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The influence of mismatches between ambient illumination and display colors on video viewers' subjective experiences

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Abstract

Mismatches between ambient illumination levels and display luminance can cause poor viewing experiences. This paper explores the influence of chromaticity differences between illumination and display on viewers' subjective evaluations of color appearance, preference, and visual comfort when watching videos. Results show that when the chromaticity biases of display and illumination are incongruent, viewers like the video less than when the biases are congruent, and find its colors abnormal.

Keywords: visual comfort, perceived color, ambient illumination, tablet display

Introduction

Nowadays, people use display devices whenever and wherever they are: in the darkness of night, near a dim light indoors, or under bright sunlight. Environmental light varies in illuminance and chromaticity, often leading to inconsistencies with the light emitted by displays. The mismatch may cause a range of problems for the viewer, summarized by visual discomfort.

Visual discomfort is defined as negative side-effects induced by certain visual stimuli, both somatic and visual/perceptual [1], such as sore eyes, dry eyes, blurred vision, double vision, and headache. Assessments of visual discomfort typically include subjective ratings of multiple symptoms. These subjective evaluations describe both emotional and physiological changes.

The influence of the environmental setting on visual discomfort from viewing displays is gaining attention. With respect to luminance, Kim et al. [2] found that the range of comfortable display luminance increases with ambient illuminance. Na and Suk [3] developed a luminance model for reading performance on smartphone displays. Display device manufacturers have incorporated auto-brightness controls on TVs and phones to adapt to the environment [4]. Although the effects of ambient illumination color on white perception [5], color appearance [6], and other aspects of displays have been explored, research on ambient illumination color and visual comfort is limited, especially for studies using videos as stimuli or eye movements as measurements.

The discovery that intrinsically photosensitive retinal ganglion cells (ipRGCs) not only entrain the circadian rhythm and influence mood and arousal but also contribute to multiple aspects of human vision [7], including white perception [8], spatial vision [9], and color vision [10], has led to the recognition that the melanopic power of illumination spectra may influence human behavioral responses. Standards have therefore been instituted for quantifying melanopic lux in lighting [11]. Yet the effects of varying melanopic lux on visual comfort have been little studied.

This study aims to explore how the interaction between the chromaticities of ambient illumination and display affects visual comfort and subjective experience. We hypothesize that visual comfort and subjective preference for color appearance will be best when the mean chromaticities of display and ambient illumination are biased in the same direction. Furthermore, we hypothesize that visual discomfort will be influenced by melanopic lux levels, at constant chromaticity and photopic lux.

Materials and methods

Display device and materials

An 11-inch tablet display (brand: IMOO), with a 9-layer scattering screen design and 2176*1600 resolution, was selected as the display device. This screen has the advantage of appearing like a reflective, matte surface. In the experiment, the screen luminance was set to the maximum (127.24 cd/m^2 when showing full-screen white) and the white point CIE [x,y] was [0.2955, 0.2969]. The display's input-output functions were fully characterized to enable conversion of displayed RGB indices to device-independent colorimetric coordinates. The measurements were made with a spectroradiometer (CS-2000; Konica Minolta, Japan).

Nine 10-minute videos (4 real scenes, 5 animations) from the IBM Open Video Scene Detection Dataset [12,13] were selected as display materials. These videos were high definition and had abundant colors and scenes. To obtain videos with congruent and incongruent chromaticity directions relative to the illumination, the original (O) versions were transformed into blueish (B) and yellowish (Y) versions, using custom code (in Matlab 2018R; Mathworks, USA). First, pixel values for every video frame were stored as 8-bit unsigned integers in non-linear RGB space. Pixel values were then transformed: for the B version, $[R\ G\ B] \rightarrow [R\ G\ B']$; and for the Y version, $[R\ G\ B] \rightarrow [R'\ G'\ B]$, where: $C' = (\rho * C + (1 - \rho) * 255)$.

