Effects of Dark Mode Graphics on Visual Acuity and Fatigue with Virtual Reality Head-Mounted Displays

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ABSTRACT

Current virtual reality (VR) head-mounted displays (HMDs) are characterized by a low angular resolution that makes it difficult to make out details, leading to reduced legibility of text and increased visual fatigue. Light-on-dark graphics modes, so-called "dark mode" graphics, are becoming more and more popular over a wide range of display technologies, and have been correlated with increased visual comfort and acuity, specifically when working in low-light environments, which suggests that they might provide significant advantages for VR HMDs.

In this paper, we present a human-subject study investigating the correlations between the *color mode* and the *ambient lighting* with respect to visual acuity and fatigue on VR HMDs. We compare two color schemes, characterized by light letters on a dark background (*dark mode*), or dark letters on a light background (*light mode*), and show that the dark background in dark mode provides a significant advantage in terms of reduced visual fatigue and increased visual acuity in dim virtual environments on current HMDs. Based on our results, we discuss guidelines for user interfaces and applications.

Index Terms: Computer graphics—Graphics systems and interfaces—Virtual reality; Human-centered computing—Interaction paradigms—Virtual reality

1 INTRODUCTION

Researchers in computer graphics and human-computer interaction have for a long time investigated the effects of color and light in user interfaces among a wide range of display technologies, and analyzed their effects and limitations for different types of tasks. Computer displays generally strive to present information with a high signal-to-noise ratio, in particular when presenting text to readers, which emphasizes the importance of strong luminance differences (instead of chromatic differences) between the foreground and background. For instance, this means that text is usually presented as dark letters on a light background (*light mode*) or as light letters on a dark background (*dark mode*) [6, 23, 30, 32]. In particular, dark mode graphical user interfaces are gaining popularity in recent years in that they are characterized by a reversal of the dominant color choices in traditional user interfaces. Normal and inverted color choices were investigated over a wide range of display technologies and environments, and were linked to effects of legibility, aesthetics, energy savings, semantic effects, and emotions [6, 23, 30, 32].

The effects of these color modes depend on the display technology [6], and can affect the legibility of text and/or the visual fatigue caused by viewing details on a computer display. In particular, virtual reality (VR) head-mounted displays (HMDs) differ from traditional screens in that they are characterized by a low angular resolution that makes it difficult and strenuous to read small text. An extenuating factor is that VR HMDs as well as video see-through augmented reality (AR) HMDs are largely based on a flat-panel display design, which leverages a 2D array of individual light-emitting elements laid out on a panel. The slight space between each pixel does not emit light, which thus appears dark. The resulting impression of a dark visual grid is denoted the *screen door effect*, which is characterized by noticeable horizontal, vertical, and/or diagonal lines [10, 12, 40]. Recent advances in consumer HMDs have reduced the noticeability of this effect by increasing the resolution, which reduced the gaps between pixels to below humanly perceivable thresholds. However, while reduced, the effect persists throughout current consumer VR HMDs due to the short distance between the users eyes and the display within the HMD. As shown in Figure 1, the screen door is most noticeable as the contrast between the light emitted from the pixels and the dark grids in between. These factors make VR-HMD displays unique to other display types, which means that the best practices for the display of text may be different for VR-HMDs than for traditional flat-panel displays.

It is our hypothesis that text presented on an HMD using light/dark foreground colors on a dark/light background, can have a significant impact on users' visual acuity and fatigue. In this paper, we discuss and investigate these color schemes as well as the amount of central/peripheral light on an HMD on the example of an Oculus S. We asked participants in a human-subject study to read text in VR with different color modes and to complete visual acuity tests with different lighting conditions. We assessed participants' visual fatigue, acuity, and preferences.

In particular, we investigated the following research questions:

- **RQ1**: Are there subjective or objective benefits of dark mode or light mode color schemes with respect to visual acuity and fatigue?
- **RQ2**: Do users subjectively prefer dark mode or light mode color schemes?
- **RQ3**: Do the subjective preferences match the objective benefits and drawbacks on users' visual acuity and fatigue?
- **RQ4**: Can increased central or peripheral lighting improve visual acuity and fatigue in the presence of different color schemes?

The remainder of this paper is structured as follows: Section 2 presents an overview of related work. Section 3 describes the human-subject study. The results are presented in Section 4 and discussed in Section 5. Section 6 concludes the paper and discusses future research.

2 RELATED WORK

In this section, we present an overview of related work focusing on visual acuity and fatigue in computer displays, text legibility and color modes, as well as the screen door effect in VR.

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2.1 Visual Acuity and Fatigue with Computer Displays

As the types and uses of displays diversify and become ubiquitous, people spend more and more time with different display devices, and various health issues related to the increasing use of displays have stood out consequently. For example, human physiology, cognitive performance, and brain function can be influenced by the lighting from different displays [7, 16, 36, 43]. Among many health concerns with displays, various ocular symptoms are dominant due to the direct visual stimuli on the eyes from the displays, such as eye-strain, tired eyes, and sensitivity to bright lights and eye discomfort, which are referred to as *computer vision syndrome* (CVS) [3, 39]. To identify the cause of such symptoms and reduce them, various recommendations have been made with regard to color and light for the graphical content and the display configurations. Campbell and Durden suggested that individual users should be able to adjust the brightness of the computer devices to select the luminance and contrast depending upon the user's context, such as time in use and the lighting condition in the environment [8]. Recently, automatic color adjustment systems using dark/night mode (or inverted imaging) are actively used to protect the user's eyes and increase the comfort level, e.g., f.lux[1] and Apple's night mode configuration[2].

