True White Point for Television Screens Across Different Viewing Conditions

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***Abstract*—This paper proposes the optimal white point settings of consumer televisions observed in different viewing conditions. The ratings from visual experiments were modeled with a bivariate Gaussian distribution to predict the optimal white points. Under dark surround conditions, where there is no effect of lighting chromaticity, the averaged optimal white point was located at a correlated color temperature of 7346 K and a Duv of −0.0015. The optimal white point was shifted toward a higher color temperature compared to the current standards. The results also indicated that current white point settings of major television manufacturers are too bluish. Neither televisions that meet the current standards nor televisions in the market would appear as true white under the viewing conditions employed in this paper. Moreover, the optimal white point depended largely on viewing conditions. Image content and ambient lighting conditions were observed to be important factors that influence the perception of the white point. The research therefore proposed to automatically change the white point of the display based on the image content and the real-time measurements of the surrounding ambient light falling on the screen. Ultimately, this paper might be of interest to the industry as a basis for future deliberations on target white points for consumer televisions designed to provide a better color appearance.**

***Index Terms*—Displays, TV, broadcasting, image enhancement, color management.**

I. Introduction

SCREEN displays are everywhere these days. Beyond traditional consumer display devices such as smartphones, personal computers, and televisions (TVs), home appliances like refrigerators, ovens, and washing machines have also begun employing screens to present visual information and to get user input. Display technologies are changing the way electronic devices communicate with consumers, offering devices with larger screens and higher image quality. Consumer electronics are increasingly adopting liquid crystal displays (LCD) and organic light-emitting diode (OLED) displays to communicate with consumers, and therefore, display color appearance has become extremely important.

It has been acknowledged that white, which is defined as a color sensation that is devoid of any hue, has a fundamental role in display color appearance [1], [2]. Correlated color temperature (CCT), measured in kelvins (K), has been a widely used specification of the white point of display devices [3]. The display image set to a lower CCT appears warmer, or more yellowish, while the same image on a display set to a higher CCT appears cooler, or more bluish. The broadcast standards use D65, which has a CCT of 6504 K, as a standard white point [4].

The white point settings of the latest television and mobile displays from leading manufacturers were measured with a spectroradiometer [5], as listed in Table I [6]–[12]. Although small-sized displays like smartphones and tablets are increasingly equipped with white point settings closer to this standard, the white points of televisions are usually quite a bit cooler than the standard, ranging from 9000 K to 12000 K. Human eyes recognize a higher CCT bluish white to be a brighter white, and therefore, consumers comparing televisions at a consumer electronics store will likely favor bluish white over a television employing the D65 standard [4], [13]. Responding to such consumer preferences at a point of purchase, most of the television manufacturers adopt a higher CCT as a white point in their systems. Unfortunately, a white point set at high CCT distorts the image color appearances displayed on the screens. Moreover, the accumulating experimental evidence has indicated that exposure to blue light can affect many physiologic functions [14]. Therefore, in order to provide consumers better viewing experiences, the white point of television screens should be thoroughly investigated.

II. Related Works

A. White Point

In one of the earliest psychophysical experiments on white perception, Priest [15] observed the average white chromaticity of four subjects at 5200 K under dark-adapted conditions. Helson and Michels [16], on the other hand, reported the dark-adapted white chromaticity at 15000 K based on data from three subjects. In response to these findings, Hurvich and Jameson [17] provided white threshold contours in color temperature, instead of a single chromaticity point. Similarly, Honjyo and Nonaka [18] provided a rather large region of white perception, ranging from approximately 5500 to 10000 K.

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TABLE I
THE WHITE POINT SETTINGS OF LEADING MANUFACTURERS

Category	Manufacturer	Mode	CCT (K)
Television	Manufacturer A [6]	Movie	6353
		Standard	10083
		Vivid	12500
	Manufacturer B [7]	Cinema	6540
		Standard	11152
		Vivid	12410
Smartphone	Manufacturer C [8]	Standard	6597
	Manufacturer A [9]	Basic	6495
		Adaptive	7618
Tablet	Manufacturer C [10]	Standard	6943
	Manufacturer D [11]	Standard	6892
	Manufacturer E [12]	Standard	6906

Recently, it has become accepted that Duv should be considered together with CCT to enhance white perception [19]. In rough terms, CCT describes a yellow-blue axis, and Duv describes a red-green axis. Either measure alone cannot accurately describe the exact color appearance, but when used together, the measures can be thought of as a two-dimensional coordinate system with visually meaningful axes. Ohno and Fein [20] indicated that light sources with negative Duv values are preferred. In a similar experiment, when CCTs are higher than 4000 K, positive Duv values were preferred, whereas for lower CCTs, negative Duv values were preferred [21]. More recently, Smet *et al.* [22] and Wang *et al.* [23] reported maximal white perception of lighting at a CCT around 6600 K with a Duv value close to zero.

