FAKULTÄT
FÜR !NFORMATIK
Faculty of Informatics

Effects of VR-Displays on Visual Acuity

BACHELORARBEIT

zur Erlangung des akademischen Grades

Bachelor of Science

im Rahmen des Studiums

Medieninformatik und Visual Computing

eingereicht von

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Wien, 21. August 2019

Lara Panfili	Michael Wimmer

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BACHELOR'S THESIS

submitted in partial fulfillment of the requirements for the degree of

Bachelor of Science

in

Media Informatics and Visual Computing

by

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Vienna, 21st August, 2019

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Erklärung zur Verfassung der Arbeit

Lara Panfili

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Lara Panfili

Danksagung

Mein hauptsächlicher Dank gilt meiner Betreuerin Katharina Krösl für ihre Unterstützung und die hilfreichen Räte bei der Implementierung dieser Arbeit.

Ein ganz besonderer Dank gilt meinen Eltern, da sie mir das Studium erst ermöglicht haben und meiner Schwester, die mir in der Zeit der Thesis-Erstellung stets Mut zugesprochen hat.

Letztlich richte ich auch ein Dankeschön an meinen Onkel und meine Tante für das Korrekturlesen meiner Arbeit.

Acknowledgements

First of all, I would like to thank my supervisor Katharina Krösl for her precious support and the helpful advice throughout the implementation of this work.

Furthermore, I want to express my deepest appreciation to my family for giving me the opportunity to accomplish my studies. A special mention to my sister, who has always encouraged me during the writing of this thesis.

Finally, I also want to express my gratitude to my uncle and my aunt for proofreading my work.

Kurzfassung

Die wahrgenommene Sehschärfe eines Menschen in der realen Welt ist nicht identisch mit der Sehschärfe beim tragen eines Head-Mounted Display, kurz HMD, und betrachten einer virtuellen Umgebung. Der Grund dafür ist die Reduzierung der Sehschärfe in der virtuellen Umgebung, die von unterschiedlichen Faktoren verursacht wird; wie zum Beispiel die schlechtere Auflösung des HMDs. Aufgrund dieser Umstände sinkt die Kapazität einer Person kleinere Details zu erkennen. Vorangegangene Studien zu Virtual Reality (VR), die die Sehkraft gemessen haben, haben verifiziert, dass die beste Sehschärfe in virtuellen Umgebungen immer eine Stufe niedriger als die natürliche Sehkraft ist. Deswegen führt alleine schon die Verwendung eines VR-Displays zur Herabsetzung der Sehschärfe in einem Ausmaß, dass als leichte Sehbehinderung eingestuft werden kann.

In dem in dieser Arbeit vorgestellten Projekt wurde erforscht, um wie viel die Sehschärfe eines Menschen in VR herabgesetzt wird, und, ob diese Verminderung der Sehschärfe in der virtuellen Realität von allen Personen gleich wahrgenommen wird, beziehungsweise welchen Einfluss Sehstörungen, wie Kurzsichtigkeit, auf die Wahrnehmung in VR haben.

Basierend auf einem vorhergehenden Projekt wurden zwei unterschiedliche Tests mit der Game Engine *Unreal Engine 4* entwickelt: eine Version in VR, für die ein HTC VIVE Headset verwendet wurde, und eine Desktop-Version. In einer User Study wurde mit Hilfe dieser beiden Versionen jeweils die Sehschärfe der Teilnehmer gemessen. Die Ergebnisse wurden miteinander verglichen um herauszufinden, inwieweit Sehstörungen die Sehschärfe beeinflussen.

Abstract

The perceived visual acuity (VA) of people in virtual reality (VR), using a head-mounted display (HMD), is not equal to their VA in the real world. The reason for this difference is the reduction of visual acuity in the virtual environment that is caused by various factors, such as the low resolution of the VR display. Based on those circumstances, the capacity of an individual to distinguish small details diminishes visibly. Previous studies regarding eyesight in VR have already verified how the best visual resolution in virtual environments is always lower than the natural vision and therefore this aspect could be seen as a mild vision impairment for the users of an HMD.

The goal of this project is to investigate how much the VA is reduced in VR and respectively whether the decrease of VA in VR is perceived similar by everyone or if visual impairments like Myopia, influence the visual perception.

Based on a previous project, two different tests were implemented with the game engine *Unreal Engine 4*, a VR version for which an HTC VIVE headset was used, along with a desktop version. These tests were used to investigate the VA of the participant in a user study and the results have been compared to each other in order to find the extent to which visual impairments have an impact on VA.

Contents

CHAPTER 1

Introduction

The idea of recreating different versions of our world and projecting them in a virtual world in order to offer users an experience of reality without actually living in it is called virtual reality (VR). At the end of the 20th century, VR became very popular [MG99] and starting from 2014 technology companies decided to invest billions of dollars in the VR-field [LaV19]. This reborn interest in VR led to a new generation of engineers, allowing the fast development of new VR-technologies and their usage in multiple activities such as games and scientific visualizations [LaV19].

The possibilities and advantages that VR could bring to humanity are manifold. Sectors like education, training and entertainment could benefit considerably from VR, making it possible to simulate potentially dangerous situations instead of experiencing them in the real world. Flight simulations represent an example; in this case pilots have the possibility to deal with scenarios and unsafe situations that would be incredibly dangerous to recreate or which would rarely happen in real life. Through VR technology, for instance, pilots can develop a greater awareness and confidence in their abilities, gaining practical experiences that could considerably increase their skills in comparison to just a theoretical education [VCJ17].

Certainly, in order to achieve a good simulation, the proposed virtual environment has to be as close to reality as possible, and, consequently, this leads to various obstacles. Until now, based on available technologies, a virtual experience can be experienced through a head-mounted display (HMD) and two motion controllers. One of the major problems of the HMD is related to the resolution and its connection to the field of view (FOV) [FMAFR03]. These two aspects lead to a less accurate visual acuity (VA) in comparison to the one that a user naturally has, namely in the real world. Moreover, another factor that could influence the VA is the brightness of the HMD and the way the light in the virtual world illuminates these virtual objects.

A low resolution in VR diminishes the experience of users with normal vision, since they perceive the virtual environments as less real or sharp than the real world. However, an important consideration should also be given to those users suffering from visual defects like Myopia, Hyperopia or Astigmatism.

The goal of this thesis is to develop a project with the game engine *Unreal Engine 4* (version 4.22.3) that offers the possibility to test the VA of users through a revisited eyesight test in a VR and a non-VR setup, in order to verify how intense the distinction in the perceived VA between the two environments for people with visual impairments is and how much this could influence the experience. Regarding people with visual defects, in this project only short-sighted subjects have participated in the user study.

For the non-VR version (desktop version), a simple monitor was used to display Landolt Cs while the test in VR has been conducted with the HTC VIVE Pro headset.

The outcome of the project should provide a tool for studying VA and investigating how the visual perception of users with visual defects is influenced when immersed in a virtual world.

CHAPTER 2

Related Work

In this chapter various works related to the theme of this thesis are presented and briefly described. These studies don't deal exclusively with the investigation of VA in the real world and in VR, rather they focus on separate elements of this subject such as HMDs, myopia and VR.

The project conducted by Fidopiastis et al. [FMAFR03] aims to provide an insight on issues of HMDs, with particular attention to the influence of the brightness and the trade-off between the resolution and the field of view of an HMD, both of which could negatively affect the VA of users. In order to test the visual perception of participants, they employed a computer generated Landolt C visual acuity test. The participants conducted the VA test on the computer and in an augmented reality environment under 3 different light levels. During the test, the participants with a VA worse than 20/20 wore either glasses or contact lenses. During the test, six different sizes of Landolt Cs were shown to the users at a distance of 1.85 metres from the monitor and 2 metres in augmented reality, since the size of the visual angle in the augmented environment wasn't equal to the one presented on the monitor. The results confirmed the hypothesis that the limit for VA using the see-through HMD system was equal to 4.1 minutes of arc (measure of the gap size). Regarding the light, there was no improvement by changing the light levels.

Turnbull and Phillips [TP17]] investigated the possibility that the extended use of a VR headset could cause ocular effects that would lead to the development of myopia. In order to study this scenario, they tested four different environments, indoor and outdoor, both in VR and in the real world, and then compared the physical changes of the eyes. According to the conducted tests, the use of the VR headset for 40 minutes did not affect the binocular vision in comparison to the vision in the real word. The results indicated that wearing HMDs in a virtual environment should not generate modifications in the visual system that could lead to myopia.

Similarly, Peli [Pel98] also studied the visual effects of HMDs. Since previous works concentrated on the visual function changes caused by short-term use of HMDs, Peli decided to investigate changes in binocular vision, resolution and accommodation after 30 minutes of using an HMD and compared them to those measured after the use of a desktop CRT display. However, the results obtained from these tests did not show a statistically significant difference in the visual system between the use of the HMD and the desktop CRT display.

A study about the different effects of head-mounted displays on visual performance [SHE+14] examined three types of HMDs in order to establish which one was the worst. To be able to accomplish this task, the authors of this study also measured the VA of participants with and without the HMD.

Krösl et al. [KEH+19] also implemented a medical test for the calibration process of VA in VR and for the determination of the HMD's influence on VA in their work regarding the simulation of vision impairments in VR. The Landolt C was chosen as symbol for conducting tests where participants had to identify five different Landolt Cs using a motion controller. If the number of correct answers was equal or higher than three, the next line of smaller Landolt Cs was presented, otherwise the test was concluded. The five rings didn't appear side by side but were shown one at time at a fixed distance to the VR headset. They also repeated the test with a simulated reduced VA and reduced contrast as part of their cataract simulation in VR. Without the simulation of this vision impairment, the participants reached a maximal value for VA equivalent to 0.5 in the decimal system (6/12), which is defined as "mild vision loss", while for the simulated tests the highest value was equal to 0.125. The VR version implemented for testing VA in this thesis is an improved version of the one used by Krösl et al.

"Evaluating the Applicability of Repurposed Entertainment Virtual Reality Devices for Military Training" is the title of another study [MOL18] regarding the quality of VR devices for military training. In this case Maxwell et al. wanted to demonstrate how the VA of users with normal vision is worse in VR due to the limitations of HMDs. Since military training requires a particular visual perception, the use of low-cost HMDs could negatively affect VR training tasks. For testing VA with the HMDs (HTC VIVE and Oculus Rift), they followed an approach similar to the one of this thesis: using a game engine (*Unity*), they developed a virtual environment, where they placed the texture of an eye chart (Snellen chart) on a geometric figure in an empty space at a distance of 20 feet from the viewport. The best VA value was equivalent to the smallest line of the eye chart recognized by the participants. With this paper, the authors proposed different methods for testing the VA of VR devices (considering the field of view, the size of the display, the pixel density and the distance to the viewed object) in order to assist in the decision of employing VR devices for military training.

CHAPTER 3

Background

The following chapter provides a theoretical background for the topic of this thesis. First the concept of visual acuity (VA) is examined. Then a description of the eye chart and its structure is presented, followed by the explanation of the VA measurements. Finally, the calculation for the size of an optotype is provided.

3.1 Visual Acuity

Visual acuity is a term used in order to describe the capability of the eyes to distinguish small details in the eye's view space from a specific distance. Two types of visual acuity can be distinguished: static VA, meaning that the observed object is stationary, and dynamic VA where either the observer, the object or both are moving [QACDS18]. VA is a measure to quantify how good and sharp the eyesight of a human being is.

