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Color Preference under LEDs with Diminished Yellow Emission

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ABSTRACT A psychophysical experiment was conducted to investigate brightness perception and color preference under illumination from typical 3000 K blue-pumped light emitting diode (LED) A19 lamps (BP-LED) and 3000 K blue-pumped LED A19 lamps with diminished yellow emission (YD-LED). Eighty-seven participants between 19 and 25 years completed brightness matching and preference comparisons between two full-size side-by-side rooms that contained chromatic objects and still life arrangements, with one lamp type in each room. Participants had higher overall preference to the room illuminated by YD-LED. Specifically, red, green, orange, and wood objects were preferred under YD-LED; no preference was found for neutral, yellow, and blue objects between the two lamp types. The words *saturated, vivid, vibrant, pleasant, inviting, colorful, stand-out, distinct, appealing*, and *comfortable* were reported as reasons for the color preference under YD-LED; *dull, dead*, and *fade* were used by participants to describe the lower color preference under BP-LED. Skin tone preference under the illumination of these two lamp types was significantly different between Asian ($n = 32$) and Caucasian ($n = 52$) participants. Caucasians evaluated their own skin tone more favorably under YD-LED, with the average assessment that skin appeared healthy and colorful under YD-LED but grey and pale under BP-LED. No preference between the two lamps was found among Asians for their skin tone, though some Asians thought YD-LED rendered their skin too red and odd. Many existing measures of color preference and gamut were able to predict the higher overall preference to YD-LED, but they could not predict the preference of specific colors or for ethnic groups. The higher saturation and preference for red and green colors under YD-LED illumination is consistent with the higher red–green opponent signal provided by YD-LED. Coupled with several past studies, the spectral region around 570–580 nm appears to be deleterious to color and brightness perception.

KEYWORDS color preference, color quality, color rendering, measures, SPD, LED

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1. INTRODUCTION

About 41% of primary energy in the United States was consumed by residential and commercial buildings in 2010, with lighting accounting for about 10% of building energy consumption [Department of Energy 2012]. In an effort to reduce the energy consumption, manufacturers are making efforts to provide energy-efficient light sources and luminaires. The luminous efficacy of many light emitting diode (LED) products now exceeds that of most filament lamps and some fluorescent products [Wei and Houser 2012b]. More and more conventional lighting has been replaced by solid-state lighting to reduce energy consumption. In residential buildings, the incandescent A19 lamp is still the most popular lamp due to familiarity, low initial cost, and ease of replacement. There is great potential for energy savings by replacing incandescent A19 lamps with LED A19 lamps [Pacific Northwest National Laboratory 2012].

Energy efficiency, however, is not the only determinant to evaluate an electric lighting system [DiLaura and others 2011; Fotios 2011; IES 2009; Wei and others 2013]. Lighting systems that poorly illuminate the colors of the objects and environments may be unacceptable to occupants. Three basic categories—fidelity, discrimination, and preference—cover different aspects of color quality of a light source [Houser and others 2013]. Color rendering index (CRI), the most widely used measure for color rendition [CIE 1995], only accounts for color fidelity and has limitations that are especially pronounced for solid-state lighting [CIE 2007; Houser 2013]. During the past few years, new measures have been proposed to evaluate color quality, either as a replacement for CRI, including Q_f in the Color Quality Scale (CQS) [Davis and Ohno 2010] and CRI2012 [Smet and others 2013], or as an addition to CRI [Freyssinier and Rea 2012; Guo and Houser 2004; Houser and others 2013; Rea and Freyssinier 2008]. No final recommendation has been made by the CIE [2012]. Currently, two CIE technical committees are making efforts to develop measures of color rendition. TC1-90 was established "to evaluate available indices based on color fidelity for assessing the colour quality of white-light sources with a goal of recommending a single colour fidelity index for industrial use"; TC1-91 was established "to evaluate available new methods for evaluating the colour quality of white-light sources with a goal of recommending new methods for industrial use. (Methods based on colour fidelity should not be included)" [CIE 2012, p. 28].

The most common method to produce white light with LED products is to employ a blue LED and a phosphor [Wei and Houser 2012b]. Some of the blue light is converted to longer wavelengths with a broad emitting phosphor, and the rest of the blue light is intentionally allowed to leak—the combination resulting in white light. This method is commonly referred to as "blue pump plus phosphor." Manufacturers are making efforts to optimize LED spectral power distributions (SPDs) to improve color quality. As a result, we can expect more products with highly structured SPDs—that is, SPDs with peaks, valleys, and discontinuities in the emission spectrum—to appear in the market. It has been demonstrated that the LEDs with structured spectra can provide high color quality and greater energy efficiency than broad emitting spectra [Miller and others 2009; Seong and others 2013]. Because fidelity, discrimination, and preference have different optimization criteria, it is impossible to simultaneously maximize these three aspects of color quality in one illuminant [Houser 2013]. In addition to comparing color to that under a reference illuminant, people also evaluate color quality in terms of appreciation or preference, especially for familiar objects such as skin, fruit, and flowers [Buck and Froelich 1948; Jost-Boissard and others 2009; Judd 1967; Sanders 1959; Smet and others 2011b; Thornton 1974].

Some measures, such as Judd's flattery index [Judd 1967], Thornton's color preference index [Thornton 1974], and the memory color rendering index [Smet and others 2011a], have been proposed to focus on preference or attractiveness. Psychophysical experiments have been conducted to evaluate whether these measures can characterize visual preference. Most of these studies have been conducted in viewing booths [Bodrogi and others 2013; Dangol and others 2013; Islam and others 2013; Jost-Boissard and others 2009; Narendran and Deng 2002; Smet and others 2010]. Sometimes, preference may be due to a brightness difference rather than color [Islam and others 2013; Rea and Freyssinier 2013] because color perceptions might improve with increases in light level (for example, Bezold-Brucke and Hunt effects [Fairchild 2005]), as might color discrimination [Boyce and Simons 1977; Rea and Freyssinier 2008].