The concept of white point of display devices, however, has seldom been investigated. Recently, Choi and Suk [3] observed maximal white perception of mobile display devices at a CCT around 7300 K with a positive Duv value. In a more recent research, Huang *et al.* [24] reported a CCT of 7500 K and a Duv of zero to be the whitest in tablet displays. These studies have agreed that the white point observed in experiments were shifted towards a higher color temperature compared to the standard white point D65.

B. Viewing Parameters

Although white perception has been studied intensively, there is quite a bit of disagreement among various psychophysical experiments in the literature, indicating that white perception depends largely upon the specifics of the viewing conditions. The display sizes, surround conditions, and the contents used on the screens are all factors that impact the white perception of displays.

By their very nature, television screens are generally observed in widely disparate viewing conditions, from dark conditions to brightly lit conditions with sunlight coming through a window. The human visual system perceives display colors differently under varying surround conditions, mainly due to the process of chromatic adaptation. Chromatic adaptation is the human visual system's ability to maintain the perceived color appearance constantly against the changes of chromaticity reflected from an object under wide variation of lights [25], [26]. A chromatic adaptation transform (CAT) model predicts these chromatic shifts; the model is developed based on a pair of color stimuli showing the same color appearance under different illuminants [1]. One of the most widely used CATs is the CAT02 transform embedded in CIECAM02 [27].

Unfortunately, these models are unsatisfactory under bright surround conditions and can only be used under quite limited viewing conditions [28]. Moreover, they do not provide a complete solution for image specification [29]. These models do not directly incorporate any of the spatial or temporal properties of human vision and the perception of images. Besides surround conditions, image content also influences the perception of the display color appearance [30]. Qin and Wang [31] observed that the optimal white point for images containing warm colors was more yellowish, whereas the images with green or blue contents were preferred with a more bluish white point setting. Similarly, Vogels and Berentsen [32] found that the optimal white point of images was correlated with the average chromaticity of the image under different ambient lightings.

As such, this paper builds on previous studies by observing the white perception of different images displayed on televisions in a real rather than a simulated environment, lit by illuminants with various chromaticities. By doing so, this study aims to propose an optimal white point setting that could be applied as the basis for enhanced color appearance of consumer televisions.

III. EXPERIMENTS

A. Display Characterization

A 55-inch quantum dot light-emitting diode (QLED) television was used for the experiment. The white point setting of the television was set to the "Movie" mode. When measured with a spectroradiometer, the native white point of the television was (0.1977, 0.4713) in the CIE 1976 u' v' chromaticity, which is equivalent to a CCT of 6353 K. The coordinates and luminance of the R (Red), G (Green), and B (Blue) primaries at peak output were as follows: $R = (0.4562, 0.5229, 85.57\ \text{cd/m}^2)$, $G = (0.1271, 0.5609, 200.11\ \text{cd/m}^2)$, and $B = (0.1822, 0.1471, 24.72\ \text{cd/m}^2)$. The television was switched on for at least an hour prior to starting the experiments to ensure a stable luminance output.

B. White Point Adjustment

Four original images with a resolution of 1920 by 1080 pixels were used in the experiment, which can be shown on the panel without clipping or scaling. The images were selected based on their color and content (Fig. 1). The "Fruit" and "Portrait" images were included because these are one of the most typical images displayed on TV and at the same time, they have strong associations with particular colors. Memory color refers to the phenomenon that recognizable objects often have a prototypical color associated, such as skin tones, red apple, green grass, or blue sky [33]. These colors

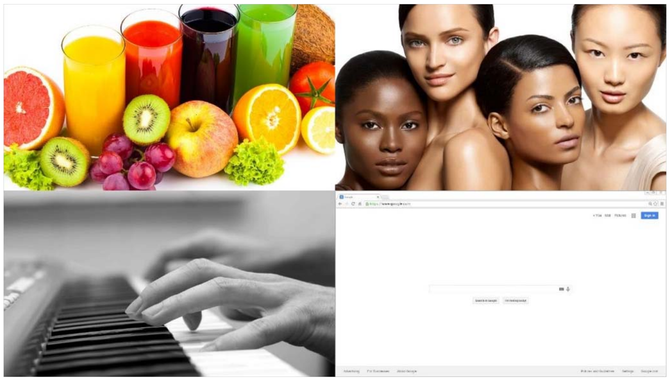

Fig. 1. Four original images presented in the experiment with varying in color and content: fruit, portrait, piano, and Web images.

