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Effects of the Elements of Color on Color Deviation under LED Light

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Abstract. The color deviation occurs when LED lighting on objects of different color. This study mainly investigated the effects of the elements of color (brightness, saturation and hue) on color deviation during LED lighting. Users were invited to distinguish the comparison color samples consisted of three variables (brightness, saturation and hue). Results revealed that the effects of elements of color on color deviation of LED light were significant. Additionally, the color deviation of LED light were different involving different principal hues (cyan, magenta, yellow). For cyan, the effects of brightness on saturation deviation and hue were significant, while on brightness and hue were significant for magenta. The deviation of brightness, saturation and hue under cyan as well as saturation under yellow were significantly affected by saturation. Hue significantly affected the deviation of hue both for cyan and yellow as well as the deviation of saturation for magenta. These results have implications for lighting design in shopping mall and other public space.

Keywords; color deviation; LED; Light; brightness; saturation; hue

1. Introduction

Since LED lights perform well in terms of saving energy, longevity and size, they developed fast and had been applied in various fields. As a kind of common light, the

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color quality is an essential factor impacting LED lighting. The Commission Internationale de L'Eclairage (CIE) established Color Rendering Index which was used to evaluate the quality of light source. Recently along with new types of light source were developed, as well as more deep researches, many problems were exposed. According to the definition from CIE about CRI, a color rendering index (CRI) is a quantitative measure of the ability of a light source to reveal the colors of various objects faithfully in comparison with an ideal or natural light source. Researchers from America, Hungary, France, discovered that, the evaluation based on CRI existed some problems when applied on LED lighting, such as uneven color space, not enough color samples and low saturation. Moreover, if the color of the objects changed, the CRI became low according to the definition of CRI which defined the color of surface as reference. For example, if the saturation increased, the clarity and brightness would increase as well. In this case, to use CRI evaluating the color quality is not appropriate. Based on the above reasons, CIE specified in the technology report in 2007 that: the CRI currently could not comprehensively reflect the color rendering quality of white light including LED light.

To amend CRI's disadvantages, American researchers Wendy Davis and Yoshi Ohno, developed a new evaluation system CQS (Color Quality Scale) which applied 15 color samples of high saturation. The value of CQS can effectively match the visual evaluation when enhance the brightness of light source, as well as the no-enhanced light source. Consequently, CQS could comprehensively stands for the color quality.

The performance of light is also affected by the color temperature of light source. The color temperature of a light source has been shown to affect user perception, cognition, and mood state. The color temperature of a light source is the temperature of an ideal black-body radiator that radiates light of a color comparable to that of the light source when it is heated, which is expressed with the unit of Kelvin (K). The correlated color temperature of LED's affects individuals' psychological states, and physiological needs. However, light sources that are not incandescent radiators have what is referred to as a correlated color temperature, with specific color temperatures depending on the type of application (office or home use) and on regional differences. The higher color temperatures are typically referred to as cooler colors and are used to enhance concentration in offices whereas lower temperatures are typically referred to as warmer colors and are often used in public areas to promote relaxation. Illuminated objects also affect LED lighting performance. In Jalil et al.'s research, multiple colors (blue, gray, beige) were proved to reduce user attention. Similarly, Kuller et al. used an electroencephalogram to test the effects of blue versus red, and observed that relative to red, blue exerted an effect of drowsiness. Study from Chia-Chen Wu et al. revealed a significant effect of the color of the standard stimulus on the accuracy of color judgments, with higher accuracy rates for magenta and yellow than for cyan. Besides, they also found that color judgment accuracy was worse for coated paper than it was for cotton and polyester fiber.

In the field of LED lighting effects on user experience, past research mainly focused on the color rendering evaluation system of light source, as well as the color judgement accuracy under certain conditions, such as color temperature, objects' color and printing material. Nevertheless, the influence of the elements of colors on color deviation of LED lighting has not been studied, which is exactly what this research focuses on.

