Analysis on Color Break-Up Effect of Time-Modulated Full Color LED Lighting during Saccadic Eye Movement

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ABSTRACT

Full color LED lighting systems are used for special effect of lighting on circadian rhythm, mood, and attention level. Under time modulated full color LED light sources, color break-up can be observed as well as the phantom array effect according to modulation frequency and overlapping phase. The color break-up usually was observed when display images produced with a color-sequential projector were viewed under saccadic eye movement. No experimental results were found for the color break-up in lighting system. This paper examines color break-up and the phantom array effect of time-modulated full color LED lighting systems. For the experiment, a full-color RGBW LED lighting system was developed to control the modulation frequency, sequence order and overlapping phase, and luminance level of the individual red, green, blue, and white LEDs. Participants observed a white rectangle target in a dark room, illuminated by the time modulated full color LED light sources under saccadic eye movement. Experimental results show that color break-up and phantom array effect can be detected even in the illuminated white rectangle when there is phase shift of turning on the Red, Green, Blue, and White LEDs. As the phase overlap of different color increases, observed color break-up frequencies decreases. Even if the phantom array is still visible, color break-up disappears when red, green, blue, and white LEDs are turned on and off simultaneously.

KEYWORDS: Color break-up, Phantom array effect, Color mixing

INTRODUCTION

Nowadays, LED lightings are widely used for residential lightings in addition to industrial lightings, due to energy efficiency and environmentally friendly composition materials. Time-modulated control methods such as PWM (pulse width modulation) are frequently used for the control of luminance of the full color LED lighting. Time-modulated light sources, however, can cause temporal light artifact (TLA) such as flicker, stroboscopic effect, and the phantom array effect. International Commission on Illumination (CIE) reports on the definition and categorization of all the TLAs mentioned above, and how to measure the visibility of flicker and stroboscopic effects [1]. If one saccades in the dark across a point source of lighting blinking rapidly on and off, one will see a spatially extended series of lights called the 'phantom array'[2]. The visibility of the phantom array effect is influenced by luminance level, geometric size of the target, and frequency of the illumination [3] and relative speed between the light source and saccadic eye movement [4].

In a field-sequential projector or display, a vivid colored blur or sequential presentation of color without mixing of the presented color is called ‘color break-up (CBU)’ [5]. The CBU is mainly studied in display to reduce CBU in display to improve display qualities. Several methods have been proposed to reduce CBU in filed-sequential color (FSC) display by mixing color sequence, color sequence rearrangement [6], field sequence primary color intensity control [7], and reducing local primary saturation. The CBU mechanism is expressed by the relationship between operating frequency, eye movement speed and brightness of illumination in display. Full color LED lightings are used for special ambient lighting in automotive and aircraft recently. The CBU can be an artifact in lighting as well as in display.

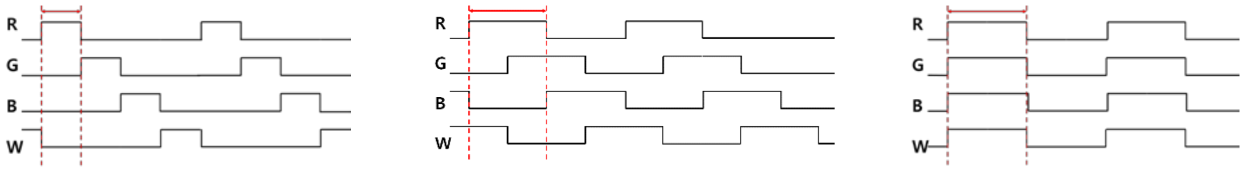
In this paper, the visibility of CBU and the phantom array effect are evaluated in the LED lighting systems with simultaneous and sequential modulation of red, green, blue, and white LEDs. During saccadic eye movement, the phantom array effect and CBU can be observed under sequential modulation of full color LEDs. We evaluated the visibility of CBU and the phantom array effect for different phase overlapping, change of color presentation order, luminance of the light sources, and CCT (Correlated Color Temperature) changes. Experimental results show visibility of the CBU in different conditions and imply methods to reduce CBU in full color LED lighting systems.

