Virtual Visus – Vision Acuity and Text Legibility in Virtual Environments

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Abstract: The display qualities of head-mounted displays (HMDs) have continuously improved in recent years. In this paper, the concept of *virtual visus* is introduced to describe the perceived visual quality of a virtual environment (VE) and relate it to visual acuity in the real world. In a small experiment, the virtual visus is exemplarily measured for one HMD and related to text legibility in VEs. The results show a coherence between virtual visus and minimal text size. The procedure for measuring virtual visus can easily be implemented, and the obtained values can be used to either express vision capabilities in VEs or determine the minimal size of visual elements in VEs.

Keywords: Virtual Environments, Vision, Display Quality

1 Introduction

Simulating reality has always been a major motivation for research regarding fully immersive virtual environments (VEs). The goal of providing multi-sensory input that is not distinguishable from the real world was formulated as the *Ultimate Display* [Sut65] at the beginning of VE research in 1965, and, since then, enormous improvements of computer technology have been made. Today, HMDs are available at affordable prices and VEs are part of our digitized culture. The visual display quality of HMDs has continuously improved over the past three decades. In 1995, the Forte VFX1 used a display with a resolution of 263 x 230 pixels per eye and a horizontal field of view (FOV) of 33.5° [Kuu15]. 15 years later, the then state-of-the-art HMD nVisor SX60 provided a resolution of 1280 x 1024 pixels per eye and a FOV of 60° [BYB18]. Today, in 2021, a number of different HMDs from various manufacturers are commercially available that further increase resolution and FOV (e.g. Valve Index, a typical consumer device of the current generation, which provides 1440 x 1600 pixels per eye and 110° FOV [Val20], and notably Varjo VR-2, which provides a resolution comparable to real-world vision [Var20]). Other factors of visual simulation such as refreshing rate, color depth and latency have also increased significantly. Nevertheless, there are still some improvements to be made until the technology reaches a level where VEs are visually indistinguishable from reality.

Publication	Ref	dmm	degree	arcmin
Dingler er al. (2018)	[DKO18]	**41**	1.8°	**108**
Hoffmann et al. (2019)	[HMK+19]	20	1.2°	**70 (m: 50)**
Solum (2019)	[Sol19]	**23 (m: 16)**	1.32°	79
Büttner et al. (2020)	[BGF20]	**m: 8**	m: 0.5°	m: 28
Kojic et al. (2020)	[KAG+20]	**17**	1.0°	58
Wei et al. (2020)	[WYD20]	**24**	**1.4°**	83

Table 1: Recent publications describing comfortable (or, when stated, minimal 'm') font size in VEs. Measurement unit originally used in publications is highlighted in bold font.

In this paper, the concept of 'virtual visus' is introduced and procedures for measuring that are transferred from real-world vision testing to VEs are presented. Virtual visus is a human-centered approach to describe the ability to perceive small visual details in VEs such as reading text and can be used to express the relation between vision in VEs and real-world vision.

The remainder of this paper structures as follows: Chapter 2 presents related work regarding the display quality and text legibility in VEs. Chapter 3 introduces the term 'virtual visus', which is used to describe visual acuity in VEs in this paper. Chapter 4 describes an exemplary experiment that determines virtual visus and minimal text size with a HMD of the current generation. Finally, we discuss the results in chapter 5 and draw a conclusion in chapter 6.

2 Related Work

Vision acuity has been discussed thoroughly in the academic research regarding digital displays (see for example [HY96, PJH12, DBBD13, DCC16]). A typical visual task within acuity testing is reading a displayed text. As the display technology of HMDs has been been evolved rapidly and a large effect of display resolution on text legibility can be assumed, findings regarding reading in VEs need to be revisited with every new generation of devices. For consumer level HMDs, recent publications offer an estimation of adequate text size (see Tab. 1) but they are not homogeneous regarding procedures, hardware, typefaces, tasks and measurement units. Dingler et al. [DKO18] instructed participants of a study to adjust text parameters to obtain preferred values for character size, contrast, color, distance and text block width. In a similar way, Hofmann et al. [HMK+19] and Kojic et al. [KAG+20] asked participants to change the size of text depending on contrast, text length and HMD to determine values for minimal and comfortable reading sizes. Büttner et al. [BGF20] expanded the concept of adjusting text size to rotated text in a 3D space while Wei et al. [WYD20] and Solum [Sol19] investigated text on curved surfaces. Further, Landolt rings were used in VEs to determine vision acuity in the case of simulating prosthetic vision [CHLS05].

