is minimized. Best-form lenses are the best spherical lenses to reduce spherical aberration, but still come with the benefits of spherical lenses, being that they are cheap and easy to produce. Best-form lenses are the best suited lenses to collimate a point source after aspheric lenses, followed by plano-convex lenses. **[44]**

Alternatively, achromatic doublets can be used to decrease the spherical aberration and minimize chromatic aberration. The disadvantage is that achromatic doublets are heavier, more expensive and harder to produce than regular lenses, while the benefit of having no chromatic aberration is limited for VR.

Furthermore, Fresnel lenses can be used, which are lenses where the curvature is divided into smaller pieces. As a result the lens can be much thinner than a regular lens, but at the cost of perceiving “god rays”: small circles that cover the image, due to the fact that light is reflected differently on the edges. An added disadvantage is that Fresnel lenses are more difficult to produce.

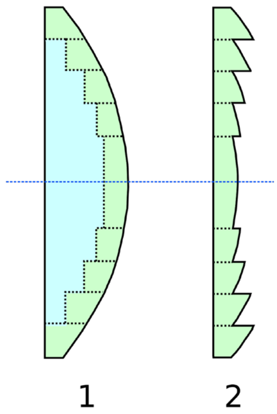


Figure 41: A plano-convex lens (1) and a plano-convex Fresnel lens (2)

In high-end VR devices there is often opted for aspheric or Fresnel lenses. Oculus, one of the biggest players when it comes to VR devices, recently filed a patent for an aspheric Fresnel lens, which will be used in their products. Lower-end VR devices usually opt for best-form lenses because they are cheap and easy to produce, while still offering the benefit of almost no spherical aberration. For this reason, best-form lenses were also chosen for this product.

9.2.4. Lens material

In order to be successful, lenses need to be made from transparent materials. The usual materials used for lenses are glass and plastic. The benefit of glass is that it has the highest optical quality, and it does not scratch easily. The disadvantages of glass are that it shatters more easily, which can be dangerous for users of VR. Furthermore glass is much denser than most types of plastic, which causes the lenses to be heavier.

Plastic does not offer the same optical quality of glass, but it is lighter than glass and it does not shatter easily. Plastic is less resistant to scratches, but this can be avoided by using an anti-scratch coating. For these reasons, plastic is usually chosen for VR purposes. Out of all types of plastic, most VR lenses are made from PMMA (poly methyl methacrylate), a material that is highly transparent when compared to glass.

9.3. Part design

The next step in the design process is to construct the different parts which in totality make up the complete product. Every part has a specific function, which will be explained in the sub-chapters below.

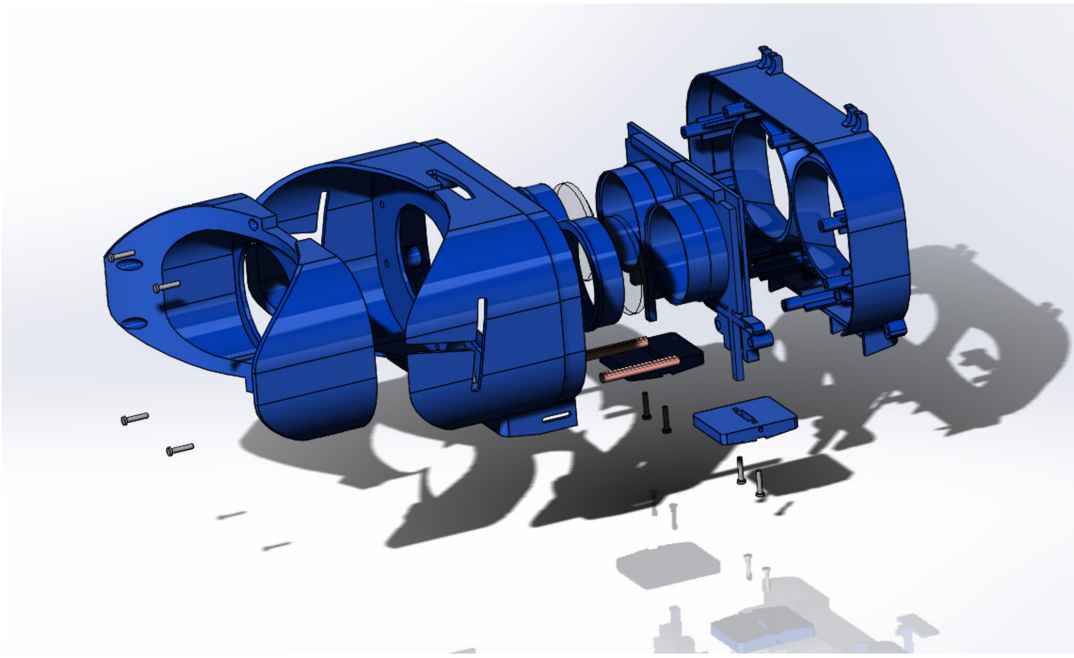


Figure 42: Exploded view of the plastic parts, lenses, screws and axes of the product

9.3.1. Front part

The front part is connected to the rear part and face mask using screws. Together with the rear part, the front part forms the casing of the product, which protects the moving mechanisms within. The front and rear part also form a basis onto which the lens mechanisms are connected. The front part contains 6 holes for connecting the axes on which the lens mechanisms are located, as well as 8 holes for connecting the axes of the rear part. Moreover, the front part contains holes for connecting the head straps to the product. The part contains looking holes where the lens tubes can fit through, and a cavity for the user's nose.

