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Abstract. The study aims to investigate the user-preferred color temperature adjustment for smartphone displays by observing the effect of the illuminant's chromaticity and intensity on the optimal white points preferred by users. For visual examination, subjects evaluated 14 display stimuli presented on the Samsung Galaxy S3 under 19 ambient illuminants. The display stimuli were composed of 14 nuanced whites varying in color temperature from 2900 to 18,900 K. The illuminant conditions varied with combinations of color temperature (2600 to 20,100 K) and illuminance level (30 to 3100 lx) that simulated daily lighting experiences. The subjects were asked to assess the optimal level of the display color temperatures based on their mental representation of the ideal white point. The study observed a positive correlation between the illuminant color temperatures and the optimal display color temperatures ($r = 0.89$, $p < 0.05$). However, the range of the color temperature of the smartphone display was much narrower than that of the illuminants. Based on the assessments by 100 subjects, a regression formula was derived to predict the adjustment of user-preferred color temperature under changing illuminant chromaticity. The formula is as follows: [Display $T_{cp} = 6534.75 \log$ (Illuminant T_{cp}) – 16304.68 ($R^2 = 0.87$, $p < 0.05$)]. Moreover, supporting previous studies on color reproduction, the effect of illuminant chromaticity was relatively weaker under lower illuminance. The results of this experiment could be used as a theoretical basis for designers and manufacturers to adjust user-preferred color temperature for smartphone displays under various illuminant conditions. [DOI: 10.1117/1.OE.53.6.061708]

Keywords: color preference reproduction; smartphone display; image quality; white point; color temperature; ambient illuminant.

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1 Introduction

Smartphone displays have been developed with much attention being paid to achieve high image quality. Conventionally, display imaging has been focused on enhancing the physical image quality. Physical image quality is achieved by maximizing the physical accuracy between an original image and a reproduced image; thus, it generally lacks consideration on the human visual characteristics.[1] However, given that the human visual system is the ultimate receiver of displayed images, the success of smartphone displays depends highly on the perception of end users.[2] Therefore, psychophysical image quality has to be seriously taken into account by focusing on the human visual characteristics and psychological perception.

Accounting for 80% of the human visual experience, color is well known for its significant effects on human emotions and satisfaction.[3] Especially in display devices where the light source is viewed directly, a small difference in color could lead to a huge dissatisfaction.[4] Despite extensive studies carried in past decades, the research on image quality and color reproduction is still ongoing.[5] Conventionally, the performance of the display color is determined under the standard illuminant D65, which represents an average daylight with a correlated color temperature of 6504 K.[6] However, given their smaller size, smartphone displays are different from large static displays, such as desktop monitors or TVs, especially in terms of their portability. Smartphone users are exposed to much more dynamic illuminant conditions compared to traditional display devices. Hence, it is important to consider the display colors viewed under real viewing conditions with varying illuminant chromaticity and intensity.[7]

As early studies have revealed, the human visual system perceives display colors differently under varying ambient illuminants mainly due to the process of chromatic adaptation and light adaptation.[8–10] When people view a piece of white paper under daylight, and move to a room with incandescent light, the paper still appears white regardless of the illuminants, due to chromatic adaptation.[11] This feature of the human visual system is called color constancy.[12] Such ability to automatically perceive the colors of objects after discounting the influences of illuminant chromaticity is referred to as "discounting the illuminant."[13] However, when observing display devices under varying illuminants, there are no illuminated objects, and hence, "discounting the illuminant" does not occur. Instead, other color appearance phenomena occur,[14] leading users to perceptual error and emotional dissatisfaction, as shown in Fig. 1.

In regards to light adaptation, the auto-brightness function has been developed and well adopted to most hand-held devices to provide a perceptually ideal luminosity depending on the brightness of viewer's lighting context.[15] On the contrary, dissatisfaction caused by chromatic adaptation has not yet been studied enough in spite of complaints about displays seeming either too yellowish or too bluish. Some smartphones are now able to read the chromaticity of ambient illuminants using an *RGB* sensor embedded in the front. This sensor detects the intensity of red, green, blue, and white