EXPERIMENT

For the experiment, an LED lighting booth with Red, Green, Blue, and White LED sources was developed with programmed control of the PWM frequency duty rate, overlapping, intensity of the light sources. The four light sources in a single-package are controlled independently. Two different color temperatures (4000K, 8000K) with two different luminance levels ($25cd/m^2$, $80cd/m^2$) are used in the experiments. Table 1 shows Red, Green, and Blue individual luminance levels in different color temperature. Overlapping ratio in sequential presentation is changed by 5 steps: 0% overlap, 50% overlap, 100% overlap, 150% overlap, 200% overlap, and 250% overlap. Simultaneous On/Off control is also evaluated for the clear comparison of the phantom array effect and CBU. Figure 1 shows sequential control with no overlapping (Figure 1 (a)) and 50% overlapping (Figure 1 (b)), and simultaneous On/Off control (Figure 1 (c)). In the sequential control, two different orders, red-green-blue-white (RGBW) and red-blue-green-white (RBGW), are used in the experiment as shown in Figure 2.

Table 1. Luminance levels of LED light sources in different color temperature and target luminance.

Color temperature	4000K		8000K	
Target luminance	$25cd/m^2$	$80cd/m^2$	$25cd/m^2$	$80cd/m^2$
Red LED sources	$4.20cd/m^2$	$13.97cd/m^2$	$3.23cd/m^2$	$11.51cd/m^2$
Green LED sources	$8.55cd/m^2$	$25.87cd/m^2$	$8.74cd/m^2$	$26.75cd/m^2$
Blue LED sources	$0.48cd/m^2$	$1.45cd/m^2$	$0.49cd/m^2$	$1.59cd/m^2$
White LED sources	$12.73cd/m^2$	$39.20cd/m^2$	$12.77cd/m^2$	$40.38cd/m^2$



(a) Sequential no overlapping case (b) Sequential 50% overlapping case (c) Simultaneous control case

Figure 1. Examples of sequential overlapping control and simultaneous control.

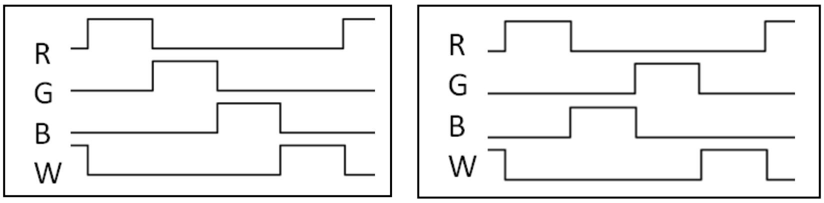
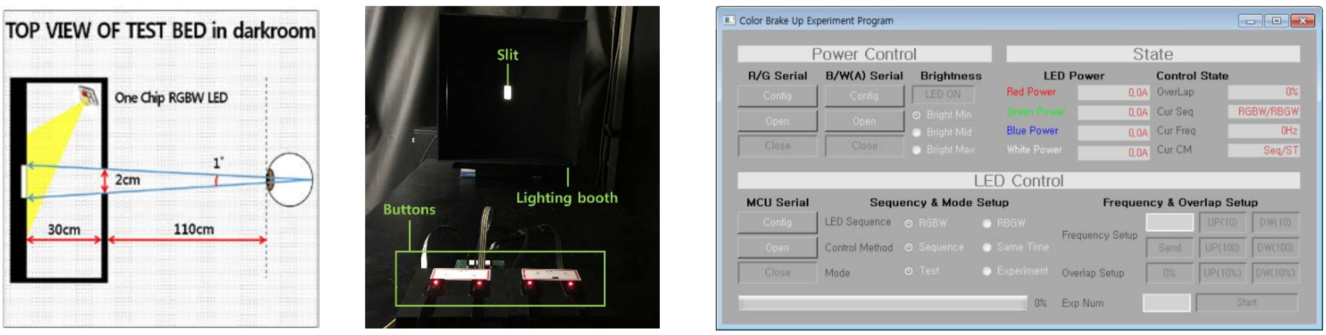


Figure 2. Different order of sequential control. Left: RGBW control, Right: RBGW control.