Appropriate ρ values for the above transformation were selected by first converting the displayed (non-linear) RGB colors to L*a*b* coordinates using the characterization measurements above. The ratios ρ were then selected to ensure that the displayed B and Y versions each had the same mean color difference in CIEDE2000 units relative to the O version. The mean color difference relative to O version was 14.86 ± 3.18 for B version and 14.74 ± 3.37 for Y version. The obtained ρ values ranged from 0.80 for the Y version of video '*1000days'* to 0.88 for the B version of video *'Sita sings the blues'*. Note that this technique was designed simply to induce a chromatic bias by an efficient modulation of the original video, not to simulate an illumination change or transparent overlay on a constant scene.

In CIE1931 tristimulus color space, the resultant mean luminance (cd/m^2) and CIE [x,y] chromaticity coordinates of the videos were [12.96, 0.2389, 0.2930] for O version, [14.98, 0.2065, 0.2007] for B version, and [15.17, 0.3382, 0.4284] for Y version. In LCH color space, for all the videos, the mean hue increased by 1.28 for B version and decreased by 1.33 for Y version; the mean Michelson contrast of lightness was 0.90 ± 0.21 for O version, 0.87 ± 0.21 for B version, and 0.84 ± 0.18 for

Y version. All values above are means of all pixels in all frames of all nine videos. A sample frame before and after the color adjustment is shown in Figure 1.

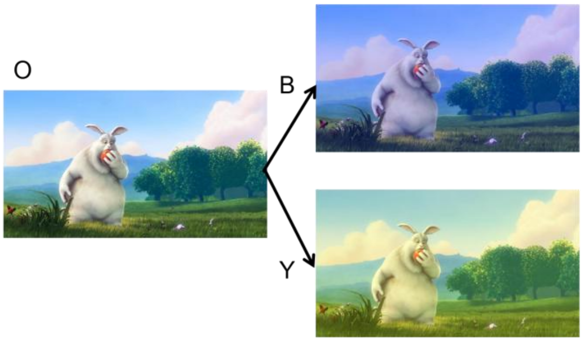

Figure 1. A sample frame in the animation Big Bulk Bunny.

Ambient illumination

Three ambient illumination spectra with varying chromaticities and melanopic power levels were generated by spectrally tuneable multi-channel LED lamps: blue-low melanopic lux (bLM), blue-high melanopic lux (bHM), and yellow (Y). The illuminance (lux) and CIE [x,y] chromaticity coordinates are shown in Table 1. The illumination spectra are plotted in Figure 2. The measurements were made using an illuminance spectrophotometer CL-500A (Konica Minolta, Japan) at eye level.

The photoreceptor weighted retinal illuminance were calculated as in [14]. The melanopic lux was 380.97 in bLM, 625.36 in bHM, and 356.55 in Y.

Thus, 9 illumination-display combination sets were obtained in total: 3 congruent (bLM-B, bHM-B, Y-Y), 3 incongruent (bLM-Y, bHM-Y, Y-B), and 3 baseline (bLM-O, bHM-O, Y-O) combinations.

Table 1. Illumination information.

		bLM	bHM	Y
Illuminance (lux)		347.60	303.00	315.80
CIE [x,y]	x	0.2255	0.2076	0.3769
	y	0.1834	0.1737	0.4543

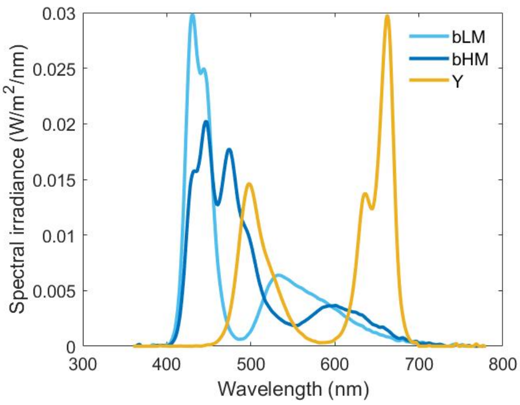

Figure 2. Illumination spectra.

