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Visibility of the phantom array effect according to luminance, chromaticity and geometry

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Light-emitting diode-based lighting systems are now applied in both general lighting and automotive lighting. Time-modulated control methods such as pulse width modulation are frequently applied as a dimming method. This paper presents the characteristics of the visibility of the phantom array effect according to luminance, chromaticity and angular field of view. The threshold frequency of the visibility of the phantom array increases in proportion to the logarithm of the luminance of the light source. As the angular field of view of the light source increases, the threshold frequency of the visibility of the array decreases exponentially over a range from 0.125° to 4° in our experimental conditions. The threshold frequency at which the array is visible depends on chromaticity at high light source modulation frequencies. When designing time-modulated light sources, our findings can be applied so as to minimize the phantom array effect.

1. Introduction

Recently, lighting systems based on light-emitting diodes (LEDs) have been applied in automotive lighting and general lighting. LED lamps provide a fast response time, high-energy efficiency and increased safety.[1–3] In addition, the small point light source provides greater optical design freedom.[4] Therefore, many general and automotive light systems employ LED light sources.

To control the luminance of LEDs, time-modulated controls, such as pulse width modulation (PWM), are frequently used. For example, rear lamps in automobiles need two luminance levels to function as rear position lamps and as brake lamps. To achieve the two luminance levels, PWM controls are frequently applied.[4]

Artefacts caused by time-modulated light sources are called temporal light artefacts (TLAs) by CIE.[5] According to Technical Report of CIE TN 006:2016, TLAs can be categorized by the observer type and environment type: static observer versus non-static observer and static-environment versus non-static environment. The static observer is an observer 'who does not move his/her eyes' (microsaccades are not counted as eye movement, even though two to three saccades and

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microsaccades are made every second, and some are large, unless the observer carefully fixates a point in space). Static environment is an environment that does not contain perceivable motion. The phantom array effect, which is also called ghosting, is defined as 'change in perceived shape or spatial positions of objects, induced by a light stimulus the luminance or spectral distribution of *six lines* which fluctuates with time, for a non-static observer in a static environment'. As originally described, the phantom array is a 'spatially extended series' of images of a light source forming a pattern when saccades are made in the dark across a time-modulated spatially extended series light source.[6,7] However, light source movement can also generate similar effect as eye movement, and there are interactions between eye-movement speed and light source movement speed in perceiving the phantom array effect according to our previous experiments.[8]

It has been reported that the phantom array can be observed for light fluctuating in brightness at frequencies in excess of 1 kHz,[9] which is much higher than the convention flicker threshold frequency. It has also been reported that the ability to observer phantom effects varies according to modulation beam size, light level, frequency and duty cycle.[10] Recently, there has been an effort to model the contrast sensitivity function (CSF) of the phantom array based on the spatial CSF.[11] In this report, we characterise the influence on the visibility of the phantom array of the luminance and chromaticity level of the light source and the angular width (AW) of the light source in the direction of a saccade. AW of a light source here refers to the visual angle subtended at the eye by light source. If a narrow light source has a width W and viewed from a distance D, then the AW can be calculated by the following equation

$$Angular\ width = 2\tan^{-1}\frac{\frac{W}{2}}{D} \tag{1}$$

This paper is an extension of a previous conference report.[12]

2. Methods

2.1. Apparatus and general method

We developed two flat panel LED lamps covered with a diffuser. Sixty RGB LED sources, composed of 4 LED light bars with 15 RGB LED chips in each, were used for two LED lamps one immediately in line above the other. One of the two lamps was controlled by time-modulated PWM signal and the other by DC power. The lamps could be switched so that the PWM signal was fed to either the upper or the lower lamp. The two LED lamps were installed in a dark viewing chamber of size 1.4 m × 2.2 m.

The duty cycle of the PWM control was fixed at 100% modulation with 50% duty cycle. The DC control provided the same luminance and chromaticity to that of the time-modulated LED lamp. The power of each LED lamp was controlled by an experiment management program. Power level was controlled according to the required luminance (high, middle, low), source type (DC, PWM) and chromaticity type (blue, green, red). Power control parameters to meet the required luminance were measured in advance. The power channels of the two different LED lamps were switched using a relay board by the signal generated from the experiment management program (Figure 1).

Each participant was asked to sit on a chair, adjusted so that the participant's eyes were 1.6 m away from the LED lamps. As participants were asked to make saccades to and fro from one corner to the other corner, participants' visual scan width was around 45°. Five minutes dark adaptation time was provided. Four buttons were provided to the participant to control his/her current experimental session; one for starting each experiment session, one for pausing the session to take a rest and restarting the session, one for detection of phantom array in the upper slit light source and one for detection of the phantom array in lower slit light source. Demonstration sessions were provided in advance for each participant to understand what constituted the phantom array effect and to be familiar with the control interface. The time-modulation frequency was automatically adjusted according to the accuracy of the actual modulated light source and the participant's choice of slit to detect a phantom array effect. A pause button was provided for the participant to take a rest when their eyes got tired, which could affect the threshold frequency. Most of the participants got familiar with the interface and easily controlled their sessions. If any participant thought he/she made a mistake during the operation, we ran the session again.