(a) Lighting booth diagram (b) Overall system screen shot (c) Control GUI

Figure 3. Experiment system configuration

Overall experiment system consists of a lighting booth, lighting control interface, and four buttons to get feedback from participants. Participants evaluated the visibility of the CBU and the phantom array effect by observed the lighting booth slot whose size is 2cm × 3.5 cm during saccadic eye movement in the dark chamber. The slot was observed from 140 cm away from the booth and the visual angle of the target slot of the booth is about 1 degree and the participant instructed to move their eyes within 40 degrees. Experiment conditions are randomized to remove ordering effect. For each given conditions, participants evaluate visibility of the CBU and the phantom array effect in different modulation frequency using O button, and X button. Eight different modulation frequencies (100Hz, 300Hz, 500Hz, 700Hz, 903Hz, 1102Hz, 1304Hz, and 1500Hz) are evaluated in each condition.

RESULTS

For the preliminary experiment, seven graduate students (six male and one female) participated in the experiment. Each student attended 416 sessions: 2 (CCT type) × 2 (different luminance levels) × 6 (overlap type including synchronized control) × 2 (sequence order type) × 8 (modulation frequencies) + 32 (On/Off control). Figure 4 shows experiment results of the visibility of CBU and the phantom array effect. Threshold frequency was estimated based the 50% detection of the frequency in different condition. The detection rate are normalized between 0 and 1 and 0.5 is used to estimate the threshold frequency as in Figure 4 (a). Based on the estimated threshold, we compare the relationship between overlapping ratio and the visibility of CBU and phantom array effect. As shown in Figure 4 (b), when the overlapping ratio increases the threshold frequency of the phantom array and the threshold frequency of CBU decreases. Compared with the CBU, the phantom array effect shows higher decrease in the threshold of visibility frequency when the overlapping increase. In the case of different CCT, the difference of the threshold of the visibility is limited and we cannot determine whether the color temperature has any effect in the threshold of the visibility of the CBU as shown in Figure 4 (c). In the case of different order of the color presentation like RGBW and RBGW, RGBW shows reduced CBU compared with RBGW as shown in Figure 4 (d). This different visibility threshold may be related to the difference of the change of primary color intensity in different sequence as shown in display [7]. In the case of simultaneous On/Off control, only the phantom array effect is visible and CBU does not appear except one subject.

