The effect of phase on flicker visibility

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Introduction

Light emitting diodes (LEDs) are revolutionizing the lighting domain because of a number of unique advantages they offer. LEDs provide long operating lifetimes, low power consumption and they are build using environmentally friendly materials (Schubert & Kim, 2005). They also allow for almost full control of their spectra, and their small size provides additional spatial possibilities. Another unique capability of LEDs is their fast response to changes in the driving current. This characteristic can be used to easily control the light output, for instance by rapidly switching the digital signal on and off to simulate a varying voltage. This control scheme is called pulse width modulation (PWM). However, improper selection of the driving parameters, but also dimming of the LEDs or voltage fluctuations in the mains, may result in visible temporal artifacts in the light output, such as flicker, the stroboscopic effect or the phantom array effect (Frier & Henderson, 1973; Hershberger, 1987; Kelly, 1961). Several solutions to reduce the occurrence of these artifacts are known, but they usually require electronics with increased cost and size. Therefore, many LEDs introduced on the market still suffer from temporal artifacts, which can result in visual discomfort and possibly negative health effects (Wilkins et al., 2010). It is therefore important to better understand the causes for the occurrence and visibility of the temporal artifacts.

Flicker is the most studied, but also the most critical artifact. It is defined as the perception of visual unsteadiness induced by a light stimulus whose luminance or spectral distribution fluctuates with time, for a static observer in a static environment. These fluctuations may include periodic as well as aperiodic variations (i.e. transient effects). Flicker visibility depends on many parameters, including the temporal frequency of the light changes, the shape of the waveform and the magnitude of change (De Lange, 1961; Kelly, 1961). A number of measures have been developed in the past with the aim of quantifying flicker perception. The Illuminating Engineering Society of North America (IESNA) developed the Flicker Index (FI). It is defined as the area above the average light output divided by its total area for a single cycle of the fluctuation. The Flicker Index can vary between 0 and 1 and IESNA recommends that for good lighting quality it should remain below 0.1 (IESNA, 2000). Another measure used to quantify flicker perception is the Flicker Percent. In literature, it is also referred to as the modulation depth (MD) and it is defined as follows:

$$MD = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} * 100\% \qquad (1)$$

Where L_{min} is the minimum luminance and L_{max} the maximum luminance emitted by the light source in one cycle of the fluctuation. Even though both the Flicker Index and the modulation depth are widely used criteria in industry and research, neither of them can accurately predict the visibility of all types of flicker. This is due to the fact that these measures do not account for the effect of frequency. Further, De Lange (1961) studied the perception of flicker of differently shaped waveforms; among others a sinusoidal modulation and a square wave modulation. He found that the ratio of the visibility threshold of a square wave over a sine wave is 0.79, while the ratio predicted by the Flicker Index is 0.6. On the other hand De Lange used a flickering stimuli consisting of a 2° test-field in central vision and for the measure to be suitable for general lighting application a stimuli should embrace the entire visual field. More recently, another measure was developed, namely the Flicker Visibility Measure (FVM), which is defined as follows:

$$FVM = \sqrt[2.4]{\sum_{m=1}^{\infty}\left(\frac{C_m}{T_m}\right)^{2.4}} \begin{cases} < 1 \text{ not visibile} \\ = \mathbf{1\ just\ visibile} \\ > 1 \text{ visible} \end{cases} \quad (2)$$

where C_m is the amplitude of the m-*th* Fourier component of the waveform and T_m is the flicker visibility threshold for a sine wave at the frequency of the m-*th* Fourier component expressed in terms of modulation depth (Perz, Vogels, & Sekulovski, 2013). FVM, contrary to FI and MD, fully accounts for the effects of frequency and wave shape. However, FVM assumes that there is no effect of the phase difference between the individual frequency components on flicker visibility. This means that two waveforms consisting of the same two frequency components, but with a different phase shift between the components would yield the same FVM value. On the other hand, a change in phase does have an effect on the shape and the modulation depth of the waveform.

The aim of this study is to test the validity of the FVM to predict flicker visibility for waveforms with different phase shifts between the frequency components. Therefore, an experiment was performed to measure the effect of phase difference between the frequency components of a waveform on the visibility of flicker.

Method

The visibility threshold of flicker for four waveforms consisting of two frequency components was determined. Each waveform was presented at two values of the phase difference. Hence, the experiment consisted of a full-factorial 4 (Frequency Combination) x 2 (Phase shift) within-subject design.

Setup

Two typical office luminaires were equipped with LEDs. Each luminaire contained four rows of cool white LEDs and four rows of warm white LEDs. The luminaires were mounted in a frame just below the ceiling, at a height of 2.5 m, next to a white wall and they were separated by 0.8 m. The voltage of the LEDs was controlled by a programmable waveform generator via a laptop. Proper calibration of the setup was ensured by measuring and transforming the relation between voltage and illumination. The color temperature of the light was 6500K. There was a fixation cross on the wall and the light level measured at the fixation cross was 58 cd/m^2.