Participants

The participants were 5 volunteers from Newcastle University (4 females and 1 male, age: 27.50±4.32 years). Before the study, standard color vision tests (Ishihara test and Farnsworth-Munsell 100-hue test) were completed to ensure none of the participants had color vision deficiency. The study complied with the tenets of the Declaration of Helsinki. Information sheets and consent forms were obtained from each participant. The study was approved by the Newcastle University Research Ethics Committee (18562/2022).

Experimental setup and procedure

The experiment was conducted in a dark environment (illuminance at the eye level < 0.1 lx, in absence of experimental stimuli). The lightbox and tablet display were the only light sources. The luminance level of the tablet was kept to the maximum during the experiment. The participant sat in a comfortable chair in front of the lightbox, with adjustable height to ensure a 120-cm eye level. The viewing distance from the eye to tablet display was set to around 40 cm [15]. The details are shown in Figure 3.

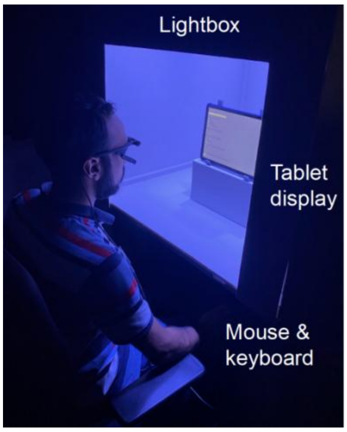

Figure 3. Experiment set-up details.

A within-subject design was applied. All participants completed all the illumination-display sets. The study procedure was presented on the display using a web server.

To avoid the accumulation of fatigue, the experiment was divided into three sessions of three trials each, with all nine illumination-display combinations presented in pseudo-random order. The interval between sessions was at least 3 days.

On each trial, first, the ambient illumination was set according to the selected combination, and the display was set to a uniform blueish or yellowish background roughly matching the illumination chromaticity. The participant adapted to this lighting environment for 5 minutes.

Then, the participant watched a 10-minute video, and afterward, answered the questionnaire, displayed as black text on the same uniform background. Throughout each session, eye movements were also recorded with a lightweight eye tracker headset (Pupil Labs, Germany). Analysis of eye movements will be reported elsewhere.

The 5-minute period for adaptation was considered sufficient for chromatic adaptation based on previous studies [5,16,17]. To specifically assess the extent of chromatic adaptation under the different ambient illumination conditions, we collected achromatic settings for a small square patch (400 by 400 pixels, 5.9 by 5.9 degrees) centred against a black background, from two participants. All viewing conditions were otherwise identical. Participants adapted to the congruent ambient illumination/display chromaticity setup for 5 minutes, then adjusted the chromaticity of the patch until it appeared achromatic, using the keyboard to navigate in a*b* coordinates. The luminance of the patch at eye level was held constant at

14.57 cd/m^2, close to the mean luminance of all videos (14.37 cd/m^2). The achromatic settings are shown in Figure 4 in u'v' color space, and indicate that participants' neutral points varied with the illumination conditions, although adaptation to the measured illumination chromaticities at the eye was incomplete.

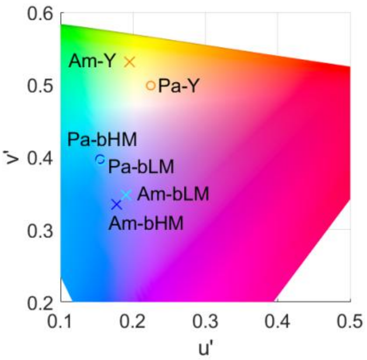

Figure 4. *Chromaticities of mean participant achromatic settings (mark: o, label: Pa-) and ambient illumination (mark: x, label: Am-), for three conditions, in u'v' chromaticity diagram.*

Data collection and analysis

The questionnaire included single-option items (1,2,4 to 9) and 2 multi-option items (3 and 10). It was divided into two parts: evaluation of color appearance (6-point Likert scales) and visual comfort (5-point Likert scales). For the single-option items, higher scores corresponded to more positive subjective evaluations. The items and options are shown in Table 2.

