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**ASSIST** *recommends...*

# Application Considerations Related to Stroboscopic Effects from Light Source Flicker

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## Abstract

This issue of *ASSIST recommends* describes new experimental data that illustrate how detection and acceptability of stroboscopic effects might change under different conditions that might be more applicable to certain lighting applications. Additionally, a framework for evaluating different applications based on the importance of flicker is provided, with several examples included.

## Document Revision History

Summarized below are the major changes made to this *ASSIST recommends* document during each revision. The most recent revision supersedes all previous versions.

### ***August 2015 revision***

This revision includes two new sections, entitled "Additional Considerations for 100-120 Hz Flicker" and "Percent Flicker and Flicker Index as Metrics for Stroboscopic Effects."

## Introduction

As described in *ASSIST recommends... Flicker Parameters for Reducing Stroboscopic Effects from Solid-state Lighting Systems* (Bullough et al. 2012a), nearly all light sources flicker, primarily as a consequence of mains electrical power systems using alternating current (AC) operating at frequencies at 50 Hz (in most of the world) or 60 Hz (mainly in North America). AC power at these frequencies tends to result in light modulation with twice these frequencies (100 Hz or 120 Hz). Light modulation at these frequencies is not directly visible (Kelly 1961; Bullough et al. 2011) but can be perceived indirectly through stroboscopic effects, at frequencies well above 120 Hz (Hershberger et al. 1998; Bullough et al. 2011; Perz et al. 2014) and even exceeding 1000 Hz (Bullough et al. 2012b; Roberts and Wilkins 2013). Stroboscopic effects from flicker can also interfere with visual performance of some tasks (Veitch and McColl 1995; Jaen et al. 2011; Bullough et al. 2013).

Based on initial findings (Bullough et al. 2011) that the flicker frequency and the amount of modulation (characterized either by percent flicker [Rea, 2000] or flicker index [Eastman and Campbell 1952]) were the most important parameters related to detection of stroboscopic effects, Bullough et al. (2012b) investigated the detection and acceptability of stroboscopic effects varying in frequency between 100 Hz and 10,000 Hz, and with the amount of modulation ranging from 5% flicker to 100% flicker (and having flicker indices from 0.03 to 0.5). The visual task used to assess stroboscopic effects was rapidly waving a white rod back and forth against a black background underneath a flickering light source, with no other source of illumination present.

The percentage of times that the stroboscopic effects were detected ( $d$ ) was modeled by the following equation:

$$d = \frac{25p+140}{f+25p+140} \times 100\% \quad (\text{Eq. 1})$$

where  $f$  is the flicker frequency (in Hz) and  $p$  is the percent flicker value; for the rectangular, 50%-duty-cycle waveforms used by Bullough et al. (2012b), the relationship between the flicker index ( $I_f$ ) and percent flicker value ( $p$ ) is given by (the relationship between flicker index and percent flicker is dependent upon the specific temporal waveform shape):

$$p = 2I_f \times 100\% \quad (\text{Eq. 2})$$

Bullough et al. (2012b) also asked observers to rate the acceptability of the stroboscopic effects on a scale of  $-2$  (very unacceptable) to  $+2$  (very acceptable). The average ratings of acceptability ( $a$ ) of stroboscopic effects were also modeled as follows:

$$a = 2 - \frac{4}{1 + \frac{f}{130 \log_{10} p - 73}} \quad (\text{Eq. 3})$$

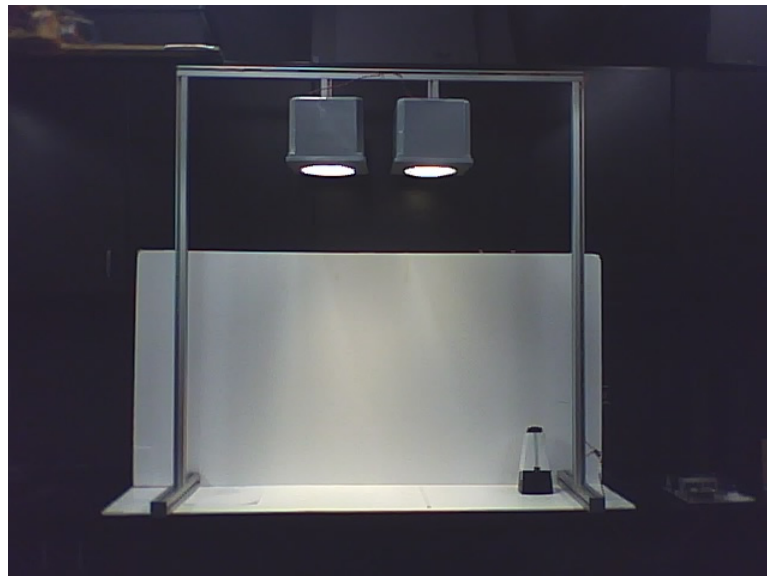
where  $f$  and  $p$  are defined as above. The rapid, high-contrast task used by Bullough et al. (2012b) maximized observers' ability to detect the stroboscopic effects and served as a sort of worst-case scenario for predicting when these effects could be seen and how acceptable or unacceptable they might be judged. Yet in many applications, lighting conditions do not maximize perceptions of

stroboscopic effects. This issue of *ASSIST recommends* describes new experimental data that illustrate how detection and acceptability might change under different conditions that might be more applicable to certain lighting applications. Additionally, a framework for evaluating different applications based on the importance of flicker is provided, with several examples included.

## Factors Mitigating Visual Responses to Flicker

In order to understand how different aspects of the luminous environment and of the visual tasks performed in an environment might influence the detection and acceptability of stroboscopic effects from flickering light, a small human factors study was performed. In contrast to previous experiments (Bullough et al. 2011; Bullough et al. 2012b), the present study used light-colored surfaces in the field of view, and two tasks for the assessment of stroboscopic effects (Figure 1):

- Waving a white rod back and forth under the luminaire; this was identical to the task used by Bullough et al. (2012b) except the background was now white rather than black, resulting in greatly reduced luminance contrast.
- Viewing a mechanical metronome consisting of a specular pendulum bar and a white-covered tempo scale; the sliding weight of the metronome was adjusted to its lowest position to produce a rhythm of 208 beats per minute (about 3.5 Hz). The motion of the pendulum bar was substantially slower than that of the rod being waved back and forth.



**Figure 1. Photograph of test space in the present human factors study.**

The illumination in the test space was provided by light-emitting diode (LED) lamps mounted above the horizontal surface of the test space. The horizontal illuminance in the center of the horizontal surface was 300 lx. The LED lamps were controlled by a custom driver that permitted operating the lamps at different frequencies and different amounts of modulation with rectangular temporal waveforms having a duty cycle of 50%. For this experiment, the amount of modulation was always set to 25% flicker, corresponding to a flicker index of 0.13. The frequency could be adjusted to 100, 200, 500 or 1000 Hz. Ten participants (age 28-52 years, mean 38 years) viewed each of the four conditions in a randomized order and answered the following questions:

- Did they detect stroboscopic effects when waving the rod back and forth rapidly?
- Did they detect stroboscopic effects when viewing the metronome's pendulum bar?
- How acceptable (−2: very unacceptable to +2: very acceptable) were the stroboscopic effects, if detected (if not detected the rating was assigned a value of +2)?

Figure 2 shows the detection percentages for both tasks, and Figure 3 shows the overall mean acceptability ratings for each of the four experimental conditions. Worst-case predictions based on the model described by Equations 1 and 3 are also shown in the figures.