As immersive VR HMDs become more popular with the growing public interest in VR [45], the perceptual issues and visual fatigue continue and even extend while using such HMDs with near-eye displays embedded [5, 21, 41]. There have been some studies about the effects of different displays on visual fatigue while also investigating the performance on visual acuity, using 3D displays and VR headsets [25, 28]. Kooi and Toet studied the effects of binocular image imperfection on visual fatigue in stereo vision systems, and found that nearly all binocular image asymmetries seriously reduced visual comfort [25]. Lambooij et al. also conducted a user study to identify visual discomfort associated with 3D stereoscopic displays compared to 2D displays, and presented that the participants with moderate binocular status experienced more visual discomfort and showed performance decrease in a reading task [28]. Similarly in AR, which becomes more popular and practical for daily use cases [22], there were a few studies that investigated visual fatigue and acuity influenced by the real background patterns and focal distance [15, 34]. Our focus in this paper is on the effects of color mode on the visual fatigue and acuity in VR. Although there was a study that investigated the dark mode effect in AR [23], there is still a large gap in the literature about the effects of color modes on visual acuity and fatigue with immersive VR HMDs. Recent night mode updates for VR HMDs, such as SteamVR or Oculus[3], also emphasize the timely importance of color mode research in VR.

2.2 Text Legibility in Virtual Reality

In our daily lives, we encounter text to read and write for absorbing information and communicating with others, e.g., which includes reading this present manuscript. Computer displays usually strive to present information with a high signal-to-noise ratio, in particular when presenting text to readers, which emphasizes the benefits of strong luminance differences instead of chromatic differences between the foreground and background. Reading on electronic computer displays often results in different reading outcomes compared to reading on physical paper [17, 18].

In the early age of electronic display technology when cathode-ray tube (CRT) monitors were prevalent, text was typically displayed in light-on-dark color scheme interfaces, i.e., light text on a dark background, because the text on the monitors was displayed by the electron beam hitting the phosphorous material for luminescence that is normally dark in its natural state. However, as the dark-on-light color scheme, i.e., dark text on a light background, was introduced in WYSIWYG editing systems to simulate ink on paper in the real world, it has been dominant in many computer user interfaces. Presenting dark text on a light background is usually referred to as *positive contrast*, which goes back to the signal processing theory, where the peak-to-peak contrast (or Michelson contrast [35]) measures the ratio between the spread and the sum of two luminances. This ratio is defined as $c = \frac{L_b - L_t}{L_b + L_t}$ with text luminance L_t and background luminance L_b, which is negative if $L_b < L_t$. While both positive and negative contrast conditions can provide the same theoretical peak-to-peak contrast ratio, a large body of literature focused on identifying benefits of one of them over the other for different display technologies and use cases.

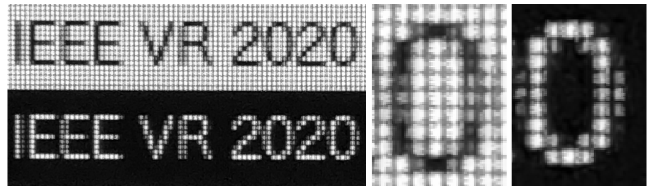


Figure 1: Illustration of the *light mode* (top) and *dark mode* (bottom) color schemes on virtual reality head-mounted displays. The dark grid indicates the *screen door effect* in VR HMDs, which affects the signal-to-noise ratio of the foreground light/dark text on a dark/light background.

Multiple studies have found that *positive contrast* has benefits when the goal is to read text on computer screens [1, 9, 44]. Trying to understand this effect, Taptagaporn and Saito observed that participants developed a smaller *pupil diameter* when they used a positive contrast display compared to a negative contrast display [42]. A small pupil diameter is known to increase the quality of the retinal image with greater depth of field and less spherical aberration, and it is largely affected by the amount of light reaching the observer's eyes. Buchner et al. investigated the display luminance in positive and negative contrast modes, showing that it is usually *higher* in positive contrast modes, e.g., when dark text is presented on a light background [6], which can be traced back to the ratio of screen space filled by (dark) letters or the (light) background.

While text is important for conveying information to users in a virtual world, e.g., when mimicking the real world, there is a dearth of research on the effects of color mode on visual acuity and fatigue in immersive VR HMDs, specifically with respect to text-based annotations. In VR/AR, the virtual content with text can spatially float around the user's environment, and the legibility of the content can vary dynamically depending on the distance and the (real/virtual) environmental conditions between the user and the content. For example, Lages et al. presented adaptive AR workspaces using virtual interfaces with text, which adaptively change its position and orientation while the user was walking [27]. In such VR/AR applications and interfaces for text annotation and visualization [29, 33], the color modes by which text are presented to users are an important research direction for making such applications more usable and effective.