2.2. Stimulus

A Konica Minolta CA-2000 2D luminance analyser was used to measure the luminance distribution of the stimulus, separately for red, green and blue lamps at the different light levels used. The peak wavelengths of the red, green and blue lamps were 631, 531 and 455 nm, respectively. The associated full width half maximum values of the red, green and blue lamps were 16, 35 and 20 nm, respectively. In experiment 1, the x, y chromaticity values for the high, middle and low red LED lamps were (0.6894, 0.3077), (0.6882, 0.3090) and (0.6871, 0.3115), respectively. Similarly, the x, y chromaticity values for the green LED lamps were (0.1552, 0.7633), (0.1836, 0.7501), (0.2043, 0.7336) and (0.1430, 0.0477) and (0.1409, 0.0612) and (0.1388, 0.0699) for the blue LED lamps. The average luminance of high

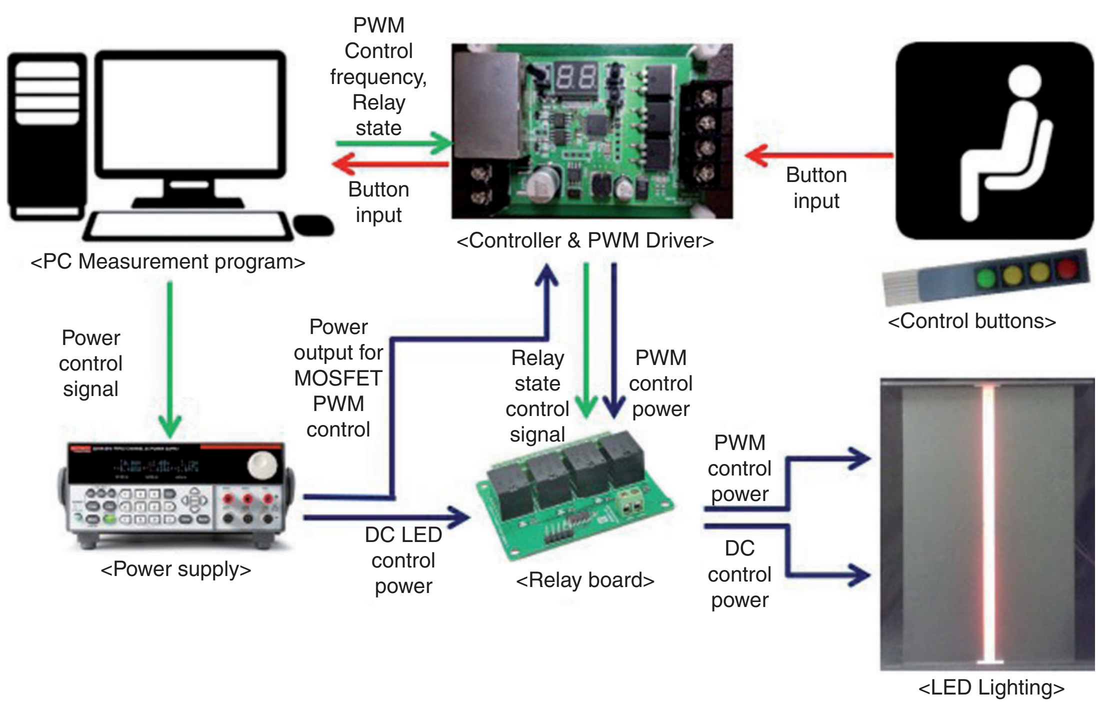

Figure 1 Experiment system configuration

luminance *was* adjusted to 400 cd/m^2, and that of middle to 100 cd/m^2 and that of low to 25 cd/m^2 for each condition in advance. The maximum luminances were 413.74, 103.41 and 25.84 cd/m^2 for the red colour, 408.18, 104.79 and 25.99 cd/m^2 for the green colour and 406.84, 104.24 and 25.59 cd/m^2 for the blue colour.

In experiment 2, we developed similar red, green and blue lamps with large AVs than in experiment 1. The luminance was adjusted to 100 cd/m^2 for the peak luminance of the area. The *x, y* chromaticity values were (0.6868, 0.3109) for red, (0.1817, 0.7486) for green and (0.1453, 0.0450) for blue. These values were similar to those used in experiment 1 but were not exactly the same as the experiment 1.