There are three common forms of reporting the perceived angular height of text elements:

Google's unit for text height, dmm (distance-independent mm) [McK17], can be obtained by dividing the element height h (in mm) by the distance d (in m). The angular diameter can be calculated with $\alpha = 2 \cdot atan\left(\frac{h/2}{d}\right)$. This angle can be converted to angular diameter in arc minutes (arcmin) by multiplying it with 60. As most publications use dmm to report findings, we state our results in the same way.

3 Virtual Vision Acuity

Visual perception is one of our primary senses to perceive the real world. For certain professions and activities a normal vision is required. Normal vision is usually defined as the ability to distinguish contours that are separated by one arc minute (circa 0.017°). Several methods exist that determine the vision capabilities of a subject. Typically, the visual acuity can be measured using charts that display certain optotypes such as letters, symbols or figures that are specifically designed for this purpose and provide visually perceptible features at a specific angular resolution, for example Snellen letters, Sloan letters and Landolt rings [BJ16]. There are also several reporting conventions for vision such as Snellen ratio, visus as decimal value and LogMAR (Logarithmic Minimum Angle of Resolution) [BJ16, Uni84], which are convertible and express corresponding visual capabilities. Normal vision can be expressed as 20/20 (Snellen ratio), 1.0 (decimal visus) or 0.0 (LogMAR).

In VEs, no standardized measure exists that is used to describe visual quality in relation to real-world vision. The usual way of stating technical specifications such as resolution and field of view makes it possible to calculate the pixels per horizontal degree (ppd), which can be compared with human vision to obtain a measurement for visual acuity. In theory, a ppd of 60 would be needed to accurately display single pixels for normal vision with one pixel for each arc minute ($=\frac{1}{60}°$). Other HMD display properties that effect the visual perception of a virtual scene such as screen door effect, aberration and distortion of lenses, pixel arrangement, display brightness and contrast as well as screen reaction time are usually not considered in these calculations.

To account for all factors that affect vision acuity, we suggest using 'virtual visus' as a human-centered value to describe the HMD-dependent visual acuity as it is perceived by users. It is related to vision acuity in the real world and utilizes the specified procedures and specifications of measuring real-world visual acuity. These procedures and specifications can be accurately transferred to VEs to obtain a value that expresses the ratio between virtual vision acuity and real-world vision acuity. Virtual visus can be empirically determined by performing a virtual vision test with normal or corrected-to-normal seeing subjects. A value between 0 and 1 expresses a reduced vision compared to the real world normal vision, a value of 1 represents a perfect replication of normal vision, and a value above 1 describes an enhanced vision that exceeds normal vision in the real world. There is no standardized way of determining the virtual visus from empirical data yet, so calculating the arithmetic average of the virtual visus in a virtual vision test that exactly follows the instructions from a real-world vision test allows for a good estimation of the population's average virtual visus

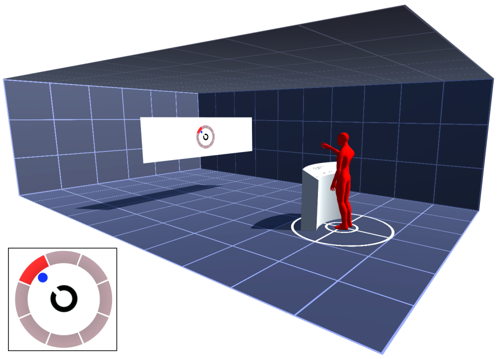

Figure 1: Virtual environment displaying a Landolt ring at visus level 0.02 and a selection circle.

Figure 2: Participants' point of view on text display (24.3 dmm, visus: 0.06).

achieved with a specific HMD. The virtual visus explicitly only measures display quality regarding perceived details, while other visual properties such as latency and framerate are not considered.

4 Evaluation

To evaluate the concept of determining virtual visus and relating it to text legibility, a simple experiment was conducted. In the first step, the virtual visus was determined using Landolt rings and procedures from real-world vision testing. In the second step, text was scaled according to the virtual visus, and the subjective legibility was rated on a 4-point ordinal scale.

