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Optimal Text-background Lightness Combination for Enhancing Visual Clarity Using a Head-up Display under Different Surround Conditions

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Abstract

Head-up displays (HUDs) can be used under various surround conditions ranging from extremely dark to very bright environments such as daylight. Many head-up displays are designed to enhance visual clarity by adjusting the brightness of the display. However, few studies aim to investigate the impacts of the text-background lightness combination of a head-up display to the visibility as the lighting level of the driving condition changes dramatically. In the study, thirteen observers assess the visual clarity of 20 text-background lightness combinations on a head-up display with paired comparisons method under a dark and a daylight surround (i.e., 15000 lx) conditions. As a result, the combination of white text with a black background and the black text with a white background presents the significant preference and the best visual clarity under the dark and the daylight surround conditions, respectively.

Introduction

In recent years, the applications of augmented reality (AR) technologies have been developed rapidly to make our life more intelligent. Comparing to the head-down display (HDD), the head-up display (HUD) performed faster response times to the urgent event [1]. Thus, the HUD was considered as one of the most representative interaction devices applied in the vehicle to assist the driver [2]. It was beneficial to displaying visual information such as speed, navigation cues, safety warnings, environment traffic and travel conditions, etc. On the windshield with a projector and simultaneously viewing the driving environment. However, there were still some issues that should be further studied to evaluate its practicality and safety [3]. Due to the intensive variance of the environmental illumination when driving, which is a high dynamic range to human vision, the appropriate visual clarity was the primary purpose of optimizing HUD. Besides, the user experience of the HUD was discussed in lots of researches to achieve a better HUD design.

The HUD was a type of see-through display in which the ambient lighting would significantly influence the visual perception of the displayed content. When projecting the information with a lower contrast against the background, it might lead to a higher driving risk. Hence, some studies contributed to enhancing the visibility of the HUD for easier recognition. The previous research suggested that the background transparency levels should be adjusted adaptively according to the illuminance of the outside environment [4]. With a higher outside illuminance, the lower transparency of the background could increase the visibility of the text. On the contrary, becoming more transparent was applicable to the dark or shadow area. Also, the visibility of color symbology under high ambient environments was investigated, and the use of white, yellow, green, and cyan text was recommended as the results [5]. A robust gamut mapping algorithm, including lightness mapping (LM) and chroma reproduction, was proposed to reduce color distortion for bright ambient light [6]. Moreover, two approaches, which were the changes of the color symbols and the addition of color outline to symbols for HUD information, were adopted for visibility enhancement determined by the similarity between HUD information and background dominant colors [7].

Although some related works focused on improving visibility [8], studying the characteristics [9] and finding the preferences of the tone reproduction curve [10] for transparent LCD and OLED under various ambient lighting conditions, there were still few studies that aimed for a HUD which the display theory and the application were slightly different from those devices. Based on the above reason, a psychophysical experiment was conducted in this study to investigate the visual clarity of a HUD with the different text-background lightness combination under daylight and dark conditions for better enhancing its visual perception.

Methods

Thirteen naïve observers, including 12 males and a female, age between 20 and 24 years old (mean = 21.1, std. dev. = 1), participate in the experiment. All of them have passed the Ishihara Color Vision Test to represent their normal color vision.

The experiment is carried out using a windshield and set up with a tripod. The viewing angle between the windshield and the horizontal is 45° at the subject's position. A 9.7-inch iPad Air 2 with a black boundary is placed on a horizontal table, as shown in Figure 1(a). The dimensions of the viewing booth are 70 cm (length) × 65 cm (width) × 80 cm (height), and interiors are covered with Munsell N7 spectrally neutral paint. Figure 1(b) shows the experimental setup captured from the observer's eye position, in which the viewing distance is about 80 cm between the eye and the iPad. The white point of iPad Air 2 reaches a peak luminance of approximately 403 cd/m^2 with chromaticities of (0.3069, 0.3266) after a 30-minute stabilization period. Besides, the viewing booth contains the illumination of a four-channel spectrally tunable LED device (ARRI SkyPanel S60-C) to produce a light source. The LED device was adopted to carefully provide a light source by adjusting the illuminance level to 15000 lx with a horizontal CCT of 6500 K. The relative spectral power distribution (SPD) is shown in Figure 2, and Table 1 lists the colorimetric characteristics of the ambient lighting conditions measured by a calibrated spectroradiometer (JETI specbos 1211TM).

