감성과학, Vol.15, No.3, pp.381-388, September 2012

Study on full color RGB LED source lighting for general lighting and Improvement of CRI (Color Rendering Index)

YungKyung Park*†
***Department of Color Design, Ewha Womans University**

Abstract

The purpose of this study is to check if LED lighting can be used as general lighting and examine the color rendering property of full color RGB LED lighting. CRI is one of the important properties of evaluating lighting. However the present CRI does not fully evaluate LED lightings. Firstly, the performance of a simple task was compared other than comparing CRI values for different lighting. For experimental preparation three types of lightings were used; standard D65 fluorescent tube, general household fluorescent tube, and RGB LED lighting. All three lightings show high error for Purple-Red. All three lightings show similar error for all hues and prove that color discrimination is not affected by the lighting. This proves that LED could be used as general lighting. Secondly, problems of the conventional CIE CRI method are considered and new models are suggested for the new lighting source. Each of the models was evaluated with visual experiment results obtained by the white light matching experiment. The suggested model is based on the CIE CRI method but replaces the color space model by CIELAB, color difference model by CIEDE2000, and chromatic adaptation model by CAT02.

Key words: LED, Color rendering index, Lighting, CIEDE2000, CAT02

1. Introduction

Lighting has developed in various types by aid of material and chemistry over these few years. Especially LED(Light-Emitting-Diode) has been replacing not only the special spot lights but also general home lighting. Although the CCT(correlated color temperature) is similarly matched to the contemporary lighting sources such as fluorescent lighting the spectrum differs and that can effect hue discrimination. We are often misled to consider RGB LED lighting to be insufficient for white general lighting due to the narrow peaks of the spectrum. Color rendering is an important criterion for quality of light source and is defined by CIE(Commission Internationale de l'Éclairage) as the "*effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant*"(CIE,1987). White RGB LED light sources have spectral power distributions with three significant peaks corresponding to their R, G and B components. Therefore, they can cause large color differences compared to the reference illuminant which has broad spectral power distribution curves. The problem is that the CRI does not fully match for LED lightings. Therefore other than comparing CRI values for each lighting, the performance of a simple task was compared.

The next step is to characterize the color rendering properties of light sources, which the CIE decided to regard the 'test-color method'(CIE, 1995), and this assesses the magnitude of the color shift of a number of

† Corresponding Author : YungKyung Park (Color Design, Ewha Womans University)
E-mail : yungkyung.park@ewha.ac.kr
TEL : 02-3277-2512

test objects illuminated first under a test source and then under a reference illuminant as the fundamental method for color rendering appraisal. A color rendering index(CRI), which is based on this principle, was recommended by CIE in 1974 as the standard method to evaluate the color rendering properties of light sources. Thus since 1974, the CIE color rendering index has been used ever since. However, a large number of papers have been published to criticize it for its outdated colorimetric techniques and its breaking down when compared with visual observations(CIE, 2002, Sándor et.al., 2003).

Moreover, the CIE test-color method has been found extremely problematic when LED-based light sources have been evaluated together with other traditional light sources. White RGB LED light sources have spectral power distributions with three significant peaks corresponding to their R, G, and B components. Therefore, they can cause large color differences compared to the reference illuminant which has broad spectral power distribution curves.

In this paper, the general lightings were compared by a simple task and the weaknesses of the CIE test-color method, such as the chromatic adaptation, uniform color space and the test color samples, are discussed respectively.

2. Hue discrimination under various lighting

2.1. Experimental

For experimental preparation three types of lightings were used; standard D65 fluorescent tube, general household fluorescent tube, and RGB LED lighting. The LED lighting consists of Red, Green, and Blue LEDs that can operate independently and the RGB levels are controlled to match CCT of 6500K. The 'Hue 100 Test' was used as the tool and participants were highly trained 20 females in their 20-30s'. They were asked to complete the task within four minutes under three lightings having 550lx. Fig. 1 shows the color discrimination experiment.

Figure 1. Color discrimination experiment

2.2. Results

Each participant's error data was recorded for 100 hues. The error data is a score of the incorrect order lining of the continuous hue. This shows discrimination level of the hue. The average of the error data is plotted against each hue. The error data shows the discrimination level of each hue.