Table 2. Questionnaire design. S-O indicates single-option, and M-O indicates multi-option.

Evaluation of color appearance part		
S-O	1	How much do you like this video? 1 = not at all 2 = very little 3 = a little 4 = moderately 5 = quite a lot 6 = a lot
	2	Do the colors look normal in the video? 1 = not at all 2 = very little 3 = a little 4 = moderately 5 = quite a lot 6 = a lot
M-O	3	What do you think of the colors in the video? Too vivid Too pale Too blue Too yellow Too bright Too dark
Visual comfort part		
S-O	4	How tired are your eyes? 1 = very tired 2 = moderately tired 3 = a little tired 4 = not tired 5 = very fresh
S-O	5	How tired do you feel? 1 = very tired 2 = moderately tired 3 = a little tired 4 = not tired 5 = very fresh
	6	How clear is your vision? 1 = very blurred 2 = moderately blurred 3 = mildly blurred 4 = clear 5 = very clear
	7	How do your eyes feel? 1 = severely strained 2 = moderately strained 3 = mildly strained 4 = fresh 5 = very fresh
	8	How is your mood? 1 = very unpleasant 2 = unpleasant 3 = neutral 4 = pleasant 5 = very pleasant
	9	How calm do you feel? 1 = very agitated 2 = agitated 3 = neutral 4 = calm 5 = very calm
M-O	10	Do you have any of these feelings? It is hard for me to see My vision is blurred I have a strange feeling around my eyes My eyes feel tired My eyes feel dry My eyes feel sore My eyes feel like they are burning My eyes are tearing I feel dizzy looking at the screen I have a headache

The statistical analysis was performed using SPSS 27 (IBM, USA) and Origin 2021 (OriginLab, USA).

Results

For single-option items, a Friedman test was performed to determine the influence of illumination-display set. For significant results ($p < 0.05$), post hoc pairwise comparisons were performed with a Bonferroni correction for multiple comparisons. The Friedman test results are shown in Table 3.

Questionnaire scores were significantly influenced by illumination-display combination only for items 1 and 2. As shown in Figure 5, the scores of these items were the highest for baseline combinations, second-highest for congruent combinations, and the lowest for incongruent combinations. For item 1, the subjective preference for the incongruent (Y-B) set was significantly lower, after Bonferroni correction, than for the baseline (bLM-O) set. For item 2, the perceived normality of color appearance for the incongruent (bLM-Y, Y-B) sets was significantly lower than for the baseline (bHM-O, Y-O) sets. No other specific pairwise comparisons reached significance after Bonferroni correction. The difference between bHM and bLM ambient settings was not significant when the display colors were the same. Using the mean scores of the three trials in each combination as a summary statistic, the mean preference and perceived normality of color appearance for incongruent combinations were significantly lower than for baseline combinations, after correction. Other single-option items showed no obvious trends over different illumination-display sets.

To further explore the effects of illumination-display set on display color appearance, the results of multi-option item 3 were sorted, as shown in Figure 6. Baseline combinations, which had the highest normality of color appearance in item 2, also received the fewest negative comments. For these, participants' opinions focused mainly on 'too vivid'. Similarly, congruent combinations received few comments, varying from person to person. The bHM-B and bLM-B sets were considered too pale by 3 participants, and the bHM-B set too dark by 2 participants. For incongruent combinations, all five participants reported Y videos were too yellow (bHM-Y, bLM-Y), and B videos were too blue (Y-B).

For multi-option item 10, visual discomfort symptoms including tired eyes, dry eyes, and difficulty seeing were also reported. However, no systematic relationships with illumination-display sets, or melanopic lux, were found.