VA is determined by the physics of the stimulus, the structure of the organism that receives and processes the external stimulus, and the reactions that trigger the response. For the evaluation of VA the eyeball per se, the receptor layer of the retina and the neural activity in the visual cortex are fundamental aspects. Specifically, the term *acuity* refers to the action that goes from seeing a physical object to the response of the organism. Through this test it is therefore possible to evaluate the correctness of the lens and cornea in focusing the light onto the retina, the responsiveness of the triggered neurophysiological reactions and the processing of information acquired through the vision. [BDE+09]

3.2 Eye Chart

In order to study and to measure the VA of a person the most common method is the eye chart, a chart that uses sets of alphanumeric symbols, called optotypes [JB04]. Usually optotypes are black characters on a white background.

One of the most common eye charts is the Snellen chart. This table of optotypes was introduced for the first time by the ophthalmologist Herman Snellen. In Snellen's table the optotypes are generated using either a 5x4 or 5x5 grid in which the thickness of the stroke measures one-fifth of the grid height and the selected typeface corresponds to the *serif*, characterized by shorter lines, in comparison to the one used to form the sign, linked to the extremities of the letter (as shown in Fig. 3.1). Regarding the style, Snellen tended to use the Egyptian paragon font. Some ophthalmologists encountered problems with this type of font, suggesting that the design, particularly the serif typeface, negatively influenced the readability of the letters, leading to identification errors during the exam. Therefore, many argued that the sans serif typeface was more suitable for this kind of test. For this reason, nowadays different versions of the eye chart exist, with different typefaces (serif or sans serif), font styles and letters. [JB04]

The most famous variant of the Snellen chart is the ETDRS chart, short for *early treatment diabetic retinopathy study chart*, which is considered to be a better version of the Snellen chart, because it does not have the same limitations such as the irregular progression of the size from one row to another and the readability of the letters [KKJ13].

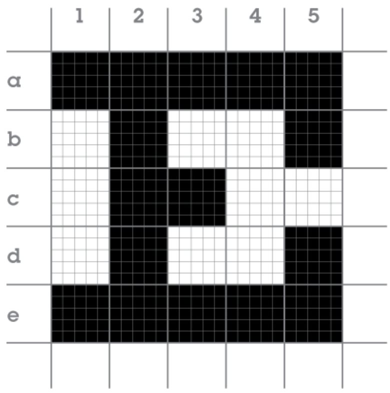


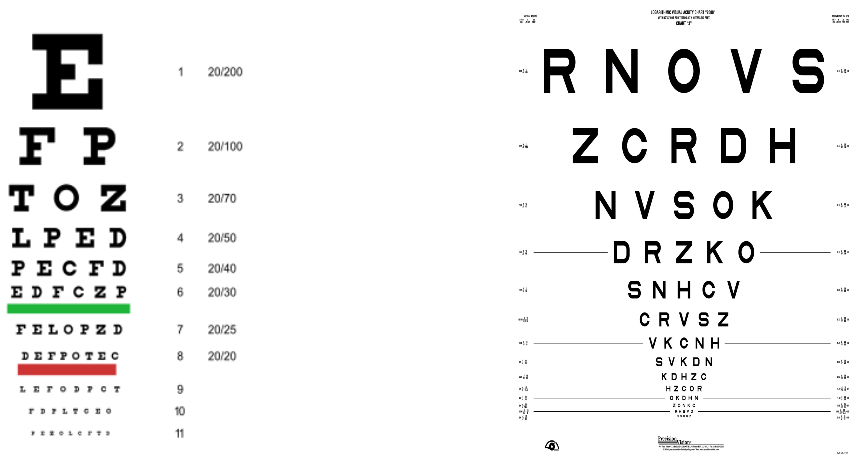
Figure 3.1: An illustration of the letter E in a 5x5 grid with the typeface serif [opt].

Concerning the measuring system, Snellen decided to use the minute of arc (*arcmin*) as unit and established that a "normal vision" should correspond to the capability to recognize an optotype subtending an angle of 5 minutes of arc from 20 feet away. The letters used were C, D, E, F, L, O, P, T, and Z, which normally are easy to differentiate; only F and P could be confused with one another when their size becomes significantly smaller. [LLC06]

All versions of the eye chart are structured in the same way, the first line contains the biggest optotypes and the following ones show a decreasing size of the symbols row after row. In modern charts the reduction in size from row to row follows a logarithmic progression [JB04].

The symbols on the Snellen chart are typically arranged in eleven rows. The first one contains one letter. Then the number of symbols in each line gradually increases and the size of optotypes decreases. (as seen in Fig. 3.2a) [LLC06]. Regarding the progression of the size from line to line in Snellen charts, as opposed to modern charts, it is established arbitrary and doesn't follow a regular scale [KKJ13].

The ETDRS chart is composed of 14 rows of letters with 5 symbols, where the distance in the row between each symbol corresponds to the size of the signs in that line, while the between-row spacing is equal to the height of the letter in the smallest line (as shown in Fig. 3.2b) [KKJ13].



(a) Snellen chart [opt]

(b) ETDRS chart [etd]

Figure 3.2: Illustration of different types of charts.

The test subject should read the symbols from a specific distance (the standard is 20 feet or 6 metres). Covering at first one eye, and then repeating the test with the other one, the subject starts from the top of the chart and continues scrolling the rows until he or she can't focus on the symbols anymore [KKJ13]. The smallest line that the subject can read without difficulties represents the VA score for the tested eye. Normally, in order to successfully pass a row and continue with the next row, the subject should recognize more than 50% of the current tested row [JB04].

As an alternative to these eye charts with common letters, there are also the *Lea Test* (as seen in Fig. 3.3), the *Tumbling E* and the *Landolt C*, also known as Landolt Ring. The first one was developed for preschool children while the last two are useful for testing subjects, who have no knowledge of the Roman alphabet or who are unable to read. The Tumbling E resembles a stylized letter E, and the goal is to indicate the direction in which the E is pointing: up, down, right or left (as shown in Fig. 3.4). [LLC06]

The variant with the Landolt C is the symbol used in the project of this thesis. According to the International Council of Ophthalmology, it represents the most solid symbol for measuring VA [LLC06]. The Landolt C, as illustrated in Figure 3.5, has the same

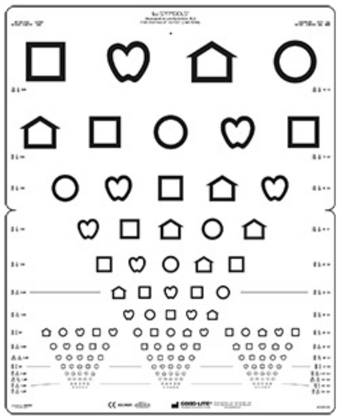


Figure 3.3: Lea test chart [lea].

Figure 3.4: Tumbling E. Reprinted from [KBB+17].

dimensions as the Snellen symbols, meaning that the size of the gap is equal to one-fifth of the sign's height. The task for the test subject is to recognize where the gap of the Landolt C is facing [VDMB07]. With this kind of eye chart the subject has to identify the orientation of the gap. Generally, the four directions are up, down, right and left; however, many variations resort also to diagonal positions (at 45 degrees) in between the classic ones.

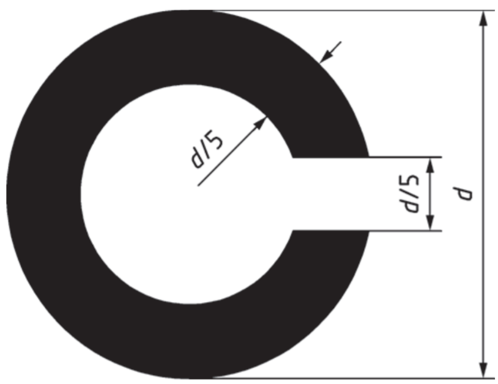


Figure 3.5: A visualisation of the Landolt ring where the size of the gap and feature are equal to 1/5 of the symbol's height. Reprinted from [ISO09]

3.3 Acuity Measurement

In order to calculate VA, different measurements are used. The value 20/20 is considered the standard for a normal vision. The first number represents the distance, in this case 20 feet, between the eye chart and the tested subject, the second specifies the distance to an object that a person with normal vision can see [BDE+09]. Figure 3.6 illustrates an example to better clarify this measure.

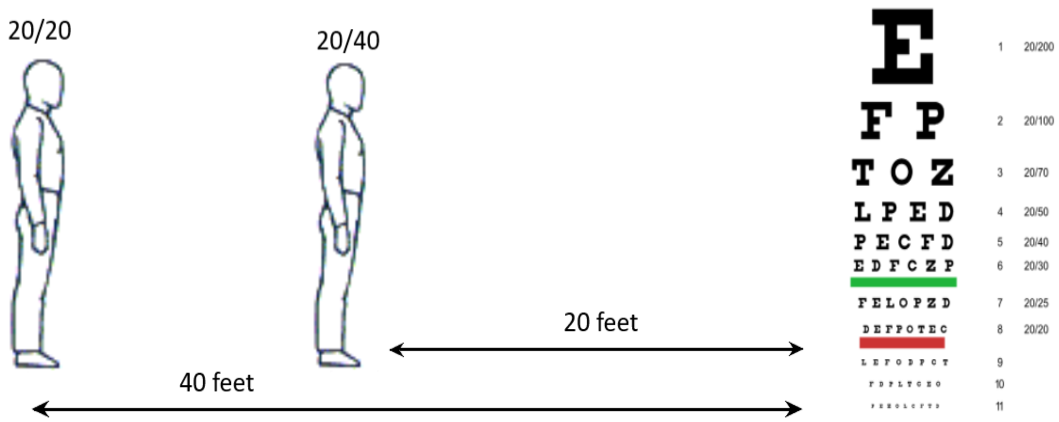
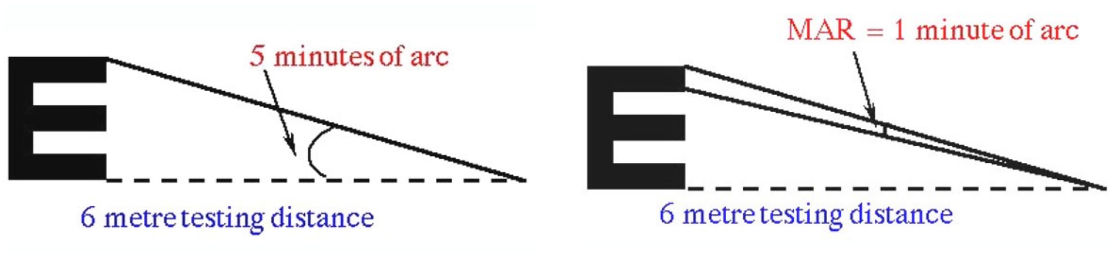


Figure 3.6: When VA is equal to 20/40, it indicates that this person has to be at 20 feet distance to be able to see the PECFD letters while someone with normal VA can normally read them from a distance of 40 feet. Adapted from [dra] and [opt].

However, in most countries of Europe and the Commonwealth that use the metric system as unit of length, this distance to the eye chart corresponds to 6 metres (around 19 ft and 8.22 inches). Consequently, the value of "6/6" is the equivalent to "20/20". In Europe the value of the acuity can be expressed also as a decimal notation, where 6/6 corresponds to an acuity of 1.0. This value is calculated dividing the first number by the second one. For instance, the equivalent decimal value for 6/60 is 0.1. [JB04]

As already mentioned, Snellen used minutes of arc as measurement. Nowadays the logMAR notation is considered a better scaling measurement for the VA in comparison to the Snellen one. The term logMAR stands for $\log_{10}$ of the minimum angle of resolution, where the minimum angle of resolution (MAR) represents the angular size of the smallest detail recognisable in an optotype, namely the visual angle at which two features can still be distinguished separately. Once this threshold is exceeded the objects start to be perceived as blurry. With standard vision (6/6) comes the ability to distinguish letters that subtend an angle of 5 minutes of arc, as shown in Figure 3.7a. This means that, since the features in the optotype are equivalent to one-fifth of the height, the eyes are able to recognize features separated by 1 arcmin (seen in Fig. 3.7b). Therefore 1 arcmin corresponds to the value for the MAR while the value of the VA in logMAR corresponds to the logarithm of the reciprocal of the Snellen Fraction, in this case 0.0. For a VA value of 6/10 the logMAR is equivalent to 0.23, since the reciprocal is $10/6 = 1.7$ and the $\log_{10}$ of 1.7 is 0.23. [AOMRM09]

The VA value can aslo be expressed in the decimal system and it corresponds to the reciprocal of the feature size in arcmin of the smallest identified optotype [LFJ+09]. The logMAR scaling method converts the progression of the Snellen chart to a linear scale [LLC06].



