Effect of Eye Movements on Perception of Temporally Modulated Light

I. M. L. C. Vogels, & I. Hernando

Philips Research, Eindhoven, the Netherlands

Introduction

LEDs are considered as *the* lighting technology of the future. Although LEDs offer many advantages, the perceptual quality of the light is not always as high as that of traditional light sources. LED based systems usually produce temporal fluctuations in the amount of light emitted, either because they are operated by pulse width modulation to control heat or they are directly driven by AC main voltage. The frequency of the light modulation can vary but is generally above the critical flicker fusion threshold of about 100 Hz (Kelly, 1961). Hence, the temporal changes are not directly visible. Under certain circumstances, however, our perception of the environment can be affected by this flickering light. First, moving objects might appear to move discretely instead of continuously, which is called the stroboscopic effect (Vogels et al., 2011). Second, a point light source might appear to exist of a series of dots, called a phantom array, when rapid eye movements (saccades) are made (Hershberger and Jordan, 1998). This can be observed, for instance, when driving behind a car with LED rear lights at night. A trail of lights can be experienced during each eye movement.

The origin of the perception of a phantom array is not fully understood yet. It is generally accepted that the perceived location of an object is determined by the summation of the retinal position of the object and an extraretinal oculomotor signal about the eye position. The mislocalization of a flickering light source during a saccade reveals that this process is not always functioning perfectly. Hershberger et al. (1998) suggested that the extraretinal signal does not correspond to the actual eye movement but it develops at a rate slower than the saccade. However, Watanabe et al. (2005) state that the localization of objects around the time of a saccade is more complicated and proposed a two-stage localization model.

Currently, only limited knowledge is available about the conditions in which the phantom array is visible. Hershberger and Jordan (1998) found that the pattern can be observed at frequencies as high as 500 Hz (the maximum frequency tested) for a light source at a luminance of 50 cd/m^2 and a visual angle of 0.2°. Recently, Roberts and Wilkins (2012) found that the maximum frequency to detect the occurrence of a phantom array for a vertical line on an oscilloscope at a luminance of 150 cd/m^2 was about 2000 Hz for saccadic amplitudes of 20-40°. Another experiment showed that the pattern of lines was less visible at smaller modulation depths of the modulated light. The pattern became invisible at modulation depths smaller than 10% for a square wave at 120 Hz.

In order to design LED based lighting systems that are experienced as pleasant, more knowledge on the perception of flickering light is needed. The aim of this paper is to investigate the visibility and annoyance of phantom patterns when making voluntary saccades across a light source that generates temporally modulated light. Different parameters of the modulated light were studied: beam size, light level, frequency and duty cycle (i.e. the time that the light is on as a fraction of the total time of one cycle). It is hypothesized that the phantom effect becomes less visible at a larger beam size, lower light level, higher frequency and larger duty cycle.

Method

Apparatus

A commercially available lamp (Elation Spot Opti White) was modified such that the

Fig. 1: Experimental setup

light level, frequency, duty cycle and waveform of the light could be controlled by a function generator. The lamp consisted of 24 white LEDs and was mounted in the front side of a closed box. A holographic diffuser (10° x 95°) was placed at 20 cm from the light source in order to make a visually uniform light spot. A black cardboard with a small vertical groove was placed in front of the diffuser to make a vertical line of light with sharp edges. A second holographic diffuser (40° x 10°) was placed at different positions from the light source to make the edges of the stimulus more gradual.

The system was placed at the back of a larger black box in order to eliminate undesired visual references that could affect the visibility of the phantom images. At the open front size of the box a chin rest was placed at a distance of 75 cm from the light source to fixate the head of the participant during the experiment (see Figure 1).

Stimuli

The stimulus was a temporally modulated vertical line of light. The transition of the edges could be modified by placing a diffuser at different distances from the light source. As a result, the width of the stimulus, i.e. the distance between the two points at which the light level is half the maximum light level, corresponded to a visual angle of 0.5° (small), 1° (medium) and 2° (large) at a viewing distance of 75 cm (see Figure 2). The light generated by the light source varied over time with a square waveform. The duty cycle of the wave was 0.2, 0.5 or 0.8. Four frequencies were tested: 200 Hz, 400 Hz, 1000 Hz and 3000 Hz. These values were chosen such that people could not perceive flicker. The maximum frequency was determined by the highest frequency that could be generated by the system. The average luminance level of the wave was 64 cd/m^2 (low), 2000 cd/m^2 (medium) or 10000 cd/m^2 (high). The luminance levels were measured with a Topcon BM-7 colorimeter at the center of the light stimulus. At the low luminance level the stimulus was still visible, the high luminance level was the maximum value that could be made, and the medium luminance level was the perceptual medium between the two extremes.