In this study, the preference of illumination from two 3000 K LED A19 lamps—where one was a typical blue-pumped phosphor product (BP-LED) and the other had a purposely designed diminished yellow emission (YD-LED)—was compared in two full-size side-by-side rooms. The rooms had the same layout and still life arrangements of familiar chromatic objects. Preference evaluations were made after the participant matched the rooms for spatial brightness in order to isolate color as the basis for preference.

2. METHODS

The experiment was approved by Penn State's Institutional Review Board.

2.1. Apparatus

The experiments were carried out in Penn State's Lighting Lab in University Park, Pennsylvania. Two rooms with nominal dimension of 10 ft (width) × 12 ft (depth) × 9 ft (height) were built adjacent to each other. Each room was enclosed by three walls that were painted with Munsell N8 spectrally neutral paint (RP IMAGING, Tucson, AZ, USA). A black felt curtain was behind the participant and out of his or her field of view during the experiment. The ceiling was 2 ft × 2 ft acoustical tiles. Grey carpeting was placed on the floor.

Four 8-ft indirect pendant luminaires were installed in each room, suspended 15 in. below the ceiling. Baffles made of white foamcore were placed on the luminaires to prevent participants from seeing the lamps directly. Nine BP-LEDs and six YD-LEDs were installed in each luminaire. BP-LEDs were connected to Lutron Grafik Eye Qs systems (Lutron Electronics Company, Coopersburg, PA, USA), with one control system for each room. YD-LEDs were connected to DC power supplies, with one for each room. Each power supply had two channels, which separately controlled two parts of the SPD of the YD-LEDs. The physical properties of the two rooms were as near to each other as reasonably possible so that SPD could be isolated as the independent variable. The lumen output of BP-LEDs could be easily changed while maintaining stable chromaticity coordinates. It was not possible to easily change the output of the YD-LEDs while maintaining constant chromaticity due to control system limitations.

Figure 1 illustrates relative SPDs, which represent the average of measurements taken at different times during the course of the experiment and in both rooms. Each set of measurements for the two conditions can be enclosed by a five-step MacAdam ellipse centered at the coordinates computed from the average SPD, as shown in Fig. 2. For either SPD, CRI and the three measures included in the National Institute of Standards and Technology's (NIST) CQS varied within 2 points. Thus, the stimuli in each room were similar to each other over the duration of the experiment; all participants experienced comparable conditions.

Figure 3 shows that various objects were placed in the rooms, including a mirror, red apple, red pepper, orange,

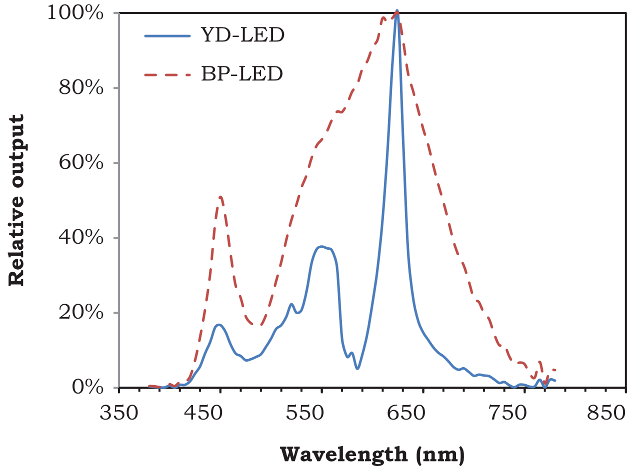

Fig. 1 Relative SPDs of YD-LED and BP-LED. These were the average of the measurements taken at different times during the course of the experiment within the experiment spaces, accounting for interreflections within the luminaire, from room surfaces, and the colored objects placed in the rooms. Measurements were taken from 380 to 780 nm in 5-nm increments with a StellarNet EPP2000c spectroradiometer (StellarNet Inc., Tampa, FL, USA).

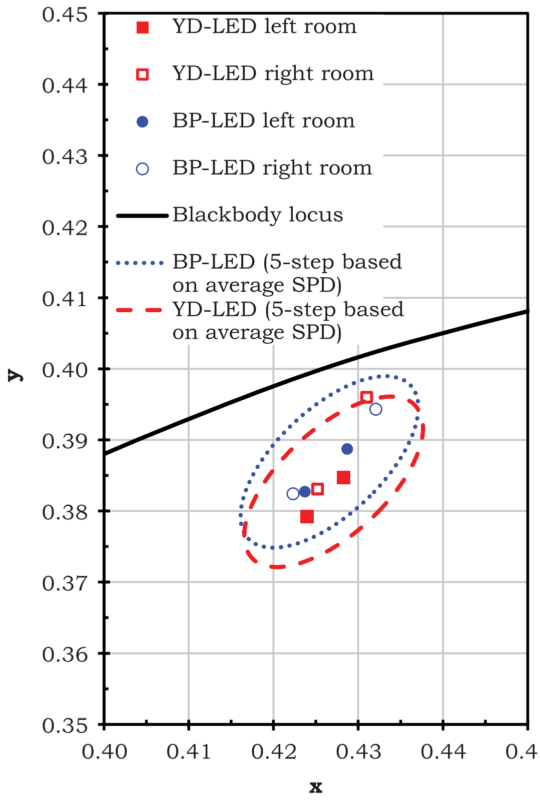

Fig. 2 Chromaticity coordinates plotted in the 1931 CIE chromaticity diagram for all measurements taken during the course of the experiment. Each measurement of the two lamp types can be enclosed by a five-step MacAdam ellipse centered at the coordinates computed from the average SPD. These measurements were taken within the experiment spaces, accounting for interreflections within the luminaire, from room surfaces, and colored objects placed in the rooms.