(a) Illustration of letter E subtending an angle of 5 armins

(b) Illustration of letter E where features subtend an angle of 1 arcmin

Figure 3.7: Optotype for a VA of 6/6 (20/20) [KL].

Figure 3.8 shows values of VA expressed in different scales.

MAR*	LogMAR	Snellen (metric)	Snellen (imperial)	Decimal*
0.50	−0.30	6/3	20/10	2.0
0.63	−0.20	6/3.8	20/12.5	1.60
0.80	−0.10	6/4.8	20/16	1.25
1.00	0.00	6/6	20/20	1.00
1.25	0.10	6/7.5	20/25	0.80
1.60	0.20	6/9.5	20/32	0.63
2.0	0.30	6/12	20/40	0.50
2.5	0.40	6/15	20/50	0.40
3.2	0.50	6/19	20/63	0.32
4.0	0.60	6/24	20/80	0.25
5.0	0.70	6/30	20/100	0.20
6.3	0.80	6/38	20/125	0.16
8.0	0.90	6/48	20/160	0.125
10.0	1.00	6/60	20/200	0.10
20	1.30	6/120	20/400	0.05
40	1.60	6/240	20/800	0.025
100	2.00	6/600	20/2000	0.01

Figure 3.8: Visual acuity scales. Adapted from [EF].

3.4 Optotype Size Calculation

Besides the theory behind VA, in order to design an eye chart, the size of the optotypes for each row has to be determined. The two required values for establishing the measurements for the letters in the metric system are the visual angle subtended by the optotype in minutes of arc, where 1 arcmin is equivalent to 1/60 of a degree [Wit08], and the distance between the person and the eye chart. The relationship between these values can be expressed as:

$$tan(\alpha) = \frac{h}{d}$$

where α stands for the angle subtended by the optotype, d is the distance between the eyes of the tested subject and the chart and h represents the height of the letter [Peñ16] (as shown in Fig. 3.9).

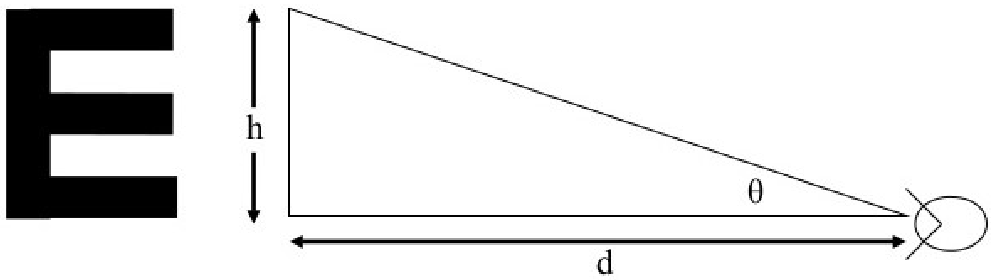


Figure 3.9: Calculation of the optotype's height [Kai].

The formula can be expressed also as:

$$h = d \times \tan(\alpha)$$

If we want to know the height in centimetres of a 6/6 row optotype where the distance d is equivalent to 6 metres, the formula would be:

$$h = 600cm \times \tan(\frac{5}{60})$$

where 5 represents the value in minutes of arc for that particular distance (6/6) and 60 the value for the conversion in degrees [vaW]. In the end, the final result is equivalent to 0.873 centimetres. If for instance, we want to know instead the size for the 6/12 row, we just substitute the 5 with the 10, because in this line the letters should be twice as big as 6/6 letters [vaW]. If instead the target is 6/24, then the minutes of arc correspond to 20.

CHAPTER 4

Factors Affecting Visual Acuity

There are several factors that influence the value of VA, like the form of the eye and its features. As an example, the visual resolution could be negatively affected by focus and refractive errors, but also by the pupil's size, whether this is either too small (2mm or less) or too large (6mm or more). The sharpness of human vision doesn't depend only on physical elements, but also on external factors like the distance to the observed object, the colour, the contrast between object and background, the surrounding environment and the time (namely the time to absorb light into the eye). [BDE+09]

4.1 Myopia

As already known, not all human beings have perfect vision. Besides eyes diseases like glaucoma or cataract, there are also other conditions that affect vision. Refraction is a phenomenon where light travels through the cornea and is focused on the retina by means of the dioptrics. The retina, then, transforms this information and triggers the processes for visual perception. Refractive errors are common visual impairments where the eyes aren't able to correctly focus the light from distant objects onto the retina. Astigmatism, near-sightedness or myopia and far-sightedness or hyperopia fall in this category. [BDE+09]

Among these problems, myopia is by far the most widespread in the population under age 40 with a percentage between 30 and 40 in Europe and the United States and almost 80% in Asia [LD].

By the term myopia, we refer to the difficulty of a person to see distant objects sharply. In this case, as illustrated in Figure 4.1, the light is focused not on the retina but in front of the retina, causing a blurring of far objects, but leaving nearby targets perfectly visible without any artefact or defect. [BDE+09]

The possible causes for this visual impairment are the length of the eyeball, which is larger than the normal one, an eye lens with a shorter focal length or a too large curvature of the cornea [Gro08] (as seen in Fig. 4.2).

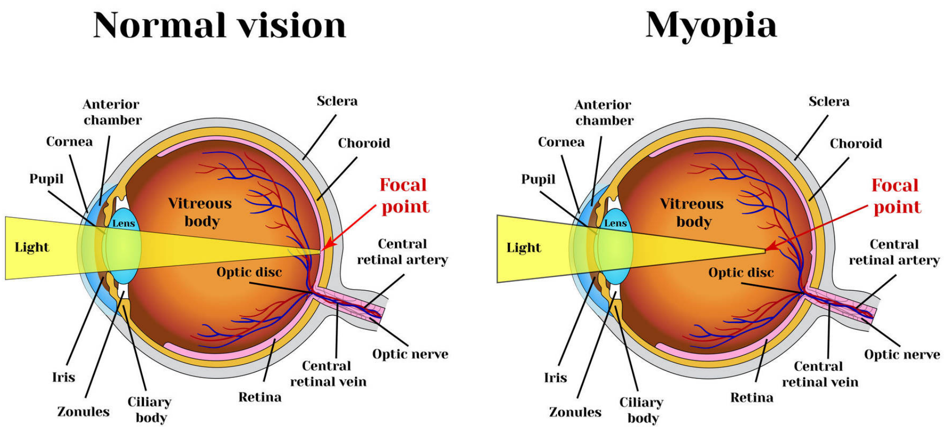


Figure 4.1: Refraction of light onto the retina [jcm].

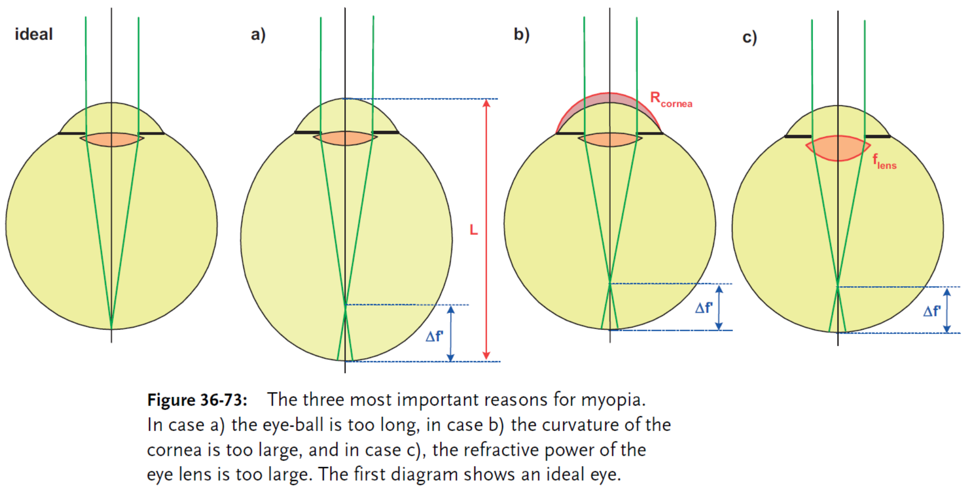


Figure 4.2: Illustration of the cause for myopia. Reprinted from [BDE+09].

4.2 Luminance

The intensity and the brightness of the light that falls onto the viewed objects represent fundamental aspects of the visual resolution too. Regarding the intensity, it has been demonstrated that starting from 30 photons as the value for the intensity of the illumination the ability to distinguish details decreases and that the VA is better under 30 photons. [Shl37]

The study conducted by Johnson and Casson [JJC96] tested how the combination between the background luminance, the stimulus contrast and the dioptric blur also influence the visual resolution. They proved that in a range of background luminance between 75 and 0.075 cd/m^2, a diminution of the luminance is directly connected to a diminution of the VA. As a consequence, a 6/6 standard vision, obtained under high illumination combined with high contrast, would drop to 6/18 under low illuminance and further to 6/30 under low contrast. This phenomenon happens also to people who don't have normal vision: A person with a VA of 6/30 would see 6/120 under low luminance and 6/240 with a low contrast condition. If the VA increases slightly with the highest background luminance, the study shows that different levels of blurriness up to about +2.0 dioptres ("a unit of refractive power,..." [oxf06]) affect the visual resolution drastically. Above +2.0 the reduction is more gradual. Moreover, the effects of blurriness on the eyes remain the same, regardless of high or low background luminance levels. Also, for all tested contrast levels, VA diminishes rapidly with levels of blurriness up to +2.0 D (dioptres). However, the blurriness in a range between 0 and 2 D affects a scenario with low contrast conditions more than one with high contrast conditions. Subsequently, the stimulus contrast in relationship with four background luminances was also tested, showing that a linear reduction of VA can be seen for a decrease of contrast up to 20%; after this threshold, i.e. with even lower contrast, the decline becomes larger.

Another fundamental aspect is the relationship between light, more precisely the intensity of ambient light, and VA. Also, in this case, fine details become more difficult to distinguish with a decrement of the illumination, The reduction of the contrast between the object and the background also has a negative effect on VA. [God04]

Shruthi, Venkatesh and Suresh [KBGS14] focused on the identification of an optimum value for the light's intensity in order to achieve a better vision resolution, concluding that the two options for achieving the best VA are the natural day light and 200 watts.

4.3 Age

Different studies focused on the change of VA at different ages, proving the reduction of visual resolution at low level luminance as well as the decreases of contrast sensitivity with the increase of age [God04]. Therefore, age has been recognized as another significant component of the visual resolution, since the combination age-luminance can have an impact on VA.

The physical modification of the vision system is a reason for this reduction of VA related to age. Due to a stronger contraction of the pupil in old age, the capability to dilate under low-light conditions (in order to capture more light) decreases and the integrity of the macular pigment and the neural pathways undergo modifications. Because of these alterations, there is a decrement of the light sensitivity and VA, a slower ability to adjust the eyesight in darker environments and a higher glare sensitivity. As a consequence, a larger amount of light is needed for older people in order to reach the same retinal illumination as younger people. The age of 65 is considered the starting point where VA begins to decline when the brightness and the intensity of the light in the surrounding environment diminish. [UGM+15]

4.4 Field Of View & HMD

An element that influences VR-technologies is the limiting optical resolution of the system.