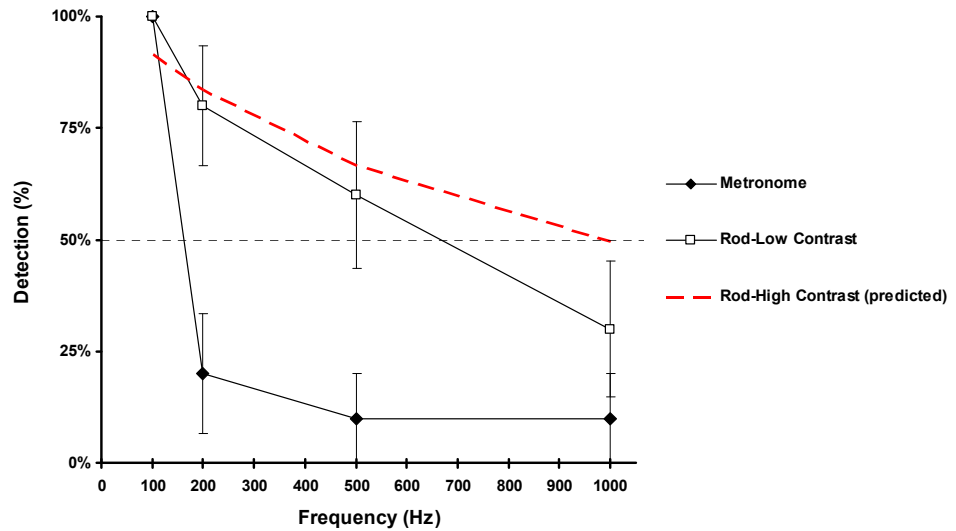
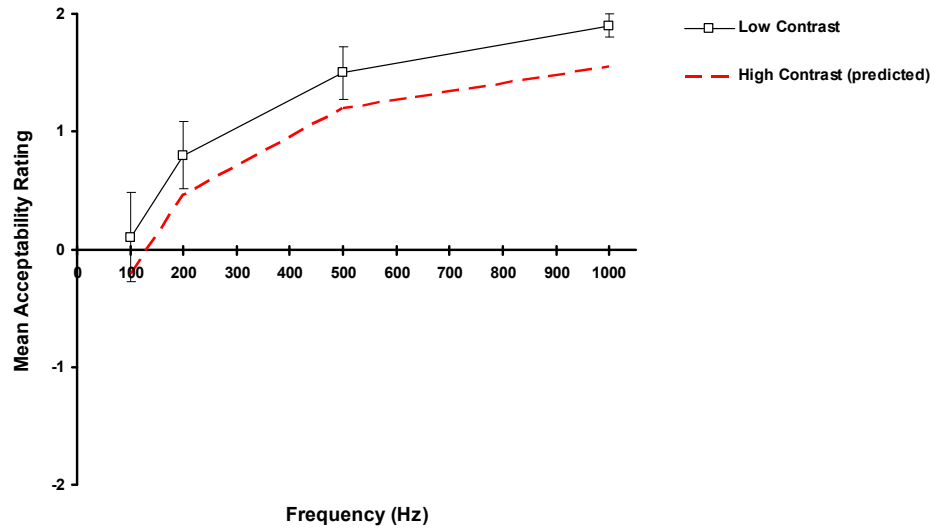


Figure 2. Detection percentages ( $\pm$ s.e.m.) for stroboscopic effects when waving a white rod against a white background (squares) and when viewing the metronome (diamonds). Also shown (dashed line) are the predicted detection percentages for waving a white rod against a black background (a high-speed, high-contrast task), based on Equation 1 (Bullough et al. 2012b).



