https://doi.org/10.2352/issn.2169-2629.2021.29.42

Effects of Display and Ambient Illuminance on Visual Comfort for Reading on a Mobile Device

***Yu Liu, Ming Ronnier Luo*[*1]**
[1]State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou, China
***m.r.luo@zju.edu.cn**

Abstract

A psychophysical experiment was carried out to investigate visual comfort when reading on three OPPO Find X3s displays at three luminance levels (100, 250 and 500 cd/m2) at five illuminance levels (0, 10, 100, 500 and 1000 lx). Twenty young observers evaluated visual comfort using a 6-category points method. The results showed that observers felt most comfortable at the illuminance of 500 lx or display luminance of 500 cd/m^2. There was an interaction between ambient illuminance and display luminance. High ambient light and display brightness levels provide a more pleasant visual experience. In low ambient light, however, the lower the brightness level, the more comfortable it is to see. Regarding the influence of background colour on visual comfort, the observers felt more comfortable having a grey background than white or black colour. When at dim illuminance, the background colour would have a great influence on visual comfort for negative contrast conditions, but when at higher illuminance, different background lightness levels had a great impact on visual comfort for positive contrast conditions. The above findings are very similar to the display luminance levels of 100 and 250 cd/m^2.

Introduction

Nowadays, almost everybody has a mobile phone. Reading text on a mobile phone is one of the most popular tasks. To give visual comfort under varied ambient lighting circumstances, it is critical to identify the ideal display conditions, such as display luminance, text, and background color.

Earlier studies have shown that several factors can affect visual comfort. Firstly, positive polarity (dark text on light background) produced more accurate faster reading results than negative polarity (light text on dark background) [1][2]. This is due to users being more familiar with the positive polarity arrangement. Secondly, positive polarity arrangement is most widely used for Internet Network information and manuscripts. The unwanted reflection from the screen, known as glare is less visible when displayed in a positive polarity arrangement [3][4]. Finally, the overall brightness of the positive polarity arrangement is significantly higher than that of negative polarity layout. Higher brightness causes pupils to shrink, making the retina image to be clearer.

Luminance contrast between text and background also has a noticeable impact on visual comfort. Ou and his colleagues found [5][6] that achromatic colours were better background colours than white and black. It was more comfortable to have a medium or light grey background with a positive polarity arrangement (i.e., light text on a dark background). Lin and Huang [7] investigated the effects of lightness contrast on visual perception on a TFT-LCD screen at a peak white luminance of 210 cd/m^2. The results are reported in visual perception time, which is defined as the time from stimulus appear to observers perceived the stimulus. They found that background luminance of 80 cd/m^2 and text luminance of 5 cd/m^2 performed better at perception time.

Nowadays the brightness of the display can be adjusted according to the user's preferences and ambient light level. Several prior studies looked into the optimal display luminance contrast under different ambient lighting conditions. Na and Suk [8] discovered 40 cd/m^2 was the best display luminance for their smartphones (peak luminance of 140 cd/m^2) in a dark environment. Sun *et al.* [9] asked 17 college students to assess video quality of display (peak luminance=462 cd/m^2) at various degrees of ambient illuminance and backlight magnitude. The visual comfort scores were first increased from low level then decreased with a raise of backlight level. Wang *et al.* [10] reported the optimal display luminance and ambient illuminance combination level for viewing 3D displays. They found a brighter display luminance produced a more comfortable feeling when viewing static pictures. At the same time, they observed that more comfortable at high level of display luminance (47.3 cd/m^2) and ambient illuminance (300 lx). As for the low level of ambient illuminance (55 lx), more comfortable were obtained at the low level of display luminance (6.7 cd/m^2).

In addition to the display luminance, ambient illuminance has been extensively investigated. Ou *et al.* [11] studied 43 observers under 4 ambient illuminance levels (50, 200, 600, 1200 lx) at a fixed CCT 6500K. The results showed that the lower illuminance, the greater visual discomfort. They [12] also investigated the effects of ambient illumination conditions and background colour on visual performance with TFT-LCD screens by character identification. In terms of illuminance intensity, the best mean character identification performance was 500 lx, followed by 250 and 1000 lx.