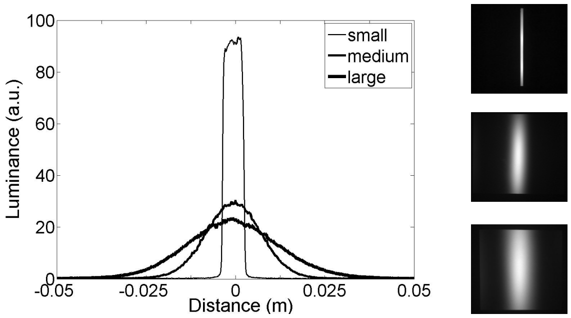

Fig. 2: Luminance profiles of the small, medium and large beam size.

Design

The experiment used a within subject design with visibility of the phantom effect as dependent variable and beam size (small, medium, large), luminance (low, medium, high), frequency (200, 400, 1000, 3000 Hz) and duty cycle (0.2, 0.5, 0.8) as independent variables. A pilot test revealed that the effect was not visible for low and medium luminance levels at a large beam size. Therefore these conditions were not included in the experiment. From the selected conditions, two full designs could be created. Design I contained all combinations with a small and medium beam size, resulting in a 2 (beam size) x 3 (luminance) x 4 (frequency) x 3 (duty cycle) design. Design II contained all combinations at a high luminance level, resulting in a 3 (beam size) x 4 (frequency) x 3 (duty cycle) design.

Participants

Ten males and five females, aged between 22 and 45 years, participated in the experiment. All participants had to fulfill a number of conditions: normal or corrected to normal visual acuity, no glasses, not suffering from epileptic seizures or migraine and able to perceive phantom images when extreme conditions are presented (see procedure).

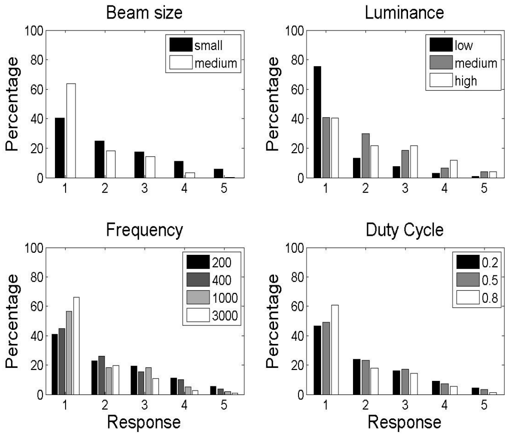

Fig. 3: The percentage of responses in each of the response categories, as explained in the text, for the data of Design I.

Procedure

The participant was seated in front of the box with his/her chin on the chinrest in a dark room. In order to test if the participant spontaneously saw the phantom array, a stimulus with a small beam size and a high luminance was presented. The phantom array was expected to be most visible at these values. Participants were asked to make rapid eye movements from one side of the box to the other side of the box, corresponding to an amplitude of about 40°. Four questions were asked similar to the questionnaire of Hershberger and Jordan (1998):

1. Each time you move your eyes do you see one line or more than one line?
2. Do all the lines appear in one region of space or do they appear to be spread out?
3. Is the spatial arrangement of the lines random or regular; that is, do you see a regular pattern such as a line of lines?
4. Is the pattern of lines vertical as in up and down or horizontal as in side to side?

Only if participants saw multiple vertical lines ordered horizontally, the experiment was continued. All participants succeeded this test. Then a short training session was presented to get the participant familiar with the range of stimuli and the rating scale. Each time a new stimulus was presented, the participant was instructed to look at the stimulus for a few seconds to adapt the eyes, make a number of large eye movements across the stimulus and evaluate if the phantom array (i.e. the appearance of multiple lines) was (1) imperceptible, (2) perceptible but not annoying, (3) slightly annoying, (4) annoying or (5) very annoying.

After the training session, three test sessions were presented. In each session, all conditions for one beam size (i.e. one distance of the diffuser plate) were shown. The presentation order of the three beam sizes was randomized across participants as well as the stimuli within one session.

Results

Since the 5-point response scale is an ordinal scale, meaning that the items on the scale describe an order but the distance between successive items does not have to be equal, an ordered logistic regression analysis was used to test for significant main and interaction effects. This was done for each experimental design separately. Only two-way interaction effects could be calculated.

Design I

Design I consisted of all conditions with either a small or a medium beam size. Figure 3 shows the distribution of responses for the different levels of beam size, luminance, frequency and duty cycle.