**Figure 3. Acceptability ratings ( $\pm$ s.e.m.) for stroboscopic effects (squares) after waving a white rod against a white background and viewing the metronome. Also shown (dashed line) are the predicted acceptability ratings after waving a white rod against a black background (a high-speed, high-contrast task), based on Equation 3 (Bullough et al. 2012b).**

The data in Figures 2 and 3 show how perceptions of stroboscopic effects are strongly influenced by the nature of the visual task. In general, detection for the tasks in the present study are lower than the model predictions, and ratings of acceptability are slightly higher. For the high-speed, high-contrast task used by Bullough et al. (2012b) to develop their model, detection of stroboscopic effects is above threshold (defined as a detection percentage of 50%) for frequencies up to nearly 1000 Hz. Reducing the contrast reduces the frequency at threshold to approximately 670 Hz, and reducing the speed of motion results in a very large reduction in the frequency at threshold, to about 160 Hz. For the ratings of acceptability, this question was asked after observers performed both visual tasks in the present study, so the increase in acceptability for data in Figure 3 compared to the worst-case predictions from Bullough et al. (2012b) may be attributable to either the reduction in speed or the reduction in contrast. The frequency at which numerical ratings changed between positive and negative was predicted to be near 130 Hz for the high-speed, high-contrast visual task, but was reduced to about 90 Hz under the conditions of the present experiment with the low-contrast background and presence of the lower-speed visual task.

Together, the results of this experiment, in comparison with the model predictions based on Equations 1 and 3, show how detection and acceptability of stroboscopic effects can be influenced by the characteristics of the visual task and the visual environment. Conditions that may be frequently detected and judged as unacceptable for some applications may be rarely detected and thus judged as acceptable in others.

## Application-specific Guidance

The literature and data described in the previous section of this document serve to demonstrate that sensitivity to stroboscopic effects from flickering light is not uniform across all environments and for all visual tasks. For example, in a room that contains mainly light-colored finishes and in which movement of light-colored



objects occurs, stroboscopic effects will not be as noticeable as in a room with the same activity but with dark-colored finishes.

Similarly, the type of task will also influence if, and how, stroboscopic effects from flickering light are perceived and judged. If a task is largely stationary, stroboscopic effects are more likely to go unnoticed, but if a task involves rapidly-moving objects it will generally be easier to see.

Table 1 lists several applications and visual tasks that might occur for those applications. In this table, a relative level of the importance of flicker to the performance of the task is provided, with justification based on basic or applied research included. This table provides a simple framework with which lighting specifiers can assess how critical stroboscopic effects from flicker might be in a given situation.

Further guidance on the relative importance of flicker and stroboscopic effects is also summarized in the 9<sup>th</sup> edition of the *IESNA Lighting Handbook* (Rea 2000), Chapter 10, Quality of the Visual Environment. This chapter lists a wide array of visual tasks for many lighting applications and gives a qualitative assessment of the importance of flicker and stroboscopic effects for each task. For example, the importance of flicker and stroboscopic effects is rated as "Very Important" for tennis, which involves a fast-moving ball, but is rated as "Not Important" for target shooting, which is performed when primarily standing still. The data from the 9<sup>th</sup> edition of the *IESNA Lighting Handbook* can be a useful first step in evaluating the sensitivity of various tasks and locations to flicker, which are not listed in Table 1.

**Table 1. Relative importance of flicker and stroboscopic effects for visual tasks performed in several different applications.**

Application	Visual Task	Relative Importance of Flicker	Justification
Industrial facilities	Work on high-speed equipment	High	Stroboscopic effects can be visible at frequencies exceeding 1000 Hz when rapid motion is present (Bullough et al. 2012b)
	Stationary work or work on low-speed equipment	Medium	When speed of motion is low or moderate, stroboscopic effects can be difficult to see at frequencies above 160 Hz (Figure 2 of present document)
Office / school facilities	Computer-based work	Low	Flicker/stroboscopic effects were barely detectable at 100-120 Hz when working on computer (Bullough et al. 2011) and rated very acceptable
	Paper-based work	Medium	Visual performance of some tasks is reduced under high-modulation flicker at 100-120 Hz (Veitch and McColl 1995; Jaen et al. 2011; Bullough et al. 2013)
Outdoor locations	Basic orientation	Low	Flicker/stroboscopic effects were barely detectable at 100-120 Hz when viewing stationary objects and scenes (Bullough et al. 2011)
	Vehicle driving	Low	Flicker modulation at 100-120 Hz is high with commonly used high pressure sodium lamps (Navigant 2012) but not judged to be problematic (Lehman and Wilkins 2014)
Retail / gallery spaces	Viewing art / merchandise	Low	Flicker/stroboscopic effects were barely detectable at 100-120 Hz when viewing stationary objects and scenes (Bullough et al. 2011)
Sports facilities	Playing sports	Medium	High-modulation flicker at 120 Hz can be objectionable to players and/or spectators (Rea and Ouellette 1988); reducing modulation at these frequencies increases acceptability.

