International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

**PO161**

# INVESTIGATION OF STROBOSCOPIC EFFECTS FROM CHROMATIC FLICKER

**John D. Bullough et al.**

DOI 10.25039/x46.2019.PO161

from

CIE x046:2019

Proceedings
of the
29th CIE SESSION
Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)



CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

# INVESTIGATION OF STROBOSCOPIC EFFECTS FROM CHROMATIC FLICKER

**Bullough, J.D.**, Skinner, N.P.
Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY, USA
bulloj@rpi.edu

DOI 10.25039/x46.2019.PO161

## Abstract

The widespread use of light emitting diode (LED) sources for general illumination has reintroduced concerns about flicker and stroboscopic effects. Consequently, recent standards and guides have appeared that address these concerns. Such documents have not addressed chromatic flicker, which can be caused by LED systems that modulate individual colour components through pulse width modulation so that at any given instant a lighting system's colour output might not match the time-averaged output that would be seen under steady-state viewing conditions. A study was conducted to assess the detection and acceptability of stroboscopic effects from chromatic and achromatic flicker profiles. The results suggest that frequency-modified flicker index is a good predictor of stroboscopic effect detection and acceptability overall, but not for chromatic effects specifically.

*Keywords*: Chromatic Flicker, Colour Break-Up, Modified Flicker Index, Stroboscopic Effects

## 1 Introduction

The increasing use of light emitting diode (LED) sources for general lighting has brought about renewed concerns about temporal light artefacts (TLAs) such as flicker and stroboscopic effects (Wilkins et al., 2010). Consequently, recent standards and guides have appeared that address these concerns, such as those from the Institute of Electrical and Electronics Engineers (IEEE, 2015), the National Electrical Manufacturers Association (NEMA, 2017), the Commission Internationale de l'Éclairage (CIE, 2016), and the Alliance for Solid-State Illumination Systems and Technologies (ASSIST, 2012, 2014, 2015, 2017).

None of the aforementioned documents have addressed chromatic flicker, which can be caused by colour-tunable LED systems that modulate individual colour components through pulse width modulation so that at any given instant a lighting system's colour output might not match the time-averaged output that would be seen under steady-state viewing conditions. Several studies of chromatic flicker at relatively low frequencies (<100 Hz) have been conducted. Van Der Horst (1969) measured sensitivity to red-green flicker and found that the threshold frequency above which directly-perceived colour flicker was no longer apparent increased as a function of contrast between the flickering colours.

Sekulovski et al. (2007) evaluated threshold frequencies at which flicker was no longer visible for changes in lightness, hue and saturation of a colour-tunable red-green-blue (RGB) LED source. They found lower threshold frequencies for hue and saturation changes than for lightness changes. Of interest, Jiang et al. (2007) reported than even when chromatic flicker was visually imperceptible, some areas of the visual cortex responded to such conditions compared to non-flickering controls with identical appearance. These results provide information about when chromatic flicker is directly visible.

Relatively little seems to have been published regarding the potential visibility of chromatic flicker at higher frequencies (≥100 Hz) where direct visual perception is generally not possible. A related phenomenon, however, is that of "colour break-up" exhibited by some displays and projector systems. Post et al. (1997) measured the detection of colour break-up for white RGB targets moving across a white background for different background luminances, target contrasts, and velocities of motion. Break-up was easier to detect as all three of these factors increased, and the frequency at which break-up disappeared could be as high as several thousand Hz. Zhang and Farrell (2003) found, qualitatively consistently, that the conditions that would correspond to lower threshold frequencies in the study by Post et al. (1997) were more easily detected in an experiment of their own, even though they used different sizes and velocities of targets and measured break-up induced during eye saccades, having much faster velocities than those evaluated by Post et al. (1997). Järvenpää (2005) investigated means for measuring RGB displays in terms of their ability to induce colour break-up using a camera, but Yohso and Ukai (2006) suggested that camera-based measurements would only be successful under limited conditions, in part because of large variations in perception among individuals during saccades.

Johnson et al. (2014) studied the visibility of colour break-up in video displays when observers were tracking objects across the display as well as when the gaze was fixed and an object moved across the screen. They found that if the frames corresponding to each colour were offset systematically, that the perception of colour break-up in the leading and trailing edges of moving objects in video scenes was minimized. Obviously, this technique could not be applied to three-dimensional illumination where it is not possible to shift a moving object's location based on the colour of illumination on it at a particular instant.