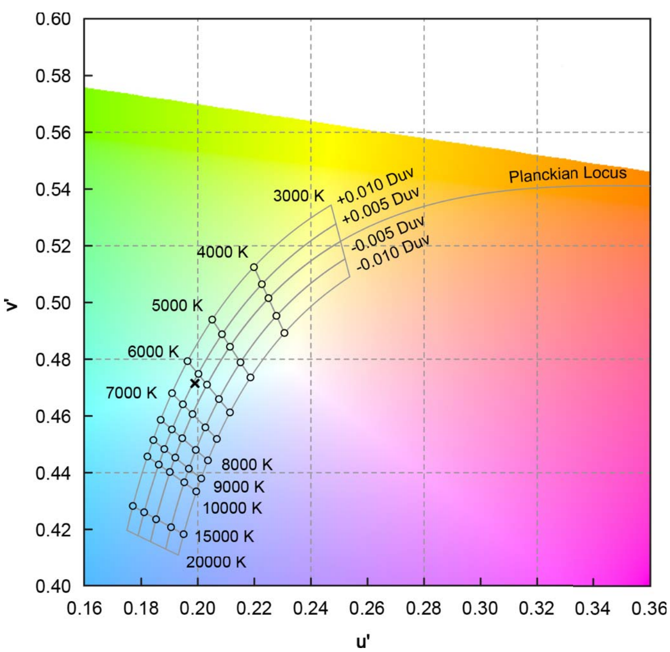

Fig. 2. A total of 40 white points at eight different CCTs and at five different Duv levels in the CIE 1976 *u' v'* chromaticity. The 40 target white points and the native white point are marked with circles and a cross.

are more critical for image color quality than others because we have such a strong memory of them. The "Fruit" image was a combination of diverse fruit colors. The "Portrait" image was included because of the skin tones. Next, the achromatic "Piano" image was added to exclude the effects of color information. Finally, the "Web" image, with white color dominantly displayed, was added to account for the emerging use of Web browser in smart TVs. The original white points estimated from the brightest pixel in each image were identical at *RGB* values of 255, 255, 255 [34].

Each test image was then processed to have different white points, appearing more yellowish, more bluish, more reddish or more greenish than the original. First, the *RGB* values of the brightest pixel were adjusted to produce 40 chromaticities which were uniformly distributed in the CIE 1976 *u' v'* chromaticity (see Fig. 2). The target white points were set up in a range of CCTs from 4000 to 15000 K, at five different Duv levels (−0.010, −0.005, 0, 0.005, and 0.010). They were

TABLE II
THE COLORIMETRIC VALUES OF TARGET WHITE POINTS

No.	CCT (K)	Duv	X	Y	Z
1	3965	-0.0104	132	124	96
2	5075	-0.0098	143	139	138
3	6037	-0.0110	146	141	166
4	6923	-0.0085	139	137	174
5	8036	-0.0103	132	128	182
6	9017	-0.0093	127	124	185
7	9909	-0.0096	122	118	185
8	15193	-0.0091	114	108	197
9	3924	-0.0041	131	127	86
10	5021	-0.0054	143	142	132
11	6019	-0.0056	137	137	152
12	7025	-0.0050	143	144	179
13	8098	-0.0047	130	131	179
14	8765	-0.0055	131	130	187
15	9508	-0.0052	125	124	186
16	14329	-0.0060	112	109	193
17	3930	0.0009	132	131	81
18	4939	-0.0016	145	146	127
19	6007	-0.0001	146	152	157
20	6927	0.0009	146	152	178
21	7851	0.0016	136	142	181
22	8757	-0.0020	131	133	188
23	9943	-0.0006	123	126	188
24	15044	-0.0010	110	110	194
25	3998	0.0049	134	136	79
26	4861	0.0056	144	151	116
27	6016	0.0057	150	159	159
28	6979	0.0058	145	155	175
29	7976	0.0055	133	142	179
30	9059	0.0054	125	133	182
31	9933	0.0049	123	130	188
32	15033	0.0040	109	112	194
33	4022	0.0089	131	135	72
34	4980	0.0094	144	154	115
35	6015	0.0110	143	157	145
36	6846	0.0102	143	157	168
37	8044	0.0095	128	140	171
38	8792	0.0114	129	143	185
39	9769	0.0104	123	134	187
40	14919	0.0093	106	113	192
41	6398	0.0049	158	168	177

The Y value corresponds to the luminance.

located at eight isotemperature lines of, nominally, 4000, 5000, 6000, 7000, 8000, 9000, 10000, and 15000 K. The intervals between each isotemperature line were carefully segmented in micro reciprocal degrees (MK^{-1}) in order to achieve visual uniformity [35]. The original white point (i.e., *RGB* values of 255, 255, 255) was added to create a total of 41 target white points. The colorimetric values of each white point setting were measured using a spectroradiometer, as listed in Table II.