The modulation frequency was changed according to the button response of each participant using a weighted up–down method:[13] three successive correct responses resulted in an increase of the step frequency twice and a decrease of the step frequency by half according to the number of incorrect responses. The weighted up–down method provided faster and more stable convergence to the correct response than simple up–down method or transformed up–down methods.[14] The initial modulation frequency was 500 Hz. Initial interval step was 200 Hz in our experiment. When the interval step was less than 20 Hz and the phantom array effect was invisible, the session ended. Participants could take a rest whenever they wanted. Figure 2 shows three example sequences to reach threshold frequency of the visibility of the phantom array.

2.3. Experiment 1

2.3.1. Participants

Twenty-six undergraduate students with normal colour vision were recruited (13 male and 13 female); average age was 21.9 years. Ishihara colour test sheets were used in advance to check colour blindness.

2.3.2. Experiment conditions and procedure

There were 18 conditions resulting from the combination of three colours (red, green and blue), three luminances (25, 100 and 400 cd/m^2) and two AWs (0.25° and 0.5°). (The AW of the light source was controlled by changing the gap (slit width) between sliding panels installed in front of each light source.)

After explaining the experiment procedure and how to use the response buttons, 18 sessions were performed, one for each condition. The conditions involving the smaller AW were administered first but the order of the remaining conditions was random. Participants were encouraged to make a rapid eye movement from one side of the apparatus to the other, requiring an eye movement of about 50°. After nine sessions, participants took a rest while the slit width (angular width) was changed. To regulate the interval between eye movements, a metronome was played at 1 Hz, and participants were asked to start an eye movement with each beat.

2.3.3. Results

All participants reported seeing a phantom array at the lowest frequency. Table 1 presents the mean (and standard deviation) of the threshold frequencies for perception of the phantom array in each condition. The data for individual participants are given in Supplementary Materials (`experiment1.csv` or `experiment1.xlsx`). An analysis of variance with colour, AW and luminance as factors revealed significant main effects of colour ($F(2,50) = 6.26$, $p = 0.004$), AW ($F(1,25) = 20.6$, $p < 0.0005$) and luminance ($F(2,50) = 35.15$, $p < 0.0005$) and no significant interaction terms. Pairwise comparisons (with Bonferroni correction) revealed that the effect of colour was largely due to the difference between green and blue ($p = 0.001$). There was a marginal difference between red and green ($p = 0.039$).