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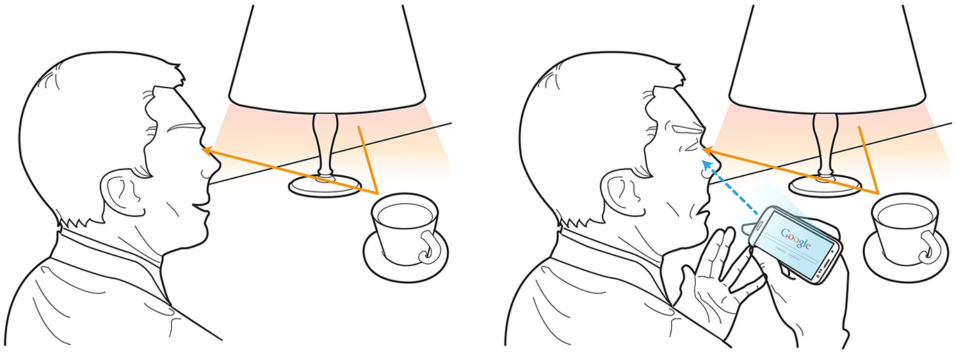

Fig. 1 Chromatic adaptation in viewing objects (left) and displays (right).

from the light source and therefore is able to adjust the display colors taking into account the ambient illuminants.

2 Related Works

It has been acknowledged that the white point, as a standard point of all colors, could be the main factor in determining user satisfaction toward display color.[16] Human vision is much more sensitive to white compared to other colors, where a small difference could be unacceptable in high-end applications.[17–19] Therefore, focusing on its particularly distinct features, the color appearance and color constancy, has long been studied. Color constancy suggests that the color appearance of a display may vary under different ambient illuminants.[20] Fairchild and Lennie[21] observed an achromatic appearance of a CRT monitor as a measure of the users' states of chromatic adaptation. However, they observed that the illuminant conditions have essentially no effect on the achromatic appearance. Therefore, Brainard and Ishigami[22] conducted an experiment to verify the effect of illuminant conditions on the color appearance under more general conditions. The study revealed that the illuminant conditions have significant effect on the appearance of CRT colors. Moreover, the study has suggested that the display stimuli and the reflective surfaces are processed by the same visual mechanisms.

However, although the problems of color appearance and color constancy have been studied significantly, there still remains one problem; the reproduction of color preferred by users.[23] The ultimate goal of a color reproduction might not always be accurately reproducing the same color, rather matching the idealized colors users perceive, known as color preference reproduction.[14,24] In order to achieve color preference reproduction in the white point, the "no reference" approach was adopted for the experimental evaluation.[25,26] In the no reference approach, the colors are reproduced to match the users' internal or mental representation of the white point, without any physical reference being presented.[27] This internal representation of an idealized image is often referred to as "sensorial image."[28]

3 Objective

The goal of this study is to find the optimal color temperature for the smartphone display rendered under varying illuminant chromaticity and intensity. The study is composed of two parts. In Part I, the study focuses on the effect of illuminant chromaticity on the optimal display color temperature. Part II investigates the effect of illuminant intensity on the user preferences. Ultimately, this research proposes user-preferred color temperature adjustment in smartphone displays that can be used by manufacturers and designers to design a display color strategy under various illuminant conditions.

4 Stimuli for Empirical Study

4.1 *Ambient Illuminant*

The experiment was carried in a room equipped with an LED luminous ceiling. The color temperature and illuminance of the ambient illuminant were controlled by adjusting R, G, B, and W values. The subjects were seated in the center of the room and were instructed to observe the smartphone at a viewing distance of about 30 cm (the distance of distinct vision).

The subjects were exposed to 19 illuminant conditions that simulated daily lighting experiences, with the combinations of color temperature and illuminance. Part I of the experiment focused on the effect of illuminant chromaticity on the optimal white point. Thus, 11 illuminants were produced that were chromatically different (2600 to 20,100 K) but of equal illuminance (approximately 1000 lx). Part II examined the effect of illuminant intensity on user preferences. Accordingly, eight illuminants with equal color temperature but of different illuminances (30 to 3100 lx) were added to the group of stimuli. In all, 19 illuminants were produced with the LED luminous ceiling. The colorimetric values of each illuminant were measured with a chroma meter (Konica Minolta CL-200), at the position where the smartphone was placed during the experiment. Moreover, the luminance of a perfect diffuser was measured using a spectroradiometer (Konica Minolta CS-2000), as listed in Table 1.

4.2 *Display Stimuli*

During the experiment, the stimuli were displayed on a Samsung Galaxy S3 smartphone. The smartphone has a Pentile organic lighting-emitting diode screen, which has become one of the most promising types of display technology with its large color gamut.[7] When measured with a spectroradiometer (CS-2000), the white point of the smartphone was 7646 K in correlated color temperature. A smartphone with a white bezel was used for the empirical study because the white bezel reflects environmental lightings most properly. The stimuli were reproductions of an e-mail application: the typical content page with a white background and a black text. The screen was displayed with only black texts and differently nuanced white backgrounds in order to prevent the effect of other colors on color judgment.