The D65 lighting used in the experiment has a relevantly broad spectrum while LED and fluorescent has narrow bands at R, G, and B wavelengths. However, in spite of the thought that broadband would be more precise for color discrimination, all three lighting shows similar error for the hue test.

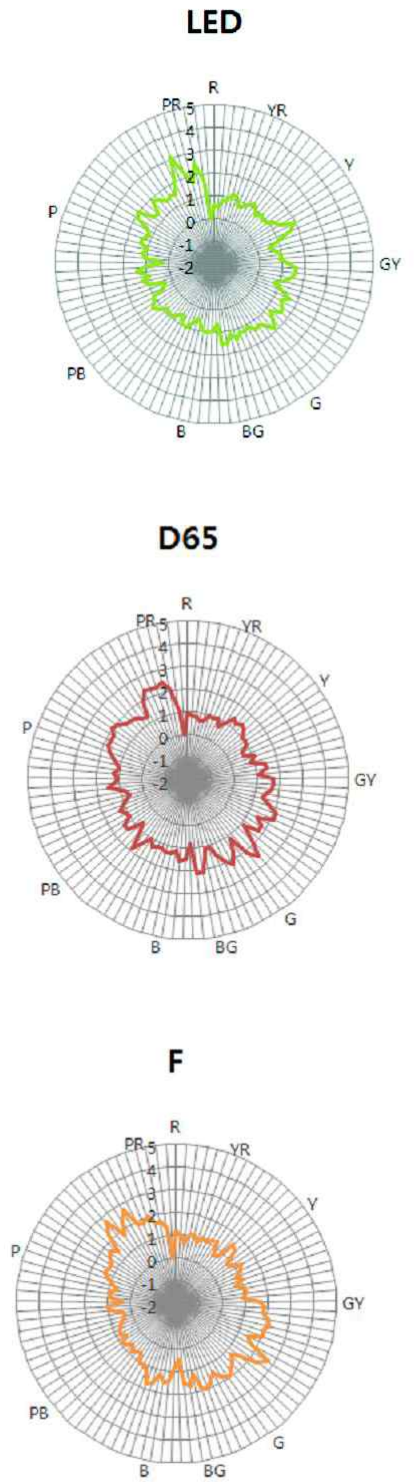


Figure 2. Color error results under LED, D65, F lighting

All three lightings show high error for Purple-Red. There are slightly higher errors under fluorescent lighting in Green-Yellow. All three lightings show similar error for all hues and prove that color discrimination is not affected by the lighting. This proves that LED consisted with R, G, B LEDs could be used as general lighting that has equal CRI(color rendering index) to general lighting and standard D65 lighting.

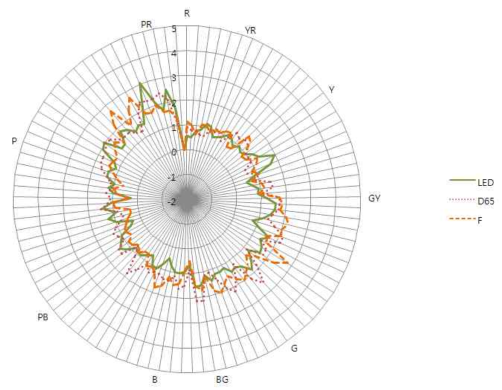


Figure 3. Color error results under LED, D65, F lighting plotted in a single diagram

Fig.3 shows Fig. 2 in one diagram. LED is marked as a single line, D65 in small dotted lines and F in large dotted lines. The error is shown as the largest in the P-PR region for all three lightings. Under F lighting GY-G shows large error while LED shows least error.

Table 1. Color error results for hues under LED, D65, F lighting

	LED	D65	F
R	0.54	0.77	1.23
YR	1.00	0.92	0.92
Y	0.85	0.92	0.77
GY	1.08	1.69	1.77
G	1.38	1.23	2.15
BG	1.38	2.23	1.85
B	0.77	1.23	1.62
PB	1.23	1.38	0.85
P	1.23	1.77	0.85
PR	2.23	2.15	1.38

Table 1 shows the error results for principle hues under LED, D65 and F lighting. The higher values show larger error for each hue. The important finding is that LED shows the least error in the B region. Blue region has the weakest power among most of the general lightings. This shows that LED lighting can improve the blue region spectrum which is the weak point in general lighting. The other finding is that PR region has the largest error for D65 and LED lightings. However the G region has the largest error under F lighting. The least error has PB and P under F where LED and D65 lighting has large error.