9.3.2. Rear part

The rear part is connected to the front part and face mask using screws. Together with the front mask it forms the casing of the product, which protects the moving mechanisms within. The part contains 8 axes which fit into the front part, with the main function of providing stability. The part also contains 6 holes for connecting the axes on which the lens mechanisms are situated. Additionally, the rear part contains features for keeping the smartphone in place while using elastic bands. Lastly, the rear part contains a feature at the bottom, where the phone holder can be attached to.

9.3.3. Mask

The face mask is connected to the front and rear part of the product using screws. The face mask is located between the front part and the user's face. The function of the face mask is to create space between the product and the user's face. The curve of the mask should match the shape of the user's face for optimal wearing comfort. Additionally, a soft mask will be attached to the face mask, consisting of polyurethane foam and leather. This soft mask will act as a cushion between the hard plastic mask and the user's face.

9.3.4. Lens tube casing

The lens tube casing is a casing for the lens tubes which allows the tubes to move to the front and to the back. The casing is the part that allows the users to alter the focus of the lenses. There are two lens casings, one for the left lens and one for the right lens. Each lens casing is connected to the front and rear part of the product using 3 metal axes. Furthermore, each lens casing is connected to a clasp, lens tube and slider. The lens casing and clasp prevent the lens tube from moving to the front, back, top and bottoms. The lens casing also facilitates that the lens tube can move a certain distance to the left and right.

9.3.5. Lens tube

The lens tube is a tube containing the lens, connected to a thin plastic plate which is connected to the lens casing. The way in which the lens tube and lens casing are designed allows for the lens to be moved to the left and right. This allows the users to alter the ILD of the lenses. The lens tube keeps the lens in place, together with the front cap of the lens tube. There are two lens tubes in the product, one for each lens.

9.3.6. Tube front cap

The front cap of the lens tube is a cap which can be connected to the lens tube. The cap keeps the lens in place on the front, while the lens tube keeps the lens in place from the back. The front cap can be connected to the tube by using an adhesive. There are two front caps in every product, one for each lens.

9.3.7. Slider

The slider is connected to the lens casing using two screws. The slider is also embedded within the front part of the product, which restricts the slider from rotating in any direction and moving sideways. Because the slider cannot rotate, it allows the movement of the lens to the front and back to happen in a smooth fashion. The slider acts as a user-friendly interface for changing the lens depth. The slider contains small notches, which make it easier for the user to find grip. There are two sliders, one for each lens.

9.3.8. Clasp

The clasp is connected to the lens casing using an adhesive. The clasp prohibits the lens tube from moving to the front, while the casing itself prevents the lens tube from going to the back, top and bottom. There are two claps, one for each lens.

9.3.9. Phone holder

The phone holder is a sub-mechanism inside the product, consisting of two parts. The parts are located to the front and back of the rear part, and are connected to each other using a screw. The purpose of the phone holder is to align the user's smartphone with the horizontal axis. If the smartphone is not aligned with the horizontal axis, this can result in double vision which cannot be solved by altering the ILD setting. The mechanism allows the user to choose three different settings for the phone holder. The best setting depends on the size of the phone. The phone holder is shaped in such a way that it cannot rotate in any direction. Its shape also prevents it from moving to the front or back, or to the left and right.

9.3.10. Prism tube

The prism tube is an additional part of the product, which was especially designed for strabismic users. The tube consists of two parts: the rear part can be clicked onto the lens tube, and contains an opening for a piece of Fresnel prism foil. The front part can be placed over the rear part, and connected to the rear part using an adhesive (superglue).

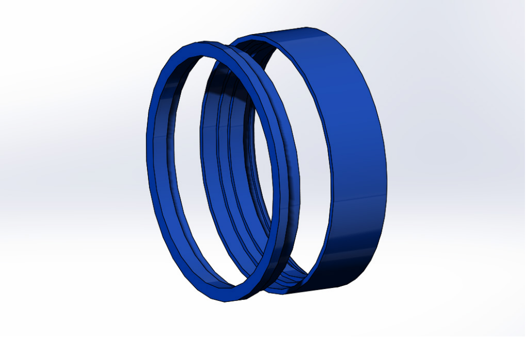


Figure 43: front and rear part of the prism tube

9.4. Product assembly

The product has been designed in such a way that the assembly and disassembly of the product is easy. The clasps are connected to the lens casings by means of an adhesive (superglue). The front caps are connected to the lens tubes by means of superglue, after placing the lenses inside the tubes. The lens tubes and lens casings are designed in such a way that the tubes can easily and quickly be placed in and out of the casings. Lastly, the sliders are connected to the lens casing by using 4 screws (steel, 2,2 x 9,5 mm).
The lens casings, containing the lens tubes, lenses, clasps and sliders, are connected to the metal rods, which are connected to the rear part of the product. The front and rear part of the phone holder are connected to the rear part of the product using a single screw (steel, 2 x 6 mm). Afterwards, the front part and the mask can be connected to the rear part by using 4 screws (steel, 2,6 x 12 mm). Finally, the two sliders are connected to the front part using 2 screws (steel, 2 x 6 mm).

