LED light with enhanced color saturation and improved white light perception

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LED light with enhanced color saturation and improved white light perception

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Abstract: The light emitting diodes (LEDs) with high light quality were investigated to enhance the color appearance of the illuminated objects and increase the white light perception of the ambience. The spectral power distributions of the LED lights were optimized by addition of the RGB components and by shifting the color coordinate below the blackbody line to get desired color rendering index (CRI) and high gamut area index (GAI). The results of the human factor study reveal that the "perfect" white light can be achieved to both enhance color saturation and improve light visual impression. The effects of observer metamerism were studied to clarify the observed phenomenon that the white lights with the same color coordinates were perceived differently by real observers.

OCIS codes: (330.1690) Color; (330.1715) Color, rendering and metamerism; (230.3670) Light-emitting diodes.

References and links

1. B. J. Babin, D. M. Hardesty, and T. A. Suter, "Color and shopping intentions," J. Bus. Res. **56**(7), 541–551 (2003).
2. P. Custers, Y. de Kort, W. IJsselsteijn, and M. de Kruiff, "Lighting in retail environments: Atmosphere perception in the real world," Lighting Res. Tech. **42**(3), 331–343 (2010).
3. O. Barlı, M. Aktan, B. Bilgili, and S. Dane, "Lighting, indoor color, buying behavior and time spent in a store," Color Res. Appl. **37**(6), 465–468 (2012).
4. J. A. Veitch, G. R. Newsham, P. R. Boyce, and C. C. Jones, "Lighting appraisal, well-being and performance in open-plan offices: A linked mechanisms approach," Lighting Res. Tech. **40**(2), 133–151 (2008).
5. A. Borisuit, F. Linhart, J. L. Scartezzini, and M. Munch, "Effects of realistic office daylighting and electric lighting conditions on visual comfort, alertness and mood," Lighting Res. Tech. **47**(2), 192–209 (2015).
6. D. Hinks and R. Shamey, "Review of retail store lighting: implications for colour control of products," Color Technol. **127**(2), 121–128 (2011).
7. C. Sáenz, B. Hernandez, M. J. Beriain, and G. Lizaso, "Meat color in retail displays with fluorescent illumination," Color Res. Appl. **30**(4), 304–311 (2005).
8. J. H. Oh, S. J. Yang, and Y. R. Do, "Healthy, natural, efficient and tunable lighting: four-package white LED for optimizing the circadian effect, color quality and vision performance," Light Sci. Appl. **2**, 1–9 (2014).
9. Y. Ohno, "Spectral design considerations for white LED color rendering," Opt. Eng. **44**(11), 111302 (2005).
10. K. Smet, W. R. Ryckaert, M. R. Pointer, G. Deconinck, and P. Hanselaer, "Correlation between color quality metric predictions and visual appreciation of light sources," Opt. Express **19**(9), 8151–8166 (2011).
11. W. Davis and Y. Ohno, "Approaches to color rendering measurement," J. Mod. Opt. **56**(13), 1412–1419 (2009).
12. M. P. Royer, K. W. Houser, and A. M. Wilkerson, "Color discrimination capability under highly structured spectra," Color Res. Appl. **37**(6), 441–449 (2012).
13. W. Davis and Y. Ohno, "Color quality scale," Opt. Eng. **49**(3), 033602 (2010).
14. K. Hashimoto, T. Yano, M. Shimizu, and Y. Nayatani, "New method for specifying color rendering properties of light sources based on feeling of contrast," Color Res. Appl. **32**(5), 361–371 (2007).
15. P. Bodrogi, S. Bruckner, T. Q. Khanh, and H. Winkler, "Visual assessment of light source color quality," Color Res. Appl. **38**(1), 4–13 (2013).
16. M. S. Rea and J. P. Freyssinier-Nova, "Color rendering: A tale of two metrics," Color Res. Appl. **33**(3), 192–202 (2008).
17. M. S. Rea and J. P. Freyssinier, "Color rendering: Beyond pride and prejudice," Color Res. Appl. **35**(6), 401–409 (2010).
18. K. Smet, W. R. Ryckaert, M. R. Pointer, G. Deconinck, and P. Hanselaer, "Colour appearance rating of familiar real objects," Color Res. Appl. **36**(3), 192–200 (2011).

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19. A. Žukauskas, R. Vaicekauskas, and M. Shur, "Solid-state lamps with optimized color saturation ability," Opt. Express **18**(3), 2287–2295 (2010).
20. O. Masuda and S. M. C. Nascimento, "Best lighting for naturalness and preference," J. Vis. **13**(7), 4 (2013).
21. M. Rea and J. Freyssinier, "White lighting for residential applications," Lighting Res. Tech. **45**(3), 331–344 (2013).
22. M. Rea and J. Freyssinier, "White lighting," Color Res. Appl. **38**(2), 82–92 (2013).
23. ASSIST, "Recommendations for specifying color properties of light sources for retail merchandising," Lighting Research Center http://www.lrc.rpi.edu/programs/solidstate/assist/pdf/AR-SpecifyColorRec-March2010.pdf. (2010).
24. A. David, M. R. Krames, and K. W. Houser, "Whiteness metric for light sources of arbitrary color temperatures: proposal and application to light-emitting-diodes," Opt. Express **21**(14), 16702–16715 (2013).
25. R. Ramanath, "Minimizing observer metamerism in display systems," Color Res. Appl. **34**(5), 391–398 (2009).
26. R. L. Alfvin and M. D. Fairchild, "Observer variability in metameric color matches using color reproduction media," Color Res. Appl. **22**(3), 174–188 (1997).
27. L. Beke, G. Kutas, Y. Kwak, G. Y. Sung, D. S. Park, and P. Bodrogi, "Color preference of aged observers compared to young observers," Color Res. Appl. **33**(5), 381–394 (2008).
28. P. Csuti and J. Schanda, "Colour matching experiments with RGB-LED," Color Res. Appl. **33**(2), 108–112 (2008).
29. Colour and Vision Research Laboratory, "CIE 2006 physiologically-relevant LMS functions," http://www.cvrl.org.
30. Colour and Vision Research Laboratory, "Stiles & Burch individual 10-deg colour matching data," htp://www.cvrl.org.
31. W. S. Stiles and J. M. Burch, "NPL colour-matching investigation: Final report," Opt. Acta (Lond.) **6**(1), 1–26 (1959).
32. A. J. Poza, J. A. Martinez, M. Melgosa, and E. Hita, "A 2° standard deviate observer from the 1955 Stiles-Burch datasheet," J. Opt. **28**(1), 20–25 (1997).