3. CRI(Color Rendering Index)

The previous experiment has showed that LED lighting is efficient enough to be used as general lighting. This next experiment is to examine and modify CRI for LED lighting.

3.1. Problems

The problems of CIE CRI have been pointed out during the past in several previous studies. A large number of papers have been published to criticize the CIE test-color method. Also pointed out where the method breaks down, and how some new colorimetry procedure, such as more advanced chromatic adaptation transform, color difference formulae, and color appearance model, should be applied to improve the color rendering index(Sándor et.al., 2003).

3.2. Modification Suggestions

A new method named Color Quality Score(CQS) (Gardner and Ohno, 2005) was proposed by the National Institute of Standards and Technology(NIST) to modify the CIE color rendering index. The eight mid saturated samples of the CIE CRI was replaced by fairly high chromatic samples. The chromatic adaptation model was changed to CMCCAT2000(Li, Luo, Rigg, Hunt, 2002) from von Kries transform(von Kries, 1970). The 1964 U*V*W* color space(CIE, 1964) and color difference equation was replaced by CIELAB(CIE, 1986).

In this paper, three different models based on the CRI are suggested and listed in Table 2. Model 1 is the conventional CIE test method and models 2 and 3 are the suggested modified models. Models 2 and 3 changed the color space model from CIEU*V*W* to CIELAB model. The color adaptation model is replaced by CAT02(Moroney, Fairchild, Li, Luo, Hunt. Newman, 2002) for both model 2 and 3. The reference illuminant is D65 and therefore models 2 and 3 are independent of CCT(correlated color temperature). The difference between models 2 and 3 are the color difference equations which are CIEDE for model 2 and CIEDE2000(Luo, 1999) for model 3.

Table 2. Three suggest models for CRI

	model 1	**model 2**	**model 3**
Color Space	CIE U*V*W*	CIELAB	CIELAB
CAT	von Kries	CAT02	CAT02
CCT	CCT Dependent	CCT Independent	CCT Independent
Illuminant	Various reference illuminant	D65	D65
Color difference equation	CIEDE U*V*W*	CIEDE	CIEDE2000

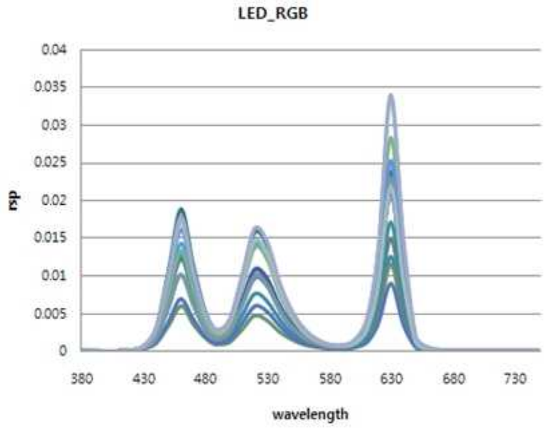
3.3 Matching D65

Visual experiments were carried out using the Macbeth ColorChecker Chart(GMCC) to provide the spectral data for testing the CRI models. Observers sat in front of two viewing booths, one with a D65 simulated illuminant and other with RGB LED clusters(Fig. 4). The aim of this experiment is to check whether the visually observed color differences are correlated with the color differences predicted by the CIE test-color method or other formulae.

