Towards Eye-Friendly VR: How Bright Should It Be?

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Abstract

Visual information plays an important part in the perception of the world around us. Recently, head-mounted displays (HMD) came to the consumer market and became a part of everyday life of thousands of people. Like with the desktop screens or hand-held devices before, the public is concerned with the possible health consequences of the prolonged usage and question the adequacy of the default settings. It has been shown that the brightness and contrast of a display should be adjusted to match the external light to decrease eye strain and other symptoms. Currently, there is a noticeable mismatch in brightness between the screen and dark background of an HMD that might cause eye strain, insomnia, and other unpleasant symptoms.

In this paper, we explore the possibility to significantly lower the screen brightness in the HMD and successfully compensate for the loss of the visual information on a dimmed screen. We designed a user study to explore the connection between the screen brightness in HMD and task performance, cybersickness, users' comfort, and preferences. We have tested three levels of brightness: the default Full Brightness, the optional Night Mode and a significantly lower brightness with original content and compensated content. Our results suggest that although users still prefer the brighter setting, the HMDs can be successfully used with significantly lower screen brightness, especially if the low screen brightness is compensated.

Index Terms: Human-centered computing—User studies; Human-centered computing—Virtual reality; Computing methodologies—Perception;

1 Introduction

Visual information plays an important part in the perception of the world around us. Virtual reality (VR) technology enables us to see things that do and do not really exist. VR is heavily relying on visual feedback in creation of the virtual world. The recent explosive development of various head-mounted displays (HMDs) started a new era of VR and finally brought the synthetic experiences to the consumer market. Like television and smart devices previously, VR headsets are on the way to be integrated in our everyday life.

Recently, the majority of HMD manufacturers eliminated the possibilities for users to regulate the screen brightness levels. While previously, it was possible to manually control the brightness of HTC Vive, as well as hue and contrast, via the video card driver software. Consequently, the brightness levels now are dependent on manufacturer's decisions and partially on content creators. Multiple users reported that brightness levels of their HMDs seem to be too high [11, 24, 27, 32]. That in turn is likely to cause computer vision syndrome, eye strain and other inconveniences during long-term use, such as insomnia.

Similar decisions had to be made previously by the manufacturers of hand-held devices. Nowadays, most smartphones and tablets

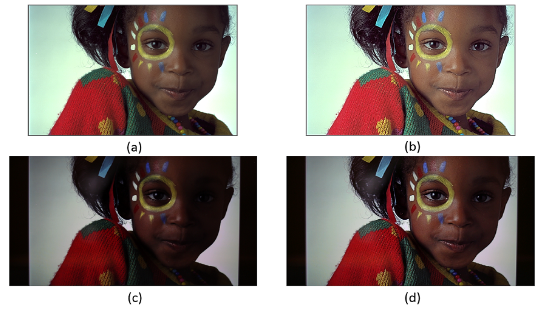

Figure 1: The image perception changes depending on the ambient light and screen brightness. (a) - the original image at full screen brightness in daylight. (c) - same image with minimum screen brightness under 0 lux of ambient light - many details are lost; (b) - image compensated for the low brightness on full brightness screen in daylight - contrast is very high and the colors seem too saturated; (d) - compensated image seems comparable to the original at minimal screen brightness and no ambient light. Image courtesy of Eastman Kodak Company.

have auto-brightness, night and reading modes, which adjust the screen brightness, features and background balance based on the environmental illuminance captured by an ambient light sensor. Yet, many manufacturers tend to opt for the higher default brightness in HMDs preferring the vibrant colors for a more impressive experience, leaving the duration of an exposure and eye care to users' discretion.

Like its predecessors, VR brings not only joy, but also concerns regarding health and wellbeing, especially after extensive use. Today, users are aware of disruptive effect of blue light on their visual and neural systems as well as negative effects of the use of various screens in the dark, especially before bed time. It has been shown that the brightness and contrast of a display should be adjusted to match the external light to decrease eye strain and other symptoms of computer vision syndrome [3]. In the dark setting, dimmed screens are healthier as the eyes can avoid the taxing phase of readjustment from bright to dark and vice versa. Unfortunately, dimmed screen also becomes less visible as human visual perception depends on the ambient light conditions. Figure 1 (a and c) shows an image that is perceived very differently with and without the ambient light with corresponding screen brightness settings. The loss of information due to the low screen brightness needs compensation Figure 1 (b and d).

An HMD might be considered as a big display placed close to the user in a room with all lights off, making it more similar to the movie theater than a hand-held screen. The Society of Motion Picture and Television Engineers (SMPTE) in their standard for the indoor theaters recommended to consider the specifics of mesopic (partially adapted to darkness) vision during screen luminance and color representation evaluations. That originated from the fact that the average screen brightness is in fact rather low ($5cd/m^2$) and the rest of the theater is even darker, but the viewers perceive the screen as bright. Yet, to our best knowledge, there is no standard that requires and describes how to compensate for the perceptual changes due to mesopic vision, which suggests that the adaptation of the content is done manually.

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Ultimately, similar considerations should be applied to the HMDs by lowering the screen brightness for the eyes' comfort and taking into account the specifics of mesopic vision for better perception. Available standard rendering methods as well as hardware settings do not take this important aspect into account, but the compensation algorithms already exist [35].

The goal of this work is to shed some light on the possibility of lowering the HMD's screens brightness with adjustment of the content for mesopic vision in order to maintain the user's experience and perceived quality of the content comparable to current default settings of HMD. We present a user study questioning the most appropriate screen brightness for an HMD. We have tested three levels of brightness: the default Full Brightness, the optional Night Mode against the conditions with dimmed screens with unmodified and adjusted for mesopic vision content, focusing on the Compensated condition. We report the participants subjective evaluation and cybersickness levels for each condition, as well as pairwise comparisons of the conditions.