As described in greater detail in Chapter 5, the technologies used for this project were a monitor with a resolution of 1920x1080 and an HTC VIVE Pro headset for the virtual experience, with a resolution of 2880x1600[viv]. Judging from this information, one might assume that the quality of the VR simulation should be higher than the quality of the desktop version, displayed on the monitor. In reality, when people with normal vision wear HMDs, they have the impression to see objects less sharp in comparison to the real world. The cause is to be found in the size of the FOV, since the FOV covered by the VR headset is wider than the one of the desktop monitor. The resolution of the screen in PPI (*pixels per inch*) and the number of pixels don't play a significant role when dealing with an object's sharpness. Therefore, even if the resolution of an HMD is superior, this does not automatically lead to a better display quality. The measure *pixels per degree* (PPD), namely the resolution of the projected virtual image, is the one to take into count. For example, the FOV of a user covered by a 20" screen from a distance of around 76 cm is equal to about 37°. [okr17]

The FOV covered by the 23.5" monitor used in our user study, viewed from a distance of 3 metres, is equal to about 11.36° [cal19]. Since the FOV of the HTC VIVE Pro headset is equal to 110° (diagonal), in the end, the viewer sees a display in the headset with a lower resolution in comparison to the 23.5" monitor.

Taking this information into account, if, for instance, a small display, whose number of PPI is very high, is extended to a specific FOV and a bigger screen with a small value for the PPI but identical resolution as the small display is brought to the same value for the FOV, the final impression will be similar. Moreover, it should be considered that in an HMD we don't see the screen directly as it happens for a normal monitor, since the display is magnified by lenses and the PPD considers this aspect. [okr17]

In current technologies, designers of HMDs have to deal with a trade-off between the resolution of the VR display and the field of view (FOV). The larger the FOV is, the lower the resolution given a fixed pixel size will be. Moreover, scientists and experts suspect that the representation of features with a MAR of 1 arcmin and at least a FOV of 30° in virtual environments might not be achievable. [Mem15]

Ideally, an HMD should be able to combine a value for the FOV as large as possible, which should be similar to the FOV of humans, with the best resolution, i.e. the highest possible resolution. The main difficulty for HMDs is to recreate the visual system of the human eye, that reaches a total FOV of 200° horizontal, as shown in Figure 4.3, and 130° vertical [Mel01] with a VA of 1 arcmin in the central foveal region [Mel98].

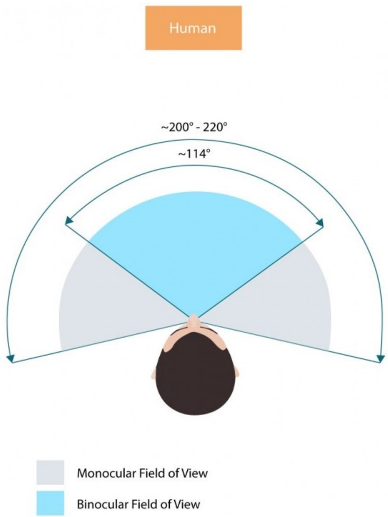


Figure 4.3: Human FOV [Jay].

The connection between the resolution and the FOV in an HMD is expressed with the function:

$$H = F \ * \ \text{Tan}\ \Theta$$

where F represents the focal length of the collimating lens used in the HMD, H refers to the size of the image source and Θ to the value of the FOV, i.e. the size of the virtual image in space. However, H could also stand for the pixel size, making Θ the value of the resolution, namely the size of the pixel in image space. Since the focal length (F) establishes at the same time the values of the FOV and the resolution, when a single image is projected onto the screen, there will be either a high resolution or a wide FOV, but not both combined together. [Mel98]

This is the reason why the resolution of HMDs appears to be on a lower level than the resolution of a normal screen, making it difficult to reach the same sharpness as the real world in VR.

HMDs used in virtual environments are devices which have small displays positioned just a few centimetres from the eyes. For this reason, it would be almost impossible for humans to focus on such near objects without any help, like, for instance, corrective lenses. The eye has a capability, called accommodation, that allows it to modify its focal length in order to distinguish far and near objects. However, these adjustments are not boundless. Based on this circumstance, if a person tries to read a text very close to the eyes, the image will appear undefined and blurred, making a clear vision impossible. [oERT06]

Because of this phenomenon, HMDs need a form of collimation. Through this collimation, the user has the impression that the point where the light rays are generated is further away, as compared to the real point on the display, making the distance between the eyes and the display larger than the actual one. This mechanism allows a person to focus on an image very near to the eyes that, otherwise, would naturally be blurred. In order to collimate light from the display, HMDs use prisms or mirrors [SWCH17]. Fresnel lenses fall within this category of technology and are the ones used in the HTC VIVE Pro headset [MOL18]. However, lenses in HMDs generate effects, like optical distortion or aberrations, and not all these effects can be fully corrected [RH93]. Various studies documented how this phenomenon also applies to the Fresnel lenses, proving how this kind of lenses and their interaction with luminance also has a negative impact on VA [KG11].

CHAPTER 5

Testing Visual Acuity

While the previous chapter focused on the theoretical background, the following chapter describes the approach of this project. Section 5.1 explains the methodology of the project, while Section 5.2 discusses briefly the technologies that were employed for the creation of this tool. Sections 5.3 and 5.4 give an in-depth description of the tests in the VR and the desktop version. Section 5.5, then reports how the user study was conducted. Finally, Section 5.6 presents the results of the user study.

5.1 Methodology

In order to study and observe the different VA perceived in VR and in the real world, two tests were developed: a VR test and a non-VR test.

We also conducted a user study with near- and normally sighted participants. The near-sighted group performed the VR and non-VR tests twice (one with glasses on and one without), the subjects with normal vision conducted the VR and non-VR tests only once. The study design is divided in two: "between-subjects" design and "between groups" design. The "between-subjects" design relates to the comparison of the results for every person, in which we observed the difference between the outcome of the VR and non-VR test. For the near-sighted participants, we examined the difference between the tests with glasses on and without separately. The "between groups" design instead compares the values between near- and normally sighted subjects. Furthermore, we asked some participants to conduct an online VA-test [Baca] in order to compare these results with the outcomes of our VA-tests. To evaluate the existence of a statistically significant difference between the outcomes, we used the two-sample Kolmogorov-Smirnov test (*kstest2*) in MATLAB on the decimal VA values.

The existence of a statistically significant difference could also be assessed using logMAR values. Since logMAR values follow approximately a normal distribution [Bacb], decimal

VA values should first be converted to logMAR values and subsequently it would be possible to proceed with the t-test. As explained by Michael Bach [Bacb], the conversion from a decimal VA value to a logMAR value can be expressed as:

$$-\log(\mathrm{VA}_{dec})$$

Since the goal of this project is to determinate how VR affects the VA of people who don't have normal vision (6/6), a tool to measure eyesight was implemented. This eyesight test is an adaptation of the typical one that ophthalmologists use with their patients. Our VA test is different in the following ways: During the two tests, the subject didn't use one eye at a time, but both eyes simultaneously. Moreover, instead of a whole eye chart, we display only one symbol at a time. This decision is based on the fact that the use of a program gives the opportunity to dynamically create new rows, instead of having different rows with various number of optotypes per line.

The primary goal of this project is not to determine the actual VA values for every user, which is usually measured separately for each eye. Instead, we want to find out how much of an impact VR on VA has and how much the eyesight of near-sighted people with a VR headset differs from their eyesight in the real world. Therefore, we investigate the overall perception of the subjects in VR by measuring their binocular vision, since in a virtual environment users look at the scene with both their eyes and not with only one. Furthermore, conducting the VA test with both eyes and not with one eye at a time allows us to keep the experiments short and avoid motion sickness or eye strain for the participants. Note that as a result of this experiment design decision, our measured binocular VA values are higher than VA values obtained from tests, which are conducted per eye.

The following test protocol provides a detailed description on how our experiment was conducted:

- *Test Protocol*

  For the two tests we use a distance of 3 metres to the Landolt C. Following the classic eye chart, the Landolt C is coloured in black and positioned on a neutral background.

  At the start of every test, the Landolt C is projected at the centre of the screen, with its gap at 1 of 8 possible positions, chosen randomly by the computer program. However, this choice is programmed in a way that the direction of the gap can never be the same two times in a row.

  During the test, participants have to indicate the orientation of the gap. The 8 possible directions are: up, down, right, left and diagonal positions in between (as seen in Fig. 5.1). In order to facilitate the test and to prevent the possibility of selecting an undesired choice, a second Landolt sign was included and displayed on the screen. The principal difference between the main and the secondary Landolt C is the size: the second Landolt C is larger, so that participants have no problem in identifying the gap, and its size doesn't change throughout the test. Through the touchpad of the motion controller, the participants can rotate this second Landolt ring until its position matches the one of the main Landolt. Then the subject confirms his decision with the trigger of the motion controller. Every time the trigger is pressed, the gap's orientation of the main Landolt C changes.

Just like the typical eyesight test, the participant has to identify the orientation of the gap several times before moving on to the next size. After a certain number of trails, the main Landolt C shrinks or increases in size depending on how many times the user has chosen the correct answer. More than 50% of the Landolt rings have to be identified correctly, in order to shrink the Landolt ring. For instance, if the subject has to recognize, for the given size, the gap of 5 Landolt Cs, with 3 correct answers the symbol will become smaller, otherwise it will increase.

The process of shrinking follows a monotonically decreasing function, illustrated in Figure 5.2, where the more the Landolt C shrinks, the lower the difference in size between the old and the new one will be.

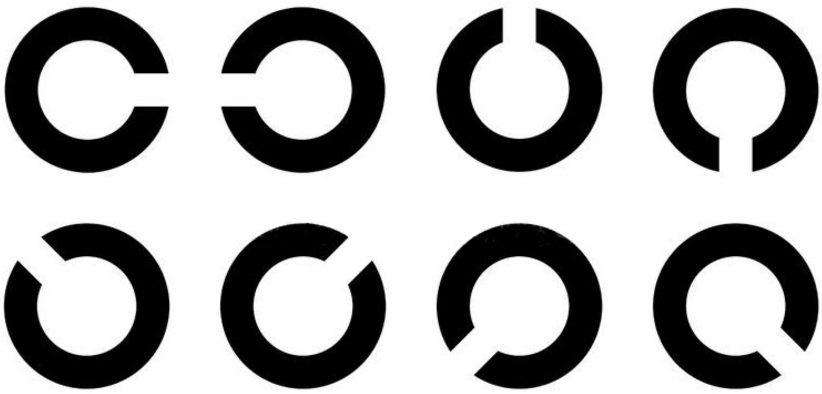


Figure 5.1: Possible directions of the Landolt C. Adapted from [CCEHLJS05].

If the subject doesn't recognize more than 50% of the symbols, the dimension of the Landolt C will grow but not to the previous size, since the subject already proved that he or she is able to see features at that size. The new size of the Landolt ring will correspond to the one in the middle between the last successfully recognized dimension and the one where the participant failed. Taking the progression shown in Figure 5.3 as reference, if, for instance, the last recognized size is equivalent to 14 arcmins and the failed one is 11, the new dimension will be 12.5. If the size 12.5 is correctly identify, the failed size 11 is proposed once again. If 11 is still too difficult, the dimension of the Landolt C will increases to ≈11.75 (the middle between 11 and 12.5). This transition between values proceeds until reaching a threshold, i.e. when the difference between the last correct value and the tested one is too small.

