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Characterizing Visual Acuity in the use of Head Mounted Displays

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Não importa o quanto tempo leve para chegar ao seu destino,
siga em frente sempre,
não ande para trás
e passe por cima das barreiras que estiverem para dificultar...
— LLUCASHR

“The software was kind of clunky when this all started,
but now people are using it so much
they’ll be surprised how fast we innovate”
— BILL GATES

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ABSTRACT

There, ophthalmology has several tools to assess and correct a person's vision. In VR, when wearing an HMD, even a user with normal vision is challenged by additional hurdles that affect the virtual environment's perceptual acuity, negatively impacting their performance in the application task. Display resolution, but also soiled lenses and bad vergence adjustment are examples of possible issues. To better understand and tackle this problem, we provide a study on assessing visual acuity in a VR setup. The variability of perceptual accuracy between users and the system is an issue still poorly explored in the literature, and this problem is the focus of this research. We designed two methods based on ophthalmology tests that allow to collect quantitative measures from how a user perceives visual details when using an HMD. Each of the two methods was tested in user experiments we conducted with more than 40 participants. We found out, among other results, that visual acuity in VR is significantly and considerably lower than in real environments. Besides, we found several correlations of the measured acuity and task performance with difficulty adjusting the HMD and use of prescription glasses.

Keywords: Perception in VR. Head-mounted Display. Virtual Reality. Visual Acuity. Snellen.

Caracterização da Acuidade Visual na utilização de "Head Mounted Displays"

RESUMO

Na oftalmologia existem várias ferramentas para avaliar e corrigir a visão de uma pessoa. Na RV, ao usar um HMD, mesmo um usuário com visão normal é desafiado por obstáculos adicionais que afetam a acuidade perceptiva do ambiente virtual, impactando negativamente seu desempenho na tarefa de uma aplicação. Resolução da tela, mas também lentes sujas e ajuste de vergência ruim são exemplos de possíveis problemas. Para melhor entender e resolver este problema, fornecemos um estudo sobre a avaliação da acuidade visual em uma configuração VR. A variabilidade da precisão perceptiva entre os usuários e o sistema é uma questão ainda pouco explorada na literatura, sendo este problema o foco desta pesquisa. Projetamos dois métodos baseados em testes oftalmológicos que permitem coletar medidas quantitativas a partir de como um usuário percebe os detalhes visuais ao usar um HMD. Cada um dos dois métodos foi testado em experimentos de usuários que realizamos com mais de 40 participantes. Descobrimos, entre outros resultados, que a acuidade visual em VR é significativa e consideravelmente menor do que em ambientes reais. Além disso, encontramos várias correlações da acuidade medida e do desempenho da tarefa com dificuldade de ajustar o HMD e o uso de óculos de prescrição.

Palavras-chave: Percepção em VR, Head-mounted Display, Realidade Virtual, Acuidade Visual, Snellen.

LIST OF ABBREVIATIONS AND ACRONYMS

AMOLED	Active-matrix OLED
AR	Augmented Reality
CAVE	Cave Automatic Virtual Environment
CBTE	Confedereção Brasileira de Tiro Esportivo
CRT	Cathodic Ray Tube
CS	Contrast Sensitivity
DoF	Degrees of Freedom
EDTRS	Early Treatment Diabetic Retinopathy Study
FOV	Field of View
ft	foot
HMD	Head Mounted Display
HDR	High Dynamic Range
HVS	Human Visual System
ICC	International Color Consortium
IEC	Commission Internationale de L'Eclairage
ICO	International Councilof Ophthalmology
IPD	InterPupillary Distance
ISSF	International Shooting Sport Federation
jpg	Joint Photographic Experts Group
LCD	Liquid-Crystal Displays
m	meters
NASA	National Aeronautics and Space Administration
OLED	Organic Light-Emitting Diode
VA	Visual Acuity

VR	Virtual Reality
RGB	Red, Green, Blue
RGB-A	Red, Green, Blue - Alpha
sRGB	standard Red, Green, Blue
SS	Simulator Sickness
SVA	Static Visual Acuity
SVT	Visual Acuity Test
TLX	Task Load Index
TMO	One Mapping Operator
UFSM	Federal University of Santa Maria
VAC	Vergence-Accommodation Conflict

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1 INTRODUCTION

Head mounted displays (HMDs) were conceived in the early 1960's, at the very foundation of computer graphics. However, only recently the display technology attained levels of quality and cost-effectiveness to allow their deployment to the general consumer. This, combined with the outstanding advancement of computer graphics, enabled immersion in highly realistic virtual worlds. Substantial improvements in the quality and availability of virtual reality (VR) hardware were seen from 2013 onwards, in addition to a lower price, the new generation of HMDs also started to offer a better quality user experience (FRØLAND et al., 2020). The quality improvement was in the so-called Field of View (FOV), as until 2013 it was between 25 and 60 degrees, while new generation HMDs have FOVs above 100 degrees (RIVA; WIEDERHOLD; GAGGIOLI, 2016).

Still, oftentimes the user experience in VR is undermined by factors dependent of the HMD construction and use. While an HMD is a display, it is also an input device that uses sensors define the head pose. Thus, the whole human vestibulo-oculomotor system is stimulated, in such way that any discrepancies cause some level of discomfort and perception issues that may hinder the user performance. The display device itself also has certain hardware limitations, such as display brightness, contrast, resolution, color fidelity, possible reflections, or latency, which can affect any virtual reality (VR) application. The visual field is also much smaller compared to the visual field of the human eye (KRUIJFF; SWAN; FEINER, 2010). This has been delaying the adoption of VR in both industrial and personal applications (POLCAR; HOREJSI, 2013; GAVGANI et al., 2018).

Nausea, disorientation and eye-strain, among other symptoms, are grouped under the cybersickness context (PALMISANO; MURSIC; KIM, 2017). Cybersickness has been linked to low refresh rate, latency, misalignment, vection, amount of head displacement and individual susceptibility. Previous studies approached the problem of cybersickness, demonstrating that it can be fairly predicted and avoided by controlling such parameters (although some of them are difficult to control).

Current FOV restrictor implementations reduce the user's FOV by rendering a restrictor whose centeris fixed at the center HMD (ADHANOM et al., 2020), which is effective when the user's eye gaze is aligned with head gaze, however, during eccentric eye gaze, users may look at the FOV restrictor itself could lead to increased VR sickness, so they developed a foveated FOV restrictor to exploit the effect of dynamically moving the center of the FOV restrictor according to the user's gaze position.

Reducing field of view (FOV) during locomotion is a strategy used to reduce VR disease by blocking peripheral optic flow perception and attenuates visual/vestibular conflict, (ZAYER et al., 2019) in their study provides insight into VR disease and spatial navigation where the found the use of a FOV restrictor to be effective in attenuating VR disease in both sexes while finding no negative effect of FOV restriction on spatial navigation performance.

The phenomenon of cybersickness is currently impeding the mass market adoption of head-mounted virtual reality (VR) (HMD) display technologies, (TEIXEIRA; PALMISANO, 2021) examined the effects of dynamic field of view (FOV) constraint on cybersickness generated by HMD-based ecological gameplay finding individual differences in spontaneous postural instability to predict cybersickness during HMD VR gameplay, cybersickness increased throughout each VR exposure being reduced by dynamic FOV constraint.

However, another phenomenon has been extensively overlooked: the variability of the perceptual accuracy among users and systems. Arguably, pixel size, lens aberration, contrast and size of the displayed objects all potentially influence the ability of the user to accurately perceive visual elements.

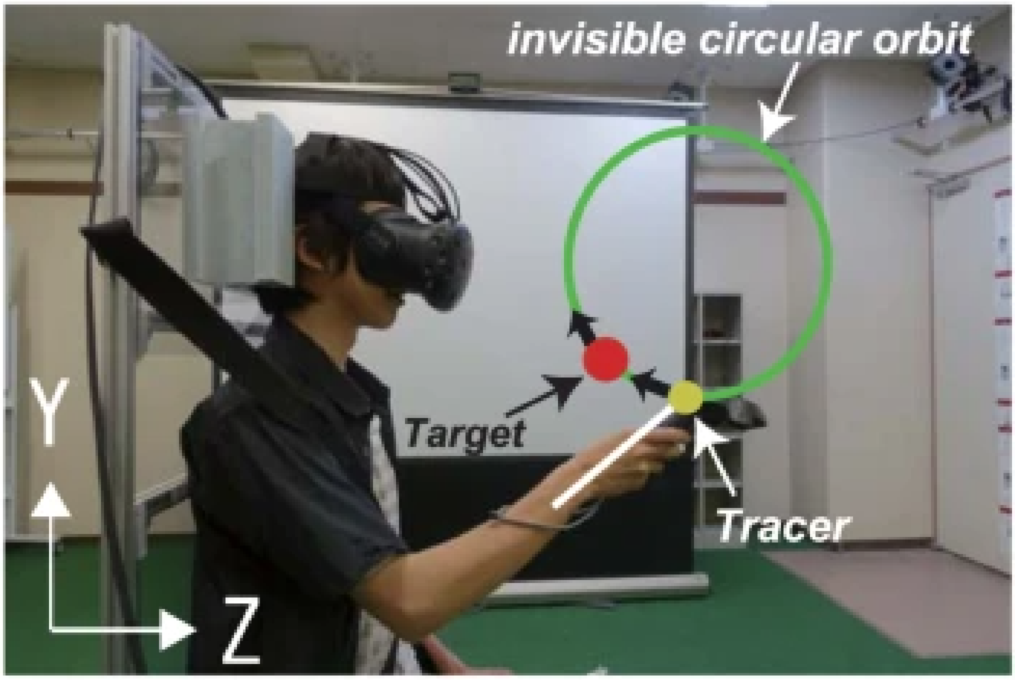
In the real world, ophthalmologists can measure any significant deviation from the average quality of the visual perception in a patient. Many types of deviations are very common and well known, such as myopia, hyperopia, astigmatism, cataracts, and others, which are caused by optical or neural factors. The disability caused by these deviations is grouped under the term low vision or low visual acuity (VA).

Visual Acuity is the ability to recognize small details with precision and is a measure relative to the normal vision. The VA is said to be normal, 6/6 or 20/20 when the individual discriminates two contours separated by 1 arc minute (or 1.75 mm) at 6 metres (or 20 feet) (MESSINA; EVANS, 2006) (SOARES; BARBOSA, 2018).

In VR, the visual acuity experienced by an individual with normal vision in a given session wearing an HMD is dependent on a number of additional factors, e.g. rendering technique, display resolution, focus, vergence, lens quality. While some factors are system dependent and are constant for the same system among different sessions and users, such as rendering and display resolution, other factors such as focus, vergence and transparency of the lenses vary considerably between sessions due to human influence (Fig. 1.1). When putting on the HMD, people soil the lenses, do not fasten enough or fasten too much the straps, do not understand how to setup vergence, cannot judge if they are seeing as well as possible.

These factors potentially affect the perceived acuity in some way, disturbing the experience. To our knowledge, visual acuity has not been characterized for HMD-based VR. In our research, we are especially concerned by the lack of control in the experimental conditions of task-based studies in VR. Our premise is that researchers do not know to which extent the results of their experiments are affected by the studied variables, e.g. an interaction technique, or by the user ability to see the elements necessary to accomplish the task.

Figure 1.1: Control in the experimental conditions of task-based studies in VR



Source: (CHOI et al., 2018)

In this dissertation, we seek to investigate visual acuity in VR and our main goal is to define the problem of inferior acuity in terms of the relevance of each potential cause. A specific goal is to propose a methodology to measure acuity by adapting known techniques from ophthalmology to VR, which is a second contribution.

We propose a shooting test as an alternative to assess visual acuity, in a game where we test the user and correlate their performance with visual acuity measured in ophthalmology tests in VR.

In a new interaction we design some tests using Landolt Rings, where users perform tasks without supervision, finally we test how users respond to a test where the HMD lenses are dirty.

We hope that researchers in the future can use this method to ensure that each subject experiences an appropriate level of visual acuity needed to accomplish a task, or to normalize the user collected data according to a measured level of visual acuity. In a set experiments with users, we assess the variability of acuity across users, sessions, and experimental conditions.

This dissertation is organized as follows. In Chapter 2, we provide an overview of approaches used in ophthalmology to assess visual acuity, and in Chapter 3 we review related work on visual perception in VR. Then, in Chapter 4, we detail our proposed adaptation of common ophtalmology exams to VR for assessing visual acuity when using an HMD.

The methodology comprises the use of four separate tests before each dimension of acuity, and also an integrated test that we designed to measure all dimensions at once during a target shooting task. Section 4.9 describes user experiments we conducted to demonstrate the acuity tests and Section 4.10 discusses the results we obtained with this first approach some conclusions.

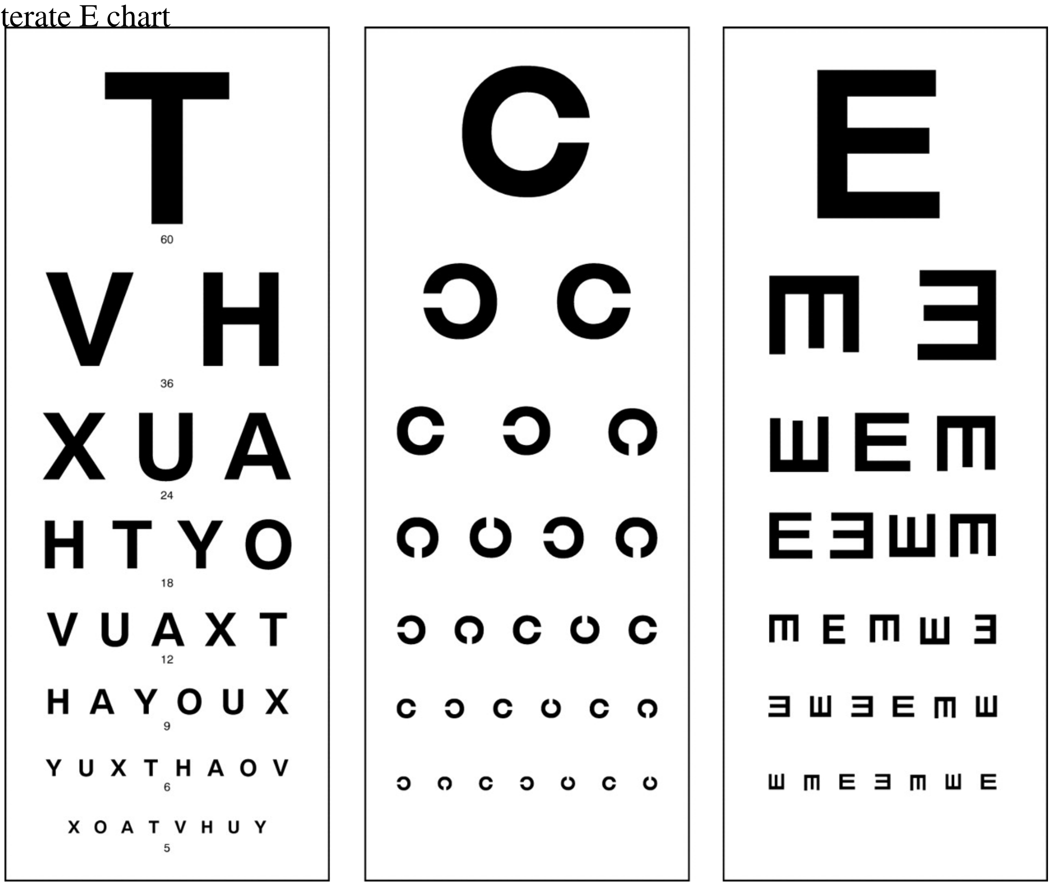
In Section 2.2 we explore the use of Landolt Rings for checking visual acuity. In Section 5 we describe the protocol as well as the design and implementation of the three tests we developed to measure users' visual acuity. The results of the experiment are shown in Section 5.6 followed by a discussion. Our general conclusions, main contributions and future work are in Section 6.

2 BACKGROUND ON VISUAL ACUITY

Visual acuity refers to the clarity of vision and the ability to distinguish details in objects. Anatomically, it is the ability of the eye to focus the image on the retina (SPROULE et al., 2019). It is also the capability of the eye to distinguish small details appearing on the visual field at a specified distance (PANFILI, 2019). Acuity can also be split into two types: static, when the object is perceived stationary; dynamic, when the observer, the object or both are in motion (JUNYENT; AZNAR-CASANOVA; SILVA, 2018).

Standard objects used to assess acuity are often called optotypes. The most common set of optotypes used to measure static VA are the Snellen chart and the Landolt C, also known as a Landolt ring. Both were created more than 100 years ago (ARTIGAS et al., 1995). There are also other more recent (Fig. 2.1) optotypes in use today (GINSBURG, 1984) (PELLI; ROBSON et al., 1988). We present them and their different uses for visual acuity assessment in the next subsections.

Figure 2.1: Examples of visual acuity charts. (A) Snellen chart. (B) Landolt C chart. (C) Illiterate E chart



Source: https://m.media-amazon.com/images/I/418VdxKiPCL.jpg

The standard ISO 8596:2018 defines visual acuity as the number that characterizes

Table 2.1: Visual acuity grades, Landolt ring sizes and minimum number of presentations

Visual acuity grades (nominal values)[d]			Gap size of Landolf ring (min. of arc)	Min. nbr. of presentations[d]
Decimal visual acuity [a]	**LogMAR acuity**	**Snellen fraction for test distance 6m**		
0.05	+1.30	6/120	20.0 [b]	2
0.063(0.06)	+1.20	6/95	15.8 [b]	2
0.08	+1.10	6/75	12.6 [b]	2
0.10	+1.0	6/60	10.0 [b]	2
0.125	+0.90	6/48	7.94 [b]	3
0.16	+0.80	6/38	6.31 [b]	3
0.20	+0.70	6/30	5.01 [b]	3
0.25	+0.60	6/24	3.98 [b]	5
0.32 (0.30)	+0.50	6/19	3.16 [b]	5
0.40	+0.40	6/15	2.51 [b]	5
0.50	+0.30	6/12	2.00 [b]	5
0.63 (0.60)	+0.20	6/9.5	1.58 [b]	5
0.80	+0.10	6/7.5	1.26 [b]	5
1.00	0	6/6.0	1.00 [b]	5
1.25	-0.10	6/4.8	0.794 [b]	5
1.60	-0.20	6/3.8	0.631 [b]	5
2.00	-0.30	6/3.0	0.501 [c]	5

[a] - The values in parentheses shall be used only for the purpose of identifying the acuity grade.
[b] - The gap is accurate to 1%. The permissible deviation is 5%.
[c] - The permissible deviation is 10 %.
[d] - The recommended number of presentations is at least 5 presentations.

the ability of the visual system to recognize optotypes, and three different scale systems are used to describe a patient's visual acuity: decimal visual acuity, Snellen fraction, LogMAR acuity.

The visual acuity grade is a number assigned to an optotype that is equal to a patient's minimum visual acuity required to recognize the optotype from a specified distance, these grades are standardized on the three different scale systems, and are shown in Table 2.1.

Decimal visual acuity is reciprocal of the minimum recognizable width of a Landolt ring measured in minutes of arc, e.g., a visual acuity of 1.0 is assigned when the smallest Landolt ring recognized by a patient has an interval width of 1 min of arc measured from the patient's viewing distance.

The Snellen fraction (Eq. 2.1) is a notation used to specify the angular subtense of an optotype, expressed as a fraction (ISO8596, 2017), with the numerator (test distance) being the distance at which visual acuity is tested, usually in *m* or *ft*, and the denominator (normal distance) being the distance at which the critical detail (limb) of the smallest recognizable optotype subtends 1 min of arc.

A Snellen fraction of 6/6 is assigned to a patient's visual resolving power when the smallest recognizable Landolt ring has a 1 min arc opening at a viewing distance of 6.0 m. Decimal visual acuity can be calculated from the Snellen fraction by evaluating the quotient (e.g., Snellen fraction 6/6 = decimal visual acuity 1.0).

$$V_{Sn} = \frac{D_t}{D_n} \tag{2.1}$$

where

V_{Sn} is the visual acuity, measured as Snellen fraction;

D_t is the test distance, measured in m or ft;

D_n is the normal distance, measured in m or ft.

LogMAR acuity is a logarithm (base 10) (Eq. 2.2) of the minimum resolution angle measured in arc minutes.

$$\text{Decimal visual acuity} = 10^{(\text{-LogMAR acuity})} \tag{2.2}$$

Section 2.1 introduces the basics of Snellen methods. Sections 2.2 and 2.3 are based on the *Irish Standard - I.S.EN ISO 8596:2018 (Ophthalmic optics - Visual acuity testing - Standard and clinical optotypes and their presentation (ISO 8596:2017)).* They detail the use of Landolt rings. The remaining sections of the present chapter introduce other concepts related to acuity in the dimensions of contrast and refraction issues.

2.1 Snellen-type Optotype

Herman Snellen, in 1862 (SNELLEN, 1862) created a table (Table 2.2) composed by letters of different sizes (optotypes - Table 2.2) representing a visual angle of 5 minutes of arc (5'). The letters are composed by elements of $\frac{1}{5}$ of this measure (ALVES et al., 1994).

Table 2.2: Snellen-type Optotype Table

Dimension	Measure in mm
I	67.891
II	136.107
III	203.999
IV	272.215
V	340.106
VI	408.323
VII	476.214
VIII	544.105
...	...

In his study (SNELLEN, 1862), Snellen specifies the dimensions of the characters and the spaces that separate them. The visual acuity (V) is the maximum distance at which the optotype is recognized (d) divided by the distance at which it should be to form an angle of 5 arc-minutes (D) (SNELLEN, 1862; SOARES; BARBOSA, 2018) as in Eq.2.3:

$$V = \frac{d}{D}. \tag{2.3}$$

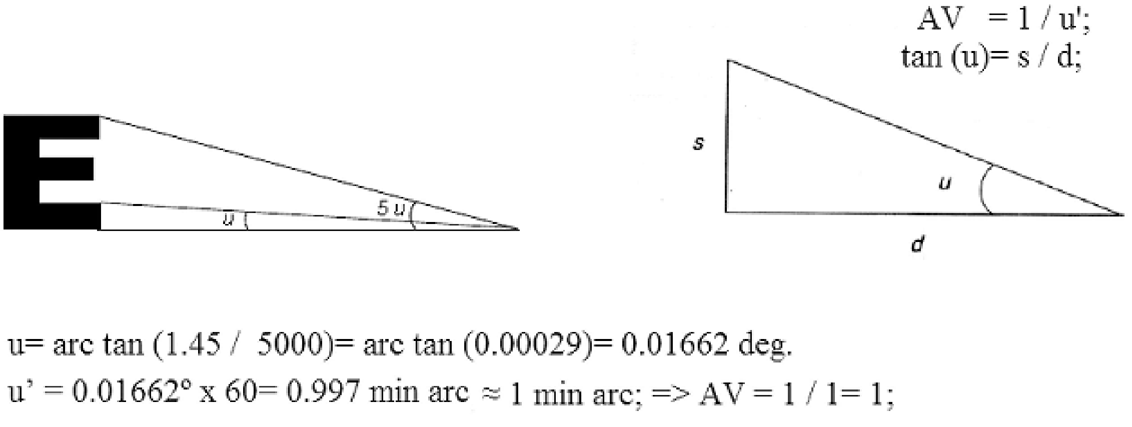
If d and D are equal and the the optotype is visible at 20 Paris foot [1], then $V = \frac{20}{20} = 1$ is defined as a normal visual acuity.

In the Snellen proposal, the minimum resolution angle is 1 arc-minute, as seen in Fig.2.2 (SOARES; BARBOSA, 2018). To determine the size of an optotype in the Snellen chart, the formula of Eq. 2.4 is used (SILVA, 2001):

$$H = 14.6\frac{D}{V} \tag{2.4}$$

where H is the height of the optotype (in mm), D is the presentation distance (in meters), V is the visual acuity (in tenths) and the constant 14.6 represents the tangent of 5 multiplied by 10,000 to compensate for the use of millimeters and tenths in the other components.

Figure 2.2: Calculation of the Static Visual Acuity (SVA) in a Snellen-type optotype. It is assumed that the observer looks at the letter from a distance of 5 meters ($d = 5m$). Therefore, the height of the letter will be $7.25mm$ and the thickness of the horizontal feature will be $s = 1.45mm$ (JUNYENT; AZNAR-CASANOVA; SILVA, 2018).



u= arc tan (1.45 / 5000)= arc tan (0.00029)= 0.01662 deg.
u' = 0.01662° x 60= 0.997 min arc ≈ 1 min arc; => AV = 1 / 1= 1;

Source: (JUNYENT; AZNAR-CASANOVA; SILVA, 2018)

In a Snellen chart (Fig. 2.3), some letters are more easily readable than others and each row has a different number of letters. This causes the phenomena of non-proportional grouping and spacing between letters and rows, making reliability and reproducibility of

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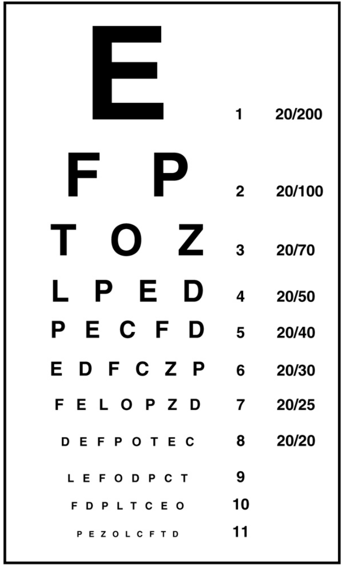
[1] (JANUÁRIO; ANTÚNES, 2005) (MARQUES, 2001) 1 Paris foot is equivalent to $324.8393mm$. 1 Paris foot = 1.06575 feet

using a Snellen chart low (ZAPPAROLI; KLEIN; MOREIRA, 2009). Nevertheless, it is widely used and universally accepted.

Figure 2.3: Snellen Table



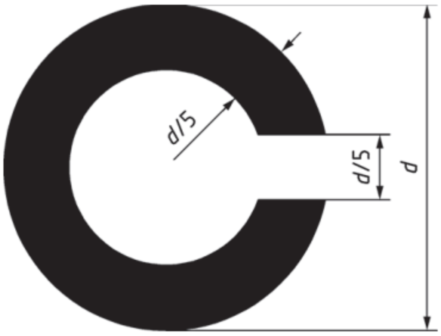
Source: http://www.stargardt.com.br/entendendo-o-que-e-acuidade-visual/

2.2 Landolt Rings

The Landolt ring (Fig. 2.4) is detailed in ISO 8596:2018 as a decimal visual acuity grade 1 that is represented by a Landolt ring whose outer diameter, *d*, subtends a 5 min arc angle and whose width, as well as the gap in its continuity, subtends a 1 min arc angle at the viewing distance.

The Landolt ring can be presented with eight different interval orientations, including left and right horizontal orientations, the top and bottom vertical orientations, and the four main diagonal orientations.

Figure 2.4: Landolt ring



Source: (ISO8596, 2017)

Key:

d diameter

The visual acuity grades can be seen in Table 2.1. The size of the standard optotype interval (Landolt ring) should be logarithmically graduated, where the quotient between the size of the optotype and that of the next smallest should be $\sqrt[10]{10} =$ (series of preferred numbers R10 from ISO 3:1973).