Fig. 3 Photograph taken by fish-eye lens of the full-size side-by-side rooms, viewed from the partcipant's standing location when performing brightness matching. A black felt curtain was behind the participant. The mirrors were hung on the dividing wall, with one in each room, which cannot be seen by the particpant when performing brightness matching.

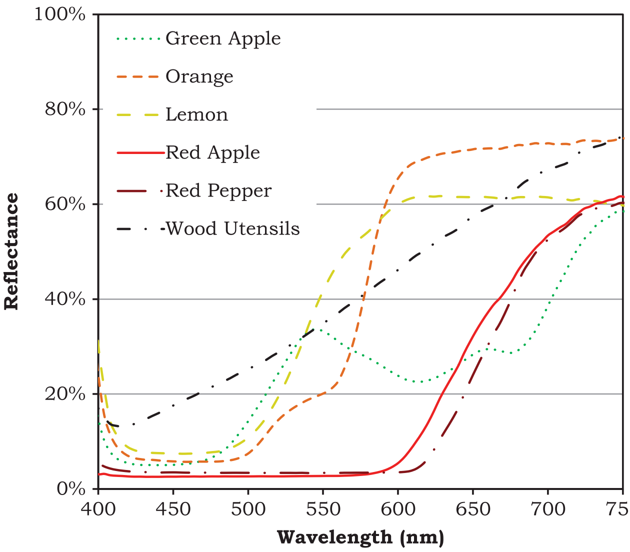

Fig. 4 Measured spectral reflectance curves of selected objects.

lemon, green apple, cutting board, bamboo bowl, bamboo utensils, hardwood floors, flowers, towels, and placemats. Realistic replicas were used rather than real fruits, which allowed greater consistency between rooms and over the duration of the experiment. The spectral reflectance curves for some of the objects are shown in Fig. 4. All objects, except the hardwood floor and mirror, were placed on tables with a neutral grey top, which were placed in the center of each room 2.5 ft from the back wall. Two mirrors were hung on the dividing wall, with one in each room, as shown in Fig. 5.

When matching brightness, the participant was instructed to stand at footprints marked on the floor, which were just outside the two rooms and aligned the participant's sagittal plane with the wall dividing the two rooms. The mirrors were not visible to the participant at that location. The participant was instructed to rotate his or her head when matching the brightness of the two rooms but not to rotate his or her body. Two Minolta T-10 illuminance meters (Konica Minolta Sensing America Inc., Ramsey, NJ, USA) with recent NIST traceable calibrations were used to measure illuminance, with one in each room, when the participant was performing brightness matching. Within each room, the illuminance meter was oriented up and positioned on a tripod centered in the room with the photocell 2.5 ft above the floor and 6 ft from the back wall. The illuminance levels were stable in the area surrounding that location. The objects and the table did not interfere with the illuminance measures. The readings of the illuminance meters were recorded outside the two rooms via Ethernet cable.

During the preference evaluation session, the participant was free to walk into the rooms to observe the objects and look at himself or herself in the mirrors and to finish two questionnaires regarding preference between the two rooms.

2.2. Participants

Eighty-seven participants within the range of 19 to 25 years were recruited for the experiment. Most of them were university students but none of them were studying lighting. Table 1 summarizes demographic data for the participants, including mean age, gender, and race. All participants had normal color vision as tested by the 24 Plate Ishihara Color Vision Test.

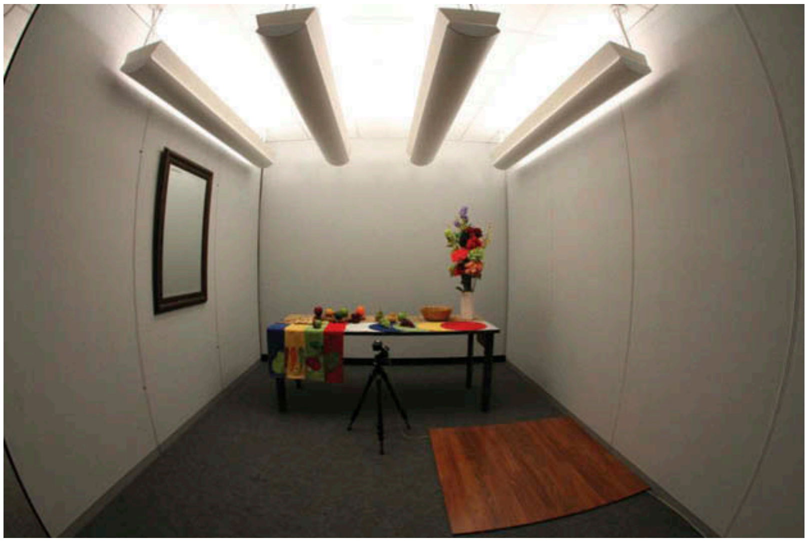

Fig. 5 Photograph taken by fish-eye lens of one room. When evaluating preference the partcipant was free to walk into the rooms to observe different objects and to observe himself or herself in the mirror.