Table 1 Correlated color temperature (K), illuminance (lx), luminance (cd/m^2), and delta *uv* values of 19 illuminants.

Target ambient illuminant			Measured values			
No.	CCT (K)	Illuminance (lx)	CCT (K)	Illuminance (lx)	Luminance (cd/m^2)	Delta *uv*
1	2500	1000	2569	915	235.52	−0.0099
2	3000	1000	3005	1053	264.51	0.0018
3	4000	1000	3989	951	244.76	−0.0008
4	5000	1000	5040	1073	276.49	0.0113
5	6000	1000	6001	1074	276.48	0.0001
6	7000	1000	7021	1034	265.22	0.0111
7	8000	1000	8049	1040	267.84	0.0037
8	9000	1000	9061	1024	264.02	0.0052
9	10,000	1000	10,110	1007	259.54	0.0074
10	13,000	1000	13,121	1021	263.49	0.0009
11	20,000	1000	20,050	1014	262.76	−0.0004
12	2500	30	2416	30	9.47	0.0159
13	2500	500	2537	505	9.46	−0.0038
14	4000	30	4107	31	9.51	−0.0194
15	4000	3000	4163	3053	9.04	−0.0119
16	6000	30	6127	30	138.32	0.0097
17	6000	3000	6060	3015	779.78	0.0037
18	10,000	30	10,450	29	771.14	−0.0022
19	10,000	3000	10,000	3050	782.91	−0.0011

A total of 13 differently nuanced whites were produced by adjusting the *RGB* values in Photoshop CS6. Moreover, the original white display on the smartphone ($R = 255$, $G = 255$, $B = 255$) was added. Thus, a total of 14 samples with different color temperatures varying from 2900 to 18,900 K were presented on the Samsung Galaxy S3 smartphone during the visual examination. Colorimetric values were measured using a spectroradiometer (Konica Minolta CS-2000). The auto brightness function of the smartphone was turned on throughout the experiment. Therefore, the chromatic values of each stimulus were measured under each of 19 ambient illuminants. However, the chromaticity of the stimulus under each illuminant was not significantly different compared to the average chromaticity throughout the 19 illuminants ($p > 0.05$, two-tailed). The averages and standard errors of the correlated color temperature and delta uv values of each stimulus are listed in Table 2.

5 Method

5.1 *Participants*

A total of 100 college students made up of 50 males and 50 females were recruited. Their average age was 21.93 years with a standard deviation of 1.94 years. All subjects were tested for color deficiency using the Ishihara's color vision test. No significant color deficiencies were observed. All subjects were paid volunteers.

5.2 *Procedure*

The subjects were asked to evaluate the optimal level of the display color temperatures using a five-point Likert scale ranging from -2 (least optimal) to $+2$ (most optimal). The visual assessment was based on the subjects' mental representation of the ideal white point, without any physical reference being presented. The purpose of the visual examination was to derive the user-preferred color temperature for the white point adjustment of smartphone displays that could satisfy the general smartphone users. Hence, the subjects were instructed to evaluate the white points objectively as if they were producers of the product, neglecting any personal biases that might arise from color preferences.

The experiment was divided into two parts. In Part I, the subjects were asked to assess 14 white stimuli under 11 illuminants with different color temperatures. In Part II, the subjects were exposed to eight illuminants with different illuminances. Moreover, a training session was employed with a fixed illuminant at 4000 K to 1000 lx in order to help the subjects before the actual experimental session

Table 2 Means and standard errors of the correlated color temperature (K) and delta *uv* values measured for the 14 display stimuli.

Target stimuli		CCT (K)		Delta *uv*	
No.	CCT (K)	*M*	SE	*M*	SE
1	2800	2857	15.57	0.0018	0.0003
2	3000	3165	17.77	0.0004	0.0003
3	4000	4018	23.69	0.0011	0.0003
4	5000	5124	28.96	−0.0115	0.0003
5	6000	6500	23.98	0.0012	0.0003
6	7000	7167	19.17	0.0146	0.0003
7	Default	7646	19.04	0.0111	0.0003
8	8000	8232	16.70	0.0162	0.0003
9	9000	9115	17.74	0.0147	0.0002
10	10,000	10,590	23.53	0.0148	0.0002
11	11,000	11,340	32.86	0.0056	0.0003
12	12,000	11,783	40.78	−0.0025	0.0003
13	15,000	13,798	59.56	0.0151	0.0002
14	20,000	18,903	167.26	0.0155	0.0001

started. Thus, judgment under the 4000 K to 1000 lx illuminant was repeated at the beginning and end of the experiment. In total, 280 judgments were performed in this experiment: $14\,(\text{display stimuli}) \times 20\,(\text{ambient illuminants})$.