Test area and optotype spacing should extend at least 0.5° in all directions from the outline of the optotypes to the end of the field of view, if more than one optotype is used in the same test area.

The spacings of Table 2.3 should be applied, in case of using more than one acuity grade in the test area, the spacing applied should be that of the largest optotype, both in horizontal and vertical spacing. As for the background the optotypes should appear uniformly bright and without any color or texture variation that could indicate their orientation.

Table 2.3: Spacing between standard optotypes (border to border)

Decimal visual acuity grades	**Minimum spacing between standard optotypes**
less than 0.06	0.4 x diameter of Landolt ring
0.06 to 0.125	1.0 x diameter of Landolt ring
0.16 to 0.32	1.5 x diameter of Landolt ring
0.40 to 1.00	2 x diameter of Landolt ring
greater than 1.00	3 x diameter of Landolt ring

The ambient brightness around the optotypes (chart background - Fig. 2.5) should be in the range of 80 cd/m^2 to 320 cd/m^2, in all presentation methods should be applied. The luminance of the optotype should not be higher than 15% of the surrounding field when measured in a darkened room and is recommended to use a background luminance 200 cd/m^2. The optotype's background luminance extends to 0.5 *d* (where *d* = optotype diameter) beyond the optotype border and shall not vary by more than ±30% from the average background luminance, which shall not vary by more than ±50%.

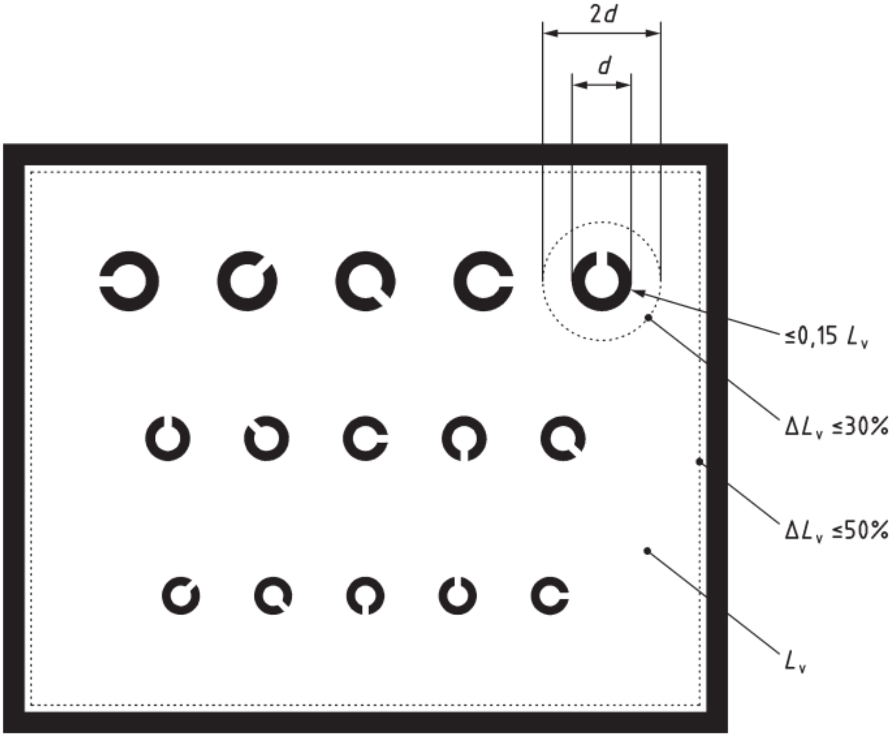
Key:

d diameter of the Landolt ring

L_v luminance of immediate surround of the optotypes

ΔL_v variability of luminance in the denoted area

Figure 2.5: Specification of luminance



Source: (ISO8596, 2017)

2.3 Visual Acuity Tests Using Landolt Rings

The World Health Organization (WHO) defines three stages of visual impairment and one for blindness, as shown in Table 2.4, using the reference set of values of 20/20 expressed in feet, or 6/6 expressed in meters (KRÖSL, 2020).

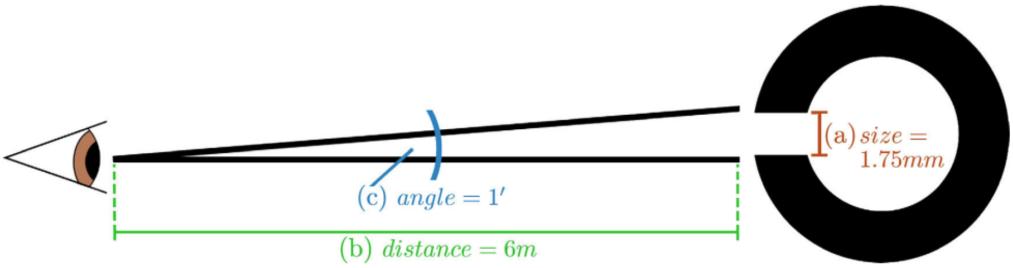
Table 2.4: Stages of visual defined by the WHO

Stage	Snellen Fraction		Decimal Acuity
Mild	<20/40 ft	<6/12 m	<0.5
Moderate	<20/60 ft	<6/18 m	<0.3
Severe	<20/200 ft	<6/60 m	<0.1
Blind	<20/400 ft	<3/60 m	<0.05

Stages of visual impairment, as defined by the WHO [WHO19], shown as Snellen Fraction (in feet and meters) and decimal acuity. Smaller VA values correspond to more severe impairments.

Visual acuity (VA) quantifies a person's ability to recognize details in a scene, and can be measured by showing subjects different optotypes with different sizes at a predefined distance which allows us to determine which size can be recognized or not. Visual acuity is usually expressed in relation to 6/6, the Snellen fraction for a distance of 6m, or 20/20 in feet, or the decimal value of these fractions, so a person will have normal vision when they can recognize a detail that spans 1 arc minute (1/60 of a degree), which would be a size of $\sim$ 1.75mm at 6 meters away (Fig. 2.6).

Figure 2.6: A person with normal vision



Source: (KRÖSL, 2020)
A person with normal vision can recognize a detail, such as (a) the gap in Landolt C, of size ∼ 1.75mm at (b) 6 m distance. (c) The respective angle of view corresponds to 1 arc minute (1/60 of a degree).

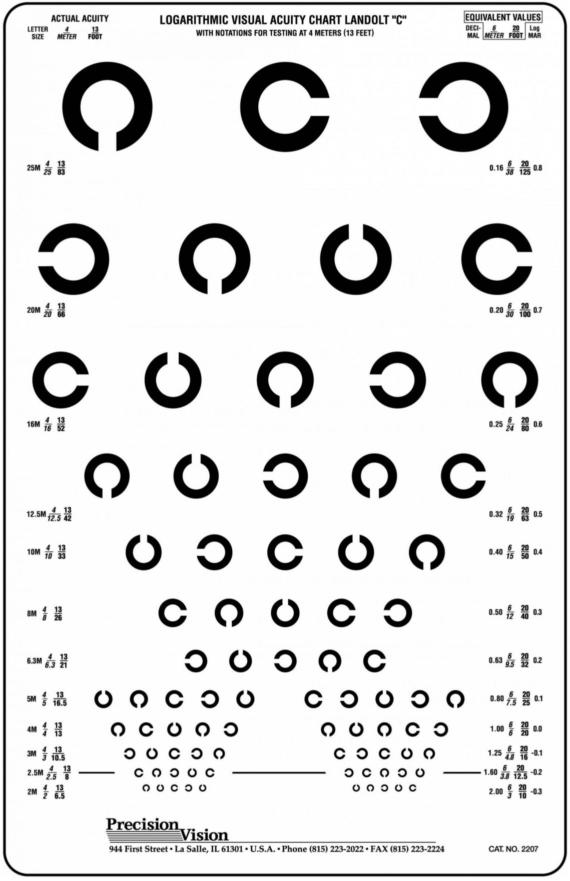
Since Snellen (SNELLEN, 1862), few improvements in the measurement of visual acuity have been made. Landolt, in 1888 proposed a modification (MESSINA; EVANS, 2006), with ringed circular optotypes having only one breaking element, with a variation in its orientation, so patients who could not read could identify the orientation of a gap in the rings (KNIESTEDT; STAMPER, 2003). Landolt-C letters are very common as a screening device in performance environments and in the differential diagnosis of eye diseases (SCHRAUF; STERN, 2001).

Only almost a century after Snellen's studies did new proposals emerge. Sloan in 1959, Hyvärinen in 1976, Taylor in 1976, Bailey and Lovie in 1976 and the Early Treatment Diabetic Retinopathy Study (EDTRS) Protocols in 1991 and International Council of Ophthalmology (ICO) in 2002 achieved consensus and standardized worldwide the subjective measurement of visual acuity by establishing a table with five letters of equal size in each row. In this way, the clustering effect and the number of the errors that could be made in each row made the letter size the only variable among the measured visual acuity levels (BECK et al., 2003).

The idea of testing visual acuity using always the same stimulus in different orientations avoids the differences in resolution that depend on the complexity of the chart. When letter optotypes are used, the stroke width is one of the most relevant details that is considered, but the acuity of the letter also depends on the complexity of the letter, its orientation and the type used (SCHRAUF; STERN, 2001).

Since not all Snellen optotypes are equally recognizable, in 1888 Landolt addressed this problem by proposing an eye letter that had only one symbol, a ring with a break at the top, bottom, left or right, and 45 degree positions in between, basically the letter C in various orientations (Fig. 2.7) . To match Snellen's results, the "standard" size of the C was 0.35" (which subtends 5 minutes of arc at 20 feet) with a range of 0.07" or 1

Figure 2.7: Logarithmic Visual Acuity Chart Landolt "C"



Source: https://storage.googleapis.com/stateless-precision-vision/2019/06/ac973568-2205fc-web-image-scaled.jpg

minute of arc (MESSINA; EVANS, 2006).

If logarithmic progression of optotype sizes is used, the progression is developed in steps of 1:(10)^{0,1}, equal to 1:1,258. Table 2.5 lists the resulting optotype sizes together with the corresponding visual acuity notations. In these acuity sequences, numbers have been rounded. Charts are prepared so that the 20/20 row (6/6 or 1,0) is precisely specified (ISO8596, 2017).

2.4 Pelli-Robson Contrast Sensitivity

Besides the high-contrast VA measurement (black optotypes on a white background) provided by Snellen charts, other contrast levels can also be used to obtain a second measure of acuity. The principle is to use gray optotypes on the same white background, showing successively lighter and lighter grays (CRUZ; MACHADO, 1995).

Contrast is defined as the relative difference of luminance between a target and

Table 2.5: Progression of acuity grades, in terms of gap size of the equivalent Landolt ring

Decimal visual acuity	LogMAR acuity	Snellen fraction for test distance				Gap size of Landolf ring (Minutes of arc)
		6 m	5 m	4 m	6.1 m (20 ft)	
0.050	+1.3	6/120	5/100	4/80	20/400	20.0 ^{a}
0.063(0.06)	+1.2	6/95	5/80	4/63	20/320	15.8 ^{a}
0.08	+1.1	6/75	5/63	4/50	20/250	12.6 ^{a}
0.10	+1.0	6/60	5/50	4/40	20/200	10.0 ^{a}
0.125	+0.9	6/48	5/40	4/32	2/160	7.94 ^{a}
0.16	+0.8	6/38	5/32	4/25	20/125	6.31 ^{a}
0.20	+0.7	6/30	5/25	4/20	20/100	5.01 ^{a}
0.25	+0.6	6/24	5/20	4/16	20/80	3.98 ^{a}
0.32 (0.30)	+0.5	6/19	5/16	4/12.5	20/63	3.16 ^{a}
0.40	+0.4	6/15	5/12.5	4/10	20/50	2.51 ^{a}
0.50	+0.3	6/12	5/10	4/8.0	20/40	2.00 ^{a}
0.63 (0.60)	+0.2	6/9.5	5/8.0	4/6.3	20/32	1.58 ^{a}
0.80	+0.1	6/7.5	5/6.3	4/5.0	20/25	1.26 ^{a}
1.00	+0.0	6/6.0	5/5.0	4/4.0	20/20	1.00 ^{a}
1.25	-0.1	6/4.8	5/4.0	4/3.2	20/16	0.794 ^{a}
1.60	-0.2	6/3.8	5/3.2	4/2.5	20/12.5	0.631 ^{a}
2.00	-0.3	6/3.0	5/2.5	4/2.0	20/10.0	0.501 ^{b}

^{a} - The permissible deviation is 5 %.
^{b} - The permissible deviation is 10 %.

the background. The whole human visual system (HVS) is involved in object detection, meaning that while the eyes capture and convert light into electric signals, the brain processes and makes the decisions about the visual perception of objects (BARTEN, 1999; SUKUMAR et al., 2010). Contrast is used to determine what is detectable by the HVS (GAMONAL-REPISO et al.,). The objects are visible if they have a contrast greater than the contrast sensitivity (CS) (SUKUMAR et al., 2010; KOENDERINK; DOORN, 1996), which is defined as the minimum contrast necessary to detect a grid in some specified spatial frequency (CORNSWEET, 2012).

CS was first measured in 1889 (REGAN, 1988), but its value was reconized only after Bodis-Wolner work in 1972 (BODIS-WOLLNER, 1972). Pelli et al. (PELLI; RUBIN; LEGGE, 1986; PELLI; ROBSON et al., 1988) first proposed a chart with variable contrast letters sized at half a degree that can measure the CS of an individual with spatial frequencies between 3 and 5 c/deg (cycles per degree). That is the best interval to determine whether an individual has a loss of sensitivity in the spatial frequency. Later, they came up with a new chart with single sized letters that change in contrast at each row.

Based on this discussion, they proposed a new graphic with letters of unique size and with changes in contrast to each line, what could be used to obtain information about the contrast sensitivity of any individual, so they created a model that allow to choose the best parameters to accurately maximize the measurements provided by the test. (PELLI; RUBIN; LEGGE, 1986) (PELLI; ROBSON et al., 1988).

Their widely used chart presents a set of Sloan font letters (SLOAN, 1959) with size of 0.5° at a distance of $3m$, although it can be used at shorter distances to assess

Figure 2.8: Miniature Pelli-Robson Letter-Sensivity Chart

Source: https://www.researchgate.net/figure/Pelli-Robson-Contrast-Sensitivity-Chart _fig1 _276159141

individuals with subnormal vision. The chart is read from left to right, from top to bottom. Each row contains two groups of three letters. The letters within each group have the same contrast, while each successive group has lower contrast than the previous one. As seen in Fig. 2.8, there is a total of 48 optotypes on a white background, divided in 16 groups. The first group is black (contrast is 100%), and each subsequent group has a contrast reduction factor of 0.707 (0.15 log units). Thus, the contrast of the last group is 0.56% (2.25 log units below 100% (WILLIAMSON et al., 1992).

The Pelli-Robson chart is considered a suitable technique to asses the visual function (LASA et al., 1992).

2.5 Glare and disability brightness

Glare is a light phenomenon that causes difficulty, and may even disable, viewing of an object due to very bright light of artificial or natural origin (CARLUCCI et al., 2015).

Most visual comfort analyses are performed in a fixed viewing position and direction, but glare depends on the viewing position and direction within a space (BIAN; LENG; MA, 2018).

Abrahamsson (ABRAHAMSSON; SJÖSTRAND, 1986) define that contrast sensitivity is the expression of the minimum contrast that the visual system is able to detect with the smallest variation of brightness that the eye can discern, whereas glare is the impairment in visual function caused by the presence of a light source close to the visual field.

The literature (HOSKINS JR., 1996; NADLER; MILLER; NADLER, 1990) states that the contrast sensitivity test provides more information on spatial vision than the simple measurement of visual acuity. Lacava and Centurion (1999) concluded that the glare test associated with the contrast sensitivity test shows that the visual acuity provided by the Snellen table does not correspond to everyday vision. Although the measurement of visual acuity using contrast sensitivity is not unanimous, it is considered more informative than the measurement of visual acuity using the Snellen table (WILLIAMSON et al., 1992) (ANDRADE et al., 1994).

Hoskins Jr. (1996) states that glare or glare testing and contrast sensitivity play a role in quantifying or describing visual impairment in some patients, although the most appropriate visual tests for the assessment of night vision disorders are predominantly performed under low contrast conditions and at low spatial frequencies using scotopic or mesopic, low contrast (urban) conditions (MUTYALA et al., 2000) (PEREZ-SANTONJA et al., 1997).

2.6 Luminance, contrast and resolution in HMDs

The human eye in good light conditions (80 cd/m^2 to 320 cd/m^2) has a resolution of 1’ (290.89 µrad) in the fovea zone (Fig.2.9). Outside this zone the resolution of the eye decreases considerably (MOITA, 2013) [2]. Thus a moderate variation in contrast or illumination will reflect very little on the user’s visual acuity, for visual perception is influenced by the difference in intensity between the object and the background (contrast), the spatial frequency (inverse of the line thickness in regular optotypes) and the area of

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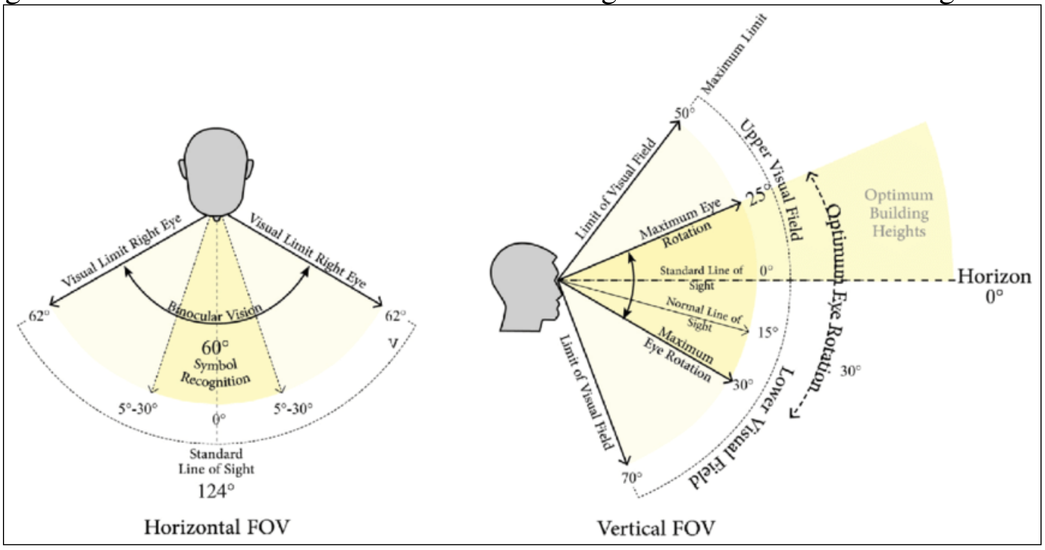
[2] H. Snellen, Probebuchstaben zur Bestimmung der Sehschärfe. Van de Weijer, 1862.

the object (SOARES; BARBOSA, 2018) [3].

Figure 2.9: Human field of vision - horizontal angle of view and vertical angle of view



Source: https://www.researchgate.net/figure/Human-field-of-vision-A-horizontal-angle-of-view-and-B-vertical-angle-of-view _fig3 _344509899

Contrast is the ratio between the highest and lowest luminance provided by the display (PAUSCH; CREA; CONWAY, 1992) and luminance is the amount of visible light emitted per unit projected area of the display (ALDRICH; RUTLEDGE, 2005). It is relative to the amount of light emitted by the display system being expressed in candelas per square meter (cd/m^2) (KEMENY; CHARDONNET; COLOMBET, 2020).

The luminance of the image displayed by a device depends on its distance from the video projector and the characteristics of the surface onto which it is projected, and luminance is sometimes confused with brightness. In their book, A. KEMENY,((KEMENY; CHARDONNET; COLOMBET, 2020)) note that luminance in the real world can reach much higher values than display systems, such as 1.6 x 10^9 cd/m^2 for the sun at noon versus 50-300 cd/m^2 at a maximum resolution on a computer monitor, so we have to take into account some characteristics such as resolution, luminance, refresh frequency and latency, which are shared by the video projector and the displays.

The technologies emerging in the HMD (Fig.2.10) market are two, the first is based on liquid crystals (LCD - Liquid-Crystal Displays), while the other is based on OLED (Organic Light-Emitting Diode). AMOLED (Active-matrix OLED) technology is currently progressively replacing LCD screens in smartphones. (BENKHALED et al., 2016) (KEMENY; CHARDONNET; COLOMBET, 2020)

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[3] FRIENDLY, D.S. Preschool visual acuity screening tests.Transactions of the American Ophthamological Society, v. 76. 1978.

Table 2.6 presents the main characteristics of these technologies:

Table 2.6: Summary of the main characteristics of LCD and OLED screen technologies (KEMENY; CHARDONNET; COLOMBET, 2020)

	LCD	OLED
Maximum resolution	8K (7680 x 4320)	8K (7680 x 4320)
Definition (minimum pixel size)	<0.040 mm	<0.040 mm
Brightness / Luminance	Around 500 cd/m^2	Around 150 cd/m^2 for full-screen white
hline Contrast	/	Virtuallity infinite as LEDs emit no light with black
Refreshfrequency	Up to 240 Hz for gamer gaming monitors	120 Hz
Latency	Between 1 and 8 ms	Under 0.1 ms
Maximum diagonal size	Up to 108" (2.78 m)	Up to 88" (2.44 m)

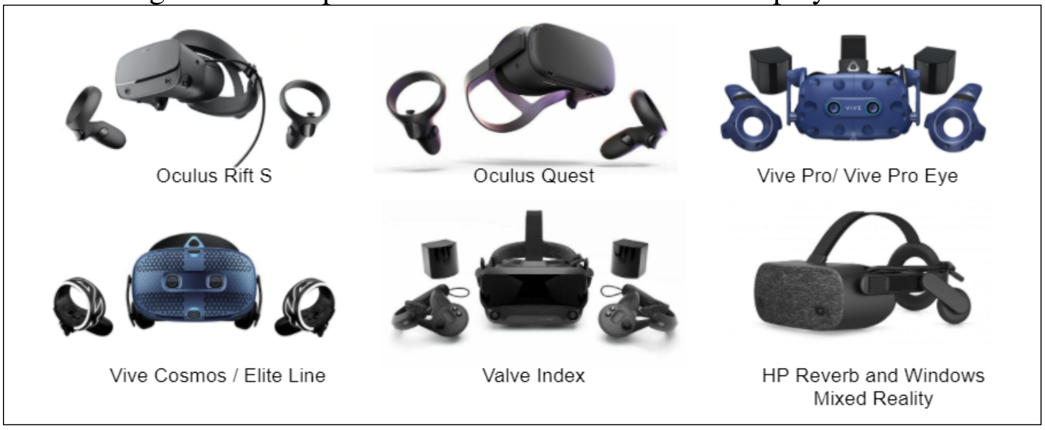
In Table 2.7 we present a comparison of the technical specifications of some HMDs (TRICART, 2017):

Table 2.7: Summary of the main characteristics of LCD and OLED screen characteristics found in commercial HMD devices for VR (KEMENY; CHARDONNET; COLOMBET, 2020)

Name	Display type	Max. Resolution*	Field of view	Luminance **
Oculus Rift	OLED	1080 x 1200	94°	176
HTC Vive	OLED	1080 x 1200	110°	183
Razer OSVR HDK 2	OLED	1080 x 1200	110°	NA
PlayStation VR	OLED	960 x 1080	100°	NA
Pimax 4K	LCD	1920 × 2160	110º	NA
Dell Visor	LCD	1440 x 1440	110º	NA
Lenovo Explorer	LCD	1440 x 1440	110º	NA
Samsung Odyssey	AMOLED	1440 x 1600	110º	NA
Asus HC102	LCD	1440 x 1440	95º	NA
HTC Vive Pro	AMOLED	1440 x 1600	110°	NA
Pimax 5K Plus	LCD	2560 x 1440	170º ("Wide") 150º ("Normal") 120º ("Small")	NA
Pimax 8K	LCD	3840 x 2160	170º (horizontal) 130º (vertical)	NA
Oculus Rift S	LCD	1280 x 1440	110º	NA
HTC Vive Cosmos	LCD	1440 x 1700	110º	NA
Varjo VR-2	AMOLED, OLED	1920 x 1080	87º	NA
Oculus Quest (Oculus Link)	OLED	1440 x 1600	100º (estimate)	NA
Oculus Quest 2 (Oculus Link)	LCD	1832 x 1920	-	NA
HP Reverb G2	LCD	2160 x 2160	114º	NA

* Max. Resolution (per eye) ** Luminance max cd/m^2 (BENKHALED et al., 2016)

Figure 2.10: Popular models of Head Mounted Displays for VR



Source: https://www.worldviz.com/post/how-to-budget-for-your-vr-project

The decrease in visual acuity under low luminance conditions is well known, and recent experimental evidence has shown that visual acuity under low luminance (mesopic) conditions is less robust than under photopic conditions. Based on this premise

(PLUHÁČEK; SIDEROV, 2018) presented a study proving that visual acuity decreased with decreased letter separation (i.e., increased crowding). However, the decrease in visual acuity for the smaller letter separation was less under the mesopic luminance condition, even after accounting for the increased size of the limiting acuity letters.

In their work the authors (ERICKSON et al., 2020) presented a human subject study investigating the correlations between color mode and ambient lighting with respect to visual acuity and fatigue in VR HMDs, comparing two color schemes, characterized by light letters on a dark background (dark mode), or dark letters on a light background (light mode) demonstrated that the dark background in dark mode offers a significant advantage in terms of reducing visual fatigue and increasing visual acuity in dark virtual environments in current HMDs.

By comparison LCD screens are thinner and lighter than LEDs due to the lack of a backlight, which is required in LED screens that emit light directly, this weight characteristic is crucial for VR headsets for comfort and "natural" user behavior: the less weight added to the user's head, the less inertia is added to the head with possible impact on head movement behavior (KEMENY; CHARDONNET; COLOMBET, 2020).

3 RELATED WORK

The VR literature is rich in papers that measure some aspect of visual perception. We researched and reviewed several published works on reliable and grounded theoretical basis in order to have a scientific validity in our research.

We freely searched for articles in several repositories, search engines and digital libraries such as SciELO, *Portal de Periódico da Capes*, *Biblioteca Digital de Teses e Dissertações da Universidade de São Paulo*, *Lume - Repositório Digital da UFRGS*, IEEEXplore, ACM DL and Google Scholar. We used variations of the following keywords in our search: Perception in VR, Head-mounted Display, Virtual Reality, Visual Acuity and Snellen. We found that weakly relater factors, like discomfort and distance estimation, are widely explored, while visual acuity considerations are still incipient.

In this chapter, we include some of these areas related to perception, even if they are not directly linked to acuity. We also report on work that explores the opposite of measuring visual acuity in the use of HMDs, that is, the use of HMDs to measure visual acuity.