As an example of how a specifier might develop limits in a specific application, consider stationary or low-speed work as might be performed in an industrial facility or workshop. Based on Figure 2, stroboscopic effects for low movement speeds are difficult to detect when the frequency of flicker is above 160 Hz and the percent flicker is 33% (flicker index of 0.165 for the waveform shape used in that study). Using the detection prediction model from *ASSIST recommends...Flicker Parameters for Reducing Stroboscopic Effects from Solid-State Lighting Systems* (Bullough et al. 2012a), the same level of detection is achieved under the following conditions:

- 100 Hz, 19% flicker (0.093 flicker index)
- 120 Hz, 23% flicker (0.117 flicker index)
- 240 Hz, 53% flicker (0.263 flicker index)
- 440 Hz (or higher), 100% flicker (0.5 flicker index)

A specifier could use these values in identifying a lighting system for the application that would not produce more detectable stroboscopic effects than 160 Hz, 33% flicker (0.165 flicker index).

Similarly, a specifier could use the acceptability data in Figure 3 for applications involving low movement speed or low-contrast object motion, when high-speed, high-contrast motion, such as the light-colored rod waved rapidly against a black background, is not present. Based on Figure 3, a positive average acceptability rating value is just achieved under 100 Hz, 33% flicker (0.165 flicker index). Using the acceptability prediction model from *ASSIST recommends...Flicker Parameters for Reducing Stroboscopic Effects from Solid-State Lighting Systems* (Bullough et al. 2012a), the same level of acceptability is achieved under the following conditions:

- 120 Hz, 51% flicker (0.255 flicker index)
- 130 Hz, 65% flicker (0.325 flicker index)
- 140 Hz, 80% flicker (0.4 flicker index)
- 150 Hz (or higher), 100% flicker (0.5 flicker index)

A specifier could use these values in identifying a lighting system for the application that would not produce lower acceptability than 100 Hz, 33% flicker (0.165 flicker index).

## Additional Considerations for 100-120 Hz Flicker

As mentioned above, flicker frequencies of 100 and 120 Hz are common for many different light sources as a consequence of using 50 or 60 Hz AC for electrical power. Because flicker at 100 and 120 Hz is common (Bullough and Narendran 2012), several studies were reviewed to identify the level of modulation at which flicker at 100 or 120 Hz was either detectable, judged as problematic, or resulted in negative consequences such as discomfort. These studies are divided into three application categories as indicated in Table 1, where flicker is of low, medium, or high importance. Results are given in terms of percent flicker or flicker index, depending upon the study (some reported both). It should be noted that most of the studies on the perception of flicker at 100 to 120 Hz have used relatively short exposure durations; the primary exception is the study by Wilkins and Nimmo-Smith (1989).

### **Low Importance**

Applications for which flicker has low importance (Table 1) include outdoor lighting, and viewing self-luminous and stationary displays.

#### **Percent Flicker**

- **100% flicker** at 120 Hz (Bullough et al. 2011) was undetectable and judged as very acceptable while performing a self-luminous computer-based task.

#### **Flicker Index**

- **0.5 flicker index** at 120 Hz (Bullough et al. 2011) was undetectable and judged as very acceptable while performing a self-luminous computer-based task.

