# Selecting Among Combinations of RGB LED Wavelength by Pair Comparison

***Chia-Ping Chang, Li-Ming Huang and Po-Tsun Lin; Technology Research & Development Center Chi-Mei Optoelectronics.; Tainan County, Taiwan.***

## Abstract

*In this article, we compared the optical characterization of 8 LED modules with cold-cathode florescent lamps (CCFL) backlight module. It is well known that LED display became the main product in the field of panel display rapidly with its characteristics of green power, high color saturation, reliability, long life, and low cost, etc. But users strongly feel certain LED display is unnatural when specific RGB wavelength combination is chosen. So we performed the psychophysics experiment and find out the RGB combination as (636/535/455nm or 630/535/455nm) can have both high efficiency and good color image quality.*

## Introduction

In TFT-LCD industry, LED is getting more popular due to its low power consumption with dynamic control, mercury-free materials, and high color saturation. In addition, user nowadays desires for stylish and artistic design, LED can help LCD module become thinner and lighter. Due to the above reasons, LED should be a good light source replacement for CCFL.

So the LED industry is working hard for creating light sources with high luminous efficacy (lm/W), high color rendering index and high saturation performance. The reason makes LED technology widely accepted. But light source for illumination is a lot more different than light source for LCD application. When trying CRI values to explain image quality, we cannot know how to evaluate LED-powered LCD display reasonably.

In general, the efficiency and performance of display using RGB LED are determined by the dominant wavelength of RGB LED. From the manufacturer's viewpoint, they think that wider color gamut, brighter luminance, and higher LED efficiency are the top considerations to optimize the product specifications. Actually, the selection could lead to one RGB combination and doesn't result in good color image quality, even worse than CCFL. For example, end-users complain that the color of panel with LED backlight is unnatural when comparing to the one with CCFL backlight, especially the color of white and preference colors. However, it is found that some RGB LED combinations have better color performance than some others. This motivates us to start out an experiment to look for a better combination of RGB LED, which should have evidence to support.

## Characterization of LED

Nowadays, LED manufacturer could only fabricate LED with some specific material and result in some limited-range wavelength. If outside the wavelength range, LED luminous efficacy becomes bad and appear too dark in brightness, even fail to manufacture. And there are some patent issue for specific material, some wavelength of LED are hardly obtained. The following table shows the limited-wavelength of LED.

**Table 1.** The limited wavelength of RGB LED

| Color | Wavelength (nm) | Semi-conductor Material |
|---|---|---|
| R | $610 < \lambda < 760$ | GaAs… |
| G | $500 < \lambda < 570$ | GaN… |
| B | $450 < \lambda < 500$ | InGaN… |

Beside the LED spectrum would change with heat. The heat comes from optical energy loss and depends on LED packing, LED material, operation current, LCD backlight design, operation time…etc. So we made the LED module for experiment operated at 35℃ and wait 20 min after turning on for Thermodynamic equilibrium. The procedure would keep LED spectrum more stable and less variation when experiment is proceeding.

We select some representative wavelength, which has chance for mass production and manufacture. It includes 3-pairs of Red, Green, and Blue LED (Red: 636nm, 630nm; Green: 535nm, 525nm; Blue: 455nm, 465nm) and arranged eight sets of RGB LED backlight in combination. The selection of different wavelength would affect the resulting brightness and color gamut but also the other color performances. For example, CCFL still has better efficiency, cost superiority than LED right now and we would choose NO4 since it has best efficiency to maximize the luminance specification in fewer LED quantity. But the image quality has been complained by end-user. They thought the color is so strange. Because of this, we design two psychophysics experiments to effectively select a combination of RGB LED with better image quality. The dominant wavelength details and color gamut of different RGB LED NO. are listed in Table 2.

