International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

OP35

EFFECT OF LIGHT LEVEL ON COLOR PREFERNECE AND SPECIFICAITON OF LIGHT SOURCE COLOR RENDITION

Wenyu Bao et al.

DOI 10.25039/x46.2019.OP35

from

CIE x046:2019

Proceedings
of the
29th CIE SESSION
Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)

CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

EFFECT OF LIGHT LEVEL ON COLOR PREFERNECE AND SPECIFICAITON OF LIGHT SOURCE COLOR RENDITION

Bao, W., **Wei, M.***
The Hong Kong Polytechnic University, Kowloon, HONG KONG

minchen.wei@polyu.edu.hk

DOI 10.25039/x46.2019.OP35

Abstract

Substantial efforts have been made to investigate how light source color rendition affects color preference. It has been widely agreed that a source with a high color fidelity score may not result in higher color preference, as a higher saturation is generally preferred. Two psychophysical experiments were designed to investigate the color preference of an artwork under nine nearly metameric stimuli with a gamut area (i.e., IES R_g) between 99 and 124 across a wide range of illuminance levels (i.e., from 20 to 15000 lx), which was never carefully studied before. These different R_g values of the stimuli were designed to be produced by systematic changes in IES TM-30 red and green chroma shifts. The findings revealed that the light level had a significant impact on color appearance and color preference, with a stimulus having a larger gamut area being preferred under a lower illuminance level. It suggested that light level should be considered when specifying light source color rendition.

Keywords: Color rendition; Light level; Lighting quality; Color preference

1 Introduction

Color rendition of a light source is of great importance in lighting community. Numerous efforts have been made to characterize the effect of light source spectrum on the color appearance of the objects and to optimize the spectrum for making the illuminated objects have preferred color appearance (Houser et al., 2013). The Commission Internationale de l'Eclairage (CIE) General Color Rendering Index R_a was first developed in 1965 and has been the most widely used measure for developing and evaluating the color rendition of lighting products (CIE, 1965). This metric, however, is a fidelity measure, which only characterizes the ability of a light source to render the color appearance of eight test color samples in comparison to a reference illuminant (Houser et al., 2013). The color appearance of objects under a source with a higher CIE R_a value may not always be preferred since CIE R_a is not intended to characterize other aspects of color rendition, such as color preference (Wei et al., 2014).

Many past studies suggested that the color rendition of a light source can be better characterized using a color fidelity measure (e.g., CQS Q_f, CIE R_a, and IES R_f) together with a gamut measure (e.g., CQS Q_g, GAI, and IES R_g) (Rea and Freyssinier, 2008; Guo and Houser, 2004; David et al., 2015; Wei and Houser, 2017). Great efforts have been made to define the ranges of color metrics for producing a preferred color appearance. The light sources with an R_a greater than 80 and a GAI between 80 and 100 were recommended by Rea and Freyssinier for general illumination where color rendition is important (Rea and Freyssinier, 2010). Wei and Houser found that setting an upper limit for gamut area is essential because oversaturation may reduce color preference (Wei and Houser, 2017). In addition, the shape of the gamut is also important since gamut area only characterizes the average chroma change (Wei et al., 2017). Sources that have a larger gamut area have been found to produce preferred color appearance, especially if the chroma enhancement happens to red hues (Wei et al., 2014; Royer et al., 2017; Royer et al., 2016; Wei et al., 2017). Recently, three psychophysical studies (Royer et al., 2017, 2018, 2019) that systematically varied color fidelity, gamut area, and gamut shape within the context of IES TM-30-15 R_f, R_g, and Color Vector Graphic were carried out. Royer et al proposed the criterion that $R_f \geq 74$, $R_g \geq 100$, and $2\% \leq R_{cs,h16} \leq 16\%$ (Royer et al., 2017) and it was later relaxed to $R_f \geq 75$, $R_g \geq 98$, and $-7\% \leq R_{cs,h16} \leq 15\%$ (Royer et al., 2018).

These various psychophysical studies (Wei et al., 2014; Wei and Houser, 2017; Wei et al., 2016; Jost-Boissard et al., 2014) were generally carried out at a single illuminance level between 200 and 1000 lx, which fell into the typical range for general illumination. However, there are applications with recommended illuminance levels outside this range where the color appearance of the objects is critically important. For example, the illuminance levels for museum lighting are generally below 200 lx and the color appearance of the exhibited artwork is important. On the other hand, it is vital to investigate the effect of extremely high light level on color rendition because the change of light level in cross-media color reproduction can be very large.