For these applications, the literature does not indicate that lighting conditions producing 100% flicker or a flicker index up to 0.5 are problematic for the acceptability of lighting.

### **Medium Importance**

Applications for which flicker has medium importance (Table 1) include reading and paper-based office tasks.

#### **Percent Flicker**

- **43% flicker** at 100 Hz (Wilkins et al. 1989) resulted in higher reported frequency of headaches and eyestrain than 7% flicker in an office setting.
- **43% flicker** at 120 Hz (Veitch and McColl 1995) resulted in poorer task performance and lower ratings of visual comfort for a low-contrast paper-based task than low-modulation high-frequency flicker.
- **90% flicker** at 100 Hz (Küller and Laike 1998) resulted in poorer paper-based proofreading performance and less pleasantness than 25% flicker for some subjects.
- **32% flicker** at 100 Hz (Jáen et al. 2011) resulted in longer paper-based visual search times and longer paper-based task completion times than 3% flicker.
- **100% flicker** at 100 Hz (Bullough et al. 2013) resulted in increased error rates on a paper-based visual task and lower levels of preference compared to 25% flicker.
- **22% flicker** at 120 Hz (Miller et al. 2013) elicited ratings between moderate flicker and almost no flicker while 7% flicker elicited ratings between no flicker and almost no flicker, in an office-type environment.

#### **Flicker Index**

- **0.14 flicker index** at 120 Hz (Veitch and McColl 1995) resulted in poorer task performance and lower ratings of visual comfort for a low-contrast paper-based task than low-modulation high-frequency flicker.
- **0.9 flicker index** at 120 Hz (Bullough et al. 2011) resulted in lower ratings of visual comfort than 0.5 flicker index.
- **0.5 flicker index** at 100 Hz (Bullough et al. 2013) resulted in increased error rates on a paper-based visual task and lower levels of preference compared to 0.125 flicker index.
- **0.07 flicker index** at 120 Hz (Miller et al. 2013) elicited ratings between moderate flicker and almost no flicker while 0.02 flicker index elicited ratings between no flicker and almost no flicker, in an office-type environment.

The median value for which detectable or unacceptable effects were found from 100-120 Hz flicker for these applications was 38% flicker or a flicker index of 0.32.

### **High Importance**

Applications for which flicker has high importance (Table 1) include those in which high-speed motion is present, such as industrial machinery and some sporting events.

**Percent Flicker**

- **84% flicker** at 120 Hz (Rea and Ouellette 1988) was judged unacceptable by spectators of a table tennis match, while 51% flicker was judged as acceptable.
- **54% flicker** at 100 Hz (Bullough et al. 2012) was judged negatively after rapidly waving an object under a task light, while 25% flicker was judged positively.
- **25% flicker** at 100 Hz (Bullough et al. 2012) was detected the majority of the time while rapidly waving an object under a task light.
- **5% flicker** at 120 Hz (Roberts and Wilkins 2013) in a flickering point-source light could be detected as a phantom array by observers the majority (63%) of the time.
- **4% flicker** at 120 Hz (Lehman and Wilkins 2014) was reported as the maximum unnoticeable modulation; **10% flicker** at 120 Hz was reported as the maximum "low risk" modulation.
- **25% flicker** at 100 Hz (Perz et al. 2015) could be detected the majority of the time while viewing a rapidly moving object under square wave flicker.

**Flicker Index**

- **0.25 flicker index** at 120 Hz (Rea and Ouellette 1988) was judged unacceptable by spectators of a table tennis match, while 0.15 flicker index was judged as acceptable.
- **0.5 flicker index** at 120 Hz (Bullough et al. 2011) was detected the majority of the time while rapidly waving a hand under a task light.
- **0.125 flicker index** at 100 Hz (Bullough et al. 2012) was detected the majority of the time while rapidly waving an object under a task light.
- **0.1 flicker index** at 100 Hz (Poplawski and Miller 2013) was judged as the maximum acceptable value for this frequency.
- **0.17 flicker index** at 100 Hz (Bullough and Marcus 2015) was the value above which observers judged stroboscopic effects unacceptable after viewing rapidly moving objects.

