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Perceptual difference between the discomfort luminance level and the brightness of a head-mounted display (HMD)

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ABSTRACT

A psychophysical experiment was conducted to compare the discomfort luminance level and the brightness of a head-mounted display (HMD). The results showed that as the size of the HMD stimulus increased, both the discomfort luminance level of the HMD and the brightness of the HMD decreased, but the influence of the size change was more dramatic on the discomfort luminance level than on the brightness. This study showed that to provide a comfortable luminance level for HMDs, the adaptation luminance level and the size of the HMD stimulus should be considered. However, it cannot be predicted in terms of brightness.

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Brightness; discomfort luminance; head-Mounted display (HMD); viewing angle

1. Introduction

It is well known that the excessive light intensity of displays can cause visual discomfort [1, 2]. Thus, the proper luminance setting depending on the surround conditions is important. The proper luminance not only provides comfortable brightness, but is also more energy-efficient [3]. Therefore, many studies have been conducted to reduce the luminance of displays while maintaining their image quality [4–6].

Proper luminance control is even more important for head-mounted displays (HMDs) to give their users a comfortable experience. According to Ha *et al.*, the discomfort luminance level (i.e. the luminance threshold that causes visual discomfort to users) increases as the luminance of the previous scene increases when the viewer fully adapts to the previous scene. Thus, a discomfort luminance level prediction model for HMD was proposed as a function of the adaptation luminance based on experimental data [7]. To understand this phenomenon better, the perceptual factors that affect the discomfort luminance level need to be investigated. Therefore, in this study, the relationship between the brightness and the discomfort luminance level is investigated because brightness is the perceptual attribute that is mainly affected by the luminance.

If the discomfort luminance level of HMDs is related to their brightness, the size of the HMD stimulus affects the discomfort luminance level of the HMD. Based on Ha

et al., the brightness of HMDs increases as the size of their stimulus increases [8]. Thus, this study investigated the discomfort luminance level of HMDs depending on their previous exposed luminance and the size of their stimulus, and compared the discomfort luminance level with the luminance of an HMD with the same brightness as the exposed luminance before the user watched the HMD.

2. Psychophysical experiment method

2.1. Overview of the experiment

To investigate the discomfort luminance level of HMDs depending on the size of their stimulus and the previous exposed luminance levels, a psychophysical experiment was conducted with Yes/No task. The LCD generates the reference stimulus before the viewer watches the HMD, and the HMD shows the test stimulus to find the HMD's discomfort luminance level and the luminance of the HMD with the same brightness as the LCD. Three luminance levels were shown on the LCD and five luminance levels were shown on the HMD, and each HMD test stimulus had three sizes. The participants were asked to determine whether the HMD was uncomfortable to watch and whether the HMD was brighter than the LCD. It should be noted that the resulting luminance of the HMD with the same brightness as the LCD was already published in [8], and the same data were compared with the discomfort luminance data in this study.

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2.2. Display characterization

The Oculus Rift DK2 (HMD) and a 27-inch EIZO LCD were used to generate the test stimuli and the reference stimuli. The resolutions, the exponent of the power function for the monitor EOTF, and the peak white of the HMD were 1920×1080 , 2.3, and 94 cd/m^2 , respectively, and those of the LCD were 1920×1200 , 2.2, and 266 cd/m^2 . The color gamut of the HMD was as large as P3, and that of the LCD was calibrated as sRGB. The gamma offset gain (GOG) model [9] was used to characterize both displays. The color patches for the characterization were measured using a CS-2000 spectroradiometer. The average ΔE_{ab}^* between the predicted XYZ based on the GOG model and the measured XYZ with eight levels of red, green, blue, and neutral color patches was 0.88 for the HMD and 0.26 for the LCD.

2.3. Reference stimuli and test stimuli

The reference stimulus displayed on the LCD was set at three luminance levels: 3.2, 32.9, and 103.8 cd/m^2 . The CIE 1931 xy coordinates were set at (0.30, 0.33), which are the same as those of the white point of the HMD, to control the chromaticity. The reference stimulus was a square patch with a resolution of 1200×1200 pixels. The distance from the participants' eyes to the LCD was 70 cm, which is the general distance needed to see the monitor. Thus, the viewing angle of the reference stimulus was 30° .