Though the interactive effect between light level and color rendition was found by Hunt in 1952 (1952), few study considered light level when specifying color rendition. The effect of light level on color rendition has not been systematically investigated. A limited number of past studies (Rea and Freyssinier, 2010, 2013; Wei et al., 2018) only investigated the color appearance change under one light level outside the above range. An experiment was carried out by Ou (Ou, 2016) to compare the color appearance between indoor and outdoor environments and to test the performance of CIECAM02 under these two conditions. It was found that CIECAM02 failed to predict the lightness under certain conditions, with a higher predicted lightness level than the perceived lightness. Kim et al (Kim et al., 2009) developed a revised color appearance model to predict the color appearance under extended light levels. The development of the model was based on the magnitude estimation experiment to investigate the color appearance under extended luminance levels (i.e., 44 – 16400 cd/m^2). We recently carried out a pilot study (Wei et al., 2018) to investigate the influence of light level on color appearance under 20 and 500 lx. The results revealed the significant effect of light level on color preference.

This article reports a study that included two experiments. Experiment 1 was designed to validate the findings of the pilot study (Wei et al., 2018) with a higher resolution in gamut area and illuminance levels (i.e., 20 – 480 lx). Experiment 2 was designed to further investigate the trade-off between light level and gamut size under higher light levels (i.e., 200 – 15000 lx).

2 Method

2.1 Apparatus and experimental setup

In Experiment 1, two seven-channel spectrally tunable LED devices (ETC D22 Lustr+) were used to produce 45 light stimuli. The peak wavelengths of the seven channels ranged between 430 and 630 nm and the intensity of each channel can be adjusted individually. A DMX controller was used to adjust and store the intensities of the seven channels for each light stimulus, so that the observers could switch between the lighting stimuli remotely.

An artwork, with dimensions of 60 cm (length) × 50 cm (width), was uniformly illuminated by the two LED devices from 45°, with the two devices being symmetrically placed. The artwork, as shown in Fig. 1, was carefully selected to contain common objects (Wei et al., 2017) and a dominant hue of red. The white vase and table cloth in the artwork provided a visual hint for the white point of the illumination. Thirteen locations on the artwork were selected for characterizing the color appearance of the artwork, as shown in Fig. 1. The spectral reflectance distributions (SRDs) were measured using a factory-calibrated Xrite i1 Pro spectrophotometer.

During the experiment, the observers were seated around 1.2 m from the artwork, with his or her chin being fixed on a chin-rest, so that all the observers experienced a similar viewing geometry (i.e., field of view around 28°). The background and the desk were covered using black felt, which was purposely designed to reduce the impact of light stimuli chromaticity variation and to stimulate the viewing condition/surround in museums.

In Experiment 2, a four-channel spectrally tunable LED device (Skypanel) was used to produce 45 light stimuli. The peak wavelengths of the four channels ranged between 430 and 630 nm and the intensity of each channel can be adjusted individually. A DMX controller was used to adjust and store the intensities of the four channels for each light stimulus, which can be recalled using a keypad remotely.

Experiment 2 was carried out using a viewing booth, with dimensions of 60 cm × 60 cm × 60 cm. The front side of the booth was partially covered with black felt, with the bottom 50 cm open to prevent observers from seeing the lighting device. The interiors of the viewing booth were painted with Munsell N7 spectrally neutral paint. A chin rest was placed outside the booth. The artwork was placed on the bottom of the viewing booth and uniformly illuminated by the LED device. During the experiment, the observers were seated in front of the viewing booth, with his or her chin being fixed on the chin-rest, to guarantee a similar viewing geometry (i.e., field of view around 74°).

Figure 1 – Photograph of the artwork, taken at the observer's viewing position during Experiment 2, with the spectral reflectance distribution measurement locations being labelled.