4.1 Hardware and Setup

To display the VE, we used Valve Index as HMD, a system that is representative of the latest consumer-level technology. It provides 1440 x 1600 pixels per eye with a FOV of 110° up to 130° [Val20] which yields a ppd (pixels per horizontal degree) of 11.07. One Valve Knuckle controller was used in the participant's dominant hand as input device. Two Lighthouse trackers were mounted on walls to provide a tracking space of approximately 5 x 5 m^2, and a participant was instructed to stand in the middle of the tracking space. A PC with a 2080TI graphics card, an Intel i9 processor and 32 GB of RAM was used to render the virtual scene with a constant frame rate of 120 Hz.

The VE (see Fig. 3) was designed as a simple and neutral virtual room with a width of 6 m, a depth of 10 m and a height of 3 m. To give a simple orientation in the VE, the floor, ceiling and walls were rendered with a 1 x 1 m^2 grid in a desaturated light blue color. The participant's position was marked with a white crosshair symbol on the floor behind a virtual console that displayed control elements in the experiment. A virtual board with a size of 4 x 1 m^2 and with a white background color was placed at a height of 1.5 m with a distance of 4 m to the participant's head along the z-axis and continuously tracked to retain

Figure 3: Typefaces of a Snellen font, Optician Sans and corresponding Landolt ring.

this distance during the study. The scene was rendered using 4x anti-aliasing.

4.2 Participants

13 students (10 male, 3 female) with a background in computer science or design from our university and aged between 21 and 33 (M=28.4, SD=3.8) participated in our study. All participants stated that they had normal or corrected-to-normal vision (5 were wearing glasses or contact lenses, and all had experienced VEs before. No participant was involved in the development of the software or the creation of this research paper. Subjects spent around 5 to 10 minutes to perform the experiment, and no participant aborted it.

4.3 Material and Methods

Before the experiment started, the participants received information about the experiment's motivation, the procedure and the controls needed in the study. They were given enough time to familiarize themselves with the HMD and the controller and to adjust the inter-pupillary distance. The application used in the study was designed to run automatically without further intervention by the experiment's supervisor. The only interaction between participant and supervisor were occasional questions.

To determine the virtual visus in the first step of the experiment, we chose to utilize Landolt rings from the available tools to measure visual acuity as they are easy to implement and evaluate. We closely followed the procedure described in ISO 8596, which is used to determine visual acuity in the real world. For that purpose, printed charts are used that display a selection of Landolt rings at a fixed distance and with certain sizes [Uni84]. In a VE, the size of a Landolt ring s at a distance of d with a visus of v can be precisely calculated using $s = 10 \cdot d \cdot arctan\left(\frac{1}{2 \cdot v} \cdot \frac{1}{60^\circ}\right)$ or, in our case, with d = 4000 mm and values of v in the range of [0.02;1.0], approximated using $s' = \frac{5.82mm}{v}$. To avoid a possible detection of ring gaps by watching the transition between two rings, the display of rings was delayed by 1 second. Starting with a visus level of 0.02 as a test round to ensure that the task and controls were understood, the visus level was gradually increased from 0.1 to 1.0 with a step size of 0.1. For each step, 5 Landolt rings were presented successively with random orientations (3 horizontal or vertical, 2 diagonal) in the center position of the virtual board (see Fig. 3). A circular selection menu around the active Landolt ring was controlled by the participants to indicate the gap of the respective ring. The orientation of a presented Landolt ring was selected by using the joystick of a controller, and pressing the trigger confirmed the selection. When less than 3 Landolt rings were successfully detected or the participant did not feel able to perceive the gap, the first experiment was terminated.

In the second step of the experiment, the legibility of text was examined at visus levels 0.04 and 0.06 and between 0.1 and 1.0 with a step width of 0.1. Optician Sans [ANT20], which is derived from Landolt rings, was chosen as the text typeface as it provided character segments with a constant size and was more legible than Snellen font [Dun20], which had also been considered due to its usage in vision testing. The height of letters h at a visus level v can be approximated with $h = \frac{5.82mm}{v}$. The text was scaled according to h at each level by utilizing signed distance field (SDF) rendering provided by TextMeshPro text rendering in Unity 3D, as suggested by Hoffman et al. [HMK+19].