Finally, the additional parts are added to the product. The straps can be connected to the front part of the product. The elastic bands can be connected to the rear part of the product. Finally, the soft mask can be connected to the plastic mask by using an adhesive.

A good thing about the design of this product is that it is easy to assemble and disassemble it, because a lot of the parts are connected using screws. Because of this, faulty parts can be replaced without needing to destroy the product in the process.

Figure 44: the QR code above links the user's phone to the VR device

9.5. Use of the product

The interaction between the user and the product starts with setting up the product. This will likely have to be done by the parents of the amblyopic children. Setting up the product will be done by scanning a QR code using the smartphone which will be used for the dichoptic training. The QR code is a code in the form of a scannable sticker, located on the VR device. The QR code contains the following information about the VR device:

- Focal length of the lenses
- ILD
- Lens alignment (with relation to top, bottom or center)
- Lens distortion coefficients

Scanning the QR code will connect the properties of the VR device with the properties of the smartphone. Doing so will make sure that the displayed image is optimized for this particular smartphone using this particular VR device. Users should always scan the QR code of the VR device they are using, but it is especially important for this product as it contains properties that are different from usual VR devices, especially regarding ILD settings.

9.5.1. Customization

Several aspects have been designed in order to improve the user's interaction with the product, which allows users to customize the product to their liking in several ways. First of all, users can choose a slightly longer face mask, which allows more space for using glasses inside the VR device. Secondly, users can choose a soft mask in one of three different sizes. These different soft mask sizes take into account the varying head sizes of users. Finally, strabismic users can use a tube containing an optical prism, which can be clicked onto the lens tube of the VR device. Customization allows users to adapt the product to different head sizes, glasses and strabismic users.

9.5.2. ILD

There are also other features of the product which can be altered by the user. The first aspect is the ILD setting. The ILD setting should be the same as the ICD setting of the in-game cameras. In other words, the hardware should match the software. Additionally, the image quality and user experience will be the best if the ICD and ILD match the user's IOD. The value of the ICD is stored in the QR code mentioned above. In order to take into account users with different IOD values, multiple QR codes will be made for different IOD brackets. This way, there will never be a large difference between the user's IOD and the ICD and ILD.

9.5.3. Lens depth

Another aspect which can be customized by the user is the lens depth, relating to the focus of the lens. Every user has an ideal focus point that might differ from other users. The ideal focus point is the point where the user can focus at without flexing the ciliary muscles in the eyes. For users without refraction errors this distance is infinitely far away. For users with refraction errors this distance is more or less than infinitely far away. In severe cases these users would be treated using glasses or contact lenses. It is not the purpose of the adaptable lens depth to completely correct for the user's refraction error. Instead, users can use their glasses or contact lenses inside the VR headset, and they can adjust the lens depth for fine tuning. Fine tuning the lens depth is very useful for users, in order to find the sweet spot where the user can focus on the image without effort of the ciliary muscles.

Chapter 10

Product Development

10. Product Development

In the previous chapter the variable design was explained, which influences the product properties. Additionally, the design of the plastic parts was explained. In this chapter will be explained how the concept can be developed into a physical product. This is done by producing all of the components using the most suitable production method, and then assembling all the components into a single product. This chapter will explain why certain materials, components and production methods were chosen for the development of this product.