2.3 Screen Door Effect and Lighting

As mentioned in the introduction, the screen door effect is caused by a dark grid in between light-emitting pixels on a flat-panel display. This results in the user observing a visual phenomenon similar to looking through a fine screen, such as a mosquito net or pool enclosure, which may reduce visual acuity (see Figure 1). There has been some effort in the past aimed at reducing the screen door effect. Sitter et al. describe one such technique, which involves adding a diffractive film onto the outer layer of the display [40].

[1] f.lux, a cross-platform software that adjusts a display's color temperature accordingly (`https://justgetflux.com/`)

[2] Apple, "How to Use Dark Mode on your Mac" (`https://support.apple.com/en-us/HT208976`).

[3] Quest, Go, and Gear VR build 8.0 release notes (2019-08-19) - Night mode added (`https://support.oculus.com/release-notes/`)

This film causes a diffraction to occur for each pixel on the display that spreads the light of the pixel outward into the surrounding black matrix. Their technique reduces the screen door effect while keeping comparable brightness and color uniformity.

As the near-eye displays in VR HMDs are so close to the users' eyes, intense virtual lighting can easily cause a smaller pupil size [46], which in turn may cause a sharper view of the content presented on the display. While increasing the amount of light emitted by pixels on a VR HMD may increase visual acuity due to a reduced pupil size, it may also exacerbate the screen door effect and make the dark regions between the pixels more noticeable, which may reduce visual acuity. However, an alternative method that can increase the amount of light reaching the user's eyes would be to add light in the periphery of the display, as proposed by Jones et al. [20] and Lubos et al. [31]. Using a ring of light-emitting diodes (LEDs) in the periphery of the HMD, these approaches can reduce the user's pupil size without causing additional issues with the screen door effect. Jones et al. [20] further showed that such peripheral light can significantly improve distance estimation in VR. Given the technical challenges in modifying HMDs with such peripheral LEDs, and the fact that modern VR HMDs already provide a reasonably large field of view, a purely software-based solution is to leverage the perimeter of the display, i.e., the outer frame of pixels on the HMD, to induce perimeter/peripheral light, which could mitigate the negative effects in the perception of virtual content, such as the aforementioned visual fatigue and acuity.

3 Experiment

In this section we present a user study in which we evaluate the impacts of color mode, perimeter lighting, and virtual lighting on users' visual acuity, visual fatigue, and preferences.

3.1 Participants

After initial pilot tests, we estimated the effect size of the expected strong effects, and based on a power analysis, we made the decision to recruit 18 participants, which proved sufficient to show significant effects in our experiment. We recruited a total of 15 male and 3 female participants (ages between 19 and 35, $M = 24.5$, $SD = 4.8$). Eligible for participation in the experiment were only healthy people who did not have any cognitive or motor impairments. All of our participants had normal or corrected-to-normal vision. Seven wore glasses and four wore contact lenses during the experiment. None of the participants reported known visual or vestibular disorders, such as color or night blindness, dyschromatopsia, or a displacement of balance. The participants were student or non-student members of the local university community, who responded to open calls for participation, and received monetary compensation for their participation. All participants had used a VR HMD before.

3.2 Material

In this section, we describe the material used for our experiment.

3.2.1 Physical Setup

Figure 2 shows a photo of a participant in the study. Participants were seated in an office chair and were instructed to wear an Oculus Rift S VR HMD. The HMD was tracked in position and orientation using a the built in inside-out tracking, where position and orientation updates are handled internally by the HMD through the use of cameras placed on the device. The HMD has a resolution of 1280×1440 pixels per eye for a total resolution of 2560×1440 and a refresh rate of 80 Hz. The virtual environment was rendered in Unity 2018.2.21f1 on a host PC tethered to the HMD (Intel Core i7-8700k @ 3.70 GHz, 32Gb Ram, NVIDIA GTX 1070Ti graphics card, Windows 10 Pro).

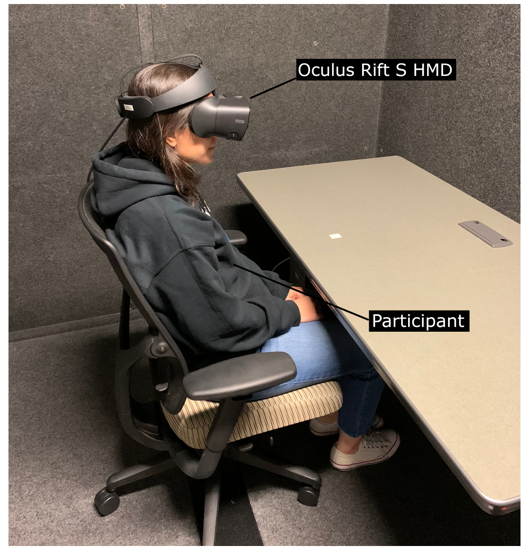


Figure 2: Annotated photo showing a participant in the study with the HMD seated at the table.