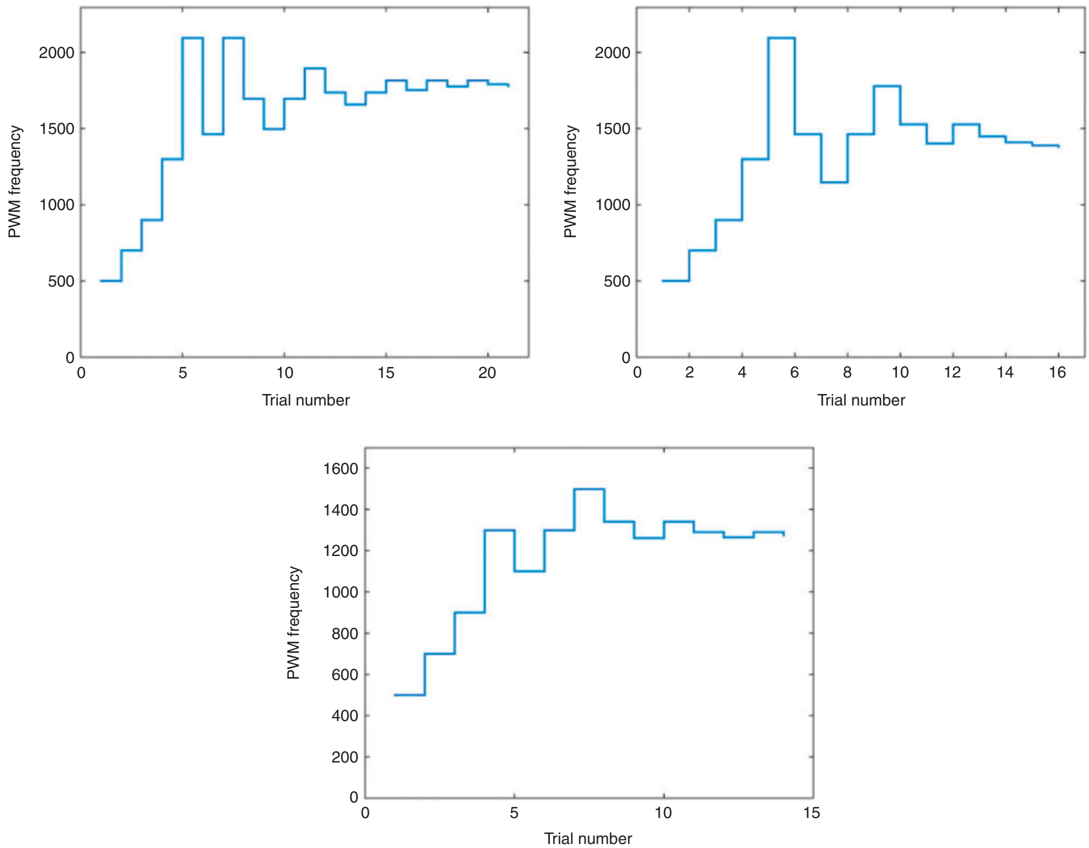

Figure 2 Example sequences in finding threshold values

Table 1 Mean (and standard deviation) of the threshold frequency for perception of the phantom arrays shown separately for the three levels of luminance, the three colours and the two AWs

Colour	AW (°)	Luminance (cd/m^2)			ALL (luminance)	ALL (luminance, colour)
		25	100	400		
Red	0.25	2257 (1140)	2751 (1213)	3057 (1388)	2419 (1217)	2347 (1152)
	0.50	1904 (929)	1942 (805)	2171 (953)	2275 (1086)	
Green	0.25	2416 (1051)	3085 (1621)	3499 (1273)	2691 (1240)	2607 (1338)
	0.50	1872 (816)	2159 (981)	2611 (1497)	2523 (2 049 795)	
Blue	0.25	2171 (1187)	2696 (1444)	2867 (1518)	2293 (1300)	2185 (1236)
	0.50	1546 (668)	1842 (960)	1988 (983)	2077 (1167)	
All (colour, slit width)		2028 (1008)	2412 (1272)	2699 (2699)		2380 (1254)

AW: angular width.

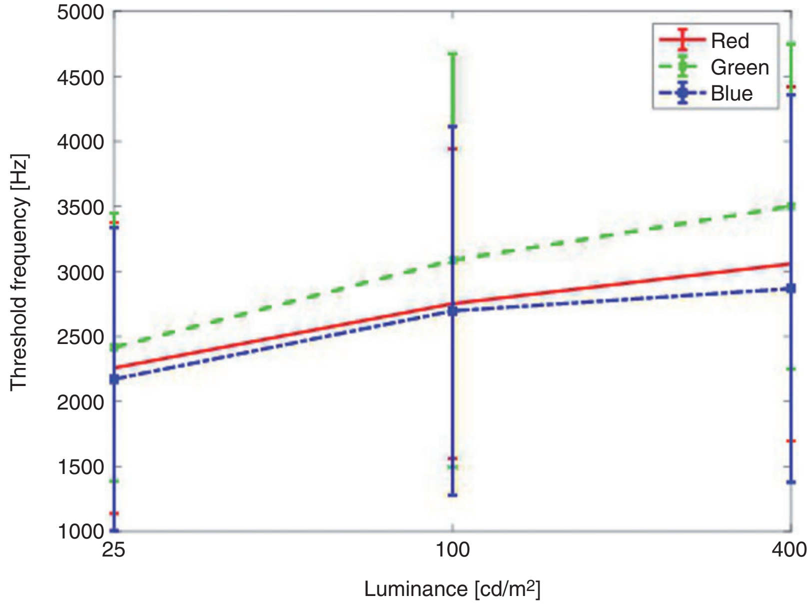

Figure 3 Chromatic and luminance dependence of the visibility frequency threshold of the phantom array effect (AW = 0.25°). Bars show standard deviations. AW: angular width

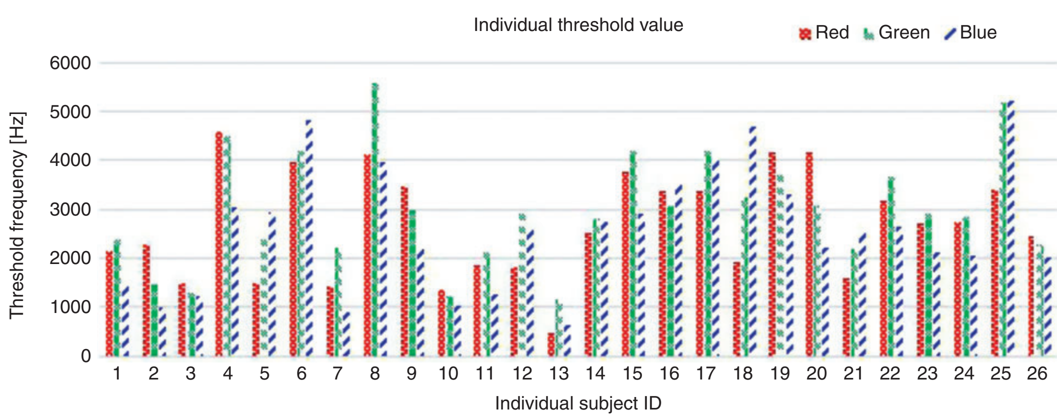

Figure 4 Individual threshold frequencies for different chromaticities (AW = 0.25°)

Although the mean threshold frequencies decreased monotonically with luminance (see Figure 3) and changed systematically with colour and slit width, there was considerable variability from one observer to another as shown in Figure 4.