The text displayed in the experiment consisted of sentences from the iRest dataset [TKD12] in capital letters and in the native language of the participant. The iRest dataset is a collection of texts that are considered to be easy to read and are mainly used to determine reading speed. For each level, a single sentence of a text was extracted and, in some cases, slightly shortened by removing omittable words to provide a length of 12 to 15 words, e.g. (in English) 'EVERY NIGHT, MICE CAME IN DROVES OUT OF THE CELLAR INTO THE SHOP.'. The text blocks had a maximal width of 35 characters to facilitate the perception at a high word count, and the font color was black, displayed on a white background (see Fig. 2).

To rate the subjective legibility, participants used a 4-item ordinal scale with five different virtual buttons on the virtual desk. The buttons were labeled 'bad', 'rather bad', 'rather good' and 'good' as well as 'non legible'. After examining a text at a certain visus level and reading it aloud, the participants selected the label best answering the instruction '*Please rate the legibility of the presented text.*'. The selection was performed by choosing the best fitting label using the controller. All data of the experiment was logged automatically by the computer system.

4.4 Results

Visus	0.02	0.1	0.2	0.3	0.4	0.5	0.6
Diameter (mm)	290	58.2	29.1	19.4	14.5	11.6	9.7
Subjects passed	100%	100%	100%	85%	62%	38%	0%
Detected gaps	5	5	5	4.23	2.77	1.85	0.154
SD (gaps)	0	0	0	1.87	2.35	2.44	0.55
Time per ring	1.4s	1.2s	1.3s	2.2s	5.3s	8.7s	-
SD (time)	0.4s	0.27s	0.31s	0.45s	2.3s	3.1s	-

Table 2: Average count of detected Landolt ring gaps using Valve Index at 4 m distance.

In the first step of the experiment, all 13 participants were able to pass the virtual visus levels 0.02 to 0.2. After visus level 0.2, the number of participants that passed the test decreased continuously and reached 0 % with a visus level of 0.6 (see Tab 2). According to the data from our experiment, the average virtual visus of the Valve Index can be calculated as $(2 \cdot 0.2 + 3 \cdot 0.3 + 3 \cdot 0.4 + 5 \cdot 0.5)/13 = 0.38$ (SD = 0.11, 95% CI: [0.32,0.45]). The average

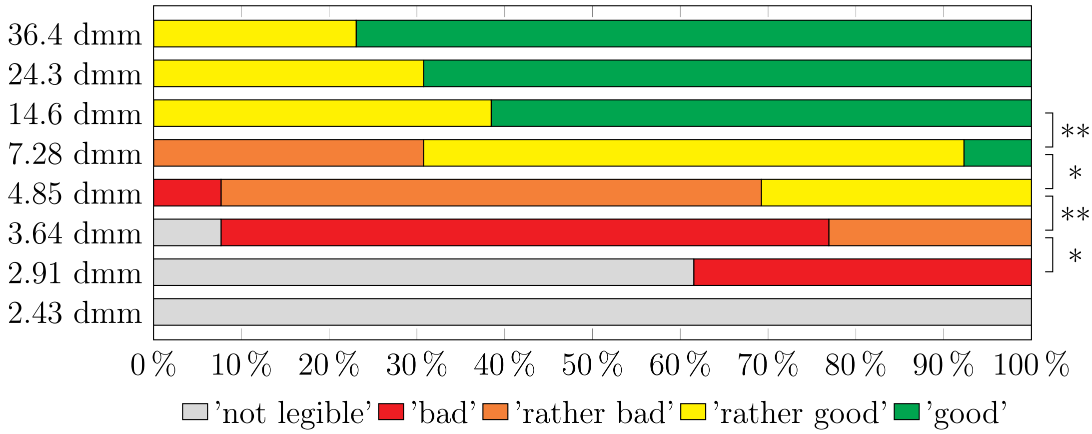

Figure 4: Subjective ratings of text legibility.

time needed to detect gaps increased considerably after visus level 0.2, and we observed that participants showed two strategies to identify the orientation of Landolt rings at difficult levels. One was to constantly move the head, while the other was to adjust the HMD's position on the head with the non-dominant hand.