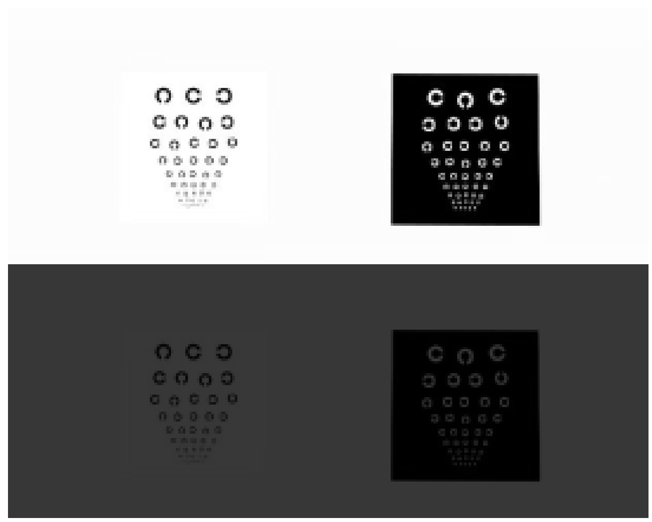


Figure 3: Illustrations of visual stimuli used in the experiment. Top-left: light mode in bright environment. Top-right: dark mode in bright environment. Bottom-left: light mode in dim environment. Bottom-Right: dark mode in dim environment.

3.2.2 Virtual Environment

The visual stimuli consisted of a virtual room in which the participant was placed near a wall facing a floating panel that contained text relevant to the conditions being displayed to them. Figure 3 shows the virtual content that we used for the tasks in the study.

The *floating panel* was designed to match realistic lighting conditions such that a diffuse white background would appear white in bright virtual lighting, but would appear gray in dim virtual lighting. It also meant that a diffuse black background would remain black independent of the amount of virtual light. The virtual lighting in the experiment could be adjusted to *bright* or *dim* by varying the intensity of a virtual point light located above the participant's head in the Unity scene. Bright in this case means that white pixels on the display were drawn at an RGB value of $(1,1,1)$, and dim means that environment lighting was reduced by 90% so white pixels on the display appeared at an RGB value of $(0.1,0.1,0.1)$.

It is important to note that the RGB values described above only describe the colors specified to the unity engine and are not indicative of the actual amount of light that was displayed from the Oculus S

HMD. The apparent contrast between black and white pixels on a display will vary across different HMDs and displays depending on the contrast ratio of the device as well as parameters associated with the display hardware.

Separate from the amount of ambient light in the virtual environment, we also implemented a *perimeter lighting mode* in which bright light originated from a ring of the out-most pixels at the perimeter of the HMD screen. This lighting mode was inspired by previous work by Jones et al. [20], who found that light reaching a VR user's eyes from the far periphery can affect (improve) spatial perception. The ring was scaled to take up 348 pixels or 13.6 percent of the total width of the display and 338 pixels or 23.4 percent of the total height of the display. These values were chosen based on pilot testing which suggested that lesser values were not noticeable to some users.

3.2.3 Task Stimuli

We implemented a *visual acuity test* that incorporated tumbling Landolt C characters, which could be oriented normally or at 90 degrees incremental rotations, so that the opening on the 'C' character could face up, down, left, or right [11]. These characters were randomly generated each time a chart was displayed, and by using this tumbling 'C' format, all acuity tests were of comparable difficulty to one another. The Landolt C characters were chosen in favor of a traditional Snellen variety acuity chart in order to avoid the possibility of having differing degrees of difficulty between same sized letters between participants. While a Snellen variety chart would have been possible, it would have required careful design to ensure that the charts used in each condition were similar in difficulty to each other to avoid potentially biasing a subset of conditions. The acuity chart was positioned at a distance of 1.52 meters (5 feet) away from the user, and at the eye level of the user. This distance was chosen because the letter sizes on our custom acuity chart were modeled after an acuity chart that was designed to be read specifically from this distance.

We further implemented a *reading task*, which consisted of four paragraphs from the Pearson Test of English Read Aloud Practice Questions, which were presented in the Liberation Sans font. This task was chosen to allow a standard time for the user to be exposed to the condition lighting and potentially induce visual fatigue prior to reading the acuity chart. These paragraphs were displayed to the participant during each condition at the same depth as the acuity chart (1.52 meters) and at a consistent field of view between all conditions as a means of evaluating the amount of eye strain induced and the readability of text in each condition.

3.3 Methods

The study used a $2 \times 2 \times 2$ full-factorial within subjects design in which each participant experienced all eight of the different conditions, and the conditions were counterbalanced among participants through the use of a Latin square. The evaluated independent variables were:

- **Color Mode**: *light mode* graphics consisting of black text on a white background or *dark mode* graphics consisting of white text on a black background.
- **Virtual Lighting**: *bright* or *dim* ambient lighting in the virtual environment.
- **Perimeter Lighting**: *enabled* or *disabled* perimeter lighting.

3.3.1 Procedure

To begin the study, participants were led into the laboratory and were asked to read over a consent form describing what would take place during the experiment. After giving consent, the participants were asked to complete two questionnaires: one which gathered demographic information, and an Ocular Surface Disease Index

Figure 4: Illustrations depicting the VR text-reading task participants had to perform during the experiment. Top-Left: Light mode in bright environment. Top-Right: Dark mode in bright environment. Bottom-Left: Light mode in dim environment. Bottom-Right: Dark mode in dim environment.

(OSDI) survey that gathered information about the current level of comfort of the participant's eyes [37].