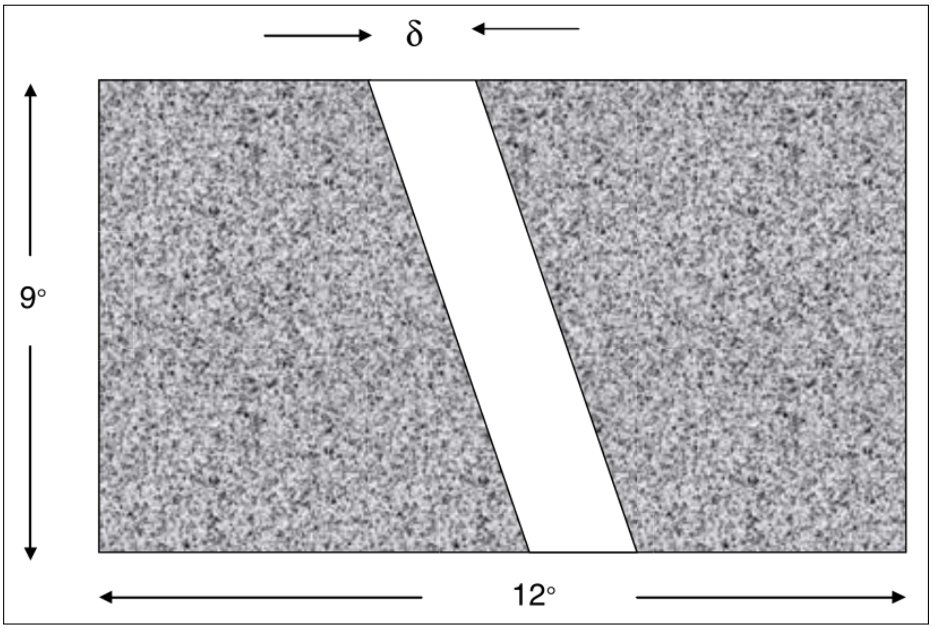
In this chapter, we included some these perception related areas even if they are not directly linked with acuity. We also report works that explore the opposite of measuring visual acuity in the use of HMDs, i.e. the use of HMDs to measure visual acuity.

3.1 Distance and depth

Visual perception is affected in many ways in immersive VEs. Some of them that are widely explored in VR literature are distance estimation and depth perception. Weg (2005) conducted two studies to investigate whether distance estimates are stable within the subjects' own frame of reference and whether there are inter-individual differences when a geometrically simple virtual environment is used. The first experiment was conducted on a VR application (3D) and the second on a standard CRT screen (2D). The results reveal systematic underestimations but also indicate individual variations. Interestingly, richer environments with reference objects allow more accurate distance estimates. The results lead to the conclusion that most subjects tend to systematically underestimate depth distances when virtual or computer-based environments are displayed. The test results revealed gender differences in distance estimation, where male subjects tended to underestimate distances in virtual and computer-based environments less than female subjects, but no consideration was given to underlying user characteristics such as expertise or cognitive and spatial abilities nor were the special features of each VR hardware considered nor was a comparison between the effectiveness of different depths in different hardware-dependent environments.

Similarly, Kooi and colleagues (KOOI; BIJL; PADMOS, 2006) conducted a test at a virtual distance of 3 meters using three HMDs (Iodisplay, Kaiser and Sony). The test correlated display resolution with stereoscopic acuity. They determined the appropriate depth resolutions for most tasks that rely on stereoscopic vision according to the spatial resolution of the HMDs tested. They found that the HMDs provide better stereo acuity (Fig.3.1) than presented in the scientific literature, which was attributed to the target used, which is much more representative of real world scenes unlike the typical static 'fine line' targets often used.

Figure 3.1: Stimulus for measuring stereo acuity. The shaded areas are placed at different depths



Source: (KOOI; BIJL; PADMOS, 2006)

The quality of depth perception in virtual environments was investigated by Armbrüster et al. (2008). The results of their experiment show that participants underestimated virtual distances but were able to perceive distances in the correct metric order, even when only very simple virtual environments are presented. The study shows that depth perception is insufficient in simple virtual environments and that simple manipulations do not improve depth estimates. Their study did not have an investigation focused on improving depth perception, suggesting that successful combinations should be extracted, and inter-individual calibrations of VR systems based on binocular ability are needed to provide a satisfactory depth impression.

A literature review on the design challenges of Virtual Reality systems and the issue of distance perception in VR was the beginning of the investigation conducted by Jamiy and Marsh (2019) focusing on the methods and techniques for distance estimation in VR and AR that were developed during their research. The research presents a complete overview of the main methods and techniques used to measure perceived distance with the main results found by authors in different works done to study depth perception concluding that underestimation of AR distances using HMD is unlikely to happen as it happens in VR. Their work is part of a project to study depth perception in real-time rendering systems in VR HDMs.

Most studies for distance perception in a virtual environment have been performed using head-mounted displays (HMD) and some with large screens, such as CAVE systems. Ghinea et al. (2018) propose to measure the accuracy of perceived distances in a virtual space ranging from 0 to 15m on a CAVE system compared to an HMD. The results showed that the HMD provides the best results for distances above 8m, while the CAVE provides the best results for close distances. The best results with HMD were found above 7m to the detriment of the CAVE system which may have occurred due to the shape, precision, dimensions and resolution of all virtual cues projected into virtual space, as for the power law (Weber's law, where the subjective discrimination threshold of a stimulus depends linearly on its intensity) cannot be confirmed, according to the author it may be degradation of distance indicators (vergence-accommodation conflict, relative size, etc.) or an excessive density of some indicators. The researcher (GHINEA et al., 2018) cites the strategy also the personal to pass the experiment, which was not evaluated due to the small number of subjects that were part of the experiment.

3.2 Discomfort and cybersickness

Several people report, when using an HMD, various types of physical discomfort, as well as symptoms such as headache, disorientation and nausea (GRASSINI; LAUMANN, 2020). These symptoms, developed during or after exposure to virtual environments, are commonly referred to as simulator sickness (SS), and potentially impairs the perception a user has from the environment.

To measure the reported side effects of user experiences with virtual reality systems, Sharples et al. (2008) developed three experiments to assess the prevalence and severity of illness symptoms experienced in each of four VR viewing conditions: head-mounted display (HMD), desktop, projection screen and reality theater, with a controlled examination of two additional aspects of viewing (active vs. passive viewing and light vs. dark conditions). Results indicate that participants experience an increase in pre and post-exposure symptoms for HMD and higher symptoms in HMD compared to viewing on other devices. No effect of lighting condition was found and higher levels of symptoms in passive viewing compared to active control with a high inter and intra-participant variability. Recommendations are offered regarding the design and use of VR systems to minimize virtual reality induced symptoms and effects (VRISE), but Sharples et al. (2008) stress that research continues so that the negative effects experienced by participants can be minimized.

Recently, Mehrfard et al. (2019) systematically compares a wide range of head-mounted VR display (HMD) technologies and designs, defining a new set of metrics that are relevant to most generic VR solutions and are important for VR-based education and training. Ten HMDs were evaluated based on various criteria, including neck strain, heat development and color accuracy, while text reading, comfort and contrast perception metrics were evaluated on three selected HMDs (Oculus Rift S, HTC Vive Pro and Samsung Odyssey+). The results indicate that the HTC Vive Pro performs the best when it comes to comfort, display quality, and compatibility with glasses, it was also noted that several metrics that were measured in the work had a direct influence on user comfort, such as image quality, heat development, tracking stability, weight, and compatibility with glasses. They noted that several metrics that were measured in their work had a direct influence on user comfort, such as image quality, heat development, tracking stability, weight, and compatibility with glasses.

Some scientific studies have shown that women are usually more sensitive to this type of discomfort. Grassini and Laumann (2020) proposed a systematic review with the aim of gathering evidence supporting and opposing a gender difference in susceptibility to this discomfort when using modern HMDs. The results show it is difficult to establish a general consensus in the literature for a gender difference in susceptibility to SS and that the differences that appear in other studies that have reported gender differences have used specific simulation environments.

3.3 Using HMDs in measuring and improving visual acuity

Objective visual acuity test is mandatory in some cases, such as children, nonverbal subjects, and subjects who need legal judgment. Based on Seohan's visual acuity test (SVT) (KIM et al., 2000) produced a new objective system for visual acuity testing. Visual stimuli were presented on a Head Mounted-Display (HMD) with the purpose of separating the stimuli from the environment, maintaining uniform size, distance from the screen to the subjects' eye, and projecting the stimulus onto the patient's entire central field. In their conclusion (KIM et al., 2000) highlights that objective visual acuity with SVT is highly correlated with subjective visual acuity, but does not ratify that the stimuli presented in the HMD can be useful in assessing visual function objectively.

Parra et al. (PARRA et al., 2014), in turn, proposed a new system based on HMD for accurate and fast measurement of most clinical parameters of visual function, while the patient plays a true-3D (stimulating vergence and accommodation) short video game (<5min). The system generates 3D images with different optotypes that allow measuring and correcting the patient's refractive state, stimulates and relaxes patient's vergence movements (through image disparity), as well as eyes accommodation (through variable focal distance), and records eyes and pupils movements. The developed system is a tool for visual function assessment and the data collected in the validation correlate with conventional optometric results, leaving to validate most parameters of visual function and patient responses by true-3D dynamic stimuli in addition to traditional methods.

In a virtual reality simulation using a head-mounted display, (CHEN et al., 2005) tested prosthetic visual acuity for rectangular and hexagonal phosphene gratings by recognizing Landolt C optotypes. The results obtained over ten sessions suggest that the electrodes implanted in the subjects increased performance in image analysis concerning size and orientation and that the hexagonal grating had a performance advantage for correctly identifying the symbols used in the test in reference to the rectangular grating. The work done (CHEN et al., 2005) was a first step toward designing more effective electrode geometries and image analysis strategies and that effective use of prosthetic vision required more learning.

Some previous works also studied how to test and correct natural loss of acuity using HMDs. A varifocal system was proposed to eliminate the need for corrective glasses within HMDs (STEVENS et al., 2018). The system generates consistent accommodation cues and provide prescription correction in HMDs, focusing on Vergence-

Accommodation Conflict (VAC) as a fundamental cause of discomfort in VR today.

3.4 Visual acuity in the use of HMDs

In this section o review some approaches can be classified as attempts to characterizing visual acuity in the use of head mounted displays. They are the most closely related works to our own.

In an early appearance of this problem in the literature, Fidopiastis et al. (2005) describe a methodology for evaluating head-mounted type display prototypes and visual environments analyzing visual acuity resolution as a function of contrast using visual performance metrics. They applied three different light levels and two different types of projection materials. The results of the studies indicate that the visual acuity resolution metric accurately identified reductions in user visual acuity, but that they still need benchmark metrics that allow comparison of the performance of the mounted prototype at each stage of the design and that the experiment performed poorly in tasks where the targets had high contrast such as targets with complex backgrounds.

Sproule et al. (2019) conducted a pilot study to assess visual acuity and contrast sensitivity using two commercially available HMDs (Oculus Rift and HTC Vive Pro). To evaluate the effectiveness of the HMDs, visual abilities were assessed with standard eye charts using three widely accepted vision tests in a real-world setting and were repeated in a VR environment by mapping a 2.13 m x 2.13 m (7 ft x 7 ft) empty room with the vision test charts posted on the walls that was scanned using a FARO Focus 3D laser scanner. The testing procedure was repeated in all three modalities: in VR using the Oculus Rift, in VR using the HTC Vive Pro, and in reality at the appropriate distances from the graphics. The interpupillary distance of the lenses was adjusted until the display was adjusted for the participants. The results of the pilot study indicated that visual acuity is limited across HMDs. Although all participants indicated a positive VR experience, they were unable to distinguish small details in vision tests. Supersampling was set based on the capabilities of the hardware and headset used which may have led to very low frame rates, producing a less than optimal VR experience. The potential effect of supersampling on visual acuity in VR was not quantified, nor was the human perception of other visual cues presented in VR compared to reality and 2D video screens.

Matsuura et al. (2019) discussed the difficulty caused in a walkthrough and its interference in viewing information on HMDs. The research used fonts used in Japan and the resulting balance of the walk that strike a balance between the intended design elements and the ease of letter recognition of the presented text. In the end, the authors found that fonts with very thin horizontal and vertical lines should not be presented in HMDs. In a next research, they intend to clarify the effect of vertical lines and create guidelines for fonts to be displayed in HMDs, as well as investigate the difference between the readability of other font types in other languages for use in HMDs.

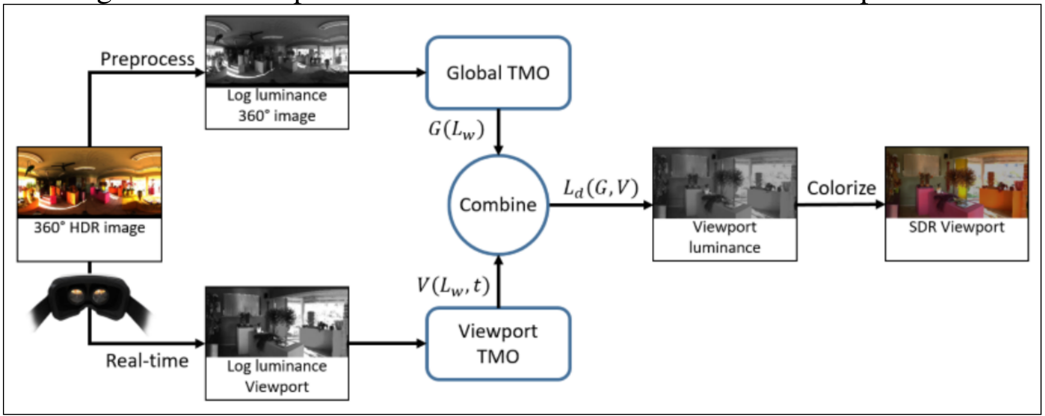
(PANFILI, 2019) investigated to what extent VA is reduced in VR and respectively whether the decrease of VA in VR is perceived similarly by everyone or whether visual impairments such as Myopia, influence visual perception. The results obtained confirm her theory that VA in the virtual world is not as good as in the real world, as well as the results seemed to suggest that normally myopic people, not wearing corrective lenses are slightly better able to recognize smaller details in a virtual experience compared to the real world, citing as a possible explanation for these results the fact that HMD technologies incorporate lenses. In the project it was conducted with a small sample of people and they were also not divided into different categories according to their diopter deficits. Another factor not taken into consideration in the outcome of the study is the difference between people who wear glasses and people who wear contact lenses, astigmatic or farsighted subjects.

In terms of contrast, Goudé et al. (GOUDÉ; COZOT; MEUR, 2020) proposed a new Tone Mapping Operator (Fig.3.2) that takes advantage of vision-dependent tone mapping that improves contrast and a Tone Mapping Operator applied to the entire 360º image that preserves global coherence by being adapted to the human eye's perception of luminance on head-mounted displays, also presented two subjective studies to model the perception of lightness in such Head-Mounted Screens.

The work by Sproule et al. (2019) already mentioned above, evaluated visual acuity and contrast sensitivity using two types of HMD (Oculus Rift and HTC Vive Pro). It is arguably the one that most closely relates to our own research. The study presented a quantitative assessment to characterize the limitations of VR with respect to visual acuity and contrast sensitivity. Some recommendations for forensic use of this technology and development of visualization tools were raised. The study had few participants and the need to expand protocols to more extensively evaluate the visual capabilities of HMD systems was raised, also there was no comparison of human visual acuity in VR with reality and 2D video displays.

The perceptual accuracy of virtual near-field distances using a size and shape con-

Figure 3.2: Our operator combines a Global TMO and a Viewport TMO



Source: (GOUDÉ; COZOT; MEUR, 2020)

stancy task on two commercially available devices was a research project by (HORNSEY; HIBBARD; SCARFE, 2020). In the tests participants wore either the HTC Vive or the Oculus Rift and adjusted the size of a virtual stimulus to match the geometric qualities (size and depth) of a physical stimulus they were referring to, so with the judgments made by the participants it was possible to indirectly measure their egocentric and virtual distance perception to the stimuli. They conclude that virtual reality headsets provide a sufficiently high degree of accuracy in distance perception that it is feasible to use them safely in future experimental vision science and other research applications. The study failed to examine specific factors in accurate perception in VR, such as the development of high-quality graphics to enhance the 3D experience, and how much these additional features may affect distance perception in immersive HMDs, also specific cues such as perspective, texture, binocular disparity, and motion parallax that are necessary to produce accurate or aesthetically pleasing visualizations within VR were not investigated.

Finally, Krösl (2020) proposed to simulate in VR and AR some of the most common visual impairments that affect humans. She investigated several factors such as participants' vision capabilities (with normal or corrected vision), resolution of the HMD, fixed focal length of the HMD leading to a vergence-accommodation conflict, possible dislodgement of the HMD, latency, refresh rate, and flicker of the display, dynamic range, and color correction of the display in her simulations. While they did not propose methods to measure acuity parameters for VR use, Krösl et al. (2020a), Krösl et al. (2020b) proposed means to calibrate the output acuity in her simulations, which is valuable for our study. It is noticeable that the interest on visual acuity in VR increased in the last couple of years. Our work appears at the same time of most works presented in this section. Still, they are exploring different perspectives of the same problem, which makes it difficult to present a meaningful comparison of how they cover the problem and how we complement them.

3.5 Dynamic Acuity

A final relevant category of previous works is that of dynamic visual acuity. Kim et all. (KIM et al., 2018) studied the effect of exercise on dynamic visual acuity by comparing the Eye Movement Development (DEM) test and a new Head Mounted Virtual Reality (VHD) test across several sport modalities. Ball sports group, aerobic exercise group, strength exercise group, and non-exercise group with no statistically significant difference between the ball sports group and the non-exercise group. As a conclusion they found that humans move their eyes first before seeing or acting on an object, that dynamic vision works to recognize objects not having a pattern unlike static vision. In VR, motion sickness is one of the problems that require solutions, and it is necessary to propose a reasonable time to use HMD by checking the manifestation symptoms of each time period. Another improvement would be to increase the interest and test effect by adding a storytelling to the proposed test, as well as the dynamic vision and training effect should be verified through comparative experiments between the expert exercise group and the non expert group.

In the paper (MACQUARRIE; STEED, 2019) explored the perceived gaze direction of volumetrically captured avatars when viewed on an HMD. In a repeated measures experiment, participants repeatedly rotated an avatar until they felt it was looking at a target. The direction of the avatar's gaze, the location of the target and the HMD were varied. As results realized that the resolution of the HMD does not affect accuracy levels. HMD was found to impact the most common erros, although this effect did not appear to be symmetrical. It also found that the results indicated that the task became more difficult as targets diverged from 0°, i.e., more difficult accuracy for targets further away from the user, as well as unlike the real world, eye direction was consistently misjudged based on target location, but not based on avatar head position direction. It concludes that the difference in estimating target location may have been affected by the known phenomenon that users tend to underestimate distances in VR. While the results indicate that ocular perception in VR does not always parallel similar tasks in the real world, further investigation may help explain the cognitive processes behind ocular comprehension.

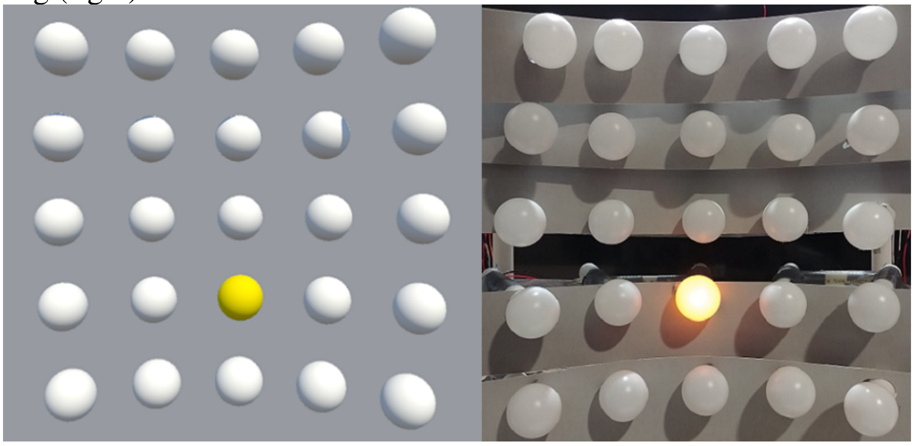
Koulieris et al. (2019) discuss human vision, hardware limitations of near-eye displays and imperfect tracking technologies and rendering of light in context of VR. The authors give a thorough introduction to the human visual system and its physiological and perceptual properties, such as optical properties, receptor processes, motor function, and cortical processing abilities. In addition to the factors listed by Kruijff, Swan and Feiner (2010), Koulieris et al. (2019) also state that when combining vision with other sensory channels, such as audio, vibration, or smell, they may affect each other. Furthermore, memory and attention can also affect processing of visual information and therefore cognition.

Faithful representation and rendering of light are also limited by current algorithms and hardware capabilities and create a discrepancy between the real and the virtual world and affect how we perceive virtual content. In the real world, we are exposed to light intensities in a dynamic range of 14 orders of magnitude, while current devices usually only offer a dynamic range of two to three orders of magnitude (KOULIERIS et al., 2019). Therefore, algorithms need to use effects to simulate light phenomena that cannot otherwise be displayed inside a display (LUIDOLT; WIMMER; KRÖSL, 2020).

We previously mention the contribution of Goudé, Cozot and Banterle (2019) that developed a tone mapping operator for viewing 360° dynamic range high-definition images on HMDs. For the continuation of their research they intend to propose tone mapping of HDR video for viewing on HMD, with the challenge being to take into account temporal coherence, sudden change in luminance range over time, naturalness of time adaptation, etc.

Pfeil et al. (2018) used eye and head tracking technology to conduct a user group study in VR or PR to identify how these natural values are observed in both environments. The results indicate that there is a difference in natural head and eye coordination between VR and PR, he also found a significant difference in head coordination between our real life scenarios, whereas in VR he did not find a significant difference between PR conditions (3.3. Among the limitations of his work he cited that he was unable to use the same devices to collect the data between the two environments and the data collected may be discrepant, he also cited that the data was classified separately although he used head tracking for both tests and the types of magnitude of height changes were not reported.

Figure 3.3: A screenshot of the virtual stimulus layout (left) and a view of the physical stimulus rig (right)



Source: (PFEIL et al., 2018)

3.6 Final Note

Despite our efforts to survey the literature for other works investigating visual acuity in VR, we could not find in previous works an efficient method to characterize visual acuity in a user-session-specific fashion. As seen above, they often focus on higher level perceptual issues, such as distance perception and cybersickness, or on specific perceptual phenomena such as ocular parallax. They sometimes consider the hardware specifications (resolution, luminance, contrast) but not the perceived values for these parameters. In the present work, we look at visual acuity in the virtual world in a similar way it is seen in the real world by ophthalmologists. We look for a quick effective acuity check to be applied at the start of any VR session after putting on the HMD.

4 EXPLORING CLINICAL OPHTHALMOLOGY TESTS IN VR

We present in this chapter an adaptation to VR of methods used to measure the visual acuity of patients in the ophthalmologist's office. In the search for a more compact yet effective measurement protocol, we also explore a target-shooting task. We explain the methods and describe an experimental evaluation we conducted in a virtual world with HMD participants.

4.1 Overview

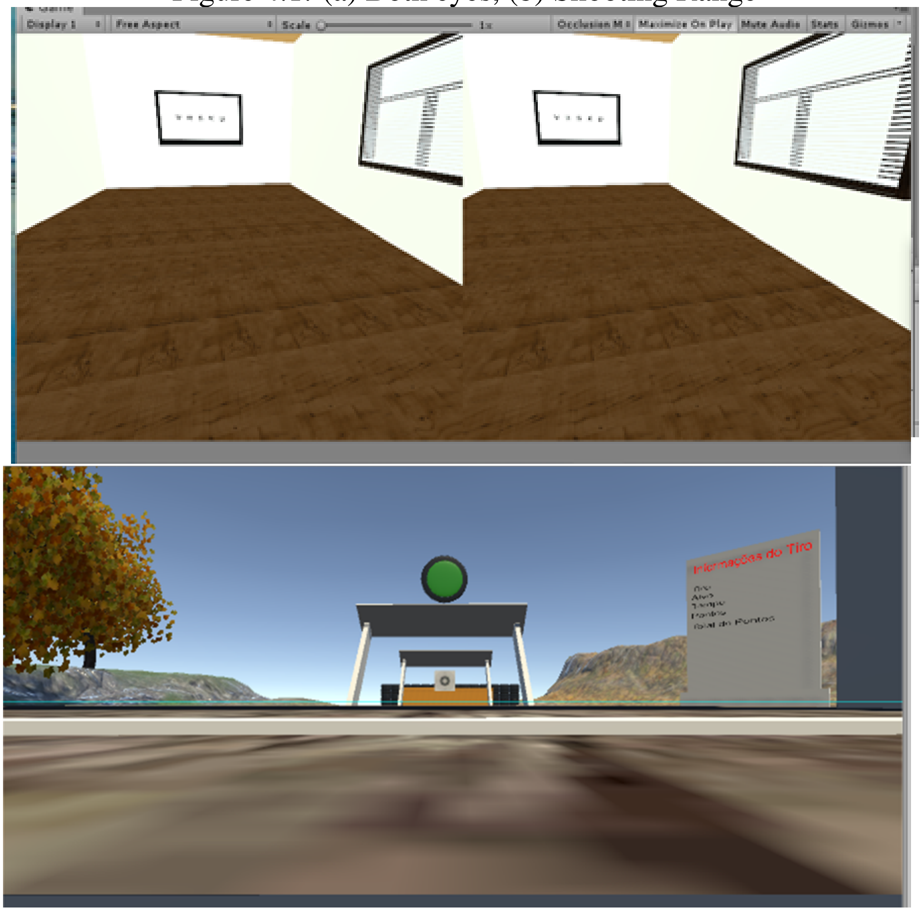
We created two immersive scenarios in the Unity 3D Engine that are viewed with an Oculus Rift using the default settings without any calibration. The first scenario is a room where the subject seats at a controlled distance from the wall in front of them, on which we present in sequence the Snellen Test, Pelli-Robson Test, Glare and Contrast Sensitivity Test - Peripheral and Glare and Contrast Sensitivity Test - Central. The second scenario is a virtual shooting range (Fig. 4.1 (b)) where they stand to perform a series of shots on target.

4.2 Procedure

Although HMDs are applicable for a variety of tasks, each individual has their own peculiarities of vision and way of adjusting these devices which can cause discomfort and nausea. Our test seeks to evaluate the visual acuity and discomfort produced by same HMDs and software on different users. In such a way, an average acuity will be obtained for the system with that population. The collected data will later be organized in different groups for analysis.

The several steps of the test are performed in sequence, with the same order of tests for each subject. The first four were performed with the users seated and the shooting test standing. The users do not remove the HMD until they have complete all the steps.

