The Optimal Color Temperature of Smartphone Display Under Various Illuminant Conditions

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***Abstract*-- The purpose of this study is to find the optimal color temperature of the smartphone display, focusing on the relationship between the illuminant conditions and the ideal whites users perceive. The subjects viewed 16 nuanced whites under 19 illuminant conditions. The study reveals that there exists a positive correlation between the color temperature of illuminant and that of a smartphone display. The optimal color temperature of a white display ranged from 6000 K to 11000 K while the color temperature of illuminant varied from 2500 K to 20000 K. However, under lower illuminance, the correlation was relatively weaker confirming previous color reproduction theories.**

I. Introduction

With the development of display devices, great attention has been paid to display color reproduction [1]. Conventionally, the performance of the display color is determined under the standard illuminant, although the real viewing conditions are not constant. The optimal display color temperature is highly dependent on the lighting condition mainly due to the viewer's chroma adaptation [2]. Facilitated by the built-in RGB sensor, some smartphones are now able to read the chromatic properties of illuminants and therefore, can adjust the display color temperature. In this regard, this study aims to find the optimal color temperature of the white displays depending on the illuminant conditions.

II. Objective

The study focuses on the color preference reproduction [3] in order to understand the cognitive representation of the optimal color temperature perceived by the smartphone users, rather than a physical white. The study is composed of two parts. In Part I, the study focuses on the effect of lighting color temperature. Part II investigates the effect of illuminance.

III. Method

A. Stimuli

1) Display Stimuli

For visual examination, Samsung Galaxy S3 with a white bezel was used. Stimuli were reproductions of an e-mail application: the typical content page with a white background black text. A total of 16 samples were prepared including the default white. Colorimetric values were measured in terms of the color temperature, luminance, and CIE 1931 Yxy values using a Spectroradiometer (Konica Minolta CS-2000). The color temperatures varied from 2800 K to 25000 K.

2) Illuminant Conditions

Subjects were exposed to 19 illuminants that simulated daily lighting experiences. Part I focused on the effect of lighting color properties. Thus, 11 illuminants were produced that were chromatically different (2500 K ~ 20000 K) but of equal illuminance (1000 lx). Part II examined the effect of illuminance. Thus, illuminants with equal color temperature but of different illuminances (30 lx ~ 3000 lx) were added. In all, 19 illuminants were produced, all of which were measured with a Chroma Meter (Konica Minolta CL-200).

B. Procedure

A total of 95 participants (50 males and 45 females) with an average age of 22.01 years and a standard deviation of ± 1.94 years were recruited. All subjects were paid volunteers with no vision problems. The subjects were asked to evaluate the optimal level of the display color temperature using a five point Likert scale ranging from -2 (least optimal) to +2 (most optimal). In Part I, the subjects were asked to assess 16 white stimuli under 11 illuminants with different color temperatures. In Part II, the participants were exposed to 8 illuminants with different illuminances. The 19 observing sessions plus the break usually required 40 minutes. The auto brightness function of the smartphone was turned on throughout the experiment.

IV. Results & Data Analysis

A. Part I: Effect of Color Temperature (K)

The total scores of the optimal level for the 16 stimuli were calculated for each of the 11 illuminants with different color temperature but equal illuminance, as listed in Table I.

Fig. 1. shows the curves of best fit for the total optimal level scores of display color temperature under 2500 K and 20000 K illuminants. The curves are relatively comparable to that of a normally distributed bell curve. The curve's peak x-value indicates the most optimal display color temperature. As the color temperature of the illuminant increases, the bell curve

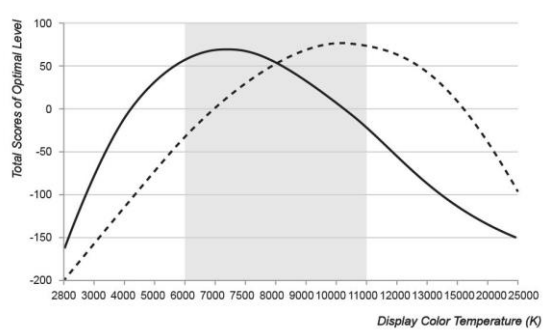

Fig. 1. The curves of best fit for the optimal level scores of display color temperature under 2500 K illuminant (solid line) and 20000 K illuminant (dashed line).