With the above in mind, the goal of the present study was to investigate the impact of ambient illuminance, display luminance, and text and background contrast have a significant impact on visual comfort.

Experimental

Observers

A total of 20 Chinese observers, including 16 males and 4 females participated in the experiment. The observers were aged between 18 and 24 years (mean=19.5, SD=1.6). All the observers had a normal colour vision, using the Ishihara's test for colour deficiency. All of the observers from the University had similar English proficiency in reading Early Modern English poems.

Display

Three 6.7-inch OPPO Find X3 mobile phones were used to evaluate the visual comfort. Auto-brightness, night mode and other parameters of the mobile phone turned off. They all had a peak white at a luminance of 500 cd/m^2 and a CCT close to 7000K. The peak white of the display luminance in the experiment was set to 502 cd/m^2 with white point chromaticity (0.3117,0.3277) (i.e., CCT=6715K). CIELAB ΔE of the three phones ranged from 0.86-1.02 (mean=0.93, SD=0.07) and CIELAB ΔE2000 of the three phones ranged from 0.83-1.14 (mean=0.98, SD=0.13). A Konica Minolta CS-2000 spectroradiometer was used to measure all colours in the experiment. The 24 colours of the X-Rite Macbeth ColorChecker Chart between the target and display colour had a mean of 1.2 ΔE^*_{ab} units. Two of the displays were also masked by Neutral Density Filters (Edmund Optics, USA) having transmittance values of 20% and 50% respectively. This resulted in 3 display luminance levels, 100, 250, 500 cd/m^2.

Ambient Illuminance

The experiment was conducted in an office setting. The window was blocked by thick curtains. A Thouslite® spectral tunable LED lighting system installed in the ceiling was used in the experiment. The illuminance levels were controlled at 10, 100, 500, 1000 lx with a CCT close to 6500K. Table 1 lists the measured desktop illuminance, CCT, Duv and colour rendering index (R_a) of the ambient lighting conditions.

Table 1. Chromaticity characteristics of 4 lighting conditions

No.	*Illuminance(lx)*	*CCT(K)*	*Duv*	R_a
1	11	6580	-0.0045	90
2	100	6524	-0.0004	95
3	498	6507	-0.0022	92
4	1010	6507	-0.0039	90

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Display stimuli

Seven achromatic colours of different lightness levels were used to evaluate the visual comfort of various text-background combinations, as listed in Table 2. All seven achromatic colour combinations resulted in 42 text-background combinations. As a result, 750 evaluations were completed, i.e. 50 combinations × 3 display luminance levels × 5 ambient illuminance levels.

Table 2. Colourimetric characteristics of the seven colours that were used for the text and background combinations for evaluating the visual comfort of text-background lightness combinations. Take one of the mobile phones as an example.

Color	*Luminance* (cd/m^2)	*CIELAB lightness L**	*a*	*b*
white	495	100	0.89	-2.23
grey80	277	80	0.65	-2.46
grey60	137	60	0.67	-2.09
grey50	89	50	0.66	-1.86
grey40	54	40	0.25	-1.20
grey20	14	20	1.35	-0.57
black	0	0.6	0.07	-0.04

Figure 1 depicts a test image using CIELAB L* values of texts and background respectively. As stimuli, the identical image including texts of Shakespeare's sonnets was used. The RGB of background grey of the Graphical User Interface as anchor colour was set to (128,128,128). Observers evaluated their visual comfort when reading text using a 6-category point scale. 1 - very uncomfortable, 2 -uncomfortable, 3 - a little uncomfortable, 4 - a little comfortable, 5 - comfortable, 6 - very comfortable. The results were used for direct comparison of the visual comfort levels under different illumination. Under each circumstance, each observer completed 50 judgements, including 8 random repetitions.