For each of the eight conditions, participants were then asked to don the HMD and observe a virtual panel consisting of four short paragraphs of text which they would read non-verbally to themselves (see Figure 4). After one minute of observation, the paragraphs would disappear and be replaced with a visual acuity chart consisting of Landolt C characters rotated at 90 degree increments [11] (see Figure 3). The participants would then read through the chart until they reached the bottom or the characters were too difficult for them to distinguish. We measured the number of errors participants made when reading the letters, the maximum row that participants could read without errors, as well as the time it took them to complete the task. Following the completion of the acuity test, the participant would take off the HMD and complete two short questionnaires: a Short User Experience Questionnaire (UEQ-S) that gathered information on the usability of the graphics interface under the testing conditions [38], and a Convergence Insufficiency Symptom Survey (CISS) questionnaire that gathered information on any eye strain noted by the participant during the condition [4]. Immediately after completing the questionnaires, participants were instructed to re-don the HMD and continue onto the next condition with no additional time to rest.

After completion of all eight conditions, participants were asked to don the HMD one final time to measure their subjective preference of the different conditions as well as which conditions they found to be easiest to read.

Specifically, we asked them to indicate their preference of *color mode* (dark mode or light mode) on four questions:

1. **Preference**: Which condition do you prefer?
2. **Comfort**: Which condition was more comfortable?
3. **Easy to read**: Which condition was easier to read?
4. **Performance**: Which condition do you think you performed better, e.g., fast and accurate reading?

We further asked them to indicate their preference of *perimeter lighting* being enabled or disabled.

3.4 Hypotheses

Inspired by the body of literature on vision modes, most notably recent work by Kim et al. [23], we defined the following hypotheses.

- **H1a (Virtual Lighting Affects Visual Acuity):** Participants will make fewer errors on their visual acuity test with bright virtual lighting than dim virtual lighting.
- **H1b (Virtual Lighting Affects Eye Strain):** Participants will experience less eye strain in dim virtual lighting conditions than they will in bright virtual lighting conditions.
- **H2a (Color Mode Affects Visual Acuity):** Participants will make fewer errors on their visual acuity test in the dark mode condition than in the light mode condition.
- **H2b (Color Mode Affects Eye Strain):** Participants will experience less eye strain when experiencing the dark mode than the light mode.
- **H3a (Perimeter Lighting Affects Visual Acuity):** Participants will make fewer errors on their visual acuity test while experiencing the perimeter lighting than they will without perimeter lighting.
- **H3b (Perimeter Lighting Affects Eye Strain):** Participants will experience more eye strain in conditions with perimeter lighting than they will in conditions without it.
- **H4 (Subjective Preference of Color Mode):** Users will prefer the dark mode over the light mode.

4 RESULTS

In this section we present the analysis and results of our experiment. We used parametric statistical tests to analyze the responses in line with the ongoing discussion in the field of psychology indicating that parametric statistics can be a valid and informative method for the analysis of combined experimental questionnaire scales with individual ordinal data points measured by questionnaires or coded behaviors [24, 26]. We analyzed the responses with repeated-measures ANOVAs and Tukey multiple comparisons with Bonferroni correction at the 5% significance level. We confirmed the normality with Shapiro-Wilk tests at the 5% level and QQ plots. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated. We had to remove two questionnaire data sets from the analysis due to incomplete responses by our participants. We only report the significant effects.

4.1 Visual Acuity

Figure 5 shows the results for the visual acuity tests.

In line with Hypothesis **H1a**, we found that users made fewer errors and could complete more rows without errors on the visual acuity charts if **virtual lighting** was bright instead of dim, while it took participants longer to complete the tasks. We found a significant main effect of virtual lighting on the number of errors made by participants on the visual acuity chart, $F(1,17) = 72.33$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.81$, indicating that bright lighting resulted in fewer errors than dim lighting. We also found a significant main effect of virtual lighting on the maximum row without errors on the visual acuity chart, $F(1,17) = 32.12$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.65$, which indicates that more rows could be completed with bright lighting than dim lighting. Further, we found a significant main effect of virtual lighting on the time spent on the visual acuity chart, $F(1,17) = 4.54$, $\boldsymbol{p = 0.048}$, $\eta_p^2 = 0.21$, indicating that it took participants longer to complete the charts under bright lighting than under dim lighting.

Contrary to Hypothesis **H3a**, our results did not show any significant effects of the **perimeter lighting** on the participants' errors, maximum rows, or time when completing the visual acuity charts. As we are not seeing significant benefits of perimeter lighting, we are focusing on the results for color modes without perimeter lighting in the following. We further found a significant interaction effect between virtual lighting and color mode on the number of errors, $F(1,17) = 13.99$, $\boldsymbol{p = 0.002}$, $\eta_p^2 = 0.45$, and on the maximum row without errors, $F(1,17) = 9.43$, $\boldsymbol{p = 0.007}$, $\eta_p^2 = 0.36$, so we present the corresponding significant effects in the following. We found no significant effects on time.