The stimuli and the illuminants were presented in random order. The randomization was intended to eliminate any sequential effect on the subjects' evaluation. In each observing session, the subjects were instructed to keep their eyes closed for 10 s, and after reopening their eyes, spend the

Fig. 2 The subjects seated in the room equipped with LED luminous ceiling.

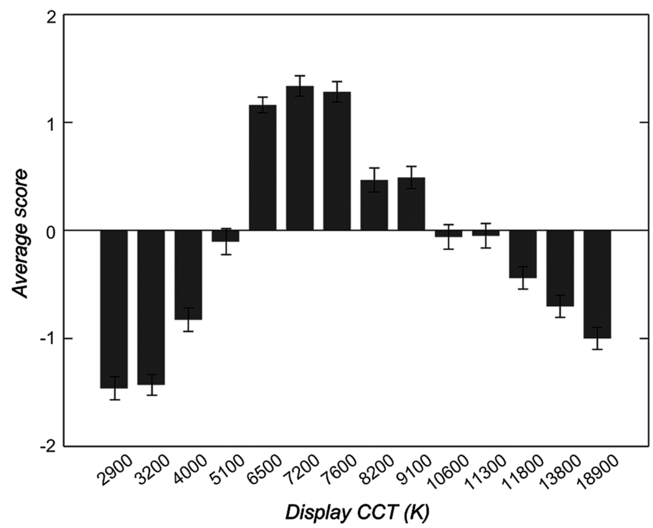

Fig. 3 The example of the average score of display stimuli under 4000 K illuminant.

Table 3 The mean scores and standard errors of the optimal level for the 14 stimuli under the 11 illuminants. The display color temperatures with the highest score for each illuminant are underlined ($N = 100$).

Display CCT (K)	Illuminant CCT (K)										
	2569	3005	3989	5040	6001	7021	8049	9061	10,110	13,121	20,050
2857	−1.37 (0.11)	−1.27 (0.11)	−1.47 (0.11)	−1.75 (0.08)	−1.76 (0.07)	−1.88 (0.05)	−1.78 (0.06)	−1.77 (0.07)	−1.72 (0.08)	−1.81 (0.07)	−1.81 (0.07)
3165	−1.20 (0.11)	−0.82 (0.12)	−1.44 (0.10)	−1.59 (0.09)	−1.61 (0.09)	−1.81 (0.06)	−1.65 (0.09)	−1.73 (0.07)	−1.68 (0.08)	−1.77 (0.07)	−1.79 (0.07)
4018	−0.53 (0.12)	−0.18 (0.12)	−0.83 (0.11)	−1.15 (0.09)	−1.15 (0.10)	−1.54 (0.08)	−1.31 (0.10)	−1.34 (0.09)	−1.35 (0.10)	−1.44 (0.08)	−1.50 (0.09)
5124	0.35 (0.12)	−0.55 (0.11)	−0.11 (0.12)	−1.12 (0.09)	−1.03 (0.10)	−1.42 (0.08)	−1.20 (0.10)	−1.13 (0.09)	−1.41 (0.08)	−1.17 (0.09)	−1.07 (0.10)
6500	<u>1.16</u> (0.10)	<u>1.16</u> (0.10)	1.16 (0.07)	0.27 (0.11)	0.98 (0.10)	−0.03 (0.11)	0.70 (0.10)	0.30 (0.13)	−0.24 (0.12)	0.00 (0.12)	−0.09 (0.13)
7167	1.03 (0.11)	1.05 (0.09)	<u>1.36</u> (0.09)	1.15 (0.09)	0.53 (0.10)	0.83 (0.10)	0.54 (0.10)	0.34 (0.12)	0.15 (0.11)	−0.02 (0.12)	0.21 (0.11)
7646	0.38 (0.10)	0.70 (0.10)	1.25 (0.09)	<u>1.71</u> (0.05)	<u>1.24</u> (0.09)	1.47 (0.08)	1.02 (0.10)	0.81 (0.12)	0.79 (0.11)	0.70 (0.11)	0.78 (0.12)
8232	0.56 (0.11)	0.93 (0.10)	0.47 (0.11)	1.26 (0.09)	0.66 (0.11)	<u>1.56</u> (0.07)	<u>1.11</u> (0.10)	0.75 (0.11)	0.55 (0.12)	0.26 (0.13)	0.36 (0.12)
9115	0.57 (0.10)	0.66 (0.12)	0.49 (0.10)	1.46 (0.07)	0.80 (0.10)	1.41 (0.09)	0.94 (0.09)	0.92 (0.10)	0.97 (0.11)	0.92 (0.10)	0.63 (0.12)
10,590	0.02 (0.13)	0.08 (0.12)	−0.06 (0.12)	0.54 (0.10)	0.20 (0.12)	1.43 (0.08)	0.86 (0.09)	<u>0.99</u> (0.10)	<u>1.22</u> (0.08)	0.90 (0.10)	0.74 (0.09)
11,340	−0.30 (0.12)	−0.11 (0.12)	−0.05 (0.11)	−0.42 (0.11)	0.36 (0.11)	−0.42 (0.11)	0.83 (0.11)	0.69 (0.11)	0.62 (0.12)	<u>1.17</u> (0.09)	<u>1.11</u> (0.10)
11,783	−0.71 (0.10)	−0.75 (0.12)	−0.44 (0.11)	−1.08 (0.10)	−0.66 (0.10)	−0.99 (0.09)	−0.33 (0.12)	−0.49 (0.12)	−0.63 (0.10)	−0.04 (0.12)	0.30 (0.12)
13,798	−0.67 (0.11)	−0.52 (0.13)	−0.71 (0.10)	−0.50 (0.09)	−0.52 (0.10)	0.18 (0.10)	0.40 (0.10)	0.49 (0.10)	0.80 (0.10)	0.24 (0.11)	0.47 (0.10)
18,903	−1.17 (0.10)	−0.98 (0.10)	−1.01 (0.11)	−1.05 (0.10)	−0.68 (0.12)	−0.87 (0.10)	−0.06 (0.12)	0.15 (0.13)	0.13 (0.12)	−0.02 (0.10)	0.13 (0.12)