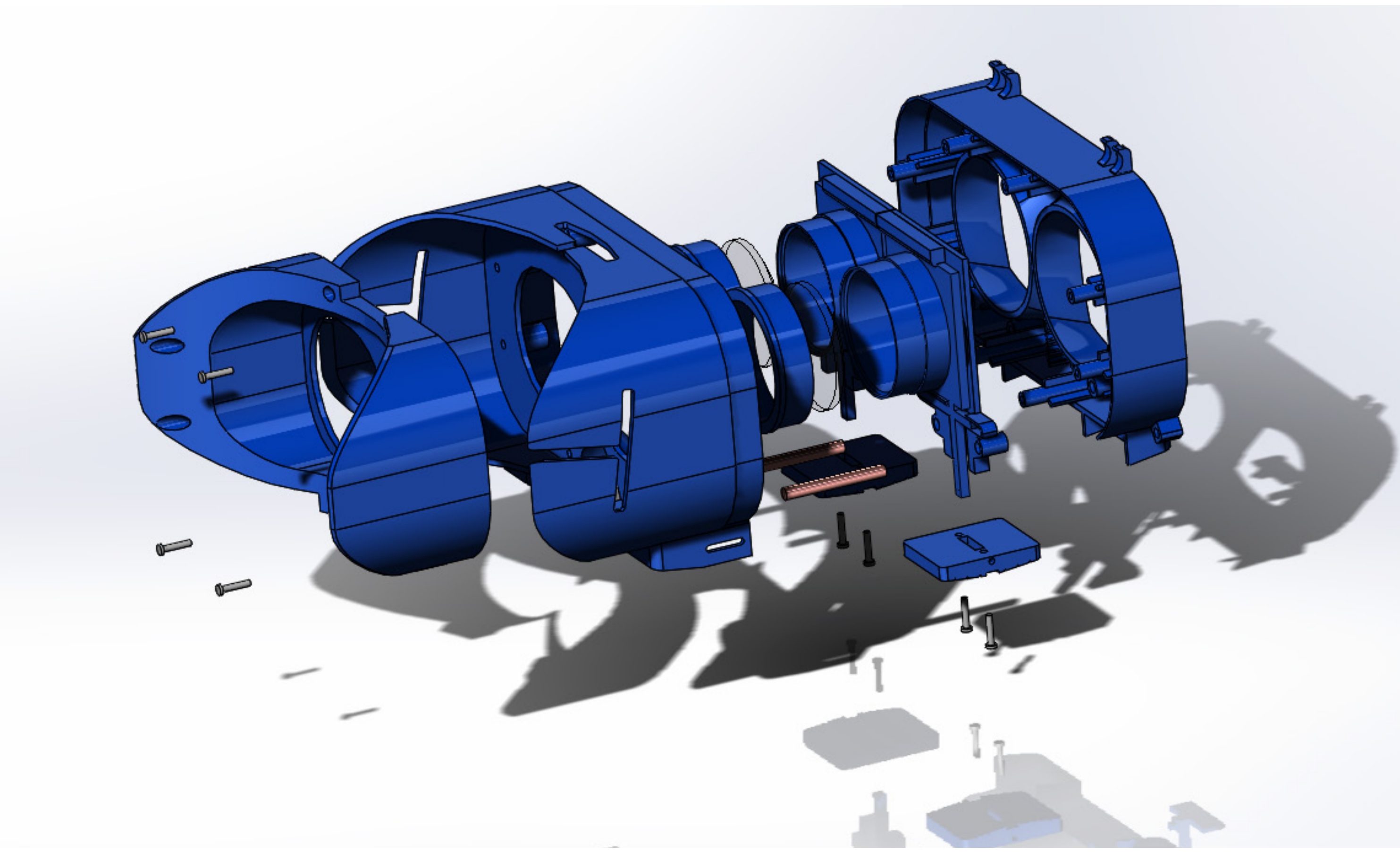


Figure 45: exploded view of the product

10.1. Plastic part development - Phase 1

As explained in chapter 3, the first phase of Vedea's product strategy will require 50 products which will be used during the clinical trial of the Vedea product. The quality of the physical product should be approximately the same as the MVP from phase 2. Due to the small batch size, 3D printing is probably the only suitable production method for this phase. The advantage of 3D printing is that it is relatively easy, it does not require an initial investment, and small quantities do not require a long lead time. The disadvantages of 3D printing are that the variable cost is very high, and the surface quality of the parts is not optimal. As a result, the products in phase 1 will be more expensive and of lesser quality than the products from phase 2. On the other hand, the initial investment for phase 1 will also be significantly less. The costs of 3D printing the plastic parts were estimated to be 60 - 80 euros per product. The initial investment for 3D printing will be zero, as all the work will be outsourced.

10.2. Plastic part development - Phase 2

In phase 2 of Vedea's product strategy, the batch size increases to 20.000 products over a period of three years. Because of the higher batch size, injection moulding would be the most suitable production technique for this phase. The advantages of injection moulding with regards to 3D printing is that the variable costs are much lower, the surface quality of the parts will be higher, and the lead time is much faster. The downside of injection moulding is that it requires a significant initial investment. Multiple companies have given a quote for the molding costs of the VR device, ranging from 20.000 to 60.000 euros. It is estimated that the molding costs will be approximately 30.000 euros in total. The material used for the injection molding will be approximately 0,39 euro (based on a price of 1,30 euro per kg). The labour and machining costs were estimated to be 7,50 euro, based on 50 parts per hour, 25 euros per hour, and 15 parts per product. The variable costs of the injection molded plastic parts will therefore amount to approximately 7,89 euros, although this number can differ based on the injection molding company.

10.3. Material choice

The type of plastic which is to be used for the plastic parts of the product needs to be considered carefully. There are many different types of plastic, and each type of plastic has different values with regards to density, yield strength, tensile strength and price per kg. The type of plastic which is used will determine the weight and the structural stability of the product. Furthermore, different types of plastic may cause more friction than other parts. Moreover, not all plastics are suitable for injection molding and 3D printing respectively. Below is a table containing various common types of plastic, rated on tensile strength, price, density and yield strength, including combinations of those four factors.