Next, the change in white point was simulated by manipulating whole pixels of the image [36], [37]. In this process, the CIE tristimulus values *XYZ* of each pixel in an image were

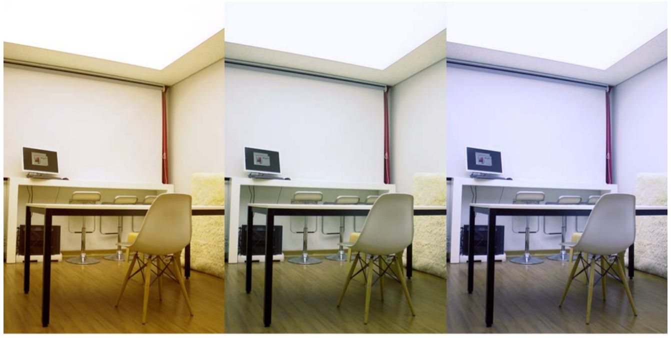

Fig. 3. Experimental room equipped with an LED luminous ceiling. A uniform lighting was realized in the room, which illuminated the entire space, ensuring that the participants fully immersed in the lighting environment. From left to right: 3500, 5000, and 6500 K lighting conditions at 500 lx.

calculated from its *RGB* digital inputs by the forward colorimetric characterization [38]. Next, the channel gains X_{gain}, Y_{gain}, and Z_{gain} were computed by:

$$X_{gain} = X_{tgt}/X_{orig} \tag{1}$$

$$Y_{gain} = Y_{tgt}/Y_{orig} \tag{2}$$

$$Z_{gain} = Z_{tgt}/Z_{orig} \tag{3}$$

where X_{tgt}, Y_{tgt}, and Z_{tgt} are the three channels of target white point, and X_{orig}, Y_{orig}, and Z_{orig} are the three channels of original white point. Then, the pixel value of each pixel in the image was adjusted by:

$$X' = X \times X_{gain} \tag{4}$$

$$Y' = Y \times Y_{gain} \tag{5}$$

$$Z' = Z \times Z_{gain} \tag{6}$$

where X, Y, and Z are the original values of pixels in the image, and X', Y', and Z' are the adjusted pixel values. Afterwards, the $X'Y'Z'$ values were converted back to digital inputs *R'G'B'* for each pixel by the reverse colorimetric characterization.

C. Test Lighting Condition

The study was conducted in a room equipped with an LED luminous ceiling, as shown in Fig. 3. A uniform lighting was realized in the room, which illuminated the entire space, ensuring that the participants fully immersed in the lighting environment. The experiments were conducted at three different chromaticities (3500, 5000, and 6500 K) according to the range of chromaticities recommended for general lighting [39]. As for the illuminance, three levels were produced (100, 500, and 1000 lx) to simulate daily indoor lighting experience [40]. Moreover, the display stimuli were also examined with the light turned off. In all, ten lighting conditions were produced with the LED luminous ceiling. The colorimetric values of each lighting condition were measured on a horizontal plane at the participants' desk level with a chromameter [41], as listed in Table III.

All curtains were closed to block off the fluctuation of natural daylight. Without the light turned on, the measured illuminance at the subject's position was less than 5 lx. The size of the room was 6.2 m × 3.3 m × 2.5 m. To reduce the bias in color perception inflicted by the surrounding environment, the room was neutral in color, using only white walls and wooden colored floors.

TABLE III
THE COLORIMETRIC VALUES OF TEST LIGHTING CONDITIONS

No.	CCT (K)	Duv	X	Y	Z
1	3560	-0.0002	135	131	70
2	3541	0.0005	509	493	259
3	3476	-0.0018	937	899	488
4	5088	0.0011	105	108	93
5	4897	0.0019	464	477	389
6	4877	0.0005	970	989	823
7	6452	-0.0006	104	107	120
8	6524	0.0008	495	513	573
9	6543	-0.0020	945	964	1108

The Y value corresponds to the illuminance.

D. Experimental Procedure

A total of 30 college students (15 males and 15 females) were recruited for the experiment, with an average age of 21.00 years and a standard deviation of 2.02 years. They had normal or corrected-to-normal visual acuity, with no significant color deficiencies. Ethical approval was obtained prior to the commencement of all of the studies concerning human participants.

The participants were asked to rate the white balance of each presented stimulus using a five-point Likert scale ranging from 1 (least balanced) to 5 (most balanced). Value 5 signified an image devoid of any particular hue sensation, i.e., neither red, nor green, nor yellow, nor blue. Values above or equal to 3 were images that could be classified as either cold, warm or neutral, with increasing balance for higher values, and values below 3 signified that a certain hue was clearly observable.

The ten lighting conditions were presented in random order. For each lighting condition, participants rated the white balance for each of the four image groups. In each image group, the 41 white points were presented in a random order to eliminate any sequential effect on the subjects' evaluation. Evaluations under each lighting condition typically took about 10 to 15 minutes, for a total of about three hours for 1640 ratings (10 lighting conditions ×4 images ×41 white points). In order to avoid visual strain and boredom, the experiment was divided into two consecutive days.