next 10 s adapting their eyes to the new environment by freely scanning the room. Subjects began a series of making 14 stimuli assessments immediately after the adaptation. There was a 10 min break between each part to allow subjects to relieve some visual strain. The 20 observing sessions plus the break usually lasted for approximately 40 min. To reduce the bias in color perception inflicted by the surrounding environment, the experiment was conducted on a black desk and the survey sheets were printed on an achromatic grayish paper, as shown in Fig. 2.

6 Result and Data Analysis

The scores of the optimal level for the 14 white stimuli were collected in each observing session. Correlation analysis was conducted to determine if the subjects' answers were consistent throughout the whole session. The analysis was carried out using the data obtained from the 4000 K to 1000 lx illuminant presented at the beginning and end of the experiment. The result showed that the subjects' answers were consistent ($r = 0.99$, $p < 0.05$, two-tailed) between the two observing sessions demonstrating that the assessments were reliable throughout the whole experiment.

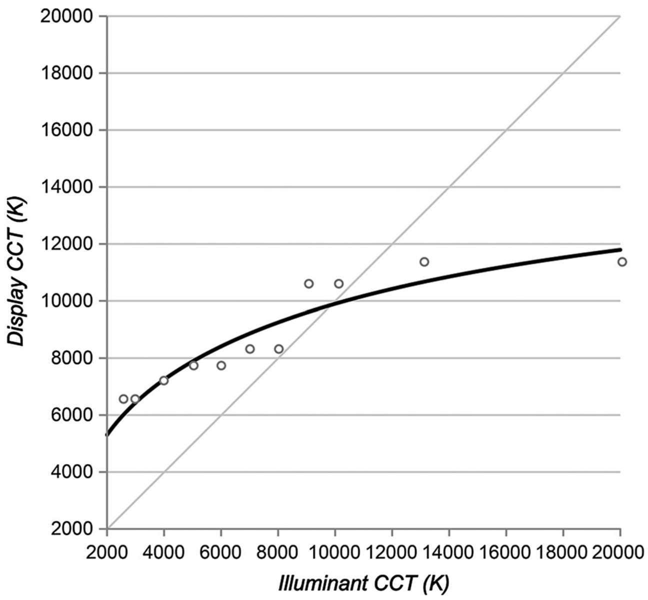

Fig. 4 The optimal display color temperatures plotted against the illuminant color temperatures. The regression formula (1) is fitted by the line.

6.1 *Part I—Effect of Illuminant Chromaticity*

The average scores of the 14 stimuli were calculated for each of the 11 illuminants with different color temperatures (2600 to 20,100 K) but of equal illuminance (approximately 1000 lx), as shown in Fig. 3.