2 The State of the Art

In recent years, mesopic vision and visual perception in the dark is getting a lot of attention from both academia and industry [4,7,8,21]. The reasons for this are the advances in Virtual Reality (VR) [33] as well as the growth in using smart devices.

An HMD is a special case of a small display that is different from a hand-held devices. The facial mask of an HMD is designed specifically to occlude as much of an ambient light as possible for immersion in VR. Unlike the other devices, the screens in HMDs are complemented by simple or even complex lenses. Moreover, they are placed just a few centimeters away from the eyes to cover a large portion of the user's field of view (FOV). The latest HMDs such as Oculus Rift and HTC Vive report to have 110° nominal FOV [22]. However, monocular FOV is much larger and reaches up to ≈100° from the center of binocular vision and is extended as far as ≈150° when the eyes move [2]. That means that that fixed FOV of an HMD is not covering a large portion of the visual field, leaving it to be dark. That should be equivalent to viewing the screen at night in a room with no ambient light, but the lenses and small distance to the eye drastically decrease the length of the light path and losses in HMD.

At the same time, lighting is said to be among the most important modifiable environmental factors related to computer vision syndrome. Loh and Redd have shown that using a bright screen in the dark might exacerbate the eye strain, due to the drastic difference in screen emitted and surrounding light [20]. The brightness has to be leveled to match the surroundings and the contrast has to be increased to eliminate the discomfort [1]. Same applies to the viewed content, where the brightness of the target object should be balanced out with the background to minimize the strain and avoid the loss of information. Moreover, using a screen before bed time has been shown to cause the effect of late stimulation and disruption of the circadian rhythms [9, 34].

Our perceived color and contrast varies significantly depending on the brightness level of the ambient environment. Based on our cones and rods photoreceptors' contribution to our vision, scientists have defined the following three visual modes. In daylight situation the cones are handling our visual response, this corresponds to photopic vision. As the luminance level falls below 10 cd/m^2 [17], our visual system moves from photopic to mesopic vision. At luminance below 0.1 cd/m^2, only rods are active and cones cannot distinguish much color, our visual system moves toward scotopic (darkness adjusted) vision. In the mesopic range, rods and cones both contribute to color vision [26]. As a result, some color retargeting or reproduction is needed to match the current standards – which are mostly based on cones response [23] – to take into account the mesopic vision characteristics.

SMPTE in their proposed standard for the indoor theaters stated expected average luminance for a typical film to be $5.5cd/m^2$ in the center of the screen and no more than 20% less on its edges [31]. Making a point on the fact that the rest of the theater is much darker than the screen, even though stray ambient light below $3.4cd/m^2$ is allowed, thus the specifics of mesopic (partially adapted to darkness) vision should be considered during screen luminance and color representation evaluation. For dimmed screens, the content will need to be modified in terms of its color saturation and contrast for it to be perceived similarly as if it is being rendered on a display with full screen brightness. Yet, to our best knowledge, there are no standards accounting for the mesopic vision, which suggests that the adjustments for mesopic vision are made manually. Consequently, automatic adjustment of the rendering to correspond to the light situation and utilization of mesopic vision in an HMD should decrease the eye strain during the long-term usage as well.

The minimum contrast visible by human eye is depending on the lighting in the environment. In 1976, Kulikowski measured the contrast visible by human eye in different lighting conditions and introduced a contrast sensitivity function based on luminance level [18].

Since then, contrast retargeting and tone reproduction to compensate for the loss of information in the dark environment has been widely investigated [19, 35]. One of the most extensive and complex color appearance models was developed by Hunt in 1991, which predicts the appearance of both unrelated and related colors at a wide range of luminance from scotopic to bleaching levels and other viewing conditions [12]. Pattanaik et al. developed a model of adaptation and spatial vision based on a multiscale representation of the human visual system, color processing, as well as luminance [25]. This model accounts for a wide range of changes, such as visual acuity, colorfulness, and apprarent contrast, which varies with illumination. Kwak et al. developed a lightness predictor which included rods' contribution to the achromatic signal for mesopic conditions [19]. Clark and Skaff [5] proposed a spectral theory of color perception, which was later extended for mesopic vision by Rezagholizadeh and Clark [29]. However, this model suffers from high computation load, which makes it hard to use in real-time applications. Shin et al. proposed a modified version of the Boynton two-stage model with fitting parameters to account for the rod intrusion in mesopic vision [30].

Based on the Shin Mesopic model, Rezagholizadeh et al. derived the inverse-Shin model and developed a color retargeting method for rendering images at mesopic light levels compensating for color appearance changes of images viewed on dimmed displays in dark environments [28]. Wanat et. al. suggested an algorithm that adjusts the color and contrast of the content, not only globally but also locally [35]. Their method adjusts the content before it is rendered on the screen based on the screen brightness. The visibility of the final result is very similar to that at full brightness of the screen.

Aside from the health concerns dimming the brightness of an HMD should also lower the power consumption and, consequently, the heat emission as well, which will be beneficial for the both PC-based and especially standalone HMDs.

In this study, we rely on the method proposed by Wanat and Mantiuk, including the inverse-Shin model and contrast sensitivity function by Kulikowski to achieve more eye-friendly and energy efficient solution. We explore the possibility to significantly decrease the brightness in HMDs and compensate for the information loss because of dimming by adjusting the content to accommodate mesopic vision. To our knowledge, this paper is one of the first attempts to address this topic for VR.

3 Experimental Design

In this study, we attempted to explore the possibility to significantly lower the screen brightness in comparison to the existing levels. We

Table 1: Luminous Intensity in Different Conditions

Conditions	Peak luminous intensity	Minimum luminous intensity
Full Brightness	$183cd/m^2$	$0.0918cd/m^2$
Night Mode	$63cd/m^2$	$< 0.01cd/m^2$
Dark & Compensated Modes	$0.73cd/m^2$	$< 0.01cd/m^2$

hypothesized that an HMD can be used with much lower screen brightness and task performance will be comparable to the default settings if there will be a compensation for the information loss due to dimming. As ratio of brightness and contrast between the screen and environmental light is connected to the computer vision syndrome, we also assumed that the lower brightness might decrease the strength of the vision-based cybersickness symptoms.