1. Introduction

Creating the right environmental setting is of prime importance for indoor activities, e.g. retails/shops, restaurants, homes, and health care facilities [1]. Among many factors influencing the environment, lighting makes a great contribution for the desired ambiance, especially for retails/shops, lighting can influence emotions, mood and cognition as well as atmosphere and spatial impressions [2–5]. Light quality is more important than luminous efficacy for these fields of interior lighting. The quantity and quality of illumination, the impression it creates about the merchandise and the effect it has on the retail area's appearance are all factors in successful sale [6,7]. Therefore, to improve customer's sense of well-being and to make merchandize look good, good lighting designs for the retails/shops are very important. Traditional technical studies in the lighting field usually only concentrate on increasing light performance, e.g. light efficacy, color rendering, and reducing cost while not considering too much about light quality.

In general, the light quality is described in terms of color rendering index (CRI) and correlated color temperature (CCT) on which the lighting industry relies to communicate color quality and visual appearance of the light sources [8]. The CRI is used as a measure of how well the color of objects will be revealed under the illumination. But the definition of color rendering by the CRI is limited, and many research papers have already shown that high CRI alone is not enough to reflect the true color of the products in some special applications, e.g. retails/shops, where the subjective characteristics such as attractiveness and preferences would be more useful [9]. Progresses have been made in recent years to develop new color quality metrics [10–15]. Among many metrics, gamut area index (GAI) can be a useful supplement to the well-established CRI in ensuring color saturation and satisfactory perception of the object color [16,17]. A light source which has enhanced chromatic saturation (chroma) can serve to increase the visual clarity of illuminated objects, the feeling of contrast, and the brightness as perceived by observers [18]. People may have a preference for an enhanced chroma of the illuminated objects [19]. The CCT is a measure of the appearance of the illumination itself. The CCT is often used to represent chromaticity of white light sources, but the chromaticity is two-dimensional, and another dimension, the distance from the Planckian locus (Duv) is often missing. Usually the light source with the chromaticity along the line of the blackbody radiation is perceived as "white". But recent researches suggest that the source with chromaticity along

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the line of blackbody radiation does not appear “white” and the perception of “white” illumination does not in fact lie on the line of blackbody radiation [20,21]. The perception of the white illumination is associated with the position of the chromaticity that falls above the blackbody locus for high CCT and that lies well below the blackbody locus for low CCT [22]. So it is necessary to combine the CCT and the Duv together to express chromaticity of the white light source to enhance the white light perception, which is an important part of our visual experience for the sense of well-being.

In this paper we present the results of light emitting diodes (LEDs) with high light quality specially for retail/shop lighting to enhance the color appearance of the illuminated products and increase the white light visual perception. Four metrics, the GAI combined with the CRI are used to classify the color quality, while the Duv combined with the CCT are used to characterize the light visual appearance of the LED light source. The spectral power distributions (SPDs) were optimized by mixing the red, green, blue (RGB) LEDs and the phosphor converted warm white (WW) LED together to have both high GAI and high CRI to get perceptually noticeable gain in color saturation in one side, and optimize the distance from the Planckian locus to improve light visual impression in another side. The influences of the LED light on the colored clothes and the ambience from a visual point of view were tested by a human factor study. The results show that the LED light by addition of the RGB components and by shifting color coordinate below the blackbody line can both enhance the color saturation and increase the white light perception. The effects of observer metamerism were studied to clarify the observed phenomenon that the white lights with the same color coordinates were perceived differently by real observers. The color coordinates for different RGB ratios were recalculated by the modified color matching functions (CMFs) to further verify observers’ observation for the real light color.

2. Experiments

2.1 Light sources

The study is specifically for retail/shop lighting to enhance the color appearance of the merchandizes to stimulate purchasing and to enhance the white light visual impression to elevate the shop ambience. Also the study methods and results can be used for other applications of interior lighting. Currently the light source mostly used in high end fashion shops is the ceramic metal halide (CMH) lamp with a high CRI and a low CCT of 3000 K as accent lighting to highlight fashion clothes. Therefore, in this study, the CMH light was used as reference lighting scenario. The influence of different LED light sources on the color appearance of the illuminated objects and the visual impression of the white light for the whole ambience were respectively compared with that of the CMH light. The CMH lamp used for the experiment was commercial ceramic metal halide lamp with high CRI of 92 (Philips, MasterColor CDM-TC Elite 930). The LED lamp was composed of red (λ_{max} = 625 nm), green (λ_{max} = 521 nm), blue (λ_{max} = 465 nm) and phosphor converted warm white (3000 K) LEDs (Osram, OSLON SSL). The SPDs of the LED lights were optimized by changing the ratios of these four types of LEDs to get desired color quality. The SPDs of all lamps were measured by a calibrated high accuracy array spectrometer (Everfine, HAAS-2000) in an integrating sphere of 1 m diameter. The CCT of the CMH lamp was 3000 K (measured data 2967 K). All LED combinations were designed to have the same CCT of 3000 K but with different color coordinates.