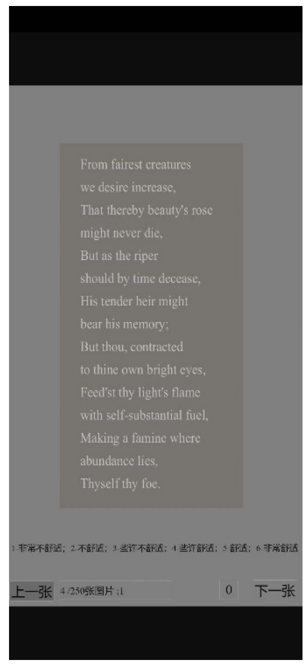


***Figure 1**. An example of the screen layouts used in the experiment.*

Experimental procedures

Upon arrival, the observer read the experiment instructions, fill out a general information survey and did the Ishihara Color Vision Test. Following that, each observer adjusted the height of the seat so that their eyes are perpendicular to the screen of the phone. The viewing/illuminating geometry was 0° /45°. Before the formal experiment, there was a training session for observers to fully understand the experimental purpose. Prior to the experiment, observers were asked to look at the screen for 2 minutes for adaptation. Each observer evaluated the visual comfort of 50 combinations when reading text. The 50 combinations were presented in random order. After evaluating 50 combinations, the observer experienced another 2-min washout period. The same procedure was repeated 15 times. The order of display luminance levels and ambient illuminance levels was random. The whole study took about 90 minutes for each observer.

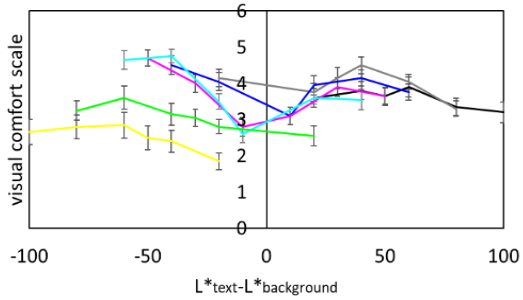
Results

Inter- and intra- observer variations

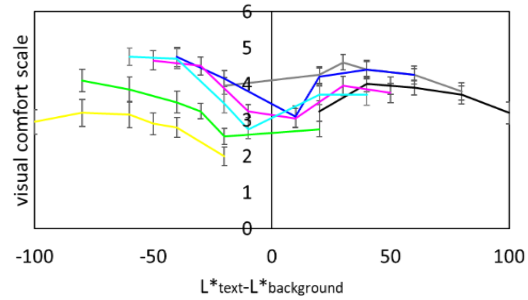
The standardized residual sum of squares (STRESS) as shown in Equation 1 was used to measure variations of the intra-observer and inter-observer. The STRESS measure was use to analyze the agreement between two sets of data. It is ranged from 0 to 100. For a perfect agreement, it will be zero. A value of 20 means 20% disagreement A higher *STRESS* value indicates a larger dispersion.

$$STRESS = \left(\frac{\sum_{i=1}^{n}(A_i - FB_i)^2}{\sum_{i=1}^{n} F^2 B_i^2}\right)^{1/2} \times 100 \qquad (1)$$

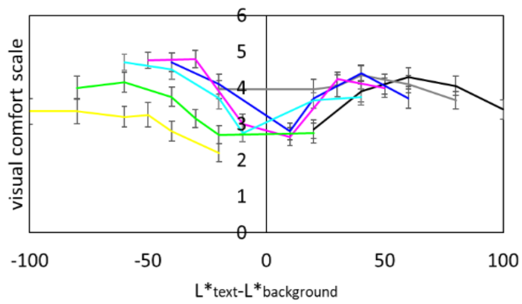
where $F = \sum_{i=1}^{n} A_i^2 / \sum_{i=1}^{n} A_i B_i$



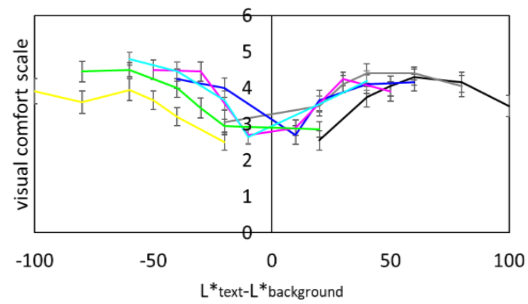
(a)