For this experiment, we decided to use the HTC Vive as one of the most wide spread and interaction-friendly virtual reality (VR) setups. Currently, this headset has two main brightness levels such as default (Full Brightness) and Night Mode. Night Mode has to be activated by the user and will be automatically disabled in the morning next day. In the Night Mode, the brightness is lower than the default and it has a slight color shift to the yellow, which is difficult to notice if the change was not directly observed during the mode activation. We have measured the luminous intensity in the HMD for one eye for peak intensity when rendering white and for the lowest intensity with black. We measured the brightness levels for both Full Brightness and Night Mode after the lens. If we assume the scattering of the light within the headset as negligible, that should roughly match how much light reaches the user's eye. The results are shown in Table 1.

To lower the brightness level suitable for mesopic vision and to avoid the color shift, which is not accounted for in the compensation algorithm, we relied on the default settings (Full Brightness). We replicated the condition as close to $5cd/m^2$ as possible, but noticed that the transition to the mesopic vision is practically not noticeable even in a side by side comparison. We tend to explain this by the specifics of the HMD as the classic measures of the sensitivity were done in the real world under different conditions. Therefore, we aimed at a even lower brightness where the mesopic vision truly manifests. Unfortunately, our brightness control with ND filters was hindered by the limited selection of the ND filters. We were able to achieve a significantly lower brightness level than in the Night Mode by applying a double neutral density filter ND1.2 (see Table 1). This low brightness condition was called Dark Mode. The case of Dark Mode with compensation for the low brightness was marked as Compensated Mode. The Compensated Mode was compared against the Dark Mode as its baseline and both manufacturer provided default brightness modes forming three conditions.

Unlike the hand-held devices, VR setup requires the maintenance of the significantly higher frame rates. For the interactive 3D scene we would need to modify the visual feed during the runtime causing a noticeable lag that would unavoidably result in bias. Therefore, we chose to modify the content (textures) for a controlled static scene offline to achieve the perfect compensation and same frame rate in all conditions. To make up for this shortcoming, we angled the textured boards and allowed the participants to move freely within the scene supporting the movement and interaction in 3D. We relied on the fact that any interaction requires from us to complete the visual search task first, in order to locate the object we want to interact with.

For the comparison of the conditions we chose visual search as a task. We asked the participants to play a "Find the Difference" game of a higher than normal difficulty that required more than 15 minutes of active search. Such a task requires attention, a lot of head and eye movements as well as interaction with the virtual environment, but ensures a highly controlled setup with a minimum of unexpected behavior.

Figure 2: Virtual environment with a sample puzzle replicated from the original image and marked differences. The size of the bounding box corresponds to the size of the difference. Original image (c) nimon/Shutterstock.com

The participants were randomly assigned to three equal groups. Each user participated only once. Each group saw only one pair of conditions: Compensated Mode and one of the other three modes (Full Brightness, Night Mode, or Dark Mode) depending on which group they belong to. Based on the described arrangement of conditions, we focused on evaluating the task performance, cybersickness symptoms and the personal preferences of the participants.

The sequence of the presentation of each pair of conditions was counterbalanced between the subjects in a group. In addition, we also counterbalanced the sequence of puzzles presentation in each condition for each group.

3.1 Content and Environment

As a source of the content, we used two puzzles from the book "Extreme spot the difference" published by Carlton Books Limited in 2014. The luminance and color retargeting algorithm performs best on colorful visual information. Therefore we used color rich imagery. Each puzzle consists of two images with 50 differences of various size and type. Figure 2 shows the example of the chosen content in the virtual scene with bounding boxes marking all the differences. The types of differences can be grouped in the following categories: a change of color of an object, adding an object to or deleting an object from the original image.

The images were used at 2K resolution (maximum texture resolution supported by Unity3D) and applied as textures to the rectangular blocks sized 2 meters high and 1,5 meter wide. The blocks were positioned relative to each other at a 150° angle to ensure visibility and reachability by free motion of the details during the task performance, also encouraging the head rotation.

3.2 Processing

In this work, we follow the main steps proposed by Wanat and Mantiuk [35] and customize it for the HMD dimmed screen condition. Wanat proposed to adjust the content for viewing in dark environment on dimmed screens. The content is adjusted in three steps; 1) Global Contrast Retargeting, 2) Local Contrast Retargeting and 3) Local Color Retargeting. Global contrast retargeting takes into account the ambient light to apply a tone curve and to minimize the perceived contrast change caused by the difference between target screen (0.73cd/m^2) and normal screen (200cd/m^2 assumed). The comparison between the unmodified and modified content is shown in Figure 3.

After the global contrast adjustment, the local contrast is being tuned taking into account the neighboring information of each pixel and minimum contrast sensitivity in each lighting condition. Here

Figure 3: Sample of unmodified (left) and modified (right) content. Note that the result for retargeting to the low brightness on the left is meant to be seen at much lower screen brightness. The visible artifacts, such as over-sharpening, disappear when seen through an ND filter. Original image (c) nimon/Shutterstock.com

we used the contrast sensitivity function based on luminance level suggested by Kulikowski [18]. It is one of the main inputs along with the level of details (Laplacian pyramid) needed for calculating the local contrast [35].