(a) (b)

Figure 1. *Experimental setup (a) Simulation of Head-up display (b) An example of viewing field (The chin rest is removed for this photograph)*

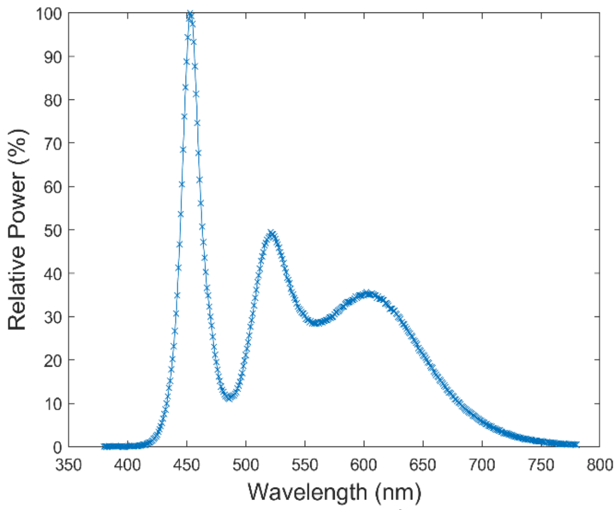


Figure 2. *The relative spectral power distribution of the light source (6500 K, 15000 lx)*

Table 1 The colorimetric characteristics of the ambient lighting conditions

CCT (K)	E (lx)	CRI R_a	D_{uv}
6471	15000	98	-0.002

The RGB values of the iPad are adjusted to produce five achromatic colors for different background lightness. The same calibrated spectroradiometer mentioned above is placed on the observer's eye position to obtain their colorimetric characteristics. The information is listed in Table 2, and Table 3 for dark and (6500 K, 15000 lx) surround conditions, respectively. Totally 20 text-background lightness combinations are acquired from these five colors with one for the text and one of the others for the background. These 20 combinations are always present as a paired-comparison for estimation, as shown in Figure 3, with a total of 190 pairs.

Table 2 The colorimetric characteristics of the five achromatic colors produced on the iPad under dark surround condition

Color	Luminance (cd/m^2)	L^*	(x, y)
Black	0.7	3.72	(0.311,0.328)
Dark grey	7.77	25.47	(0.321,0.338)
Medium grey	32.9	51.1	(0.318,0.333)
Light grey	82.6	75.19	(0.317,0.332)
White	170	100	(0.317,0.331)

Table 3 The colorimetric characteristics of the five achromatic colors produced on the iPad under 15000 lx

Color	Luminance (cd/m^2)	L^*	(x, y)
Black	950	93.81	(0.32,0.323)
Dark grey	957	94.08	(0.32,0.323)
Medium grey	981	94.99	(0.32,0.323)
Light grey	1030	96.81	(0.319,0.323)
White	1120	100	(0.319,0.324)

Before starting the experiment, two minutes of dark adaption is required. The observer is requested to fix the viewing distance to 80 cm with a chin rest. Therefore, thirteen observers can experience a similar viewing geometry as possible. For each pair of the text-background lightness combination, the observers are asked to choose the one that provided relatively better visual clarity. A neutral grey image is displayed for one second before the next pattern shows. The procedure is adopted to eliminate the effect of visual afterimage from the previous one. Under each ambient condition, the observer evaluates 210 pairs in random order. Each observer assesses 20 of the 190 pairs twice for verification. The entire experiment takes around 35 minutes for each observer.