Based on the relative dearth of published data describing visual perceptions under chromatic flicker when the flickering light is a source of illumination, an objective of the present study was to develop a preliminary understanding of some of the ways that chromatic flicker impacts the perception of stroboscopic effects when rapid motion is present in an illuminated scene.

## 2 Method

A 20 cm diameter plastic sphere was painted white on the interior surface and black on the exterior surface, and a 10 cm diameter circular aperture was cut out of the bottom of the sphere. Equally spaced along the inside edge of the aperture, five high-powered red/green/blue (RGB) LEDs were mounted on heat sink plates so that when the LEDs were energized, they uniformly illuminated the interior of the sphere thus integrating the output of the individual LEDs. The integrated illumination from the individual RGB colour chips was emitted from the aperture at the bottom (see Figure 1).

**Figure 1 – Photograph of Integrating Sphere Used to Generate Lighting Conditions**

The relative output of each of the RGB components was always adjusted to produce white illumination on a black table top having an illuminance of 40 lux. The correlated colour temperature (CCT) of the illumination was 4870 K and the (x,y) chromaticity coordinates were (0.350, 0.366).

Four temporal profile types were created (Figure 2), denoted *phased*, *staggered*, *spaced* and *constant*. In the phased profile type, the red, green and blue components were controlled simultaneously to produce on-off flicker with a rectangular waveform having a duty cycle of 33% (Figure 2a), so that the resulting flicker was achromatic; none of the individual RGB components were illuminated by themselves at any time. For the staggered profile type, each of the RGB components were energized sequentially (red, green, then blue) over the entire cycle to create chromatic flicker, so that each component had a duty cycle of 33%, but one of the RGB components was on throughout the entire cycle (Figure 2b), and the resulting duty cycle was 100%. For the spaced profile type, each of the RGB components started at staggered times separated by one-third of the cycle duration, but the duration of each component was only 20% of the entire cycle so that between each RGB component there was a duration where none of the colour components were energized (Figure 2c). The resulting duty cycle of this chromatic flicker condition was 60%. Finally, for the constant profile type, all three RGB components were energized continuously (producing an achromatic appearance) without any flicker (Figure 2d) and a resulting duty cycle of 100%.