2.3.4. Discussion

Each of the variables (colour, AW and luminance) affected the perception of the phantom array but there was no interaction between their effects. The threshold frequency increased linearly with log luminance under low background luminance. The contrast (i.e. the ratio between the target and the background) may be important for the development of a general visibility model of the phantom array effect. The threshold was greater for narrow slit widths. The effects of AW and colour (chromaticity) were explored further in the second experiment.

2.4. Experiment 2

2.4.1. Participants

Participants were 31 undergraduate and graduate students with a corrected visual acuity of and above and without colour blindness or colour weakness.

2.4.2. Experiment conditions and procedure

There were 33 conditions resulting from the combination of three colours (red, green and blue) and 11 slit width steps. The light sources had a fixed luminance of 100 cd/m^2 and red, green and blue LED lamps. The subject's eyes were 1.4 m away from the light panel. The AW was set to 11 steps (0.125°, 0.25°, 0.5°, 0.75°, 1.0°, 1.5°, 2.0°, 3.0°, 4.0°, 6.0°, 8.0°) by controlling slit width based on the fixed viewing distance.

All sessions were randomized to minimize the order effect. We randomized the presented slit width and chromaticity order based on pre-generated pseudo random numbers. Figure 5 shows the set-up for experiment 2, and the AW was computed based on the distance to the target luminaire and its slit width. Each subject could relax when they were tired using the Pause/Restart button to turn on/off the experimental lights directly.

2.4.3. Results

Among the 31 participants, 28 subjects' data are used in the analysis; three subjects had difficulty in detecting phantom array, and their data were removed from the analysis.

Table 2 presents the mean (and standard deviation) of the threshold frequencies for perception of the phantom array in each condition. The data for individual participants are given in Supplementary Materials (`experiment2.csv` or `experiment2.xlsx`). An analysis of variance with colour and slit width as factors revealed significant main effects of colour ($F(2,54) = 33.7$, $p < 0.0005$) using the sphericity assumption and slit width ($F(1.99, 53.7) = 124.4$, $p < 0.0005$) using Greenhouse–Geisser and a significant interaction effect ($F(7.3, 197.6) = 6.7$, $p < 0.0005$). Pairwise comparisons (with Bonferroni correction) revealed that the effect of colour was largely due to the difference between red and

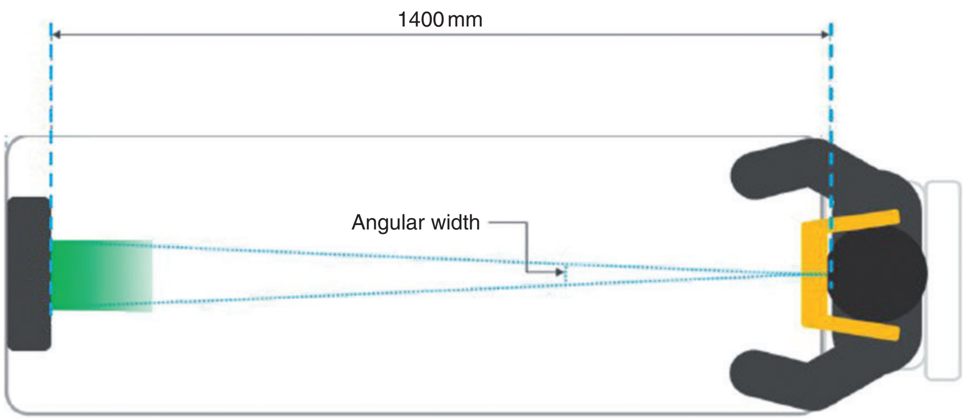

Figure 5 Experiment set-up: subject location and angular fields of view

Table 2 Mean (and standard deviation) of the threshold frequency for perception of the phantom arrays shown separately for the 3 colours and 11 slit widths