The Duv is used to represent the distance between the color coordinate of the light source and of the Planckian radiator of the same CCT in the CIE 1931 2° color space. A positive Duv means that the color coordinate is above the Planckian locus, and a negative Duv means that the color coordinate is below the Planckian locus. Eight LED lights with different Duv were designed for experiments by mixing different percentages of the RGB components with the phosphor converted warm white LED. Two types of CRI, respectively of 90 and 80, and four

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types of Duv varying from 0 on the blackbody line to −0.015 below the blackbody line were designed. The measured SPDs for these nine light sources are shown in Fig. 1. The measured color qualities are characterized in terms of the CCT, CRI, GAI, color coordinate and Duv in the CIE 1931 2° color space, and are listed in Table 1. Here, WW means a phosphor converted warm white LED with a CCT of 3000 K. Eight types of LED lights are donated as LED1 to LED8. The ratios of the RGB are calculated by the lumen output of the red, green and blue LEDs divided by the total lumen output of all LEDs. The ratios among the red, green, and blue LEDs for different lights are not same since their color coordinates are different. The CCT cannot be kept exactly the same as 3000 K for the real lamps due to experiment error, but the error is very small and it is within the range of 1% so it will not influence the experimental results.

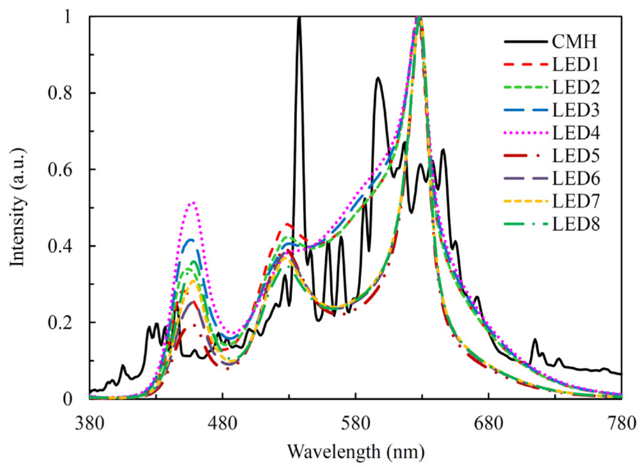

Fig. 1. Spectral power distributions of the nine light sources used. All light sources have same CCT of 3000 K. The LED light sources of LED1 to LED4 have CRI above 90 with Duv varying from 0 on the blackbody line to −0.015 below the blackbody line, and the LED light sources of LED5 to LED8 have CRI of 80 with Duv varying from 0 on the blackbody to −0.015 below the blackbody.

Table 1. Color characteristics of the nine light sources.

Light source	CCT (K)	CRI	GAI	x	y	Duv
CMH	2967	92	107	0.4386	0.4036	0
LED1 (24% RGB + 76% WW)	2997	96	103	0.4369	0.4036	0
LED2 (22% RGB + 78% WW)	2959	95	118	0.4330	0.3911	−0.005
LED3 (20% RGB + 80% WW)	2980	94	131	0.4241	0.3754	−0.01
LED4 (18% RGB + 82% WW)	3012	92	143	0.4165	0.3631	−0.015
LED5 (50% RGB + 50% WW)	2989	80	113	0.4372	0.4033	0
LED6 (47% RGB + 53% WW)	2949	80	129	0.4333	0.3906	−0.005
LED7 (46% RGB + 54% WW)	2980	80	144	0.4231	0.3745	−0.01
LED8 (45% RGB + 55% WW)	2986	80	159	0.4170	0.3615	−0.015

2.2 Experimental setup

In order to let observers have real feelings for the shop environment, a virtual shop was built in a room equipped with the mannequins. The room was separated into two parts respectively installed with the CMH lamps and the LED lamps. The LED lamps had eight tunable light scenarios with the performances listed in Table 1. The mannequins dressed with clothes of different colors were respectively put in these two parts for side by side comparison to check the influence of different lights on the color appearance. Figure 2 shows the experimental setup. The clothes with typical six colors in the CIE 1976 LAB color space, such as white wrap, red coat, yellow T-shirt, orange T-shirt, blue jean, green trouser were selected for the test. The qualities of the lights were assessed based on the color appearance of the illuminated clothes and the white light visual perception of the whole room. The illuminance at the position of the clothes was set to the same level of about 2000 lx for all lights in order not to have an impact of the brightness to the observer behavior. The influences of the eight LED lights on the color appearance and the white light perception were respectively compared with that of the CMH light, which was taken as reference light and set to be zero value.

Fig. 2. Experimental setup, the left part of the room installed with the CMH lamps and the right part of the room installed with the LED lamps with eight tunable light scenarios. Mannequins dressed with clothes of six different colors for side by side comparison. Illuminance at the position of the clothes was set to the same level of about 2000 lx.