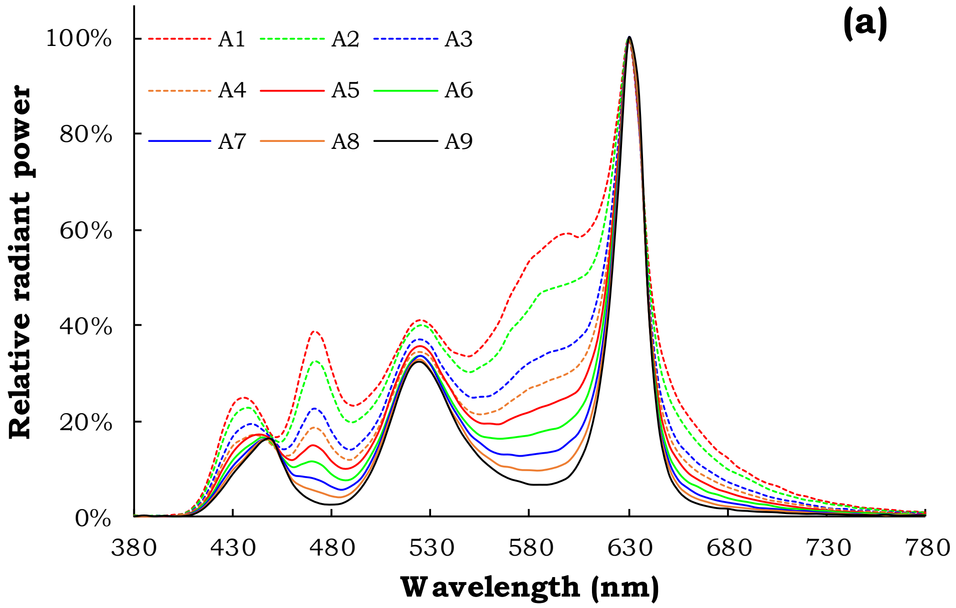
2.2 Lighting stimuli

In Experiment 1, five illuminance levels (i.e., 20, 50, 100, 200, and 480 lx) were used to cover a range of illuminance that can happen in interior spaces. The stimuli were designed to be metameric with a correlated color temperature (CCT) of 3000 K and a D_{uv} of -0.005, but with different relative gamut areas R_g from 100 to 124 with a step of 3. Note that the increase of R_g was designed to be caused by the increase of $R_{cs,h1}$, $R_{cs,h16}$, $R_{cs,h8}$, and $R_{cs,h9}$.

The 45 light stimuli, comprising nine SPDs (A1 to A9) at five illuminance levels, were carefully calibrated using a calibrated JETI 1411 Specbos spectroradiometer and a reflectance standard being placed at the center of the artwork. Due to the limitation of the LED devices, the 45 stimuli had a CCT of 3094 ± 74 K and a D_{uv} between -0.0078 to +0.0018. Figure 2(a) shows the SPDs of the stimuli at 480 lx, with the colorimetric characteristics and Color Vector Graphics being shown in Table 1 and Fig. 3(a).

In Experiment 2, five illuminance levels (i.e., 200, 2000, 5000, 10000, and 15000 lx) were used to cover a wide range of illuminance in exterior spaces. The stimuli were designed to have the same CCT of 3000 K and a D_{uv} of -0.005, but with different values of R_g from 100 to about 117 with a step of 2 to 4. Similar to Experiment 1, the increase of R_g was designed to be mainly caused by enhancing the saturation of red and green colors.

Experiment 2 also included 45 light stimuli which comprised nine SPDs (B1 to B9) at five illuminance levels. The light stimuli were calibrated to have a CCT of 3025 ± 20 K and a D_{uv} ranging from -0.0042 to -0.0021. The SPDs of the stimuli at 200 lx are shown in Fig. 2(b), with the colorimetric characteristics and Color Vector Graphics being shown in Table 2 and Fig. 3(b).



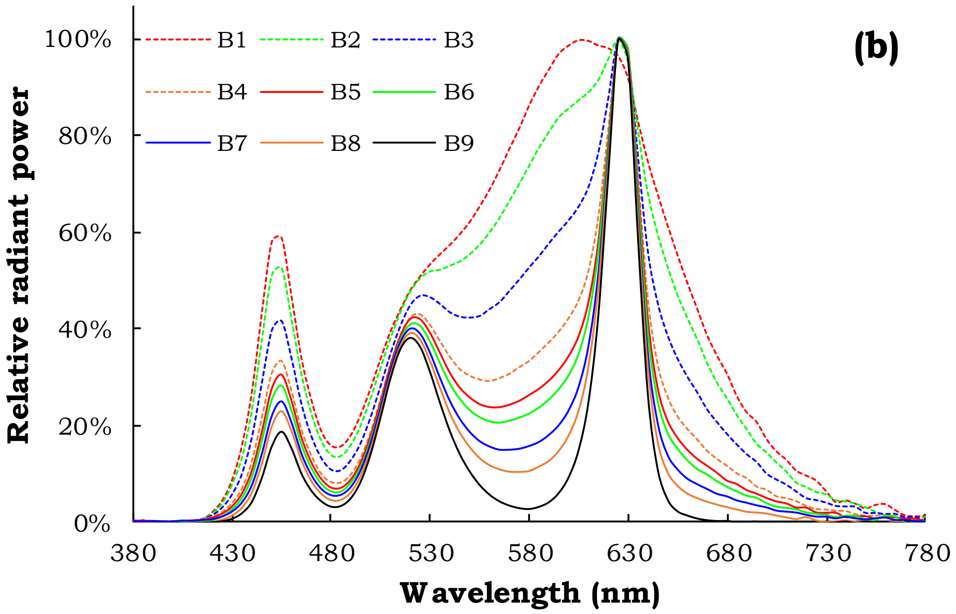


Figure 2 – Relative SPDs of the nine stimuli (a) at 480 lx in Experiment 1; (b) at 200 lx in Experiment 2.