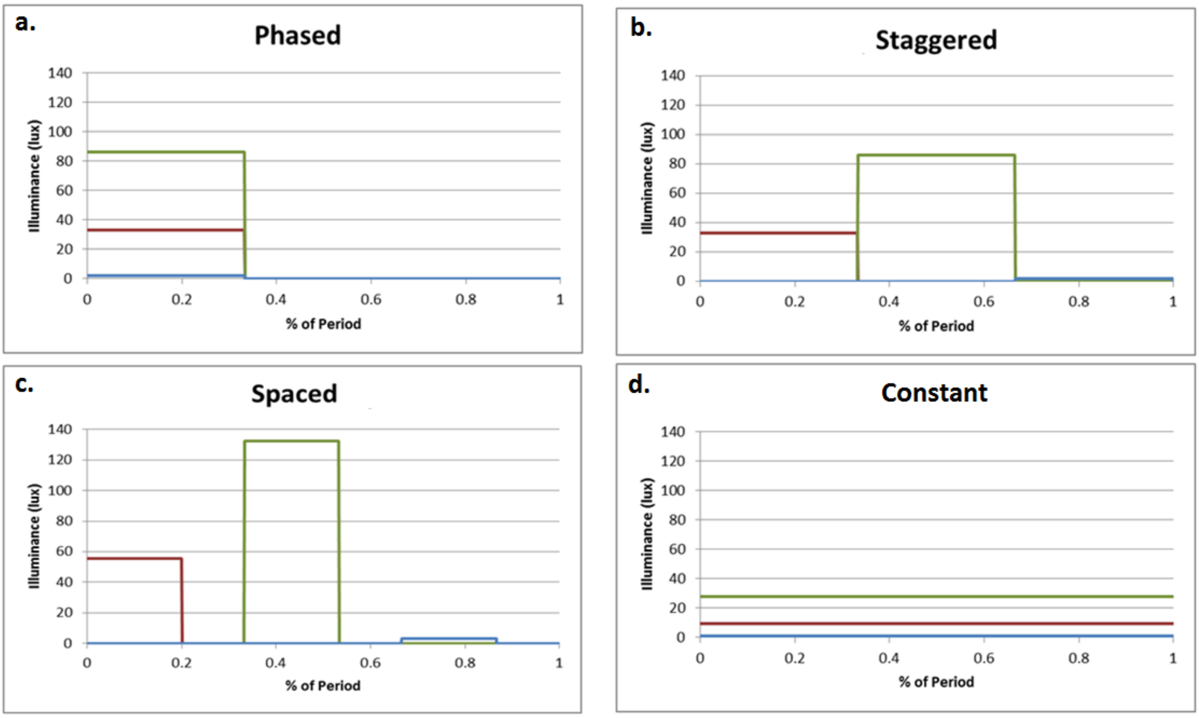


**Figure 2 – Temporal Profile Types Used in the Experiment (a: Phased, b: Staggered, c: Spaced, d: Constant)**

Each of the first three profile types (phased, staggered and spaced) could be generated with an overall frequency of 100, 300 or 1000 Hz. (Since the constant profile type did not produce any flicker, it does not have a frequency.) This resulted in a total of 10 experimental conditions (three profile types × three frequencies + constant). These conditions were presented to each of 12 observers twice in a randomized order for each observer. Before participating, subjects signed an informed consent form approved by Rensselaer's Institutional Review Board (IRB).

For each experimental trial, once the lighting condition was set, observers were asked to read a few sentences of laser-printed text on a piece of office paper, and to wave their hands and a light-coloured rod back and forth under the aperture of the sphere. After a short time, each observer was asked to provide answers to the following questions:

- Were you able to detect any colour separation or colour flicker?
- Were you able to detect any stroboscopic effects at all (either achromatic or chromatic)?

- How acceptable would you judge the flicker characteristics of this condition as general lighting for office work (-2: very unacceptable, -1: somewhat unacceptable, 0: neither acceptable nor unacceptable, +1: somewhat acceptable, +2: very acceptable)?

If no stroboscopic effects were detected at all for a given condition, the last question was assigned a response value of +2. Each experimental session took about 15 minutes.

# 3 Results

## 3.1 Detection of Chromatic Effects

Figure 3 shows the percentage responses to the first question about detecting colour effects, for each of the three modulating profile types (phased, staggered, spaced), as a function of the frequency at which they were displayed. As a check against false positive responses, none of the observers ever reported detecting colour effects for the constant temporal profile.

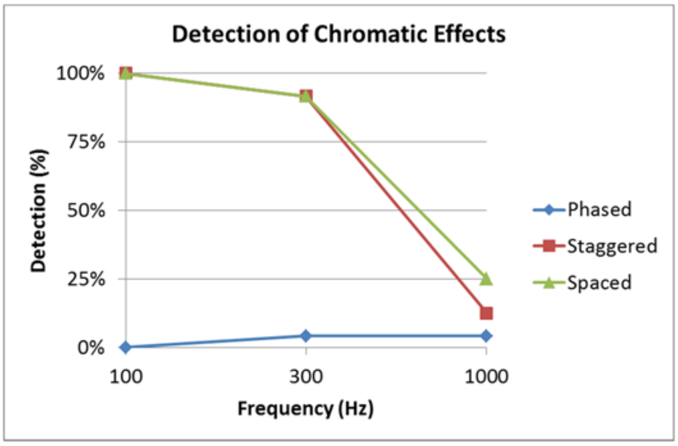


**Figure 3 – Detection of Chromatic Effects for Each of the Flickering Lighting Conditions**

In general, Figure 3 shows that it was generally more difficult to detect chromatic effects as the frequency increased from 100 to 1000 Hz. For the phased temporal profile type, when the RGB light pulses were simultaneous (thus producing only white light), colour effects were generally imperceptible.

A binary logistic regression analysis was performed on the data in Figure 2 to identify any statistically reliable effects. Both the flicker frequency ($p<0.05$) and the temporal profile type ($p<0.001$) demonstrated reliable effects. The two-way interaction between frequency and profile type was also statistically reliable ($p<0.001$).

## 3.2 Detection of Stroboscopic Effects (Chromatic or Achromatic)

Figure 4 illustrates how likely observers were to detect stroboscopic effects of any type, whether they were chromatic or achromatic (if they responded "yes" to the first question, the answer to this question was automatically assigned an answer of "yes"). Again, as the flicker frequency increased from 100 to 1000 Hz, detection was more difficult. At 100 and 300 Hz, detection of stroboscopic effects was high for all three profiles (and highest for 100 Hz, with a detection percentage of 100%); at 1000 Hz, detection was highest for the phased profile and lowest for the spaced profile.