As seen in Table 3, there appears to be a general correlation between the optimal display color temperatures and the illuminant color temperatures. The color temperatures of display ranged from 6500 to 11,300 K while the color temperatures of illuminant varied from 2600 to 20,100 K. Within this boundary, a positive correlation is observed; the optimal display color temperature increases as the illuminant color temperature rises ($r = 0.89$, $p < 0.05$).

Moreover, display stimuli with color temperatures higher than the surrounding illuminant are perceived to be ideal, up until the illuminant color temperature reaches 10,100 K. When the illuminant is above 10,100 K, even if the illuminant color temperature increases, the optimal display color temperature does not rise beyond 11,300 K. In other words, 11,300 K is the marginal value of the optimal white points.

Furthermore, the display color temperatures ranging from 7200 to 10,600 K, including the default white point (7600 K), generally received positive scores for every illuminant. The displays with positive scores were on average shifted toward higher color temperatures compared to the standard white point D65. Moreover, there was no significant difference observed between the male and female subjects ($p > 0.05$, two-tailed).

Table 4 The chromaticity of the white paper reflecting the ambient illuminant versus the optimal white point under 11 illuminants.

Illuminant CCT (K)	White paper				Optimal white point			
	CCT (K)	delta *uv*	*x*	*y*	CCT (K)	delta *uv*	*x*	*y*
2569	2455	−0.0116	0.4550	0.3751	6500	0.0012	0.3133	0.3257
3005	3029	−0.0010	0.4333	0.4002	6500	0.0012	0.3133	0.3257
3989	3821	−0.0100	0.3809	0.3565	7167	0.0146	0.2997	0.3386
5040	4923	0.0099	0.3498	0.3758	7646	0.0111	0.2946	0.3258
6001	5832	−0.0003	0.3253	0.3341	7646	0.0111	0.2946	0.3258
7021	6891	0.0115	0.3048	0.3375	8232	0.0162	0.2858	0.3263
8049	7825	0.0039	0.2954	0.3123	8232	0.0162	0.2858	0.3263
9061	8783	0.0057	0.2859	0.3050	10,590	0.0148	0.2687	0.3021
10,110	9790	0.0085	0.2772	0.3001	10,590	0.0148	0.2687	0.3021
13,121	12,209	0.0019	0.2704	0.2782	11,340	0.0056	0.2711	0.2865

Table 5 The mean scores and standard errors of the optimal level for the 14 stimuli under the 12 illuminants. The display color temperatures with the highest score for each illuminant are underlined ($N = 100$).