In practice, the adjustment of the contrast resulted in the a few over exposed regions in the images visible in the targeted HMD setup. We tend to explain it with the fact that the light situation within HMD is more complex than for the hand-held devices in the dark. Firstly, we initially targeted the situation between the lens and the eye, while the local contrast is also dependent on the light situation between the screen and the lens. Secondly, the HMD shader is adjusting the content to fit the lower resolution of the HMD's screens. Both of these factors can contribute to occasional grows of local contrast. Thus we decreased from previously assumed 6 (darker screen requires higher level of details) to 3 levels of Laplacian pyramid used for local contrast to achieve the desired effect. Determination of the suitable level of details was done empirically and might differ for other HMDs.

The last step is the local color retargeting after adjusting the contrast of the content. Human color perception changes based on rodes and cones contribution to our vision in the mesopic range. To address these changes, we used inverse-Shin mesopic color appearance model that provided the baseline for the color retargeting [28].

4 Technical Setup

The environment was implemented using the Unity 3D 5.6.4 game engine. For tests, we used two identical HTC Vive head-mounted displays with the 110° nominal field of view and a resolution of 1080x1200 per eye, with a refresh rate of 90 Hz. For the lower brightness setup, one of the HTC Vive was equipped with a double layer neutral density film filter ND1.2. Light bleeding from the edges of the film was blocked with foam. The virtual environment was rendered on two identical custom made laptops with the i7 CPU and dual NVIDIA 550M GPU (no NVIDIA Optimus). The participants' global head position was estimated using the HTC's Lighthouse laser tracking system with millimeter precision. In addition, participants used an HTC Vive hand-held controller for interaction.

5 Procedure

At the beginning of the study, participants signed an informed consent, confirming that they are physically fit and aware of possible consequences and got the general recommendations for Virtual Reality (VR) experience. We also informed participants that they may take a break between tasks or discontinue the experiment at any moment. After that, participants filled the general information paper-based questionnaire that checked for possible issues with vision. The study setup allowed correction only with lenses in order to prevent additional light reflections and minimize the possibility of damage or displacement of the ND filters. Next, participants read the task explanation leaflet and were able to ask questions. We additionally tested the understanding of the task and the setup. That was followed by seating the participant and fitting him with an HMD and instructions on adjusting the interpupillary distance (IPD).

Figure 4: Participant in the tracked workspace during the task performance.

When the participants were ready, the questions were rendered using the VR GUI. During the questions block, participants were encouraged to adjust the IPD for a better experience as well as the position of the goggles on their face and their physical position if needed. However, we asked participants not to remove the goggles unless they want to discontinue the experiment, as this time was important for the adjustment of the eyes to a new light situation.

Participants provided answers using the intuitive ”laser pointer” point-and-click metaphor to toggle the most fitting answer and confirm each answer by pressing the virtual ”Done” button. The questions addressed gaming experience and mobile phone usage habits, and also included the Kennedy's simulator sickness questionnaire (SSQ) [14].

After the first question block was answered, the first task started. The participants were presented with two screens with almost identical imagery. The participants had to find as many differences as possible within next 15 minutes and mark them by pointing at where the difference was found on any of the images and pressing a controller's trigger button. The ”laser pointer” was active for the whole experiment. The participants were allowed to change their chair position in space to get closer or further from the content as well as to stand up, sit or hunker down at any time (see Figure 4). For safety, the participants were observed by the staff at all times and assisted when necessary.

When the time for the task was over, the participant was prompted to evaluate the experienced condition and indicate the desired levels of changes in settings on a scaled slider that supported fractions. Each answer was confirmed by pressing a virtual button.

For the evaluation of each individual experience we asked the following questions: 1) How comfortable were you feeling during the task? 2) How easy was it to look for the differences during the task? 3) How easy was it to spot changes in color during the task? For the evaluation of the desired changes in settings we used a generic question ”Would you like any changes in these screen settings for the previous task?” and changed the aspect we were addressing as well as the scale descriptive (brightness, contrast, sharpness, color (shade) adjustment). The scales for all questions were enumerated from -5 to +5 and allowed the fractions input. The border values were annotated as follows: *comfort* – from ”very uncomfortable” to ”very comfortable”; *difficulty of the search* and *spotting the color change* – from ”very difficult” to ”very easy”; *brightness* – from ”dimmer” to ”brighter”; *contrast* – from ”less contrast” to ”more contrast”; *sharpness* – from ”more blur” to ”sharpen”; *color adjustment* – from ”more green/blue” to ”more red/yellow”.

After that, the participant was prompted to change the HMD, if needed (in case of paired Dark Mode and Compensated Mode conditions the same HMD with ND filters was used). We purposely dimmed the light in the experimental room to decrease the time necessary for re-adaptation. When ready, the participant was prompted with a set of questions regarding how they are feeling (SSQ). This time was also used for re-adaptation and adjustment of the HMD. Then the second task followed with a different imagery. When the task's time was over, participants answered the questions regarding the condition evaluation and SSQ. After that, participants were asked to remove the HMD.

Lastly, a one-page paper-based comparison questionnaire was administered. The participants were asked the following questions: 1) During which of the two tasks did you feel more comfortable? 2) Which settings made it easier for you to find differences? 3) During which task did you have to strain your eyes more? 4) Settings from which task would you choose for long-term work in VR?

6 POPULATION

Participants were recruited via Facebook and a mailing list for VR research participants on a volunteer basis. They were required to be over 18 years old, with normal or corrected to normal vision, not suffering from severe motion sickness, epilepsy or any other critical condition, as well as contact-transmitted diseases.

36 people took part in the user study. 20 participants were male and 16 were female, aged from 27 to 52 with a mean of 34.39 (standard deviation SD = 7.57). All of the participants had normal or corrected to normal vision. Half of the study's population were professionals and another half equally split between students and researchers; all in different areas, such as marketing, law, psychology, music, architecture, data analysis, etc.