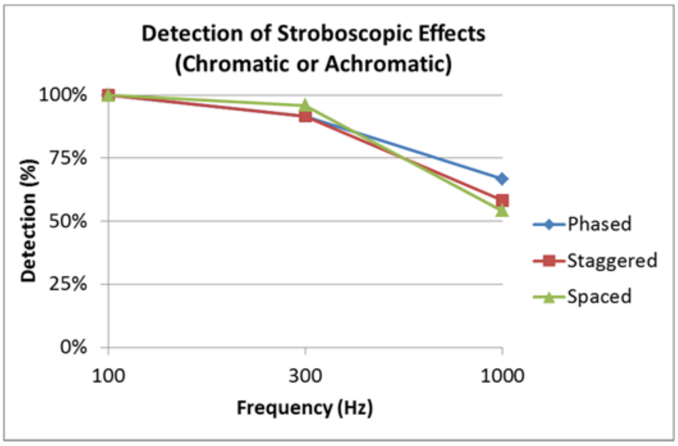


**Figure 4 – Detection of Chromatic or Achromatic Stroboscopic Effects for Each of the Flickering Lighting Conditions**

Despite the trends evident in Figure 3, a binary logistic regression analysis on the data in Figure 4 revealed no statistically reliable main effects ($p>0.05$) of flicker frequency nor of the temporal profile type, nor was there a statistically reliable interaction ($p>0.05$) between these factors on the detection of stroboscopic effects.

### 3.3 Acceptability for Office Work

Figure 5 shows the mean rating values for the question of how acceptable each lighting conditions was for general office lighting. Acceptability increased as the flicker frequency increased from 100 to 1000 Hz. There was also a slightly higher mean acceptability rating for the phased condition (producing achromatic flicker) at each frequency, especially at a frequency of 100 Hz.

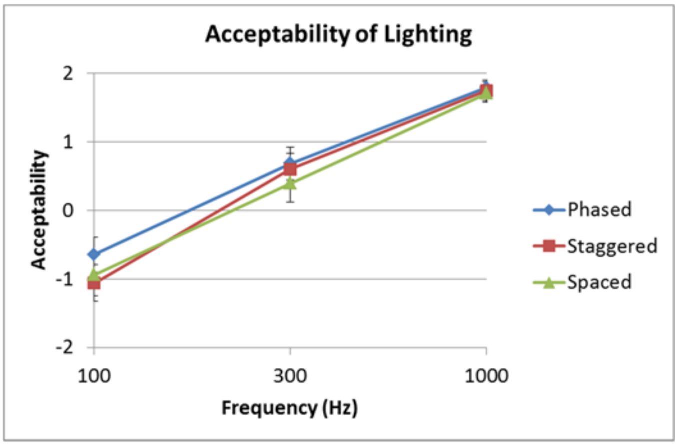


**Figure 5 – Mean (+/- S.E.M.) Ratings of Acceptability for Each of the Flickering Lighting Conditions**

A repeated-measured analysis of variance (ANOVA) on the acceptability ratings revealed statistically reliable main effects of both the flicker frequency ($p<0.001$) and the temporal profile type ($p<0.05$) on acceptability, but no statistically reliable interaction ($p>0.05$) between them.

## 4 Discussion

The results of this preliminary experimental investigation suggest that depending upon how they are driven, RGB LED lighting systems could elicit noticeable chromatic stroboscopic effects such as colour separation in the presence of moving objects. Obviously, and not unexpectedly, driving RGB light sources that use sequential displays of colours at higher frequencies can reduce the likelihood of detecting chromatic effects. Possibly, temporal profiles with dark intervals will increase the likelihood of detecting chromatic effects (e.g., the spread between the staggered and spaced temporal profile types in Figure 3 at 1000 Hz), but this only seems to occur when the flicker frequency is high enough so that chromatic effects are not always seen. In general, differences among the temporal profile types in the present study were small compared to differences among the flicker frequencies used.