2.3 Human factor study

Twenty observers participated in the experiments. All observers had normal color vision. The mean age was 30 years with a range of 22-37 years. Observers were asked to make their evaluation of the color appearance of every cloth regarding color vividness, color shift, color preference, and their opinions for the white light visual perception regarding white light difference, white light preference and white light impression respectively under the illumination of the eight LED lights compared with that by the reference CMH light. The judgment of "color naturalness" was not evaluated because the observers said that they could not distinguish what was natural color since all objects were illuminated by artificial light sources. Figure 3 is the questionnaires used by the observers to evaluate the color appearance of the illuminated clothes and the white light perception for the whole environment. Seven-point scales (−3 to 3) are used to record observers' rating for three parameters: color vividness, color preference, and white light preference. The three right hand points of the scale are labelled as a positive response for the three parameters when the illumination of the tested LED light is regarded as better than the CMH light. The three left hand points of the scale are labelled as a negative response to the tested LED light. The middle zero point of indicates there are no color differences and people do not have a preference between the tested LED light and the CMH light. The scale from 0 to 6 is used to record the color difference and the white light difference between the tested LED light and the CMH light. In order to better understand observers' preference for the white light, observers were asked to give their opinions for the visual perception of the white light, whether the LED light appeared reddish, yellowish, greenish, bluish or the LED light really looked like perfect white.

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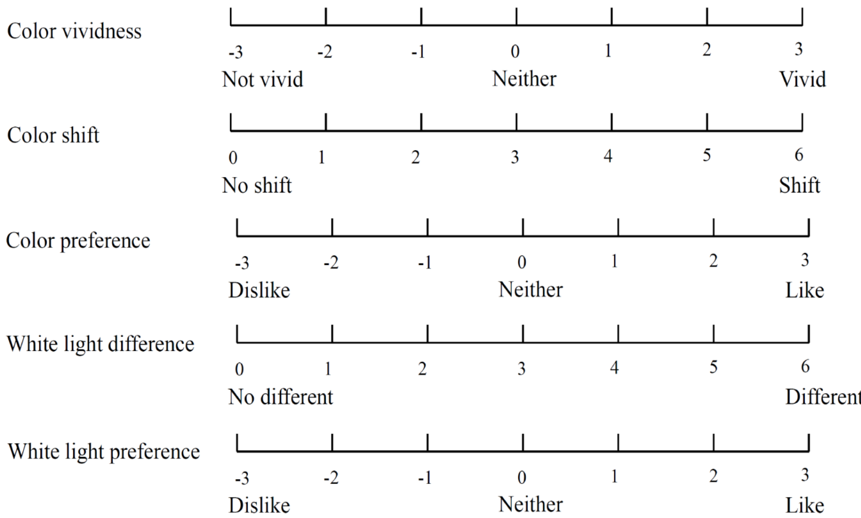

Fig. 3. Questionnaire for observers to evaluate the color appearance of the illuminated clothes and the white light perception of the ambience.

3. Results and discussions

3.1 Color enhancement

In order to understand how the change of the RGB ratio and the distance from the Planckian locus will influence the color appearance and the white light visual perception, firstly the theoretical calculation is done to get the relationship between the color performance, the RGB ratio and the distance from the Planckian locus. The GAI is used together with the CRI to quantify the color performance, which is calculated according to the measured SPDs of the light sources. Gamut area of the light source is commonly calculated as the area of the polygon defined by the chromaticity in the International Commission on Illumination (CIE) 1976 u'v' color space of the eight CIE test color samples when illuminated by a test light source [23]. Figure 4 shows the relationship between the RGB ratio and the CRI/GAI for different Duv in the case of the same CCT of 3000 K. It can be seen that the GAI increases with increasing the RGB ratio while the CRI has a maximum. When increasing the distance from the Planckian locus, the GAI can be increased greatly while keeping the same CRI. Therefore, high GAI can be achieved while without sacrificing the CRI by optimizing the SPDs through mixing a suitable amount of the RGB LEDs components together with the phosphor converted LED and by increasing the distance from the Planckian locus.

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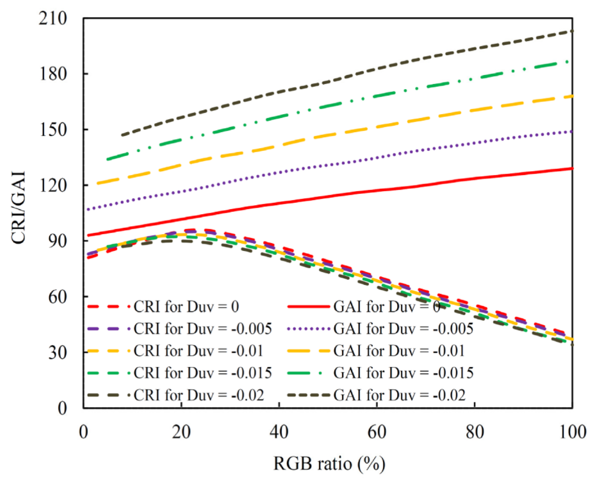

Fig. 4. Relationship between RGB ratio and CRI/GAI for different Duv in the case of the same CCT of 3000 K.

In this paper, the *t*-test is used to compare judgments of the color performance and the white light visual perception between the LED light and the CMH light. Analysis of variance (ANOVA) is conducted for judgments among different LED lights themselves. The observers' mean ratings and the associated standard errors of the mean are shown in the Figs. Figure 5(a) shows the observers' mean rating for color vividness of the average of the six colors. The observers indicate a higher level of color vividness under the LED light. The color vividness is a little better at the middle CRI of 80 than at the high CRI of over 90 and increases with increasing the distance from the Planckian locus. The LED lights with the Duv of −0.010 and −0.015 have statistically significant influence on the color vividness in the case of both high and middle CRI (t = 3.981, $p = 0.001$ for LED3; t = 4.401, $p < 0.001$ for LED4; t = 5.372, $p < 0.001$ for LED7; t = 5.637, $p < 0.001$ for LED8). The ANOVA shows that there are also statistically significant differences among different LED lights (F = 5.488, $p < 0.001$). Figure 5(a) and the statistical analysis support the hypothesis that the LED light with high GAI can render the objects more vivid. When the LED illuminants have strong components in the region of narrowband wavelength of the RGB cluster, the color coordinates of the colored samples will shift toward increased chroma, which generally have a positive impact on the perceived color quality. In another side, when increasing the distance from the Planckian locus, the GAI will increase too as shown in Fig. 4. The color of the objects will appear more saturated under the illumination of the light with high GAI. Consistent with other findings, the light sources with high GAI could produce more vivid color and observers found saturated hues to be the most influential in making their judgments of the vividness. So the optimized LED light sources can realize enhanced color characteristics while without sacrificing the CRI compared with the traditional discharge lamps.