Figure 4.1: (a) Both eyes, (b) Shooting Range



4.3 Snellen Test

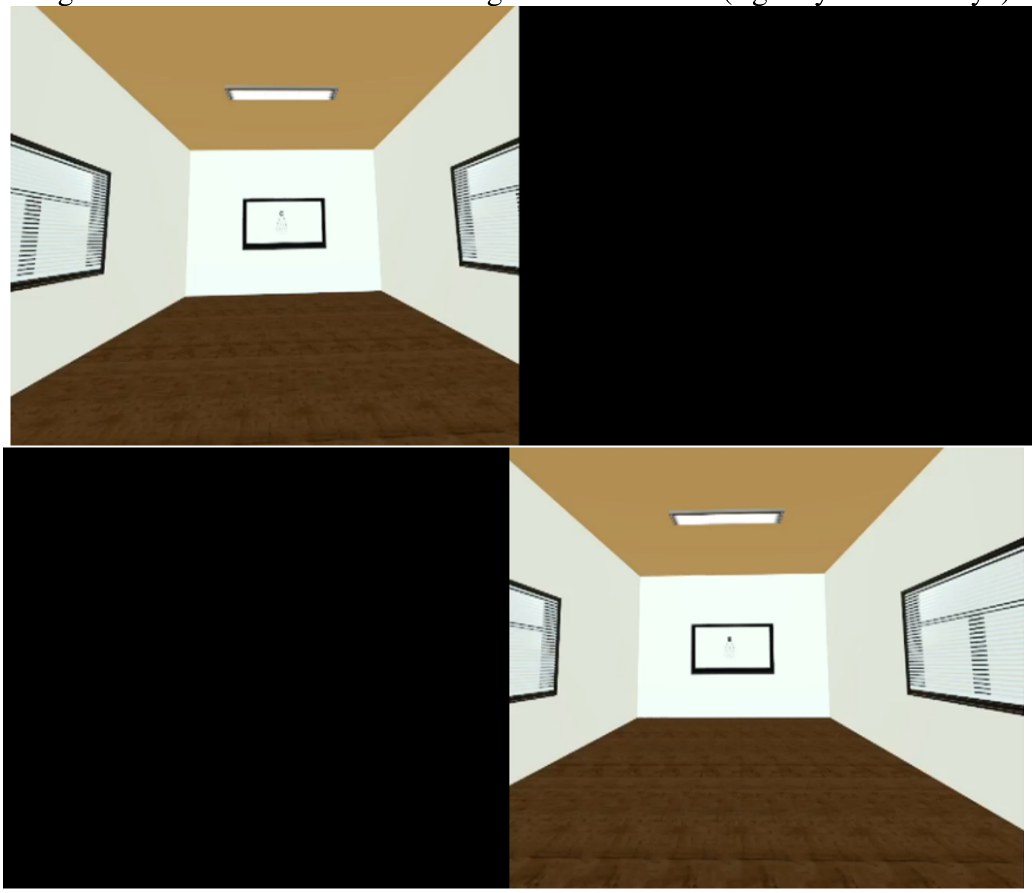
To implement the Snellen test in a virtual environment, we used Table 4.1 (SNELLEN, 1862) to determine the size of optotypes based on the visual angle of 0.5 arc-minutes viewed from a distance of 6.10 meters (20 Paris foot).

Table 4.1: Used optotype table

Description	H (mm)	Observation
20/200	88.72	
20/100	44.36	
20/80	35.49	
20/60	26.62	
20/50	22.11	
20/40	17.74	
20/30	13.24	
20/20	8.87	NORMAL
20/15	6.69	
20/10	4.44	

During our VR Snellen Test, the participant is seated, and a Snellen Chart with a set of letters of different sizes is presented on the wall in front of them. The participant is asked to read the letters out-loud as they are underlined in red, starting from the largest to the smallest, until they can no longer identify them. The test is applied to one eye at a time, first with the left eye and then with the right eye. There is no need for the participant to close the other eye, because the image is presented in the HMD to one eye at a time (Fig. 4.2).

Figure 4.2: Volunteer's vision during the Snellen Test (right eye and left eye)



4.4 Pelli-Robson Contrast Sensitivity Test

For this test, the reference we use is the Pelli-Robson table of contrast sensitivity (Table 4.2):

The values of the test results are the numbers on each side of the table, given in logarithmic unit (log unid.), and correspond to each group of three letters (e.g.: $0.60 = (1/10^{0.60} = 0.25 = 25\%)$.

The tests are monocular, sitting three meters from the table so that the participant's vision is directed to the center of the table, with different tables for each eye (Table 4.3), so that the user does not memorize the sequence of letters.

Table 4.2: Pelli-Robson table of contrast sensitivity

Log Unid	**Letters**	**Letters**	Log Unid
log 0.00	**HSZ**	**DSN**	log 0.15
log 0.30	**CKR**	**ZVR**	log 0.45
log 0.60	**NDC**	**OSK**	log 0.75
log 0.90	**OZK**	**VHZ**	log 1.05
log 1.20	**NHO**	**NRD**	log 1.35
log 1.50	**VRC**	**OVH**	log 1.65
log 1.80	**CDS**	**NDC**	log 1.95
log 2.10	**KVZ**	**OHR**	log 2.25

Source: Oliveira et al. (2005).

Table 4.3: Left and Right Eye Table

HSZ	DSN	VRS	KDR
CKR	ZVR	NHC	SOK
NDC	OSK	SCN	OZV
OZK	VHZ	CNH	ZOK
NHO	NRD	NOD	VHR
VRC	OVH	CDN	ZSV
CDS	NDC	KCH	ODK
KVZ	OHR	RSZ	HVR

During the test, the table is shown on the wall in front of the user who views with only one eye at a time (Fig. 4.3). The recorded visual acuity result is the decimal number in the last row where the participant can see more than half of the optotypes.

We consider that the result of this test will be influenced by the contrast and brightness of the HMD monitors.

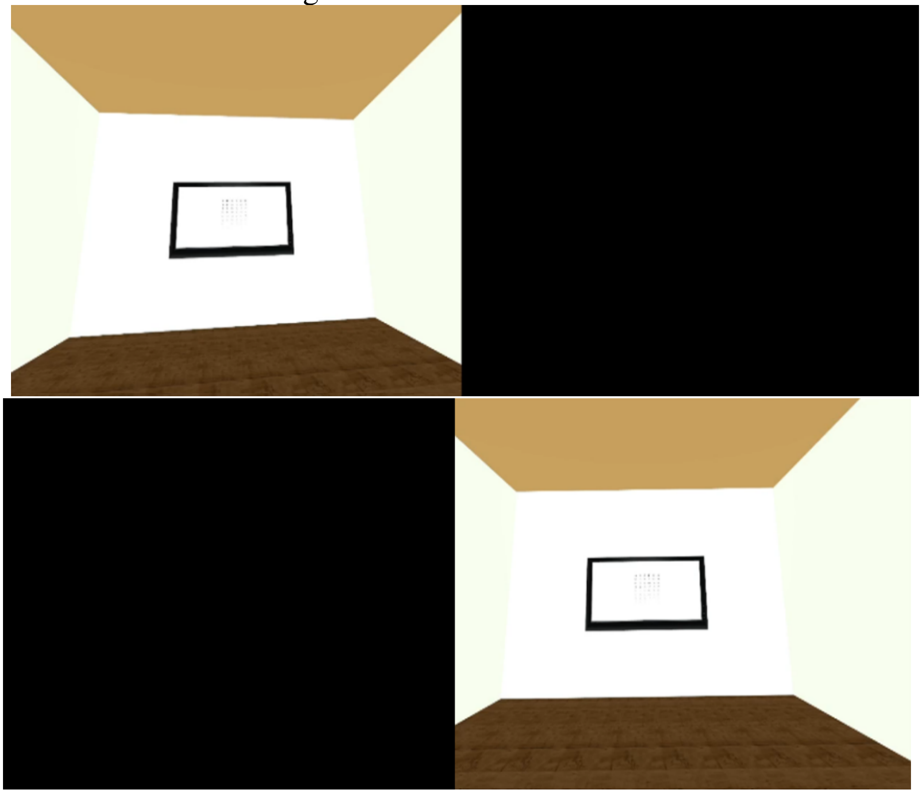
4.5 Glare and Contrast Sensitivity Test - Peripheral

During this test (Fig. 4.4), a sequence of five optotypes of the same size in black is shown on the wall in front of the volunteer in a frame, which must be identified with both eyes simultaneously (Fig. 4.6).

The key element to this test is the presence of a light source in the peripheral area of the optotypes that may create a luminance veil as it scatters through the eye lenses and hit the fovea.

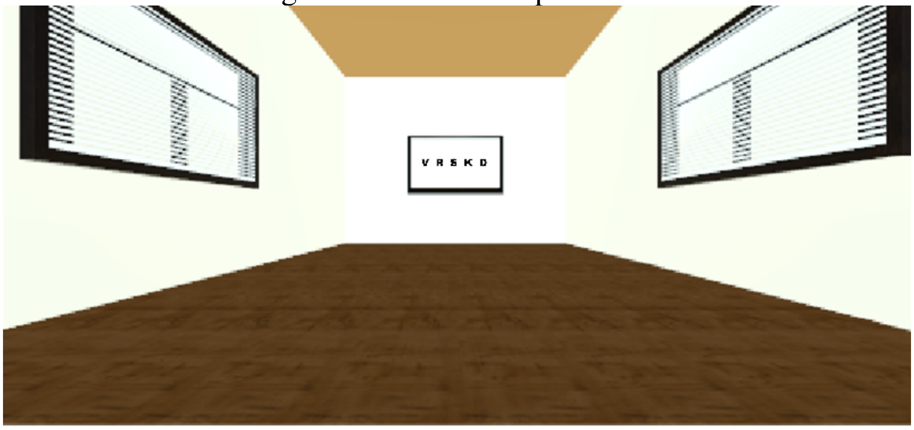
In our implementation, we simulate the light source by increasing the brightness of the ambient diffuse light on site, in order to include a light source close to the frame of the optotypes.

Figure 4.3: Pelli-Robson Test



Unity has an intensity multiplier parameter for that purpose[1]. We empirically decided that the Intensity Multiplier should be set to 2.47 in Unity Engine (Fig. 4.5).

Figure 4.4: Glare Peripheral Test



The result of the recorded visual acuity is the decimal number of the last row that the volunteer can see more than half of the optotypes (Table 4.4).

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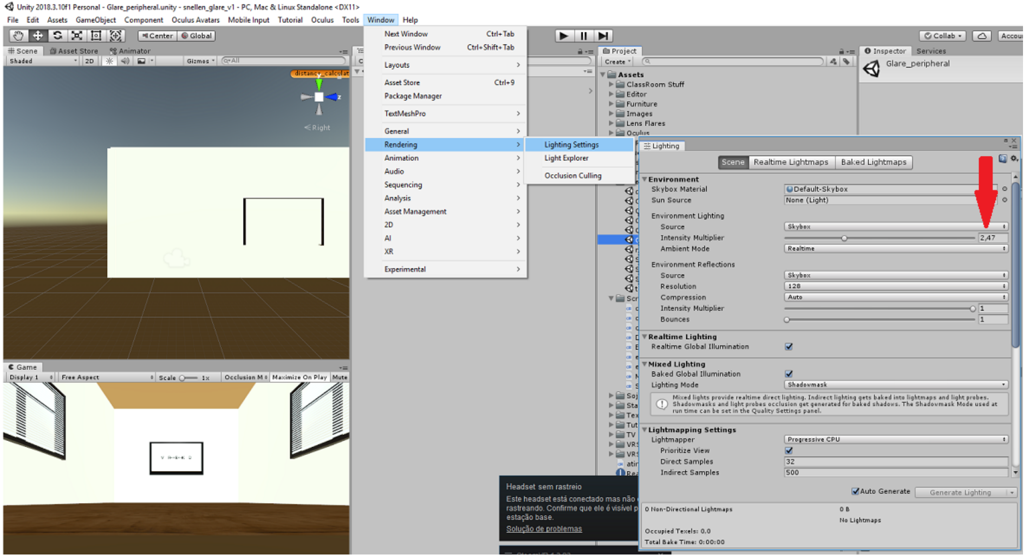
[1] Windows/Rendering/Lighting Setting/Scene/Environment Lighting/Intensity Multiplier

Figure 4.5: Brightness parameters used in the environment of the Glare and Contrast Sensitivity Test - Peripheral


Unity 2018.3.10f1 Personal - Glare_peripheral.unity - snellen_glare_v1 - PC, Mac & Linux Standalone <DX11>

Window > Rendering > Lighting Settings

Lighting — Scene

Environment
- Skybox Material: Default-Skybox
- Sun Source: None (Light)
- Environment Lighting
  - Source: Skybox
  - Intensity Multiplier: 2,47
  - Ambient Mode: Realtime
- Environment Reflections
  - Source: Skybox
  - Resolution: 128
  - Compression: Auto
  - Intensity Multiplier: 1
  - Bounces: 1

Realtime Lighting
- Realtime Global Illumination: ☑

Mixed Lighting
- Baked Global Illumination: ☑
- Lighting Mode: Shadowmask

Mixed lights provide realtime direct lighting. Indirect lighting gets baked into lightmaps and light probes. Shadowmasks and light probes occlusion get generated for baked shadows. The Shadowmask Mode used at run time can be set in the Quality Settings panel.

Lightmapping Settings
- Lightmapper: Progressive CPU
  - Prioritize View: ☑
  - Direct Samples: 32
  - Indirect Samples: 500

☑ Auto Generate

0 Non-Directional Lightmaps 0 B

No Lightmaps

Occupied Texels: 0.0

Total Bake Time: 0:00:00

Figure 4.6: Optotypes Seen in the Test

V S R K D

Table 4.4: Peripheral Glare Table

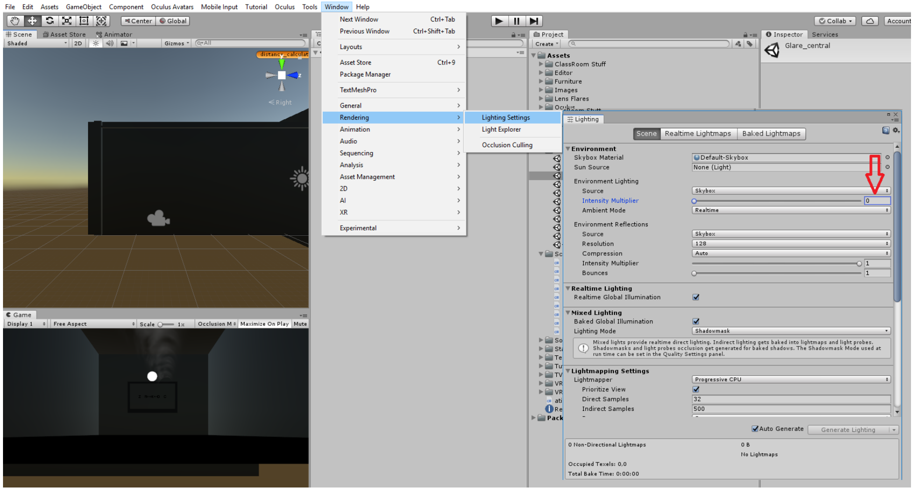
Letters	Description
V S R K D	20/200
H C S O K	20/100
S C N O Z	20/80
N H Z O K	20/50
N O D V H	20/40
D N Z S V	20/30
K C H O D	20/15
S Z H V R	20/10

4.6 Glare and Contrast Sensitivity Test - Central

In order to perform the test (Fig. 4.8), a sequence of five optotypes of the same size in black is shown on the wall in front of the volunteer, on a whiteboard (Fig. 4.9), with a light source placed above the board and directed to the center of the participant's eyes. The environment is completely without light, as we set the intensity of the directional light in the environment to 0 (zero) (Fig. 4.7). In Unity the default value for a directional light is 0.5. The default value for a Point, Spot or Area light is 1.

The result of the recorded visual acuity is the decimal number of the last line that

Figure 4.7: Glare Central Test - Scene setup in Unity



Environment
Skybox Material: Default-Skybox
Sun Source: None (Light)
Environment Lighting
Source: Skybox
Intensity Multiplier: 0
Ambient Mode: Realtime
Environment Reflections
Source: Skybox
Resolution: 128
Compression: Auto
Intensity Multiplier: 1
Bounces: 1
Realtime Lighting
Realtime Global Illumination: ☑
Mixed Lighting
Baked Global Illumination: ☑
Lighting Mode: Shadowmask
Mixed lights provide realtime direct lighting. Indirect lighting gets baked into lightmaps and light probes. Shadowmasks and light probes occlusion get generated for baked shadows. The Shadowmask Mode used at run time can be set in the Quality Settings panel.
Lightmapping Settings
Lightmapper: Progressive CPU
Prioritize View: ☑
Direct Samples: 32
Indirect Samples: 500
☑ Auto Generate
0 Non-Directional Lightmaps 0 B
No Lightmaps
Occupied Texels: 0.0
Total Bake Time: 0:00:00

the volunteer can see more than half of the optotypes (Table 4.5).

Figure 4.8: Glare Central Test

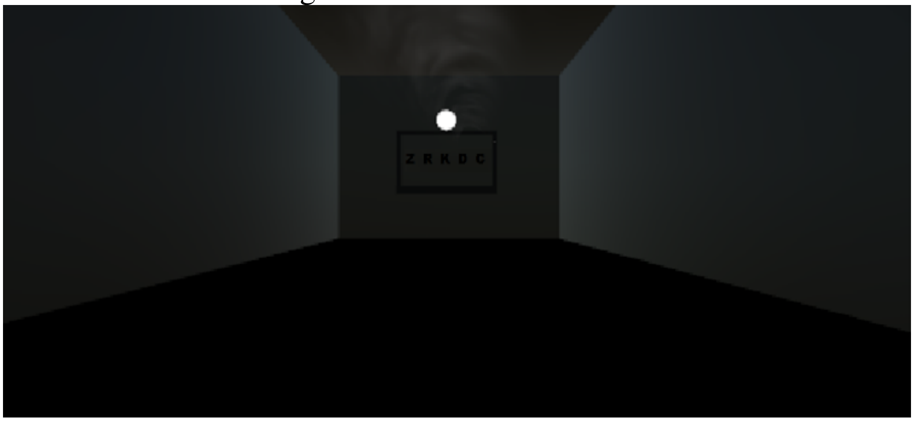
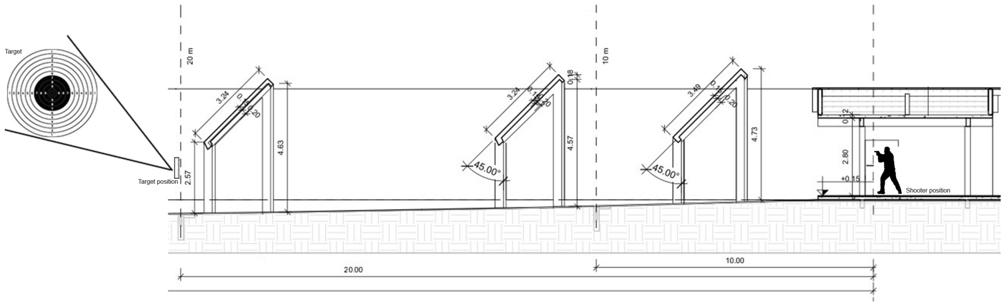


Figure 4.9: Optotypes Seen in the Test

Table 4.5: Central Glare Table

Letters	Description
Z R K D C	20/200
D N C H V	20/100
C D H N R	20/80
R V Z O S	20/50
O S D V Z	20/40
N O Z C D	20/30
R D N S K	20/15
O K S V Z	20/10

Figure 4.10: Schematic of the shooting range and target



Source: http://www.comprasnet.gov.br/ConsultaLicitacoes/Download/Download.asp?
coduasg=160454&numprp=12013&modprp=3&bidbird=N

4.7 Shooting test

For the purpose of comparing with the results obtained in the previous tests, we created a virtual shooting stand (Fig. 4.10 (a)) based on a model designed for a military unit of the Brazilian Army [2].

With the shooting experiment we hope to measure not only the visual acuity of the volunteers, but also their motor coordination.

The stand has a shooting module, inside which the shooter is positioned to perform their shots, two stop-bullets and a target (Official CBTE type - ISSF Air Pistol) (Fig. 4.10 (b)) positioned 30 meters in front of the shooter. The result of each shot is shown on a scoreboard positioned to the right of the shooter.

The test simulates day and night (Fig. 4.11) so that the volunteer performs the shots with varying brightness. The test cadence is controlled by the system, in such a way that a full cycle of sunrise, daylight, sunset and night time is experienced. Between shots, a green light positioned above the stop-ball lights up and authorizes the shot. The time for the ten shots is 1 minute and 20 seconds, divided into 10 times of 12 seconds; the first three and the last two are with light, and the other five without.

During the experiment, photos were taken and video footage was taken of the volunteers' performance during the test, with their prior permission.

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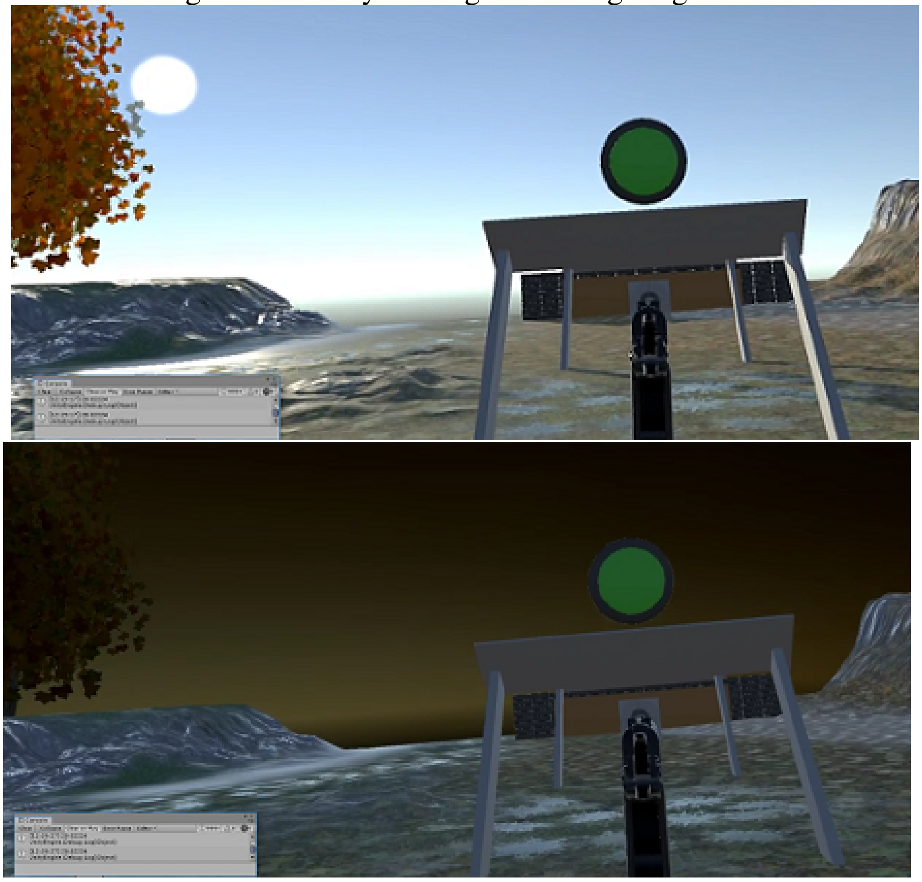
[2] MINISTRY OF DEFENSE, Bidding Nº 1/2013 - Available at: http://www.comprasnet.gov.br/ConsultaLicitacoes/Download/Download.asp? coduasg=160454&numprp=12013&modprp=3&bidbird=N

Figure 4.11: Day and night shooting range view



4.8 User Experiment

We recruited 23 volunteers in the campus to participate in a user study. They were invited to "try a VR shooting game", Fig. 4.13 shows the local used for study. Our aim with the study was to collect visual acuity data with the sequence of tests described above. The study was exploratory and no formal hypotheses were formulated. Our main goal was to find out how the overall average acuity differs in VR when compared to similar tests in the context of clinical ophthalmology. Other goals were to identify correlations between subjective and objective acuity, with personal profile parameters, and with performance in our shooting game. Fig. 4.14 presents a flowchart of the experimental protocol.

After responding that they were comfortable in the immersive environment (Fig. 4.15) the tests started, informing them that the first two were performed initially with the right eye and then with the left eye. During these tests (Snellen and Pelli-Robson), the researcher asks the volunteer: "Which letter or set of letters is underlined in red?", and if the volunteer answers the letter or set of letters correctly, the researcher moves on to the next row of letters one until the participant does not identify what is being shown underlined.

Figure 4.12: How to hold the Oculus Rift controller

Figure 4.13: Place where the tests were performed

At the end of the first four tests, the researcher helps the volunteer to stand up for the shooting test (the participant's HMD is NOT removed). They will be told that they must perform a series of ten shots on the target and that the result is shown on the scoreboard.

Before starting, the participant received basic instructions about the purpose, how to hold the Oculus Rift controller (Fig. 4.12), how to control breathing for shooting, that they must close one eye to take aim, stay in a comfortable position to perform the shots, the importance of accuracy in the shot, that after each shot, they must lower the hand and restart the procedure always keeping calm and may interrupt the test at any time.

They were instructed how to proceed during the tests and guided on how they should adjust the HMD to be as comfortable as possible.

At the end of the ten shots, we finish the shooting test and the researcher helps the

Figure 4.14: Flowchart of the experimental protocol

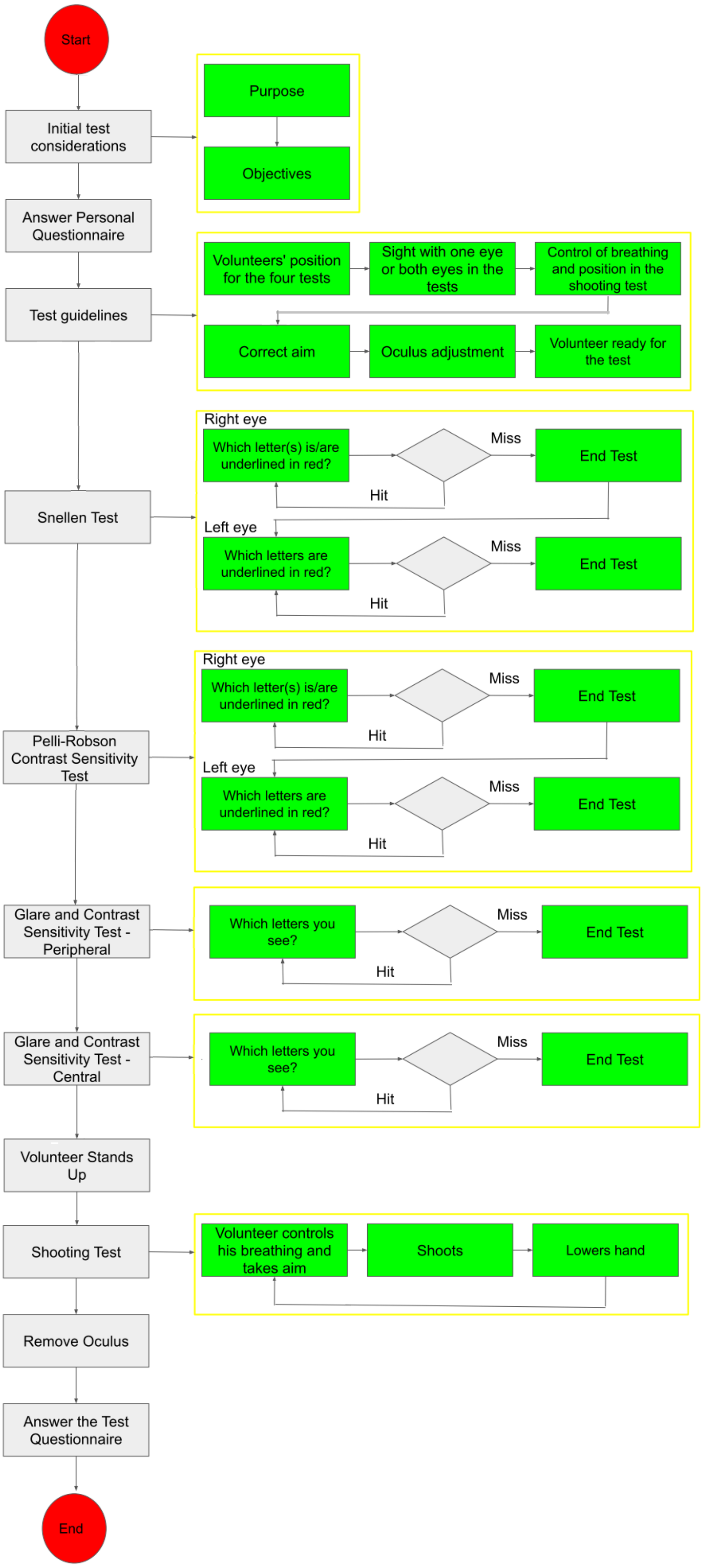


Figure 4.15: The volunteer adjusts the HMD until he/she has a comfortable view within the immersive environment by following the instructions of the researcher

volunteer to remove the HMD to answer a questionnaire about the tests performed and about the test as a whole.