The subjects were seated in the center of the room, and their full view was completely adapted to the illumination. The viewing distance was approximately 2.5 m, providing a field of view (FOV) of 27.4° (see Fig. 4). The room's ambient conditions were maintained for human comfort [42]: ambient temperature = 24.2 ± 2 °C; ambient humidity = 37 ± 5%; and ambient noise = 45.2 ± 10 dB(A).

IV. RESULTS AND DISCUSSION

A. Modeling of White Region

The error ellipse has been frequently adopted to represent the yes and no boundary for the perception of

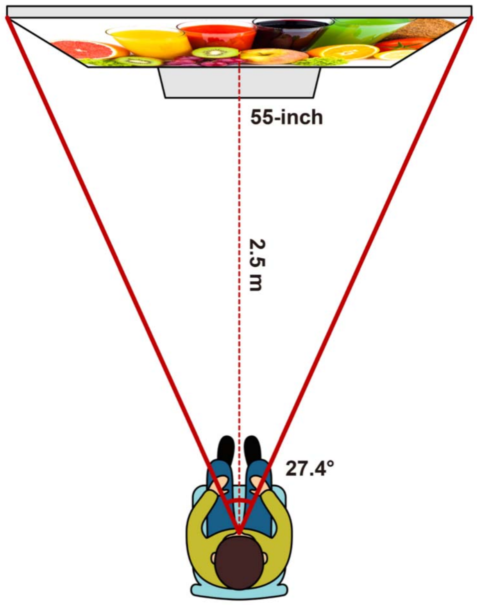

Fig. 4. Experimental environment with a viewing distance of approximately 2.5 m, providing a field of view (FOV) of 27.4°.

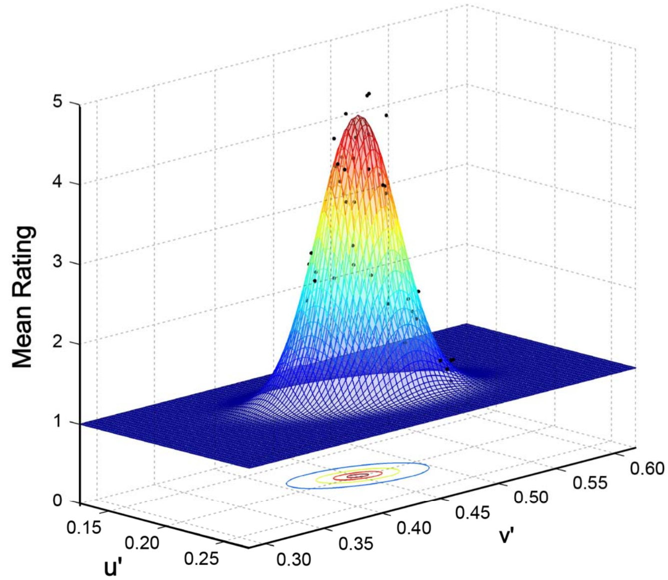

Fig. 5. Bivariate Gaussian distribution and its elliptical contours, as obtained by fitting the full data set in the CIE 1976 $u'v'$ chromaticity. The mean ratings for each chromaticity point are also shown as dots.

white. The bivariate Gaussian distribution is a logical extension to the error ellipse that incorporates a full data set [3], [22], [24], [43]. The adoption of a bivariate Gaussian distribution offers several advantages compared to fitting an error ellipse, for which only "yes" ratings are taken into account. Since all data points are used, fitting a distribution is less susceptible to outliers and hence more accurate in predicting the center. Moreover, it becomes much less critical to have a grid with high-rated values fully enclosed by low-rated values. The bivariate Gaussian distribution also results in a simple metric to predict the degree of neutrality of any stimulus viewed by an average observer. Hence, the full ratings was modeled with a bivariate Gaussian distribution, as described by

$$W = a_6 \cdot e^{-0.5\left[a_1(u'-a_3)^2+a_2(v'-a_4)^2+2a_5(u'-a_3)(v'-a_4)\right]} \quad (7)$$

with W as the degree of whiteness, a_1 to a_6 as the fitting parameters, and u' and v' as the CIE 1976 chromaticity coordinates. The bivariate Gaussian distribution was fitted for each of the four images under each ambient lighting condition, with Fig. 5 illustrating the resulting distribution of "Fruit" image evaluated under dark conditions as an example. The mean ratings for 41 chromaticity points and the 25%, 50%, 75%, and 95% elliptical contours of the bivariate Gaussian model were also plotted. The goodness of fit was quantified by calculating the Spearman correlation coefficient ρ and standardized residual sum of squares (*STRESS*). The average Spearman correlation coefficient was 0.88 ($p < 0.01$), and the average *STRESS* value was 0.12, suggesting that the bivariate Gaussian functions were accurately modeled.