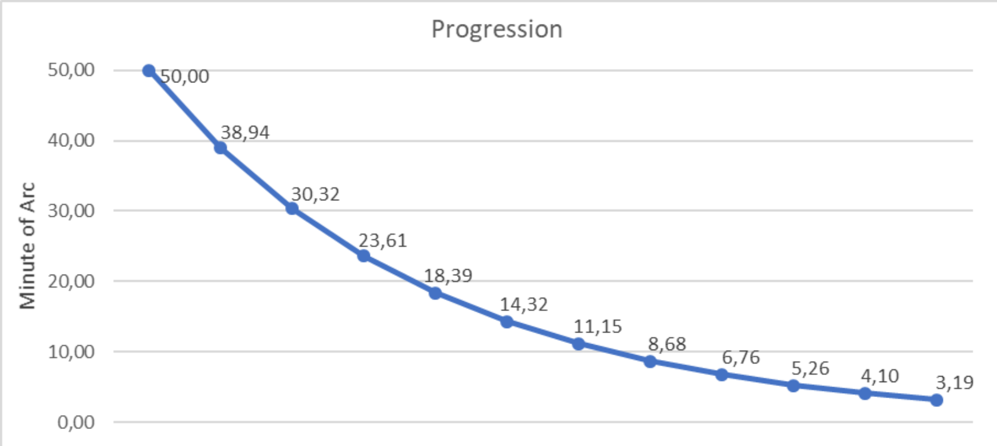


Figure 5.2: Shrinking process when initial dimension is 50 arcmins.

Then the test ends. Another condition that leads to the end of the test is when the participant doesn't recognize any of the in-between sizes. Taking again the previous example, this would happen if the subject can't correctly distinguish any size between 14 and 11, making 14 the last size, that the subject has successfully seen.

5.2 Technology

The program used for the development of this project was Epic's game engine *Unreal Engine 4* (UE4), version 4.22.3 [Epi]. Like many other game engines, UE4 supports the development of VR-projects and therefore, the use of an HMD. *Blueprints Visual Scripting* [blu] was chosen as scripting system, which is characterized by the employment of a node-based interface in order to create gameplay elements. Only the results of the user study were recorded with the use of a C++ file.

We used the HTC VIVE Pro headset shown in Figure 5.3, which is supported by *SteamVR*, a tool for experiencing VR content. The HTC VIVE Pro headset features a display with a resolution of 2880 x 1600 (1440 x 1600 per eye) and a refresh rate of 90 Hz. The value of the pixel density is equivalent to 615 PPI (pixels per inch) per eye, while 110° (diagonal) represents the FOV.

The desktop version of the project was tested on a 23.5" full HD monitor connected to a PC with an NVIDIA GeForce GTX 1070, AMD Ryzen 7 1800X 3.60 GHz CPU, and 32 GB RAM.

Figure 5.3: HTC VIVE Pro headset [htc].

5.3 Non-VR Visual Acuity Test

The aim of the desktop version (non-VR) is to reproduce the normal eyesight test as closely as possible. Therefore, a widget class (as illustrated in Fig. 5.4) is used in order to project the two Landolt Cs on the screen as a HUD (head-up display). The main motivation for this choice is the possibility to control the dimension of the elements in pixels in a widget class. This simplifies the establishment of the correct scale for the optotypes based on the visual angle. Since the size of the HUD depends on different factors, it is necessary for the calculation of the number of pixels to consider the PPI, the resolution and the dimension of the monitor in order to obtain the right size and to be sure that the size corresponds to the indented size in centimetres.

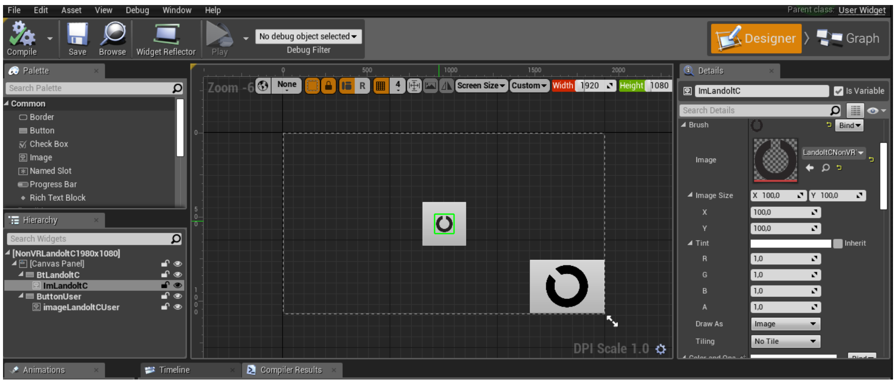
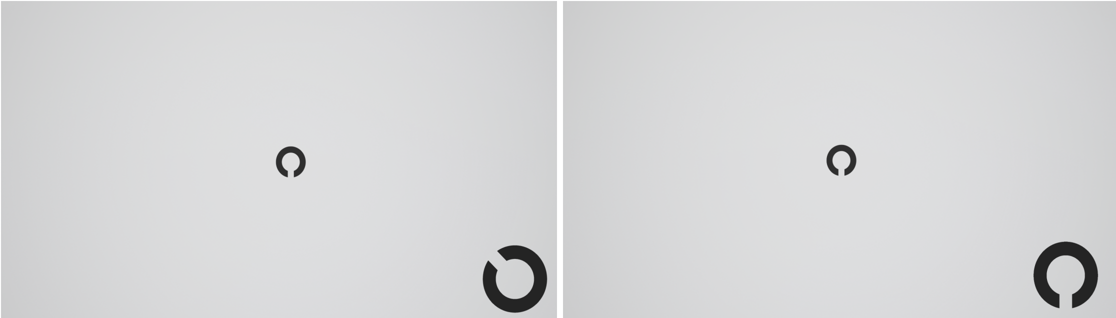


Figure 5.4: Screenshot of the Widget Class

The second Landolt ring, as illustrated in Figure 5.5, is positioned on the lower-right corner of the screen.



(a) Start of the non-VR test (b) Second Landolt C has been rotated

Figure 5.5: Screenshots of non-VR test.

5.4 VR Visual Acuity Test

The implementation of the VR-version is based on the previous project conducted by Krösl et al. [KEH+19], in which the authors also implemented an eyesight test in a virtual environment.

In the VR experience the concept of the desktop version remains the same. However, in this case, the creation of a HUD for displaying the symbol wasn't necessary because the Landolt C is represented as a 3D-plane object. The dimensions of virtual objects in the virtual environment correspond to the same dimensions as in the real world. Consequentially, the size of the Landolt C can be specified in centimetres. The motion controller is visible in the VR experience and the secondary Landolt C is positioned above it, as shown in Figure 5.6.

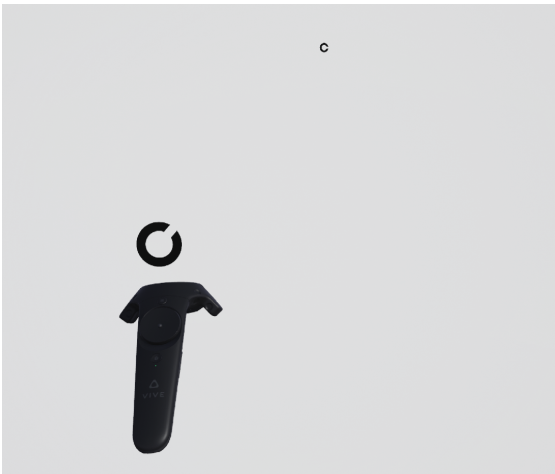


Figure 5.6: Screenshot of the eyesight test in the VR version.

In order to recreate the required distance between the 3D plane representing the Landolt ring and the person, the 3D object is positioned 3 metres away from the player (as seen in Fig. 5.7).

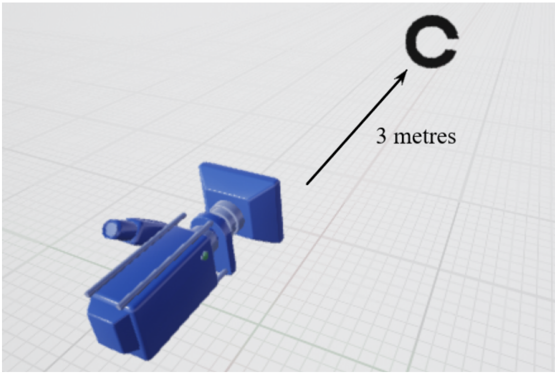


Figure 5.7: Simulation of the eyesight test in VR version with UE4.

To avoid the undesired effects that a virtual environment may cause, such as sensory conflicts, stress or perceptual shift [SCMRW08], the Landolt C is projected on a specific position in the VR world, which does not change for the entire duration of the test. In the first prototype, the primary Landolt C was always positioned relative to the camera orientation and displayed at the centre of the subject's view, meaning that every time the participant moved the head, the Landolt C changed its position according to it. Later this aspect has been removed because the constant change of position affected the sharpness of the figure. Moreover, we wanted a VR version as similar as possible to the desktop version and to a normal eyesight test: The typical eyesight test is a stationary one, where the subject stays focused on a particular point in the room and where the eye chart, in this case the symbol, does not move.

Regarding the before mentioned undesired effects, previous studies [SCMRW08] have demonstrated that a lack of experience in VR may lead users to perform actions, like moving the head very often or taking unusual positions, that could negatively affect the whole experience. This aspect represents an additional reason for the implementation of a stationary Landolt C in this VR version. Since the participants repeated the tests more than once, under different conditions, for instance with and without wearing corrective glasses, we avoided leaving the participants in a virtual environment for more than 10 minutes. This decision was made, because undesired effects could also emerge due to the duration of the test and 20 minutes seemed to be a good time limit for this kind of tests [SCMRW08].

5.5 User Study

Fifteen participants, either members of the computer graphic's department or students, took part in the user study (4 female and 11 male). The average age was 32 years old, where the youngest was 19 years old and the oldest 63. Of these fifteen, five persons had normal vision, the remaining ten were near-sighted with a deficit in dioptres between -1.5 and -6. Since all of them wore glasses, the near-sighted subjects performed the VA test four times, twice in the VR version (one with the glasses on, one without) and two in the desktop version, with a duration between 3 and 6 minutes per test. The participants with normal vision, instead, conducted the test only twice, once in the VR and once in the non-VR. All participants performed the non-VR test first and then they proceeded with the VR version. We decided to use a distance of 3 metres, since this was the largest possible length between the monitor and the person, achievable in the room. During the VR test, all participants were sitting on a chair in the same room.

For the desktop version, every subject was positioned at the same spot 3 metres away from the monitor, as shown in Figure 5.8, and no light, apart from that of the screen, was employed in order to avoid artefacts in the results, since light could affect VA (see Section 4.2). Moreover, during the VR test, the only perceived light was the one coming from the HMD; therefore, no natural light was included. In this way the two types of test were conducted under the most similar conditions possible.

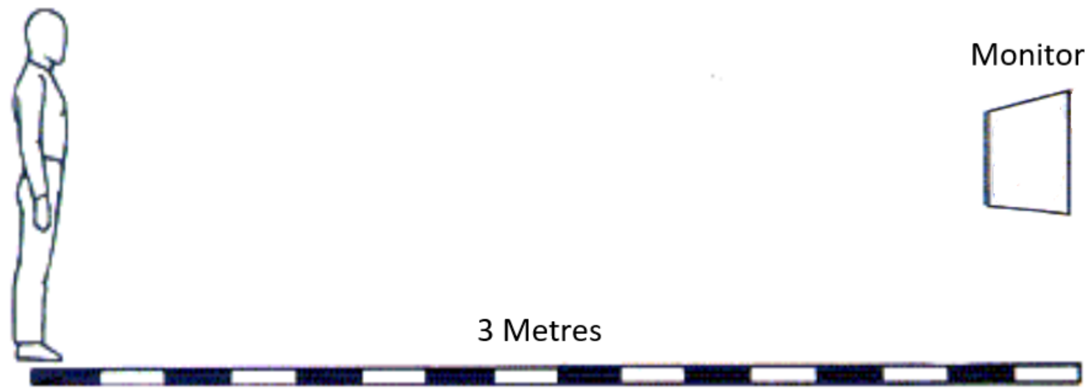


Figure 5.8: Recreation of the non-VR test. Adapted from [dra].

