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Light Sources with a Larger Gamut Area Can Enhance Color Preference under a Lower Light Level

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Abstract

Past studies suggested that sources with a high color fidelity may not always be preferred, while sources enhancing color saturation, especially the saturation of red colors, can result in higher preference. These studies, however, were typically carried out between 200 and 1000 lx. The color preference under a low light level was seldom investigated and illuminance was seldom varied in an individual experiment. This paper reports an experiment which was specifically designed to test a prior hypothesis that color preference reduced with illuminance level and sources with a larger gamut area can compensate the low preference caused by the illuminance reduction. Twenty-two observers compared the color appearance of an artwork under nine nearly metameric 3000 K stimuli under two illuminance levels (i.e., 20 and 480 lx). The stimulus with an R_g of 118 was the most preferred under 20 lx, while the stimulus with an R_g of 109 was the most preferred under 480 lx. The findings clearly revealed the importance of illuminance level in evaluating and specifying light source color rendition.

Introduction

Color rendition refers to the influence of the light source spectrum on the objects' color appearance, which is of great interest to the lighting community [1]. The Commission Internationale de l'Eclairage (CIE) recommended the General Color Rendering Index (CRI-R_a) to evaluate the color rendition of light sources in 1965 [2]. CRI-R_a, however, is indeed a color fidelity measure, which characterizes the similarity of a source to render the test color samples in comparison to a reference illuminant. It has been found that CRI- R_a cannot accurately characterize the color rendering of sources with highly structured spectra (e.g., LEDs) [3-7]. Furthermore, sources with good color fidelity may not always be preferred, as color fidelity penalizes color shift regardless of direction [3]. In contrast, sources that can enhance color saturation, especially the saturation of red colors, may enhance color preference [3]. Thus, it has been widely agreed that a single color fidelity measure cannot accurately characterize the color rendition of a light source [8-10]. Great efforts have been made to develop alternatives to CRI- R_a and measures characterizing change of color saturation [10-13]. It has been found that a two-measure system including a fidelity measure and a relative gamut measure can better characterize light source color rendition [14-16]. In 2015, the Illuminating Engineering Society (IES) published IES TM-30-15, in which a color fidelity metric R_f and a relative gamut metric R_g were proposed. In addition, a Color Vector Graphic was also proposed to characterize the gamut shape of a source, which has been found to significantly affect the color rendition of a light source [17, 18].

Table 1. Summary of the past studies investigating color preference

Author/Year	Illuminance	Findings
Liu, et al. 2013 [19]	300 lx	1. Illuminants with larger gamut area were preferred. 2. When assessing familiar objects, subjects relied on their memory.
Wei, et al. 2016 [18]	300 ± 10 lx/ 500 ± 20 lx	A higher preference under the 120-series (R_g = 113-117) spectra than the reference; a higher preference under the 110-series (R_g = 104-108) spectra than the reference (R_g = 97).
Royer, et al. 2017 [20]	207 ± 2 lx	R_f ≥ 75, R_g ≥ 98 and -7% ≤ $R_{cs,h1}$ ≤ 15% were preferred.
Royer et al. 2017 [17]	214 ± 4 lx	R_f ≥ 74, R_g ≥ 100 and 2% ≤ $R_{cs,h1}$ ≤ 16% were preferred.
Wei and Houser 2016 [21]	415 ± 5 lx	Q_g within a certain range (116 to 134) were preferred over Q_g of 97, 106 and 140.
Wei, et al. 2014 [22]	500 lx	VLED97 (Q_f = 94, Q_g = 100) was preferred over BLED85 (Q_f = 85, Q_g = 97).
Teunissen, et al. 2015 [23]	722 ± 3 lx	CRI70R (RGAI = 113) and CRI80R (RGAI = 110) were preferred over CRI80A (RGAI = 94).
Dikel 2013 [24]	500 lx	E (Q_g = 119 max) was the most pleasant preset spectra.
Wei 2013 [3]	350 or 150 lx	YD-LED (Q_f = 83, Q_g = 115) was preferred over BP-LED (Q_f = 83, Q_g = 100).
Lin et al. 2015 [8]	460 ± 20 lx	For restaurant and retailing, SPD B (Q_f = 86, Q_g = 97) were preferred over A (Q_f = 75, Q_g = 94).