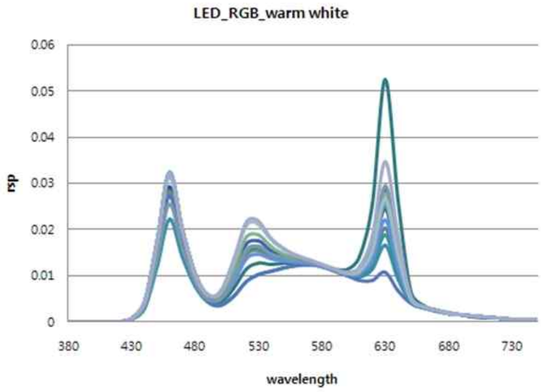
Figure 4. Experiment set up

Fifteen females in their 20s has participated the experiment. The observers were asked to adjust the relative powers of the R, G and B LEDs(digital values 0-255) until a best average match was obtained for all patches to match color chart under D65 light source. RGB values were adjusted separately with and without the warm white turned on. Note that the luminance of the D65 light source was adjusted to maintain the same value as the LED light source.

Fig 5 shows the 15 observers' relative spectral power curve of the RGB LED light source matching the D65 light source. The top (a) shows the RGB LED and bottom (b) shows the RGB LED with the warm white source turned on. The results show that the relative peaks are similar to each other.



(a)



(b)

Figure 5. Spectral power curve of RGB LED (a) (+ warm white (b)) matching the D65 light source

1	2	3	4	5	6
7	8	9	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24

Figure 6. Experiment set up

The second task was to evaluate the color difference of each color patch on the GMCC chart. The observers gave a score of 5 if it is an exact match and 1 if it is totally different from the D65 viewing booth. Fig 6 shows the GMCC chart along with the sample number starting from 1 to 24. Sample 19 to 24 which are achromatic colors were excluded from the color difference.

The average score for all color patches are shown in Fig 7. The dark and mid grey bars represent the color difference under RGB LED and RGB LED with warm white respectively. The color difference is smaller when the warm white is on for all 18 color samples. In other words, CRI should be higher with the warm white on and it is closer to D65 light source. Therefore, the spectrum with the warm white on along with the RGB LED was used to test the CRI models.

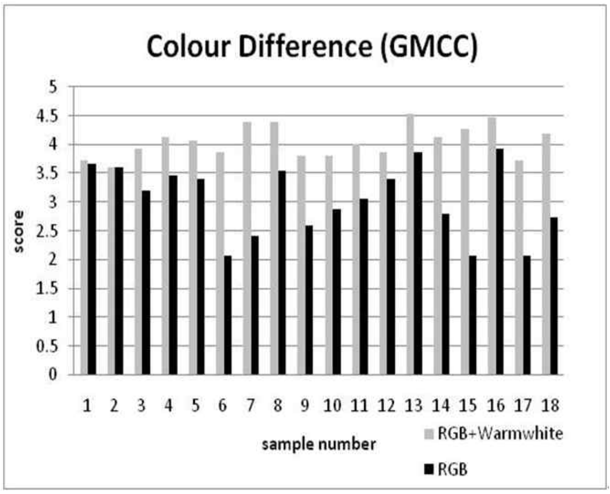


Figure 7. Colour difference scores for GMCC chart (dark: RGB, mid grey: RGB with warm white)

3.4. Results

3.4.1. Testing different Models

All three models were tested using the spectral power curve of all 15 observers. The spectral power curves were obtained carefully by all 15 observers which should give high quality of lighting. The CRI score for all three models of 13 observers(two observers were excluded of poor repeatability) are shown in Fig 8. Note that only the CIE 1964 test samples were used.

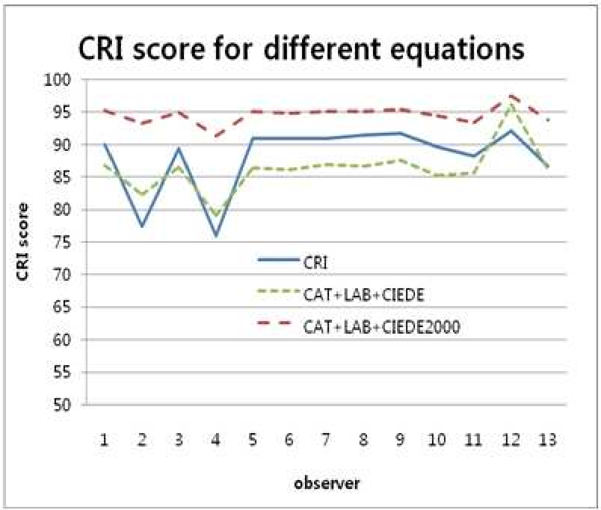


Figure 8. CRI score for different models

The full line represents the CRI score for the CIE color-test method(model 1). The small and large dashed line represents model 2 and model 3 respectively. We know that all 13 observer results showed show high and similar CRI scores to each other. Thus, model 3 shows the best performance among all three models.