In line with Hypothesis **H2a**, without perimeter lighting, we found significant effects of the **color mode** on the results. However, interestingly, the results show the opposite effect depending on the virtual lighting:

For *bright* environments, we found a significant effect of the color mode on the number of errors participants made when reading the visual acuity chart, $F(1,17) = 9.15$, $\boldsymbol{p = 0.008}$, $\eta_p^2 = 0.35$, indicating fewer errors for the light mode over the dark mode. We also found a non-significant trend between the color mode and the maximum row that a participant could reach without making any errors, $F(1,17) = 3.28$, $\boldsymbol{p = 0.088}$, $\eta_p^2 = 0.16$, suggesting that more rows may be completed with the light mode than the dark mode.

For *dim* environments, we found a significant effect of the color mode on the number of errors participants made when reading the visual acuity chart, $F(1,17) = 4.91$, $\boldsymbol{p = 0.041}$, $\eta_p^2 = 0.22$, indicating fewer errors for the dark mode over the light mode. We also found a significant effect of the color mode on the maximum row that a participant could reach without making any errors, $F(1,17) = 5.28$, $\boldsymbol{p = 0.035}$, $\eta_p^2 = 0.24$, indicating that more rows could be completed with the dark mode than the light mode.

4.2 Visual Fatigue

Figure 6 shows the visual fatigue results for the CISS questionnaire.

In line with Hypothesis **H2b**, we found a significant main effect of **color mode** on the visual fatigue scores, $F(1,15) = 8.10$, $\boldsymbol{p = 0.014}$, $\eta_p^2 = 0.34$, indicating lower visual fatigue for the dark mode compared to the light mode. Interestingly, this result is independent of the virtual lighting and applies to both bright and dim environments (see results for visual acuity).

Contrary to Hypothesis **H3b**, our results did not show any significant effects of the **perimeter lighting** on the visual fatigue scores. As we are not seeing significant benefits of perimeter lighting, we are focusing on the results without perimeter lighting in the following.

In line with Hypothesis **H1b**, without perimeter lighting, we found a significant effect of **virtual lighting** on the visual fatigue scores, $F(1,15) = 5.17$, $\boldsymbol{p = 0.038}$, $\eta_p^2 = 0.26$, indicating higher visual fatigue for the bright environment compared to the dim environment.

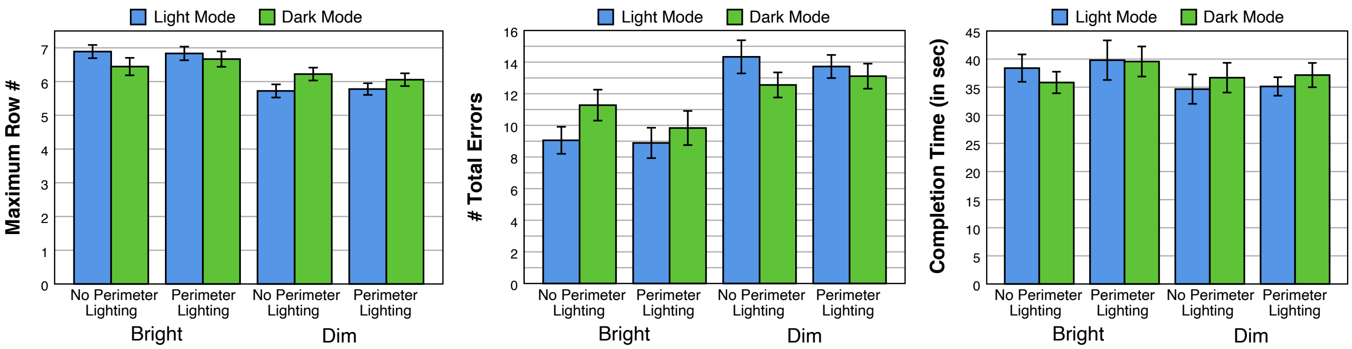
4.3 Usability

Figure 7 shows the usability results for the UEQ-S questionnaire, in which users rated various aspects of the condition using a seven point scale [38]. We found no significant effects of virtual lighting, perimeter lighting, or color mode on the usability results.

4.4 Subjective Preferences

Figure 8 shows the participants' preferences of the dark mode for all conditions in the experiment.

We performed a two-tailed binomial test analysis on the subjective preference data with a test value of 0.5 and a confidence interval of 95%, where users responded to questions about their preference of color mode between either dark mode or light mode under each of the study conditions. Users were specifically asked which color mode they preferred, which was more comfortable, and which was easier to read. We found a non-significant trend in the number of participants who preferred the dark mode when trying to read in a dim virtual environment with perimeter lighting turned on ($\boldsymbol{p = 0.096}$, $Proportion = 0.722$) and turned off ($\boldsymbol{p = 0.096}$,



(a) (b) (c)

Figure 5: Results for the *visual acuity* tests: (a) maximum row on the acuity chart that could be completed without errors (between 0 and 9; higher is better), (b) total number of errors on acuity chart (lower is better), and (c) completion time for the acuity chart (lower is better).

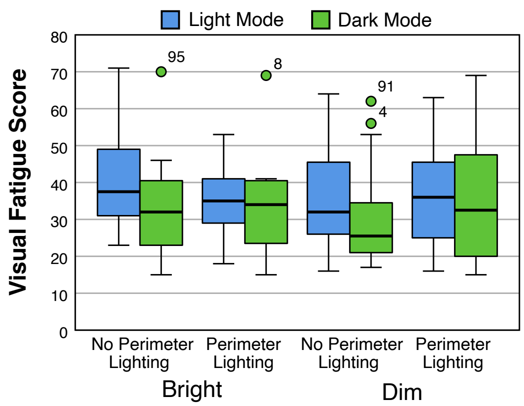


Figure 6: Results for the *visual fatigue* questionnaire (CISS): overall fatigue scores (lower is better).