Material	Tensile strength (psi)	Price (€/kg)	Density (kg/m3)	Yield strength (MPa)	Yield strength / density (MPa*liter/kg)	Tensile strength / density (psi*m3/kg)
ABS	4,100	0.64	1,052	39	37.1	3.9
LDPE	1,400	0.78	913	11.5	12.6	1.5
HDPE	4,000	0.25	941	26.3	27.9	4.3
PC	9,500	0.95	1,190	64.3	54.0	8.0
PET	11,500	0.41	1,450	40	27.6	7.9
POM	10,000	0.71	1,410	59.5	42.2	7.1
PP	4,800	0.57	913	38	41.6	5.3
PS	7,600	0.75	640	33.7	52.7	11.9
PVDF	6,000	-	1,770	55	31.1	3.4
TPE	3,000	0.74	1,183	20.5	17.3	2.5
PETG	6,450	21.98	1,380	43.5	31.5	4.7

When looking at yield strength, the best materials would be PC and POM. If we factor in density too the best materials would be PC and PS, followed by POM and PP. When looking at tensile strength, the best materials would be PC, PET and POM. When factoring in density too, the best material would be PS, followed by PC, PET and POM. Because the material cost of the plastic parts is insignificant compared to the total costs of the product, it is best to select a material based on density, yield strength and tensile strength alone. In this case, the most suitable materials would be PC and PS, followed by POM and PP.

10.4. Additional parts

While the plastic parts of the product will have to be tailor-made for this project, other parts of the product can be bought from stores. First of all the product will require 11 screws and 2 elastic bands. These are parts which can be bought as stock products. These parts do not require customization and are readily available for a low price. Secondly the product requires 4 metal rods. While long metal rods with the right diameter can be bought from stock, it is likely that the rods will have to be cut into the desired length. This will require an extra step of manual labour, which will make those parts extra expensive.

10.4.1. Straps

The straps are a product made of elastic bands and a leather connection piece. The function of the straps is to keep the VR device in place and connected to the user's head. Straps for VR devices are readily available on Alibaba.com.

10.4.2. Face cushion

The face cushion or soft mask is a part that acts as cushioning between the plastic parts of the VR device and the user's head. While there are face cushions available in certain shapes and sizes, the face cushion should be tailored to the shape of the front mask of the VR device. For this product, a supplier was found on Alibaba.com which develops custom-made soft masks for VR devices. The soft masks cost up to 1,40 euro and require a 300 euro investment for the tooling costs.

10.4.3. Lenses

Finally, the lenses will also be bought from a third party supplier. The lenses are the most complicated part which has to be store-bought, and they also require the most customization. The chosen lenses for this product are best-form convex lenses, with a focal length of 45 mm and a diameter of 42 mm.

10.5. Cost analysis

The costs of the product can be divided into variable and fixed costs. Both the variable and fixed costs depend on the chosen production method.

Variable costs

3D printing	
Plastic parts	70 euros
Injection molding	
Plastic material	0,39 euro (1,30 euro per kg)
Labour and machining costs	7,50 euro (25 euro per hour, 50 parts per hour)
Total:	7,89 euro
Other	
Straps	0,80 euro
Lenses	1,00 euro
Soft mask	1,40 euro
4x metal rod	0,67 euro
11x screw	0,28 euro (11 x 0,025 euro)
Elastic bands	1,00 euro
Assembly costs	2,00 euro
Packaging	0,07 euro
Total:	6,22 euro

Fixed costs

Mold plastic parts	30.000 euros
Tooling costs soft mask	300 euros

Total costs

3D printing costs:	300 fixed + 76,22 per product
Injection moulding costs:	30.300 fixed + 14,11 per product

It can be seen that the fixed and variable costs differ greatly depending on the used production method. 3D printing requires hardly any initial investment, but the products will cost approximately 75,22 euros per product. This is not ideal, because it is not a competitive price when compared to similar existing VR devices. By using injection moulding, the variable price can be brought down to approximately 13,11 euros per product. This price is very competitive, and is much cheaper than similar existing VR devices. The downside of this option however is that it requires an initial investment of 20.000 to 60.000 euros for the design and production of the moulds. Another downside of injection moulding is that it adds certain risks. If a flaw in the design of the product is found after producing the moulds, this will require a new mould or even a complete set of moulds. This is a problem that does not occur with 3D printing. Another problem with injection moulding is that it is only profitable when there are enough customers. The break-even point for changing to injection-moulding is when there are 483 new customers.

It should be noted that the costs given in this chapter are not the total costs of the product. For example: storage, packaging and transportation of the product are not taken into account in this cost analysis. Furthermore, a cost analysis of a product usually contains a profit margin and overhead costs. It should be noted that in the case of Vedea it may not be necessary to make a profit on the sale of the VR device. The reason for this is that Vedea's main activity is the development of VR gaming content, which can be rented to users on a subscription basis. Making profit on the sale of the VR device is optional, and therefore depends on Vedea's company strategy.

Chapter 11

Evaluation

11. Evaluation

In order to evaluate the product design, the product will be evaluated based on three criteria. First of all, there will be reflected on how well the product meets the project assignment. Secondly there will be reflected on how well the product meets the design requirements of chapter 8. Lastly, the product will be compared to two existing VR headsets which are also marketed towards younger children. The goal of this chapter is to give more insight into the specifications of the product.