**Table 2.** Different RGB LED wavelength

| | R (nm) | G (nm) | B (nm) | Color gamut |
|---|---|---|---|---|
| NO1 | 636 | 535 | 455 | 91 |
| NO2 | 636 | 525 | 465 | 88 |
| NO3 | 636 | 535 | 465 | 84 |
| NO4 | 636 | 525 | 455 | 97 |
| NO5 | 630 | 535 | 465 | 82 |
| NO6 | 630 | 525 | 455 | 95 |
| NO7 | 630 | 535 | 455 | 89 |
| NO8 | 630 | 525 | 455 | 85 |
| CCFL | | | | 69 |

The RGB primary of eight LED modules are illustrated on CIE1976 u'v' diagram. There are three clusters represented primary, which are measured by spectrometer, MINOLTA CS-1000A. The device would measure visual spectrum and calculate luminance value and chromaticity coordinates based on the color matching function of CIE *1931 2° Standard Observer*. In general, LED spectrum is coupled with color filter, liquid crystal, polarizer, backlight film and that causes primary chromatic spread.

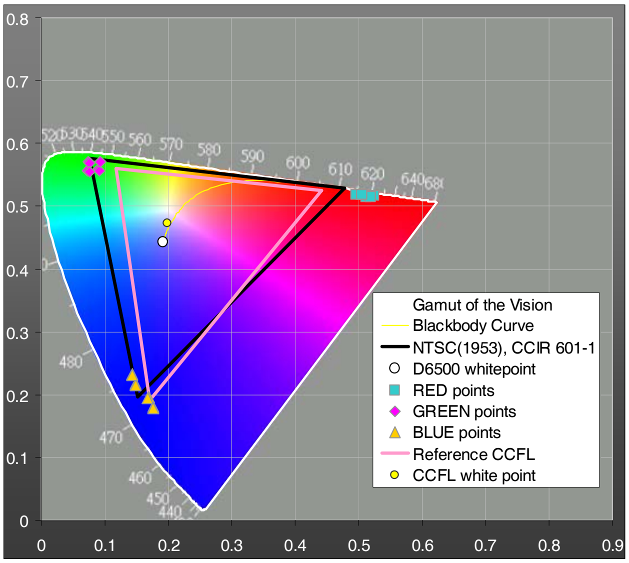


***Figure 1.*** *The measured chromaticity coordinates of Red, Green, and Blue primary of eight RGB LED combinations.*

The backlight spectrums of NO.1 LED modules and CCFL module are shown in Figure 2 for comparison. LED spectrum is generally simpler than CCFL so it has larger color gamut and lower luminance. The other LED backlight spectrums are similar to NO.1 but with different dominant wavelengths.

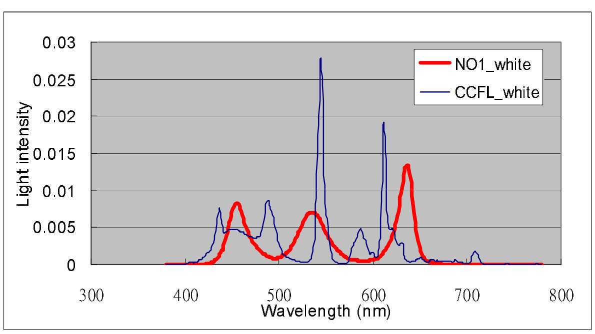


***Figure 2.*** *Backlight spectrum of NO.1 RGB LED and CCFL when white point is adjusted to D65 (x, y) coordinate.*

## Experimental Setup

To search for a wavelength combination of better image quality, we set two targets to look for. Firstly, customers prefer CCFL white than LED white and we plan to find a wavelength combination closest to CCFL white. Secondly, preference colors, such as skin, green grass, and blue sky are the top concerns when monitor makers evaluate LED module. Because the choices of specific wavelength affect the performance of overall color, we use pair comparison method to know which wavelength combination is the better one in the psychophysics experiments.

The subject includes ten people, eight male and two female. Their ages ranged from 25 to 30. They have no color expertise and not well trained. Before experiments, the observers were screened for their visual acuity by the Snellen Vision Screen Chart, and for normal color vision by using Ishihara test. Besides, the environment is in a dark room and there is no illumination in the room. In the two experiments, the same environment is set and all subject participate in both experiments twice.

LED backlight is sensitive to temperature vibration, and it is necessary for the stability of brightness. Hence, each module was power up for at least 20 minutes before the experiments. For necessary, RGB LED power can be respectively modified via RGB Pulse Width Modulation (PWM) control to change color temperature of LED module. We also prepare two set of glass, which is made in the same lot to diminish the variation of process.