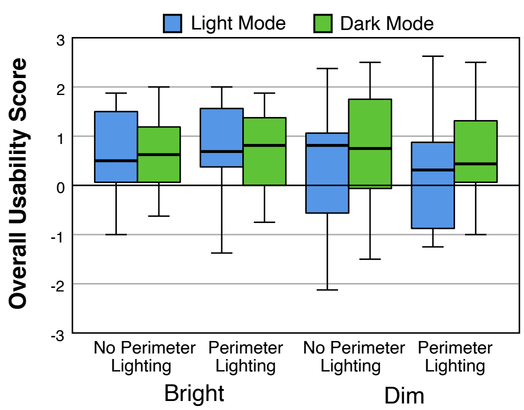


Figure 7: Results for the *usability* questionnaire (UEQ-S): overall usability scores (higher is better).

$Proportion = 0.722$). We also found a non-significant trend in the number of participants who preferred the dark mode as more visually comfortable in dim lighting conditions with perimeter lighting turned off ($\boldsymbol{p = 0.096}$, $Proportion = 0.722$). We also found that a significant number of participants preferred having perimeter lighting turned off as opposed to turned on ($\boldsymbol{p = 0.008}$, $Proportion = 0.833$).

5 Discussion

In this section, we discuss the main findings and their implications for VR HMDs.

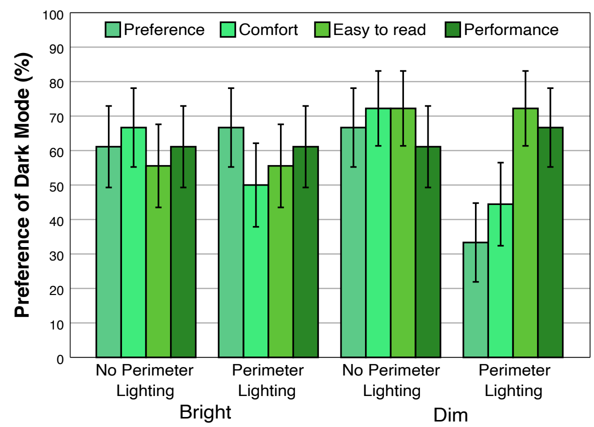


Figure 8: Subjective results in percent of participants who preferred the dark mode in the different experimental conditions.

5.1 Dark Mode Improves Visual Acuity Only in Dim Lighting Conditions

Our results shown in Section 4.1 indicate that the *dark mode* improves the visual acuity of the user in dim lighting conditions on VR HMDs, effectively making it easier for users to identify Landolt C characters or make out small visual details. Conversely, the *light mode* improves the visual acuity of the user in bright virtual environments.

This result stands in partial contrast to the results of prior work by Kim et al., who investigated dark mode user interfaces in AR optical see-through HMDs and found that the dark mode yielded better visual acuity regardless of lighting conditions [23]. It stands to reason that the difference in the display's light model, in particular the *additive light model* [14] of current optical see-through displays as well as the *screen door effect* that is prevalent in current immersive HMDs have a strong effect on the results.

In VR HMDs, the screen door effect is very prominent when pixels on the display are illuminated with bright light, and is more obscured from view when pixels are darker (see Figure 1). However, even in the presence of an increased screen door effect in bright virtual environments, we found a significant main effect that the user's visual acuity under bright lighting is significantly higher than under dim lighting. This result matches previous work, which indicates that increasing the amount of light reaching the user's eyes will reduce their *pupil diameter*, which in turn is known to increase the quality of the retinal image with greater depth of field and less spherical aberration [42]. It is interesting to see that the positive effects of the increased light out-weighted the negative effects of the increased screen door effect in VR HMDs.

As shown in Figure 1, with the *dark mode*, the screen door effect is primarily hidden from view in the dark background but does appear directly over the foreground letters. In contrast, in the *light mode*, the screen door effect is clearly noticeable in the light background but is more obscured in the foreground letters. One's first intuition may suggest that having the screen door effect over the letters and not the background would make them more difficult to see, but our results suggest that this only occurs in bright lighting conditions and that the opposite occurs in dim lighting conditions.

It is further interesting to note that the aforementioned study by Kim et al. incorporated a *lighting-independent text mode* (as used in AR heads-up displays) for the visual acuity charts that were displayed to the users, meaning that the light/dark RGB color values on the chart were constant and were not affected by virtual lighting in the AR environment [23]. In contrast, our study took place in VR as opposed to AR, where the RGB color values of text in the virtual environment were affected by changes in the amount of virtual light, denoted as a *lighting-dependent text mode*. Because of this, when the virtual lighting is bright, white text appears as RGB value $(1,1,1)$ and black text as $(0,0,0)$. However, as the virtual lighting dims, the white text darkens to a value between $(1,1,1)$ and $(0,0,0)$, while black text remains black $(0,0,0)$ and unaffected by the amount of virtual light. A decrease in virtual light thus reduces the visual contrast between the light colors and dark colors and the signal-to-noise ratio between the foreground text and its background, which is known to reduce the visual acuity [19].