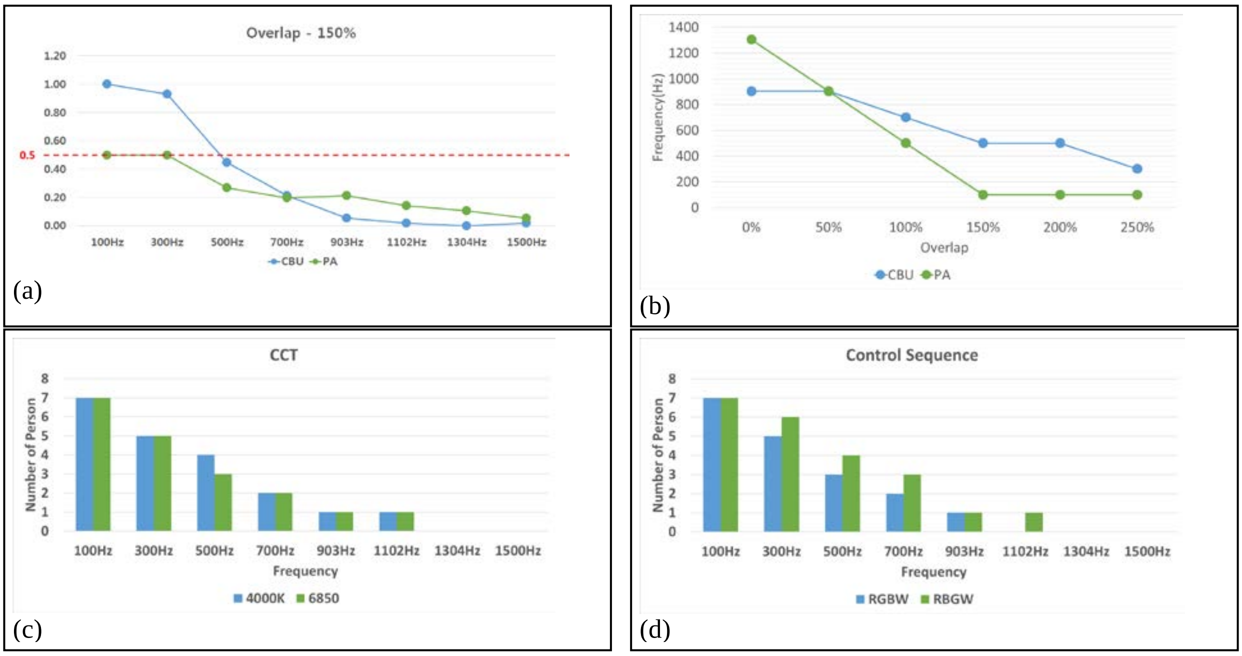


Figure 4. Visibility threshold of CBU and the phantom array effect: (a) An example detection ratio of the visibility of the CBU and the phantom array effect. (b) Visibility threshold frequency of the CBU and the phantom array effect. (c) Detection ratio of the visibility in different CCT. (d) Detection ratio of the visibility in different order of the sequence.

CONCLUSION

In this paper, we evaluated the visibility of the CBU and the phantom array effect in full color LED lighting systems. Experimental results show that the CBU can occur in full color LED lightings as well as field sequence color displays. Increasing overlapping ratio can be one way to decrease CBU in LED lighting systems in addition to increase modulation frequency in PWM control. The visibility of the CBU is also affected by the presentation order of red, green, and blue colors. We need further investigation to clarify othering effect of the color, CCT and luminance level in CBU of full color LED lighting systems.

This experiment results may be useful for the design and implementation of full color LED lighting systems with different modulation of red, green and blue LEDs. For high-quality lighting systems, CBU and the phantom array effect have to be considered and must be reduced.

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REFERENCES

[1] CIE Technical Note (2016), Visual Aspects of Time-Modulated Lighting Systems-Definitions and Measurement Models, CIE TN 006:2016.

[2] Hershberger WA, Jordan JS (1998) The phantom array: a perisaccadic illusion of visual direction. *The Psychological Record*, 48(1): 21-32.

[3] Lee C-S, Park SW, Kim SY, Lee JI, Pak HS (2016) Effect of colour and luminance intensity on the phantom array. In: *CIE proceedings*, 3-5 March, Melbourne.

[4] Lee C-S, Lee J-H, Pak H, Park SW, Song D-W. Phantom array and stroboscopic effects of a time-modulated moving light source during saccadic eye movement, *Lighting Research and Technology*, 2017.

[5] Yohso A, Ukai K(2006) How color break-up occurs in the human-visual system: The mechanism of the color break-up phenomenon. Journal of the SID, 14(12) 1127-1133.

[6] Chen C-H, Lin F-C, Hsu Y-T, Huang Y-P, Shieh H-P (2009) A Field Sequential Color LCD Based on Color Fields Arrangement for Color Breakup and Flicker Reduction, Journal of Display Technology, 5(1) 34-39.

[7] Cheng HC, Rao L, Wu S-T (2010) Color Breakup Suppression in Field-Sequential Five-Primary-Color LCDs. Journal of Display Technology, 6(6), 229-234.