Colour	AW (°)											All (slit width)
	0.125	0.25	0.5	0.75	1	1.5	2	3	4	6	8	
Red	2770.3 (873.1)	2349.5 (1081.0)	1812.1 (914.2)	1567.0 (841.3)	1305.0 (742.9)	1048.0 (741.3)	787.3 (691.8)	449.8 (534.4)	199.6 (241.6)	112.0 (113.7)	83.3 (76.8)	1134.9 (1116.7)
Green	2891.6 (998.8)	2304.6 (1163.4)	1848.5 (996.9)	1641.7 (881.7)	1257.3 (588.4)	996.7 (666.8)	752.8 (665.7)	425.0 (521.1)	202.9 (256.3)	126.5 (152.4)	85.2 (64.2)	1139.3 (1146.3)
Blue	2324.2 (897.5)	1736.0 (816.0)	1439.3 (751.4)	1213.0 (652.2)	1030.9 (545.9)	821.7 (534.0)	580.0 (560.5)	299.8 (379.6)	108.2 (115.9)	75.8 (33.1)	87.8 (103.3)	883.3 (904.3)
All (colour)	2662.0 (945.9)	2130.0 (1056.4)	1700.0 (901.9)	1473.9 (810.5)	1197.7 (635.2)	955.4 (652.4)	706.7 (640.6)	391.5 (482.1)	170.2 (216.0)	104.7 (112.2)	85.4 (82.1)	1052.5 (1066.9)

AW: angular width.

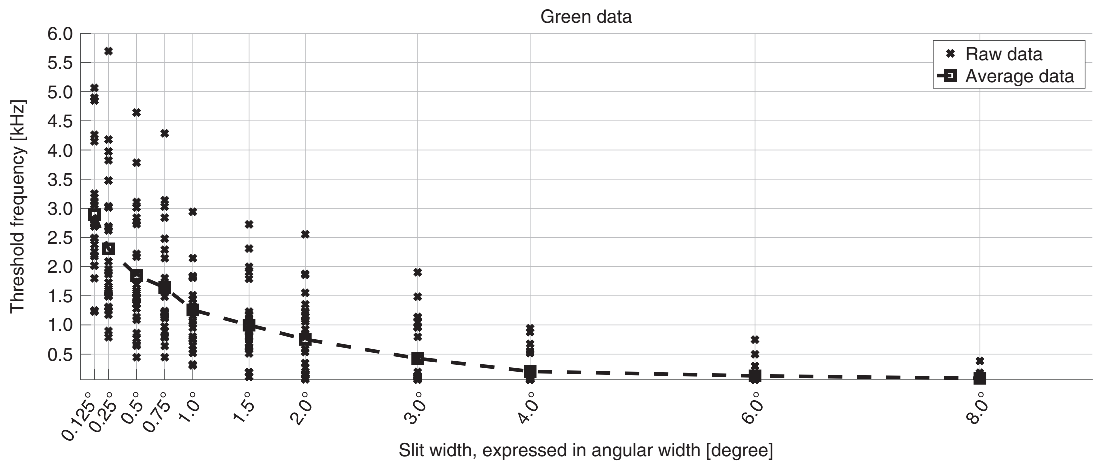

Figure 6 Raw data and average for green colour LEDs in different AWs

blue ($p = 0.000$) and the difference between green and blue ($p = 0.000$).

Figure 6 shows the threshold frequency value of the visibility of the phantom array on different slit widths, expressed in terms of their AW (degrees) for the green colour LED light sources. The average and standard deviation of the threshold frequency of the AWs for the green colour LED light sources are also plotted in Figure 7.

The experimental data show that the relationship between the AW and the sensitivity of the phantom array effect is an exponential relationship in which the sensitivity decreases as the AW increases. Figure 8 shows a linear fit of the angular field on a log scale. The best-fitting linear model of the green colour in the experiment can be expressed by

$$y_{green} = -1639x + 1334 \tag{2}$$

However, the error becomes larger above 4.0° of AW when fewer observers saw the phantom array.

Red and blue colours show similar trends to that of the green colour in Figure 8. Figure 9 shows the threshold frequency in

