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An Adaptive Model for Predicting Visual Comfort of Displays Accounting for Luminance Contrast in Various Ambient Light Conditions

Zhenzhen Li*[1], *Ming Ronnier Luo*[1]
[1] ***State Key Laboratory of Extreme Photonics and Instrumentation, Zhejiang University, Hangzhou, China.***

Abstract

The ubiquitous use of mobile devices has underscored the importance of evaluating display visual comfort to reduce eye strain and fatigue. This developed and tested visual comfort model for display visual comfort, taking into account key factors such as ambient illuminance, display luminance, text-background luminance contrast. The VC_{ALL} *model was built based on three psychophysical experimental datasets: Neutral Colour Combination (NC), Coloured Combination (CC), and Neutral Colour Combination with Dim Ambient Light (NCD), which involved 103 participants spanning various age groups. Two new experiments were conducted to verify the model' performance. One is to use the model to access displays' visual comfort, using an LCD and a QD_mini-LED, comparing with the results from various other testing methods. The other experiment was conducted to verify the performance of* $VC_{reverse}$ *by computing optimal text-background luminance combinations for any display under varying ambient light.*

Introduction

Reading on mobile devices has become a significant part of daily life. While the human eye is capable of functioning in various lighting conditions through its adaptive mechanisms (1), prolonged use of electronic devices can lead to a range of visual issues, including dry eyes, eye strain, and blurred vision. These symptoms indicate the need to address visual fatigue and safeguard eye health (2). Therefore, it is crucial to investigate the factors affecting display visual comfort and to develop comprehensive methods for quantifying and predicting this comfort to mitigate potential health risks.

Visual comfort of display was defined as achieving suitable contrast levels and minimizing glare to allow participants to clearly perceive the text content in this study (3) . Current research focuses on multiple factors, including ambient illuminance (4), viewing distance (5), age (6), and display related factors, such as luminance (7) and resolution (8). Benedetto et al. studied the combined effect of display luminance and ambient illuminance on visual fatigue during long-term digital reading, and found that high screen lightness resulted in faster saccade and reading speed, as well as fewer blinks (9). The luminance contrast between the text and background is considered to have a significant impact on visual comfort, which has been extensively discussed (10). The study conducted by Nooree et al. suggested that high lightness contrast which was determined through a non-linear transformation of the luminance could significantly enhance visual performance in various aspects, including reaction time, reading ability, search efficiency, and visual acuity (11). It was also found that digital displays with high luminance contrast, positive polarity and adequate chroma were preferred for better visual comfort (12). However, the factors influencing visual comfort in these studies are quite varied, and there has been no comprehensive comparison of which factors have the greatest impact on visual comfort.

We have conducted multiple studies in similar reading scenarios and with similar displays (13–16). The results show that the colour temperature of ambient light has no significant effect on display visual comfort, while the illuminance of ambient light has a significant effect on visual comfort and interacts significantly with the luminance of the display (13). Additionally, the content displayed on the screen is crucial for visual comfort, especially the lightness contrast of the text and background, significantly affect visual comfort (13,15). The chroma of the text also affects display reading comfort, but increasing chroma has little impact on comfort (16).

The display visual comfort models included in current research can be categorized into the following types. The first category investigates the relationship between display luminance and ambient illuminance (17–19). However, these models often neglect the interaction between various factors, which can lead to reduced display clarity in low-light environments, ultimately diminishing user experience. The second category focuses on ophthalmological parameters and physiological signals (20–23). While these models exhibit a strong correlation with subjective data, they are often more complex to implement, requiring advanced testing methods and technical expertise. In contrast, the visual comfort model developed in this study effectively captures the interplay between ambient illuminance, display luminance, and text-background contrast, offering a practical and accessible framework for quantifying and predicting visual comfort during screen use. Notably, the reverse implementation of this model can be conveniently applied in real-world scenarios, enabling adaptive contrast optimization based on varying ambient lighting conditions.