In the second step of the experiment, a decrease in subjective legibility is visible (see Fig. 4) and a Wilcoxon signed-rank test showed a significant decrease with every level between 14.6 dmm and 2.91 dmm (14.6 dmm vs. 7.28 dmm: $[Z = -2.934, p < .005]$; 7.28 dmm vs. 4.85 dmm: $[Z = -2.073, p < .05]$; 4.85 dmm vs. 3.64 dmm: $[Z = -2.934, p < .005]$; 3.64 dmm vs. 2.91 dmm: $[Z = -2.934, p < .005]$).

5 Discussion

The average **virtual visus** of the Valve Index lies between 0.32 and 0.45 and is therefore lower than 'normal' vision acuity in the real world. The maximal virtual visus is 0.5 (reached by only 5 out of 13 participants), which is still considerably lower than normal vision in the real world. Both the average and the maximal visus contain useful information: While the former states what degree of details can typically be perceived by the population, the latter describes what is possible under perfect conditions considering the sample size is large enough. We suspected to see a sharper fall-off in the data and a clearer boundary value, but the visus was not homogeneous between subjects. Some variation in our data may be explained by not perfectly adjusting the HMD for the study and by individual differences (for example regarding additional glasses worn inside the HMD).

The median ratings of **text legibility** of 'good' and 'rather bad' may be considered to identify a comfortable reading size and an acceptable minimal reading size for VEs. In our experiment, the comfortable reading size ('good') was determined as 14.6 dmm (visus: 0.1), while the minimal ('rather bad') reading size was 4.85 dmm (visus: 0.3). These values are close to other research results in this field (see Tab. 1) even though a comparison is only possible to a limited degree as materials and methods differ considerably.

Additionally, the average virtual visus 0.38 in our experiment seems to be related to a hardly legible text size (median rating: 'bad', 3.64 dmm, visus: 0.4). The values for comfortably and acceptably legible text are slightly lower than values reported in other research publications (see Tab. 1), which can be explained by us letting participants rate the legibility of presented text and reporting the lower bound value instead of letting them choose their preferred parameters and reporting the average. Using our procedure, we can confirm that user vision in VEs is considerably lower than real-world vision, and a character height of 6 dmm (e.g. a book with 2.1 mm letter height at a distance of 35 cm), which is considered a convenient reading size in reality [HY96], is still too small to be displayed with the technology of current HMDs.

The data of our experiment suggests a correlation between virtual visus and legibility of text, but further studies will be required to confirm this. The virtual visus can therefore be used in three different ways: first, for measuring the perception of visual details in VEs, second, for predicting the comfortable size of visual elements in a VE with a known virtual visus, and lastly, to ensure the correct visual perception of a VE by requiring participants to achieve a specific visus level (for example by adjusting the HMD).

We believe that adapting the vision acuity test using Landolt rings to VEs is a good choice to measure virtual visus as it is well-defined, easy to implement and analyze and should yield consistent results. Other vision tests, such as letters or numbers decreasing in size, would also be possible to implement but from our point of view, the use of Landolt rings is well-suited for vision experiments in VEs, and other tasks are much less standardized.

6 Conclusion and Future Work

The term 'virtual visus' introduced in this paper can be used as a measurement for perceived display quality. Empirically determining this value is simple as procedures and specifications from real-world visual acuity measurements can be accurately transferred to VEs. The virtual visus allows for predicting the minimal detectable size of contours, which can assist the design of virtual elements such as text label sizes and texture resolutions in VEs.

In the future, we plan to further investigate different HMDs and compare their virtual visus and text legibility performance to analyze the dependence of virtual visus on the utilized HMD and identify other factors that may affect the virtual visus. To receive more detailed results, the step width of both experiments may be reduced from 0.1 to 0.05 or even 0.02 in the future. Moreover, defining standardized tools and procedures to determine the virtual visus and text legibility may help to compare the results of different studies. Optician Sans (or other sans serif typefaces with constant segment widths such as Arial bold and Verdana) seems a plausible choice for experiments regarding text legibility as the relation between font size and visus is maintained, and using text from a standardized set such as iRest dataset will ensure that there is no negative effect on text reading due to long or difficult words.

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