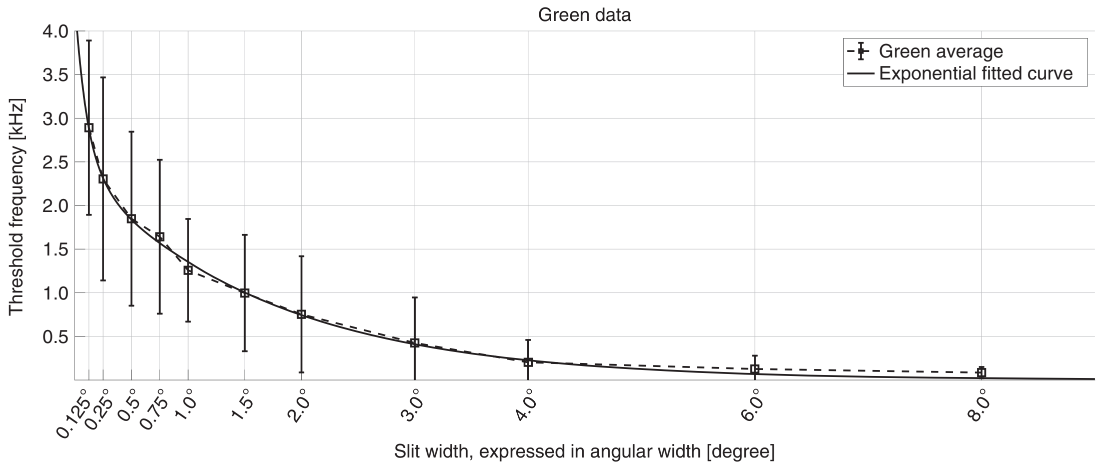

Figure 7 Average and standard deviation for visibility threshold frequency of the green colour LEDs at different AWs

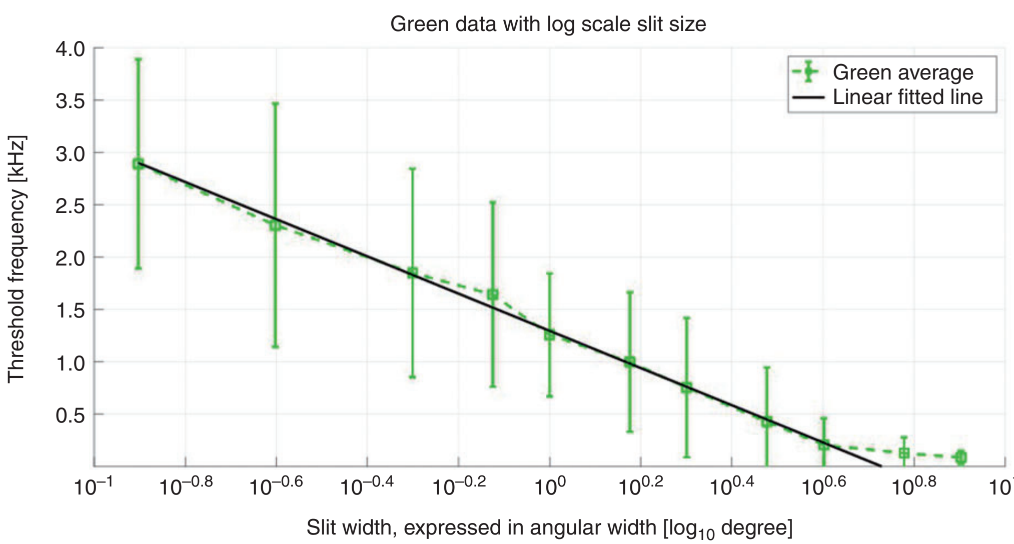

Figure 8 An example of linear fitting of the threshold frequency against angular with on a log scale

blue and red colours in addition to green colour LEDs. Best-fitting linear model on the log scale AW can also be estimated as shown in Figure 10. The best-fitting equations are as follows

$$y_{red} = -1600x + 1325 \tag{3}$$

$$y_{blue} = -1293x + 1037 \tag{4}$$

In Figure 10, it is clear that the threshold frequency of the blue is lower frequency than red and green colour.

2.4.4. Discussion

The AW of the slit affected the perception of the phantom array. The threshold frequency decreased linearly with log AW but