The results of the questionnaire showed that, regardless of the illumination color, the participants preferred the baseline combinations the most, considered its colors the most normal, and reported the fewest complaints about these, especially under the bHM illumination. The congruent combinations received fewer negative comments than incongruent combinations.

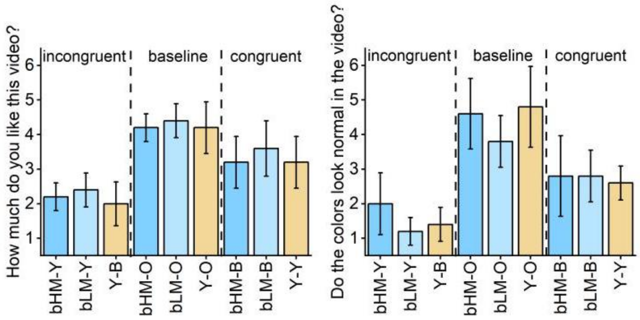

Figure 5. Questionnaire single-option items with significant changes. X-axis: illumination-display sets. Y-axis: score of items. The colors indicate illumination color. The error bar shows standard error of the mean.

Table 3. Friedman test results for the effect of illumination-display set on single-option questionnaire items.

Item		df	Test Statistic (X^2)	Asymptotic Sig. *(p)*
1	How much do you like this video?	8	27.072	0.001
2	Do the colors look normal in the video?	8	30.741	0.000
4	How tired are your eyes?	8	9.880	0.274
5	How tired do you feel?	8	8.670	0.371
6	How clear is your vision?	8	6.667	0.573
7	How do your eyes feel?	8	5.408	0.713
8	How is your mood?	8	11.823	0.159
9	How calm do you feel?	8	11.323	0.184

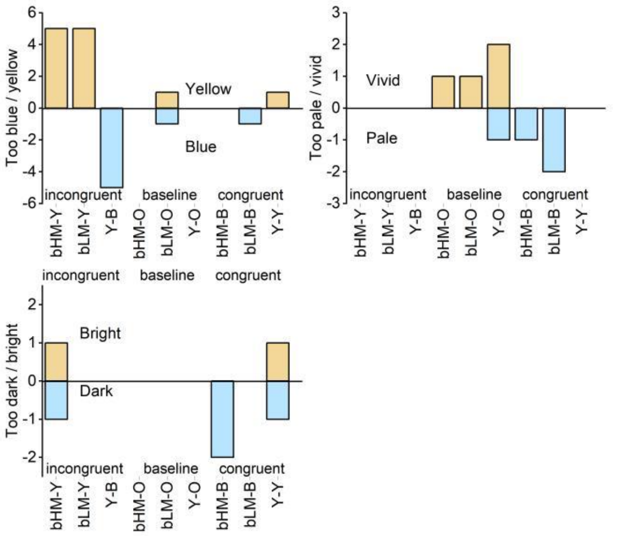

Figure 6. Questionnaire multi-option items. X-axis: illumination-display sets. Y-axis: frequency distributions.

Conclusion

This study explores how chromaticity differences between illumination and display influence viewers' subjective evaluations of color appearance, preference, and visual comfort when watching videos. The results of a subjective questionnaire show that the illumination-display combination significantly affects evaluations of color appearance. Compared to baseline combinations, for incongruent combinations, subjective preferences for videos were reduced, and color appearance was perceived as less normal. For the original (unaltered) videos, especially under blueish illuminations, the relative lack of negative evaluations of color appearance suggested that a blueish chromatic bias was more readily compensated than a yellowish bias in the ambient illumination. The limited subjective negative evaluations of color appearance for the congruent combinations suggested that chromatic adaptation to the ambient illumination, although incomplete, was effective in normalizing the chromatic bias of the display. The findings may be of help in the design of tablet screens and contribute to the reduction of visual discomfort or displeasure caused by displays. However, research with more participants and factor levels is needed.

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