Figure 5(b) shows the observers' mean rating for the color vividness of each color. The saturation enhancement for each color depends on the detailed color type. There are statistically significant differences in the observers' rating for the white (t = 6.049, $p < 0.001$ for LED3; t = 7.094, $p < 0.001$ for LED4; t = 4.098, $p < 0.001$ for LED7; t = 6.532, $p < 0.001$ for LED8) and the red (t = 5.284, $p < 0.001$ for LED3; t = 6.658, $p < 0.001$ for LED4; t = 9.189, $p < 0.001$ for LED7; t = 9.488, $p < 0.001$ for LED8) under the LED lights with the Duv of −0.010 and −0.015 at both high and middle CRI. The yellow and the orange appear more vivid under the LED lights but there are no statistically significant differences. The vividness of the green is a little better in the case of the middle CRI of 80 due to high GAI. The blue appears less vivid when the absolute value of the Duv is less than 0.010 for both high and middle CRI. The ANOVA shows

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that there is statistically significant difference among different LED lights for the white (F = 11.328, $p < 0.001$), the red (F = 4.854, $p < 0.001$) and the blue (F = 23.394, $p < 0.001$) whereas not for other colors. The best LED light to enhance the color vividness of all colors is at the Duv of −0.010 and the CRI of 80.

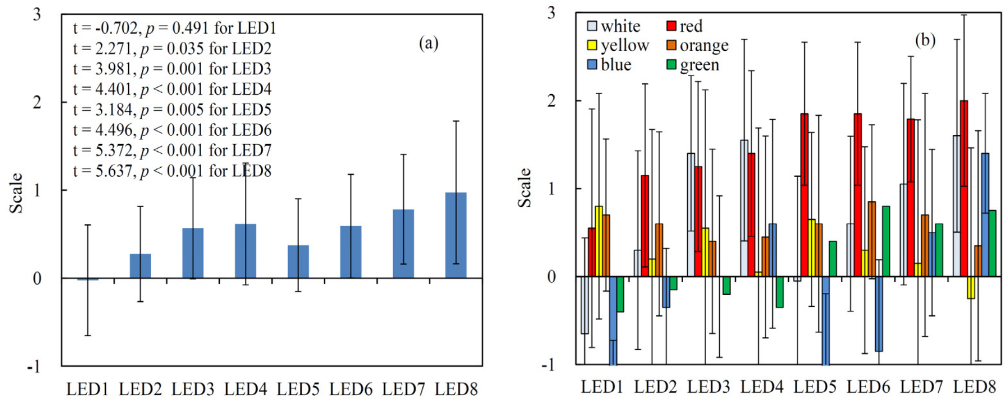

Fig. 5. (a) Meat ratings of color vividness for the average of six colors under the eight different LED lights. (b) Mean ratings of color vividness for each color under the eight different LED lights. Error bars represent ± one standard error of the mean (n = 20).

Figures 6(a) and 6(b) show the observers' mean rating for the color shift of the average of the six colors and each color. All colors appear different under the LED lights compared with how they appear under the CMH light. All LED lights have statistically significant influences on the color shift (t = 8.105, $p < 0.001$ for LED1; t = 6.522, $p < 0.001$ for LED2; t = 7.016, $p < 0.001$ for LED3; t = 8.709, $p < 0.001$ for LED4; t = 8.380, $p < 0.001$ for LED5; t = 7.765, $p < 0.001$ for LED6; t = 8.903, $p < 0.001$ for LED7; t = 9.397, $p < 0.001$ for LED8). The ANOVA shows that there is no statistically significant difference among different LED lights (F = 2.265, $p = 0.032$). The finding shows that when the LED light source is used to replace traditional discharge light source, the color of the illuminated objects will always appear different and it is not related to the LED design no matter if it has a high or low CRI and whether the color point is deviated from the line of the blackbody radiation.

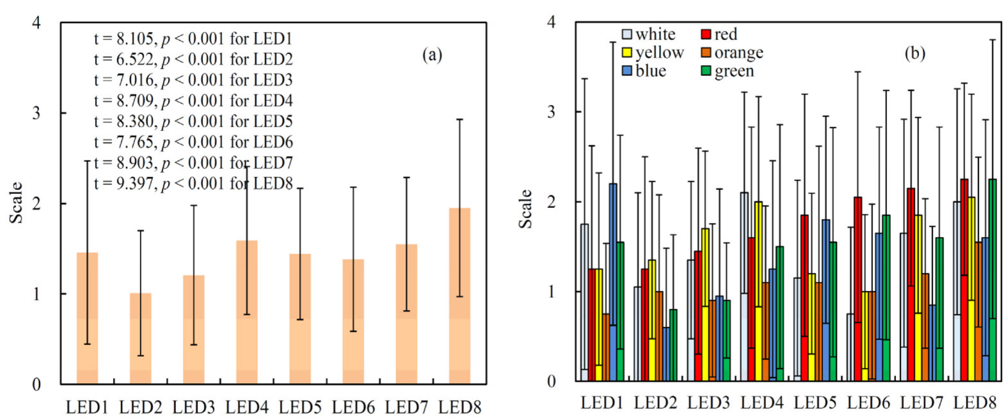

Fig. 6. (a) Mean ratings of color shift for the average of six colors under the eight different LED lights. (b) Mean ratings of color shift for each color under the eight different LED lights. Error bars represent ± one standard error of the mean (n = 20).