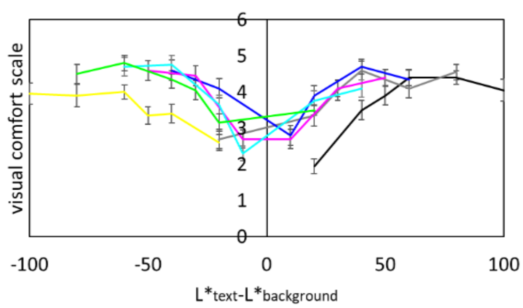
(b)



(c)



(d)



(e)

***Figure** 2. Average visual comfort plotted against lightness difference between text and background on the screen of display luminance of 500 cd/m^2 under each ambient illuminance: (a) 0, (b) 10 lx, (c) 100 lx, (d) 500 lx, (e) 1000 lx. The black, grey, blue, magenta, cyan, green and yellow lines represent the background L* values of 0.6, 20, 40, 50, 60, 80, 100, respectively. Error bars show the 95% confidence intervals.*

When the intra-observer variations were calculated, the A and B data were the evaluation of visual comfort obtained from two sets of repeated judgments under the same condition. When the inter-observer variations were calculated, the A and B data were mean and individual observer's results, respectively. The average intra-observer variations ranged from 5.7% to 26% (mean=13, SD=4) and inter-observer variations ranged from 16% to 49% (mean=26, SD=7).

IBM SPSS 22® software was used to analyze the data. There is some research that shows a parametric test can be used with a Likert scale [13-15]. Main repeated factors 'ambient illuminance' (0, 10, 100, 500, 1000 lx) and 'display luminance' (100, 250, 500 cd/m^2) of mixed-model analysis were applied.

Effect of Background Colour and Contrast

To see whether the background colour had any impact on visual comfort, the average visual comfort results were plotted against the lightness contrast defined by the lightness of text (L^*_{Text}) minus the lightness of the background ($L^*_{Background}$)., when display luminance is 500 cd/m^2 as shown in Figure 2(a)-2(e) from dark 0 to bright 1000 lux levels, respectively. Note the other 2 luminance of display did have similar results to 500 cd/m^2 so that only the results from 500 cd/m^2 were given here. All the figures showed that greys were better background colours than white and black. Where the visual comfort curve is always similar for background luminance of 20-60. The white background score increases as the ambient illuminance rises. In low-light levels, the black background score is quite similar to the grey background score. However, as the ambient illuminance increases, the black background score falls below that of the grey background. It can be seen the trend of visual comfort of all background colors to be similar. As the absolute value of contrast rises, visual comfort could be continuously rises, or first rises and then declines. As the ambient illumination increases, the visual comfort also increases.

Effect of Ambient Illuminance

Figure 3 shows the mean visual comfort results plotted against ambient illuminance. Multivariate test result showed that ambient illuminance caused significant changes in visual comfort ($F(4,836)=9.456$, $p<0.001$, $\eta^2=0.043$). Post hoc test shows that the visual comfort score of 500 lx is higher than the other conditions (*p*s.<0.05), whereas the visual comfort score of 0 is lower than other conditions (*p*s.<0.05). From 0 to 500 lx, the higher the illuminance level, the greater visual comfort. When the illuminance reached 1000 lx, however, spectators became uneasy. As mentioned before, there was a trend that visual comfort of 600 lx was a little higher than 1200 lx, 200 lx and 50 lx according to Ou et al.'s [11] experiment. The results of two experiments are quite similar.

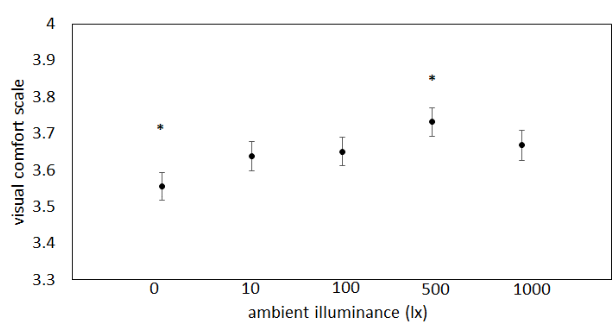


*__Figure 3.__ Visual comfort plotted against ambient illuminance. * Showing visual comfort score of 500 lx is higher than other conditions and visual comfort score of 0 is lower than other conditions (p<0.05). Error bars show the 95% confidence intervals.*