B. Image Dependence

In order to observe the effect of different images, the white perception of each image was investigated under dark surround conditions, where there is no effect of lighting chromaticity. The fitting parameters and the center of the bivariate Gaussian models of four images are summarized in Table IV.

1) Fruit Image: In Fig. 6, the 50% bivariate Gaussian elliptical contour of the "Fruit" image was plotted over the ANSI C78.377 [39] and CIE S 004 [44] standard white regions for light sources. The standard white point D65 was also plotted. The ellipse was located near the Planckian locus within the CCT range of 6060 to 10885 K and the Duv range of −0.0104 to 0.0060. The optimal white point arose at (0.1970, 0.4517) in the CIE 1976 $u'v'$ chromaticity as predicted by the center of the bivariate Gaussian distribution, which is equivalent to a CCT of 7814 K. With regard to the Duv value, the ellipse was centered at −0.0022, which is slightly below the Planckian locus.

2) Portrait Image: The 50% elliptical contour of the "Portrait" image encompassed 6006 to 9969 K in CCT and −0.0091 to 0.0052 in Duv. The white center was situated at the chromaticity coordinates of (0.1978, 0.4543), which is equivalent to a CCT of 7520 K and a Duv of −0.0020.

3) Piano Image: For the "Piano" image, the 50% elliptical contour encompassed 5956 to 9151 K in CCT and −0.0086 to 0.0062 in Duv. The center of the bivariate Gaussian distribution was located at (0.1983, 0.4575), which is equivalent to a CCT of 7213 K and a Duv of −0.0012.

4) Web Image: As seen in Fig. 6, the white region of the "Web" image surrounded closely the Planckian locus in the CCT range of 5730 to 8844 K and the Duv range of −0.0080 to 0.0085. The optimal white point, as represented by a cross mark situated at (0.1982, 0.4613), is equivalent to a CCT of 6942 K. With regard to the Duv value, the optimal white point was located at 0.0002, sufficiently near the Planckian locus.

TABLE IV
BIVARIATE GAUSSIAN MODELS OF FOUR IMAGES UNDER DARK CONDITION

Image	a_1	a_2	a_3	a_4	a_5	a_6	u'_{center}	v'_{center}	$\text{CCT}_{\text{center}}$ (K)	$\text{Duv}_{\text{center}}$
Fruit	5844.82	1525.37	0.20	0.45	-1212.41	3.35	0.1970	0.4517	7814	-0.0022
Portrait	7321.54	2064.87	0.20	0.45	-1757.71	3.76	0.1978	0.4543	7520	-0.0020
Piano	8268.56	1945.33	0.20	0.46	-1129.53	3.66	0.1983	0.4575	7213	-0.0012
Web	7278.50	1577.10	0.20	0.46	-748.42	3.53	0.1982	0.4613	6942	0.0002

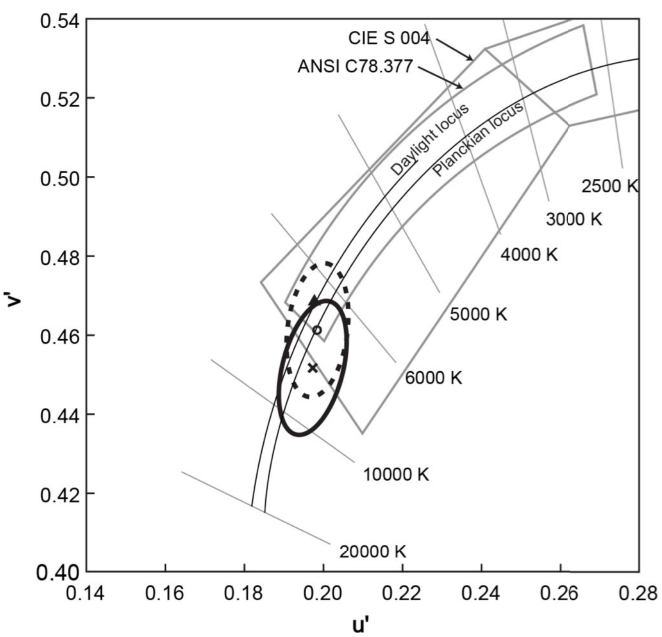

Fig. 6. 50% bivariate Gaussian ellipses fitted for “Fruit” image plotted as a solid line with a cross center, and “Web” image plotted as a dashed line with a circle center. The standard white point D65 is marked with a filled triangle. The ANSI C78.377, and CIE S 004 standards are also shown, along with the Planckian and daylight loci.

For all images, the optimal white point shifted towards higher color temperatures compared to the standard white point D65, at least under dark surround conditions. The low and high CCT ends of ANSI C78.377 and CIE S 004 standards tend to overestimate and underestimate the white region of television displays, respectively. By averaging the evaluations for four images, the averaged white point under dark surround conditions was situated at (0.1980, 0.4562), which is equivalent to a CCT of 7346 K and a Duv of -0.0015.