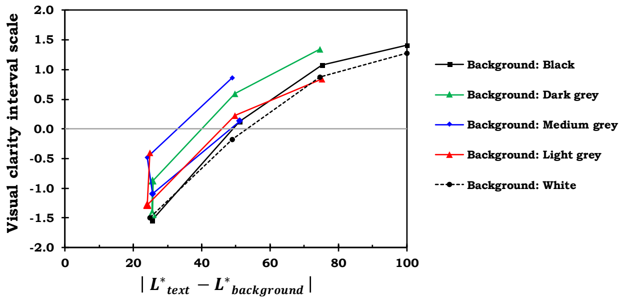
Figure 3. *A screenshot of the paired-comparison presented on the iPad*

Results and Discussions

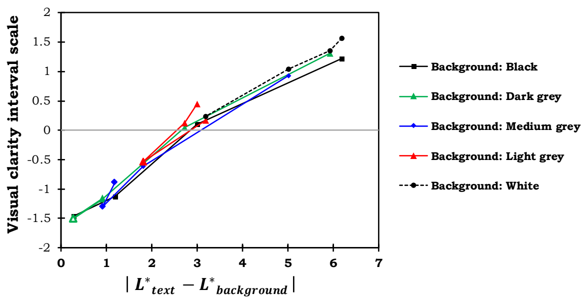
For the 20 pairs that are evaluated twice under dark surround condition and 15000 lx, the observers make identical judgments for the 93.3% pairs on average, suggesting the high reliability of the experiment.

Evaluations of different text-background lightness combinations

It is obvious that better visual clarity can be perceived with the increase of the difference in lightness between text and background, especially for 15000 lx surround condition. The result indicates that the observers tend to read the content from high to low luminance contrast between text and background. Referring to Figure 4(a), a text-background lightness combination—white text with black background (i.e., $L^*_{\text{background}} = 3.72$; $L^*_{\text{text}} = 100$)—is consistently judged the clearest when the surround is dark. For the daylight, which is simulated by 15000 lux, the text-background combination of black text with a white background ($L^*_{\text{background}} = 100$; $L^*_{\text{text}} = 93.81$) is judged as the clearest as shown in Figure 4(b). When the ambient lighting is 15000 lx, the observers generally prefer the combinations with a white background to be more apparent than those with a black background under the same difference in lightness. In contrast, the combinations with a black background can provide better visual clarity than those with a white background under dark surround condition.



(a) Dark



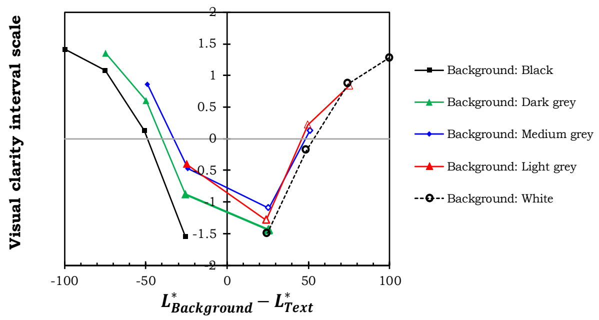
(b) 6500 K, 15000 lx

Figure 4. *Visual clarity Interval scale of the 20 text-background combinations evaluated by the observers under each surround condition (a) Dark; (b) 6500 K, 15000 lx*

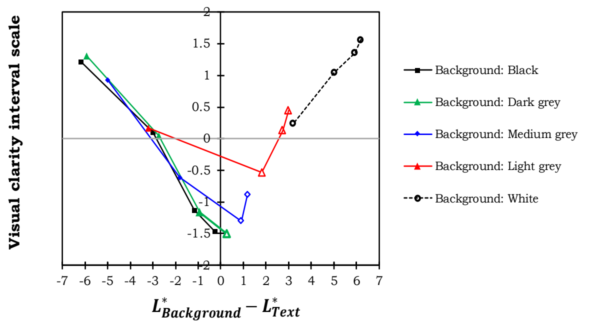
The influence of positive and negative contrast to the observers' response in the visibility is discussed. The results are shown in Figure 5. For the same background with the same text-background lightness difference, a higher positive contrast (i.e., the text is darker than the background) is better to increase the visual clarity for the white and light grey backgrounds under dark surround condition. However, a negative contrast (i.e., the text is brighter than the background) is beneficial to the improvement of visual clarity for the rest of the three backgrounds.