The HMD test stimulus was set at five luminance levels for each reference stimulus based on the result of the pilot test. When the luminance of the reference stimulus was 3.2 cd/m^2 , the luminance range of the test stimulus was $1.1\text{--}7.4 \text{ cd/m}^2$; and when the luminance of the reference stimulus was 32.9 cd/m^2 or 103.8 cd/m^2 , the luminance range of the test stimulus was set at $11.8\text{--}76.6 \text{ cd/m}^2$. The luminance intervals of the test stimuli were set to have the same difference on the log scale. Additionally, three different sizes, 10° , 50° , and 90° , were simulated for each test stimulus.

2.4. Procedure of the psychophysical experiment

A total of 20 university students, 10 males and 10 females, with normal vision without eyeglasses, participated in the experiment. Before the experiment was started, an Ishihara test was conducted to confirm normal color vision. Initially, the participants adapted to the dark room for five minutes. Then they were asked to observe the reference stimulus on the LCD for 10 s and to remember the brightness of the reference stimulus. After that, they put the HMD in front of their eyes to see the HMD screen. It took one to two seconds depending on the participants,

and then they were asked to answer two questions with Yes or No: i.e. whether the HMD was brighter than the LCD and whether the HMD was uncomfortable. Discomfort meant that the participants felt that they needed to reduce the luminance of the HMD because of glare or visual fatigue from a stimulus on the HMD that was too bright. Thus, a 'Yes' response meant the participants wanted to reduce the luminance of the HMD because it was too bright, and a 'No' response meant that the luminance of the HMD did not cause them discomfort. The test stimulus appeared for less than two seconds to prevent the participant's adaptation to the test stimulus. This process was repeated until the last stimulus.

From the psychophysical experiment, 45 responses were obtained from each participant without repetition (3 reference luminance levels \times 3 test stimulus sizes \times 5 test luminance levels). To minimize the effect of the stimulus sequence, the stimulus sequence was randomly selected using a Latin square, which is a generalization of the randomized-block design [10]. All 900 participant responses were used to calculate the proportion of 'Yes' responses to each question.

2.5. Method of analyzing the responses in the psychophysical experiments

Equation 1 below shows the logistic function that was used to estimate the proportion of the responses:

$$F_L(x; \alpha, \beta) = \frac{1}{1 + \exp(-\beta(x - \alpha))}, \quad (1)$$

wherein x is the stimulus intensity, α is the threshold at 0.5 correction, and β is the slope of the psychometric function. The discomfort luminance level of the HMD and the luminance of the HMD with the same brightness as the LCD were extracted using the logistic psychometric function, wherein the proportion of the responses was 50%. The parameters for the psychometric function were estimated using the Palamedes Toolbox in MATLAB [11].

The bootstrap analysis was conducted to generate many random hypothetical data sets based on the actual experiment results [12]. The psychometric function was predicted using each new hypothetical data set, and the parameters α and β were predicted. The standard deviations of the predicted parameters α across all the hypothetical data sets were calculated to check the errors in the predicted α parameters. The number of trials was set at 400 to achieve an acceptable degree of accuracy of the error estimation.

When the luminance of the LCD was 3.2 cd/m^2 , the proportion of the 'discomfort' responses was always less than 10% for 10° . This implies that few participants felt

visual discomfort when the stimulus was very small. Thus, in the case of 10° under the 3.2 cd/m^2 LCD luminance, the discomfort luminance level was not calculated. In another case, if the highest proportion of the 'discomfort' responses was less than 50%, the discomfort luminance level was calculated by extrapolating the psychophysical function.

3. Results

Figure 1 summarizes the results of the psychophysical experiment. The x-axis represents the luminance of the LCD, and (a) in the y-axis represents the discomfort luminance level of the HMD, and (b), the luminance of the HMD with the same brightness as the LCD. As a result, both the discomfort luminance level and the luminance of the HMD with the same brightness as the LCD increased as the luminance of the LCD increased. Additionally, the luminance of the HMD with the same brightness as the LCD was generally lower than the LCD luminance. This means that when the participants saw the lower luminance on the HMD compared to the LCD, they felt that the brightness of the HMD was the same as that of the LCD. It seems that the HMD looked brighter than the LCD even though both displays generated the same luminance, because the surround condition of the HMD were darker than the dark condition [8]. Also, both the discomfort luminance level and the luminance of the HMD with the same brightness as the LCD decreased as the size of the HMD stimulus increased.