Khanh et al. 2016 [25]	920 lx	MaxQg0 (Q_f = 97, Q_g = 111) and rot0 (Q_f = 89, Q_g = 106) were preferred over the five light sources without object over-saturation.
Khanh et al. 2016 [5]	550 lx	A (R_f = 73, R_g = 107 max) has the highest preference.
Islam et al. 2012 [26]	500 lx	SPD2 (Q_g _new = 115, GAI = 72), SPD5 (Q_g _new =117, GAI = 66) and SPD8 (Q_g _new = 105, GAI = 54) were preferred over SPD4 (Q_g _new = 78, GAI = 35) and SPD6 (Q_g _new = 87, GAI = 41).
Baniya et al. 2013 [27]	485 ± 5 lx	The reference SPD (Q_g = 119, R_a = 82) were over the SPDs (Q_g = 100 to 114, R_a = 86 to 96).
Harper 2013 [28]	540 lx	Near-white illuminants that saturated one or more hues were preferred to those that were neutral-white.

Numerous psychophysical studies [3, 5, 8, 17-29], as summarized in Table 1, have been carried out to define the criteria of fidelity, gamut area, and gamut shape for producing higher color preference. It can be found 1) the sources that can enhance the color saturation to some extent were more likely to be preferred, 2) the saturation of red colors was critically important to color preference evaluation, and 3) the color appearance of familiar objects (e.g., fruits) played a more important role in color preference evaluation, as the observers may have a better idea about their color appearance.

These studies, however, only investigated the color preference under a single illuminance level between 200 and 1000 lx, which fell into the range of the photopic vision and the range for general illumination [29]. Thus, how color preference varies with illuminance level, especially under low illuminance level, was never carefully investigated before. This study aimed to investigate how light level affects human color preference, which was specifically designed to test a *prior* hypothesis that sources with a larger gamut area can compensate the lower color preference caused by a lower illuminance level.

Methods

Apparatus and light settings

Two seven-channel spectrally tunable LED lighting devices were used in this study. The intensities of the seven channels were carefully adjusted to produce nine nearly metameric light stimuli at two illuminance levels (i.e., 20 and 480 lx). The spectral power distributions (SPDs) of these nine stimuli were carefully designed to have a correlated color temperature (CCT) around 3000 K and a D_{uv} of 0. Moreover, these nine light stimuli were designed to have a R_g between 100 to 124 with an increase in $R_{cs,h1}$ and $R_{cs,h8}$, so that they enhanced the saturation of red colors. A piece of artwork, as shown in Figure 1, was carefully selected to have familiar objects and red colors as the dominant color, which allowed the observers to have a better idea about the color appearance [19] and the nine light stimuli to change its color appearance. The two lighting devices were symmetrically placed to illuminate the artwork from 45°. The observer was seated around 1.2 m from the artwork, with his or her chin being fixed on a chin-rest.

Fig.1 Photograph of the artwork, viewed from the observer's eye position during the experiment

The light stimuli were calibrated to have a CCT within 3094 ± 74 K and a D_{uv} ranging from -0.0075 to +0.0018 using a calibrated Xrite i1Pro spectrophotometer. The relative SPDs and the Color Vector Graphics of the nine stimuli at the two illuminance levels are shown in Figures 2 and 3, with the colorimetric characteristics being summarized in Table 2.