Figure 3 shows that the number of “imperceptible” responses increases when the beam size becomes larger. At the same time, the number of responses in the categories “imperceptible but not annoying”, “slightly annoying”, annoying” and “very annoying” decreases. This means that the phantom effect becomes less visible as the beam size increases. Similar conclusions can be drawn for the other variables. The phantom effect becomes less visible when the luminance level decreases and the frequency increases.

An ordered logistic analysis (χ^2=283, df=10, p<0.001) showed a significant main effect of beam size (p<0.001), luminance (p=0.025) and frequency (p<0.001). The effect of duty cycle was not significant (p=0.247). In addition, the interaction effects between beam size and frequency (p<0.001) and between duty cycle and frequency (p=0.009) were significant.

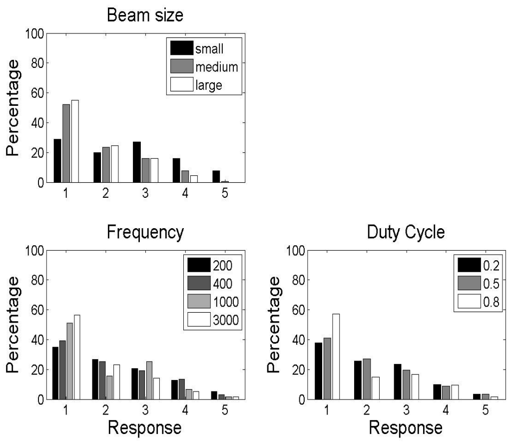

Fig. 4: The percentage of responses in each of the five response categories, as explained in the text, for the data of Design II.

A closer look at the data revealed that the interaction effects are caused by the fact that the phantom array was not visible to most participants at the highest frequency independent of the other variables. At lower frequencies a clear effect of beam size and duty cycle could be observed.

Design II

Design II consisted of all conditions with a high luminance level. Figure 4 shows the distribution of responses for the different levels of beam size, frequency and duty cycle. The phantom effect becomes less visible when increasing the beam size, frequency and duty cycle of the light.

An ordered logistic analysis (χ^2=93.6, df=6, $p<0.001$) revealed significant effects of beam size ($p<0.001$), frequency ($p<0.001$) and the interaction between beam size and frequency ($p<0.001$). The effect of duty cycle ($p=0.062$) and the interaction between duty cycle and frequency ($p=0.061$) almost reached the significance level of 0.05.

Discussion

This study demonstrates that the visibility of an array of light sources when rapid eye movements are made across a flickering light source depends on several parameters, such as the size, light level, frequency and duty cycle of the modulated light. The phantom array is most clearly visible at a small light source with sharp edges. For a wider stimulus with soft edges the effect is much less pronounced. It would be interesting to investigate if this was due to the width of the stimulus or the slope of the light transition. We assume that both aspects play a role, as the visibility is probably related to the contrast of the resulting phantom array. This means that only for applications using small light sources it is important to take the phantom effect into account.

Roberts and Wilkins (2012) found that the maximum frequency to observe the phantom effect was about 2000 Hz. Our study showed that the maximum frequency depends on other stimulus parameters. For instance, the phantom array was visible at 1000 Hz for the small light beam but not for the wider stimulus. Therefore, guidelines or regulations for flickering light should not only take the modulation frequency into account. A more complicated model is needed to fully describe the effect. Such a model should also include the modulation depth and probably the color of the light.

For practical applications, the chance of being annoyed by the phantom array should be as low as possible. Preferably, the viewing angle of the light source should be significantly larger than 2°. When small light sources are used in a dim environment, such as the tail lights of a car, the luminance should be lower than 64 cd/m^2 and/or the frequency should be larger than 3000 Hz. It is expected that the acceptable luminance level will be higher when the ambient light level is increased.

References

Hershberger, W.A. and Jordan J.S. (1998). The phantom array: a perisaccadic illusion of visual direction. *Psychological Record*, 48, 21-32.

Kelly, D.H. (1961). Visual response to time-dependent stimuli: I. Amplitude sensitivity measurements. *Journal of the Optical Society of America*, 51: 422-429.

Roberts, J.E. and Wilkins A.J. (2012). Flicker can be perceived during saccades at frequencies in excess of 1 kHz. *Lighting Research and Technology* (in press).

Vogels, I., Sekulovski, D. and Perz, M. (2011). Visible artefacts of LEDs, *Proceedings of the 27th Session of the CIE*, South Africa, 42-51.

Wantanabe, J., Noritake, A., Maeda, T., Tachi, S. and Nishida, S. (2005). *Vision Research*, 45, 413-430.