This study utilizes three psychophysical experimental datasets—Neutral Colour Combination (NC), Coloured Combination (CC), and Neutral Colour Combination with Dim Ambient Light (NCD)—involving 103 participants across different age groups, to develop a visual comfort model for display-based reading. To testing the model's applicability and effectiveness, subjective and objective critical flicker fusion (CFF) tests were conducted using LCD and QD_mini-LED displays. In addition, another verification experiment was conducted to verify the performance of $VC_{reverse}$ by computing optimal text-background luminance combinations for any display under varying ambient light.

Methods

Measurements

In this study, the evaluation of visual comfort was conducted using both subjective and objective assessment methods. The model development primarily relied on subjective evaluation, with objective methods employed to supplement and validate the findings. The dataset used in this research was gathered using a 6-point Likert scale (24). During the experimental phase, participants were exposed to a range of visual stimuli displayed on a screen. They

Table 1. Details of three training datasets and testing dataset for the visual comfort model VC_{ALL}.

Study	Dataset	Observers	Stimuli
Y., Liu (2022)	NC (Neutral Colour Combination)	Children: 20 (12 males, 8 females)	A total of 750 evaluations: (42 combinations + 8 repetitions) × 3 display luminance levels × 5 ambient illuminance levels.
		Young Adults: 20 (10 males, 10 females)	
		Older Adults: 20 (16 males, 4 females)	
Z., Li (2024)	CC (Coloured Combination)	Young Adults: 20 (12 males, 8 females)	A total of 230 evaluations: 192 combinations (3 background levels × 4 text hue levels × 4 colour difference levels) + 38 repetitions.
Z., Li (2025)	NCD (Neutral Colour Combination with Dim Ambient Light)	Young Adults: 23 (14 males, 9 females)	A total of 145 evaluations: (30 combinations + 5 repetitions) × 4 ambient illuminance levels.)
Testing Dataset	Using LCD and QD-mini LED displays for testing	Young Adults:9 (2 females, 7 males)	A total of 360 evaluations: (2 display types × 3 luminance levels × 30 images × 2 repetitions)
Verification Dataset	Using three mobile phones	Twenty-one participants (12 males, 9 females)	A total of 40 evaluations (5 contrast levels × 2 repetitions × 4 ambient illuminance levels)

were instructed to read the content carefully and then rate their perceived visual comfort according to the Six-level Likert scale: 1 (very uncomfortable), 2 (uncomfortable), 3 (slightly uncomfortable), 4 (slightly comfortable), 5 (comfortable), and 6 (very comfortable). Both the NC and CC datasets were acquired using this methodology. To validate the subjective findings, the Critical Flicker Fusion (CFF) method was utilized (20). CFF thresholds have been widely documented in previous studies as a reliable measure of visual perception [11, 32]. A lower CFF value is indicative of diminished alertness resulting from fatigue [57]. In this study, CFF measurements were taken three times both before and after the validation experiments. The difference between the pre-test and post-test CFF values, termed the Critical Flicker Frequency Difference (dCFF), was computed. A higher dCFF value reflects a greater degree of fatigue attributable to the visual performance test.

Training Dataset

This study employs three datasets as training sets to develop a display visual comfort model. As shown in Table 1, the datasets consist of the NC (Neutral Colour Combination) dataset, the CC (Coloured Combination) dataset, and the NCD (Neutral Colour Combination with Dim Ambient Light) dataset. Collectively, these datasets offer a comprehensive evaluation of visual comfort across various environmental conditions.

The NC (Neutral Colour Combination) dataset, sourced from Y. Liu (2022), included evaluations from three age groups: children, young adults, and older adults. A total of 60 participants were involved, including 20 children (12 males, 8 females), 20 young adults (10 males, 10 females), and 20 older adults (16 males, 4 females). The dataset comprised 750 evaluations, derived from 42 unique combinations and 8 repetitions, tested under three display luminance levels (100, 250, and 500 nits) and five ambient illuminance levels (0, 10, 100, 500, and 1000 lux). This comprehensive design provided a robust assessment of visual comfort across varying lighting conditions and demographic groups.