The initial size of the Landolt C for the participants with normal vision was equivalent to 30 arcmins (2,61 centimetres), while for near-sighted subjects the chosen value was 50 arcmins. Since various near-sighted participants had issues in the identification of the gap for this dimension, the initial size of the Landolt was increased for them up to 70 arcmins. For every test the collected data were saved in a csv file. Each time the Landolt C changed size, different details were recorded on this file: the number of attempts for the current dimension, the number of correct answers, the current size in minutes of arc and centimetres and the last recognized size in minutes of arc.

The most significant information for every test was the last correctly recognized size in minutes of arc identified by the participant. However, according to the European norm [ISO09], the decimal notation represents the acuity standard measure in European countries. Therefore, we converted the values of the results from minutes of arc into the decimal system, calculating the reciprocal of the minimum recognizable gap width of the Landolt C [ISO09]:

$$Acuity = \frac{1}{[gap\ size\ in\ arcmin]}$$

For instance, the acuity of a person with normal vision (6/6) corresponds to 1/1, since in this case the optotypes subtend an angle of 5 arcmins and the size of the gap, which represents the minimum recognizable gap width, is equivalent to 1 (see Section 3.3).

5.6 Results

The outcomes of the different tests for every category are shown in two types of graphs: a bar chart and a scatter plot. The comparisons between our results and the results of the online VA test ('FrACT') are presented only in a bar chart. All values are reported as a decimal number and have been rounded to the nearest hundredth. To calculate a possible statistically significant difference between the results we used the Kolmogorov-Smirnov test.

Before presenting the results, a few clarifications need to be made. The tests were conducted with both eyes and, as mentioned earlier, the actual VA-value obtained for every participant is not the focus of this project. It has to be considered that regarding visual tasks, binocular performance is usually better than monocular vision and therefore, binocular acuity values are higher than monocular acuity [BF73]. Different studies ([Rab95],[PP18]) proved the enhancement of VA using both eyes, as compared to a single eye. Furthermore, this improvement, resulting from a binocular viewing, varies widely from person to person [BF73]. Finally, it should be mentioned that some participants leaned unintentionally forward to better see the Landolt C, when this symbol was too small, which could also affect the results to some extent.

- *Comparisons of VR and non-VR Test Results*

  Figure 5.9 shows the acuity score in decimal number reached by the 5 normally sighted participants in the VR and non-VR tests. The highlighted gridline represents the corresponding acuity value for normal vision. Figure 5.10 depicts the relationship between the two different acuity scores of the VR and desktop version.

  Figure 5.11 shows the acuity score reached by the 10 near-sighted participants in the VR and non-VR tests performed with glasses. The highlighted gridline represents the corresponding acuity value of the normal vision. Figure 5.12 portrays the relationship between the values of the acuity score obtained in the VR and non-VR tests. The colours used in this plot illustrate the dioptres of every participant. The values linked to the colours can be found on the right side, next to the plot. The value that indicates the missing dioptres is the average of the two eyes. For instance, if the right eye has -3 and the left -4, the average would be -3.5.

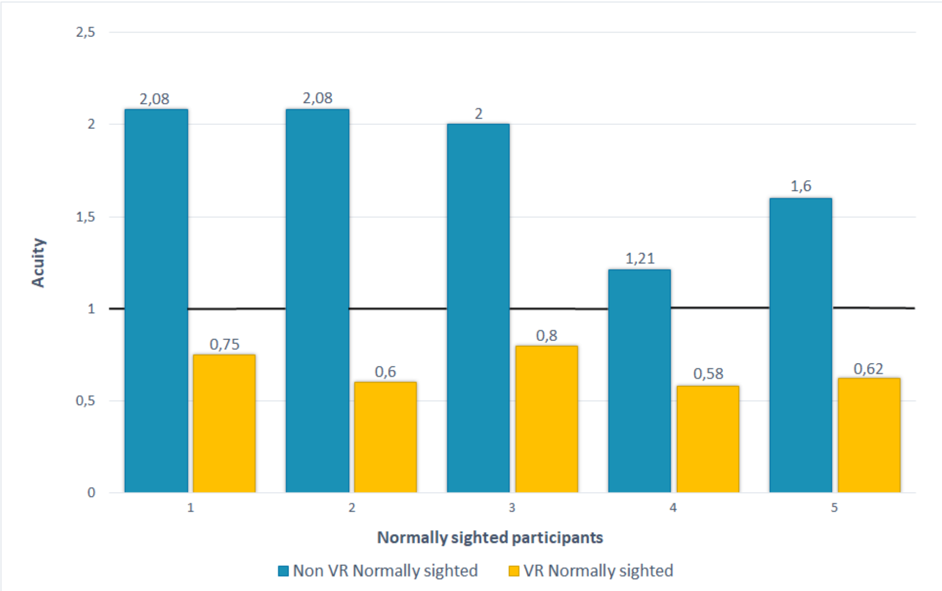


Figure 5.9: Bar chart of the results of normally sighted participants.

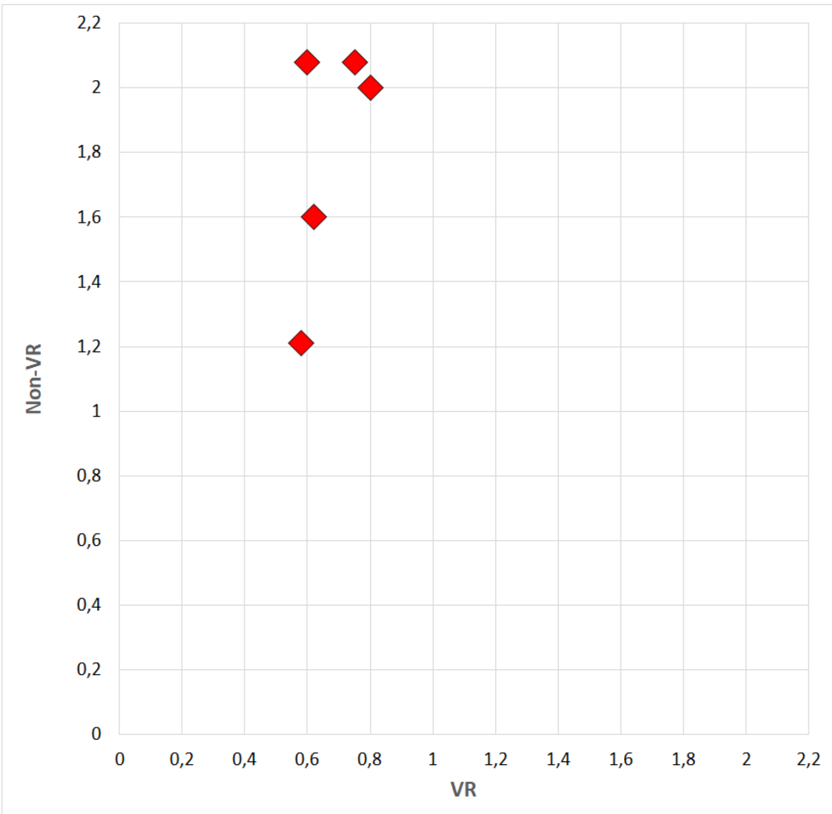


Figure 5.10: Results of normally sighted participants represented in a scatter plot.

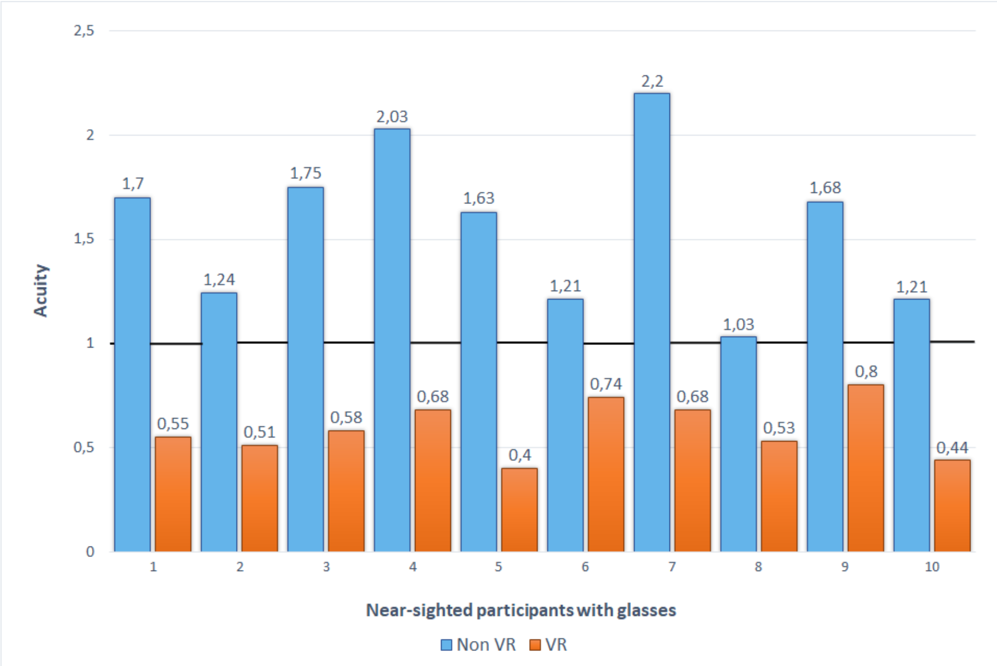


Figure 5.11: Bar chart of the results of near-sighted participants with glasses.

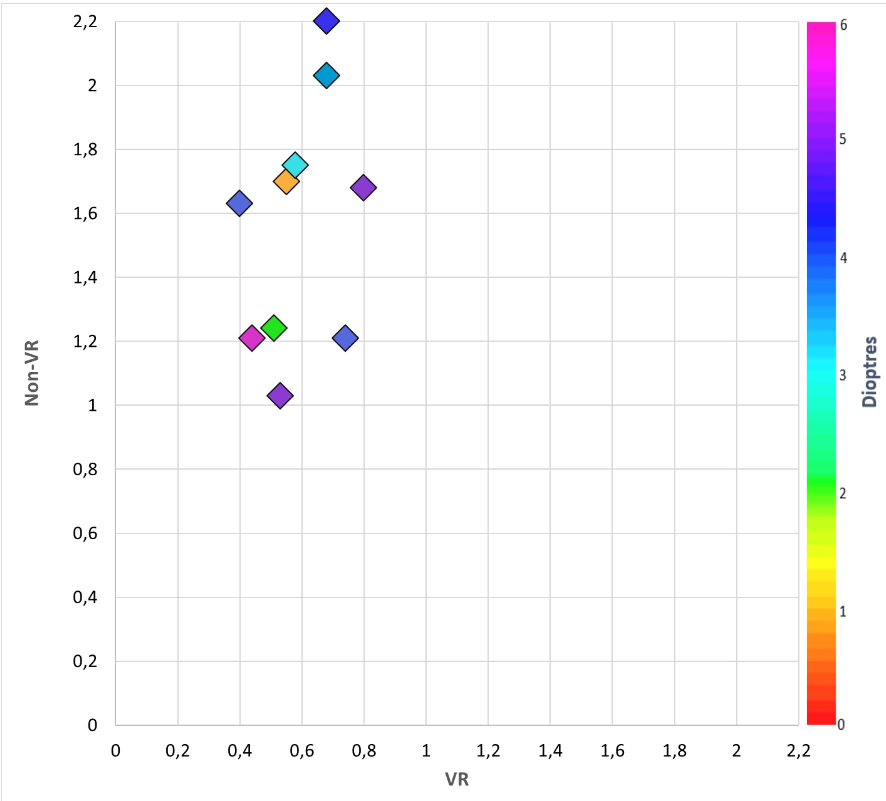


Figure 5.12: Results of near-sighted participants with glasses in a scatter plot.