Figure 46: high quality render of the product in a home setting

11.1. Reflection on the project assignment

The goal of this project was to develop a VR headset for amblyopic children that meets the following criteria:

1. *Children should be able to use the smartphone devices of one of their parents.*

The product relies on the user's smartphone.

2. *Children should be able to comfortably wear the head mounted display for 30-60 minutes per day.*

The product is smaller and lighter than conventional VR headsets, therefore it will be more comfortable than existing devices. The product contains cushioning on the face mask, so that the VR device can be comfortably worn. The left and right straps allow the user to make the fitting more or less tight, while the strap on the top allows the user to adjust the height of the VR device.

Regarding the visual experience, the VR device has an adjustable lens depth as well as an adjustable ILD. The adjustable lens depth allows the user to project the image at infinity, which allows for minimal stress on the ciliary muscles in the eye. The adjustable ILD in combination with the right QR code allows the user to match the ILD and ICD to his IOD. Doing so minimizes double vision as well as warp distortion. A good fit between ILD and IOD minimizes the physical discomfort that is caused by having an ILD that is higher than the user's IOD. **[9]**

3. *The head mounted display should be customizable to head circumference.*

The mask fit of the product is smaller in width because the head breadth of young children is smaller than that of adults. Additionally, users can choose different thicknesses of cushioning, which allows for customization of the mask width.

11.2. Reflection on design requirements

The following requirements are additional requirements for the MVP based on the analysis and product strategy:

Requirement	Result
The maximum production costs of the product are €40,-	The product has an estimated variable cost of 13,11 euros when injection molded. The production costs can be lower than 40 euros depending on the mold costs and production volume.
The product is compatible with the majority of contemporary smartphones.	The product is compatible with the 12 most popular smartphones in the Netherlands in 2019, which comprises 50% of all smartphones in the Netherlands in 2019. **[52]** It is therefore assumed that the product is compatible with the majority of contemporary smartphones.
The lens depth is adjustable.	Yes.
The ILD is adjustable.	Yes, ranging from 47 to 62 mm.
The focal length of the lenses does not exceed 60 mm.	The focal length is 45 mm.
The product is compatible with children aged 4-7.	The ILD is compatible for 83% of children aged 4-7. **[54]** For children aged 6 and older this number will be higher. (see chapter 11.3.1)
The product is compatible with users with refraction errors.	Users with refraction errors can wear prescription glasses or contact lenses inside the VR device.
The product is compatible with strabismic users.	Users with strabismus can use a corrective prism, which was designed as an add-on for the product.
The image distance can be set to infinity.	Yes.
The ICD matches the ILD of the lenses.	The ICD can be matched to the ILD using a QR code.
The maximum weight of the product is 300 grams.	The weight of the product is 250 grams.
The VR device does not cause physical discomfort, eye-strain or nausea.	Steps have been taken to reduce physical discomfort, such as matching the IOD, ILD and ICD, using proper lenses, and using proper cushioning.

The following aspects are wishes for the product:

Wishes	Result
The refresh rate is at least 90 Hz.	The refresh rate depends on the user's smartphone. Some smartphones have the option to set the refresh rate to 90 Hz or higher, but most have a fixed refresh rate of 60 Hz.
The ICD and ILD match the user's IOD.	The ICD can be matched with the ILD. The ILD ranges from 47 to 62 mm, making it suitable for 83% of children aged 4-7, and more for older children. **[54]**
The resolution is at least 9 PPD (15% visual acuity).	The resolution depends on the display resolution of the smartphone. The resolution will be lower at the center, and higher at the edges of the viewing window.
The VR device has a horizontal FOV of at least 70 degrees.	The product has a horizontal FOV of 90,6 degrees.
The product is compatible with users with an IPD between 47 and 62 mm.	The product is compatible with users with an IOD between 47 and 62.

11.3. Comparison with competitor products

In order to determine how the product relates to existing VR devices for children, the product will be compared to the Destek VR Dream **[11]** and the Heromask **[12]**. Both of these devices are marketed towards younger children (5-15 years old and 5-12 years old respectively). The Vedea VR headset is mainly designed for children aged 4-7.

11.3.1. ILD

The gravest difference between the Vedea VR headset and its competitors is the ILD range of the lenses. The Destek and Heromask have a minimum ILD of 57 and 62 mm respectively. According to Dodgson, **[46]** 4 year old girls have a mean IOD of 47 mm, 4 year old boys and 5 year old girls have a mean IOD of 49 mm, and 5 year old boys have a mean IOD of 51 mm, the standard deviation of all groups being 3 mm. This means that for boys and girls aged 4-5 years, the Destek would have a mismatch between the IOD and ILD in 99% of the cases. The Heromask would even have a mismatch in 100% of the cases. The Vedea VR headset with a minimum ILD of 47 mm would only cause a mismatch in 27% of the cases, which makes it significantly more suitable for younger children. This is of importance for VR devices, because having an ILD which is higher than the user's IOD can cause a number of unwanted symptoms, such as headache, eye-pain and nausea. **[9]** Furthermore, a mismatch between IOD and ILD causes optical distortion of the provided images, causing a decreased optical quality of the virtual environment.