TABLE I
THE TOTAL SCORES OF THE OPTIMAL LEVEL FOR THE 16 STIMULI UNDER THE 11 ILLUMINANTS.

Display CCT (K)	Illuminant CCT (K)										
	2569	3005	3989	5040	6001	7021	8049	9061	10110	13120	20050
2812	-130	-120	-139	-166	-167	-178	-168	-167	-165	-171	-173
3138	-113	-80	-137	-151	-154	-172	-156	-164	-159	-168	-170
3930	-54	-18	-79	-109	-108	-146	-123	-127	-128	-136	-143
5015	36	-50	-9	-107	-98	-135	-112	-108	-134	-110	-105
6085	108[a]	108	109	27	89	-3	64	30	-21	-2	-13
6802	-96	103	126	107	46	75	49	31	13	-21	15
7251	31	66	120	161	117	140	95	74	75	67	72
7734	50	90	45	119	61	147	105	71	50	24	31
8986	55	61	46	138	74	133	88	83	96	87	60
9844	0	7	-4	51	21	135	81	89	112	81	70
10655	-27	-10	-3	-38	35	-36	79	65	59	112	104
11434	-68	-74	-42	-102	-62	-95	-32	-44	-59	-5	32
12569	-65	-47	-63	-50	-49	16	37	43	72	25	42
16456	-111	-92	-93	-102	-63	-81	-6	13	13	-5	11
19193	-130	-108	-149	-129	-122	-115	-37	-44	-50	-51	-46
24739	-150	-145	-150	-153	-141	-116	-111	-87	-95	-96	-85

[a]The display color temperatures with the highest score for each illuminant are underlined.

shifts towards the right.

A positive correlation is observed between the optimal display color temperature and the illuminant color temperature ($r=0.90$, $p<0.05$). Color temperature of illuminant varied from 2500 K to 20000 K. However, the display color temperatures perceived as the most optimal were fixed in range from 6000 K to 11000 K. The display color temperature higher than the surrounding illuminant is perceived to be ideal, up until the illuminant color temperature reaches 10000 K. When the illuminant is above 10000 K, even if the lighting color temperature increases, the optimal display color temperature does not rise beyond 11000 K. In other words, 11000 K is the marginal value of the ideal whites perceived. Such tendency is consistent with the previous study [4] on the display color reproduction of a large display under various illuminants.

Nonlinear regression analysis was performed in order to predict the optimal display color temperature (T_D) by taking the illuminant color temperature (T_I) as independent variables ($R^2=0.91$, $p<0.05$). The derived formula is as follows:

$$T_D = 2814.47 * \ln(T_I) - 16422.55 \quad (1)$$

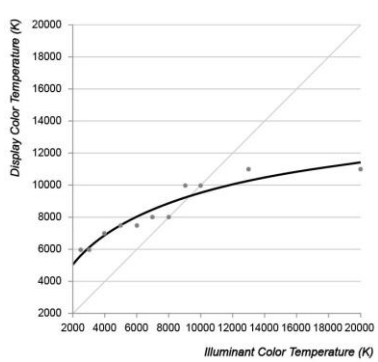

Fig. 2. The optimal display color temperatures plotted against the illuminant color temperatures. Equation (1) is fitted in a line.

B. *Part II: Effect of Illuminance (lx)*

The total scores of the 16 stimuli were calculated under the 12 illuminants with different illuminances (30 lx ~ 3000 lx). At lower illuminance (30 lx), the color temperature perceived as the most optimal ranges in a more restricted range: from 7200 K to 9000 K. Moreover, the optimal color temperature has a tendency to become more similar to the color temperature of illuminant as the illuminance increases up to 3000 lx, which complies with the previous study [5].

V. CONCLUSION

The study observed the effects of illuminant properties on the perception of optimal display color temperature by the smartphone users. Part I, focusing on the effect of illuminant color temperature, indicated that the display color temperature perceived to be ideal increases as the illuminant color temperature rises; however, the optimal color temperature is restricted within the range of 6000 K to 11000 K. Part II provided empirical verification that the optimal display color temperature draws closer to the illuminant color temperature as the illuminance increases. These findings could be used as the theoretical basis for designers and manufacturers when designing a color strategy of smartphone display.

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