Finally, it is interesting to note that detection and acceptability did not always appear to follow the same trends. For example, it was easier to detect any type of stroboscopic effects from the phased profile type (which was achromatic) than from the others (at least at 1000 Hz, as shown in Figure 4). However, despite that (nonsignificant) difference, this profile had slightly higher acceptability, especially at a frequency of 100 Hz (as shown in Figure 5).

Existing metrics for quantifying flicker do not adequately address chromatic flicker. Bullough and Marcus (2016) defined a frequency-modified version of flicker index ($FI_m$), defined as:

$$FI_m = 100\,FI/f \qquad (1)$$

where FI is the flicker index and $f$ is the fundamental frequency (in Hz) of the temporal waveform. Bullough and Marcus (2016) found that this modified flicker index provided a good way to rectify the stimulus for flickering waveforms varying in waveform shape, duty cycle and frequency, in terms of detection and acceptability. Figures 6, 7 and 8 show the relationships between the modified flicker index and the mean responses to each question in the present study, for each lighting condition. It can be seen that while the modified flicker provides a reasonable rectification for detection of stroboscopic effects (achromatic or chromatic) overall (Figure 7), it is a relatively poor rectifying variable for chromatic effects (Figure 6).

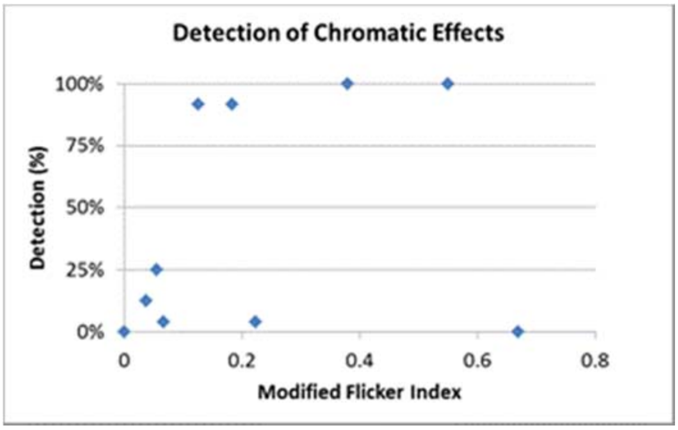


**Figure 6 – Detection of Chromatic Effects in the Present Study as a Function of Modified Flicker Index**

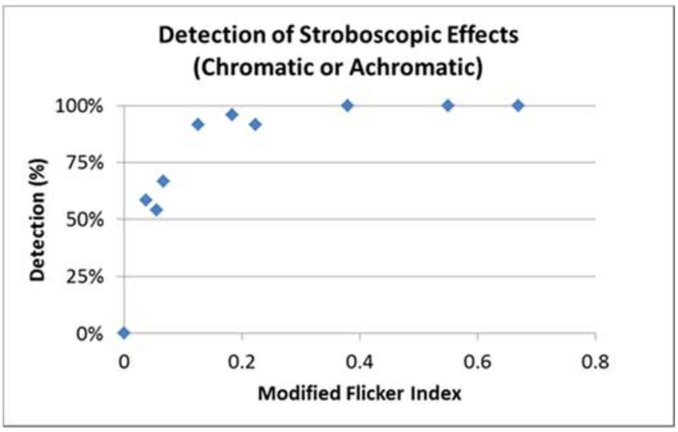


**Figure 7 – Detection of All Stroboscopic Effects (Achromatic or Chromatic) in the Present Study as a Function of Modified Flicker Index**

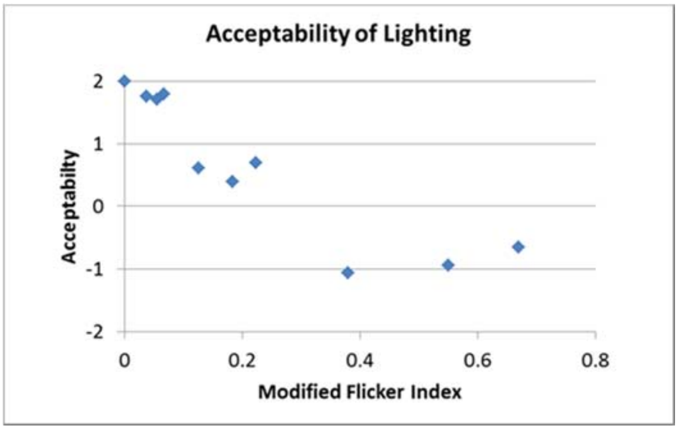


**Figure 8 – Acceptability of All Lighting Conditions in the Present Study, as a Function of Modified Flicker Index**

Regarding the acceptability ratings, the data in Figure 8 appear to be moderately correlated with the modified flicker index, but there is a systematic pattern whereby the phased (achromatic) temporal profiles had the highest mean acceptability rating at each frequency. The phased profiles had higher flicker index values than the chromatic temporal profiles (staggered and spaced) and would otherwise have been expected to have the lowest acceptability.