While the Vedea VR device was specifically designed for children aged 4-7, it may also prove useful for older children. According to Stubgaard & Fledelius **[55]**, 37% of children aged 8-10 have an IOD lower than 57 mm, making the Destek incompatible. For the Heromask, the in-compatibility would be 91% with regards to children aged 8-10. Even some adults, especially females, may profit from using the Vedea VR device instead of a regular VR device. It was found using statistical analyses that 5% of adult females and 1% of adult males are not able to use the Destek, while 50% of adult females and 25% of adult males are not able to use the Heromask.

11.3.2. FOV

The Destek, Heromask and Vedea headsets all make use of lenses with a diameter of 42 mm. It should be noted that approximately the outermost 2 mm of the lens are not visible due to the shape of the lens tubes, which applies to all products. The differentiator with respect to FOV is in this case the size of the looking hole. The Destek has a FOV of 73,5 x 67,4 degrees, based on the size of its looking hole. The Vedea product has a FOV of 76,8 x 71,5 degrees. Finally, the Heromask has a FOV of up to 90,0 x 70,8 degrees, although this number can be lower based on the selected display position.

11.3.3. Product width

The average six year old has a head width of 8,7% smaller than the average adult **[56]**. If this number is extrapolated for caucasians, the average head width of a caucasian six year old would be 135 mm. The Vedea VR device has a mask width of 170 mm. The Heromask has a width of 184 mm, and the Destek has a width of 175mm. The Vedea VR device has a mask width that better approaches the actual head width of young children. For the Vedea device, a width of 170 mm was chosen in order to make space for children with prescription glasses. It is okay if the mask width is higher than the head width of the user, because the fit can be adjusted using straps and cushioning.

11.3.4. Product weight

It was found during playtests by Vedea that children aged 4-7 sometimes have trouble withstanding the weight of VR devices. For this reason the Vedea VR headset was deliberately designed to be lighter than its competitors, albeit at the cost of the product's structural stability. The Destek has a weight of 0.32 kg and the Heromask a weight of 0.33 kg, while the Vedea product only weighs 0.25 kg.

11.3.5. Conclusion

The Vedea VR device has a lower minimum IPD setting, making the product more compatible for young children than the Destek and Heromask. The Vedea device is also 23% lighter and has a smaller mask fit. The FOV of the Vedea device is higher than that of the Destek, but the Heromask can achieve a higher FOV depending on the display placement.

	Minimum ILD (mm)	Compatibility IOD 4-5 year olds	Max. FOV (degrees)	Product width (mm)	Weight (kg)
Destek	57	1%	73,5 x 67,4	175	0.32
Heromask	62	0%	90,0 x 70,8	184	0.33
Vedea	47	73%	76,8 x 71,5	170	0.25

Chapter 12

Conclusion

12. Conclusion

The purpose of the design assignment belonging to this report was to design a VR headset for amblyopic children aged 4-7. In order to design an optimal product for this situation, research was conducted on how a VR device for amblyopic children should differ from a regular VR device. The conclusion of this research is split into two parts. First will be examined how a VR device for children should be designed. Secondly will be examined how a VR device for amblyopes should be designed.

Figure 47: high quality render of the product in a home setting

12.1. VR device for children

In this thesis it was researched how VR can be implemented to provide medical treatment for children. It was found that there are a number of points where a VR device for children differs from a VR device for adults. First of all, children have smaller heads than adults, because children's heads have not fully grown yet. For VR, this is especially noticeable regarding the head width. The average 6 year old has a head width that is 8.7% smaller than that of the average adult. **[56]** To combat this, VR devices for children should contain a front mask that is less wide, depending on the age of the child.

Secondly, the weight of the VR device causes a moment, which results in additional stress on the neck muscles and the cervical spine. From testing by Vedea Healthware BV on children aged 4-7 it became apparent that children in this age group had more difficulty with handling the weight than the average person. This led to the hypothesis that children aged 4-7 require a product that induces less stress on the neck. This can be done by reducing the weight of the VR device, or by decreasing the product depth in order to reduce the arm causing the moment. Decreasing the weight can be done by reducing the wall thickness, but this will also reduce the stability of the product, causing it to break more easily. Reducing the product depth can be done by choosing a lower focal length and object distance. This will however increase the lens aberrations and cause a higher content magnification. Reducing the forces on the neck will always come with certain negative consequences. For this reason, good trade-offs should be made between weight and other factors.

Thirdly, small children have an IOD that is much smaller than that of the average person. Most VR devices are not compatible with people with low IODs, let alone children. If there is a mismatch between the ILD of the lenses and the user's IOD, this will result in a distortion of the image. The larger the mismatch, the greater the distortion will be. Even more importantly, according to Regan and Price **[9]**, having an IOD that is smaller than the ILD of the lenses will result in e.g. headaches, eye-pain, double vision, blurred vision and nausea. Statistical analyses show that 73% of children aged 4-7 are compatible with the Vedea VR device, compared to 1% and 0% of other VR devices for children.