The evaluation under dark surround condition showed that the optimal white point highly depends on the image. The optimal white point of the “Web” image was closest to the standard white point D65, and the optimal white point deviated towards higher color temperature in the order of “Piano,” “Portrait,” and “Fruit.” The difference in CCT between the optimal white points of “Web” and “Fruit” image was Δ872 K, while the difference in Duv was minimal. In order to test whether the effect of image is the same for other lighting conditions, correlation coefficients were calculated between ten lighting conditions for the $u'v'$ chromaticity coordinates of the optimal white point. The correlation averaged across all combinations of lighting conditions was $\rho = 0.88$ for the u' coordinate and $\rho = 0.80$ for the v' coordinate, indicating that the effect of image on white perception was consistent across different lighting conditions. The average CCT difference between the “Web” and “Fruit” images under ten lighting conditions was Δ795 K.

C. Ambient Lighting Dependence

Televisions are generally observed in various lighting conditions, in which the white perception may differ considerably from dark surroundings due to chromatic adaptation. In order to observe the effect of ambient lighting conditions, the evaluations for four images were averaged, and herein the central tendency of the four images was reported. The fitting parameters and the center of the bivariate Gaussian models under ten lighting conditions are summarized in Table V.

1) Chromaticity Dependence: The average data set was modeled with a bivariate Gaussian distribution for each of the three illuminants with different CCTs (3541, 4897, and 6524 K) but of equal illuminance (approximately 500 lx), which is a recommended illuminance level for normal activities [45]. The full data set was modeled with a bivariate Gaussian distribution for each of the three lighting chromaticities. As listed in Table V, the coordinates and CCT of the maximal whiteness perception for the 3541, 4897, and 6524 K lighting conditions were (0.2034, 0.4643, 6375 K), (0.2025, 0.4611, 6640 K), and (0.1999, 0.4593, 6958 K), respectively. When compared to the dark-adapted white center (0.1980, 0.4562, 7346 K), the chromatic-adapted white centers were shifted towards the chromaticity of the lightings. The difference in CCT between the optimal white points of low- and high-CCT end-lighting conditions was Δ583 K. Within these bounds, the CCT of the optimal white point increased as the lighting CCT rose. With regard to the Duv value, negative Duv values were preferred under every lighting condition. However, there was no systematic trend with regard to the surround lighting conditions.

2) Illuminance Dependence: The study observed changes in optimal white points under varying illuminance levels. At lower illuminance (approximately 100 lx), the effect of lighting chromaticity on the display white perception was relatively weaker. The CCTs of the optimal white points were within a more restricted range from 6919 to 7038 K, with a difference of Δ119 K. However, the effect of lighting chromaticity increased as illuminance increased to approximately 1000 lx, for which the CCT of the optimal white point varied in a much wider range, from 6133 to 6791 K, with a difference of Δ658 K. The CCTs of optimal white points drew closer to the CCT of the lighting condition as the surround lighting

TABLE V
BIVARIATE GAUSSIAN MODELS ESTIMATED UNDER DIFFERENT LIGHTING CONDITIONS

Lighting condition		Fitting parameters and the center of the bivariate Gaussian model									
CCT (K)	Illuminance (lx)	a_1	a_2	a_3	a_4	a_5	a_6	u'_{center}	v'_{center}	CCT_{center} (K)	Duv_{center}
0	0	7115.83	1697.07	0.20	0.46	-1164.01	3.53	0.1980	0.4562	7346	-0.0015
3560	131	7476.15	1756.85	0.20	0.46	-1211.96	3.62	0.2006	0.4591	6919	-0.0026
5088	108	7556.31	1773.91	0.20	0.46	-1229.48	3.68	0.1997	0.4591	6983	-0.0018
6452	107	7054.43	1744.96	0.20	0.46	-1134.54	3.66	0.1994	0.4587	7038	-0.0017
3541	493	6284.89	1435.02	0.20	0.46	-910.25	3.61	0.2034	0.4643	6375	-0.0029
4897	477	6528.13	1634.48	0.20	0.46	-958.60	3.60	0.2025	0.4611	6640	-0.0034
6524	513	7846.83	1761.78	0.20	0.46	-1404.79	3.57	0.1999	0.4593	6958	-0.0019
3476	899	5681.28	1494.59	0.21	0.47	-989.66	3.56	0.2054	0.4662	6133	-0.0037
4877	989	6448.64	1748.21	0.20	0.46	-958.73	3.67	0.2036	0.4618	6517	-0.0040
6543	964	7507.11	1782.34	0.20	0.46	-1078.75	3.59	0.2017	0.4597	6791	-0.0033

became brighter. In other words, the amount of chromatic adaptation increased as the level of illuminance increased. However, no meaningful interpretations were derived to relate the illuminance levels and the Duv values.