TABLE 1 Demographic summary of the particpants

	Number of participants			Age	
Race	Total	Male	Female	Mean	Standard deviation
Asian	32	17	15	22.8	1.75
Black	1	1	0	22.0	–
Caucasian	52	38	14	20.9	1.41
Hispanic/Latino	2	1	1	21.5	0.50
Total	87	57	30	21.6	1.76

2.3. Experimental Design

The independent variable was SPD, with two levels: BP-LED and YD-LED. Each participant only observed one pair of light settings, with BP-LED in one room and YD-LED in the other. In order to minimize the possible positional bias associated with the side-by-side method [Fotios and Houser 2013], the positions of the two SPDs were counterbalanced between participants—47 participants experienced BP-LED in the left room and 40 experienced BP-LED in the right room.

The location of the two lamp types was counterbalanced between experimental days, which was done to maintain stable chromaticity. Thus, all participants on a given day of the experiment observed the same left–right presentation (that is, BP-LED in the left room and YD-LED in the right room or BP-LED in the right room and YD-LED in the left room). All of the lamps had been turned on for 4 h before the arrival of the first participant in order to ensure stability in chromaticity.

2.3.1. Brightness matching

The brightness matching task was designed to eliminate brightness as a reason for preference. Because the light level of BP-LED could be adjusted with stable chromaticity, the room illuminated by BP-LED was the variable room, whose illuminance level could be increased or decreased. The room illuminated by YD-LED was the reference room, whose illuminance level was fixed for all participants.

Each participant instructed the experimenter to raise or lower the light level in the variable room illuminated by BP-LED to match the brightness of the reference room illuminated by YD-LED. The participant was instructed to not match brightness based on small areas in the two rooms but to consider the overall brightness in the two rooms. The illuminance level in the reference room was set around 250 lux; the initial illuminance in the variable room was either 350 or 150 lux, which created an obvious brightness difference between the two rooms. The initial illuminance setting in the variable room was counterbalanced across participants.

The dependent variable was the ratio of illuminance in the variable room (that is, BP-LED) to that in the reference room (that is, YD-LED) measured at the calibration points. When the participant declared equal brightness of the two rooms, the readings of the illuminance meters were recorded by the experimenter.

2.3.2. Preference evaluation

The preference evaluation task immediately followed the brightness matching task, which held constant the equal brightness of the two rooms just matched by the participant. The participant was asked to make a series of subjective preference ratings between the two rooms, with one lamp type in each room.

The dependent variables were nine 6-point ratings of preference between the two rooms (that is, 1 = *strongly prefer left room*; 2 = *moderately prefer left room*; 3 = *slightly prefer left room*; 4 = *slightly prefer right room*; 5 = *moderately prefer right room*; 6 = *strongly prefer right room*). It was designed as a forced choice; no "neutral" could be chosen by the participant. The nine questions focused on different aspects and appeared on the questionnaire as follows:

Q1: Overall preference
Q2: Preference of your skin tone (for example, from mirror or your hand)
Q3: Preference of neutral colors (for example, walls, carpet)
Q4: Preference of red colors (for example, red apples, red pepper, flowers, towel, and placemat)
Q5: Preference of orange colors (for example, orange, flowers)
Q6: Preference of yellow colors (for example, lemon, flowers, towel, and placemat)
Q7: Preference of green colors (for example, green apple, flowers, towel, and placemat)
Q8: Preference of blue colors (for example, towel, flowers, and placemat)
Q9: Preference of wood surface (for example, cutting board, bamboo bowl, bamboo utensils, and hardwood floor)

In addition to rating each question on the 6-point scale, participants were asked to briefly explain their preference for each question.

In an effort to avoid prejudicing the participants about what criteria might be employed to evaluate overall preference, Q1 was asked first using its own individual questionnaire and without notifying participants that they would be asked additional questions. It was only after the participants completed Q1 that they were given a second questionnaire with Q2–Q9.

2.4. Experiment Procedure

Upon arrival, the participant read a brief description of the experiment, signed an informed consent form, and completed a general information survey that included a question about race.

The participant was then escorted into the experiment room and instructed to stand at footprints marked on the floor. The light settings in both rooms were set according to a prewritten script. The experimenter read the instructions and answered questions raised by the participant. The instructions were always read from a script to minimize variation between participants. During that time, the participant adapted to the conditions. After the experimenter read the instructions and answered questions about the procedure, the participant was asked to close his or her eyes for 5 s and then to open his or her eyes and observe the rooms for 30 s. After 30 s, the experimenter told the participant which room was fixed and which room could be changed. Then the participant instructed the experimenter how to change the light level in the variable room to make the two rooms appear equally bright. He or she was allowed to take as much time as necessary and was encouraged to ask the experimenter to adjust the light level up or down until the two rooms were equally bright. The participant was instructed to not focus on small areas within the space but to consider the overall amount of light within the space (that is, spatial brightness) and to ignore the color differences when making judgments. When the participant declared equal brightness, the experimenter recorded the illuminance meter readings in each room.

Then the first questionnaire was given to the participant, which only contained Q1. The participant was free to walk back and forth between the rooms and look at the objects in the rooms. No criteria were provided for the participant to make an evaluation about preference. After giving the rating and a reason, the participant was asked to give the first questionnaire to the experimenter and the second questionnaire was given to the participant, which included Q2–Q9. After finishing all questions, the participant was escorted out of the experiment room.

The 24 Plate Ishihara Color Vision Test was then administered in a windowless room illuminated to 300 lux under a typical 3000 K fluorescent lamp. The Ishihara Test was administered at the end of the experiment to avoid a suggestion or hint about the role that color might play in the participant's evaluative impressions. The entire procedure took between 10 and 15 min for each participant.

3. RESULTS

3.1. Brightness Matching

The average ratio of the illuminance provided by BP-LED in the variable room to that provided by YD-LED in the reference room for equal brightness was 0.965. This indicates that, on average across the 87 participants, the illuminance of BP-LED was set to be 3.5% lower than that of YD-LED for equal spatial brightness. The ratio was statistically different from unity as tested by a one-sample t test (P value $= 0.005$).