3.4.2. Testing Different Models with Different Test Samples

The different models were tested using different test samples. The conventional test samples are the 8 color samples of CIE 1964 test samples. The CQS test samples are the 15 high chromatic suggested by NIST for LED light sources. The test samples are plotted on CIELAB a*-b* plane in Fig 9. Squares and diamond represent CQS and CIE 1964 test samples respectively. All two samples circle the hue evenly. As the distance from the origin indicates the chromaticity of the samples, CQS test samples show higher and even chromaticity than the CIE 1964 test samples.

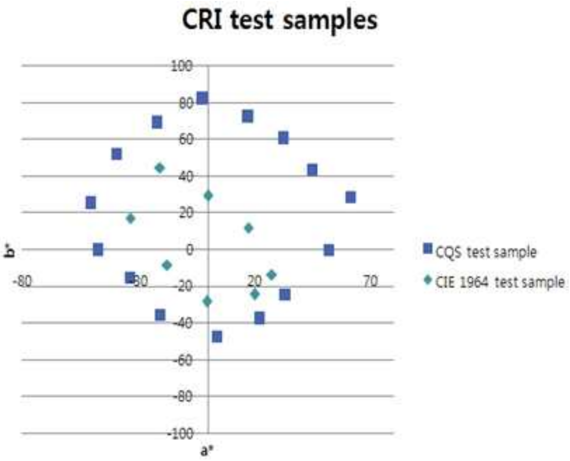


Figure 9. Test sample plotted on CIELAB a*-b* plane(square: CQS test sample, diamond: CIE 1964 test sample)

Both test sample set were used to test all three models. The results are shown in Fig 10 and Table 3.

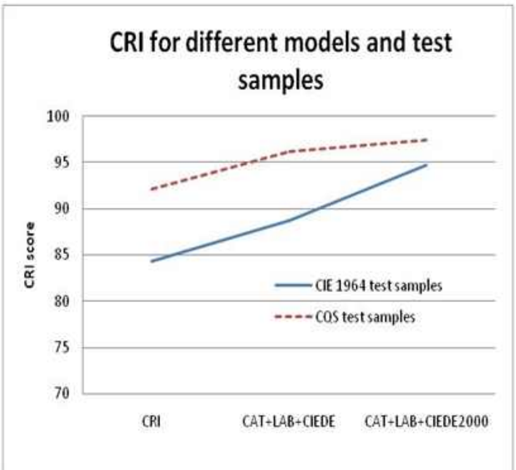


Figure 10. CRI for different models and test samples.

The CRI scores predicted by 3 different models are plotted in Fig 10. The full line is results using the CIE 1964 test samples and dotted line is CQS test samples. Model 3 shows similar CRI scores for all two different kinds of test sample sets.

Table 3. CRI score for different models and test samples.

Model Test Samples	CRI(1)	CAT+LAB +CIEDE(2)	CAT+LAB +CIEDE2000(3)
CIE 1964	84.3	88.7	94.7
CQS	92.1	96.2	97.4

4. Conclusions

The finding of this paper is that LED consisted with R, G, B LEDs could be used as general lighting in spite of the narrow peaks of the spectrum. Another important finding is that LED shows the least error in the B region that has the weakest power among most of the general lightings. This shows that LED lighting can improve the blue region spectrum for lighting.

The conventional color rendering index, CIE test color method, for full color RGB LED was revised along with two modified versions. Model 3(CAT02, CIELAB, CIEDE2000) shows stable CRI scores using visual data obtained by the white matching experiment. Additionally, it scores similarly using different test color sample sets. Therefore, model 3 is suggested as the appropriate color rendering index for RGB LED lighting.

This work was supported by the IT R&D program of KEIT, [10040037, An intelligent IT lighting system development using interactive information exchange in complex space]

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Received : 2012.08.02
Revised : 2012.08.28
Accepted : 2012.09.14