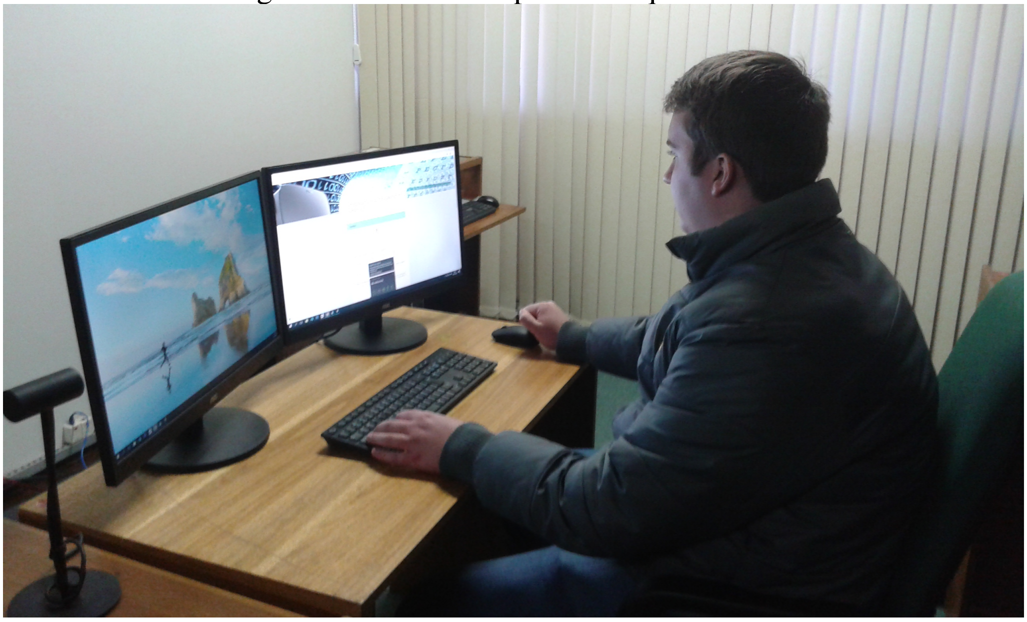
The quantitative dependent variables we collected are the results of the visual acuity tests (Snellen, Pelli-Robson and Glare) and the score in the shooting test.

As for the qualitative attributes, users were asked to answer a questionnaire (Fig. 4.16) at the end of each test performed, with the traditional NASA TLX (HART; STAVELAND, 1988)(Task Load Index) multidimensional assessment tool following a Likert (LIKERT, 1932) scale.

4.9 Results

A total of twenty-three subjects took the tests (six women) with ages ranging from 15 to 30 years, with a mean of 21.5 and standard deviation (SD) of 2.3. As for having vision problems, twelve answered yes, being the most cited myopia, hyperopia and astigmatism 4.6. As for the use of glasses, eleven answered that they use them regularly, and of these, only seven preferred to perform the tests using their glasses. As for having had some kind of eye surgery, all of them said they had never undergone it, and if they had any disease that could influence their vision (hypertension, diabetes or autoimmune disease), all of them also said no. As for having already used virtual reality glasses (HMD), eleven said yes. Asked if they had any previous experience with firearms (shooting stand,

Figure 4.16: Users respond to a questionnaire

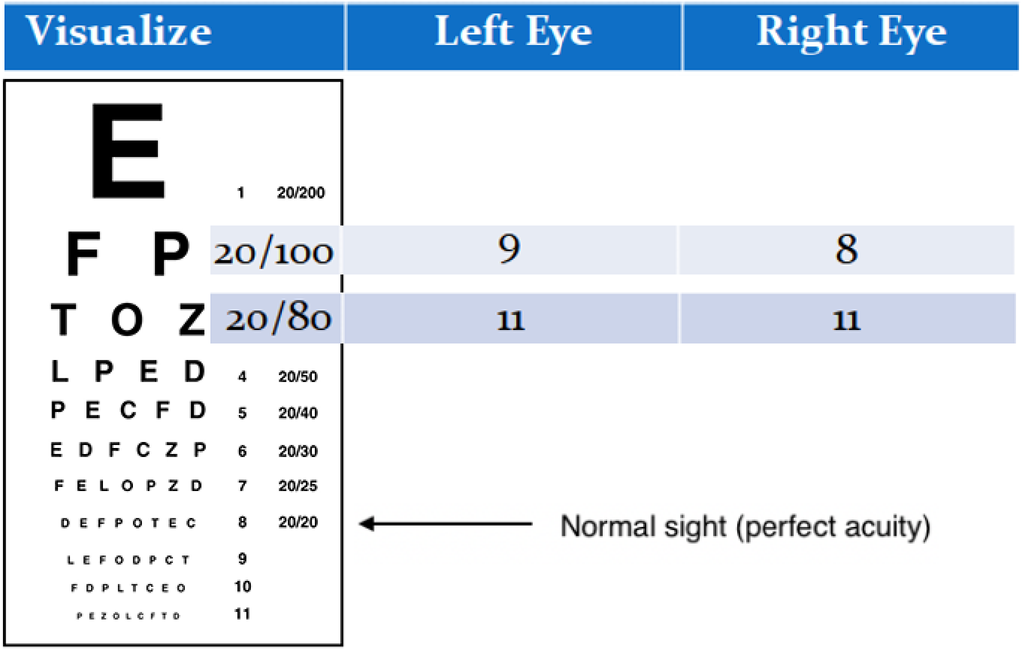


hunting, armed forces, etc.), six said yes.

4.9.1 Quantitative results

The Snellen Test results show that eleven subjects were able to visualize the 20/80 optotypes with both the left and right eye. The 20/100 optotypes were visualized by eight subjects with the right eye and nine with the left eye (Fig. 4.17).

Figure 4.17: Snellen Test Performance



Visualize	Left Eye	Right Eye
20/100	9	8
20/80	11	11

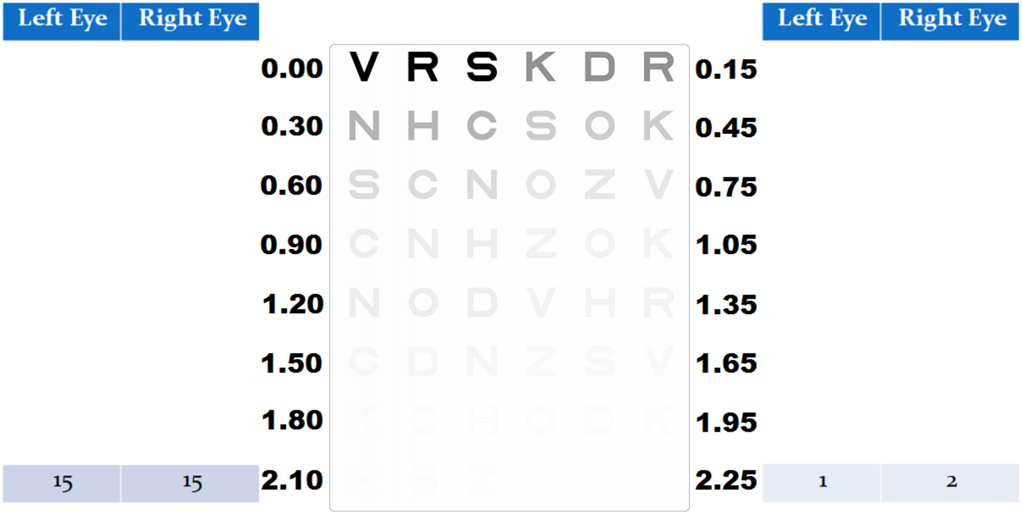
The results of the Pelli-Robson Contrast Sensitivity Test show that 15 subjects had

Table 4.6: Visual impairments reported.

ID	Has impairment?	Condition type
1	No	-
2	Yes	Astigmatism
3	No	-
4	No	-
5	No	-
6	Yes	Myopia
7	Yes	Myopia
8	Yes	Hyperopia and Astigmatism
9	No	-
10	Yes	Myopia
11	Yes	Astigmatism
12	Yes	Myopia
13	No	-
14	No	-
15	No	-
16	Yes	Astigmatism
17	No	-
18	Yes	Hyperopia and Astigmatism
19	No	-
20	Yes	Myopia
21	No	-
22	Yes	Myopia and Astigmatism
23	Yes	Myopia

contrast sensitivity of 2.10 with the left and right eye. The contrast sensitivity of 2.25 only two subjects had it with the right eye and one with the left eye (Fig. 4.18).

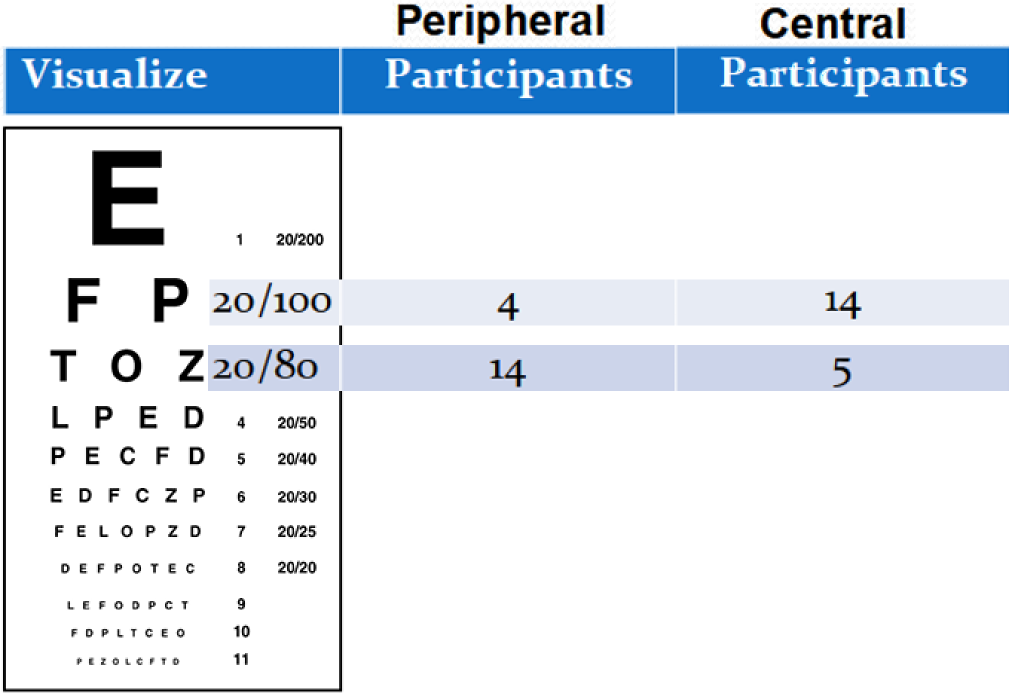
Figure 4.18: Pelli-Robson Contrast Sensitivity Test Performance



The results of the Glare Test - Peripheral Contrast Sensitivity Test show that fourteen subjects were able to visualize the 20/80 optotypes. The 20/100 optotypes were visualized by only four subjects (Fig. 4.19).

The results of the Glare Test - Central Contrast Sensitivity Test show that fourteen subjects could visualize the 20/100 optotypes. The 20/80 optotypes were visualized by five subjects (Fig. 4.19).

Figure 4.19: Glare Test Performance



Visualize	Peripheral Participants	Central Participants
20/100	4	14
20/80	14	5

In the Shot Test performed by the subjects, the daytime shots had a mean of 17.22 points with 13.03 standard deviation, the nighttime shots had a mean of 20.04 points with 13.49 standard deviation. The overall average was 37.26 points with 25.21 standard deviation (Fig. 4.20).

In the first daytime shot eleven subjects missed the target but in the last daytime shot only six missed. In the same situation in the night shot, eight subjects missed the first shot and only five missed the last night shot (Fig. 4.20).

Since the volunteers did not have any training sessions before the test, the better results for the night shot, may be due to their learning during the experiment.

4.9.2 Qualitative results

The raw NASA TLX results are shown in Fig. 4.21 and Fig. 4.22 with the mean score for each statement answered by the subjects.

The unweighted TLX score for mental load was evaluated as 26.04 for the Snellen Test, 23.52 for Pelli-Robson Contrast Sensitivity Test, 24.09 for Glare - Peripheral Contrast Sensitivity Test, 25.39 for Glare - Central Contrast Sensitivity Test, and 27.48 for Shooting Test (Fig. 4.23).

We questioned whether subjects had difficulty adjusting the HMD, and this was

Figure 4.20: Shot Test Performance - Shot Daytime and Nighttime

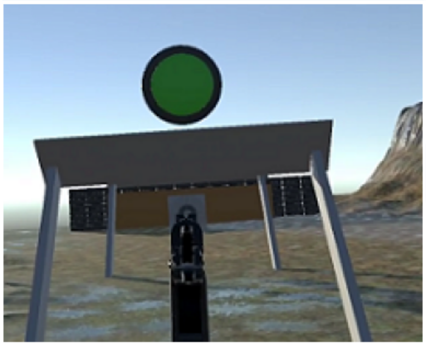
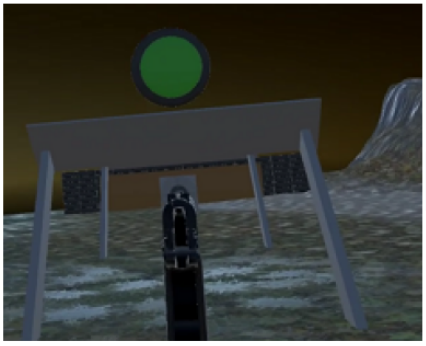
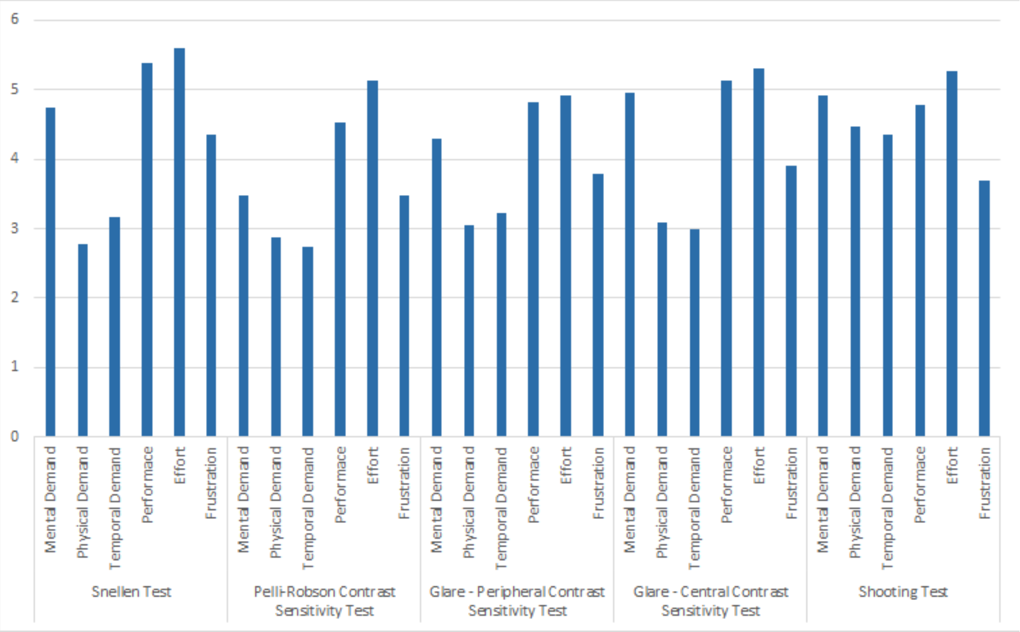
Shots	Mean	SD
	17.22 / 50	13.03
	20.04 / 50	13.49

Figure 4.21: NASA TLX - Qualitative questionnaire results



rated as 2.35 (Fig. 4.24 (a)). As for being comfortable in the virtual environment where the tasks were performed was rated as 3.65 (Fig. 4.24 (b)).

Figure 4.22: NASA TLX - Results of volunteers

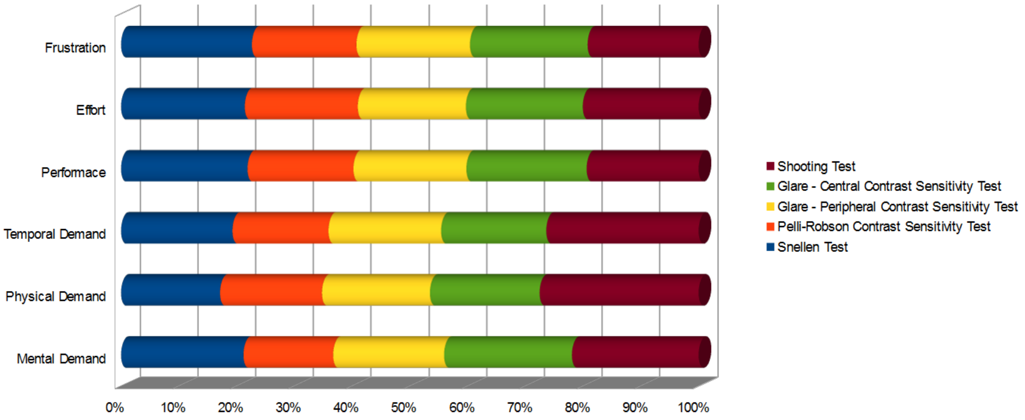


Figure 4.23: Unweighted TLX score

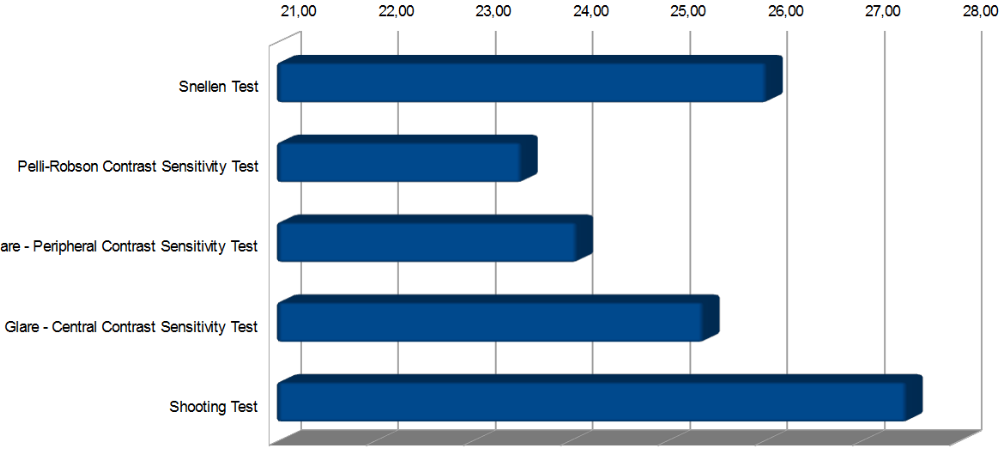
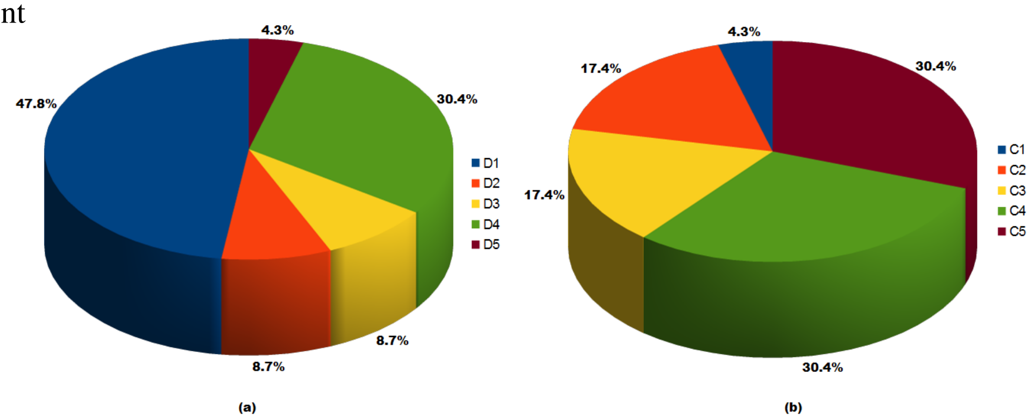


Figure 4.24: (a) Difficulty adjusting the oculus, (b) Comfortable in the virtual environment



4.10 Discussion

Out of the seven subjects who wore prescription glasses, only one had previously used a firearm.

Although they had no difficulty in adjusting the HMD and was comfortable in the immersive environment they had a low score in the target shooting, which may have been due to not having changed his prescription glasses in the correct period, because some vision problems tend to increase over time.

Another problem found among the subjects was that the eight who reported difficulty in adjusting the HMD scored low on target shooting, reinforcing that correct HMD adjustment is essential for good visual acuity.

Among the thirteen subjects who had no difficulty adjusting the HMD, ten of them were better in the night shot than in the day shots, characterizing that correctly adjusting the HMD can improve visual acuity in a low-light environment.

Of the five subjects who were better at daytime shooting all had grade 2.10 on the Pelli-Robson test in both eyes and 20/80 on the Peripheral Glare test and none of them had difficulty adjusting the HMD. Similarly, the five subjects who did not achieve any points in the first and last daytime shots all had 20/80 on the Peripheral Glare test and four of them had 20/100 on the Central Glare test and were all comfortable in the virtual environment, which may in a testing with more subjects be prove a pattern.

The five subjects who did worst on the night shooting, four wore prescription glasses, all had 20/100 on the central Glare test and on the Pelli-Robson test four had 2.10 on the right eye, which may be due to the choice of the wrong eye to aim at, since the dominant eye in the shot (THIBODEAUX, 2003) should always be the eye opposite to the hand that holds the gun. Closing the cross-dominant eye before the shot allows for one last adjustment to better align the barrel of the gun.

Of the subjects who did not wear prescription glasses but have Myopia, two scored 20/200 on the Snellen test in both eyes and on the Pelli-Robson test 1.25 and 1.20 (very low) in the left eye, in addition, they had difficulty adjusting the HMD and preferred to perform the test without their prescription glasses. Both obtained a score of 50 pts on the shot (the average was 37 points). In myopia, light rays entering the eye are focused in front of the retina, rather than directly on it, so that distant objects appear blurry (KAUR et al., 2020) this differential may have helped the subjects' performance by correlating the shot test with the tests with optotypes.

Another aspect to consider is the fact that although the virtual target is placed far away, the real HMD is close to the subject's eyes, which could favor a myopic volunteer.

We tried to find out how experiment results are affected in studies based on VR tasks.

We demonstrate that some factors such as the correct HMD setting, the subject being comfortable in the immersive environment and good results on the Snellen, Pelli-Robson, peripheral and Central Glare tests considerably influence visual acuity in VR.

The acuity tests developed is proof of these results in a test that is influenced by vision, although with some limitations, substantiate the importance of the factors presented above, which can serve as a basis for the investigation of new technologies, devices more capable and less demanding in correcting the vision of its users.

5 METHOD AND EXPERIMENT TO MEASURE VISUAL ACUITY IN VR USING LANDOLT RINGS

From the experience gained with our previous experiment (Chapter 4) we sought to develop a quick test (close to 3 minutes) for capturing information regarding the vision peculiarities of each individual. Although HMDs are used in a wide range of tasks and applications, a correct adjustment of the device in the immersive environment with a focus on each user's individual vision should reduce the discomfort and nausea often caused by incorrect adjustment of the HMD, as well as the quality of vision in the environment can be improved if after a quick test the system adjusts to that individual's vision.

In this chapter we describe the new method that we devised to assess acuity in VR based on the ISO 8596:2018 standard (see Sec. 2.2 and 2.3). We also present an experimental evaluation conducted with 13 users.

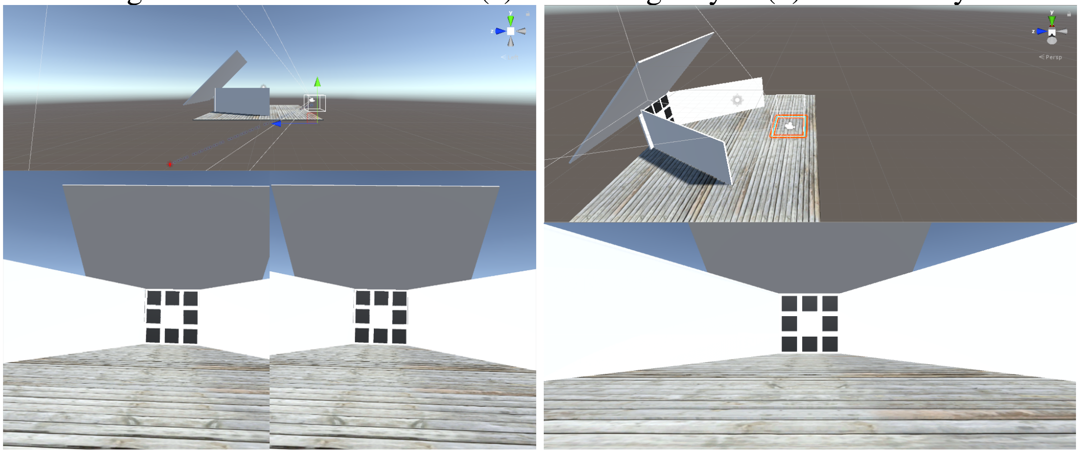
5.1 Overview

Our second acuity testing method uses Landolt rings. We also implemented the concept on the Unity 3D engine and used an Oculus Rift device with the default settings without any calibration. The user holds the Rift controller, which allows them to make selections with the standard laser pointer. We created an immersive scenario composed of a large white wall in front of which the volunteer is seated at a certain distance (Fig. 5.1). On the wall there are eight large black squares that will serve as buttons for the user to provide responses. The method has three tests that will be applied in sequence: distance control; contrast control; dirty lenses. We describe the tests in detail in the next three subsections.