In order to minimize possible biases in side-by-side matching tasks (see, for example, Fotios and Cheal [2011]; Fotios and others [2008]; Hu and others [2006]), dimming direction and location of the two lamp types were counterbalanced. Analysis of variance (ANOVA) suggests that dimming location was not a significant factor affecting the illuminance ratio (P value $= 0.596$), which suggests that the physical properties of the two rooms were very close to each other and that SPD was successfully isolated as the primary factor affecting perception. ANOVA also suggests that dimming direction was a significant factor that affected the illuminance ratio (P value < 0.001). Figure 6 is a main effects plot for illuminance ratio based on means across dimming direction and location. It can be observed that the illuminance of the variable room was set to a higher level at the matched condition when starting from a high initial illuminance than when starting from a low initial illuminance, which is consistent with the trend found in previous studies [Fotios and Cheal 2007; Fotios and Levermore 1997].

3.2. Preference Evaluation

The judgments made by each participant were recorded on a word scale of preference with six options. These data were converted to a numerical 6-point rating for statistical analyses (1 = *strongly prefer BP-LED*; 2 = *moderately prefer BP-LED*; 3 = *slightly prefer BP-LED*; 4 = *slightly prefer YD-LED*; 5 = *moderately prefer YD-LED*; 6 = *strongly prefer YD-LED*).

The average preference rating for each question is given in Fig. 7. Though a selection of neutral was not provided in the rating scale, a mean value of 3.5 would indicate no preference between the two light settings.

Both two-sample t tests and Mann-Whitney tests were employed to test the null hypothesis that means and medians were equal to 3.5. As shown in Table 2, the mean and median rating for overall preference, skin tone, red colors, orange colors, green colors, and wood were statistically different from 3.5, all of which were higher than 3.5. Thus, generally speaking, the participants preferred the room illuminated by YD-LED based on overall preference. Specifically, skin tone, red, orange, green, and wood were preferred under YD-LED illumination, whereas no preference was found between YD-LED and BP-LED for neutral, yellow, and blue colors.

To test whether a difference existed between Asian and Caucasian participants, two-sample t tests and Mann-Whitney tests were employed. As shown in Table 2, significant differences were found for two colors. Caucasians preferred skin tone and orange under the illumination of YD-LED, whereas Asians had no preference between the two lamp types (Note: because only one participant was African American and two were Hispanic/Latino, only Asian and Caucasian participants were included in the analyses based on ethnic groups.) No significant difference was found between male and female, as shown in Table 3.

To summarize, YD-LED was preferred by all of the participants, irrespective of race. For Asians, YD-LED was preferred for red colors and wood; for Caucasians, YD-LED was preferred for skin tone, red, orange, green colors, and wood. Significant differences were found for the preference of skin tone and orange color between Asians and Caucasians. Parametric and nonparametric statistical analyses provided the same statistical results.

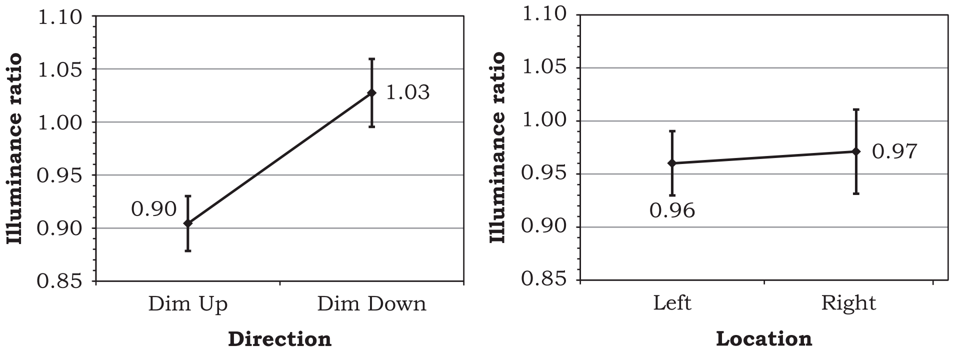

Fig. 6 **Main effects plot showing the means for illuminance ratio by dimming direction and dimming location with 95% confidence interval.**