Effect of Display Luminance

Figure 4 shows the higher the display luminance, the more visual comfort will be. Multivariate test revealed a significant effect of display luminance ($F(2,838)=6.164$, $p=0.002$, $\eta^2=0.014$).Visual comfort of 500 cd/m^2 is higher than other conditions (*ps.*<0.01). Na and Suk [8] found 40 cd/m^2 was the best display luminance for cellphones (maximal luminance of 140 cd/m^2) in a dark surround. Our results showed that background L* 60 (luminance was about 30 cd/m^2) was the best display luminance when display luminance equal to 100 cd/m^2. These two results were rather close.

There was a significant interaction between ambient illuminance and display luminance ($F(8,832)=13.861$, $p<0.001$, $\eta^2=0.118$). From Figure 5, it is clear that under 1000 lx the higher the display luminance, the more comfortable it is, but the darker the surround, the more comfortable it is, especially at low display luminance (100 cd/m^2). There is one exception for ambient illuminance 10, i.e. at display luminance=100 the comfort is high, then at display luminance=250 the comfort lowers and higher again at display luminance=500.

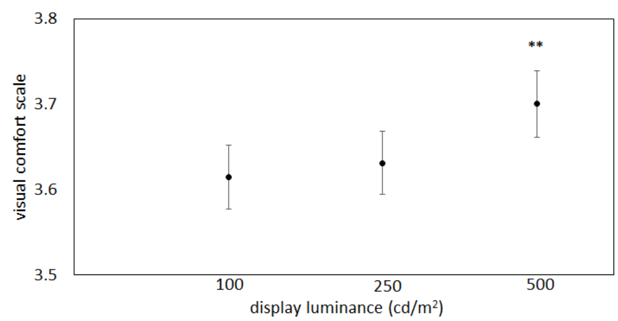


*__Figure 4.__ Visual comfort plotted against display luminance. ** showing visual comfort of 500 cd/m^2 is higher than other conditions (p<0.01). Error bars show the 95% confidence intervals.*

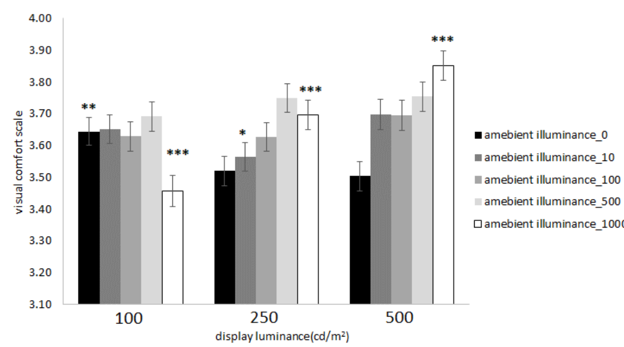


__Figure 5.__ Visual comfort plotted against display luminance under 5 ambient illuminance levels. Error bars show the 95% confidence intervals.

Conclusion

A psychophysical experiment was conducted to evaluate the visual comfort of 20 young observers when reading on OPPO Find X3s of three display luminance levels (100, 250 and 500 cd/m^2) under various illuminance levels (0, 10, 100, 500 and 1000 lx). Summaries of experimental results are: 1) observers feel most comfortable when ambient illuminance reached 500 lx or display luminance reached 500 cd/m^2.; 2) the observers feel more comfortable reading documents with a grey background than documents with a background colour of either white or black; 3) a lower lightness contrast produces the least visual comfort. The present study only investigated visual comfort under various ambient illuminance levels of young observers. Our further study should be done to investigate the visual comfort of observers of various ages under different CCT lightings using 6-category points.

Acknowledgement

The authors like to thank the support of OPPO Guangdong Mobile Telecommunications Co., Ltd.

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Author Biography

Yu Liu received her BSc degree from College of Optical Science and Engineering, Changchun science and technology University, Changchun, China. She is currently a PhD student supervised by Professor Ming Ronnier Luo at Zhejiang University since 2018. Her research interests include health lighting and visual comfort.