The tests are performed in the same environment and always in the same order. All three tests are to be performed seated, and the user must not remove the HMD before concluding all the three tests.

The Landolt ring used in our tests was created in Photoshop 2020, saved in .jpg format (Joint Photographic Experts Group) with ICC profile (INTERNATIONAL COLOR CONSORTIUM): sRGB IEC61966-2.1 (determined by the Commission Internationale de L'Eclairage), in the dimensions 377 px x 377 px (8.87 mm x 8.87 mm) with a resolution of 1080 Pixels/inch, maximum quality (12), baseline "Standard" and RGB color 0.0.0.

Figure 5.1: View of the wall: (a) left and right eye - (b) with both eyes

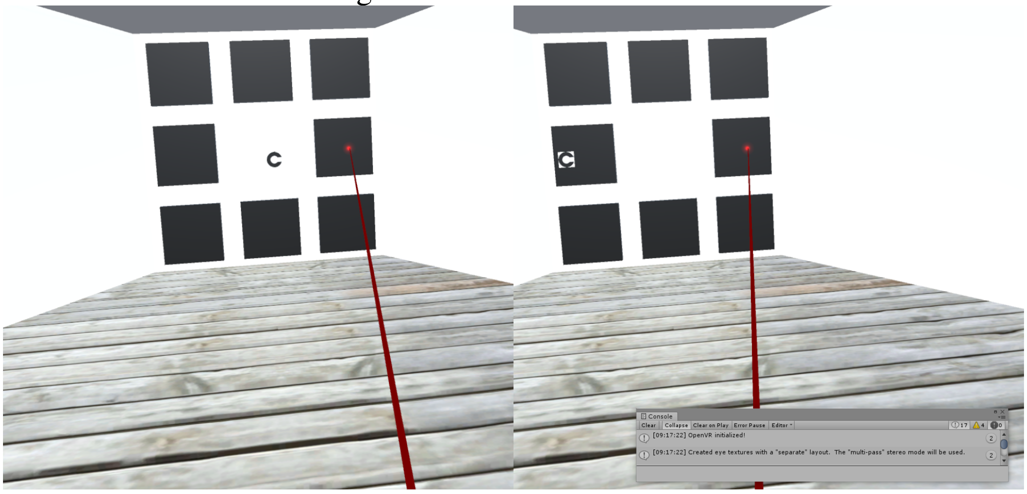


The size 8.87 mm x 8.87 mm, was defined according to Table (4.1) (SNELLEN, 1862) which determines the size of optotypes based on the visual angle of 0.5 minutes of arc seen from a distance of 6.10 meters (20 Paris foot), at a description of 20/20 which is considered normal vision.

5.2 Distance Control Test

To perform the test in a virtual environment (Fig. 5.2), we used the "C" size as described in session 2.2 at an initial △ distance 0.6 m from the HMD camera.

Figure 5.2: Distance test view



```
[09:17:22] OpenVR initialized!
[09:17:22] Created eye textures with a "separate" layout.  The "multi-pass" stereo mode will be used.
```

During the test, the user is shown a "C" at a △ distance right in front (Table 5.1). When identifying the "C", the user must point the laser to the wall ahead and select the button corresponding to the orientation of the "C" opening (Fig. 5.3). If the option chosen is the correct one, the "C" is moved away (current distance plus the △ value) and rotated to a random orientation. The user then performs a another selection. The process is repeated while the correct orientation is selected.

Table 5.1: Rotation of the "C" in the distance test

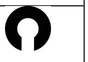
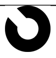
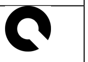
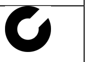
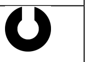
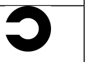
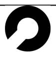
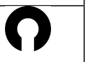
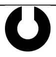
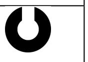
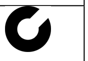
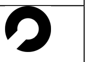
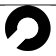
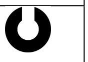
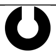
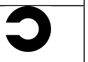
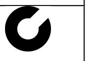
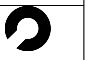
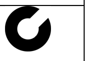
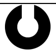
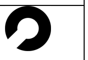
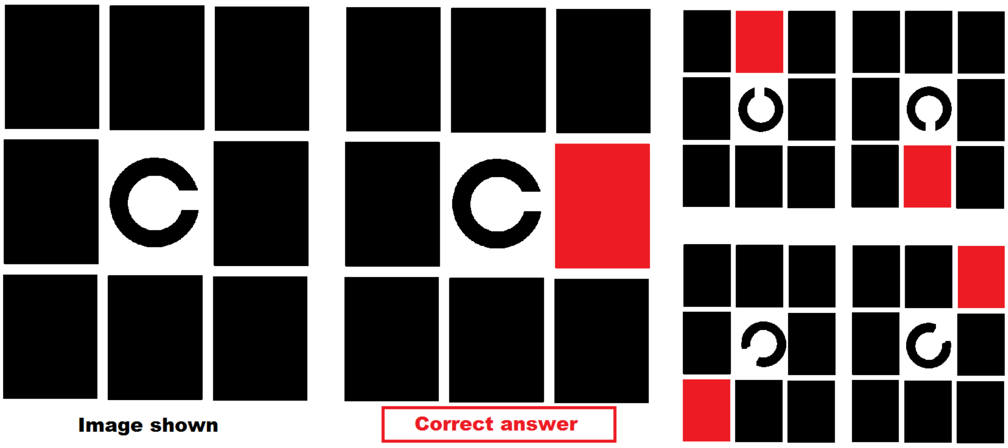
Level	Hit	Error
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		

Figure 5.3: Example of correct answer



When the wrong orientation is selected, the "C" is moved closer by a distance of

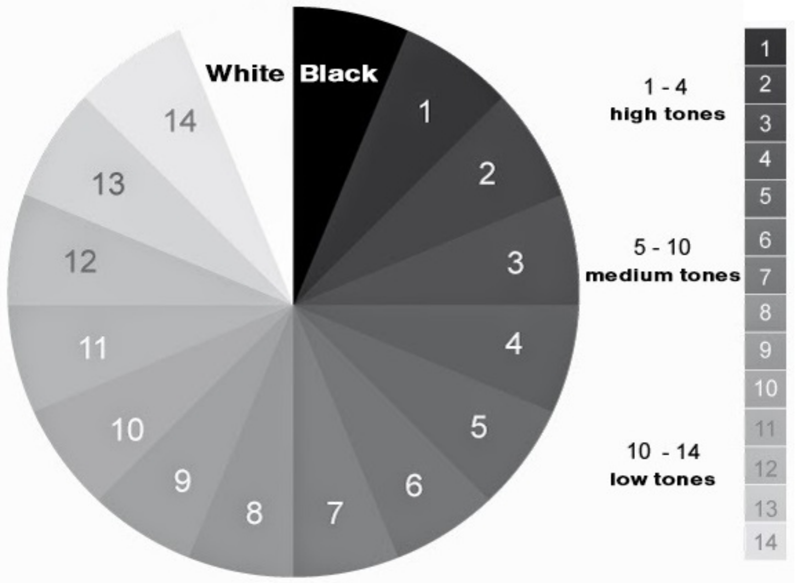
△ divided by two (△ / 2) and rotated randomly. The user then makes a final selection. The test ends both if the selection is wrong or right. When this last selection is correct, the result is recorded as the current distance to the camera. If it is incorrect, the recorded result is the previous "C" distance, i.e. the one before the first wrong selection. Whatever happens, the recorded distance is the maximum distance from the virtual camera after the second check of the volunteer's correct or wrong answer in the test, and the spatial resolution is given by half-△.

We used as maximum distance, the closest distance between the camera and the "C" that was achieved at this level of the test, because although the user is seated, he can throw his body forward, which would shorten the distance slightly, making it easier to see the image of the "C".

5.3 Contrast Control Test

To perform the contrast test in a virtual environment, we use Fig. 5.4 as a parameter to paint the Landolt Ring. We divide it into a scale of values, with the first group being black (the contrast is 100%), and each subsequent group has a contrast reduction factor of 0.707 (0.15 log units), so the contrast of the last group is 0.56% (2.25 log units below 100%) (WILLIAMSON et al., 1992).

Figure 5.4: Gray value scale

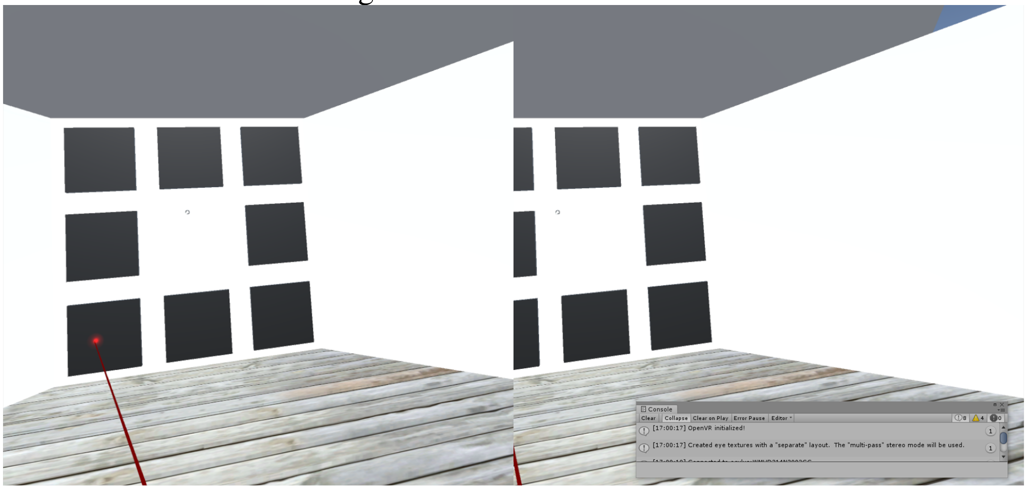


Source: https://br.pinterest.com/pin/859343172643199551/

During the test, a "C" is presented in front of the user at a fixed distance of 2/3 of the value obtained by this individual in the Distance Test (Fig 5.5). When identifying the

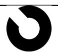
"C", the user must point the laser to the wall in front and choose the button corresponding to the direction the "C" opening is turned to. If the option chosen is the correct one, the "C" is rotated and its gray scale is modified to the next lower contrast gray (Table 5.2). The user then makes a new selection until a wrong answer is given.

Figure 5.5: Contrast test view



```
[17:00:17] OpenVR initialized!
[17:00:17] Created eye textures with a "separate" layout.  The "multi-pass" stereo mode will be used.
```

Table 5.2: Rotation of "C" and percentage in the contrast test

Level	**Hit**	**Error**	Percentage RGB-A
1			1
2			0.9944
3			0.9233
4			0.8523
5			0.7813
6			0.7103
7			0.6393
8			0.5682
9			0.4972
10			0.3551
11			0.2841
12			0.2131
13			0.142
14			0.056
15			0

In case of error in the choice of direction, the "C" is rotated and its gray scale is kept at the same level for a second and final trial.

If the user hits the correct answer for this last trial, the current gray scale level will be recorded as the maximum level reached in the test. If, instead, the user misses this last trial, the maximum level recorded for this user will be the previous level.

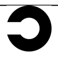
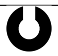
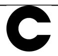
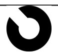
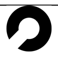
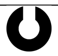
5.4 Dirty Lenses Test

While distance-dependent acuity and contrast-dependent acuity had already been considered in our previous method (Chapter 4, in this third test we consider a new factor: possible presence of any kind of dirt covering the HMD lenses, with the purpose of checking how the volunteers would behave to overcome this difficulty..

Notice that even when the lenses are cleaned just before use, involuntary contact with the skin of the face when putting on the HMD often soild the lenses.

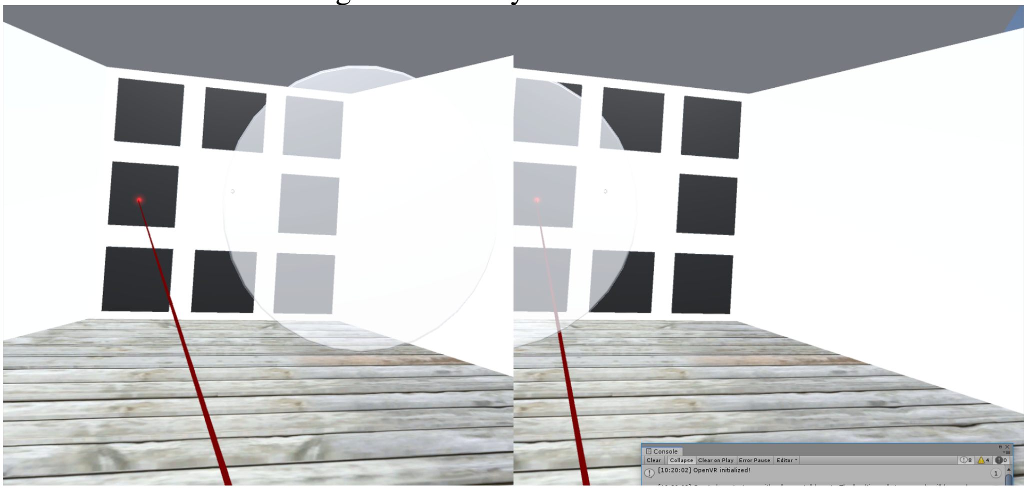
To perform the test in a virtual environment, we created a virtual lens very close to the camera. The virtual lens is a small flattened white sphere $0.0001mm$ thick (on the camera z-axis) with an initial diameter of $0.65mm$ and that increases its size and modifies its transparency/alpha (Table 5.3) as the user advances levels in the test. This translucent sphere simulates a parameterized stain at the center of the user's line of sight. It remains stationary to the camera (see Fig. 5.6).

Table 5.3: Transparency and rotation of the "C" in the dirty lenses test

Level	**Dirty**		**Landolt Ring**
	Opacity (Alpha)	Diameter (mm)	
1	0.25	0.65	
2	0.25	0.75	
3	0.25	0.85	
4	0.50	0.65	
5	0.50	0.75	
6	0.50	0.85	
7	0.75	0.65	
8	0.75	0.75	
9	0.75	0.85	

During the test, a "C" is presented in front of the volunteer at a fixed distance of 2/3 of the value obtained by the volunteer in the Distance Test (Sec. 5.2). Upon identifying

Figure 5.6: Dirty lenses test view



```
[10:20:02] OpenVR initialized!
```

the "C", the user must aim the laser at the wall and select the respective button indicating the "C" opening direction. Regardless of whether the chosen option is correct or not, the "C" is rotated, its size and transparency are modified (Table 5.3), and the user chooses a new option until he or she completes the nine levels of the test.

5.5 User Experiment

The three tests described above provide us information about the focus/sharpness acuity, the contrast perception and how the users deal with light blocking dirt on the HMD lenses. To explore the capability of theses tests in providing us with useful information, and to measure the efficiency of the method, we designed and conducted an experiment with users.

The experiment was exceptionally conducted outside the UFRGS campus due to several restrictions imposed by the Covid-19 pandemic. Yet, it was performed in the premises of another computer science laboratory, at the Federal University of Santa Maria (UFSM). There, with the support from Prof. Dr. Cesar Pozzer, we recruited 13 volunteers on the campus to participate in our study. Our goal with the study was to learn more about visual acuity in the use of HMDs to help developing a quick visual acuity test for better user experience. The study was exploratory and no formal hypothesis was formulated.

5.5.1 Safety Protocol and Precautions Before the Tests

Due to the Covid-19 pandemic, we followed the guidelines of UFRGS and UFSM (Federal University of Santa Maria) where the tests were carried out with users. We created a safety protocol for the activity. The room where the test was carried out had its windows open for better ventilation. Inside the room there was only the researcher and the volunteer who would perform the tests, and it was mandatory to wear a protective mask.

The hands, keyboards, mouse, HMD, and controls were sanitized with 70% alcohol gel every time a volunteer entered the room. A minimum distance of 1.5 meters was kept between the two, and physical contact, such as hugging or shaking hands, was forbidden.

5.5.2 Procedure

At the beginning of the experiment, the participant answered a profiling questionnaire (Fig. 5.7). The researcher then presented the Oculus Rift, and advised the participant on the correct way to adjust the HMD to the head and how to use the controller, thus familiarizing himself with the equipment (Fig. 5.8). After answering that the HMD was adjusted and that the volunteer felt comfortable in the immersive environment, the tests started sequentially until they were finished or the volunteer decided to stop for whatever reason.

The participant was informed that all tests would be performed sitting on a chair and with both eyes open, and that they could stop and leave the test at any time. The right-hand Oculus controller was used to point and select with the conventional laser pointer technique. They were instructed on how to point with the laser on the wall to select the appropriate button indicating the position/direction of the "C" opening.

All the data from the experiment were captured automatically, not requiring the volunteer to provide any extra information besides the answers to the questionnaires.

At the end of the three tests, the researcher helps the volunteer to remove the HMD, guiding them to answer a post-test questionnaire about their experience and satisfaction and workload (NASA TLX (Task Load Index) multidimensional assessment tool (HART; STAVELAND, 1988)).

The rotation of "C" for each trial was predetermined according to Table 5.1 so

Figure 5.7: Users answer an initial questionnaire

Figure 5.8: The volunteer adjusts the HMD until he has a perfect view into the immersive environment

that parity occurs among all volunteers.

5.6 Results

A total of thirteen volunteers (five women) between the ages of 15 and 50 participated in the experiment, with a mean of 30.57 and a standard deviation (SD) of 12.15 years (Fig. 5.9). Out of the 13 participants, three reported no vision problem. Out of the remaining ten, three have Myopia, one has Astigmatism, one Hyperopia, three have Myopia and Astigmatism and one has Hyperopia and Astigmatism. Six volunteers wear glasses regularly, none had eye surgery, nor do they have other eye diseases mentioned in the questionnaire. As for having already used virtual reality glasses (HMD), ten said yes. (Table 5.4)

Figure 5.9: Demography

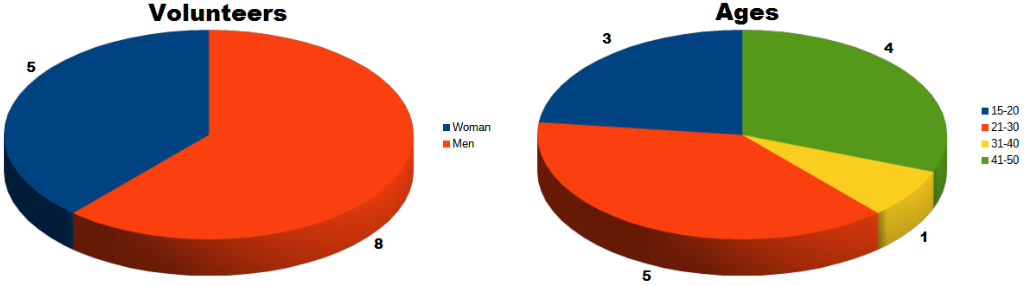


Table 5.4: Volunteer Profile

ID	Age	Sex	Vision Problem	What is the problem	Used HMD
1	41-50	Male	Yes	Myopia	Yes
2	21-30	Female	Yes	Myopia and Astigmatism	No
3	21-30	Male	Yes	Myopia	Yes
4	21-30	Male	Yes	Astigmatism	Yes
5	41-50	Male	Yes	Hyperopia	Yes
6	21-30	Male	Yes	Myopia e Astigmatism	No
7	21-30	Male	No	-	Yes
8	15-20	Male	No	-	Yes
9	15-20	Male	Yes	Hyperopia and Astigmatism	No
10	41-50	Female	Yes	Astigmatism and Myopia	Yes
11	41-50	Female	Yes	Myopia and Astigmatism	Yes
12	31-40	Female	No	-	Yes
13	15-20	Female	Yes	Myopia	Yes

5.6.1 Objective Results

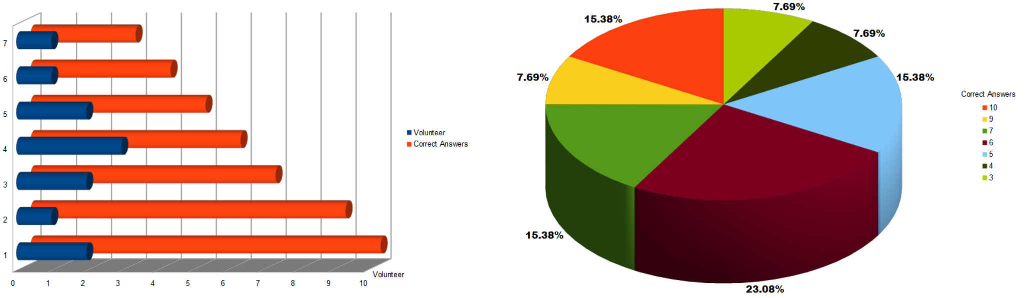
The volunteers took an average of 3 min and 9 seconds (03:08:993) to complete the three tests. The volunteer who performed the tests in the shortest time took 90 seconds (01:30:081), and the one who took the longest time concluded in a little more than 6 and a half minutes (06:35:309).

In the Distance Test the average time was 00:48:900, the shortest time was 00:20:054 and the longest time was 01:28:042. The average maximum distance reached by the volunteers was $2.257m$, and the participant who saw the farthest reached a distance of $3.723m$. Two participants saw only at the shortest distance of $1.944m$. In the test only two volunteers reached level 10 (out of 18 levels) and two did not reach beyond level 3.

Also in the Distance Test, 23.08% of the volunteers scored the Landolt Ring position six times. Other 15.38% of the volunteers scored ten times. The same percentage scored seven times and five times (Fig. 5.10).

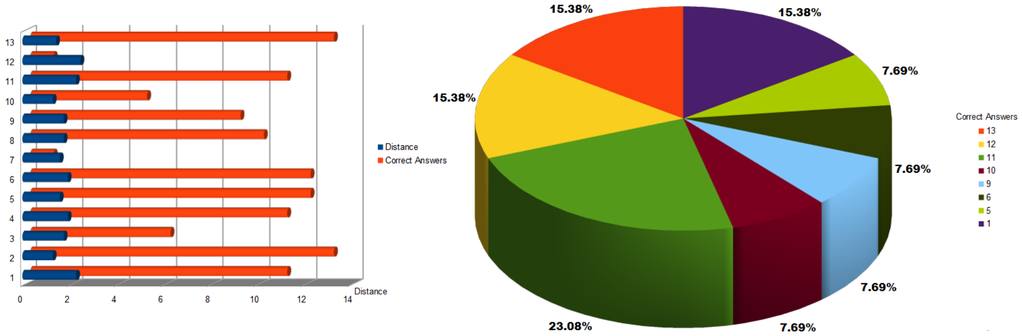
In the Contrast Test the average performance time was 00:40:818, the shortest time was 00:23:013 and the longest time was 01:07:145. Only two volunteers reached level 13 (out of 14) and two did not see beyond level 1 (see table 5.4 for a better idea of the grey levels used).

Figure 5.10: Percent of Volunteers and Correct Answers - Distance Test



Also, in the Contrast Test, 23.08% of the volunteers hit the correct Landolt Ring position eleven times out of 13 possible contrast levels. Remember that each participant performs the contrast test with reference to the maximum distance they could reach in the Distance Test. The 15.38% of the volunteers scored thirteen times, twelve or once (Fig. 5.11).

Figure 5.11: Percent of Volunteers and Correct Answers - Contrast Test



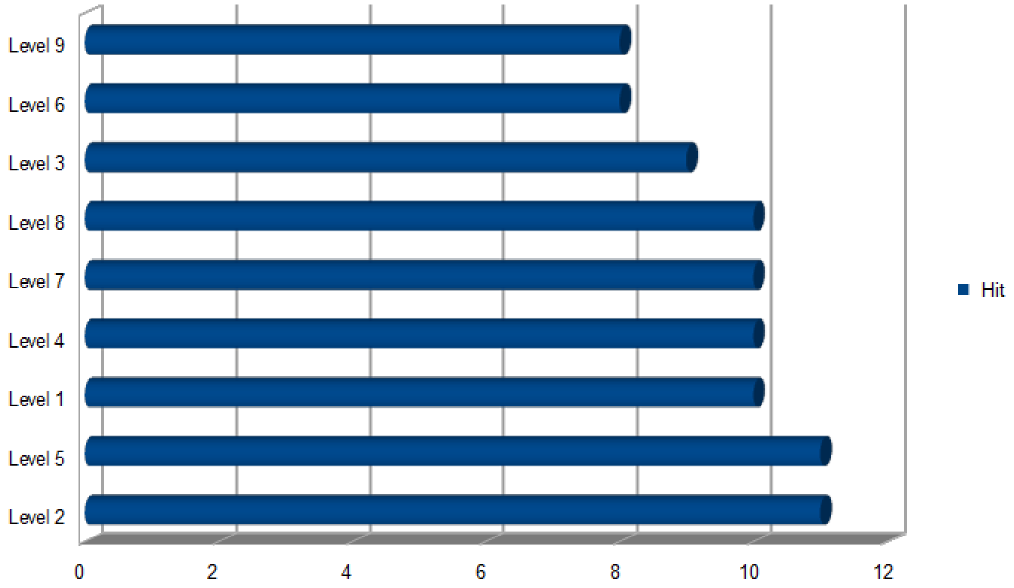
In the Dirty Lenses Test the average time of completion was 01:41:276, the shortest time was 00:37:226 and the longest time was 04:33:688. One volunteer dropped out of the test because they could not see anything at the level 1. The test is composed of 9 levels and we present some results compiled in Table 5.5.

Table 5.5: Results compiled from Dirty Lenses Test

	Average Time	**Shortest Time**	**Longest Time**	**Accuracy**
Level 1	00:10:640	00:02:210	00:23:809	0.75
Level 2	00:06:366	00:00:934	00:11:912	0.83
Level 3	00:13:801	00:01:567	00:12:179	0.67
Level 4	00:06:556	00:02:579	00:22:578	0.75
Level 5	00:08:052	00:00:911	00:26:066	0.83
Level 6	00:14:770	00:02:865	00:54:212	0.67
Level 7	00:09:711	00:01:877	00:35:467	0.83
Level 8	00:08:784	00:01:688	00:34:660	0.67
Level 9	00:13:880	00:01:701	00:37:067	0.58

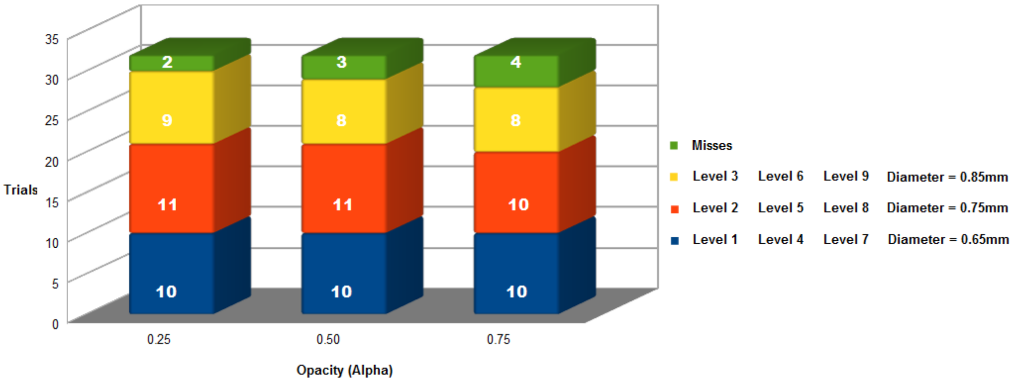
Of the twelve volunteers who completed the Dirty Lens Test, eleven correctly answered Level 2 and 5 of the test, Levels 1, 4, 7 and 8 were answered correctly by ten volunteers. (Fig. 5.12).