Overall, the present results indicate that chromatic stroboscopic effects can be detected with some success at frequencies as high as 1000 Hz. They also suggest that frequency-modified flicker index is a good predictor of stroboscopic effect detection and acceptability overall, but not for chromatic effects specifically.

## 5 Acknowledgments

This study was supported by the members of the Alliance for Solid State Illumination Systems and Technologies (ASSIST). N. Narendran and J.P. Freyssinier from the Lighting Research Center are gratefully acknowledged for their contributions to the study.

## References

ALLIANCE FOR SOLID STATE ILLUMINATION SYSTEMS AND TECHNOLOGIES. 2012. *Flicker Parameters for Reducing Stroboscopic Effects from Solid-state Lighting Systems.* Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

ALLIANCE FOR SOLID STATE ILLUMINATION SYSTEMS AND TECHNOLOGIES. 2014. *Application Considerations Related to Stroboscopic Effects from Light Source Flicker*. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

ALLIANCE FOR SOLID STATE ILLUMINATION SYSTEMS AND TECHNOLOGIES. 2015. *Recommended Metric for Assessing the Direct Perception of Light Source Flicker*. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

ALLIANCE FOR SOLID STATE ILLUMINATION SYSTEMS AND TECHNOLOGIES. 2017. *Evaluating Light Source Flicker for Stroboscopic Effects and General Acceptability*. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

BULLOUGH, J.D., MARCUS, D. 2016. Influence of Flicker Characteristics on the Perception of Stroboscopic Effects. *Lighting Res. Technol.*, 48, 857-870.

COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE. 2016. *Visual Aspects of Time-Modulated Lighting Systems: Definitions and Measurement Models,* TN 006:2016. Vienna, Austria: Commission Internationale de l'Éclairage.

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS. 2015. *Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers*, IEEE 1789-2015. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

JÄRVENPÄÄ, T. 2005. Measuring Color Breakup of Stationary Images in Field-Sequential-Color Displays. *J. Soc. Info. Disp.*, 13, 139-144.

JIANG, Y., ZHOU, K., HE, S. 2007. Human Visual Cortex Responds to Invisible Chromatic Flicker. *Nat. Neurosci.*, 10: 657-662.

JOHNSON, P.V., KIM, J., BANKS, M.S. 2014. The Visibility of Color Breakup and a Means to Reduce It. *J. Vis.*, 14, 10.

NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION. 2017. *Temporal Light Artifacts: Test Methods and Guidance for Acceptance Criteria*, Publication 77-2017. Rosslyn, VA: National Electrical Manufacturers Association.

POST, D.L., MONNIER, P., CALHOUN, C.S. 1997. Predicting Color Breakup on Field-Sequential Displays. *Proc. SPIE*, 3058, 57-65.

SEKULOVSKI, D., VOGELS, I.M.,VAN BEURDEN, M. CLOUT, R. 2007. Smoothness and Flicker Perception of Temporal Color Transitions. *Proc. 15$^{th}$ Color Imag. Conf.*, Albuquerque, NM: Society for Imaging Science and Technology.

VAN DER HORST, G.J. 1969. Chromatic Flicker. *J. Opt. Soc. Am.*, 59: 1213-1217.

WILKINS, A., VEITCH, J., LEHMAN, B. 2010. LED Lighting Flicker and Potential Health Concerns: IEEE Standard PAR1789 Update. *IEEE Energy Conv. Cong. Expo.*, Atlanta, GA: Institute of Electrical and Electronics Engineers.

YOHSO, A., UKAI, K. 2006. How Color Break-Up Occurs in the Human-Visual System: The Mechanism of the Color Break-Up Phenomenon. *J. Soc. Info. Disp.*, 14, 1127-1133.

ZHANG, X., FARELL, J.E. 2003. Sequential Color Breakup Measured with Induced Saccades. *Proc. SPIE*, 5007, 210-217.