Another point of attention is that young children may have difficulty with the correct configuration of the VR device. First of all, the ILD of the lenses needs to be adjusted to the ICD of the software. Secondly, the lens depth has to be adjusted to the sweet spot of the individual user. It was found during testing by Vedea that children aged 4-7 generally do not seem to understand the terminology associated with the configuration of the product. Children generally do not understand terms like a 'sharper' image, which makes it difficult to set up the product correctly. In the case of Vedea, the users of this product are amblyopic children with underlying eye conditions, which makes it even more difficult to correctly set-up the product as these children are not used to seeing clear images with their weaker eye.

12.2. VR dichoptic training for amblyopic children

In chapter 2.2 it was explained why dichoptic training is a more effective and more child-friendly treatment than existing treatments for amblyopia. It was also explained that VR is a suitable medium for dichoptic training, because it is more immersive and keeps users more engaged than other media.

Providing VR dichoptic training for amblyopic children comes with the usual challenges of VR devices for children as explained in the previous section: head width, weight, IOD and configuration should be taken into special consideration. However, providing dichoptic training also comes with additional challenges. It should be taken into account that amblyopes usually have underlying eye conditions, the most common ones being refractive errors and strabismus. Refractive errors can in theory be corrected by adjusting the lens depth up to a certain point, but usually it is better to correct this using glasses or contact lenses. The reason for this is that changing the lens depth too much will decrease either the vertex distance or FOV.

Secondly, strabismus should be corrected by using a corrective prism. Luckily, it is possible to attach a corrective prism to the VR device, which allows strabismic users to use the VR device as well. The prism should be tailored to the user's eye deviation. It should be noted however, that an optical prism does decrease the optical quality of the image. Additionally, children with esotropia (one or both of the eyes turning inwards) may have an increased difficulty finding the right ILD, as the ILD will need to be several mm lower than their IOD.

Probably the most important variable when designing a VR headset for amblyopic children is the match between IOD, ILD and ICD. It was found in chapter 5 that a mismatch between ILD and ICD causes double vision, and a mismatch between IOD and ILD causes a warped image. While these effects are undesirable in general, they are even worse for amblyopes as they are already prone to ignore the visual information coming from their weaker eye. A mismatch between IOD, ILD and ICD will make it even harder for their eyes to work together, and therefore undermines the purpose of dichoptic training.

Chapter 13

Discussion and Recommendations

13. Discussion and Recommendations

It was found in this study that a VR device for children should be slightly different than a VR device for adults. Younger children require a lighter and smaller product, with the option to set the ILD and ICD to a low value, preferably equal to their own IOD. Using this product for amblyopic children comes with its own challenges, namely that the product should adapt to the underlying eye-conditions of the users. The most common conditions in this regard are refractive errors and strabismus, which can both be solved by using optical tools.

It is not surprising that a VR device for children has different requirements than a VR device for adults. While VR headsets for children did already exist before writing this report (although these were hard to find), it was surprising to find that the existing headsets for children were so unsuitable to young children in certain aspects. The minimum ILD, the mask width and the weight of these products were still very high, and not much different from a regular VR headset for adults. The actual target group for existing VR devices for children is actually much higher than advertised. For this reason, the Vedea VR device fills a gap in the market. While the Vedea VR device was specifically designed for children aged 4-7, it will also be useful for a large minority of children aged 8-10 (37%), and even for adults with low IODs (5% of adult females and 1% of adult males). The product is also suitable for children without amblyopia.

The main focus of this research is to find out in which ways a VR device should be adapted in order to be suitable for amblyopic children. The main focus with regards to this is on the hardware product. However, an important aspect of the dichoptic training is the software content, while the hardware is merely the enabler of the dichoptic training. Because Vedea's game content is still in development at the time of writing, no testing has yet been done on how to best perform the dichoptic training. It may be a worthwhile addition to this research to find out how dichoptic training can be optimally performed. This could also be linked to specific hardware requirements, such as a minimum FOV or display resolution.

Another recommendation for further research is the effectiveness of the dichoptic training based on the IOD - ILD mismatch. According to statistical analyses of the IOD of the target group, it was found that with the product's current ILD range it would match 83% of all children aged 4-7 (low estimate, based on caucasian children) **[54]**. It would be interesting and useful to find out if dichoptic training is still effective with an IOD - ILD mismatch of 1 or more millimeters. It should be found out if the effectiveness of dichoptic training decreases when the mismatch becomes larger.

Lastly, Vedea will start its clinical trial in the fall of 2021. During the clinical trial it will be found out if the dichoptic training offered by Vedea is as effective as existing methods for dichoptic training. If the training by Vedea is not as effective as existing training methods, this would indicate a flaw in the hardware and/or the game content. Additionally, during the clinical trial it can be found out if the hardware product is indeed suitable for amblyopic children aged 4-7, how the product compares to conventional VR devices.

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