The CC (Coloured Combination) dataset, contributed by Z. Li (2024), focused on young adults, consisting of 20 participants (12 males, 8 females). This dataset included 230 evaluations, comprising 192 unique combinations and 38 repetitions. The combinations were generated by varying three background levels, four text hue levels, and four colour difference levels. This dataset provided an in-depth exploration of the impact of colour combinations on visual comfort, particularly in dynamic and diverse visual environments.

The study also included an unpublished dataset, referred to as the Neutral Colour Combination with Dim Ambient Light (NCD) dataset. This dataset involved 23 young adult participants (14 males, 9 females) and was focused on evaluating visual comfort under low ambient lighting conditions. A total of 145 evaluations were performed, comprising 30 unique combinations and 5 repetitions, tested across four ambient illuminance levels. This dataset was designed to explore the interplay between neutral colour combinations and dim lighting environments, providing valuable insights into visual comfort in settings with reduced illumination. This dataset complements the existing NC and CC datasets, thereby enhancing the robustness and generalizability of the model.

The last dataset is NCD (Neutral Colour Combination with Dim Ambient Light). As shown in Table 2, it illustrates the relationship between the predicted values of the VC_{NC} model (a visual comfort model based on the NC dataset) and the participants' subjective ratings at different lighting levels. The results show that the R^2 values for the three datasets under 500 lx ($R^2 < 0.8$) are generally lower than those for the model above 500 lx ($R^2 > 0.8$), indicating that the original VC_{NC} model is less accurate in dim lighting conditions compared to high illuminance ambient lighting. Consequently, the NCD dataset was created to improve the model's accuracy in predicting display visual comfort in dim lighting conditions

Testing Dataset

This testing experiment aims to compare the visual comfort assessment of displays using various testing methods against the predictions of the VC_{ALL} model to evaluate their consistency. This experiment recruited 9 participants from Zhejiang University (2 females and 7 males), all of whom passed the Ishihara colour vision test and were confirmed to have normal colour vision ability.

The experiment was split into two groups, where LCD screen and LED screen were used as the experimental equipment. In order to maintain consistency, the luminance of both monitors was adjusted to three levels: 150 nit, 300 nit, and 450 nit. Despite the difference in physical size between the two displays, the stimulus images were standardized to 8.27 inches by 11.69 inches. The stimulus material comprised images of English poetry text, with Times New Roman font set at a size of 22 pt. The text-background colour combinations were formed through pairings of six colours, along with three sets of white point configurations, producing 30*3 test images per condition, followed by repetition. The experiment was designed with (2 display types × 3 luminance levels × 30 images × 2 repetitions), requiring each participant to perform 360 evaluations.

The experiment took place in a fully darkened environment, with the viewing distance fixed at 45 cm. The experimental scene layout can be seen in Figure 1. Prior to the experiment, the displays underwent a 30-minute colour temperature stabilization process using the Gain-Offset-Gamma (GOG) model, with features like auto-brightness adjustment and night mode disabled. Each experimental group underwent Critical Fusion Frequency (CFF) tests three times before and after the experiment to evaluate the participants' visual fatigue. A 10-minute break was scheduled between the two phases of the experiment. Participants were required to carefully examine each image and rate visual comfort on a 6-point scale, with the experiment lasting around 30 minutes.