V. DISPLAY COLOR ENHANCEMENT FOR TRUE WHITE

The optimal white point of television was investigated under dark and lit surround conditions using four images varying in color and content. Under dark surround conditions, where there is no effect of lighting chromaticity, the optimal white points of all images were shifted toward a higher color temperature compared to the standard white point D65. Combined, the optimal white point predicted by the average of the four images was 7346 K in CCT and −0.0015 in Duv. The experimental results suggest that the standard white regions for light sources (i.e., ANSI C78.377 and CIE S 004) are also not applicable for television displays. This is in agreement with the results obtained from the earlier studies [3], [24], [46], [47], reporting that the perceptually preferred white could have a slightly bluish tint. In this study, negative Duv values were preferred except for the "Web" image. However, there is still a lot of inconsistency in the exact value of Duv among previous studies [19]–[22], [46].

By comparing the experimental results to the white point settings of the televisions selling in markets, it seems obvious that the white points adopted by major television manufacturers are too bluish (see Table I). The current white point settings would not be perceived as white under the viewing conditions employed in this study. In order to provide consumers better viewing experiences, the white point of televisions should be set closer to 7346 K. Otherwise, a consumer adjustable white point with color balance slider controls would allow consumers to set the white point that they prefer.

Moreover, the experimental results showed that the CCT of the optimal white point depends largely on the image and surrounding conditions. With regard to the Duv value, no meaningful interpretations were derived. In order to compensate for such changes in white perception, the research proposes to automatically change the white point of the display based on the image content and the real-time measurements of the surrounding ambient light falling on the screens. The chromaticity of ambient lighting could be measured by an ambient light sensor that measures the chromaticity of ambient light in addition to its illuminance. Color-sensitive light sensors such may be distributed at different locations on television to detect light from different directions. Fig. 7 is a flowchart of illustrative steps involved in adjusting the white point of televisions based on the image contents and ambient lighting conditions.

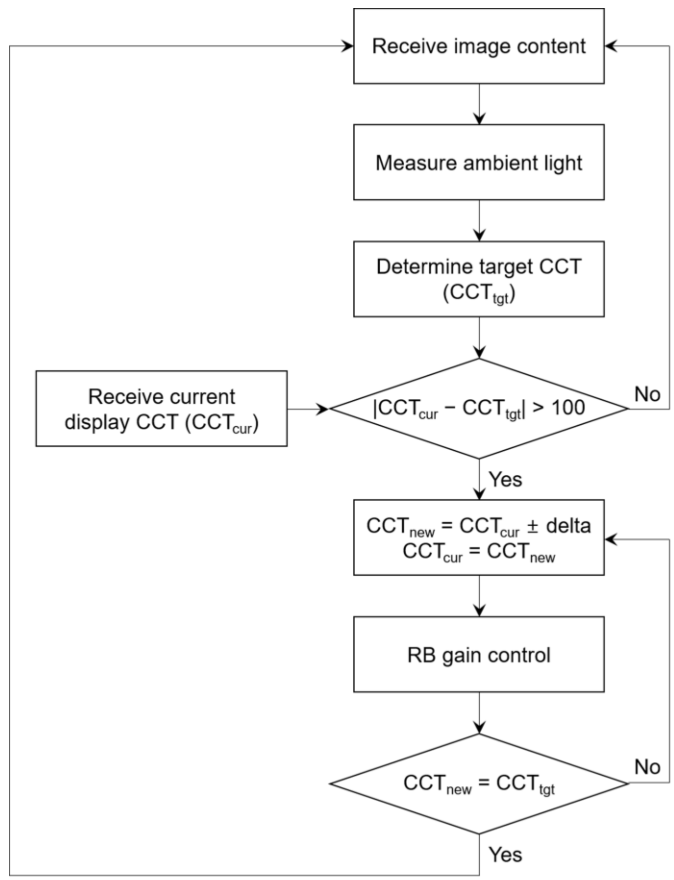

Fig. 7. Flowchart of adjusting the white point of televisions based on the image contents and ambient lighting conditions.

VI. CONCLUSION

The purpose of this study was to propose optimal white point settings for consumer televisions. The visual evaluation was conducted for different images displayed on televisions in a real environment rather than a simulated one, lit by illuminants with various chromaticities. The ratings on 41 chromaticity points were fitted into a bivariate Gaussian distribution. The result showed that the optimal white point under dark surrounding conditions was at 7346 K in CCT and -0.0015 in Duv. This indicated that the televisions in the markets and the televisions that meet the current standards would probably not be perceived as true white. Moreover, the optimal white point was highly dependent on the image content and the surrounding ambient illuminant; hence, the present study suggests varying the white point based on the real-time measurements of the image content and ambient lighting. Although further research is necessary, the results of this study are expected to be the basis for enhanced white appearance on consumer televisions.

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