VR Experience: 21 participants (58%) of the study's population indicated that they were not experienced with VR, 16 of them never used an HMD before. At the same time, 12 participants reported that they own an HMD or a Google-cardboard-like device.Seven participants reported to have very little experience with 3D games and VR, and two said to be experienced. Although, they used an HMD or a device like Google cardboard no more than a couple of days per year.

Experience with the Task: The majority (23) of the participants indicated that they seldom play a "Find the Difference" game. The game is mostly played on paper (reported by 22 participants) and less often on a PC (7) or phone (7). Only nine participants played games with more than 10 differences and only one of them played "Find the Difference" game with more than 20 differences.

7 RESULTS

Participants were split in three equal groups of 12. All of them experienced Compensated Mode and one of three other conditions. Note that although Compensated Mode is present in many comparisons, the actual data samples used in each case are different and independent from the other groups. Therefore, the correction of the significance threshold is not necessary.

Given that the majority of the obtained results violate the assumptions of normality according to the Kolmogorov-Smirnov normality test, we used assumption-free non-parametric tests with significance level 0.05 for the data analysis. In addition, we report the means (M) and standard deviations (SD). For the quantitative measure of the strength of a phenomenon, we rely on the measure independent Pearson's correlation coefficient (r) for effect size estimation and Cohen's benchmark for interpretation ($r \approx 0.1$ - small, $r \approx 0.3$ - medium, and $r \approx 0.5$ - large effect).

7.1 Learning and Image effects

The largest data sample we obtained for the Compensated Mode condition with a total of N = 36 samples. Note that the study was fully counterbalanced, thus we assume minimal bias. Therefore, we used this data sample to control for the learning effects as well as the differences between the images used.

For the learning effect the mean result of the first task was $M = 32.56, SD = 4$ and for the second task – $M = 30.22, SD = 3.4$. The independent Mann-Whitney test detected a statistically not significant effect of a small size ($z = -1.463, p = 0.152, r = -0.24$).

The results associated with the images produced very similar results: $M = 31.56, SD = 4.2$ for the first image and $M = 31.22, SD = 3.6$ for the second. The independent Mann-Whitney test was not statistically significant and the difference produced a very small size of effect ($z = -0.493, p = 0.628, r = -0.08$). We have cross-tested the same assumptions for the other conditions – none of them produced a statistically significant result. Thus, the probability of influence of these factors on the conditions' overall evaluations is low and we will not address them further.

7.2 Task Performance

In this section, we focus on the within-subject comparison of the number of the found differences for each group. We have logged the sequence and amount of the differences found. As expected, the large differences were found first and brighter conditions performed slightly better than the dark.

When comparing the results from Full Brightness ($M = 34.83, SD = 6.337$) and Compensated Mode ($M = 31.4, SD = 3.8$), the Wilcoxon Signed-Rank test detected only a trend for significance associated with the medium-sized effect of Full Brightness ($z = 1.87, p = 0.061, r = 0.38$). However, post hoc comparison of two independent samples for Full Brightness and Dark Mode conditions the difference is significant ($z = 2.054, p = 0.04, r = 0.42$). The comparison test between the Compensated Mode and Night Mode ($M = 34, SD = 2.6$) detected a statistically significant difference associated with a large effect size attributed to the Night mode ($z = 2.813, p = 0.005, r = 0.57$). The comparison between the Compensated Mode and Dark Mode ($M = 30, SD = 4.7$) was not statistically significant, but the Compensated Mode still produced a small size effect ($z = -0.981, p = 0.327, r = -0.2$).

7.3 Evaluations of the Conditions Within Groups

Right after the end of each task, we asked seven questions regarding the comfort, ease of difference search, spotting the color differences, brightness levels, contrast, image sharpness, and image shade. These questions targeted each condition individually. Participants answered using a slider VR GUI. The results of the Wilcoxon Signed-Rank tests are presented in Table 2.

The comparisons of Compensated Mode to other conditions produced non-significant small effects regarding the *comfort levels, difficulty of the color change spotting, color/shade adjustments, and sharpness*. The obtained results suggest that the comfort levels were comparable, but not perfect for all the conditions (approx. 3 out of 5 for all conditions) and the difficulty of the color change was minimally affected by the brightness change. It also seems that the light-yellow tint of the Night Mode was not obvious to the participants. Finally, participants indicated a desire to sharpen the visual output by about the same amount (approx. by 2 points out of 5) in all the conditions.

Difficulty of the search: In this aspect, only the comparison between the Night Mode and Compensated Mode was statistically significant in favor of the Night Mode.

Brightness: Both Dark Mode and Compensated Mode conditions were evaluated on average as slightly not bright enough (scored on average slightly above 1 out of 5), while the preferences for the brightness levels of the Full Brightness and Night Mode did not deviate much from zero. Respectively, there was a significant difference between the Compensated Mode and Full Brightness condition, as well as Night Mode, but not with the Dark Mode.

Table 2: Summary of the Wilcoxon Signed-rank Tests[a] for the Evaluations of the Conditions Within Groups

Conditions		Comfort	Search Ease	Color Change	Brightness	Contrast	Sharpness	Shade
Full Bright. vs Compensated Mode	z	1.481	1.255	1.334	**-2.803**	*-1.682*	-1.423	-0.195
	p	0.139	0.21,	0.18	**0.005**	*0.093*	0.155	0.273
	r	0.3	0.43	0.27	**-0.57**	*-0.34*	-0.29	0.22
Night Mode vs Compensated Mode	z	0.622	**2.118**	1.569	**-2.497**	**-2.045**	0.533	-0.169
	p	0.534	**0.034**	0.117	**0.013**	**0.041**	0.594	0.866
	r	0.13	**0.43**	0.32	**-0.5**	**-0.41**	0.11	-0.04
Dark Mode vs Compensated Mode	z	0.267	-0.445	-0.356	0.98	-0.42	-0.978	*-0.674*
	p	0.79	0.66	0.72	0.327	0.874	0.328	*0.5*
	r	0.05	-0.09	-0.07	0.2	-0.08	-0.2	*-0.14*

[a] The sign of the z and r values show which condition in a pair had higher values. Negative values show that Compensated Mode had higher result and the other way around. For the correct interpretation, please, refer to the scale used for each question.