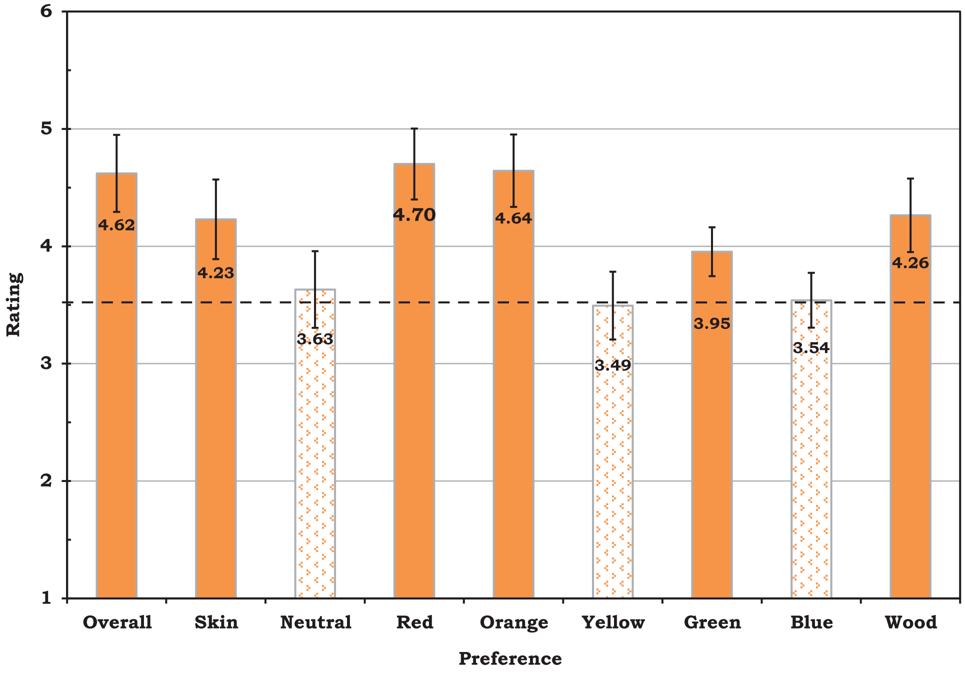

Fig. 7 **Average of preference rating for each question, shown with 95% confidence interval bar. The higher the rating, the stronger the preference to YD-LED. The solid bars indicate strong preference to YD-LED; the shaded bars indicate no preference between YD-LEDs and BP-LEDs.**

4. DISCUSSION

We minimized the effects of the most common experimental biases by counterbalancing the dimming location and dimming direction for brightness matching [Fotios and others 2008]. We were unable to counterbalance the dimming sources because the two-channel power supply for YD-LED prevented us from dimming the YD-LED with stable chromaticity. The dimming direction bias that we found was also present in previous studies [Fotios and Cheal 2007; Fotios and Levermore 1997] but should be unimportant because dimming direction was counterbalanced. We also implemented long warm-up periods to stabilize chromaticity and output.

The main objective of this study was to compare color preference between the two SPDs. The brightness matching task was included to eliminate brightness as a reason for preference, which was successful because none of the participants cited brightness as a reason for preference. In addition to the experiment described in this article, we conducted a separate brightness matching experiment of these two lamp types. In that experiment, 30 participants completed a brightness matching task in the same side-by-side rooms but without any objects in the space. Null condition matching of BP-LED was included. The results, not provided here, showed that dimming direction was the only significant factor for the null condition trials. The illuminance ratio of BP-LED to YD-LED was not significantly different from the result in this experiment. Thus, the presence of color and objects did not affect the result of the brightness matching task when the two visual fields were identical except for lamp SPD, which corroborates the results of Fotios and Cheal [2011].

The phrases given by the participants as reasons for the overall preference and preference of the red, orange, and green color in the room illuminated by YD-LED included *vibrant* (22 participants), *stand-out* (8), *vivid* (7), *contrast* (5), *saturated* (3), *enjoyable* (2), and *attractive/appealing* (2). In comparison, the room illuminated by BP-LED was evaluated as *too dull* (4) and *faded* (1). For blue and yellow colors, most participants did not report a large difference between the two light settings. For the wood colors, participants frequently commented that the wood floor was redder under the illumination of YD-LED, which was cited as a reason for their preference.

Based upon participants' comments and their preference evaluations, the YD-LED illumination rendered red and green colors more favorably than BP-LED. Specifically, YD-LED was able to increase the saturation of these colors. As shown in Table 4, these two SPDs are not correctly ordered with CRI. CRI should not be expected to predict preference because it only accounts for the magnitudes of the chromaticity shift in comparison to a reference

TABLE 2 Summary of the statistical analyses of the preference evaluation

	All participants ($N = 87$)				Ethnic groups ($N = 84$)									
					Asian ($N = 32$)				Caucasian ($N = 52$)					
	Mean	*P* value of one-sample *t* test	Median	*P* value of Wilcoxon signed rank test	Mean	*P* value of one-sample *t* test	Median	*P* value of Wilcoxon signed rank test	Mean	*P* value of one-sample *t* test	Median	*P* value of Wilcoxon signed rank test	*P* value of two-sample *t* test	*P* value of Mann-Whitney test
	μ	H_0: $\mu = 3.5$	M	H_0: M $= 3.5$	μ	H_0: $\mu = 3.5$	M	H_0: M $= 3.5$	μ	H_0: $\mu = 3.5$	M	H_0: M $= 3.5$	μ (Asian) $= \mu$ (Caucasian)	M (Asian) $=$ M (Caucasian)
Overall	4.62	<0.001	5.0	<0.001	4.56	0.001	5.0	0.002	4.60	<0.001	5.0	<0.001	0.925	0.927
Skin	4.23	<0.001	4.5	<0.001	3.44	0.852	3.5	0.911	4.62	<0.001	5.0	<0.001	0.003	0.010
Neutral	3.63	0.424	3.5	0.474	3.81	0.276	4.0	0.291	3.56	0.786	3.5	0.827	0.473	0.498
Red	4.70	<0.001	5.0	<0.001	4.31	0.008	4.5	0.012	4.90	<0.001	5.0	<0.001	0.085	0.152
Orange	4.64	<0.001	5.0	<0.001	4.03	0.083	4.0	0.071	4.94	<0.001	5.0	<0.001	0.010	0.027
Yellow	3.49	0.969	3.5	0.961	3.53	0.907	3.5	0.911	3.52	0.913	3.5	0.967	0.970	0.956
Green	3.95	<0.001	4.0	<0.001	3.88	0.070	4.0	0.068	4.06	<0.001	4.0	<0.001	0.434	0.635
Blue	3.54	0.733	3.5	0.664	3.31	0.325	3.5	0.326	3.64	0.375	3.5	0.295	0.185	0.144
Wood	4.26	<0.001	4.5	<0.001	4.13	0.025	4.0	0.032	4.35	<0.001	4.5	<0.001	0.507	0.51

Statistical tests with a *P* value < 0.05 are shaded.