2. Methods

A. Literature review

The differences between colors are expressed in the differences of three color attributes of brightness, saturation and hue. Brightness indicates the different shades of color; saturation indicates different freshness of color; hue indicates the degree to which a stimulus can be described as similar to or different from stimuli that are described as red, green, blue, and yellow. The evaluation of color difference is very important in industry and commerce, which typically used in the color matching and color quality control of mass production. The CIE Lab color space describes mathematically all perceivable colors in the three dimensions. L for lightness and a and b for the color opponents green–red and blue–yellow. The terminology "Lab" originates from the Hunter 1948 color space, CIE Lab color space defined the first color-difference formula which is expressed as

$$\Delta E=\sqrt{\Delta L^2+\Delta a^2+\Delta b^2}$$

The Natural Color System (NCS) is a proprietary perceptual color model. It is based on the color opponency hypothesis of color vision, first proposed by German physiologist Ewald Hering. The NCS states that there are six elementary color percepts of human vision — which might coincide with the psychological primaries — as proposed by the hypothesis of color opponency: white, black, red, yellow, green, and blue. Colors in the NCS are defined by three values, expressed in percentages, specifying the degree of blackness which is relative visual similarity to the black elementary color; chromaticness which is relative visual similarity to the "strongest", most saturated color; and hue which is relative similarity to the chromatic elementary colors red, yellow, green and blue. No hue is considered to have visual similarity to both hues of an opponent pair; i.e. there is no "redgreen" or "yellowblue". The blackness and the saturation together add up to less than or equal to 100%. For example, NCS 0580-Y10R means a color with 5% blackness, 80% chromaticness, and 90% yellow along with 10% red.

Practical Color Co-ordinate System (PCCS) was developed by Japan Color Research Institute, which defined color with two factors: hue and tone. In the PCCS, brightness and saturation are combined into one concept tone, and this concept is close to the daily expression of color, such as bright red and dark blue, of which bright and dark stand for tone, and red and blue stand for hue. PCCS defines 12 tones to specify different colors based on 24 hues. The method of defining tone into 12 scales is significant feature.

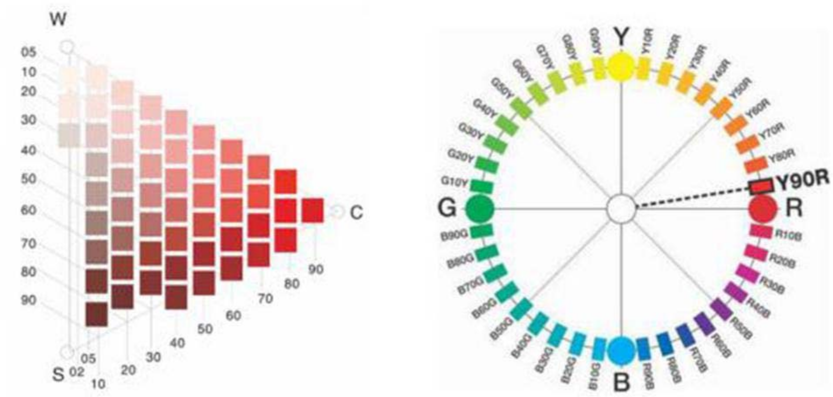

Fig 1. Natural Color System (NCS)

B. Color deviation

According to the printing color system, cyan, magenta and yellow were selected as the principal hues, and black was eliminated considering it was neutral color. There were three factors affecting color which were the variable factors in this study: brightness, saturation and hue. To simplify experiment samples, those three factors were set in two levels. Based on the quantitative NCS system, the three basic color samples C（NCS S1565-B）, M（NCS S1070-R10B）and Y（NCS S0575-G90Y）were deviated in two levels (from ±5% to ±20%) in terms of three factors. Specifically, each hue value of the basic color was deviated into right level with -10% scale and left level with +10%. Take S2070-R20B as an example, S2070-R30B was the left level in terms of hue, and S2070-R10B was the right level. For blackness (the antonym of brightness) and saturation, levels were defined into low level and high level. By applying the deviation method for the principal hues C, M, and Y, 12 pairs of color were obtained for each principal hue in terms of brightness deviation and another 12 pairs in terms of saturation deviation.

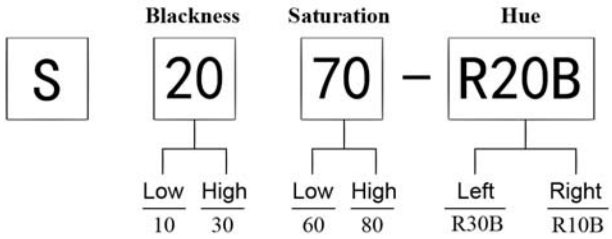

Fig 2. NCS Color Deviation Method

To simplify the samples and verify all the samples were deviated in a reasonable scale, PCCS 12-level tone scale was selected as a reference. 30 pairs of color in brightness and 30 pairs of color in saturation in PCCS were selected and analyzed, for example, PCCS-b (L73,a-36,b31) and PCCS-s（L59,a-52,b32）were a pair of color in brightness, and PCCS-v（L61,a54,b62）and PCCS-dp（L52,a54,b44）were a pair of color in saturation. According to the calculating formula of color difference