Verification Dataset

The verification experiment aimed to validate the effectiveness of $VC_{reverse}$ model in generating optimal background and text luminance combinations for visual comfort under varying ambient lighting conditions. Twenty-one participants (12 males, 9 females) from Zhejiang University, all of whom passed the Ishihara color deficiency test, were recruited. The experiment was conducted in an office environment using a ceiling-mounted Thouslite® spectral tunable LED system, which provided ambient illuminances of 0, 100, 500, and 1000 lx at a correlated color temperature (CCT) of approximately 6500K. Three mobile phones, each with a peak white luminance of 700 cd/m² and chromaticity close to 6500K, were utilized. All display colors were measured with a Konica Minolta CS-2000 spectroradiometer, and the displays were fully characterized. Participants were asked to read meaningless English texts, counted target words, and rated the visual comfort of the images using Six-level Likert scale. Each participant completed 40 evaluations across five contrast levels and four ambient illuminance settings, all presented in randomized order. The VC_{ALL}（Equation 1）and $VC_{Reverse}$ models (Equations 2 and 3) determined the background and text luminance values, producing five contrast conditions: VCmax (optimal comfort for the specific ambient light, VC score higher than 4.5), VChigh (VC score of 4.4), VClow (VC score of 3.5), VCpositive (VC score ~4, text brighter than background), and VCnegative (VC score ~4, background brighter than text).

Result and Discussion

Visual comfort model

Based on these datasets, a visual comfort model was developed, incorporating ambient illuminance, text-background lightness contrast, and background lightness, in the form of equation (1).

$$VC_{ALL} = a \times \Delta L^{*2} + \mathrm{b} \times {L_B^*}^2 + \mathrm{c} \times Ea \times |\Delta L^*| + \mathrm{d} \times Ea \times L_B^* + \mathrm{e} \times |\Delta L^*| \times L_B^* + \mathrm{f} \times |\Delta L^*| + \mathrm{g} \times L_B^* + h \quad (1)$$

where ΔL^* represents the lightness contrast between text and background and L_B^* represents the lightness of the background. Ea represents the illuminance level of the ambient lighting.

Figure 1 illustrates the predictive performance of the VC_{ALL} model on these three datasets: the NC dataset, the CC dataset, and the NCD dataset. Each subplot clearly shows the relationship between the model's predicted visual comfort score and the actual subjective visual comfort score. In Figure 1 (a), corresponding to the NC dataset, the R² value is 0.7. The model accurately predicts the visual comfort for this dataset.

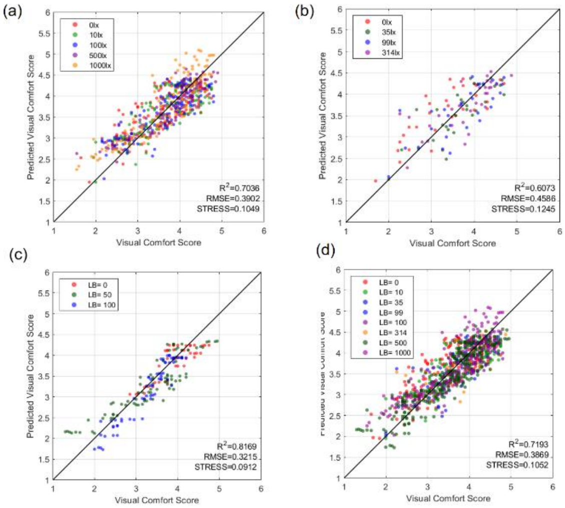

__Figure 1.__ Prediction performance of VC_{ALL} for (a) NC dataset, (b) CC dataset, and (c) NCD dataset (d) All dataset

Testing Result

The results in the Table 4 show that the CFF values for both experimental groups decreased after the experiment, suggesting that visual fatigue significantly increased after 15 minutes of screen usage. Specifically, the ΔCFF value for the QD_mini-LED display was -0.96, significantly lower than the ΔCFF value of -0.66 for the LCD, which indicates that the QD_mini-LED display induces a higher degree of visual fatigue than the LCD display. This conclusion aligns with the subjective visual fatigue scores, where the subjective score for the LCD was 3.12, and the score for the QD_mini-LED was 3.03.