TABLE 3 Statistical analyses of the preference evaluation between genders

	P value of two-sample *t* test μ (Male) = μ (Female)	*P* value of Mann-Whitney test M (Male) = M (Female)
Overall	0.610	0.602
Skin	0.172	0.170
Neutral	0.672	0.676
Red	0.534	0.320
Orange	0.117	0.278
Yellow	0.776	0.674
Green	0.589	0.568
Blue	0.694	0.801
Wood	0.171	0.1293

TABLE 4 Summary of the color measures of YD-LED and BP-LED. Please refer to the recent review paper by Houser and others [2013] for a brief introduction of these measures and cited references for detailed information

Measures	BP-LED	YD-LED
CCT	2976	2968
x	0.4354	0.4378
y	0.3981	0.4019
u	0.2522	0.2521
v	0.3458	0.3471
u'	0.2522	0.2521
v'	0.5188	0.5207
R9	38	50
CRI	86	78
CQS 9.0	84	89
Q_f (CQS v9.0)	83	83
Q_g (CQS v9.0)	100	115
Q_p (CQS v7.5)	87	96
R_f	81	86
CPI	88	124
CDI	59	67
CRC	0.237	0.250
CRC_Volume	0.642	0.675
CSA	0.032	0.034
Pointer	76	75
RCRI	86	84
FCI94	116	147
FCI02	109	123
MCRI	88	93
FMGamut	54	64
nCRI	88	87
FSCI	63	50
GAI	60	68

illuminant but not the directions of the chromaticity shift. Saturation enhancement is often preferred [Buck and Froelich 1948; Jost-Boissard and others 2009; Judd 1967; Ohno 2005; Smet and others 2011a; Thornton 1974]. The measures Q_a and Q_f from the NIST's CQS are calculated using similar procedures. Q_f is a measure of fidelity that penalizes all chromaticity shifts, whereas Q_a does not penalize light sources for increasing object chroma. YD-LED has a higher value of Q_a than BP-LED, and both sources have the same value for Q_f. Taken together, the NIST's CQS system suggests that YD-LED and BP-LED have similar color fidelity but that YD-LED increases objects' saturation. All of the measures in Table 4 that have some relationship to color preference or color quality (that is, R_9, Q_a [CQS 9.0], Q_p, R_f, color preference index, FCI94, FCI02, memory color rendering index) and those that are based on gamut area (that is, Q_g, CDI, CRC, CRC_Volume, CSA, FM Gamut, GAI) correctly rank the overall preference of these two SPDs.

The difference between ethnic groups on skin tone corroborates earlier works [Islam and others 2013; Quellman and Boyce 2002]. Some Caucasian participants thought that YD-LED illuminated their skin in a manner that was *colorful* (4 participants), *healthy* (3), and *alive* (1), but BP-LED made skin look *pale* (11), *grey* (3), *dull* (2), and *dead* (1). Some Asian participants thought that the YD-LED illumination made their skin look *odd* (4) and *too red* (1) but no significant difference was found between the two lamps. The preference for a ruddier and chromatic complexion of Caucasian people was also found in previous work [Fotios and Cheal 2011; Quellman and Boyce 2002; Sanders 1959; Smet and others 2011a; Yano and Hashimoto 1997].

In this study, YD-LED was able to increase the saturation of red and green colors, but both SPDs have similar performance for yellow and blue colors. This is illustrated in Fig. 8, which are saturation icons from the CQS v 9.0 calculation program.

When considering V(λ)-based quantities (for example, lumen output, illuminance, luminance), BP-LED was


(a) (b)

Fig. 8 Color saturation icon of YD-LED and BP-LED computed from CQS v9.0 calculation program: (a) YD-LED and (b) BP-LED.

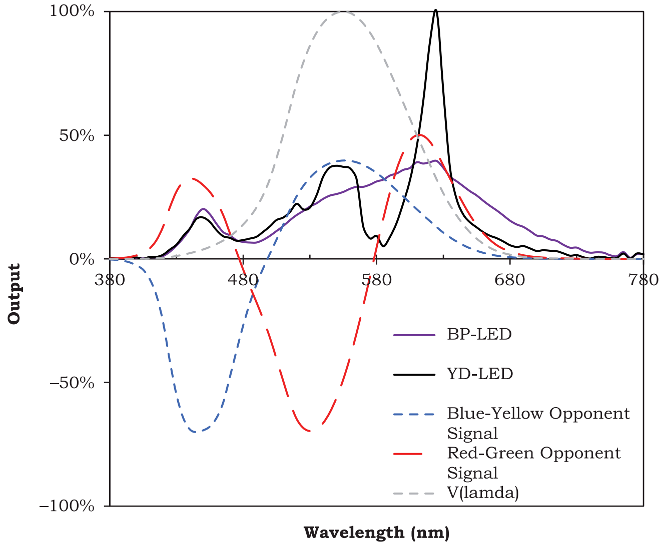

Fig. 9 Red–green, blue–yellow, and luminance opponent channel responses [Hurvich 1981]. SPDs of BP-LED and YD-LED scaled to the same V(λ)-based quantities (for example, lumen output) are overlaid in arbitrary *y*-axis units for visual comparison on the basis of wavelength. The ratio of the total red–green signal of YD-LED to BP-LED is 1.18 and the ratio of total blue–yellow signal is 0.97. When taking the 3.5% fewer lumens of BP-LED for equal brightness perception, the ratios become 1.22 and 1.01 for the red–green and blue–yellow signals, respectively.

purposely designed to have diminished emission above about 610 nm because longer wavelengths provide relatively fewer lumen per watt. However, the peak of the red–green opponent signal curve occurs near 610 nm, as shown in Fig. 9. The emission from the BP-LED is not optimized for generating a red–green opponent signal.