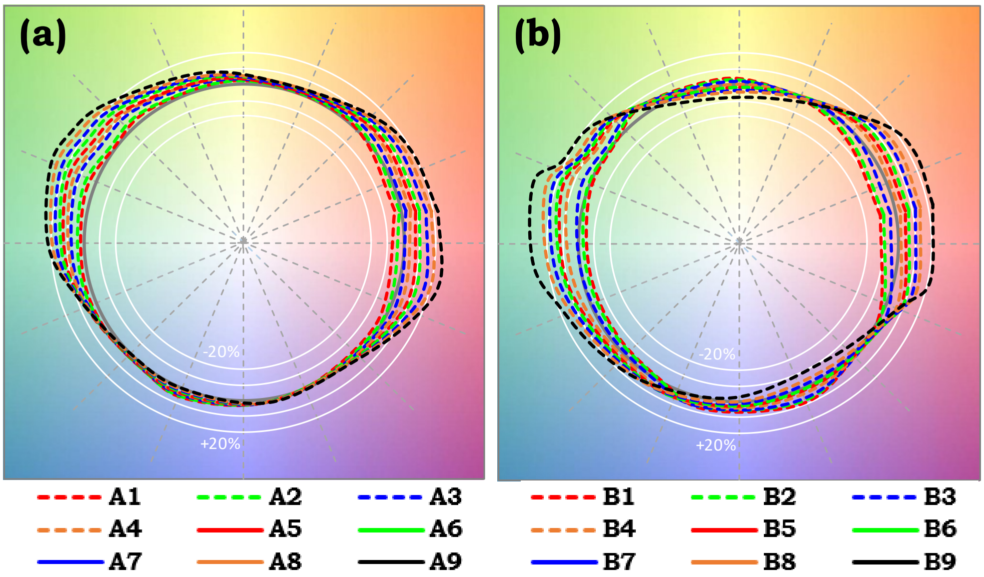


Figure 3 – IES TM-30-15 Color Vector Graphics (CVGs) of the nine stimuli (a) at 480 lx in Experiment 1; (b) at 200 lx in Experiment 2. The grey circle denotes the reference illuminant.

Table 1 – Colorimetric characteristics of the nine stimuli at 480 lx in Experiment 1.

Stimulus	A1	A2	A3	A4	A5	A6	A7	A8	A9
x	0.4185	0.4175	0.4192	0.4231	0.4193	0.4217	0.4206	0.4214	0.4209
y	0.3794	0.3808	0.3822	0.3823	0.3849	0.3842	0.3861	0.3868	0.3874
CCT	3125	3156	3136	3062	3157	3106	3143	3133	3148
D_{uv}	-0.0075	-0.0068	-0.0064	-0.0070	-0.0053	-0.0060	-0.0050	-0.0048	-0.0045
R_a	92	92	86	81	75	68	59	52	44
R_f	93	93	90	87	84	80	76	71	67
R_g	100	103	106	109	112	115	118	121	124
$R_{cs,h1}$	-3%	0%	4%	6%	9%	12%	15%	18%	22%
$R_{cs,h2}$	-2%	0%	3%	5%	7%	10%	12%	15%	17%
$R_{cs,h3}$	0%	1%	3%	4%	5%	6%	8%	9%	10%
$R_{cs,h4}$	0%	0%	1%	1%	1%	2%	2%	3%	4%
$R_{cs,h5}$	0%	0%	2%	3%	4%	5%	6%	7%	8%
$R_{cs,h6}$	1%	3%	6%	8%	10%	13%	15%	19%	19%
$R_{cs,h7}$	1%	4%	10%	13%	17%	20%	26%	28%	35%
$R_{cs,h8}$	2%	5%	10%	13%	16%	20%	24%	27%	31%
$R_{cs,h9}$	2%	4%	7%	9%	11%	13%	16%	18%	20%
$R_{cs,h10}$	2%	3%	4%	5%	5%	6%	6%	7%	7%
$R_{cs,h11}$	3%	3%	2%	3%	1%	1%	0%	-1%	-2%
$R_{cs,h12}$	6%	5%	4%	3%	3%	3%	2%	1%	0%
$R_{cs,h13}$	3%	3%	3%	3%	2%	3%	1%	0%	0%
$R_{cs,h14}$	2%	2%	3%	1%	4%	3%	5%	6%	7%
$R_{cs,h15}$	-1%	0%	3%	5%	6%	8%	10%	12%	14%
$R_{cs,h16}$	-6%	-3%	2%	5%	8%	12%	16%	20%	24%

Table 2 – Colorimetric characteristics of the nine stimuli at 200 lx in Experiment 2.