A lower score indicates stronger discomfort during reading. Additionally, a non-parametric Wilcoxon signed-rank test was performed on the visual comfort ratings for the LCD and QD_mini-LED, with the results showing that the visual comfort of the QD_mini LED display is significantly lower than that of the LCD display ($p<0.001$). Such a result further corroborates the negative impact of the QD_mini-LED display on visual fatigue and visual comfort. Moreover, the VC_{ALL} model was used to predict the visual comfort scores for the LCD and QD_mini-LED, yielding results of

3.63 and 3.03, respectively, which were highly consistent with the subjective assessment results. This further demonstrates the model's strong accuracy and effectiveness in predicting visual comfort. Consequently, based on these data and the model's predictions, it can be concluded that the QD_mini-LED display induces a more significant degree of visual fatigue compared to the LCD display.

Table 4. The comparison result of XDR and QD_mini-LED

Display	LCD		LED	
	BT	AT	BT	AT
CFF Score	42.26	41.60	43.04	42.08
ΔCFF	-0.66		-0.96	
Subjective VC score	3.12		3.03	
VC_{ALL}	3.43		3.26	

Reverse model and verification

Equations (2) and (3) were derived by fitting the most comfortable luminance values calculated using Equation (1) for the VC_{ALL} model. These formulations also account for the display's white point, enhancing the model's applicability across displays with different white point characteristics. Using Equations (2) and (3), one can compute the optimal luminance and luminance contrast for displays with varying white points under different ambient lighting conditions. Given that displays have varying sensitivity to ambient light and that the polarity of luminance contrast influences visual comfort, Equations (2) and (3) provide distinct calculation methods based on ambient lighting conditions. Figure 2 illustrates a schematic representation of the optimal reading luminance contrast for a mobile phone display with a white point luminance of 534 nits. Under low ambient lighting conditions, luminance contrast increases with ambient light, exhibiting positive polarity. It remains constant under moderate illumination but becomes negative at higher illuminance levels.

$$\mathrm{L_b} = \begin{cases} L_w * (k_1 \times Ea + k_2)^3,\ a \le Ea < b \\ \gamma,\ b \le Ea < c \\ L_w * (k_3 \times Ea + k_4)^3,\ c \le Ea \le d \end{cases} \quad (2)$$

$$\Delta L = \begin{cases} L_w * e^{k_5 + k_6 \ln(k_7 Ea + k_8)},\ a \le Ea < b \\ \delta,\ b \le Ea < c \\ L_w * e^{k_9 + k_{10} \ln(k_{11} - k_{12} Ea)},\ c \le Ea \le d \end{cases} \quad (3)$$

where ΔL represents the luminance contrast between text and background and L_b represents the luminance of the background. Ea represents the illuminance level of the ambient lighting. L_w represents the peak luminance of the display. k1~k12 represent the coefficients.

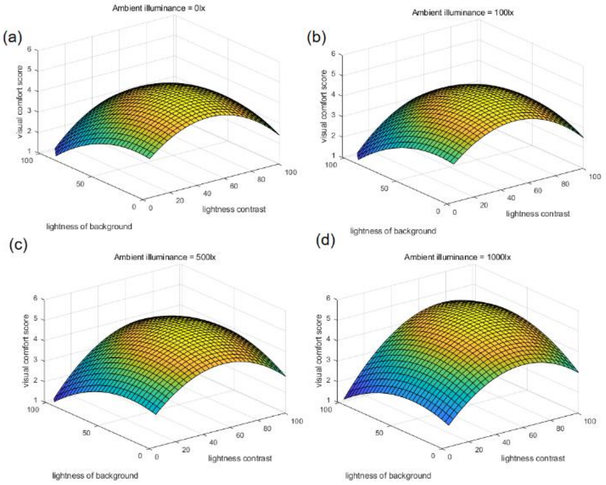

Figure 2. Subjective experimental comparison results of five different contrast combinations with different visual comfort scores calculated using the visual comfort model. (a) Ambient illuminance is 0lx. (b) Ambient illuminance is 100lx. (c) Ambient illuminance is 500lx. (d) Ambient illuminance is 1000lx.