The perceptual responses to the two sources studied here, in terms of enhanced red–green saturation, can be considered with reference to the opponent process of the visual system [Hurvich 1981]. When the two SPDs are scaled to have equal V(λ)-based quantities, the ratio of the total red–green signal of YD-LED to BP-LED is 1.18 and the ratio of total blue–yellow signal is 0.97. By scaling for the fact that BP-LED can provide equal spatial brightness with 3.5% fewer lumens than YD-LED, the ratios become 1.22 and 1.01 for the red–green and blue–yellow signals, respectively. Thus, YD-LED yields a stronger red–green signal and approximately equivalent blue–yellow signal, indicating higher saturation and contrast for red–green colors but not much difference for blue–yellow colors. An earlier study with linear fluorescent lamps found a similar advantage to improve the red–green signal while maintaining similar blue–yellow signals [Wei and Houser 2012a]. The abilities to render red and green colors and to provide contrast between red and green colors have been thought to be vital for good color rendering [Davis 2006; Hashimoto and others 2007; Worthy 1982].

The R_9 value of the two SPDs merits comment. As a special index of CRI, R_9 characterizes the color rendition of a saturated red under the test illuminant in comparison to that under the reference illuminant. Like CRI, R_9 does not credit the ability of a light source to increase the saturation of the red color. The fact that YD-LED has a higher R_9 value than BP-LED only suggests the color shift of the saturated red test color sample between YD-LED and the reference illuminant (that is, a blackbody radiator around 3000 K for these two lamps) is smaller than that between BP-LED and the reference illuminant. By comparing the chromaticity of the test color sample under the two lamps and the reference illuminant in CIE 1964 Uniform Color Space (UCS; CIE 2004), YD-LED tends to increase the saturation of the red test color sample in comparison to that under the reference illuminant, whereas the saturation of the red test color sample under BP-LED is lower than that under the reference illuminant. The higher preference of the red objects under YD-LED may be due to its ability to increase the saturation, rather than being due to the higher R_9 value. The preference for a saturated color does not necessarily mean that higher saturation is always preferred. The tolerance or limit of saturation is worth further investigation.

Furthermore, under comparable photometric conditions, BP-LED has more optical radiation in the region around 570 to 580 nm but less around 540 to 550 nm and 610 to 630 nm in comparison to YD-LED. These three regions correspond to the prime color and antiprime spectral regions identified by Thornton [1992a, 1992b, 1992c], who noted that the antiprime spectral region near 570 to 580 nm was especially harmful to color perception [Thornton 1972]. Perhaps counterintuitively, his results suggest that removing the optical radiation from 570 to 580 nm would enhance color perception, as we found in this study.

Though YD-LED is generally preferred to BP-LED and color preference measures have higher values for YD-LED than BP-LED, it does not necessarily mean that all colors will be preferred under YD-LED illumination. At a fundamental level, color rendering is application dependent [Rea and Freyssinier 2010]. Ethnicity, illuminance level, spectral reflectance, and many other factors affect color preference and color quality.

A single measure or a designation that attempts to bundle two or more aspects of color perception cannot address all lighting applications. For example, when color preference is important, the lighting of a meat case in a grocery store will require a different SPD than lighting patrons in a beauty salon. A designation that can capture the most important aspects of color quality and is applicable to general application is needed. As pointed out in previous analyses, the output values of many newer measures are not significantly different from the older ones, even though new measures are based on stronger theories and models [Houser 2013; Houser and others 2013]. We believe that many existing measures can be employed to make informed decisions, even though it can always be argued that more research is needed to support the development of improved measures. Graphical information beyond numbers, such as the color saturation icon, is also useful for understanding color rendition.

5. CONCLUSIONS

Brightness perception and color preference were studied for a pair of 3000 K LED A19 lamps with equivalent chromaticity coordinates but different SPDs. Eighty-seven participants between 19 and 25 years of age made assessments of color preference of different colors between two full-size side-by-side rooms containing chromatic objects and still life arrangements, with one lamp type in each room, after matching the rooms in brightness. A 6-point scale without a neutral point was employed for the assessment, from which we conclude the following:

- The room under the illumination of the YD-LED had higher overall preference in comparison to that under typical BP-LED. Specifically, participants preferred the red, green, orange, and wood objects under the illumination of YD-LED, using words such as *vivid, vibrant, stand-out*, and *distinct*. No preference was found for neutral, yellow, and blue objects.
- Ethnicity affected the preference of skin tone under the illumination of these two lamp types. Caucasians preferred skin tone under YD-LED illumination, which made their skin look healthy and colorful; the skin under BP-LED looked pale and grey. No significant difference was found among Asians, though some of them thought their skin was too red under YD-LED illumination.
- The general preference of red and green colors under YD-LED can be explained by the greater saturation, and can be traced to and quantified with the higher red–green opponent process signals provided by YD-LED. The two lamp types provide approximately equivalent blue–yellow signals, and no difference in preference was found for blue and yellow colors. The tolerance or upper limit of saturation preference merits further investigation.
- Most color measures characterizing color preference and gamut-based measures are able to predict the higher overall preference to YD-LED but fail to make prediction on specific colors and for different ethnic groups.

As with past work [Houser and Hu 2004; Houser and others 2004, 2009; Royer and Houser 2012; Wei and Houser 2012a; Wilkerson 2013], the results reported here suggest that the spectral region around 570–580 nm may be deleterious to color and brightness perception. These results are consistent with both Thornton's prime color theory [1992a, 1992b, 1992c] and the opponent process theory of Hurvich [1981]. When color and brightness perception per watt of optical radiation are important, it is inadequate to structure SPDs based on CRI and V(λ).

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