Stimuli

Waveforms consisting of two frequency components with equal amplitudes, were used as lighting conditions, see Table 1. Their modulation depth was varied between 0 and 5%. For each frequency combination two values of the phase difference were chosen such that the resulting MD of this waveform was either relatively small (depicted as Phase 1 in Table 1) or relatively large (depicted as Phase 2 in Table 1). The light stimulus was covering the entire visual field of the participant.

Tab. 1: Frequency combinations measured in the experiment, together with their phase shift

Frequencies (Hz)	Phase 1 (π)	Phase 2 (π)
1. 10Hz 15Hz	-0.25	1.05
2. 10Hz 20Hz	1.5	0.1
3. 10Hz 30Hz	0	1
4. 20Hz 60Hz	0	1

Procedure

Participants were welcomed and seated on a chair 1 meter from the wall. They read through and signed the consent form, confirming their eligibility for the study. First, they were given oral instructions on the experimental procedure and they were thoroughly explained what flicker was. Additionally, they were given a short demonstration of the test. Participants were instructed to look at the fixation cross at the wall and indicate on a portable numerical keyboard whether the light was flickering or not. They were instructed to press the right arrow key when they observed flicker, and the left arrow key otherwise. For each of the lighting conditions, the visibility threshold was measured using a staircase method (Engeldrum, 2000). This means that the modulation depth that was presented in a given stimulus depended on the response of the participant to the preceding stimulus. The starting modulation depth was set randomly across participants, but always large enough, so that flicker was clearly visible. The modulation depth was decreased if a participant indicated that flicker was visible and otherwise increased. The modulation depth at which the answer changed from ”yes” to ”no” or from ”no” to ”yes” was called a reversal point. The visibility threshold at the probability of 50 % correct was obtained as an arithmetic mean of four last reversal points for each lighting condition (Rose, Teller, & Rendleman, 1970). In order to prevent flicker adaptation, constant light of the same luminance and color temperature was presented after each stimulus for 4 seconds. All staircase stimuli for all lighting conditions were intermingled and presented in a random order, different per participant. The experiment took about half an hour per participant.

Participants

We excluded participants that might be oversensitive to flicker, meaning that we only included participants that did not suffer from epilepsy nor had a family history of epilepsy, and that did not suffer from migraines. The experiment included 14 males and 8 females with their age ranging between 19 and 32 years.

Results

Figure 1 shows the mean visibility thresholds expressed in terms of modulation depth (Equation (1)) (left) and in terms of the Flicker Visibility Measure (Equation (2)) (right) for the four complex waveforms with different phase difference between the frequency components. Black circles represent the thresholds of the waveform with the first phase shift (corresponding to a small modulation depth); whereas red crosses represent the second phase shift (corresponding to a larger modulation depth).

Figure 1 suggests that the visibility thresholds, expressed in terms of modulation depth, are always larger for the waveforms with the second phase shift as compared to waveforms with the first phase shift. An ANOVA was performed with Phase and Condition as fixed factors, Participant as random factor and modulation depth as dependent variable. It was found that Phase had a statistically significant effect on modulation depth ($F(1,126)=7.2$, $p<0.01$). Both Condition and Participant were found not to be significant ($F(3,126)=0.18$, $p=0.90$ and $F(18,126)=1.17$, $p=0.30$ respectively). Further, Figure 1 shows that the visibility threshold expressed in terms of FVM is the same for both phase shifts, for the second composite waveform (10 Hz and 20 Hz).