Stimulus	B1	B2	B3	B4	B5	B6	B7	B8	B9
x	0.4321	0.4323	0.4329	0.4320	0.4301	0.4316	0.4313	0.4303	0.4288
y	0.3945	0.3959	0.3971	0.3951	0.3945	0.3946	0.3936	0.3919	0.3919
CCT	3003	3012	3012	3010	3039	3013	3010	3013	3041
D_{uv}	-0.0032	-0.0026	-0.0023	-0.0029	-0.0029	-0.0031	-0.0035	-0.0040	-0.0038
R_a	85	89	95	87	79	75	64	55	32
R_f	84	87	91	90	86	84	77	72	59
R_g	99	100	104	108	110	111	113	115	117
$R_{cs,h1}$	-10%	-8%	-3%	3%	6%	8%	12%	16%	24%
$R_{cs,h2}$	-7%	-5%	-2%	4%	7%	8%	12%	15%	22%
$R_{cs,h3}$	-2%	-1%	0%	3%	4%	5%	7%	9%	12%
$R_{cs,h4}$	3%	3%	1%	0%	-1%	-1%	-3%	-4%	-7%
$R_{cs,h5}$	4%	3%	2%	0%	-1%	-2%	-3%	-4%	-7%
$R_{cs,h6}$	6%	6%	7%	8%	9%	9%	10%	11%	13%
$R_{cs,h7}$	-1%	0%	3%	7%	9%	10%	12%	15%	20%
$R_{cs,h8}$	-2%	0%	5%	12%	15%	17%	22%	26%	33%
$R_{cs,h9}$	-6%	-4%	0%	7%	10%	12%	16%	20%	28%
$R_{cs,h10}$	-5%	-4%	-1%	3%	5%	7%	10%	12%	15%
$R_{cs,h11}$	-1%	0%	1%	3%	3%	4%	5%	5%	6%
$R_{cs,h12}$	6%	6%	6%	5%	5%	4%	4%	3%	1%
$R_{cs,h13}$	7%	6%	5%	3%	2%	2%	0%	-1%	-4%
$R_{cs,h14}$	7%	7%	5%	3%	1%	0%	-2%	-4%	-8%
$R_{cs,h15}$	-1%	0%	1%	3%	3%	3%	4%	5%	7%
$R_{cs,h16}$	-4%	-3%	1%	5%	8%	9%	12%	15%	22%

2.3 Observers

Forty observers (33 males and 7 females) and 30 other observers (15 males and 15 females) participated in Experiment 1 and 2, respectively. In Experiment 1, all the observers were between 20 and 28 years of age (mean = 21.15, std. dev. = 1.53). In Experiment 2, all the observers were between 20 and 24 years of age (mean = 21.93, std. dev. = 1.05). Two observers in Experiment 1 and one observer in Experiment 2 had color deficiency so their data were excluded in data analysis. Other observers all had a normal color vision, as tested using the 24 Plate Ishihara Color Vision Test.

2.4 Experimental procedures

The two experiments had similar experimental procedures in general.

Upon arrival, the observer completed a general information survey and the Ishihara Color Vision Test. Then the observer was given a brief introduction about the experiment and escorted to the experimental area. He or she was seated in front of the artwork, with his or her chin being fixed on the chin rest. All the lights in the experimental space were switched off, expect for the LED devices. Under each illuminance level, the observer was asked to look at the artwork under the stimulus with the lowest R_g (i.e., A1 or B1) for two minutes for adaptation. After the adaptation, the observer was instructed to switch between the nine stimuli, to carefully compare the color appearance of the artwork under the stimuli, and to select the one under which the artwork had the most preferred color appearance. He or she was free to switch back and forth between the stimuli in any order without time limitation.

In Experiment 1, the evaluations were made twice under each illuminance level, with the nine buttons being arranged in two reverse orders—one from the lowest to the highest R_g (i.e., from A1 to A9) and the other from the highest to the lowest R_g (i.e., A9 to A1). In Experiment 2, the nine stimuli were also arranged in two reverse orders under each illuminance level—one from the lowest to the highest R_g (i.e., from B1 to B9) and the other from the highest to the lowest R_g (i.e., from B9 to B1). For each observer, different orders were used at different light levels. Moreover, the two orders were used alternatively for different observers under the same illuminance. Each observer made the evaluation twice under 15000 lx for assessing the intra-observer variations. After the judgment was made, the experimenter recorded the selection and moved on to the next condition.

3 Results

3.1 Experiment 1

A chi-square test of independence was used to test the possible order bias by comparing the stimuli that were selected by the same observer under two different orders. The statistical results show that the presentation order and the selection of the light stimulus were independent of each other (x^2 = 2.02, df = 8, P = 0.980).

Figure 4 summarizes the frequency of each stimulus that was selected to produce the most preferred color appearance of the artwork at each illuminance level in Experiment 1. At 20, 50, and 100 lx, A7 (R_g = 118) had the highest frequency. A3, A4, and A6 had similar frequencies at 200 lx while A4 (R_g = 109) had the highest at 480 lx. The effect of illuminance on the selection of stimulus for producing the most preferred color appearance was tested using a chi-square test of independence. The selection of the light stimulus turned out to be dependent on the illuminance level (x^2 = 69.04, df = 32, P < 0.001).