Figure 7(a) shows the observers' mean rating for the color preference of the average of the six colors. The observers indicate a higher preference for the colors illuminated by the LED

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lights with sub-Planckian locus. The LED lights with the Duv of –0.010 and –0.015 have statistically significant main effects on the overall color preference (t = 3.989, p = 0.001 for LED3; t = 4.109, p = 0.001 for LED4; t = 4.271, p < 0.001 for LED7; t = 4.611, p < 0.001 for LED8). The ANOVA shows that there is statistically significant difference among different LED lights (F = 4.504, p < 0.001). From the results it is clear that the observers prefer more vivid colors. It is reasonable to state that the LED lights with high GAI by addition of the RGB components and by shifting the color point below the blackbody line do have a saturation enhancing effect. The effects of these lights on the object appearance are also more preferred and the colors are found to be more attractive and real looking, suggesting that enhancing the saturation of an object has appealing effects.

Figure 7(b) shows the observers' mean rating for the color preference of each color. The observers indicate a higher preference for the colors whose saturations are enhanced, e.g. white and red. Statistically significant differences are found for the LED lights with the Duv of –0.010 and –0.015 in their influences on the observers' preference for the white (t = 6.990, p < 0.001 for LED3; t = 4.254, p < 0.001 for LED4; t = 3.979, p = 0.001 for LED7; t = 6.110, p < 0.001 for LED8) and the red (t = 5.805, p < 0.001 for LED 3; t = 3.823, p = 0.001 for LED4; t = 5.357, p < 0.001 for LED7; t = 5.835, p < 0.001 for LED8). The observers' preferences for other colors, e.g. orange and yellow are higher under the LED light but there are no statistically significant differences. The observers do not prefer the blue and the green when the light has high CRI of over 90. The ANOVA shows that there are statistically significant differences among different LED lights for the white (F = 6.533, p < 0.001) and the blue (F = 11.604, p < 0.001) whereas not for other colors.

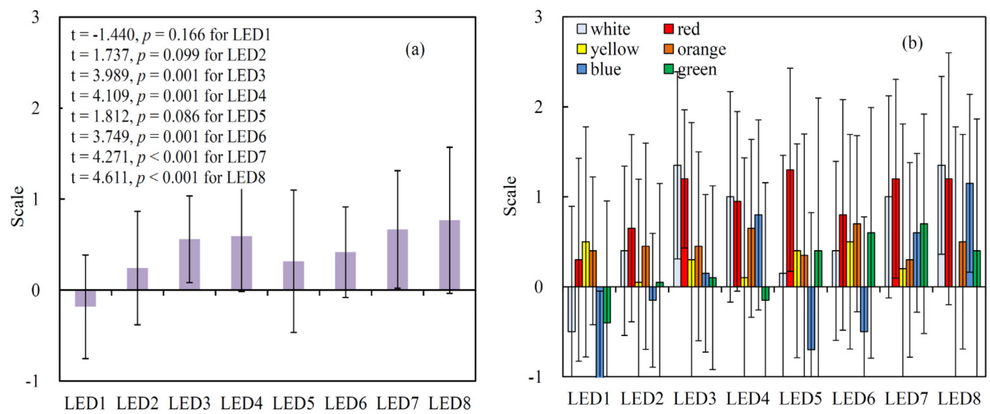

Fig. 7. (a) Mean ratings of color preference for the average of six colors under the eight different LED lights. (b) Mean ratings of color preference for each color under the eight different LED lights. Error bars represent ± one standard error of the mean (n = 20).

Generally, the observers' preference for color appearance corresponds with their judgments for color vividness. Increasing in the color saturation may yield better visual clarity and enhance perceived brightness. Overall, the colors under the LED light with the color coordinate below the blackbody line are more preferred than that under the CMH light, which shows that the LED light with the optimized spectral design provides better color quality than the CMH light. The result suggests that the optimized LED design has significant influence on color vividness and color preference. Therefore, optimizing the SPDs to increase GAI is very important to enhance color saturation for the attractive appearance of the textiles in fashion shops. Other scientific investigations show the same findings that the preference for the object colors can be increased by high GAI, which is better predicting subjective judgment of "vividness" and "preference" [16,17].

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3.2 White light perception

In this study, all light sources have same CCT of 3000 K, but the white light emitted from the LED lamp appeares different even for that with the chromaticity on the line of the blackbody radiation, as the result shown in Fig. 8(a). The observers indicate a higher preference for the white light emitted from the LED lamp with the sub-Planckian locus than one from the CMH lamp as shown in Fig. 8(b). Light with the chromaticity along the line of the blackbody radiation is considered to be "white" but the study shows that the perceptions of all lights no matter for the LED light or the CMH light do not necessarily appear "white", including the light with the chromaticity exactly on the blackbody line. In most observers' eye, the LED light with the chromaticity below the blackbody line appeares more like perfect white compared with the CMH light, which may be the reason why the observers prefer the LED light with the sub-Planckian locus. Some observers think that the LED light with the chromaticity on the blackbody (LED1 and LED5) appears yellowish/greenish. Increasing the distance from the Planckian locus will drop the yellowish/greenish rating and increase the reddish/bluish rating (Fig. 9). Observers systematically rank reddish/bluish light as more white and yellowish/greenish light as less white. The result suggests that the visual perception of the white light can be enhanced by increasing the distance from the Planckian locus. Other researchers found that the white light with a slight blue saturation was perceived as whiter than the reference white, while the light with a yellow saturation appears less white [24].