Figure 5.12: Volunteers and Correct Answers - Dirty Lenses Test



As for the opacity of dirt on the lens during the Dirty Lens Test, the opacity value of 0.25 was agreed upon by most of the volunteers. As for the opacity of 0.50 and 0.75, we note that at Levels 6 and 9 (the most challenging), where the most dirt is present, only eight of the twelve volunteers got the position of the Landolt Ring (Fig. 5.13).

Figure 5.13: Opacity (Alpha) - Dirty Lenses Test



When we analyzed from the perspective of the size of dirt on the lens, the average size of 0.75 mm had the correct answers for the position of the Landolt Ring in Level 2 and Level 5 by eleven. Again at Level 9 with dirt size 0.85 mm we noticed that only eight of the twelve volunteers got the position of the Landolt Ring right, as this is the level of greatest difficulty in the test (Fig. 5.14). The heatmap in Fig. 5.15 shows how the hit frequency varies with opacity and diameter of the dirt stain.

Figure 5.14: Diameter (mm) - Dirty Lenses Test

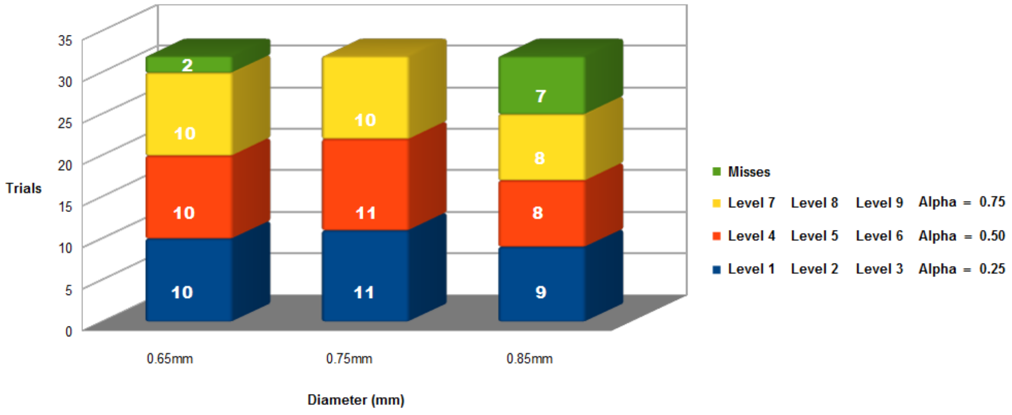
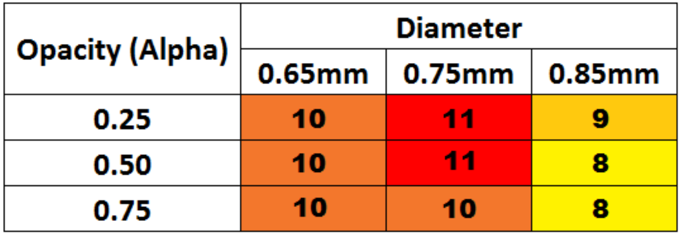
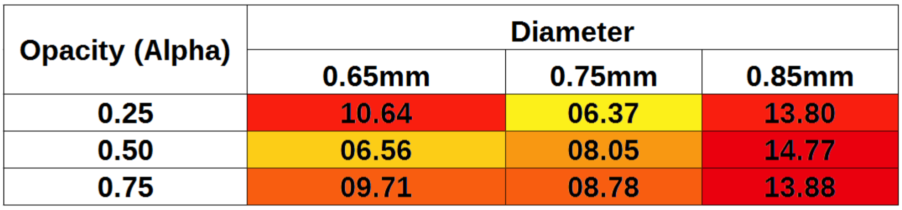


Figure 5.15: Volunteers Hits - Dirty Lenses Test



Opacity (Alpha)	Diameter		
	0.65mm	0.75mm	0.85mm
0.25	10	11	9
0.50	10	11	8
0.75	10	10	8

Figure 5.16: Average Response Time for Volunteers - Dirty Lenses Test (in seconds)



Opacity (Alpha)	Diameter		
	0.65mm	0.75mm	0.85mm
0.25	10.64	06.37	13.80
0.50	06.56	08.05	14.77
0.75	09.71	08.78	13.88

In the following table we show all the hits and misses of each volunteer in all levels of the Dirty Lenses Test (Table 5.6).

Table 5.6: Overall result of the Dirty Lenses Test per participant

ID	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8	Level 9	Hits
1	H	H	H	H	H	H	H	H	H	9
2	H	H	H	H	H	H	H	H	H	9
3	H	H	H	H	H	H	H	H	H	9
4	H	H	H	H	H	H	H	H	H	9
5	M	H	M	H	H	H	H	H	M	6
6	H	H	H	H	H	M	H	M	M	6
8	H	H	H	H	H	H	H	H	H	9
9	H	H	H	H	H	H	H	H	H	9
10	H	H	M	M	H	M	H	M	M	4
11	H	H	H	H	H	H	H	H	H	9
12	H	H	H	H	M	M	M	H	H	6
13	M	M	M	M	H	M	M	H	M	2

H - Hit
M - Miss
∗ Volunteer ID 7 dropped the test.

The heatmap in Fig. 5.16 shows how the time to respond varies with opacity and diameter of the dirt stain. We see that, in general, the time spent increases with diameter but not with opacity. A greater time for $A = 0.25$ with $= 0.65$, which is the theoretical easiest condition, is explained by the fact that this condition is the first experienced by each participant, showing a learning effect.

One volunteer had a difference in InterPupillary Distance (IPD) value in the third test, another volunteer gave IPD difference in all three tests, and one volunteer had difference in IPD from the first to the second test while keeping the least value for the third test. They probably adjusted the position of the HMD for the next test (none removed the HMD during the tests)

5.6.2 Subjective Results

The task load assessed with the unweighted TLX score was 4.33 for the Distance Test, 2.67 for the Contrast Test, and 5.50 for the Dirty Lenses Test ina a ten-point scale. The Table 5.7 presents the unweighted mental load score for each test performed by the volunteers.

Table 5.7: Unweighted task load score for each test by factor (10-point scale)

	Distance Test	**Contrast Test**	**Dirty Lenses Test**
Mental	5.08	5.38	7.23
Physical	3.85	4.00	6.77
Temporal	3.88	4.15	4.65
Performace	4.31	4.38	5.46
Effort	5.54	4.15	7.69
Frustation	3.31	3.00	5.08

As for the difficulty of adjusting the HMDs, the average score was 1.85 in a 5-point scale, showing that most participants had no difficulty in adjusting the equipment. Asked if they felt comfortable in the environment, the average score was 4.54 in a 5-point scale, showing that most felt comfortable in the immersive environment developed.

5.7 Discussion

Volunteer ID 12 managed to visualize the greatest distance in the Distance Test 3.723m in a time of 01:28:042. In his questionnaire he answered that he has no vision problem and that he had already used an HMD, had no difficulty in adjusting the HMD and felt comfortable in the test environment. Provides evidence to support the conclusion that correctly adjusting the HMD and feeling comfortable in the virtual environment improves the performance of the proposed activities for users.

Two volunteers were able to visualize the shortest distance in the Distance Test 1.944m, with volunteer ID 2 performing the test in a time of 00:54:036 and ID 10 in a time of 00:35:733. Volunteers ID 2 and ID 10 in their questionnaires answered that they have myopia and astigmatism, and that they wear glasses regularly. These results suggest that myopia and astigmatism should be further investigated as causing difficulty viewing in a virtual environment, because myopia is a problem in vision that makes it difficult to focus on the image of more distant objects and astigmatism causes vision to not form a sharp image regardless of the distance of the object. However, other myope participants without astigmatism do not corroborate to this correlation, meaning that the most probable cause for the reduced acuity in these cases is astigmatism.

In the Contrast Test a volunteer ID 2 reached the maximum level of the test (Level 13), and in the next level the image of "C" would be totally white contrasting with the background of the same color. This result helps us to show that knowledge of the correct adjustment of the HMD is of paramount importance for a good performance, since the volunteer had already used HMD, had no difficulty in adjusting the HMD and felt comfortable in the test environment.

Seven participants (ID 1, ID 2, ID 4, ID 5, ID 6, ID 8 and ID 11) scored level 10 or above, all of them missed at least one level of the Dirty Lenses Test but all of them got level five of the test right, where the transparency value is 0.50 and the size of the dirt on the lens is 0.75mm (Table 5.3). All reported some vision problem such as myopia, hyperopia and astigmatism or two of them combined, none had difficulty in adjusting the HMD and all felt comfortable in the virtual environment. With these results we verify that these vision problems do not generate difficulty for the perception of contrast in a virtual environment, and that a medium-sized dirt and transparency does not prevent correct viewing, all this being added to a correct adjustment of the HMD and the comfort felt in the environment.

The worst result in the Contrast Test was achieved by two volunteers, one of them being volunteer ID 12 and the other ID 7. Neither of them reported any vision problems, both had already used an HMD and felt comfortable in the environment. They are surprising outliers, being two participants with normal vision with greater difficulty in visualizing the correct contrast in a VR environment. Unfortunately, with a small population, we could not determine the factors leading to this result, but we can argue that some randomness such as luck in the distance test could have made the contrast test too challenging for these users. Remember that the contrast test is applied with a distance defined from the individual result in the distance test.

Comparing the results of the participants regarding medium and low shades of gray, we find the same situation as in the previous experiment (Sec. 4.10), where the volunteers who said they had myopia or some vision problem showed better results in the tests. Further investigation on contrast and myopia is necessary to determine if this tendency is real and what are the causes.

The 9 levels of the Dirty Lenses Test were successfully completed by 7 of the 13 volunteers. Of the 63 (7 volunteers x 9 levels) choices that the volunteers made 51 (80.95%) of them were between 0 and 8 seconds, with three volunteers making their choice in less than a second. If we take into account all the correct answers of the volunteers, we arrive at a total of 87 correct options made (12 volunteers x 9 levels = 108), of these 53 (49.07%) were answered in between 0 and 8 seconds and 34 (31.48%) in more than 8 seconds. With this information we can see that the faster the user's response, the greater the chance of success. The errors are made on low confidence choices that may be driven by distortion or vision fatigue in the environment over time.

Three volunteers had to corrected the placement of their HMD during the experiment (ID 1, ID 3 and ID 4). All of them reported that they had difficulties in adjusting their HMD. While it is positive that they noticed the adjustment could be better after being challenged by the tests. However, as they performed part of the experiment with a less fitted device, we cannot determine if the performance was affected by the self-correction. All of them performed overall near the average.

No effect could be found between the distance perceived in the Distance Test and the Contrast Test. There are mixer results. The two participants who did worse in the Contrast Test (ID 12 and ID 7) achieved a distance of 3.723m and 2.400m respectively in the distance test, and volunteer ID 2, who performed best in the contrast test attained at a distance of 1.944m in the Distance Test.

During testing, four volunteers with vision problems: myopia, hyperopia, and astigmatism had difficulty adjusting the HMD and did not feel well in the virtual environment. Even so, they reached the average gray scale, and three of them achieved the same result in the Distance Test and reached the maximum level in the Dirty Lens Test.

So we can say that these vision problems did not prevent the participants from performing at or above average, and the fact that they had difficulty adjusting does not mean that they did not achieve a good fit. It is even possible that those who found it easy to adjust did not realize that they were not well adjusted.

We cannot claim that with a larger number of volunteers our method could help the HMD fit, nor can we prove that the method we used can objectively measure acuity with statistical significance.

6 GENERAL CONCLUSIONS

The current level of technology used in HMDs has made them more affordable for the general consumer, and greatly improved the overall experience. However, the quality of the visual elements perceived in VR, AR and other systems based on head mounted displays (HMDs) depends on several factors, and their interplay is difficult to understand and control. It may seem obvious that higher display resolutions will allow users to see more detail.

It is indisputable that pixel size, lens aberration, contrast, and size of the displayed objects, potentially influence the user's ability to accurately perceive the visual elements in the immersive environment. Besides, we still have to account for focus, interpupillary distance, luminance, soiled lenses, etc. Besides HMD specifications and rendering techniques, when users put on the HMD, they often get the lenses dirty, do not fasten the straps tight enough or too tight, do not know how to adjust the vergence, cannot judge if they are seeing at the best possible quality.

The variability of perceptual accuracy between users and the system is an issue that is still little explored in the literature. This problem was the focus of this dissertation. We studied the ophthalmologists' techniques to measure quality deviations in a patient's visual perception and proposed approaches to obtain similar measurements in virtual reality. We targeted specifically on assessing the visual acuity experienced by an individual with normal vision in a given session using an HMD.

With our methods, we experimentally measured the visual acuity in more than 40 VR sessions with different users. The most striking observations is that the acuity in VR is lower in VR when compared to the physical reality by a very large margin. Another observation is that contrast sensitivity in VR is not significantly different than it is in reality.

We also refined our methods to optimize them in terms of testing acuity time for a user-HMD pair in less than one minute. By including more detailed measurements, the test can still be completed in less than 3 minutes. This is important in the sense that it can be used at the beginning of any VR session to certify that the visualization is being perceived at least at a minimum standard level, so our research further explored the variability of perceptual accuracy between the user and the system. In VR research, user experiments are often invalidated because the subjects are not seeing as well as the researcher, for example.

6.1 Main contributions

In this research, we introduce the problem of acuity with HMDs for the first time. Although previous research approached some aspects of HMD perceived output, none of them were especially concerned by the lack of control in the experimental conditions of task-based studies in VR due to lack of acuity.

We proposed a method that adapts typical acuity tests from ophthalmology, such as the Snellen and Pelli-Robson Test, to VR. We conducted an experimental evaluation and found that visual acuity is 20/80 or worse in our Oculus Rift CV1 based system, very far from the normal 20/20 acuity.

We hypothesized that a simple shooting game test could be an alternative to assess acuity. We implemented a game and tested it with users, correlating shooting performance matches to visual acuity measured by our VR eye test, even though other random factors such as shooting experience could influence results with regular use.

Moreover, we noticed that the use of appropriate glasses for hyperopia and astigmatism, the correct adjustment of the HMD and the fact that the subject feels comfortable in the immersive environment strengthen the correlation. This also confirms that myopia does not affect acuity in HMDs because the screen is fixed at a short distance of the eyes.

In a second iteration designing an approach to measure acuity, we proposed 3 new tests that users can pass without supervision. Using the Landolt "C", users can respond to what they see by pointing and clicking. The system gathers the response to report a final score. The method takes between 20 and 60 seconds to measure acuity and a similar time for contrast assessment.

These tests, being simple and quick, can be used by researchers in the future to aid in the conditions/conclusions of experiments so that each researcher has a level of visual acuity as suitable as possible for performing a given task, or to normalize the user's performance to the measured level of their visual acuity. It is also useful to demonstrate the variability of acuity between users and VR sessions using the same HMD.

Another issue we tested is how dirty lenses affect visual perception. We simulated dirt stains with a disc-shaped obstacle of variable size and opacity in front of the virtual camera. We saw that lower opacity, up to 50%, still allow to see through, although with less contrast. For higher opacity, the user has to turn the head and look sideways to avoid the stain. This strategy was learned naturally by some users, but not all of them. And even when they applied it, the time to respond was affected by the size of the obstacle.

In the year 2021 we submitted the result of our experiment of exploration of clinical ophthalmology tests in VR with the title "Characterizing Visual Acuity in the use of Head Mounted Displays" at Computer Graphics International 2021, being accepted and published in the book: Advances in Computer Graphics, 38th Computer Graphics International Conference, CGI 2021, Virtual Event, September 6-10, 2021, Proceedings (pp.589-607).

6.2 Limitations and future work

In our research, we did not measure the user's vision with moving objects and in random positions within a virtual environment, nor the time it took to answer each test and the optotypes they had more difficulty viewing, nor did we measure the maximum distance the user could see an optotype of the size proposed by Snellen for a user with vision considered normal (8.87 mm at 6 m in the real world).

Within the Unity 3D engine, we had difficulties in creating a light source that was directed directly at the user's eyes and in a punctual way to simulate a more intense glare of vision during the Central Glare Test. This should be solved with a more physically based rendering, but we did not have time to explore other possibilities and the light effect generated may not be comparable to a real light source.

Another difficulty was the correct calculation of the luminosity inside the proposed virtual environment, which is measured in Candelas per square meter (cd/m^2).

We believe that these difficulties were due to a lack of more study time for a greater knowledge of the Unity development environment and the programming languages that can be used (C# and C++).

Of the problems we had in the development of our proposed tasks I believe that the correct calculation of the luminosity within the environment is the most important to give greater accuracy in the luminosity.

If I had the opportunity to continue my studies in this area, I would try to develop a quick task that could collect data on the user's visual acuity before using the HMD for any task, so that the system would automatically calibrate itself to the user's vision level.

Among the discoveries that occurred during the development of our experiment, we observed the ability of users with nearsightedness to have an easier time getting the proposed tasks right than users who declared they had normal vision and did not wear glasses. We believe that this is information that can be further explored in a future work.

Although we explored the effect of dirt on the lenses, we did not design a test for actual soiled lenses, which we leave for future works.

The eye acuity tests that we adapted to VR helped us to substantiate the importance of the above factors, which can serve as a basis for research into new technologies, devices that are more capable and less demanding in correcting the vision of their users.

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APPENDIX A — RESUMO EXPANDIDO

A.1 Introdução

A acuidade visual é a capacidade do usuário em reconhecer pequenos detalhes com precisão e é uma medida relativa à visão normal. Este trabalho investiga a acuidade visual em realidade virtual pela primeira vez. A nossa motivação é que os pesquisadores não sabem até que ponto os resultados das suas experiências são afetadas pelas variáveis estudadas, por exemplo, a técnica de interação usada ou a capacidade do usuário de ver os elementos necessários para a realização da tarefa proposta.

Enquanto alguns fatores dependem do sistema e são constantes para o mesmo sistema entre diferentes sessões e usuários, outros fatores variam consideravelmente entre as sessões devido à influência humana. A acuidade percebida de alguma forma é afetada, podendo alterar a qualidade da experiência do usuário em um ambiente de realidade virtual.

Em nossa investigação focamos especialmente na falta de controle das condições dos experimentos nos estudos baseados em tarefas em realidade virtual.

A.2 Métodos de Avaliação

Para avaliar a acuidade visual dos HMDs, propomos em nosso primeiro método a adaptação de testes de acuidade típicos da oftalmologia, onde cada um dos testes medirá uma das dimensões de acuidade selecionadas: foco (Snellen), contraste (Pelli-Robson), brilho central e brilho periférico. Para testar nossas hipóteses e caracterizar como a acuidade se corporta em um ambiente imersivo, implementamos estes testes que foram aplicados em uma experiência com usuários. Para analisar a influência da acuidade visual nas tarefas, concebemos outro teste experimental que consiste num estande de tiro onde os usuários realizam disparos sob diferentes condições visuais.

Com a experiência adquirida no experimento anterior desenvolvemos um teste rápido que captura as informações a respeito das peculiaridades de visão de cada indivíduo utilizando Anéis de Landolt. Esse novo método desenvolvido consiste em três testes que medem a distância máxima e o contraste que os voluntários conseguem visualizam um Anel de Landolt do tamanho utilizado na Tabela de Snellen para um individuo com visão normal (20/20). No terceiro teste implementamos uma dificuldade, simulando uma sujeira na lente que aumenta seu tamanho e opacidade a cada nível atingido.

A.3 Explorando Testes Oftalmológicos Clínicos em RV

O experimento consiste em realizar a sequência de quatro testes de acuidade na mesma ordem, seguindo após para o teste de tiro ao alvo. Os participantes sentam-se em uma cadeira fixa e colocam o HMD e são instruídos a ajustar o HMD até que se sintam confortáveis para começar o experimento.

Os dois primeiros testes são realizados inicialmente com o olho direito e depois com o olho esquerdo, sendo que uma imagem completamente escura é exibida no outro olho. Durante os testes de Snellen e Pelli-Robson, o investigador pergunta ao voluntário: “Qual a letra ou conjunto de letras que está sublinhado em vermelho?”, se o voluntário responder a letra ou o conjunto de letras corretamente, o investigador passa para a linha seguinte, até que o participante não identifique corretamente o que está sendo mostrado sublinhado. A última resposta correta é registada para uma análise posterior.

Após os quatro testes de acuidade é aplicado o teste de tiro. Neste momento, o investigador ajuda o participante a levantar-se para realizar o teste. O HMD do participante não é removido. O participante deve realizar uma série de dez disparos no alvo, sendo o seu desempenho mostrado em um painel de pontuação. O tempo máximo de duração para completar os dez disparos é de 1 minuto e 20 segundos, divididos em 10 espaços de 12 segundos. O sol e as condições de iluminação completam o ciclo de um dia durante a sessão de 80 segundos, com início e fim ao meio-dia, de tal forma que os três primeiros e os dois últimos disparos são feitos com a luz do dia, e os outros cinco sem iluminação.

A.4 Método e experiência para medir a acuidade visual em VR usando Anéis de Landolt

Utilizamos nesse segundo método de teste de acuidade os anéis de Landolt, onde o voluntário usa o controle do Oculus Rift CV1 para fazer seleções com um ponteiro laser padrão.

O cenário imersivo é composto de uma grande parede branca na frente da qual o voluntário está sentado a uma certa distância. Colocamos oito grandes quadrados pretos que servem como botões para o usuário responder os testes utilizando o ponteiro do laser na parede a sua frente. O método tem três testes que serão aplicados em sequência: controle de distância; controle de contraste e lentes sujas.

Os testes são realizados no mesmo ambiente e sempre na mesma ordem. Todos os três testes foram realizados sentados, e o usuário não deve remover o HMD antes de concluir todos os testes.

No teste de distância mostramos ao voluntário um "C" a uma distância inicial da câmera que vai sendo afastado e girado a cada acerto da orientação da abertura do "C". Caso erre por mais de uma vez o teste termina sendo computada a distância máxima que o voluntário conseguiu visualizar o "C".

No teste de controle de contraste usamos como distância para apresentação do "C", 2/3 da distância máxima atingida no teste anterior, a cada acerto o "C" é rotacionado e seu contraste diminuído até que o voluntário não consiga mais visualizar o "C", sendo esse nível do teste armazenado como resultado alcançado.

No teste de lentes sujas, também utilizamos como distância para apresentação do "C", 2/3 da distância máxima atingida no teste anterior, a cada nível do teste o "C" é rotacionado, sendo aumentada o tamanho e a opacidade da sujeira na lente. O voluntário deve passar por todos os níveis do teste, embora erre a posição da abertura do "C", sendo armazenado os resultados atingidos em todos os nove níveis do teste.

A.5 Resultados

Estudamos as técnicas dos oftalmologistas para medir desvios de qualidade na percepção visual de um paciente e propusemos abordagens para obter medidas semelhantes na realidade virtual. Visamos especificamente avaliar a acuidade visual experimentada por um indivíduo com visão normal em uma determinada sessão usando um HMD.

Com os resultados analisados, conseguimos provar que alguns fatores, tais como a utilização de óculos para hipermetropia e astigmatismo, ajuste correto do HMD e o usuário estar confortável no ambiente imersivo, correlacionam com os bons resultados nos testes de Snellen, Pelli-Robson, Glare Periférico e Central.

Com nossos métodos, medimos experimentalmente a acuidade visual em mais de 40 sessões de RV com diferentes usuários. A observação mais marcante é que a acuidade em RV é menor em RV quando comparada com a realidade física por uma margem muito grande. Outra observação é que a sensibilidade ao contraste na RV não é significativamente diferente da realidade.

Notamos que todas as variações puderam ser detectadas utilizando o mesmo HMD e com os mesmos parâmetros físicos (resolução, ótica, sistema de renderização).

A.5.1 Considerações Finais

Os resultados obtidos em nossos experimentos comprovam que a acuidade visual experimentada por um indivíduo com visão normal usando um HMD depende de uma série de fatores adicionais.

Embora os HMD sejam usados em uma ampla gama de tarefas e aplicações, um ajuste correto do dispositivo no ambiente imersivo com foco na visão individual de cada usuário deverá reduzir o desconforto e a náusea frequentemente causados pelo ajuste incorreto do HMD, bem como a qualidade da visão no ambiente pode ser melhorada se, após um teste rápido, o sistema se ajustar à visão desse indivíduo.

Contribuímos para definir que o problema da acuidade visual tem sua relevância em diversos resultados de pesquisas.

Propomos uma metodologia simples e rápida para medir acuidade com a adaptação de técnicas conhecidas de oftalmologia à realidade virtual, que podem ser utilizadas por pesquisadores no futuro para assegurar que cada sujeito estará experimentando um nível adequado de acuidade visual necessária para cumprir uma tarefa proposta, ou para normalizar os dados de desempenho do usuário recolhidos de acordo com seu nível medido de acuidade visual.

Contribuímos também com nossa experiência para verificar a variabilidade da acuidade entre os usuários e as sessões.

Também refinamos nossos métodos para otimizá-los em termos do tempo necessário para testar a acuidade do usuário de um HMD em menos de um minuto. Ao incluir medições mais detalhadas, o teste ainda pode ser concluído em menos de 3 minutos.

APPENDIX B — QUESTIONNAIRES APPLIED - VISUAL PERCEPTION IN IMMERSIVE ENVIRONMENTS

PERCEPÇÃO VISUAL EM AMBIENTES IMERSIVOS

-

*Obrigatório

Pular para a pergunta 1Pular para a pergunta 1

Termo de Consentimento Livre e Esclarecido

Pesquisador responsável: Anderson Maciel
Pesquisador participante: Vladimir Soares da Fontoura
Instituição: Universidade Federal do Rio Grande do Sul - UFRGS

Você está sendo convidado para participar, como voluntário, de um experimento onde será usuário de um sistema imersivo desenvolvido no contexto de um projeto de pesquisa. As informações coletadas serão anonimizadas e usadas apenas agrupadas para estudo estatístico.
Você pode a qualquer momento pedir esclarecimentos sobre a tarefa e os procedimentos do experimento.
Você também poderá parar de participar a qualquer momento apenas avisando o pesquisador sem sofrer qualquer tipo de penalidade ou prejuízo.