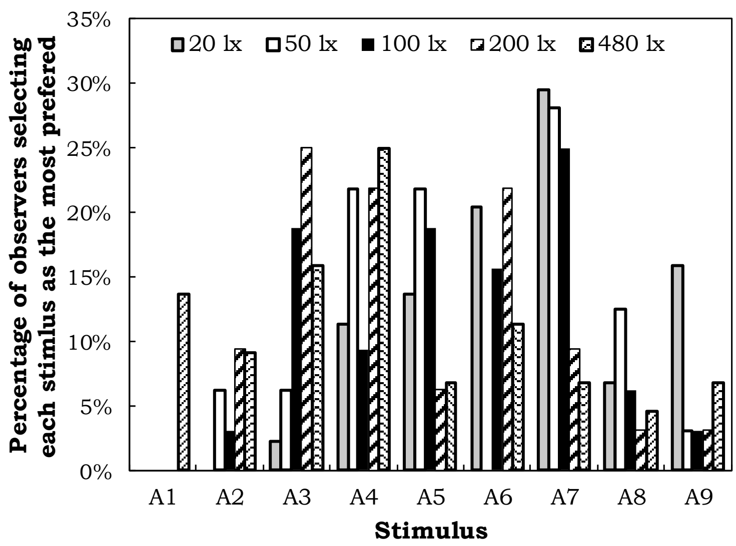


Figure 4 – Percentage of the observers selecting each stimulus under which the artwork had the most preferred color appearance at each illuminance level in Experiment 1.

3.2 Experiment 2

The intra-observer variation was evaluated by comparing the two sets of stimuli that were selected by each observer at 15000 lx using a chi-square test of independence. The intra-observer consistency was confirmed (x^2 = 1.09, df = 5, P = 0.955). The effect of presentation order on preference judgements was tested using a chi-square test of independence. The results show that the order was not a significant factor (200 lx: x^2 = 8.09, df = 5, P = 0.151; 2000 lx: x^2 = 9.26, df = 6, P = 0.159; 5000 lx: x^2 = 3.38, df = 4, P = 0.496; 10000 lx: x^2 = 4.57, df = 3, P = 0.206; 15000 lx: x^2 = 8.89, df = 5, P = 0.114).

Figure 5 shows the frequency of each stimulus that was selected to produce the most preferred color appearance of the artwork at each illuminance level in Experiment 2. B7 (R_g = 113) had the highest frequency at 200 lx while B4 (R_g = 108) had the highest frequency at 2000 and 5000 lx. B3 (R_g = 104) had the highest frequency at 10000 lx while B2 (R_g = 100) had the highest frequency at 15000 lx. The selections of the light stimulus and the illuminance level were associated with each other, as tested using a chi-square test of independence (x^2 = 147.17, df = 32, $P < 0.001$).

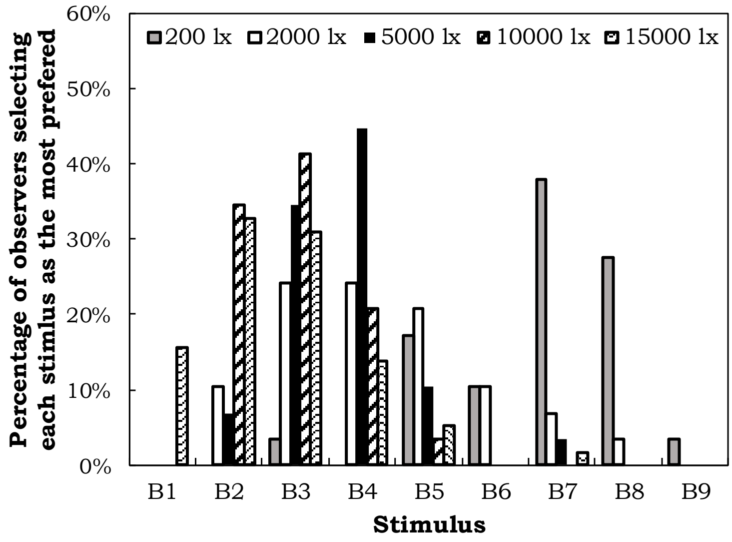


Figure 5 – Percentage of the observers selecting each stimulus under which the artwork had the most preferred color appearance at each illuminance level in Experiment 2.