From Figure 5(b), a higher positive contrast can approach the highest scale value of visual clarity with the white background under the 15000 lx lighting condition. This finding is much more significant comparing to the dark surrounding condition. Besides, it can be found that the positive contrasts are appropriate for the background with higher luminance inclusive of the white and light grey backgrounds. In comparison, the backgrounds with relatively lower luminance, such as black, dark grey, and medium grey, need apparent negative contrast to increase the legibility of the text under these two ambient lighting conditions.

Figures 4(a) and 5(a) illustrate that the visual clarity of the combinations with white backgrounds is slightly worse than those with black backgrounds under the dark environment. In contrast to the dark surround, the text with white background contributes to a much higher visual clarity scale under 15000 lx, as shown in Figure 5(b). Therefore, adopting a higher background luminance is recommended to enhance the visual clarity under an extremely bright environment.



(a) Dark



(b) 6500 K, 15000 lx

Figure 5. *Visual clarity Interval scale of the 20 text-background combinations evaluated by the observers under each surround condition. The open markers are used to represent positive contrast. (a) Dark; (b) 6500 K, 15000 lx*

Modeling

The second-order polynomial regression model, a nonlinear analysis method, is utilized to describe the relationship between the input parameters and the visual clarity scale. The model can be formulated as Equation 1, where the *s* is the illuminance of the surrounds, *b* and *t* represent the luminance of the backgrounds and text, respectively. They are selected as the inputs for the training procedure. A feature scaling method, Min-Max Normalization, is applied to the input data for improving accuracy and faster convergence.

$$C(s,\ b,\ t) = -95.63s^2 + 5.16b^2 + 22.27t^2 + 203.51s \cdot b$$
$$-250.68b \cdot t + 174.50t \cdot s - 95.63s + 20.48b + 16.41t \quad (1)$$

Two evaluation metrics, including the coefficient of determination (R^2) and root-mean-square error (RMSE), are commonly used to evaluate a machine learning model's performance. According to Figure 6, which is the scatter plot of the predicted values and the ground-truth, the visual clarity scale obtained from the observers can be well predicted with high R-squared and low RMSE, where the values are 0.94 and 0.24, respectively. Additionally, the model shows a high correlation coefficient, and Pearson's r value is 0.97. The models can be further applied to the AR industry and its manufacturer for developing an advanced HUD with real-time enhancements corresponding to the changes in luminance of driving conditions.

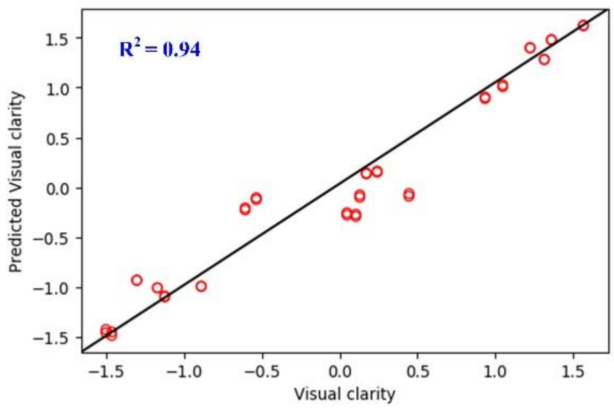


Figure 6. *Scatter plots of prediction for the visual clarity*

Conclusions

In the study, a psychophysical experiment is carried out to investigate the visual clarity of different text-background lightness combinations by using a head-up display under a dark surround condition and a bright environment. Thirteen observers evaluate the visual clarity of different text-background lightness combinations, where the 20 pairs among 190 pairs are displayed twice.

From the experimental results, the combination of the white text with black background (i.e., $L^*_{\text{background}}$ = 3.72; L^*_{text} = 100) is the clearest under the dark surround. Under the bright environment (15000 lx), the clearest text-background combination composed by the black text and white background ($L^*_{\text{background}}$ = 100; L^*_{text} = 93.81). Besides, the judgments of visual clarity under the dark surround show that the combinations of text with white background provide less visual clarity than those with a black background. On the other hand, the observers generally consider that combining with a white background is clear than those with other backgrounds luminance for 15000 lx. Furthermore, a second-order polynomial regression model is developed based on the visual data with a high correlation of determination. The findings of this work can be regarded as guidelines for the head-up display design to enhance drivers' visual perception depending on the ambient illuminance level.

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