Unlike color matching, the appearance of the light depends not simply on the physical property of the light but also upon the visual infrastructure of the observers as well. Colorimetry is based solely upon the spectral characteristics of the light source. But apparent color is not. The color apperance of a light or of an illuminated object is not determined directly by the neural signals from the three cone types (long, middle, and short wavelength sensitive cones); rather, our perception of color represent processed information from the neurons that receive input from those cone types [22]. Results presented here support the hypothesis that the white light perception can be enhanced by shifting the chromaticity below the blackbody line and observers prefer slightly reddish/bluish white light. This will be further explained in section 3.3.

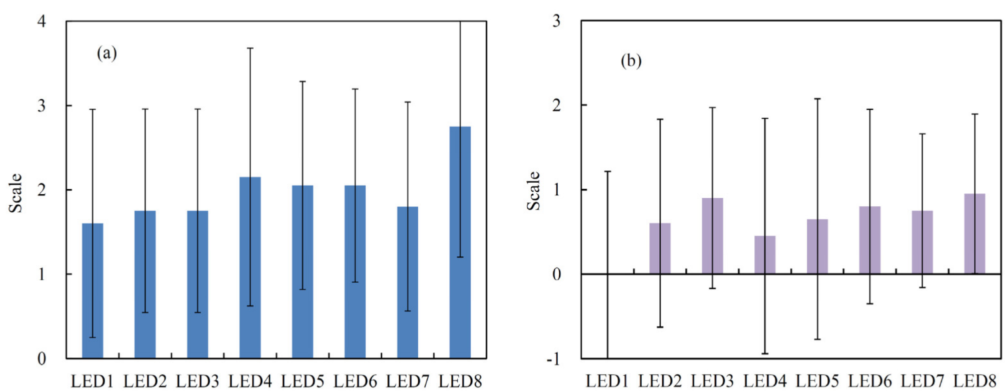

Fig. 8. (a) Mean ratings of white light difference for the eight different LED lights. (b) Mean ratings of white light preference for the eight different LED lights. Error bars represent ± one standard error of the mean (n = 20).

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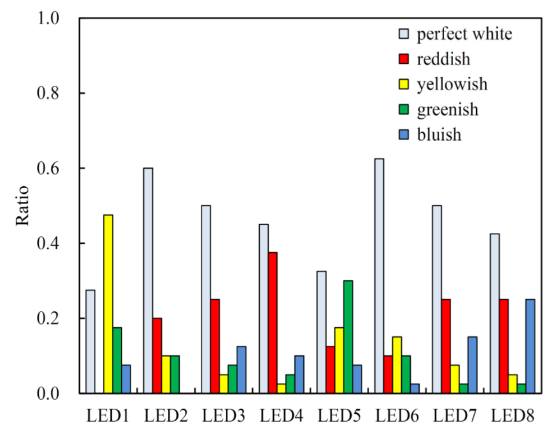

Fig. 9. Mean ratings of white light impression for the eight different LED lights.

3.3 Observer metamerism

When the light has same color coordinate on the blackbody line, in principle, the light should appear same white, but in fact in real observers' eye, the light color looks different as the results obtained in this study. For the LED light with the color coordinate exactly on the line of the blackbody radiation (LED1 and LED5), most observers perceive the white light as greenish/yellowish. The reason is that the color coordinate is calculated according to the color matching functions (CMFs) of the CIE 1931 standard observers, while the CMFs of real observers are different with that of the CIE standard observers [25,26]. So the real observers perceive light differently with that obtained by the theoretical calculation. This phenomenon is referred as observer metamerism. Also, the lens pigment density, the cone density and the cone sensitivity are different for different people, so even same light might look differently for individual people [27].

A mean standard observer was defined by the CIE 1931, which was currently the standard for most color metrics. The data of the CIE 1931 observers was based on a relatively small statistical database, and also only broadband light sources were used to characterize color matching functions. So for the narrowband light source, e.g. the RGB LED, the color deviation is significant between what is predicted by the CIE 1931 observers and what real observers actually perceive in the experiments [28]. To explain and reduce the light color deviation problem, the color coordinate is recalculated by the modified CMFs for the same SPDs. Three typical light sources, respectively the CMH, the phosphor converted warm white LED and the pure RGB LED are chosen for comparison. They have same color coordinate of $x = 0.4369$ and $y = 0.4041$ exactly on the line of the blackbody radiation in the CIE 1931 2° color space. The recalculated color coordinates in the CIE 2006 10^0 color space [29] and in the Stile & Burch color space with 53 different observers [30–32] are shown in Figs. 10(a) and 10(b). It can be seen that the color coordinate of the RGB LED obtained by the modified CMFs shifts above the blackbody line and moves towards the green/yellow direction, while the color coordinates of the phosphor converted LED and the CMH shift below the blackbody line and move towards the red direction. The result in the modified color space maybe can explain the observed phenomenon that the white light emitted from the RGB LED lamp is perceived greenish/yellowish, while the white lights emitted from the phosphor converted LED lamp and the CMH lamp are perceived reddish. Also the color coordinates are significantly scattered in the Stile & Burch color space, which is caused by different color matching functions of different observers. Therefore, even if the light sources have same chromaticity in the CIE 1931 color space, the light will appear different for individual observer.