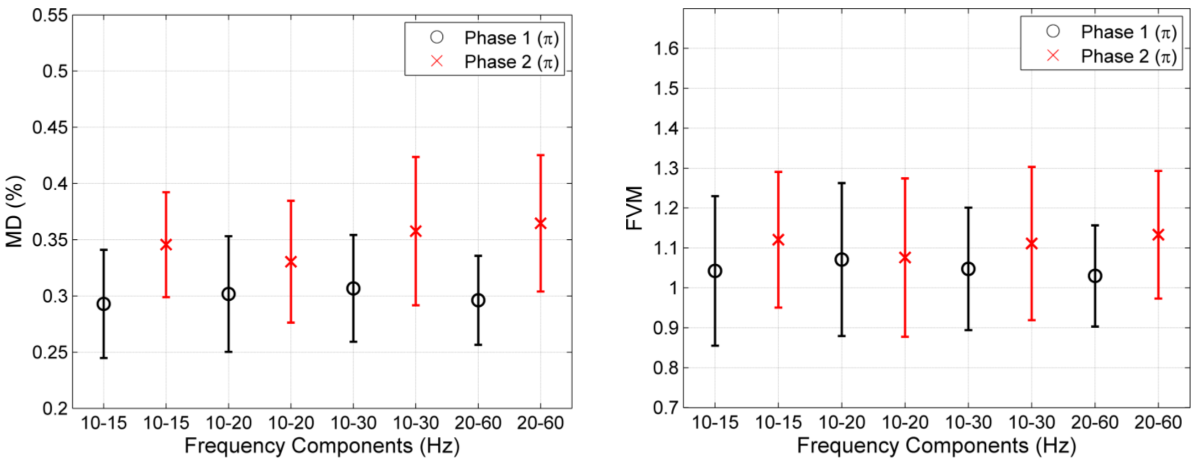

Fig. 1: Mean visibility thresholds expressed in terms of modulation depth (left) and in terms of Flicker Visibility Measure (right) for four different complex waveforms with two different phase shifts. The error bars correspond to the 95% confidence interval of the mean.

For all the other conditions the visibility threshold for the waveforms at second phase shifts are slightly larger compared to the first phase. An ANOVA showed that none of the variables: Condition, Phase and Participant had a significant effect on FVM ($F(3,126)=0.004$, $p=1$, $F(1,126)=1.05$, $p=0.30$ and $F(18,126)=1.52$, $p=0.10$ respectively). Further, a t-test was performed to compare the FVM values at different phases to the expected value of 1. It was found that these effects were not significant (first phase: $t(75)=0.13$, $p=0.90$, second phase: $t(75)=0.28$, $p=0.78$)

Discussion

It was previously reported that the commonly used measures, Flicker Index and Flicker Percent (modulation depth) cannot predict the visibility of temporal light artifacts of all kinds of waveforms. This is because both measures are based on the analysis of a single waveform period, and consequently neither is able to account for the effect of frequency. It was also demonstrated that the ratio of visibility threshold of a square over a sine waveform at the same frequency cannot be predicted by the Flicker Index (De Lange, 1961).

Nowadays, LEDs introduced to the market are characterized by light output with different kinds of regular and irregular waveforms at various frequencies, and therefore it is important to correctly quantify temporal light artifacts. The Flicker Visibility Measure (FVM) is a new measure, which can predict flicker visibility of all kinds of waveforms with different shapes and frequencies. It was developed for stimuli covering the entire visual field, to make it suitable for general lighting application. In the current study, an experiment was conducted with the general aim of testing the validity of FVM by investigating the effect of phase difference between the frequency components on the flicker visibility. It was shown that the visibility threshold expressed in terms of modulation depth depends on the phase difference between the frequency components. This means that it is not possible to set one general limit for the visibility threshold of flicker in terms of modulation depth. Therefore, we confirm that modulation depth is not a suitable measure to consistently quantify flicker visibility. On the other hand, the thresholds expressed in terms of Flicker Visibility Measure remained constant, regardless of the phase shift. The FVM values at threshold were not significantly different from the expected value of 1, which confirms that FVM is a valid measure to predict flicker visibility. Recently, an experiment was conducted, in which the visibility of flicker of real life waveforms were compared with several measures quantifying flicker. The experiment also showed the advantage of FVM over the other measures. The results of this experiment will be discussed at the conference.

References

De Lange, H. (1961). Eye's Response at Flicker Fusion to Square-Wave Modulation of a Test Field Surrounded by a Large Steady Field of Equal Mean Luminance. *Journal of the Optical Society of America*, 51(4): 415-421.

Engeldrum, P. G. (2000). *Psychometric Scaling: A Toolkit for Imaging Systems Development*. Winchester, MA: Imcotek Press.

Frier, J. P., & Henderson, A. J. (1973). Stroboscopic Effect of High Intensity Discharge Lamps. *Journal of the Illuminating Engineering Society*, 3(1): 83–86.

Hershberger W. (1987) Saccadic eye movements and the perception of visual direction. *Perception and Psychophysics*; 41(1):35-44.

Illuminating Engineering Society of North America (2000), IESNA Lighting Handbook, Ninth Edition, New York.

Kelly, D. H. (1961). Visual Responses to Time-Dependent Stimuli. I. Amplitude Sensitivity Measurements. *Journal of the Optical Society of America*, 51(4), 422–429.

Perz, M., Vogels, I. M., & Sekulovski, D. (2013). Evaluating the Visibility of Temporal Light Artifacts. In *Proceedings of Lux Europa 2013 – the 12th European Lighting Conference*. Krakow.

Rose, R. M., Teller, D. Y., & Rendleman, P. (1970). Statistical properties of staircase estimates. *Perception & Psychophysics*, 8(4), 199–204.

Schubert, E. F., & Kim, J. K. (2005). Solid-State Light Sources Getting Smart. *Science*, 308(5726), 1274–1278.

Wilkins, A., Veitch, J., & Lehman, B. (2010). LED lighting flicker and potential health concerns: IEEE standard PAR1789 update. In *2010 IEEE Energy Conversion Congress and Exposition (ECCE).*