In the first experiment, we prepare a module with CCFL backlight and set luminance to 200 nits with the correlated color temperature (C.C.T.) of D65. The luminance and chromaticity of eight LED modules are also aligned to 200 nits and D65 by PWM. Starting from LED NO1. Module, the modules of CCFL and RGB LED are put side-by-side and the observers can view both modules at the specific position. Pattern of full-screen white are displayed on both CCFL and LED modules. Then, observers are asked to adjust the power of each RGB channel of LED module and match CCFL modules white. The same procedure is repeated on other seven LED modules to match the CCFL white. The schematic diagram is as Figure 3.

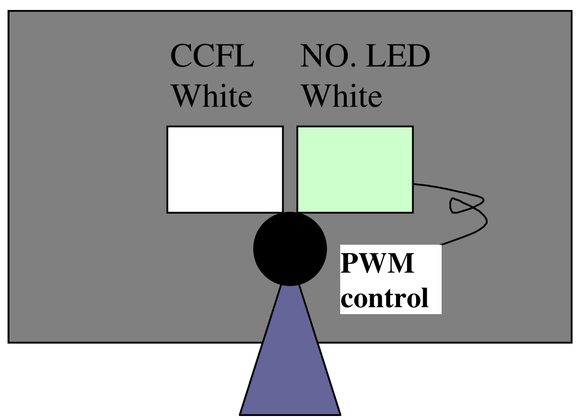


***Figure 3.*** *Schematic diagram of the first experiment set up.*

In the second experiment, the pair-comparison method [1],[2],[3] is utilized to choose the one with higher preference to find out which LED combination showing better white and better memory colors. There are two sub-tests. One is for testing LED "preference white" when there is no CCFL for reference and the other is for testing LED "preference color". The luminance and chromaticity of eight LED modules are still aligned to 200 nits and D65 by PWM and subject don't change RGB PWM in the second experiment. They just see and compare which one is preferred. The schematic diagram is as Figure 4.

In the first sub-test, each subject picked two LED modules at a time and put side-by-side for choosing and repeat many times until they can rank "whiter preference". In the second sub-test, we repeat again the above procedure with six memory color images to generate the rank order of "preference color". Regarding to picture selection, there were six different images chosen for evaluating. The images shown in Figure 5 include three groups: skin, green grass and blue sky.

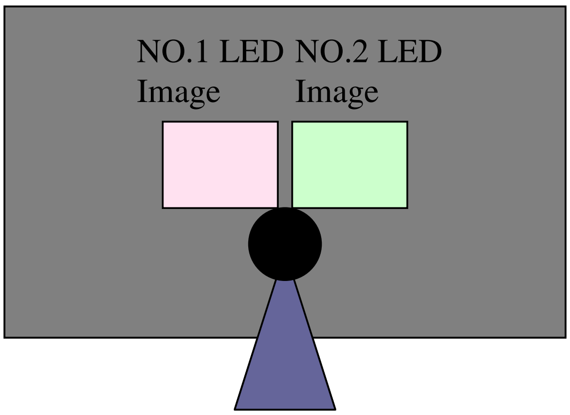


***Figure 4.*** *Schematic diagram of the first experiment set up.*

***Figure 5***. *Test image of preference color (skin, sky, and grass)*

## First Experiment Results

We list the chromaticity result of 8 combinations in Figure 6 and Figure 7. Figure 7 is drawn by (x, y) coordinate system of *CIE1931*. The circle dots with gray color indicate the ideal white point D65 and the triangle dots means the actual CCFL white point. The ten blue dots in each single sub-figure are the chromaticity coordinates measured by spectrometer after ten observers adjusted RGB PWM to match CCFL white. Then we calculate color difference □xy between LED white adjusted by ten observers and CCEL white and show as Figure 6.