$$\Delta E=\sqrt{\Delta L^2+\Delta a^2+\Delta b^2}$$

30 results of color difference in brightness and 30 results of color difference in saturation were obtained. Subsequently, average value in brightness was calculated which was 17.7814, and standard deviation is 7.16956 meaning the difference range in brightness was from 10.61184 to 24.95096. For the color difference in saturation, the average value was 32.2366, and standard deviation was 11.6604 meaning difference ranged from 20.5762 to 43.897. All the samples obtained before were verified if they were in the reasonable range defined by PCCS, and 8 pairs of color were selected for each principal hue as the reasonable samples in total.

The experimental environment was defined by the two factors illumination and color temperature. 2700k and 4000k were the two typical color temperature values used in shops and malls. According to the study of Chia-Chen Wu et al.**오류! 책갈피가 정의되어 있지 않습니다.**, 750lux and 1500lux were selected as the illumination conditions.

There were 6 variables in this experiment for each principal hue (C, M, Y): brightness, saturation, hue, color temperature, illumination and printing material. The experimental samples were optimized with fractional factorial experimental design (2^{k-p}, k=6, p=2), and 16 samples were defined for each principal hue as they were listed on the figure, and 48 samples in total.

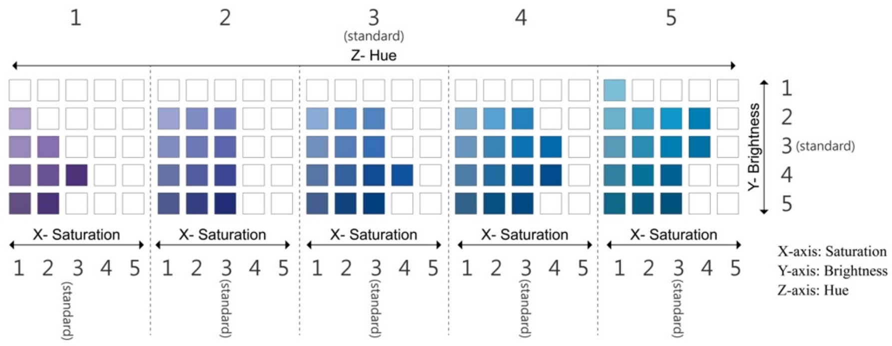

Fig 3. Likert scale of comparison color matrix

3. Results

A. Brightness

For principal cyan, the effect of brightness on the deviation of saturation was significant (F=14.021, P=0.006), as well as on the deviation of hue (F=23.532, P=0.001). The average deviation of saturation was 2.430 when brightness was at low level, comparing 2.094 when brightness was at high level. The average of deviation of hue was 3.184 when brightness was low comparing 3.633 when brightness was high. These results suggest that when brightness rises, the deviation of saturation increases and saturation becomes lower, and the deviation of hue increases and the hue deviates to right according to the hue circle of NCS.

For principal magenta, the effect of brightness on the deviation of brightness was significant (F=8.714, P=0.018), as well as on the deviation of hue (F=8.591, P=0.019). The average deviation of brightness was 2.473 when brightness was at low level, comparing 2.820 when brightness was at high level. The average of deviation of hue was 2.027 when brightness was low comparing 1.680 when brightness was high. These results suggest that when brightness goes down, the deviation of brightness increases and saturation becomes lower, meanwhile the deviation of hue increases and it deviates to left according to the hue circle of NCS.

TABLE I. THE EFFECTS OF BRIGHTNESS ON THE ELEMENTS OF COLOR

Principal hue	Deviation variable	Brightness	Average	σ	Amount
Cyan	Saturation	1	2.430	.568	4
		2	2.094	.316	4
		Total	2.262	.477	8
	Hue	1	3.184	.465	4
		2	3.633	.516	4
		Total	3.408	.528	8
Magenta	Brightness	1	2.473	.306	4
		2	2.820	.368	4
		Total	2.646	.373	8
	Hue	1	2.027	.358	4
		2	1.680	.164	4
		Total	1.854	.323	8

B. Saturation

For principal cyan, the effect of saturation on the deviation of brightness was significant (F=14.922, P=0.005), as well as on the deviation of saturation (F=32.038, P=0.000) and on the deviation of hue (F=10.009, P= 0.013). The average deviation of brightness was 3.000 when saturation was at low level, comparing 3.465 when saturation was at high level. The average of deviation of saturation was 2.516 when saturation was low comparing 2.008 when saturation was high. The average of deviation of hue was 3.262 when saturation was low comparing 3.555 when saturation was high. These results suggest that when saturation rises, the deviation of brightness increases and brightness becomes higher, and the deviation of saturation increases and saturation becomes lower, as well as the deviation of hue increases and the hue deviates to right according to the hue circle of NCS.