To validate the optimal text-background luminance combinations derived from Equations (2) and (3), a verification experiment was conducted, and the results are presented in Figure 3. Five luminance contrast combinations were subjectively compared based on visual comfort scores derived from the VC_{ALL} and$VC_{reverse}$. Under ambient illuminance levels of 0 lx, 100 lx, 500 lx, and 1000 lx, the most comfortable contrast combination, VCmax—calculated using Equations (2) and (3)—consistently outperformed other contrast levels, particularly surpassing the VChigh condition. These results demonstrate that the optimal reading luminance combinations derived from Equations (2) and (3) are effective across different mobile phone displays.

Additionally, subjective visual comfort scores for the VChigh condition, calculated using the VC_{ALL}, were consistently higher than those for the VClow condition. Under ambient lighting conditions of 0 lx, 100 lx, and 500 lx, the VCpositive condition (where text is brighter than the background), also derived from the VC_{ALL} model, received scores of 4.25, 4.39, and 4.96, respectively—each exceeding the corresponding VCnegative scores of 3.89, 4.10, and 4.91. As shown in Figure 3, experimental results confirmed that participants' subjective comfort ratings closely aligned with the model's predictions: VCpositive contrast combinations were rated more comfortable than VCnegative combinations under all lighting levels except at 1000 lx. At this highest illuminance, the model predicted a comfort score of 5.66 for the positive polarity condition, lower than the 5.92 predicted for the negative polarity condition. Experimental data similarly indicated that participants found the negative polarity more visually comfortable when the ambient light illuminance is high. These findings provide strong validation for the VC_{ALL} and $VC_{reverse}$ models in determining the most visually comfortable display contrast configurations across varying ambient lighting conditions. Further validation experiments involving displays with different substrate technologies are planned.

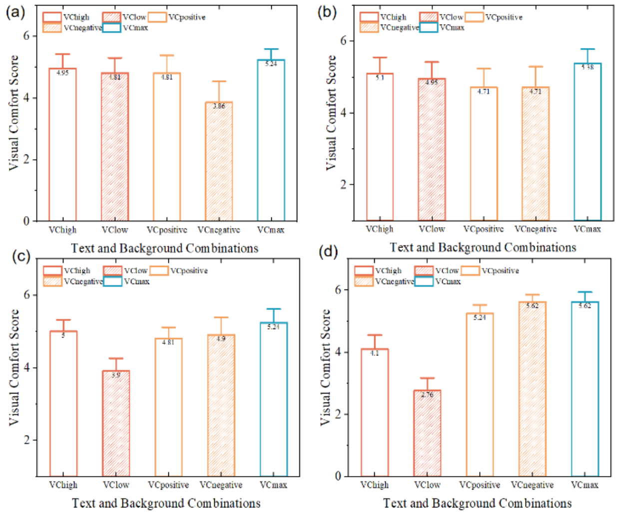

Figure 3. *Subjective experimental comparison results of five different contrast combinations with different visual comfort scores calculated using the visual comfort model. (a) Ambient illuminance is 0lx. (b) Ambient illuminance is 100lx. (c) Ambient illuminance is 500lx. (d) Ambient illuminance is 1000lx.*

Conclusion

A visual comfort model, VC_{ALL} , is introduced. It predicts visual comfort during display reading by considering the parameters of ambient illuminance, text-background lightness contrast, and background lightness. Built upon three psychophysical datasets (NC, CC, NCD), the model demonstrated robust predictive performance across all datasets. A key advancement of VC_{ALL} lies in its significantly improved accuracy under dim-light conditions (<100 lx), outperforming the earlier VC_{NC} model. The model can also be used to test the visual performance of various displays. In addition, this study introduced the $VC_{reverse}$ equations, enabling the determination of optimal text-background luminance combinations for displays with varying white points under different ambient lighting conditions. Verification experiments confirmed the effectiveness of these optimal combinations.

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