Our results indicate that it is advantageous to use the *light mode* under bright virtual lighting, but when the contrast between letters and their background is reduced due to dim virtual lighting, then it is advantageous to switch to the *dark mode*. We believe that this is partially due to a *color bleeding effect* that occurs when a light colored letter is presented on a dark background, where the light from the letter partially illuminates neighboring background pixels and results in a letter that appears slightly larger [13]. It stands to reason that the magnitude of this effect is affected by virtual lighting paired with the nature of the letter identification task. In our study, participants were asked to identify Landolt C characters on the visual acuity chart, and if the magnitude of the color bleeding effect was too significant (in the case of bright virtual lighting) then it is possible that while the letters did appear slightly larger, the opening on the 'C' is reduced to appear more as an 'O,' and thus the direction of the opening is more difficult to distinguish. In the case of dim lighting conditions, the characters still appear slightly larger, but the magnitude of the color bleeding effect is not as strong as in the bright lighting condition, resulting in an opening on the 'C' that is easier to distinguish than for the light mode.

If this color bleeding effect is responsible for the results obtained here, then it is possible that different results may be obtained from a similar future study where the pixel density of the VR HMD is increased. This increased pixel density may result in less of a color bleeding effect around the perimeter of the letters, which means that letters will appear slightly smaller on the high-density display and thus be more difficult to read. However, there is a trade-off to this reduced color bleeding effect as the openings in letters will be easier to identify than when this effect is more apparent, which should make letters with similar features such as 'C,' 'E,' and 'O' easier to distinguish from one another.

5.2 Dark Mode Decreases Visual Fatigue

As shown in Section 4.2, our results show that the *dark mode* resulted in significantly lower visual fatigue (CISS) scores than the *light mode*, which suggests that the dark mode causes less eye strain than the light mode. This result was also observed by Kim et al. for AR optical see-through HMDs [23]. Further, in line with related work in the field, we also found that increasing the amount of (virtual) lighting caused more eye fatigue than our tested dim lighting condition [2]. For the least amount of visual fatigue in VR HMDs, our guideline is to dim the amount of virtual lighting and make use of the dark mode when presenting text or other visual details.

5.3 Preference of Dark Mode over Light Mode

As shown in Section 4.4, the majority of participants responded with a preference of the dark mode over the light mode, although this was only a non-significant statistical trend and further research would be required to come to a more general conclusion. Both color modes offer benefits to the users' visual acuity depending on the virtual lighting of the scene. A slight shift in preference for the dark mode might stem from perceived benefits due to reduced visual fatigue. It is possible that the preferences would have become clearer in favor of the dark mode after a longer VR exposure.

5.4 Perimeter Lighting Showed no Significant Effects

As shown in Section 4.4, our results indicate that the majority of participants preferred the *perimeter lighting* to be turned *off*. We also found no significant effects of perimeter lighting on visual acuity, visual fatigue, or usability. We were surprised to not see clear benefits of the perimeter lighting on the results as the relevant literature suggested that a decrease in pupil size due to added light should improve the retinal image due to greater depth of field and reduced spherical aberration [42]. In theory, it should not matter whether the light that is affecting the user's pupil size originates in the center or the periphery/perimeter of the display.

Some of our participants commented on the perimeter lighting, e.g., stating that turning the perimeter light on *felt* like the rest of the virtual environment was getting darker. Another mentioned that they felt as though a dark gradient was placed over the center of the screen when the perimeter lighting was on.

For future work in this direction, we suggest looking into far-periphery lighting (instead of perimeter lighting) as used by Jones et al. [20] or Lubos et al. [31], who added an LED strip around the screen in the periphery of a VR HMD. We expect that an increased amount of peripheral light might result in benefits for visual acuity in VR, although we also see potential drawbacks due to increased visual fatigue.

6 Conclusion and Future Work

In this paper, we presented a human-subject study in which we investigated the effects of the color mode (dark mode or light mode), perimeter lighting, and virtual lighting on visual acuity, visual fatigue, usability, and preferences when reading text and completing a visual acuity test in VR. Among other results, we showed unique benefits of the *dark mode* under dim lighting conditions on visual acuity and fatigue, of the *light mode* under bright lighting conditions on visual acuity, as well as increased visual acuity and fatigue under bright virtual lighting. Our results may serve as guidelines for practitioners in the design and implementation of VR user interfaces that require high legibility and/or reduced visual fatigue.

Its important to note that the results and conclusions obtained from the described study above cannot be generalized to other head-mounted displays due to differences in parameters associated with the built-in display, such as contrast ratio and luminance. Because our group did not have the equipment necessary to perform such measurements at this time, future work should investigate other head-mounted displays and take measurements of such parameters so that their impact on user visual acuity and eye strain can be further evaluated.

As the resolution of VR displays increases, future work should investigate how the resolution and intentional color bleeding effects as in the PlayStationVR may impact visual acuity and fatigue in the presence of different color modes and lighting. Future studies may also find further advantages and disadvantages in the use of perimeter lighting to provide benefits to the user such as increased visual acuity.

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