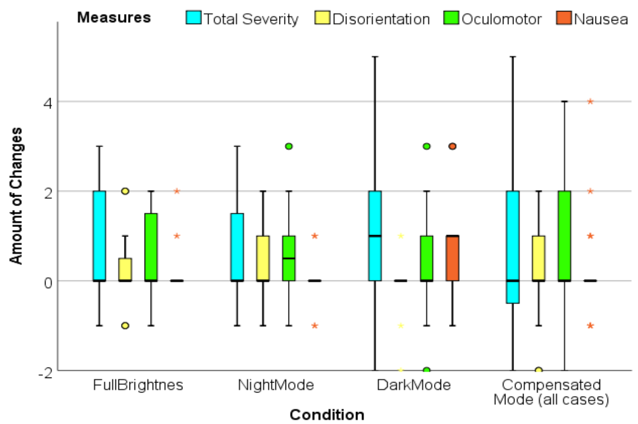

Figure 5: Sub-scales of the changes in the SSQ self-reports according to the condition. Positive change describes increase of the symptoms severity, negative - relief. Note, the boxplot presents 36 of Compensated Mode samples.

Contrast: The statistically significant difference to the Compensated Mode was produced only by the Night Mode.The Full Brightness condition produced only a trend and there was no significant difference to the Dark Mode.

7.4 Cybersickness

Kennedy SSQ was administered before the exposure and after each of two tasks. The strength of each symptom is evaluated on a scale: 0 – none, 1 – slight, 2 – moderate, 3 – severe. We calculated the change in the state of each participant after exposure to each condition. Using these values, we computed the three factor cumulative scores for Nausea (N), Oculomotor (O), and Disorientation (D) subscales, as well as the Total Severity (TS) of cybersickness over all 16 symptoms according to Kennedy et al. [15]. The comparisons of the sub-scales turned out to be not statistically different on all the sub-scales for all pairs of the conditions. The results are shown in Table 3. Figure 5 shows the boxplot of the obtained values. Note that the Compensated Mode in the boxplot presents all 36 data samples, which automatically increases the variation. In addition, we performed the post hoc analysis for individual symptoms. Due to their large number we will present in detail only the symptoms with significant statistical differences.

Salivation: The groups with the Full Brightness and Night Mode conditions did not observe any difference in this symptom (p = 1). However, the comparison of the Dark Mode to Compensated Mode revealed that salivation was significantly increased in the Dark Mode condition: $z = 2, p = 0.048, r = 0.41$.

Fullness of Head: regarding this symptom the Compensated Mode compared to Full Brightness as well as Dark Mode produced the same not statistically significant results ($z = 1.342, p = 0.18, r = 0.27$). Although, the Night Mode produced significantly higher changes in the state of the participants ($z = 2, p = 0.046, r = 0.41$).

Blurred vision: There was no statistically significant difference between the Compensated Mode and the Full Brightness ($z = -1.141, p = 0.157, r = 0.29$), or Night Mode ($z = 0, p = 1, r = 0$). Interestingly, in the Compensated Mode participants reported a significantly higher occurrence of blurred vision than in the Dark Mode condition ($z = -2.126, p = 0.033, r = -0.43$).

7.5 Users' Preferences

The comparison questionnaire was administered at the very end of the study after both conditions have been experienced. We asked the participants to express their preferences for one of the conditions that they have experienced if there was a difference. To avoid bias in the answers, we used the words ”first condition” and ”second condition” as well as ”no difference” for the answer options. Then we remapped the answers to the corresponding condition names if the preference was expressed. Due to the comparatively small groups' sizes and three nominal answer values available, it is sufficient to look at the distribution of the answers. The results of the participants' preferences are summarized in Table 4.

Comfort: There was a strong preference for the Night Mode over Compensated Mode, and the Compensated Mode was preferred over the Dark Mode by half of the participants in this group, but no clear preferences in group with Full Brightness.

Ease of search: The preferences seem to be brightness dependent, deeming no difference between the Compensated and Dark Modes.

Eye strain: This symptom also seems to be brightness dependent as both brighter modes were indicated as the least strenuous. In the group with Dark Mode, the participants split in two groups on their opinions which condition was more strenuous, with only one person with answer ”no difference”. This suggest the possible split in the sensitivity to our compensation manipulations.

Long-term work in VR: Here again the brighter conditions were chosen more often than the darker setting by more than half of the participants in the respective groups. There was no clear difference between the Dark and Compensated Modes and majority of the participants did not notice the difference in this aspect.

8 Discussion

The aim of this study was to explore whether it is possible to greatly lower the brightness of the HMD's screen and address the possible consequences of such change regarding the visual search task performance, comfort, cybersickness, and personal preferences.