For principal yellow, the effect of saturation on the deviation of saturation was significant (F=5.633, P=0.045). The average deviation of saturation was 3.984 when saturation was at low level, which was 3.477 when saturation was at high level. These results suggest that when saturation rises, the deviation of saturation increases and saturation becomes higher.

TABLE II. THE EFFECTS OF SATURATION ON THE ELEMENTS OF COLOR

Principal hue	Deviation variable	Saturation	Average	σ	Amount
Cyan	Brightness	1	3.000	.568	4
		2	3.465	.316	4
		Total	3.232	.477	8
	Saturation	1	2.516	.465	4
		2	2.008	.516	4
		Total	2.262	.528	8
	Hue	1	3.262	.510	4
		2	3.555	.537	4
		Total	3.408	.528	8
Yellow	Saturation	1	3.984	.444	4
		2	3.477	.720	4
		Total	3.730	.634	8

C. Hue

For principal cyan, the effect of hue on the deviation of hue was significant (F=72.041, P=0.000). The average deviation of hue was 3.816 when hue was at right level, compared with 3.000 when saturation was at high level. These results suggest that when hue turns right from the hue circle of NCS, the deviation of hue increases and hue deviate towards to red.

For principle magenta, the effect of hue on the deviation of saturation was significant (F=12.174, P=0.007). The average deviation of saturation was 2.758 when hue was at right level, comparing 3.445 when hue was at left level. These results suggest that when hue turns left, the deviation of saturation increases and saturation becomes high.

For principal yellow, the effect of hue on the deviation of hue was significant (F=48.499, P=0.000). The average deviation of hue was 2.922 when hue was at right level, comparing 4.082 when hue was at left level. These results reveal that when hue turns left, the deviation of hue increases and hue deviate towards to red.

TABLE III. THE EFFECTS OF HUE ON THE ELEMENTS OF COLOR

Principal hue	Deviation variable	Hue	Average	σ	Amount
C	Brightness	1（Right）	3.816	.360	4
		2（Left）	3.000	.296	4
		Total	3.408	.528	8

M	Saturation	1（Right）	2.758	.418	4
		2（Left）	3.445	.430	4
		Total	3.102	.542	8
Y	Hue	1（Right）	2.922	.507	4
		2（Left）	4.082	.286	4
		Total	3.502	.719	8

4. Conclusion

Results revealed that the effects of elements of color on color deviation of LED light were significant. Additionally, the color deviations of LED light were different involving different principal hues (cyan, magenta, yellow). For cyan, the effects of brightness on saturation deviation and hue were significant, while on brightness and hue were significant for magenta. The deviation of brightness, saturation and hue under cyan as well as saturation under yellow were significantly affected by saturation. Hue significantly affected the deviation of hue both for cyan and yellow as well as the deviation of saturation for magenta. These results have implications for lighting design in shopping mall and other public space.

References

Recently along with new types of light source were developed, as well as more deep researches, many problems were exposed [1]. For example, if the saturation increased, the clarity and brightness would increase as well. In this case, to use CRI evaluating the color quality is not appropriate [2]. The color temperature of a light source has been shown to affect user perception, cognition, and mood state [3]. The correlated color temperature of LEDs affects individuals' psychological states [4][5] and physiological needs [6]. However, light sources that are not incandescent radiators have what is referred to as a correlated color temperature, with specific color temperatures depending on the type of application (office or home use) and on regional differences [7]. The higher color temperatures are typically referred to as cooler colors and are used to enhance concentration in offices, whereas lower temperatures are typically referred to as warmer colors and are often used in public areas to promote relaxation [8] [9].

Similarly, Kuller et al. used an electroencephalogram to test the effects of blue versus red, and observed that relative to red, blue exerted an effect of drowsiness [10]. ANOVA analyses revealed a significant effect of the color of the standard stimulus on the accuracy of color judgments, with higher accuracy rates for magenta and yellow than for cyan [11].

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