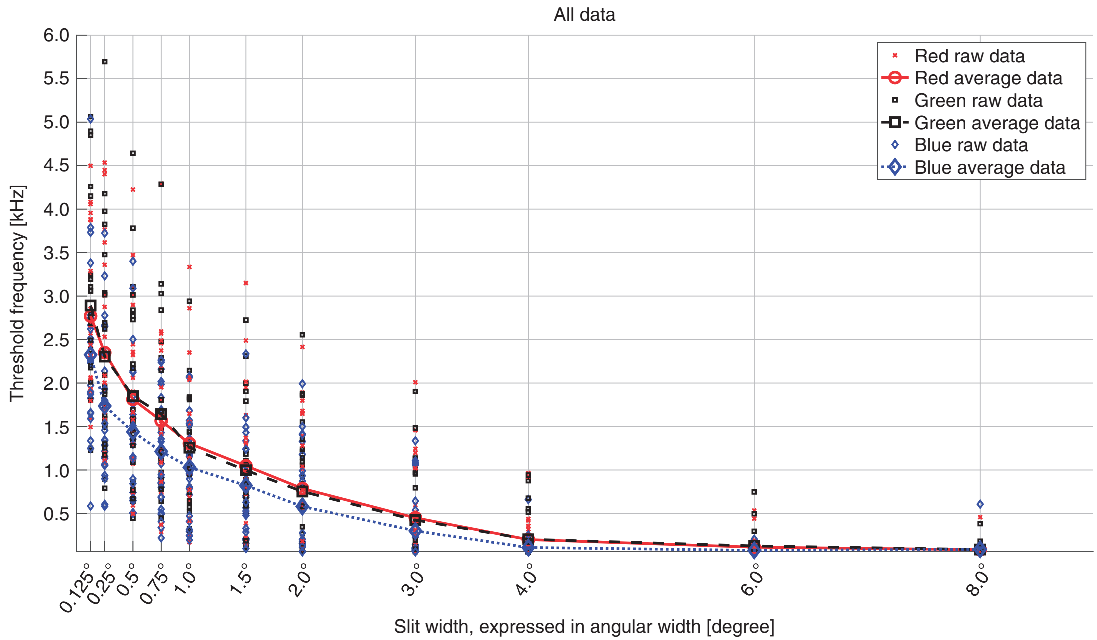

Figure 9 Visibility threshold frequency plotted against slit width for red, green and blue colours

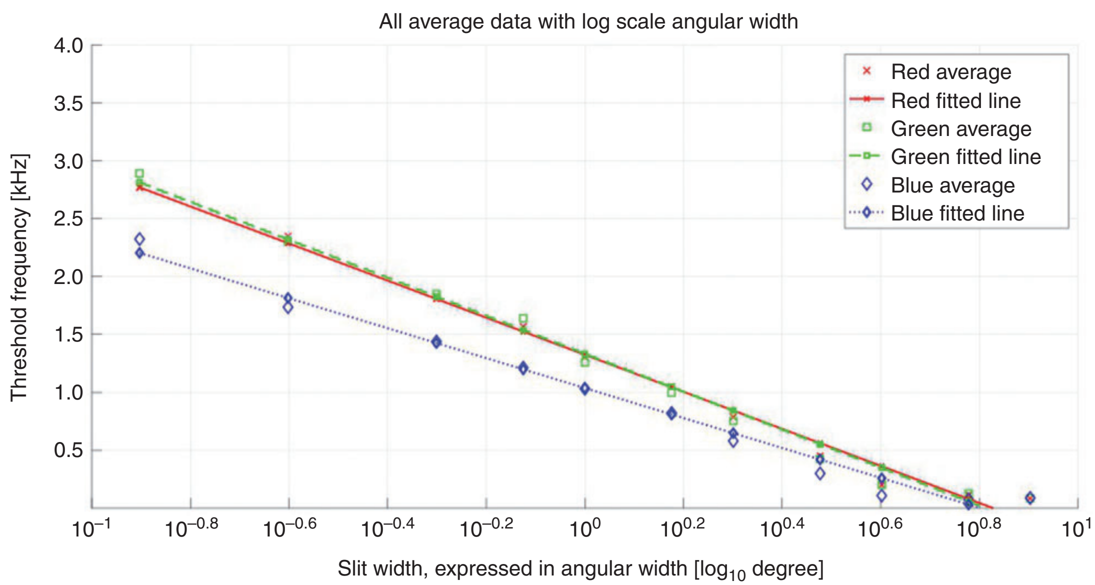

Figure 10 Linear fitting of the threshold frequency plotted against the log scale of AW for red, green and blue colours

differently for each chromaticity. The extended AW test shows that the threshold frequency of the visibility of the phantom array effect according to log AW is well approximated by a linear model from 0.125° to 4° in our experiment. An analytic model of the visibility of the phantom array based on spatially separated mapping of the light source on the retina[15] predicted that the visibility of the phantom array effect would be proportional to the reciprocal of the slit width.

3. Conclusions

The results of this study show that the phantom array effect can be influenced by many different factors and can be detected in the laboratory experiments at very high frequencies with small bright light sources. The threshold frequency of the visibility of the phantom array increases in proportion to the log luminance and decreases in proportion to the log AW.

The presented numerical model is based on our specific experimental data and may not apply outside the range of parameters used. Nevertheless, the relationship presented in this paper may be useful in the development of a general model.

Further investigation may be needed to characterize the chromaticity dependence of the visibility of the phantom array, which may be due to the response time or number of the L, M and S cones in the retina. S-cone contrast sensitivity is reduced at all spatial frequencies due to the comparatively low density of S cones relative to M and L cones.[16] Low threshold frequency of the visibility of the phantom array effect of the blue LED may be relevant to these neural factors even though the neural visual system has the same CSF when optical factors are taken into account.[16]

The phantom array effect may be important not only for night-time automobile lamp design but also for PWM-dimmed LED luminaires in dark environments such as movie theatres. The phantom array effect also occurs at indoor light levels with high contrast edges in the field of view. The presented characteristics of the phantom array effect may be applicable to automotive lamp designs and general lighting lamps for safe and comfortable TLA-free lighting systems and display systems.

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Supplemental material

Supplemental material for this article is available online.

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