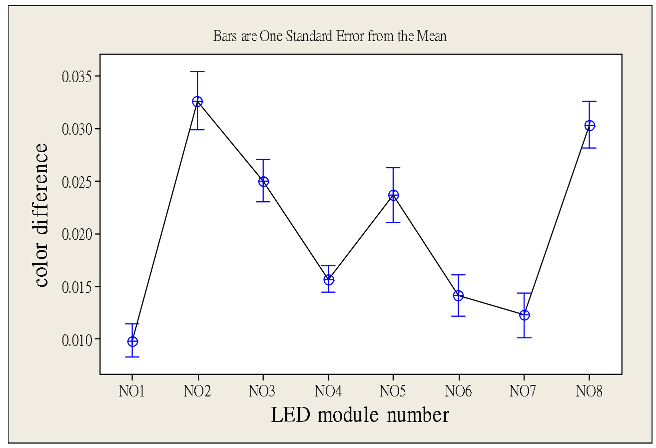


***Figure 6.*** *The color difference between LED white and CCFL white.*

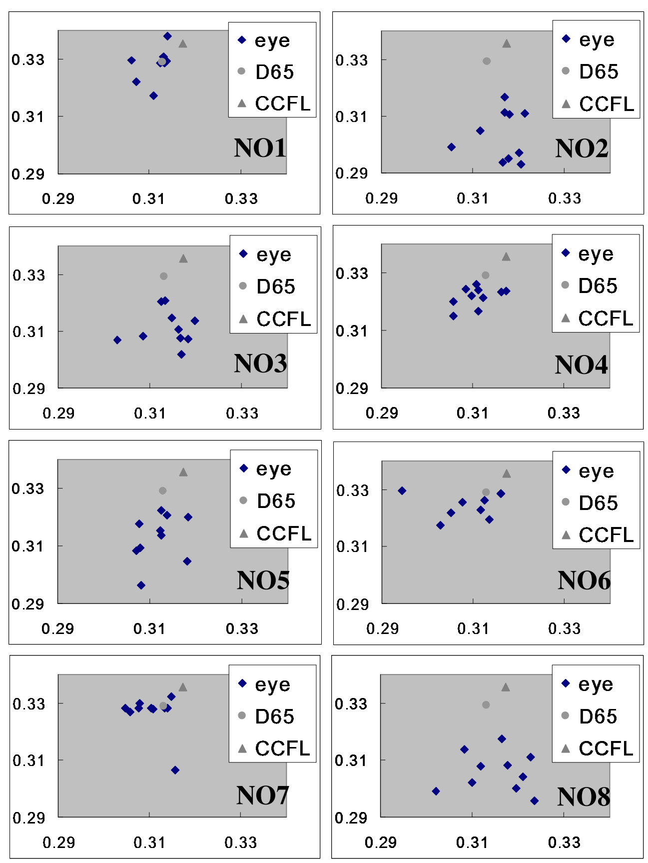


***Figure 7.*** *The measured white chromaticity coordinates.*

From the above chromaticity result, we have some simple conclusions. NO1 (636, 535, 455) has minimum mean and is the closest combination to CCFL white; NO7 (630, 535, 455) is the second closest one. It means that NO1& NO7 are not only closer to CCFL white than others but also more acceptable for most observers. If RGB wavelength selection respectively:

- **R dominant wavelength selection**

When observers choose R wavelength as 636nm or 630nm, perception D65 is similar.

- **G dominant wavelength selection**

IF observers choose G wavelength as 526nm(ex: NO. 2,4,6,8) and try to match CCFL white, the match D65 after measured becomes less greenish. That means most observers feel LED white greenish before PWM adjusting.

- **B dominant wavelength selection**

If observers choose B wavelength as 466nm (ex: NO. 2,3,5,8), and try to match CCFL white, the match D65 after measured also becomes less greenish.

Now we know that Green 526nm and Blue 466nm lead to greenish LED white. The cause may be that Green and Blue LED spectrum is too close to each other. That change G and B primary luminance and chromaticity and change RGB primary mixing ratio to make white.

Figure 8 shows the luminance result of eight LED modules after ten observers adjusting. The range is from 243 to 192 nits and it's hard to explain the relationship between luminance and RGB wavelength. We just can say NO1 have small standard error.