However, the degree of the effect on the size change differed. For example, the luminance of the HMD with the same brightness as the LCD did not show a significant

difference between 10° and 50° even though the discomfort luminance level of the HMD showed a significant difference. This implies that the discomfort luminance level is different from the brightness of the HMD, and the discomfort luminance level cannot be determined based on the brightness of the HMD. Figure 2 compares the results depending on the size of the HMD test stimulus. The y-axis represents the discomfort luminance level or the luminance of the HMD with the same brightness as the LCD. There are three major findings on the discomfort luminance level.

First, as the luminance of the LCD increased, the discomfort luminance level of the HMD also increased, which indicates that the discomfort luminance level was affected by the previous luminance that was observed for 10 s. In other words, if a participant was exposed to dim light for 10 s, the luminance of the HMD had to be reduced to prevent visual discomfort. This finding implies that the luminance of the content needs to be controlled by considering the previously presented content, even if the previous content was presented for only a few seconds. For instance, when the scene changes from a dark scene to a bright scene on the HMD, the luminance of the bright scene must be chosen carefully to prevent discomfort.

Second, as the size of the HMD test stimulus increased, the discomfort luminance level of the HMD decreased. This means that the HMD caused greater discomfort when the stimulus size increased, even if the luminance levels were the same. Thus, the size of the HMD stimulus must be considered when content is displayed on HMDs to prevent discomfort. Additionally, we conclude that high luminance in a small area of the display, like the test stimulus with a 10° viewing angle, tends to be

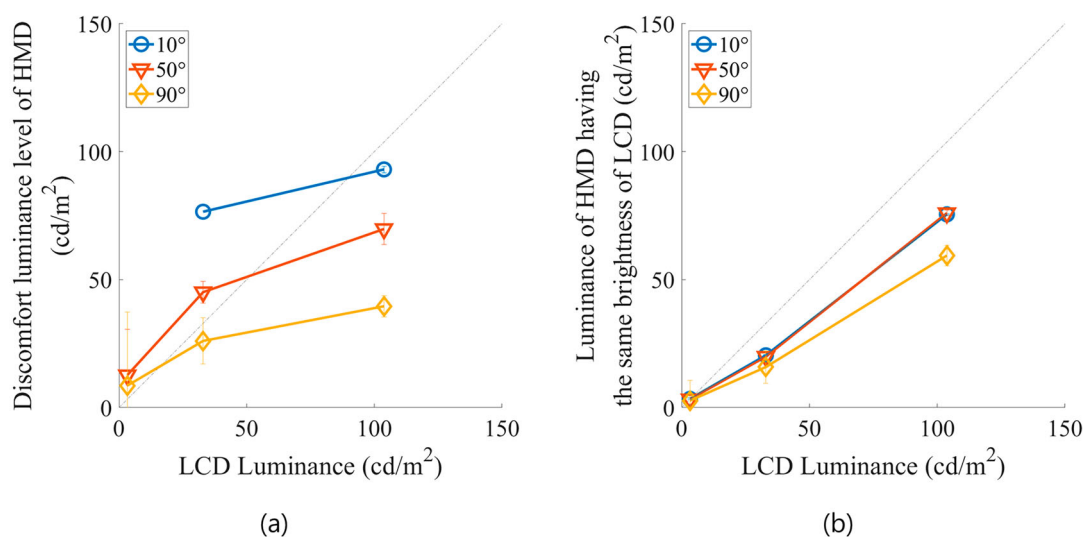


Figure 1. Summary of the psychophysical experiment results: (a) Discomfort luminance level of the HMDs and (b) luminance of the HMD with the same brightness as the LCD.