4 Discussion

The average R_g of the stimuli that were selected to produce the most preferred color appearance of the artwork under each illuminance was summarized in Fig. 6. It can be noticed that the observers generally preferred a stimulus with a higher value of R_g under a lower illuminance. In consideration of the different LED devices used in the two experiments, the average $R_{cs,\ h1}$ and $R_{cs,\ h16}$ of the selected stimuli were calculated at each illuminance level. Figure 7 shows the relationship between the average R_g, $R_{cs,\ h1}$, and $R_{cs,\ h16}$ of the selected stimuli and illuminance. The average R_g, $R_{cs,\ h1}$, and $R_{cs,\ h16}$ decreased with the increased illuminance. At 50, 100, 200, 480, 2000, and 5000 lx, all the stimuli that were selected by the observers to produce the most preferred color appearance of the artwork had different levels of chroma enhancement (i.e., R_g > 100). It corroborated the findings that sources with good color fidelity may not always be preferred and those with larger relative gamut areas within a certain range were preferred (Wei et al., 2014; Wei and Houser, 2017; Royer et al., 2017, 2018; Jost-Boissard et al., 2014). Specifically, R_f, R_g, and $R_{cs,h16}$ of the most preferred stimulus that were selected under 50, 100, 200, 480, 2000, and 5000 lx were within the range defined in the two recent studies (Royer et al., 2017, 2018)—$R_f \geq 74$, $R_g \geq 100$, and $2\% \leq R_{cs,\ h16} \leq 16\%$, though they were carried out around 200 lx. At 10000 and 15000 lx, however, most of the stimuli that were selected by the observers had R_g values around 100. And the most preferred stimuli under the two highest illuminance had an $R_{cs,\ h16} \approx 0$.

Such a different result between different light levels indicates that the preference to the colors with enhanced chroma was probably caused by the lower illuminance in comparison to the light levels under daylight. In addition, a linear relationship between the chroma change and the logarithm of illuminance level can be noticed by combining the results of the two experiments, as shown in Fig. 7(b).

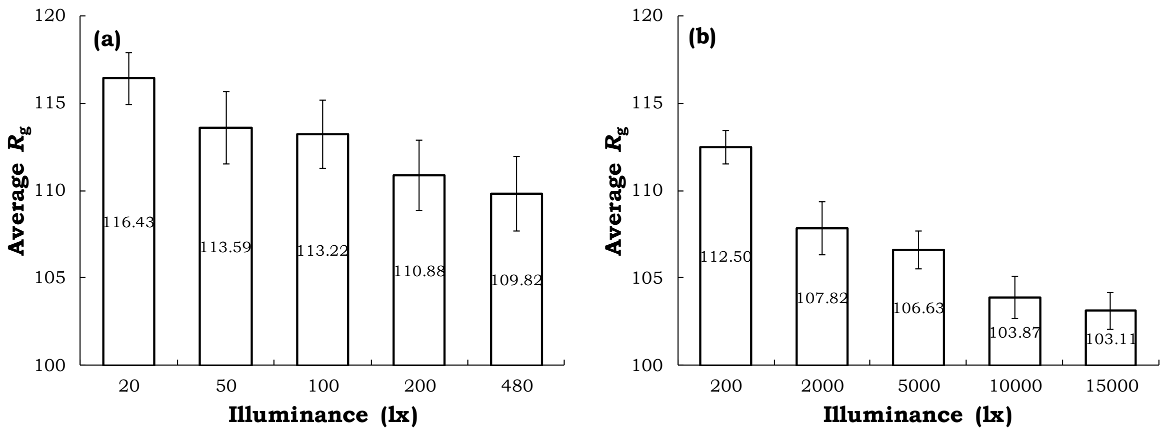


Figure 6 – Average R_g, together with the 95% confidence interval, of the stimuli that were selected by the observers to produce the most preferred color appearance of the artwork at each illuminance level in (a) Experiment 1 and (b) Experiment 2.

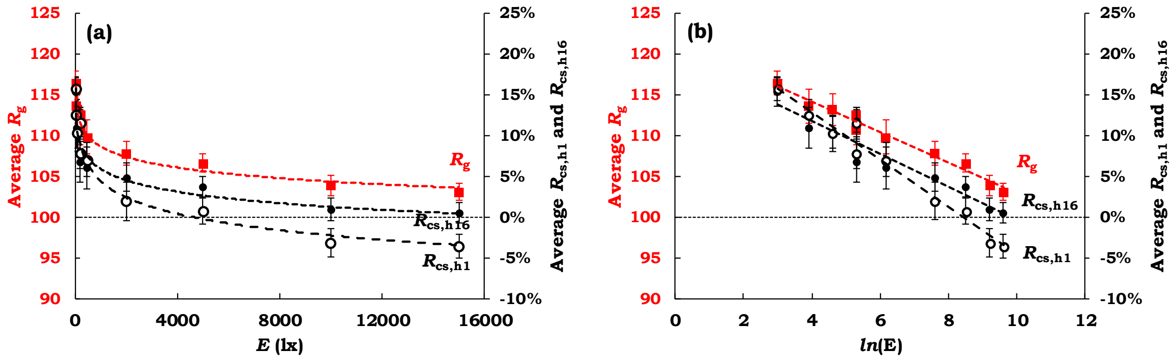


Figure 7 – Relationship between the average R_g, $R_{cs,h1}$, and $R_{cs,h16}$ of the selected stimuli and illuminance levels. (a) Average R_g, $R_{cs,h1}$, and $R_{cs,h16}$ versus illuminance E; (b) average R_g, $R_{cs,h1}$, and $R_{cs,h16}$ versus illuminance ln(E).