Task: In the results of task performance in different conditions, we have observed slight decrease in the number of differences found as the brightness levels declined. Neither order of conditions nor type of content used had any effect. Some of the participants commented that although both puzzles were brightly colored one had a sort of a regular pattern that made the search procedure to differ from the

Table 3: Summary of the Results for the SSQ Sub-scales Comparisons

Compensated M. vs. Cond.	Total Severity			Nausea			Oculomotor			Disorientation		
	z	p	r	z	p	r	z	p	r	z	p	r
Full Brightness	0.598	0.55	0.11	1.414	0.157	0.29	0.284	0.776	0.06	0.212	0.832	0.04
Night Mode	0.987	0.323	0.2	0.378	0.705	0.08	0.849	0.396	0.17	1.236	0.216	0.25
Dark Mode	-0.835	0.404	-0.17	0.586	0.558	0.12	-1.697	0.09	-0.35	-1.543	0.123	-0.31

Table 4: Summary of the Subjective Preferences

Compensated Mode vs. Condition	Answers[a]											
	Comfort			Ease of Search			Eye Strain			Long-term Use		
	CM	ND	OC	CM	ND	OC	CM	ND	OC	CM	ND	OC
Full Brightness	4	5	3	1	3	**8**	**7**	4	1	1	3	**8**
Night Mode	1	2	**9**	3	3	**6**	**8**	1	3	4	1	**7**
Dark Mode	**6**	2	4	4	5	3	6	1	5	3	5	4

[a] Abbreviations stand for the following answers: CM - Compensated Mode, ND - No difference, OC - Other condition (Full Brightness, Night Mode, or Dark Mode). Numbers stand for the number of participants in each group, which chose this answer.

other task without the pattern. Thus, the experience gained in the first task was not very helpful in the second task.

Interestingly, a rather drastic difference in screen brightness between the default Full Brightness and Compensated Mode conditions did not produce a statistically significant difference in the tasks results. That suggests that in terms of visual search during these two conditions the brightness was not that crucial. Yet, we observed a stable and large statistically significant effect in favor of the Night Mode over the Compensated Mode. The Night Mode varies in brightness (approximately three times lower than the Full Brightness) with a slight color shift to yellow. This suggests, that the spectrum of the light emitted by the screen of an HMD might require a more careful consideration in the future. That is supported by the ergonomics research, where warm light is associated with relaxation [34]. That way, the minor color shift in the Night Mode might have mitigated the stress caused by the task and still high contrast in brightness levels within the HMD itself.

Within Groups Evaluations: Some participants found the Full Brightness condition to be too bright, shifting the mean values for this condition below zero. As could have been expected, the participants wanted to increase the *brightness* in the Compensated and Dark Modes. However, it was not as extreme as could have been expected based on the differences in luminance to other conditions. Interestingly, the mean scores were revolving around 30% of the maximum possible score, indicating that only a slight increase in brightness is necessary, even in comparison to the brighter conditions.

The reported *comfort* levels for all conditions fluctuate around the middle of the positive scale, indicating that all conditions were perceived as comfortable with a possibility for improvement. Very similar results were obtained for the *ease of color change detection*. That indicates, that nothing in all conditions substantially hindered the color perception, even in the case of color overlay in the Night Mode. The evaluation of *shade* (color temperature) revealed no significant difference between the conditions despite the color shift of the Night Mode that had an effect on task performance, ease of search, brightness and contrast evaluations.

For the *ease of the search for differences*, again only the Night Mode condition produced significantly higher scores than the Compensated Mode condition, which conforms with the result of the task performance, suggesting that the previously obtained results were not an accident, but rather a consciously detected difference in conditions. That in turn, leads us to an assumption that both Full Brightness and Compensated Mode conditions are not optimal for the visual search. Similarly, the *contrast* evaluation showed only a trend for significance between the Compensated Mode and Full Brightness conditions that again became significant when the Compensated Mode was compared to the Night Mode. Overall, the darker conditions were scored in favor of more contrast, again aiming at the increase at about 30% of the maximum scale, which correlates with the brightness evaluation. The *sharpness* evaluation indicated the need to be about 40% sharper of the maximum scale for all the conditions. This could be explained by the insufficient screen resolution, screen-door effect, "God rays" effect, and some imperfections of the Fresnel lenses used. Even though the current specifications of the HTC Vive are rather good, in comparison to the desktop displays the scene shown with the HMD seems insufficiently sharp with visible artifacts. Moreover, the results indicated that for conditions with higher brightness the requirements to sharpness are noticeably higher than for the darker conditions. This is most likely caused by the fact that the artifacts mentioned above become less visible as the screen brightness gets lower.

Cybersickness: With the rapid improvement of the VR technology, the levels of hardware-dependent cybersickness decreased, but the interaction-bound components are still as strong as before. To evaluate the effect of brightness on SSQ, we have intentionally created the VE and used the task that requires frequent head rotations, in order to simulate a longer exposure and stay within the limits of natural interaction. Consequently, every participant performed more than 500 head rotations with an amplitude ranging from 5 to 45 degrees in order to successfully complete a task. The participants were also actively changing their position in the scene in both tasks, as soon as it became harder to find the differences.

Overall, the conditions appeared to be not significantly different from the brighter conditions. Only the individual symptoms suggested some possible differences. *Fullness of Head* might be connected with the color shift in the Night Mode. Ergonomics research suggests that both brightness and color of the light are connected to the attention and state of alertness as well as circadian rhythm [34]. *Salivation* is often used as a stress indicator [16]. That suggests the adjustments made for the loss of information due to low brightness in Compensated Mode might have an effect, resulting in the lower stress levels. That is supported by the lack of significance in comparisons of the Compensated Mode to the brighter conditions. A possible explanation of the *Blurred Vision* symptom in the Compensated Mode might be that the compensation algorithm for the hand-held devices is only sub-optimal for the HMD and most likely needs to take into consideration the specifics of light transport within the HMD for the improvement of the global contrast. Finally, the results of the group that experienced both dark conditions showed slightly bigger changes in the SSQ self-reports of the participants than in groups that experienced the Compensated Mode and one of the brighter conditions. We contribute this to the double time at the low brightness with no second brightness adaptation and HMD calibration phase. This slightly shortened the break between the two tasks and could put a bit more strain on the participants. That was not the case for other two groups and might have had an effect on the self-reports.