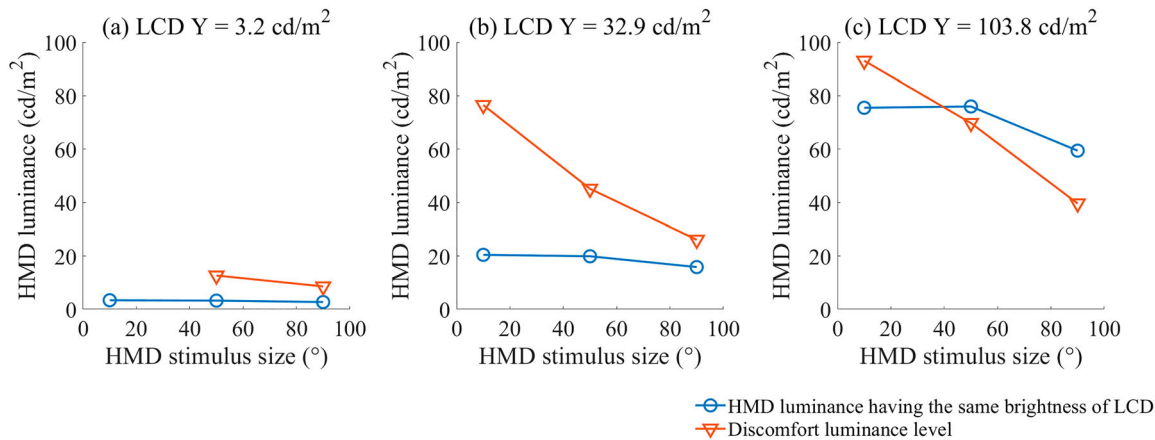


Figure 2. Comparison of the results of the brightness experiment and the discomfort experiment.

acceptable to viewers. Therefore, the tolerable luminance range for specular highlight areas, such as a sunrise, will be wider. This finding gives further evidence that the size of the stimulus must be considered to predict the discomfort luminance level.

Third, the discomfort luminance level decreased more sharply as the HMD test stimulus increased compared with the luminance of the HMD with the same brightness as the LCD. For example, Figure 2(c) shows that the luminance of the HMD with the same brightness as the LCD at 10° and 50° are similar, but the participants felt discomfort at 50° and they did not feel such discomfort at 10°, even though the degrees of perceptual brightness were similar. This implies that the size affected both the brightness and the discomfort luminance level, but the influence differed.

4. Conclusion

The discomfort luminance levels of an HMD with three different viewing angles were investigated after the participants were briefly exposed to three different luminance levels of an LCD in a dark room. A psychophysical experiment was conducted with 20 participants using the method of constant stimuli. The experiment results showed that the discomfort luminance level and the luminance of the HMD with the same brightness as the exposed light before the participant watched the HMD increased as the previous exposed luminance increased and as the size of the HMD stimulus decreased.

In summary, this study had three major findings. First, when the participants were previously exposed to a higher LCD luminance, they found a higher HMD luminance acceptable, which confirmed the findings of previous studies. This means that the HMD luminance should be controlled by taking into consideration the

user's previous adaptation condition. Second, as the HMD viewing angle increased, the degree of discomfort increased even if the HMD luminance level did not change. This means that the degree of influence on the size change is higher at the discomfort luminance level than at the brightness. Third, the discomfort caused by the HMD luminance was not directly related to the brightness. Two HMDs with the same luminance but different viewing angles will produce the same brightness, but a larger viewing angle produces higher discomfort.

In conclusion, to predict the discomfort luminance levels of HMDs, it is necessary to consider not only the adaptation luminance but also the viewing condition such as the viewing angle of the display, the adaptation time, and the surround condition. In addition, the participants in this experiment were only university students, and thus, young. Thus, these results do not cover the discomfort luminance level depending on the age of the user. To verify how the discomfort luminance level changes depending on the age of the user, further study is recommended. Also, even though this experiment was conducted using the HMD, the discomfort luminance level is also applicable to other displays that have a large viewing angle such as a TV. According to Fang *et al.*, the glare threshold of an HDR TV also decreases as the size of the stimulus increases [13]. However, as the discomfort luminance level affects other factors such as the viewing condition, the display types, and the viewing angle of the adapting field, further studies on the discomfort luminance level are recommended.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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