O que você precisará fazer nos testes:
1. Ouvir as instruções do pesquisador.
2. Preencher um pequeno questionário de perfil.
3. Vestir óculos de Realidade Virtual (Head-Mounted Display) e tentar cumprir as tarefas indicadas pelo pesquisador.
4. Expressar-se verbalmente para informar dificuldades e estratégias usadas para realizar as tarefas.
5. Preencher um questionário sobre suas experiências ao realizar todas as tarefas.

1. Aceito participar como voluntário(a) na pesquisa *

Marcar apenas uma oval.

○ Sim *Pular para a pergunta 2*
○ Não *Pular para a seção 3 (Agradecimento)*

Agradecimento

Agradecemos imensamente o tempo cedido para participar de nossa pesquisa. Desta forma, não é necessário responder o restante do questionário.

Perguntas sobre você

2. Idade *

Marque todas que se aplicam.

☐ 15 - 20
☐ 21 - 30
☐ 31 - 40
☐ 41 - 50
☐ Mais de 50

3. Sexo *

Marque todas que se aplicam.

☐ Feminino
☐ Masculino
☐ Outros

4. Tem algum problema de visão *

Marcar apenas uma oval.

○ Sim
○ Não

5. Se você respondeu "Sim" na pergunta anterior, especifique qual seu problema de visão

____

6. Utiliza óculos regularmente *

Marcar apenas uma oval.

○ Sim
○ Não

7. Realizou alguma cirurgia ocular *

Marcar apenas uma oval.

○ Sim
○ Não

8. Possui alguma dessas doenças *

Marcar apenas uma oval.

○ Hipertensão Arterial
○ Diabetes
○ Doença autoimune
○ Não

9. Já usou óculos de realidade virtual *

Marcar apenas uma oval.

○ Sim
○ Não

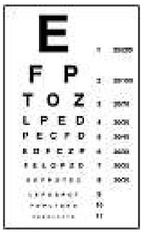
10. Tem alguma experiência prévia com arma de fogo (stand de tiro, caça, forças armadas, etc.) *

Marcar apenas uma oval.

○ Sim
○ Não

Pular para a pergunta 11

Snellen



11. Quão mentalmente exigente foi a tarefa? *

Quanta atividade mental e perceptiva foi necessária (por exemplo, pensando, decidindo, calculando, lembrando, olhando, pesquisando, etc)? A tarefa era fácil ou exigente, simples ou complexa, exigente ou indulgente?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

12. Quão fisicamente exigente foi a tarefa? *

Quanta atividade física era necessária (por exemplo, empurrando, puxando, girando, controlando, ativando, etc)? A tarefa era fácil ou exigente, lenta ou rápida, frouxa ou cansativa, repousante ou laboriosa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

13. Quanto acelerado foi o ritmo da tarefa? *

Quanto tempo você sentiu pressão devido ao ritmo no qual as tarefas ou os elementos da tarefa ocorreram? O ritmo era lento e vagaroso ou rápido e frenético?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco	○	○	○	○	○	○	○	○	○	○	Muito

14. Quão bem-sucedido você acha que foi ao realizar o que lhe foi pedido? *

Quão bem sucedido você acha que foi em realizar os objetivos da tarefa definida pelo pesquisador (ou por você mesmo)? Quão satisfeito você estava com o seu desempenho no cumprimento desses objetivos?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Bem-Sucedido	○	○	○	○	○	○	○	○	○	○	Mal-Sucedido

15. Quanto esforço você teve que fazer para atingir seu nível de desempenho? *

Quão árduo você teve que trabalhar (mentalmente e fisicamente) para atingir seu nível de desempenho?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Esforço	○	○	○	○	○	○	○	○	○	○	Muito Esforço

16. Quanto frustrado você se sentiu ao realizar as tarefas? *

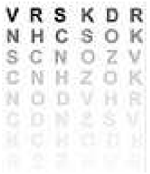
Quão insegura, desanimada, irritada, estressada e aborrecida versus segura, gratificada, satisfeita, relaxada e complacente você se sentiu durante a tarefa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Frustrado	○	○	○	○	○	○	○	○	○	○	Muito Frustrado

Pular para a pergunta 17

Glare



17. Quão mentalmente exigente foi a tarefa? *

Quanta atividade mental e perceptiva foi necessária (por exemplo, pensando, decidindo, calculando, lembrando, olhando, pesquisando, etc)? A tarefa era fácil ou exigente, simples ou complexa, exigente ou indulgente?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

18. Quão fisicamente exigente foi a tarefa? *

Quanta atividade física era necessária (por exemplo, empurrando, puxando, girando, controlando, ativando, etc)? A tarefa era fácil ou exigente, lenta ou rápida, frouxa ou cansativa, repousante ou laboriosa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

19. Quanto acelerado foi o ritmo da tarefa? *

Quanto tempo você sentiu pressão devido ao ritmo no qual as tarefas ou os elementos da tarefa ocorreram? O ritmo era lento e vagaroso ou rápido e frenético?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco	○	○	○	○	○	○	○	○	○	○	Muito

20. Quão bem-sucedido você acha que foi ao realizar o que lhe foi pedido? *

Quão bem sucedido você acha que foi em realizar os objetivos da tarefa definida pelo pesquisador (ou por você mesmo)? Quão satisfeito você estava com o seu desempenho no cumprimento desses objetivos?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Bem-Sucedido	○	○	○	○	○	○	○	○	○	○	Mal-Sucedido

21. Quanto esforço você teve que fazer para atingir seu nível de desempenho? *

Quão árduo você teve que trabalhar (mentalmente e fisicamente) para atingir seu nível de desempenho?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Esforço	○	○	○	○	○	○	○	○	○	○	Muito Esforço

22. Quanto frustrado você se sentiu ao realizar as tarefas? *

Quão insegura, desanimada, irritada, estressada e aborrecida versus segura, gratificada, satisfeita, relaxada e complacente você se sentiu durante a tarefa?

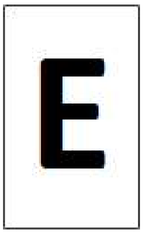
Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Frustrado	○	○	○	○	○	○	○	○	○	○	Muito Frustrado

Pular para a pergunta 23

Sensibilidade ao Contraste

Periférico



23. Quão mentalmente exigente foi a tarefa? *

Quanta atividade mental e perceptiva foi necessária (por exemplo, pensando, decidindo, calculando, lembrando, olhando, pesquisando, etc)? A tarefa era fácil ou exigente, simples ou complexa, exigente ou indulgente?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

24. Quão fisicamente exigente foi a tarefa? *

Quanta atividade física era necessária (por exemplo, empurrando, puxando, girando, controlando, ativando, etc)? A tarefa era fácil ou exigente, lenta ou rápida, frouxa ou cansativa, repousante ou laboriosa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

25. Quanto acelerado foi o ritmo da tarefa? *

Quanto tempo você sentiu pressão devido ao ritmo no qual as tarefas ou os elementos da tarefa ocorreram? O ritmo era lento e vagaroso ou rápido e frenético?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco	○	○	○	○	○	○	○	○	○	○	Muito

26. Quão bem-sucedido você acha que foi ao realizar o que lhe foi pedido? *

Quão bem sucedido você acha que foi em realizar os objetivos da tarefa definida pelo pesquisador (ou por você mesmo)? Quão satisfeito você estava com o seu desempenho no cumprimento desses objetivos?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Bem-Sucedido	○	○	○	○	○	○	○	○	○	○	Mal-Sucedido

27. Quanto esforço você teve que fazer para atingir seu nível de desempenho? *

Quão árduo você teve que trabalhar (mentalmente e fisicamente) para atingir seu nível de desempenho?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Esforço	○	○	○	○	○	○	○	○	○	○	Muito Esforço

28. Quanto frustrado você se sentiu ao realizar as tarefas? *

Quão insegura, desanimada, irritada, estressada e aborrecida versus segura, gratificada, satisfeita, relaxada e complacente você se sentiu durante a tarefa?

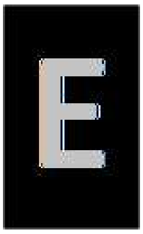
Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Frustrado	○	○	○	○	○	○	○	○	○	○	Muito Frustrado

Pular para a pergunta 29

Sensibilidade ao Contraste

Central



29. Quão mentalmente exigente foi a tarefa? *

Quanta atividade mental e perceptiva foi necessária (por exemplo, pensando, decidindo, calculando, lembrando, olhando, pesquisando, etc)? A tarefa era fácil ou exigente, simples ou complexa, exigente ou indulgente?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

30. Quão fisicamente exigente foi a tarefa? *

Quanta atividade física era necessária (por exemplo, empurrando, puxando, girando, controlando, ativando, etc)? A tarefa era fácil ou exigente, lenta ou rápida, frouxa ou cansativa, repousante ou laboriosa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

31. Quanto acelerado foi o ritmo da tarefa? *

Quanto tempo você sentiu pressão devido ao ritmo no qual as tarefas ou os elementos da tarefa ocorreram? O ritmo era lento e vagaroso ou rápido e frenético?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco	○	○	○	○	○	○	○	○	○	○	Muito

32. Quão bem-sucedido você acha que foi ao realizar o que lhe foi pedido? *

Quão bem sucedido você acha que foi em realizar os objetivos da tarefa definida pelo pesquisador (ou por você mesmo)? Quão satisfeito você estava com o seu desempenho no cumprimento desses objetivos?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Bem-Sucedido	○	○	○	○	○	○	○	○	○	○	Mal-Sucedido

33. Quanto esforço você teve que fazer para atingir seu nível de desempenho? *

Quão árduo você teve que trabalhar (mentalmente e fisicamente) para atingir seu nível de desempenho?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Esforço	○	○	○	○	○	○	○	○	○	○	Muito Esforço

34. Quanto frustrado você se sentiu ao realizar as tarefas? *

Quão insegura, desanimada, irritada, estressada e aborrecida versus segura, gratificada, satisfeita, relaxada e complacente você se sentiu durante a tarefa?

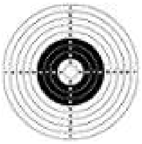
Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Frustrado	○	○	○	○	○	○	○	○	○	○	Muito Frustrado

Pular para a pergunta 35

Central

Estande de Tiro



35. Quão mentalmente exigente foi a tarefa? *

Quanta atividade mental e perceptiva foi necessária (por exemplo, pensando, decidindo, calculando, lembrando, olhando, pesquisando, etc)? A tarefa era fácil ou exigente, simples ou complexa, exigente ou indulgente?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

36. Quão fisicamente exigente foi a tarefa? *

Quanta atividade física era necessária (por exemplo, empurrando, puxando, girando, controlando, ativando, etc)? A tarefa era fácil ou exigente, lenta ou rápida, frouxa ou cansativa, repousante ou laboriosa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

37. Quanto acelerado foi o ritmo da tarefa? *

Quanto tempo você sentiu pressão devido ao ritmo no qual as tarefas ou os elementos da tarefa ocorreram? O ritmo era lento e vagaroso ou rápido e frenético?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco	○	○	○	○	○	○	○	○	○	○	Muito

38. Quão bem-sucedido você acha que foi ao realizar o que lhe foi pedido? *

Quão bem sucedido você acha que foi em realizar os objetivos da tarefa definida pelo pesquisador (ou por você mesmo)? Quão satisfeito você estava com o seu desempenho no cumprimento desses objetivos?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Bem-Sucedido	○	○	○	○	○	○	○	○	○	○	Mal-Sucedido

39. Quanto esforço você teve que fazer para atingir seu nível de desempenho? *

Quão árduo você teve que trabalhar (mentalmente e fisicamente) para atingir seu nível de desempenho?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Esforço	○	○	○	○	○	○	○	○	○	○	Muito Esforço

40. Quanto frustrado você se sentiu ao realizar as tarefas? *

Quão insegura, desanimada, irritada, estressada e aborrecida versus segura, gratificada, satisfeita, relaxada e complacente você se sentiu durante a tarefa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Frustrado	○	○	○	○	○	○	○	○	○	○	Muito Frustrado

Pular para a pergunta 41

Considerações Finais

41. Eu tive dificuldade em ajustar o óculos *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Plenamente	○	○	○	○	○	Concordo Plenamente

42. Eu me senti à vontade, como se estivesse vivendo de fato no local virtual onde as tarefas foram realizadas *

Participando de fato naquele lugar e não apenas assistindo a cena em uma tela

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Plenamente	○	○	○	○	○	Concordo Plenamente

43. Sugestão/Opinião sobre os testes realizados

APPENDIX C — QUESTIONNAIRES APPLIED - VISUAL ACUITY MEASUREMENT IN AN IMMERSIVE ENVIRONMENT USING LANDOLT RINGS

Medição da acuidade visual num ambiente imersivo usando Landolt Rings

*Obrigatório

Pular para a pergunta 1Pular para a pergunta 1

Termo de Consentimento Livre e Esclarecido

Pesquisador responsável: Anderson Maciel
Pesquisador participante: Vladimir Soares da Fontoura
Instituição: Universidade Federal do Rio Grande do Sul - UFRGS

Você está sendo convidado para participar, como voluntário, de um experimento onde será usuário de um sistema imersivo desenvolvido no contexto de um projeto de pesquisa. As informações coletadas serão anonimizadas e usadas apenas agrupadas para estudo estatístico.
Você pode a qualquer momento pedir esclarecimentos sobre a tarefa e os procedimentos do experimento.
Você também poderá parar de participar a qualquer momento apenas avisando o pesquisador sem sofrer qualquer tipo de penalidade ou prejuízo.

O que você precisará fazer nos testes:
1. Ouvir as instruções do pesquisador.
2. Preencher um pequeno questionário de perfil.
3. Colocar o óculos de Realidade Virtual (Head-Mounted Display) e tentar cumprir as tarefas indicadas pelo pesquisador.
4. Expressar-se verbalmente para informar dificuldades e estratégias usadas para realizar as tarefas.
5. Preencher um questionário sobre suas experiências ao realizar todas as tarefas.

1. Aceito participar como voluntário(a) na pesquisa *

Marcar apenas uma oval.

○ Sim *Pular para a pergunta 2*
○ Não *Pular para a seção 3 (Agradecimento)*

Agradecimento

Agradecemos imensamente o tempo cedido para participar de nossa pesquisa. Desta forma, não é necessário responder o restante do questionário.

Perguntas sobre você

2. Idade *

Marque todas que se aplicam.

☐ 15 - 20
☐ 21 - 30
☐ 31 - 40
☐ 41 - 50
☐ Mais de 50

3. Sexo *

Marque todas que se aplicam.

☐ Feminino
☐ Masculino
☐ Outros

4. Tem algum problema de visão *

Marcar apenas uma oval.

○ Sim
○ Não

5. Se você respondeu "Sim" na pergunta anterior, especifique qual seu problema de visão

____

6. Utiliza óculos regularmente *

Marcar apenas uma oval.

○ Sim
○ Não

7. Realizou alguma cirurgia ocular *

Marcar apenas uma oval.

○ Sim
○ Não

8. Possui alguma dessas doenças *

Marcar apenas uma oval.

○ Hipertensão Arterial
○ Diabetes
○ Doença autoimune
○ Não

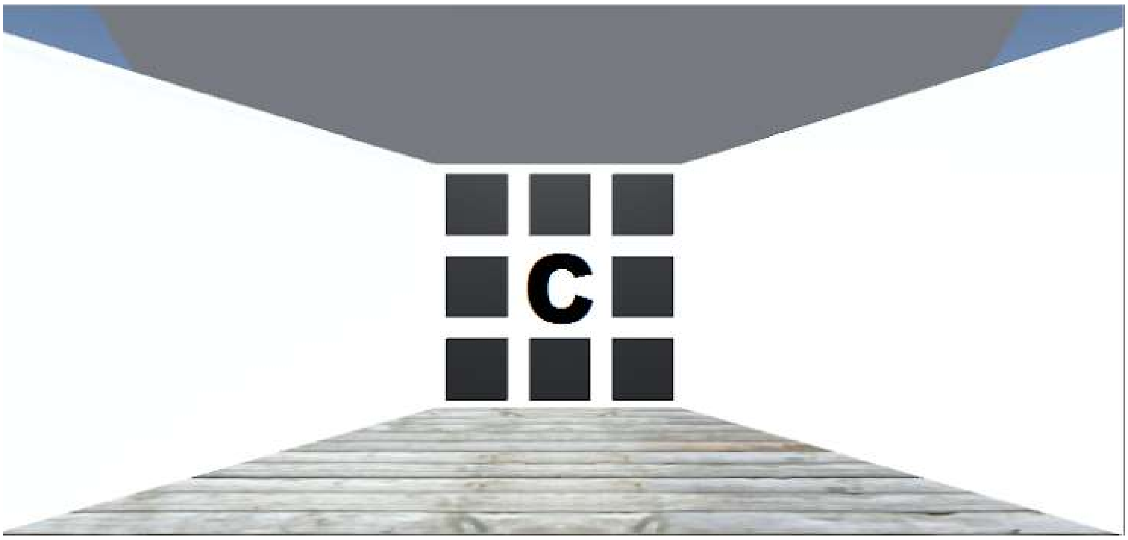
9. Já usou óculos de realidade virtual *

Marcar apenas uma oval.

○ Sim
○ Não

Pular para a pergunta 10

Controle da Distância



10. Quão mentalmente exigente foi a tarefa? *

Quanta atividade mental e perceptiva foi necessária (por exemplo, pensando, decidindo, calculando, lembrando, olhando, pesquisando, etc)? A tarefa era fácil ou exigente, simples ou complexa, exigente ou indulgente?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

11. Quão fisicamente exigente foi a tarefa? *

Quanta atividade física era necessária (por exemplo, empurrando, puxando, girando, controlando, ativando, etc)? A tarefa era fácil ou exigente, lenta ou rápida, frouxa ou cansativa, repousante ou laboriosa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

12. Quanto acelerado foi o ritmo da tarefa? *

Quanto tempo você sentiu pressão devido ao ritmo no qual as tarefas ou os elementos da tarefa ocorreram? O ritmo era lento e vagaroso ou rápido e frenético?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco	○	○	○	○	○	○	○	○	○	○	Muito

13. Quão bem-sucedido você acha que foi ao realizar o que lhe foi pedido? *

Quão bem sucedido você acha que foi em realizar os objetivos da tarefa definida pelo pesquisador (ou por você mesmo)? Quão satisfeito você estava com o seu desempenho no cumprimento desses objetivos?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Bem-Sucedido	○	○	○	○	○	○	○	○	○	○	Mal-Sucedido

14. Quanto esforço você teve que fazer para atingir seu nível de desempenho? *

Quão árduo você teve que trabalhar (mentalmente e fisicamente) para atingir seu nível de desempenho?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Esforço	○	○	○	○	○	○	○	○	○	○	Muito Esforço

15. Quanto frustrado você se sentiu ao realizar as tarefas? *

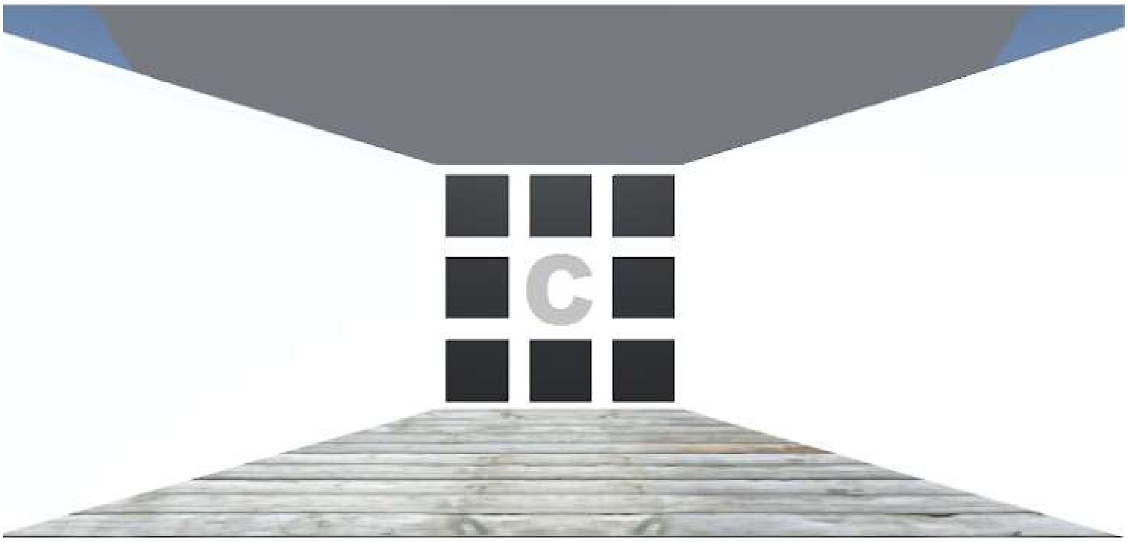
Quão insegura, desanimada, irritada, estressada e aborrecida versus segura, gratificada, satisfeita, relaxada e complacente você se sentiu durante a tarefa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Frustrado	○	○	○	○	○	○	○	○	○	○	Muito Frustrado

Pular para a pergunta 16

Controle do Contraste



16. Quão mentalmente exigente foi a tarefa? *

Quanta atividade mental e perceptiva foi necessária (por exemplo, pensando, decidindo, calculando, lembrando, olhando, pesquisando, etc)? A tarefa era fácil ou exigente, simples ou complexa, exigente ou indulgente?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

17. Quão fisicamente exigente foi a tarefa? *

Quanta atividade física era necessária (por exemplo, empurrando, puxando, girando, controlando, ativando, etc)? A tarefa era fácil ou exigente, lenta ou rápida, frouxa ou cansativa, repousante ou laboriosa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

18. Quanto acelerado foi o ritmo da tarefa? *

Quanto tempo você sentiu pressão devido ao ritmo no qual as tarefas ou os elementos da tarefa ocorreram? O ritmo era lento e vagaroso ou rápido e frenético?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco	○	○	○	○	○	○	○	○	○	○	Muito

19. Quão bem-sucedido você acha que foi ao realizar o que lhe foi pedido? *

Quão bem sucedido você acha que foi em realizar os objetivos da tarefa definida pelo pesquisador (ou por você mesmo)? Quão satisfeito você estava com o seu desempenho no cumprimento desses objetivos?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Bem-Sucedido	○	○	○	○	○	○	○	○	○	○	Mal-Sucedido

20. Quanto esforço você teve que fazer para atingir seu nível de desempenho? *

Quão árduo você teve que trabalhar (mentalmente e fisicamente) para atingir seu nível de desempenho?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Esforço	○	○	○	○	○	○	○	○	○	○	Muito Esforço

21. Quanto frustrado você se sentiu ao realizar as tarefas? *

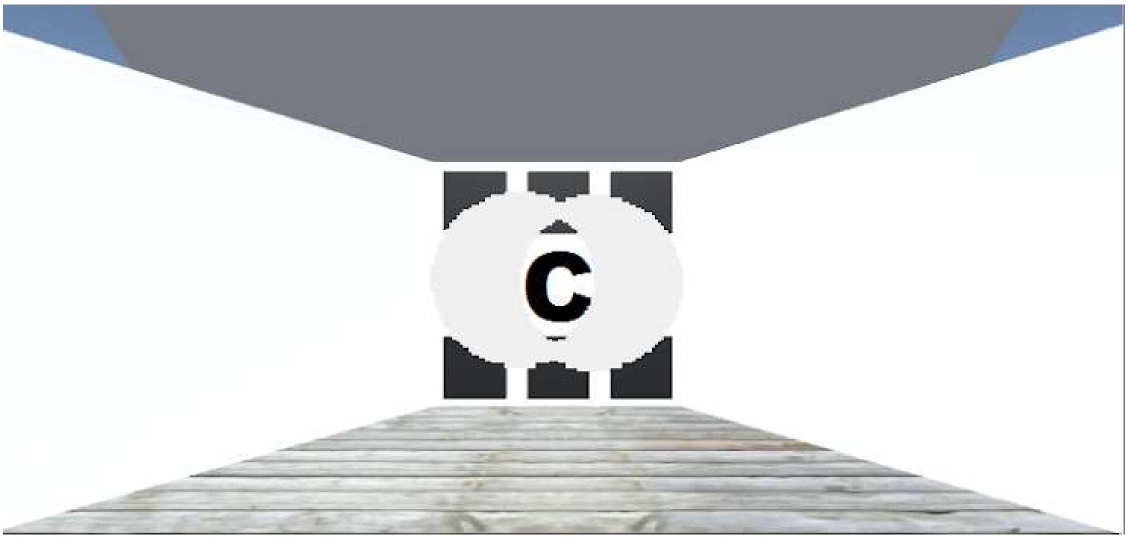
Quão insegura, desanimada, irritada, estressada e aborrecida versus segura, gratificada, satisfeita, relaxada e complacente você se sentiu durante a tarefa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Frustrado	○	○	○	○	○	○	○	○	○	○	Muito Frustrado

Pular para a pergunta 22

Lente Suja



22. Quão mentalmente exigente foi a tarefa? *

Quanta atividade mental e perceptiva foi necessária (por exemplo, pensando, decidindo, calculando, lembrando, olhando, pesquisando, etc)? A tarefa era fácil ou exigente, simples ou complexa, exigente ou indulgente?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

23. Quão fisicamente exigente foi a tarefa? *

Quanta atividade física era necessária (por exemplo, empurrando, puxando, girando, controlando, ativando, etc)? A tarefa era fácil ou exigente, lenta ou rápida, frouxa ou cansativa, repousante ou laboriosa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Exigente	○	○	○	○	○	○	○	○	○	○	Muito Exigente

24. Quanto acelerado foi o ritmo da tarefa? *

Quanto tempo você sentiu pressão devido ao ritmo no qual as tarefas ou os elementos da tarefa ocorreram? O ritmo era lento e vagaroso ou rápido e frenético?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco	○	○	○	○	○	○	○	○	○	○	Muito

25. Quão bem-sucedido você acha que foi ao realizar o que lhe foi pedido? *

Quão bem sucedido você acha que foi em realizar os objetivos da tarefa definida pelo pesquisador (ou por você mesmo)? Quão satisfeito você estava com o seu desempenho no cumprimento desses objetivos?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Bem-Sucedido	○	○	○	○	○	○	○	○	○	○	Mal-Sucedido

26. Quanto esforço você teve que fazer para atingir seu nível de desempenho? *

Quão árduo você teve que trabalhar (mentalmente e fisicamente) para atingir seu nível de desempenho?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Esforço	○	○	○	○	○	○	○	○	○	○	Muito Esforço

27. Quanto frustrado você se sentiu ao realizar as tarefas? *

Quão insegura, desanimada, irritada, estressada e aborrecida versus segura, gratificada, satisfeita, relaxada e complacente você se sentiu durante a tarefa?

Marcar apenas uma oval.

	1	2	3	4	5	6	7	8	9	10	
Pouco Frustrado	○	○	○	○	○	○	○	○	○	○	Muito Frustrado

Considerações Finais

28. Eu tive dificuldade em ajustar o óculos *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Plenamente	○	○	○	○	○	Concordo Plenamente

29. Eu me senti à vontade, como se estivesse vivendo de fato no local virtual onde as tarefas foram realizadas *

Participando de fato naquele lugar e não apenas assistindo a cena em uma tela

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Plenamente	○	○	○	○	○	Concordo Plenamente

30. Sugestão/Opinião sobre os testes realizados