5 Conclusions

Two psychophysical experiments were conducted to investigate the interactive effect of illuminance and color rendition on color preference. Nine nearly metameric stimuli with a CCT of 3000 K were created to have different gamut areas, with a range of R_g from 99 to 124, across a wide range of illuminance levels (i.e., 20 – 15000 lx). At each illuminance level, the observers compared the color appearance of the artwork under the nine stimuli and selected the one under which the artwork had the most preferred color appearance. Illuminance was found to have a significant effect on the preference judgements made by the observers. The stimulus with a higher value of R_g was generally preferred under a lower light level. At the two highest light levels (i.e., 10000 and 15000 lx), the observers preferred the color appearance of the artwork under a stimulus with an R_g around 100. At other light levels, however, the observers always preferred the color appearance of the artwork under a stimulus with an R_g greater than 100. The results suggest that the preference to the colors with enhanced chroma was likely to be caused by the lower illuminance levels in comparison to the daylight illuminance.

References

CIE 1965. CIE 13:1965. *Methods of Measuring and Specifying Colour Rendering Properties of Light Sources.* Vienna: CIE.

DAVID, A., FINI, P.T., HOUSER, K.W., OHNO, Y., ROYER, M.P., SMET, K.A.G., WEI, M., WHITEHEAD, L. 2015. Development of the IES Method for Evaluating the Color Rendition of Light Sources. *Opt. Express*, 23, 15888-15906.

GUO, X., HOUSER, K.W. 2004. A Review of Colour Rendering Indices and Their Application to Commercial Light Sources. *Lighting Res. and Technol*., 36, 183-197.

HOUSER, K.W., WEI, M., DAVID, A., KRAMES, M.R., SHEN, X.S. 2013. Review of Measures for Light-source Color Rendition and Considerations for A Two-measure System for Characterizing Color Rendition. *Opt. Express*, 21, 10393-10411.

HUNT, R.W.G. 1952. Light and Dark Adaptation and the Perception of Color. *JOSA*., 42, 190-199.

JOST-BOISSARD, S., AVOUAC, P., FONTOYNONT, M. 2014. Assessing the Colour Quality of LED Sources: Naturalness, Attractiveness, Colourfulness and Colour Difference. *Lighting Res. Technol*., 47, 769-794.

KIM, M.H., WEYRICH, T., KAUTZ, J. 2009. Modeling Human Color Perception under Extended Luminance Levels. *Proceedings of ACM Transactions on Graphics (TOG)*. New Orleans (USA).

Ou, L. 2016. A Comparison of Colour Appearance between Indoor and Outdoor Environments. *Proceedings of CIE 2016 Lighting Quality & Energy Efficiency*. Melbourne (Australia).

REA, M.S., FREYSSINIER, J.P. 2013. White Lighting for Residential Applications. *Lighting Res. Technol*., 45, 331-344.

REA, M.S., FREYSSINIER, J.P. 2008. Color Rendering: A Tale of Two Metrics. *Color Res. Appl*., 33, 192-202.

REA, M.S., FREYSSINIER, J.P. 2010. Color Rendering: Beyond Pride and Prejudice. *Color Res. Appl*., 35, 401-409.

ROYER, M.P., WILKERSON, A., WEI, M. 2018. Human Perceptions of Color Rendition at Different Chromaticities. *Lighting Res. Technol*., 50, 965-994.

ROYER, M.P., WILKERSON, A., WEI, M., HOUSER, K.W., DAVIS, R. 2017. Human Perceptions of Colour Rendition Vary with Average Fidelity, Average Gamut, and Gamut Shape. *Lighting Res. Technol*., 49, 966-991.

ROYER, M.P., WEI, M., WILKERSON, A., SAFRANEK, S. 2019. Experimental Validation of Color Rendition Specification Criteria Based on ANSI/IES TM-30-18. *Lighting Res. Technol*. (Online first).

WEI, M., BAO, W., HUANG, H.P. 2018. Consideration of Light Level in Specifying Light Source Color Rendition. *Leukos*, 1-11.

WEI, M., HOUSER, K.W. 2017. Systematic Changes in Gamut Size Affect Color Preference. *Leukos*, 13, 23-32.

WEI, M., HOUSER, K.W., ALLEN, G.R., BEERS, W.W. 2014. Color Peference under LEDs with Diminished Yellow Emission. *Leukos*, 10, 119-131.

WEI, M., HOUSER, K.W., DAVID, A., KRAMES, M.R. 2016. Colour Gamut Size and Shape Influence Colour Preference. *Lighting Res. Technol*., 49, 992-1014.