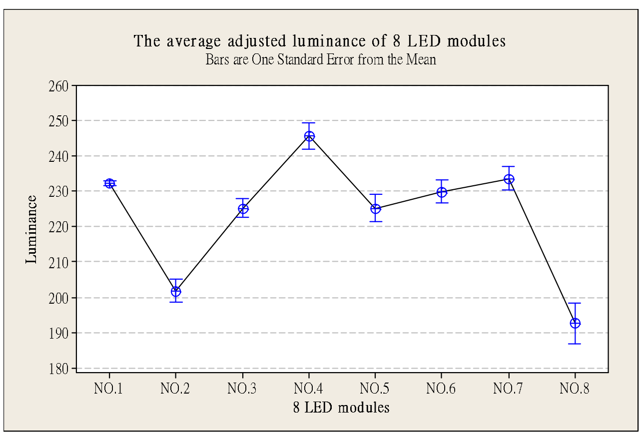


***Figure 8.** The luminance of eight LED modules after adjusting PWM*

## Second Experiment Results

For the first sub-test, the white preference result is shown in figure 9, in which the vertical axis is a psychophysical scale and horizontal axis is LED module number. From the diagram, the NO1, NO4, NO6, NO7 BLU has positive scale and coincidentally all their B wavelength is 455nm. That means B 455nm can be "better white" or "whiter" than B 465nm when we survey LED BLU wavelength. If we choose B 455nm, the observer perception of white is much preferable and closest to the their memory. And the result is also conformed to the first experiment result fortunately.

Regarding the NO2, NO3, NO5, and NO8 BLU has negative scale, observers explain that the perception of LED white is greenish if choosing B as 465nm and they don't prefer that.

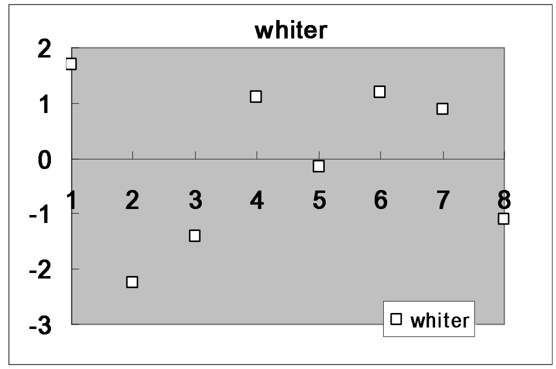


***Figure 9.** The scale of preference white*

The second sub-set experimental result shows in Figure 10. Their rank of scale is:

| | Scale Rank (only positive) |
|---|---|
| Skin | 5>6>8>4 |
| Sky | 1>7>6>4 |
| Grass | 7>1>6>4 |

The rank shows that skin color has different tendency from sky and grass color and the above-mentioned experiment results. So we ask observers about what they have seen in the experiment. The individual conclusion is described as:

- **skin color**

There is no obvious difference in the chart since NO4, NO5, NO6, and NO8 BLU just have slightly positive scale. But we still give a short comment. It could be that observers prefer G as 527nm or B as 466nm because the skin color in these situations is yellowish and more saturated. And our observers just like saturated color more.

- **sky color**

The NO1, NO4, NO6, and NO7 BLU apparently are preferred. The entire B wavelength is 455nm. The observers said that the blue sky is more saturated and real, so they prefer.

- **grass color**

The NO1, NO4, NO6, and NO7 BLU have positive scale. It means observers prefer G as 535nm and B as 455nm. The observers said that the grass color gets yellow-greenish and observers like it.

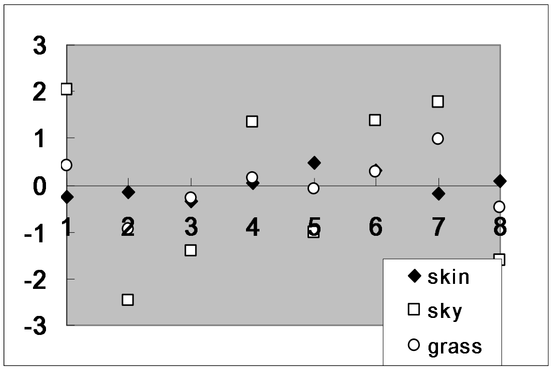


***Figure 10.*** *The scale of preference color*

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## Author Biography

*Chia-Ping Chang received her BS degree in Physics from Tsing-Hua University in 2001. Her major research field focuses on color application in liquid crystal display. She is a Fellow of the IS&T and is currently an engineer in Chi-Mei Optoelectronics Corp.*