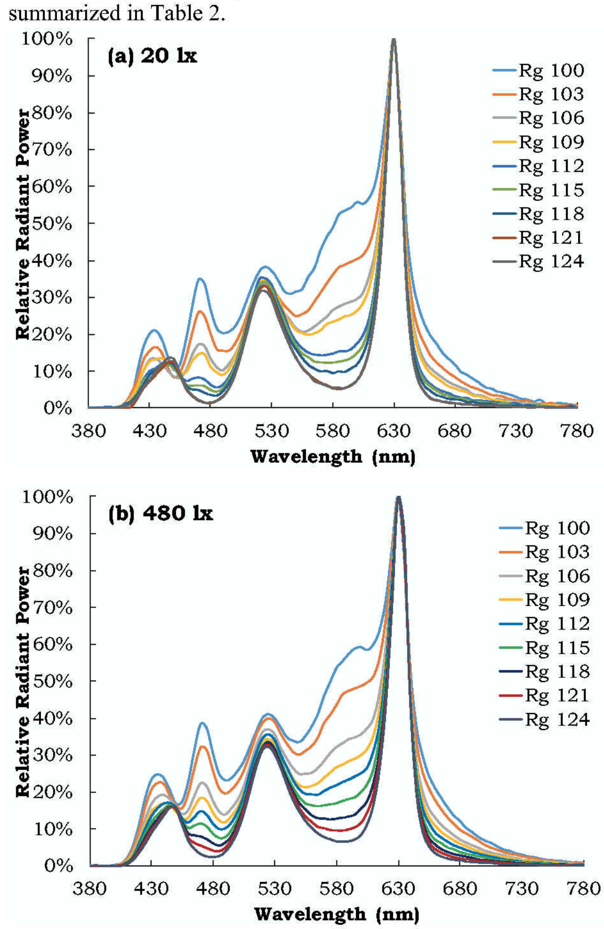

Fig.2 The relative SPD of the nine stimuli under two illuminance levels (a) 20 lx; (b) 480 lx.

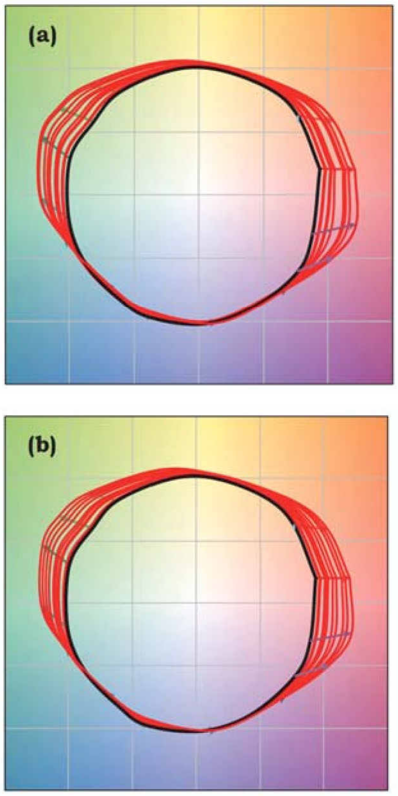

Fig.3 The IES TM-30-15 Color Vector Graphic (CVG) of the nine stimuli (a) 20 lx; (b) 480 lx.

Table 2 Summary of the colorimetric characteristics of the light stimuli

	Stimulus	CIE 1931		CCT	D_{uv}	Ra	IES TM-30-15	
		x	y				R_f	R_g
20 lx	Rg 100_20 lx	0.4301	0.3878	2980	-0.0057	92	93	100
	Rg 103_20 lx	0.4339	0.3899	2932	-0.0053	90	92	103
	Rg 106_20 lx	0.4372	0.3970	2937	-0.0029	83	88	106
	Rg 109_20 lx	0.4313	0.3963	3033	-0.0024	79	86	109
	Rg 112_20 lx	0.4295	0.4058	3142	+0.0018	65	79	112
	Rg 115_20 lx	0.4313	0.4063	3115	+0.0017	61	76	115
	Rg 118_20 lx	0.4300	0.4023	3107	+0.0003	54	72	118
	Rg 121_20 lx	0.4283	0.4048	3157	+0.0016	43	66	121
	Rg 124_20 lx	0.4267	0.3968	3119	-0.0015	42	65	124
480 lx	Rg 100_480 lx	0.4185	0.3794	3125	-0.0075	92	93	100
	Rg 103_480 lx	0.4175	0.3808	3156	-0.0068	92	93	103
	Rg 106_480 lx	0.4192	0.3822	3136	-0.0064	86	90	106
	Rg 109_480 lx	0.4231	0.3823	3062	-0.0070	81	87	109
	Rg 112_480 lx	0.4193	0.3849	3157	-0.0053	75	84	112
	Rg 115_480 lx	0.4217	0.3842	3106	-0.0060	68	80	115
	Rg 118_480 lx	0.4206	0.3861	3143	-0.0050	59	76	118
	Rg 121_480 lx	0.4214	0.3868	3133	-0.0048	52	71	121
	Rg 124_480 lx	0.4209	0.3874	3148	-0.0045	44	67	124

Observers

Twenty-two observers (19 males and 3 females) ranging from 20 to 28 years of age (mean = 21.41, std. dev. = 1.89) participated in the experiment. All the observers had normal color vision, as tested using the 24 Plate Ishihara Color vision Test.