	Ambient illuminant											
	2500 K			4000 K			6000 K			10,000 K		
Display CCT (K)	30 lx	500 lx	1000 lx	30 lx	1000 lx	3000 lx	30 lx	1000 lx	3000 lx	30 lx	1000 lx	3000 lx
2857	−1.18 (0.13)	−0.75 (0.14)	−1.37 (0.11)	−1.73 (0.08)	−1.47 (0.11)	−1.58 (0.10)	−1.84 (0.06)	−1.76 (0.07)	−1.81 (0.07)	−1.85 (0.06)	−1.72 (0.08)	−1.80 (0.07)
3165	−0.76 (0.14)	−0.37 (0.13)	−1.20 (0.11)	−1.62 (0.07)	−1.44 (0.10)	−1.54 (0.09)	−1.82 (0.05)	−1.61 (0.09)	−1.64 (0.08)	−1.76 (0.07)	−1.68 (0.08)	−1.70 (0.08)
4018	−0.51 (0.13)	−0.07 (0.12)	−0.53 (0.12)	−1.17 (0.10)	−0.83 (0.11)	−1.05 (0.10)	−1.46 (0.08)	−1.15 (0.10)	−1.16 (0.09)	−1.38 (0.09)	−1.35 (0.10)	−1.34 (0.10)
5124	−0.84 (0.10)	−0.20 (0.11)	0.35 (0.12)	−0.85 (0.10)	−0.11 (0.12)	0.26 (0.11)	−1.37 (0.08)	−1.03 (0.10)	−0.82 (0.11)	−1.38 (0.09)	−1.41 (0.08)	−0.94 (0.11)
6500	0.54 (0.10)	1.13 (0.10)	1.16 (0.10)	0.84 (0.11)	1.16 (0.07)	0.74 (0.10)	0.38 (0.11)	0.98 (0.10)	1.1 (0.09)	0.08 (0.11)	−0.24 (0.12)	0.32 (0.13)
7167	0.79 (0.10)	0.76 (0.10)	1.03 (0.11)	0.70 (0.11)	1.36 (0.09)	−0.07 (0.11)	0.80 (0.10)	0.53 (0.10)	0.25 (0.10)	0.42 (0.11)	0.15 (0.11)	−0.19 (0.10)
7646	1.07 (0.10)	1.26 (0.10)	0.38 (0.10)	1.17 (0.09)	1.25 (0.09)	0.28 (0.11)	1.16 (0.09)	1.24 (0.09)	1.05 (0.10)	1.01 (0.10)	0.79 (0.11)	0.56 (0.12)
8232	0.86 (0.09)	0.93 (0.10)	0.56 (0.11)	0.81 (0.11)	0.47 (0.11)	0.05 (0.11)	1.27 (0.09)	0.66 (0.11)	0.52 (0.10)	0.84 (0.10)	0.55 (0.12)	0.10 (0.13)
9115	0.91 (0.09)	1.08 (0.11)	0.57 (0.10)	0.79 (0.10)	0.49 (0.10)	0.19 (0.10)	1.24 (0.09)	0.80 (0.10)	0.89 (0.10)	1.27 (0.10)	0.97 (0.11)	0.57 (0.11)
10,590	−0.10 (0.11)	0.21 (0.12)	0.02 (0.13)	0.45 (0.12)	−0.06 (0.12)	−0.37 (0.13)	0.86 (0.09)	0.20 (0.12)	0.38 (0.11)	0.91 (0.09)	1.22 (0.08)	0.72 (0.11)
11,340	0.05 (0.11)	−0.15 (0.12)	−0.30 (0.12)	0.49 (0.11)	−0.05 (0.11)	0.07 (0.12)	0.38 (0.11)	0.36 (0.11)	0.43 (0.12)	0.41 (0.11)	0.62 (0.12)	0.92 (0.11)
11,783	−0.79 (0.09)	−0.44 (0.11)	−0.71 (0.10)	−0.29 (0.11)	−0.44 (0.11)	−0.02 (0.12)	−0.73 (0.11)	−0.66 (0.10)	−0.56 (0.12)	−0.48 (0.10)	−0.63 (0.10)	0.67 (0.11)
13,798	−0.34 (0.11)	−0.47 (0.11)	−0.67 (0.11)	0.10 (0.12)	−0.71 (0.10)	−0.73 (0.11)	0.04 (0.10)	−0.52 (0.10)	−0.37 (0.11)	0.38 (0.11)	0.80 (0.10)	0.10 (0.11)
18,903	−0.80 (0.09)	−0.91 (0.11)	−1.17 (0.10)	−0.74 (0.11)	−1.01 (0.11)	−1.07 (0.10)	−0.49 (0.10)	−0.68 (0.12)	−0.79 (0.11)	−0.35 (0.12)	0.13 (0.12)	−0.26 (0.11)

In order to predict the optimal display color temperature (T_D), nonlinear regression analysis was performed by taking the illuminant color temperature (T_I) as independent variables ($R^2 = 0.87$, SE = 713.09, $p < 0.05$), as shown in Fig. 4. The regression line is best fitted in between the illuminant color temperature range from 2000 to 20,000 K, with an illuminance at approximately 1000 lx. The derived regression formula is as follows:

$$T_D = 6534.75 \log(T_I) - 16304.68 \; (R^2 = 0.87, p < 0.05). \tag{1}$$

Moreover, the display color temperatures evaluated as the most optimal were compared with the chromaticity of a white paper reflecting the ambient illuminant, as listed in Table 4. According to Brainard and Ishigami,[22] display stimuli and the reflective surfaces are processed by the same visual mechanisms. Therefore, the chromaticity of the white paper could be interpreted as an adapted white point (the most achromatic color), while the result of this study could be interpreted as an optimal white point (the most preferred color). As seen in Table 4, the range of the optimal white point (6500 to 11,300 K) is much narrower than the adapted white point (2500 to 17,300 K).

6.2 *Part II—Effect of Illuminant Intensity*

The average scores of the 14 stimuli were calculated for each of the 12 illuminants with different illuminance levels (30 to 3100 lx), as listed in Table 5. The study observed changes in optimal display color temperatures under varying illuminance levels. At lower illuminance (approximately 30 lx), the effect of illuminant chromaticity on the display color temperature is relatively weaker. The color temperatures perceived as most optimal are within a more restricted range from 7600 to 9100 K. However, the effect of illuminant chromaticity increases as illuminance increases to approximately 3000 lx, for which the optimal color temperature varies in a much wider range from 6500 to 11,300 K. The optimal color temperatures have a tendency to draw closer to the color temperature of the illuminant as the illuminant becomes brighter. In other words, the amount of chromatic adaptation increases as the level of illuminance increases.