Figure 5.13 represents the acuity score reached by the 10 near-sighted participants in the VR and non-VR tests performed without the glasses. In this chart the dioptres of the 10 participants for both eyes are also reported. The *X* symbol indicates the participants who weren't able to identify the correct position of the gap in the Landolt C at the initial size of 70 arcmins (≈6,1 centimetres) in the non-VR test. Figure 5.14 depicts the same results in a scatter plot.

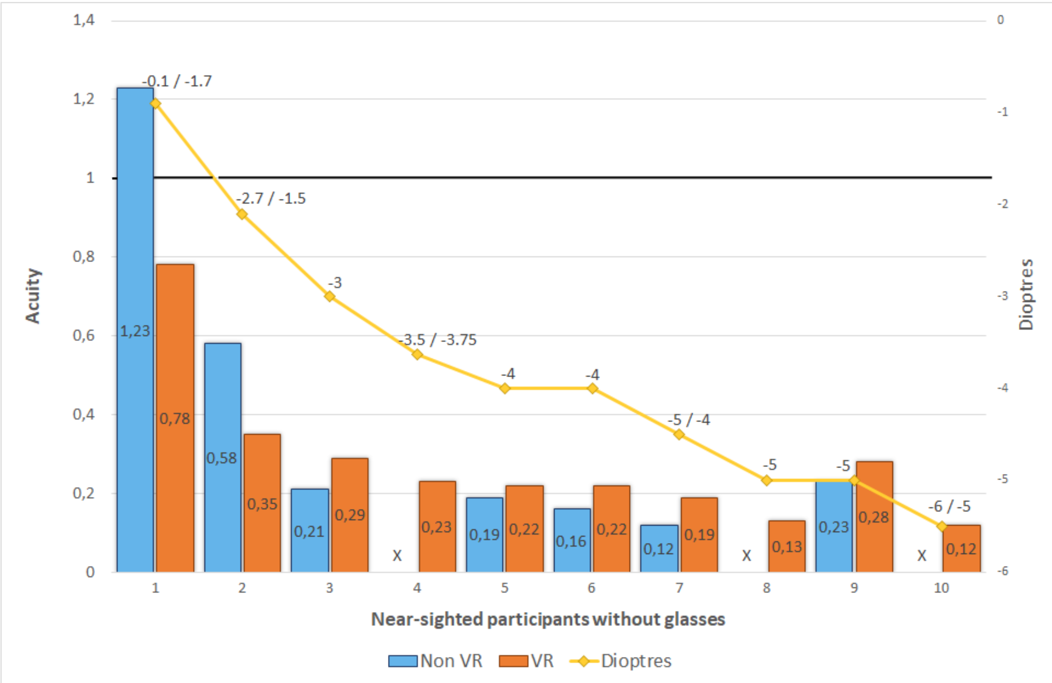


Figure 5.13: Results of near-sighted participants without glasses.

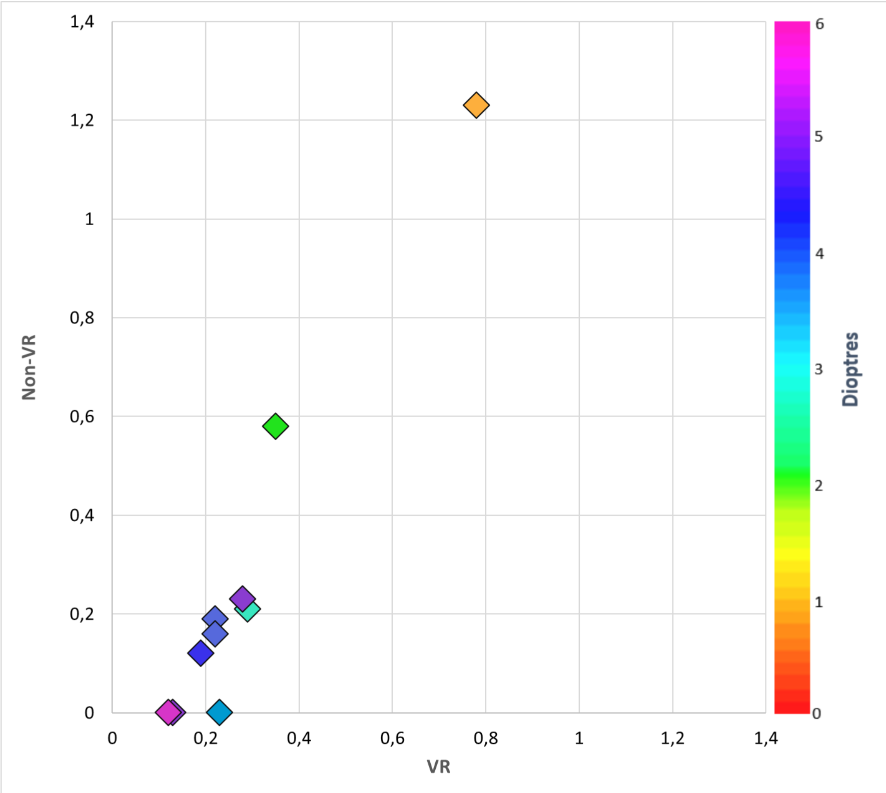


Figure 5.14: Results of near-sighted participants without glasses in a scatter plot.

Figures 5.9, 5.10, 5.11 and 5.12 support the theory, that VA in VR is not as high as in the real world. Section 4.4 provides an explanation for this aspect. The results for all 15 participants (normally sighted and near-sighted with glasses) demonstrate that, the value of VA obtained in the VR-version is always inferior to the non-VR for people with normal or corrected sight (wearing glasses). In the desktop version, all subjects reached and passed the standard value (1) for VA, supporting the hypothesis of several studies, which claim that the average VA for people younger than 50 years with no ocular diseases or defects is better than 6/6 [JB04].

Regarding the data collected from the tests of near-sighted people without glasses, some interesting details have emerged. The sharpness of the visual resolution without glasses for all subjects was, for obvious reasons, not as good as the one with the glasses on. For 20% of the participants, the results follow the pattern of the test with the glasses: The VA in the VR version has considerably decreased compared to the non-VR. In both cases the two subjects had a dioptric defect less severe than -3. Starting from -3 D, all the other subjects either reached a similar value to the one of the non-VR test or were able to recognize smaller details in the VR test.

During the execution of the test, the following observations were made: Some people have experienced difficulties in wearing the HMD with glasses due to the form and thickness of the eyeglasses' frame; some others leaned forward in order to better see the Landolt C, whereas others claimed to have tired eyes.

- *Statistical Analysis*

  The Kolmogorov-Smirnov test did not reveal any statistically significant difference (with $\alpha = 0.05$) between the data collected for normally sighted people and near-sighted participants with glasses, with a p-value of 0.5402 for the non-VR (Fig. 5.15) and 0.2668 for the VR (Fig. 5.16). The variance for both normally sighted (with a mean of $\sim$1,568) and near-sighted people (with a mean of $\sim$1,794) corresponds to $\sim$0,147 in the non-VR version. In the VR version these values are moderately smaller with a mean of $\sim$0.63 and a variance of $\sim$0,017 for the near-sighted and 0,0097 for the normally sighted. From these data we can conclude that people with normal vision and users with visual defects that wear corrective lenses experience a virtual environment similarly.

  Regarding the comparison between the normally sighted subjects and the near-sighted participants without glasses, there was a statistically significant difference, with a p-value of 0.0030 for both the VR and non-VR version. This difference can also be seen in Figures 5.17 and 5.18. The mean is $\sim$0,277 in both versions, while $\sim$0,0356 and $\sim$0,143 are the means for the VR and non-VR test respectively. Also, in this case, we can observe how the outcomes for the near-sighted subjects wihout glasses in the VR version are higher than the non-VR version.

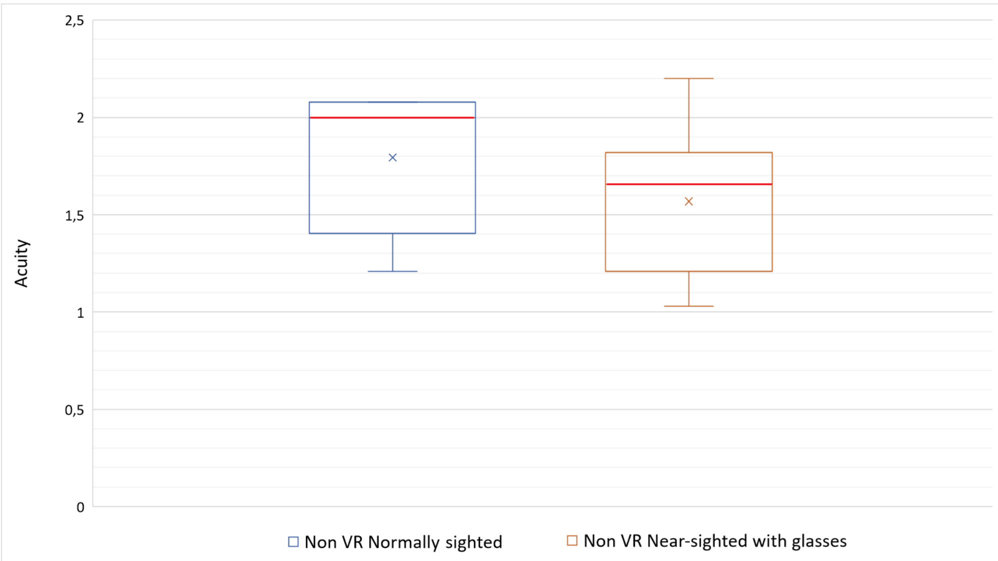


Figure 5.15: Comparison of the results in non-VR version between normally sighted and near-sighted (with glasses) participants.

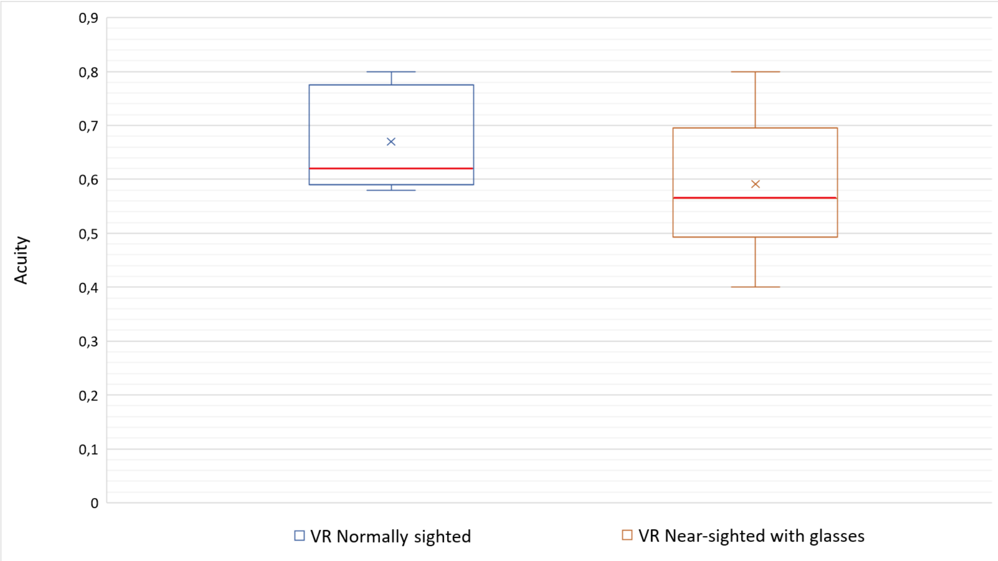


Figure 5.16: Comparison of the results in VR version between normally sighted and near-sighted (with glasses) participants.