Experimental design and procedure

Upon arrival, the observer completed a general information survey and the Ishihara Color Vision Test. The experimenter then explained the experimental procedure to the observer and answered any questions raised by him/her.

The observer was then escorted to the experimental space and being seated in front of the artwork, with his or her chin being fixed on a chin rest, so that all the observers experienced a similar viewing geometry. The artwork was illuminated under R_g, 100_20 lx and the observer was asked to observe the artwork for two minutes for adapting to the low illuminance level. The observer was then given an iPad whose background was set to black and luminance was set to the lowest. The iPad was programmed to switch between the nine light stimuli. The observer was asked to compare the color appearance of the artwork by switching between the stimuli and select the one under which the color appearance of the artwork was the most preferred. Under each illuminance level, the evaluations were completed twice, with one from R_g, 100 to R_g, 124 and the other from R_g, 124 to R_g, 100, to counter a possible order bias. The order of these two evaluations were counterbalanced between the observers. After completing the evaluations under 20 lx, the same procedure was followed for 480 lx. In order to avoid the brightness adaptation problem from 480 to 20 lx, all the observers completed the evaluations under 20 lx first. The entire experiment took about 30 minutes for each observer.

Results and discussions

The possible order effect was tested by comparing the most preferred stimuli selected by each observer using a paired-sample t-test. No significant difference was found between the two orders (i.e., 20 lx: $t_{d.f.=21}$=-0.45, *P*-value = 0.658; 480 lx: $t_{d.f.=21}$=-1.60, *P*-value = 0.125).

Figure 4 summarizes the average of R_g, together with the 95% confidence interval, being selected by the observers under which the artwork had the most preferred color appearance at each illuminance level. It can be observed that the observers preferred the color appearance of the artwork under a light stimulus with a greater R_g under a lower light level.

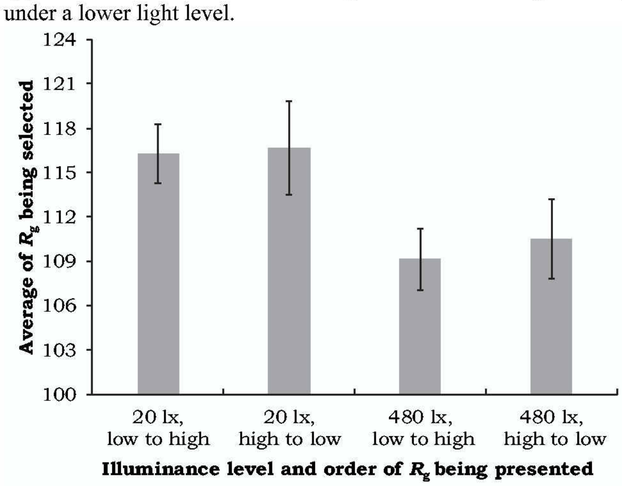

Fig.4 Average of R_g, together with the 95% confidence interval, being selected by the observers to provide the most preferred appearance of the artwork

Figure 5 shows the histogram of the number of observers selecting each stimulus as the most preferred one, together with the fitted Gaussian distribution, under each illuminance level. It can be observed that the stimulus with an R_g of 118 was selected by the highest number of the observers under 20 lx; while the one with an R_g of 109 was selected by the highest number of the observers under 480 lx.