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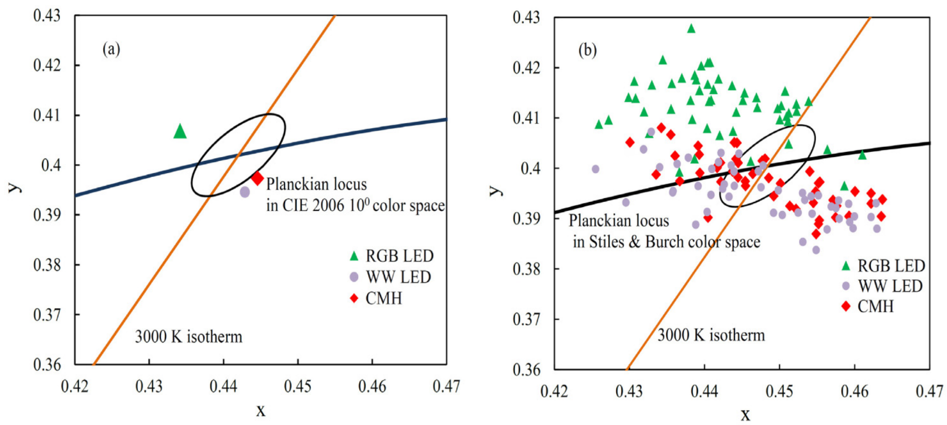

Fig. 10. (a) Recalculated color coordinates of the pure RGB LED, the phosphor converted warm white LED and the CMH light in the CIE 2006 10^0 color space. (b) Recalculated color coordinates of the pure RGB LED, the phosphor converted warm white LED and the CMH light in the Stiles & Burch color space. The ellipse is 3 MacAdam ellipse.

In order to better understand the influence of the LED light with addition of the RGB components on the white light visual perception, the color coordinate for different RGB ratios is recalculated by the modified CMFs. The LED lights mixed with different RGB ratios are set to have same color coordinate of x = 0.4369 and y = 0.4041 on the blackbody line in the CIE 1931 2° color space. The recalculated color coordinates by the modified CMFs in the CIE 2006 10^0 color space [29] and in the Stile & Burch color space with mean observers [30] are shown in Figs. 11(a) and 11(b). It can be seen that the color coordinates do not lie on the blackbody line again in the modified color space with the change of the RGB ratio. The color coordinate moves linearly from the red position to the green direction with increasing the RGB ratio, which is consistent with most observers' observation for the real light color. When the RGB ratio in the LED light is increased, the light appears gradually from reddish to greenish. So the amount of RGB components mixed with the phosphor converted LED is important in order not to influence the light color.

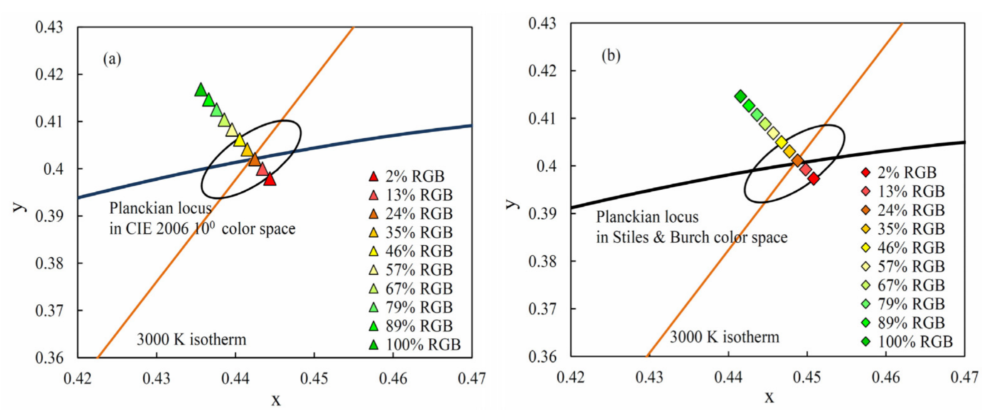

Fig. 11. (a) Recalculated color coordinates of the LED lights mixed with different RGB ratios in the CIE 2006 10^0 color space. (b) Recalculated color coordinates of the LED lights mixed with different RGB ratios in the Stiles & Burch color space. The ellipse is 3 MacAdam ellipse.

4. Conclusions

The LED light with high quality is obtained to improve the color appearance of the illuminated objects and increase the white light perception. The spectral power distributions of the LED light were optimized by addition of the RGB components and by optimizing the distance from the Planckian locus to get both high CRI and high GAI. The influences of the LED light on the color appearance of the clothes and the white light perception of the ambience were investigated by a human factor study. The effects of observer metamerism were studied to clarify the improved white light perception. Following results are obtained from the experiments and the theory analysis.

(1) The LED light by mixing with a suitable amount of the narrowband RGB components and by shifting color coordinate below the blackbody line can increase the GAI while without sacrificing the CRI. The LED light with high GAI can enhance the color appearance of the illuminated textiles significantly, make the clothes appear more vivid and saturated. The observers indicate a higher preference for the colors whose saturations are enhanced and generally the observers' preference corresponds with their judgments for the color vividness. The enhancement of the color saturation is attributed to the increase of gamut area of the light source, which is accompanied by an increase in the color chroma.

(2) The white light emitted from the LED lamp appears different with that from the CMH lamp although they have same CCT. Observers prefer light from the LED lamp with the sub-Planckian locus, which appears more like perfect white. The LED light with the color coordinate on the blackbody line looks yellowish/greenish. Increasing the distance from the Planckian locus will drop the yellowish/greenish rating and increase the reddish/bluish rating. Observers rank reddish/bluish light as more white. The white light perception can be enhanced by increasing the distance from the Planckian locus while keeping the same CCT as other light sources.

(3) The color matching functions of real observers are different with that of the CIE standard observers, which result in the observed phenomenon that the light appears different even for that with the same color coordinate, referred as observer metamerism. The recalculated color coordinates by the modified CMFs move linearly from the red position to the green direction with increasing the RGB ratio, which is consistent with most observers' observation for the real light color.

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