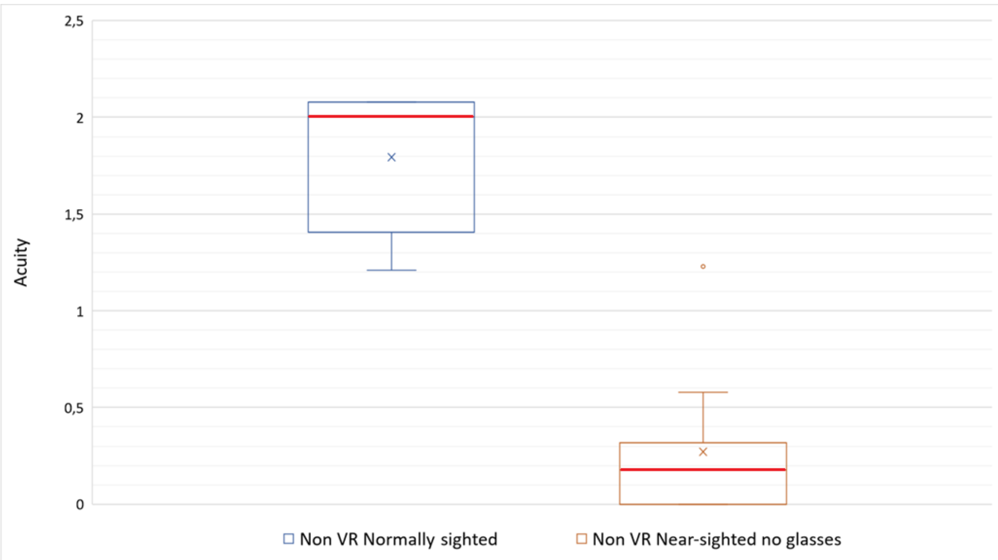


Figure 5.17: Comparison of the results in non-VR version between normally sighted and near-sighted (without glasses) participants.

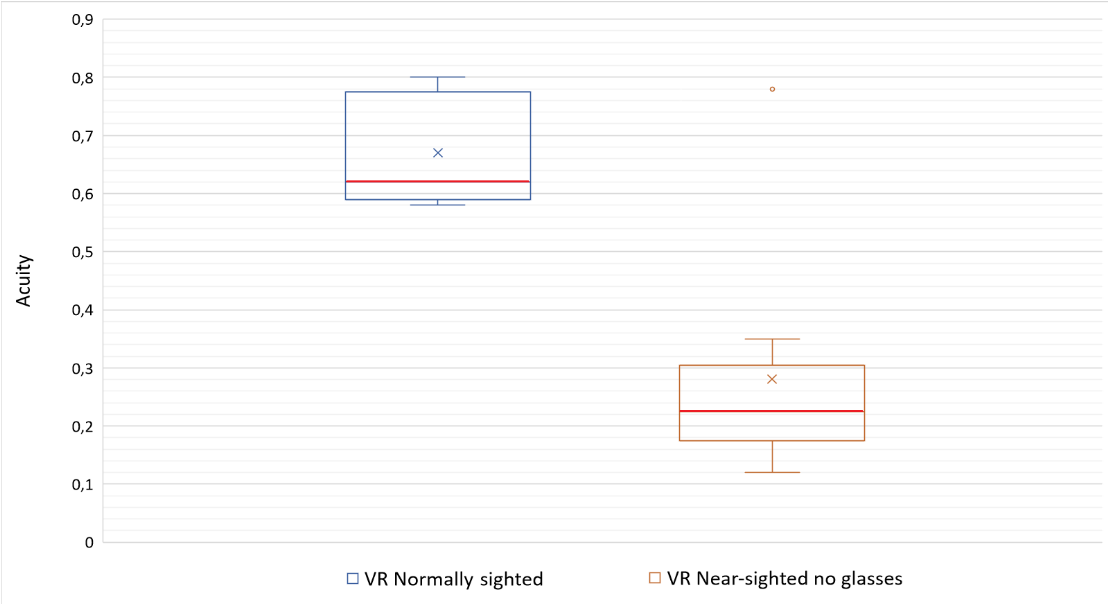
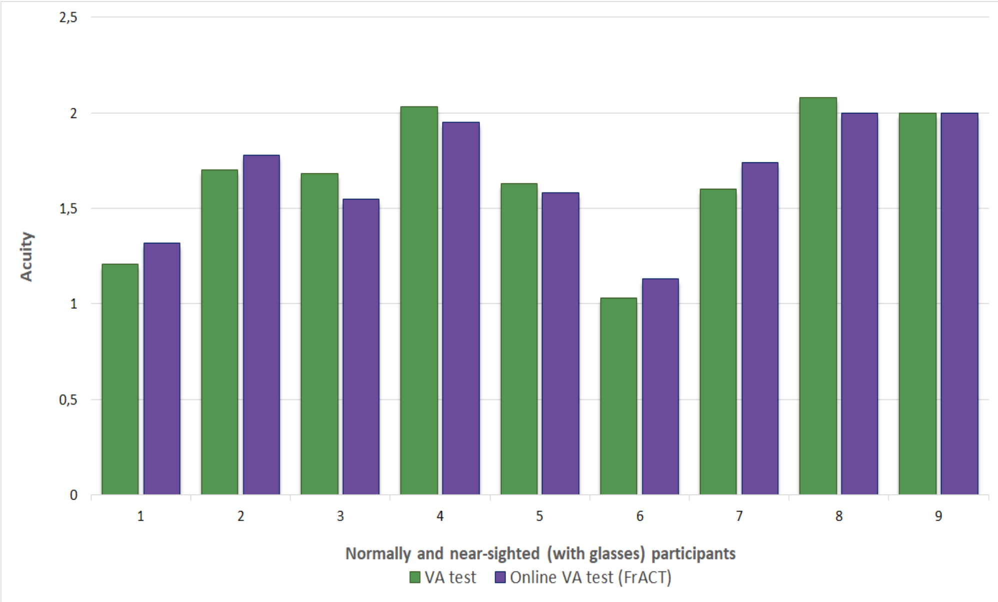


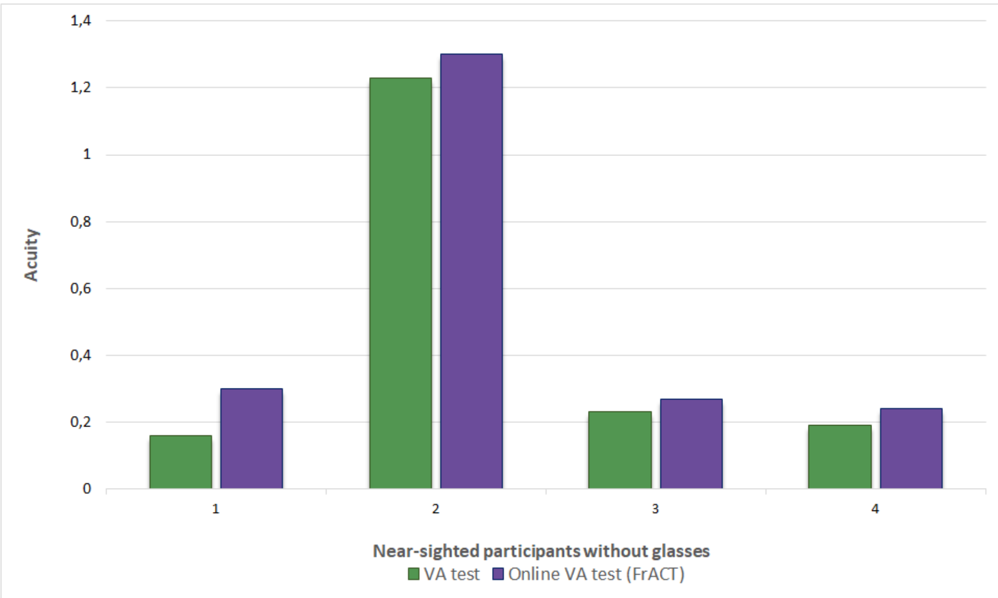
Figure 5.18: Comparison of the results in VR version between normally sighted and near-sighted (without glasses) participants.

- *Comparisons to the Freiburg Vision Test ('FrACT')*

  As mentioned at the beginning of this chapter, some of the participants also conducted a second VA test. For this test we decided to use an established online VA test, the Freiburg Vision Test ('FrACT') by Michael Bach [Baca]. The values that we obtained from the second test were similar to the values obtained from our non-VR test. We used the Kolmogorov-Smirnov test ($\alpha = 0.05$) to calculate a possible statistically significant difference between the results of the two VA tests. Since the Kolmogorov-Smirnov test did not reveal any statistically significant difference (with a p-value of 0.8281), it confirmed the reliability of the outcomes collected from our VA test. Figures 5.19a and 5.19b show the comparison between the results of the two VA tests. Figure 5.19a reports the comparison of the values for normally sighted and near-sighted participants with glasses, while Figure 5.19b depicts the comparison for the near-sighted participants without glasses.



(a) Comparison of the results for normally and near-sighted (with glasses) participants



(b) Comparison of the results for near-sighted participants without glasses

Figure 5.19: Comparison between the two VA tests.

CHAPTER 6

Conclusion & Future Work

After testing the VA of 15 people (10 near-sighted with glasses and without and 5 normally sighted) in a virtual and a normal environment, the data collected from the user study follow consistent patterns. The obtained results support the theory that VA in the virtual world is not as good as in the real world. Therefore, all subjects (normally sighted people and near-sighted with glasses) proved to have a superior VA in the real world. Moreover, the outcomes seem to suggest that usually near-sighted people without corrective lenses are slightly more capable of recognizing smaller details in a virtual experience in comparison to the real world. The only exceptions were the two participants with a dioptric defect, less severe than -3. A possible explanation for these results could be the fact that HMD-technologies incorporate lenses. Eyes with visual defects need corrective lenses in order to reach normal vision. Consequently, since users see objects in VR through the lenses of HMDs, this could lead to a small correction of the vision for near-sighted people with at least -3 D and without glasses on. Another factor that could moderately improve vision in VR for near-sighted users without glasses is the distance between the pupils and the displays of the HMD. Even if HMDs are designed in such a way that this space between the eyes and the displays appears larger than the actual one (see Section 4.4), the fact that the displays are so closed to the user's face could influence the process of accommodation of the visual system. Since near-sighted people have abnormal amplitudes of accommodation [JOA01], this limited distance between eyes and displays could affect them positively.

This research provides a starting point for various future works and more in-depth studies. First of all, the conducted project could be repeated with a larger sample of people divided into different categories according to their dioptric deficit. With a larger number of participants in which most of the dioptres' range are represented, it would be possible to investigate if the results obtained in this thesis occur also on a larger scale or if they are just a coincidence. For instance, it should be examined if near-sighted persons without glasses and a deficit smaller than -3 D cannot achieve a superior VA in VR in contrast to the ones with more than -3 dioptric defect. Moreover, it would be interesting to see if there is a different outcome between people who wear glasses and people who use contact lenses.

A similar study as the one of this thesis could be conducted with astigmatic or far-sighted subjects. The fascinating aspect of this research is represented by the suggestion that far-sighted users would not need corrective lenses when using an HMD. Accordingly, their VA would be higher in VR. Therefore, a comparison between these various groups of people could lead to a better understanding of HMDs and their impact on people with visual defects.

List of Figures

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