7 General Discussion

The study observed the effect of illuminant chromaticity and intensity on the optimal color temperature of smartphone display that users prefer. Part I investigated the effect of illuminant chromaticity on the user preferences. The study found that there exists a positive correlation between the color temperature of illuminant and that of a smartphone display ($r = 0.89$, $p < 0.05$). Such tendency is qualitatively consistent with the previous studies[22,29] regarding the effect of varying illuminants on the adapted white point of a traditional display. However, the range of the optimal white points was much narrower than the chromaticity of a reflective white paper (adapted white point). Confirming the results of a previous study,[30] the optimal color temperature of the smartphone display shifted toward the illuminant color temperature, but to a lesser extent compared to the adapted white point. Hence, the optimal white point should be predicted differently than from predicting the adapted white point.

In Part II, the effect of illuminant intensity on the optimal color temperature was observed. The study observed that the effect of illuminant chromaticity is relatively weaker for lower illuminance, Moreover, the optimal color temperatures shifted toward the chromaticity of the illuminant as the illuminance increased, which agrees with the study of Choh et al.[31] According to the study, the effect of illuminant chromaticity increases as the illuminance level increases. Moreover, the fact that user preferences were less affected under lower illuminance is qualitatively consistent with the Helson–Judd effect,[32,33] where the increments on a background have their sample color less affected by the background than decrements. However, because this study mainly focused on examining the effect of the chromatic properties of illuminants, the effect of illuminance level was not fully observed. Thus, further experiments are required to observe the effect of illuminance level in a more elaborative manner.

From the study, display color temperatures ranging from 7200 to 10,600 K were generally evaluated as optimal under every illuminant. The user-preferred color temperatures were on the average shifted toward higher color temperatures compared to the standard illuminant D65, which complies with the previous studies.[34,35] Moreover, in this study, the subjects were instructed to evaluate the white points objectively to satisfy the general smartphone users. Therefore, individual variation on the preference was marginal. However, it might be interesting to carry a future research regarding the individual variations in the white point preference and to observe if these variations are consistent across varying illuminants. A customized color adjustment formula could be developed, which in turn, could satisfy users' personal tastes.

For this empirical study, display stimuli were generated in terms of the correlated color temperature. Correlated color temperature in colorimetric values is generally adopted to describe the colorific properties of a light source, mainly due to its convenience and intuitiveness. Yet, Vogels and Heynderickx[36] observed that the range for the white point setting could be acceptable up to ± 0.02 in delta uv value. Thus, it might be worthwhile to conduct a research that focuses on the effect of delta uv variations on the perception of optimal white.

In terms of practical application, the research proposes two opportunities. One is related to automatic adjustment of smartphone displays. Nowadays, some smartphones have built-in *RGB* sensors that are capable of reading ambient color temperature in real time (e.g., Samsung's Galaxy S and Note series). Referring to the color adjustment formula (1), a device could dynamically shift the color temperature toward an optimal white point. The other opportunity is regarding a static situation. Depending on the color properties of lit environment where a display is viewed, an optimal color temperature could be applied in order to maximize observer's aesthetic satisfaction.

8 Conclusion

The purpose of the research was to investigate the user-preferred color temperature adjustment for smartphone displays by focusing on the effect of ambient illuminants on the optimal white points that users perceive. The study, in particular, investigated internal representation of an idealized white point referred to as the color preference reproduction. Part I, focusing on the effect of illuminant chromaticity, indicated that the display color temperature perceived to be most optimal increases as the illuminant color temperature rises; however, the relationship was not linear. The optimal color temperatures were restricted within the range of 6500 to 11,300 K. Based on the assessments by 100 subjects, a regression formula was derived to predict the user-preferred color temperature adjustment under changing the illuminant chromaticity as follows: [Display $T_{cp} = 6534.75 \log(\text{Illuminant } T_{cp}) - 16304.68$ ($R^2 = 0.87$, $p < 0.05$)]. Part II provided empirical verification that the effect of illuminant chromaticity increases as it becomes brighter. The optimal display color temperatures draw closer to the illuminant color temperatures as the illuminance increases. Although further research should be implemented to increase the validity of these experimental results, these findings can be used as the theoretical basis for designers and manufacturers to adjust user-preferred color temperature for smartphone displays under various illuminant conditions.

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