Subjective Preferences: Looking at the pairwise comparisons, we can assume that lowering the default brightness might be beneficial for several reasons. One of them is the comfort levels. Default setting of Full Brightness seemed to be equally comfortable or possibly equally uncomfortable as our radically low in brightness mesopic vision oriented Compensated Mode. The Night Mode was strongly preferred over it in direct comparisons. There is also seems to be a noticeable disparity between what the participants thought to be correct for direct comparisons and what they reported immediately after the exposure. Direct post-exposure comparisons of the conditions showed that participants assumed the search to be easier and less eye-straining in the brighter conditions. However, that is only partially supported by the cybersickness self-reports and overall task performance results in favor of the Night Mode and not Full Brightness. Majority of participants also stated that one set of the images that was somewhat more colorful was easier in terms of task performance, which in fact turned out to be incorrect.

The results on brightness and contrast let us assume, that the **possible optimal brightness** settings for the HMD lie way below the default Full Brightness level and probably lower than the $5cd/m^2$ of the screen brightness suggested by the SMPTE [31]. There are principal differences between the HMD and a movie theater: the distance between the source and observer, FOV, decreased light diffusion and scattering - all of that alters the visual perception. Moreover, an HMD always includes a combination of a magnifying and Fresnel lenses. This needs to be considered as well. We have relied on our prior knowledge from the area of mobile devices to identify the acceptable compensation levels. The minor differences between the Compensated and the Dark Modes suggest that the adjustments for the low brightness level were not optimal and the existing methods need to be adapted for the HMD for the better and more visible result.

An **alternative** to lowering the screen brightness could be to brighten the background of the HMD. Yet, we believe this also should be done with caution. Although the peripheral vision is a low resolution sensory input, its stimulation might have a number of effects. Jones et al. showed that putting a light bar in the lower part of the FOV helps with the distance judgments [13]. At the same time, putting a light frame around the virtual FOV has an opposite effect. According to Jones et al. increase of the FOV is the most beneficial solution in this respect. That in turn, suggests that extension of the bright areas in the currently available HMDs should follow the approach of the Microsoft's IllumiRoom, where the background light is dynamic and conformed with the main screen.

Ultimately, the **applicability** of the low brightness settings is not universal. It is difficult to simulate the bright sunlight in low light conditions. Although some amendments might be made, such as warm color overlay similar to the Night Mode, halo or other visual effects might be perceived as unnatural. Possibly, the HMDs should adopt the preset modes like those of the desktop displays. However, human eyes adapt to the light situation over time and after that we perceive the VE as real, unless there is a clear discrepancy. Thus, we can easily imagine the use of the Compensated Mode for the moderate and low light scenes with the normal levels of immersion and presence. After all, even degradation of the texture resolution by 25%, which can be compared to the loss of the information in the dark, has been shown to have no effect on presence [6], whereas the compensation algorithms aim at improvement of the visibility of the details. In the future, we would recommend the improved Compensated Mode for the long-time or night use, as well as in cases where the power saving is needed.

Finally, we would like to address the **power efficiency benefits** of the lower brightness. As, the specification of the exact screens used in the HTC Vive is not publicly available, we can take look at the AMOLED screens of the same generation, such as those used for the Samsung Galaxy S6. According to the test results reported by Anandtech, lowering the brightness from the default $200cd/m^2$ to $1cd/m^2$ will decrease the power consumption by a factor of two: from 790mW to 358mW [10]. Although, we are aware that the power efficiency of the screens is increasing over time, the size and resolution of the screens used in HMDs is growing as well. This suggests that, in the future, the question of power efficiency will be open for the HMDs.

9 Conclusions

In this paper, we explored the possibility to significantly lower the screen brightness of an HMD and compensate for the information loss using the methods previously suggested for the hand-held devices. We compared our Compensated Mode condition to the existing settings of the HMD at default Full Brightness as well as at the optional Night Mode. As a control condition, we used the original content with the lowered brightness. For comparison of the conditions we used the visual search task. The task performance results were slightly but not significantly different, decreasing together with the brightness levels.

Furthermore, we asked the participants to evaluate each of the conditions separately and Compensated Mode against the other conditions. The results suggest that participants noticed the differences between the conditions. However, in many aspects, the differences becomes more outstanding between the Compensated and Night Modes rather than Full Brightness condition. Consequently, the default Full Brightness might be indeed brighter than is comfortable for the user. In fact, both manufacturer provided settings have the screen brightness set much higher than the brightness recommended for a screen in the movie theater, which is the closest analog of the HMD. Our results show that the task can be successfully performed under the brightness that is even lower than the SMTPE recommended value. Albeit, the preferences leaned towards the higher brightness settings, our significantly darker conditions made minimal impact on the task performance.

In addition, we tested for the cybersickness that turned out to be very mellow with only three symptoms that produced significant differences. The Dark Mode seemed to be linked with the stress indicator – increased salivation. The Compensated Mode did not differ from brighter conditions, but against the Dark Mode had higher rates of blurred vision. At the same time, the Fullness of Head symptom was significantly stronger in the Night Mode than in the Compensated Mode. That, in turn, suggests that the slight color shift might also cause some other effects aside from increasing comfort at night with the consequent good sleep. Hence, the connection between the brightness, color overlay, and cybersickness requires further investigation.

Our findings suggest that there seems to be a potential in lowering the default brightness of an HMD and compensating for it accordingly. However, further research is needed for the optimization and adaptation of the existing compensation methods to the specifics of HMDs. Seeing that the usage of an HMD at Full Brightness at night or Compensated Mode at a sunny day might lead to discomfort and substantial adaptation time, enforcing the use of only certain brightness and color settings might not be an optimal solution. Therefore it is logical to consider the ambient light of the real environment in order to utilize the HMD from the first second it was equipped to soften the transition to the optimal settings both for VR and user's eyes. We believe that an auto-adjustment feature in the HMD can ease the adaptation to the change of the light situation during the transition from the real world to the HMD optimal settings and the other way around. And certainly, it is also important to leave the possibility for the users to adjust the settings to meet their specific needs.

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