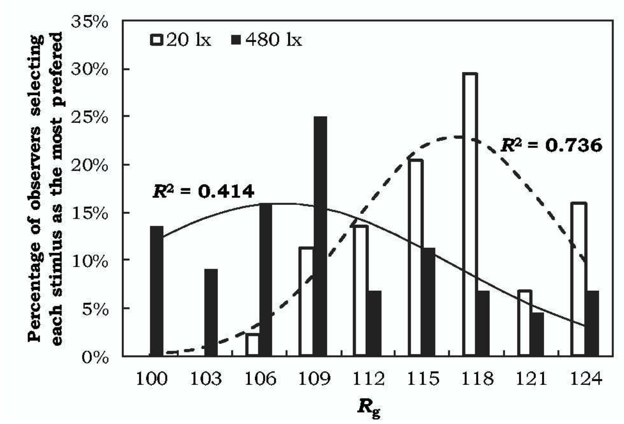

Fig.5 Histogram of the percentage of observers selecting each stimulus as the most preferred one under the two illuminance levels, together with the fitted Gaussian distribution curves.

The effect of illuminance level on color preference judgement was evaluated by comparing the judgments made by each observer under each illuminance level using a repeated-measure analysis at a significance level $\alpha = 0.05$. As summarized in Table 3, the illuminance level significantly affected the preference judgements made by the observers.

Table 3 Results of a repeated-measure analysis

Source	Sum of Squares	*df*	Mean Square	F	*P*-value
E	962.28	1	962.28	21.22	<0.001
order	17.28	1	17.28	2.26	0.147
E × order	5.01	1	5.01	0.53	0.476
Error(E)	952.47	21	45.36		
Error(order)	160.47	21	7.64		
Error(E × order)	199.74	21	9.51		

The findings in this study were consistent to those in the past studies that sources with a higher fidelity may not always be preferred [3] and sources with a relative gamut area beyond 100 can enhance color preference [3,6-9,15,17-22]. The criteria for a light source to produce higher color preference (i.e., $R_f \geq 74$, $R_g \geq 100$, and $2\% \leq R_{cs,h1} \leq 16\%$) proposed by Royer et al [17], however, were only applicable to the results under the illuminance of 480 lx (i.e., the stimulus with R_f of 87, a R_g of 109, and $R_{cs,h1}$ of 5%). The finding that the stimulus with a larger R_g and a higher score for $R_{cs,h1}$ (i.e., R_g = 118 and $R_{cs,h1}$ = 17.8%) clearly suggested the necessity to consider the effect of illuminance when evaluate and specify the color rendition of a light source.

The significant effect of illuminance on color preference, especially the necessity to have a higher saturation under a lower illuminance level, found in this study also suggested the possibility that the preference for a higher saturation under an illuminance between 200 and 1000 lx found in past studies [3,6-9,15,17-22] may also due to a relatively lower illuminance compared to daylight [30]. The color appearance of surface colors under extremely high illuminance levels was seldom investigated before and is not considered in the existing color appearance models, which merits further investigation.

Furthermore, the findings of this study can be practically used in selecting light sources for applications requiring a low illuminance but good color rendition, such as museum lighting. The selection of light sources for museum aims to achieve a balance between good color rendition and protection of artwork [31-33]. A combination of a CRI R_a of 80 and an illuminance between 50 and 200 lx [33] has been agreed as a good balance. The illuminance, however, has to be specified with an exposure time, so that the total amount of radiation (i.e., lx·hour/year) is below a certain level. This study suggested the possibility to further reduce the illuminance level by using a source with a larger gamut, which not only provides a better color appearance but also allows a longer display period with a good protection.

Summary and Conclusions

Nine stimuli with a CCT of 3000 K were produced to illuminant an artwork under two illuminance levels (i.e., 20 and 480 lx). These stimuli were carefully created to be metameric, but have different abilities to enhance the saturation of red and green colors, with an R_g from 100 to 124. Twenty-two observers evaluated the color appearance of the artwork under the nine stimuli and selected the one under which the color appearance of the artwork was the most preferred at each illuminance level. The judgements made by the observers clearly suggested that illuminance played an important role in color rendition, with a lower illuminance level requiring a source with a larger gamut area. Such a finding implied the necessitity to consider illuminance level when specifying the color rendition of a light source and the possibilities to use sources with a larger gamut area under a lower illuminance level.

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