The median value for which detectable or unacceptable effects were found from 100-120 Hz flicker for these applications was 25% flicker or a flicker index of 0.17.

**Summary**

Table 2 summarizes the median percent flicker and flicker index values for each visual task or application classification (where flicker is of low, medium, or high importance). These median values could be used as the basis for a specification of flicker for different task/application classes; using light sources that produce percent flicker or flicker index values no greater than those in Table 2 could be expected, on average, to limit the perception of stroboscopic effects.

**Table 2. Summary of median percent flicker and flicker index values where stroboscopic effects were detected based on the literature review.**

Relative Importance of Flicker	Percent Flicker Criterion	Flicker Index Criterion
Low	100%	0.5
Medium	38%	0.32
High	25%	0.17

## Percent Flicker and Flicker Index as Metrics for Stroboscopic Effects

As indicated in the previous section, results on the perception of stroboscopic effects from flickering illumination have been made in terms of percent flicker or in terms of the flicker index. Bullough and Marcus (2015) conducted a study in which different temporal flicker waveforms at several frequencies (100, 120, 300 and 1000 Hz) were viewed. In one of their experiments, Bullough and Marcus compared waveforms all producing the same percent flicker (100%) but with variations in the flicker index. The results suggested that flicker index was a superior metric for characterizing stroboscopic effects than percent flicker. This finding is important because some published specifications for limiting stroboscopic effects (e.g., IEEE 2015) use percent flicker as the basis for their recommendations. Specifications based on flicker index will more meaningfully predict responses to stroboscopic effects than those based on percent flicker.

A weakness of both of these metrics is that they are independent of the frequency of flicker. For example, stroboscopic effects under a flicker index of 0.3 may be easily detected at 100 or 120 Hz, but may be difficult to detect at 1000 Hz. To facilitate comparisons in flicker index at different frequencies greater than or equal to 100 Hz, Bullough and Marcus (2015) developed a modified flicker index, where the flicker index is multiplied by  $100/f$  (where  $f$  is the frequency). They found that conditions with the same modified flicker index values were equally detectable and judged equally acceptable, even if they differed in frequency. The modified flicker index provides a way to compare temporal waveforms that product flicker, independently of their frequency.

## References

- Bullough, J. D. and D. Marcus. 2015. Influence of flicker characteristics on stroboscopic effects. *Lighting Research and Technology*, doi: 10.1177/1477153515599566.
- Bullough, J. D. and N. Narendran. 2012. Quantifying stroboscopic effects from flickering light sources. *Council for Optical Radiation Measurements 2012 Annual Conference*, Ottawa, ON, May 29-June 1.
- Bullough, J. D., K. Sweater Hickcox, T. R. Klein and N. Narendran. 2011. Effects of flicker characteristics from solid-state lighting on detection, acceptability and comfort. *Lighting Research and Technology* 43: 337-348.
- Bullough, J. D., K. Sweater Hickcox, T. Klein, A. Lok and N. Narendran. 2012a. *ASSIST recommends...Flicker Parameters for Reducing Stroboscopic Effects from Solid-State Lighting Systems*. Vol. 11, Iss. 1. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.
- Bullough, J. D., K. Sweater Hickcox, T. R. Klein, A. Lok and N. Narendran. 2012b. Detection and acceptability of stroboscopic effects from flicker. *Lighting Research and Technology* 44: 477-483.
- Bullough, J. D., N. P. Skinner and K. Sweater Hickcox. 2013. Visual task performance and perceptions of lighting quality under flickering illumination. *Journal of Light and Visual Environment* 37: 189-193.
- Eastman, A.A., and J.H. Campbell. 1952. Stroboscopic and flicker effects from fluorescent lamps. *Illuminating Engineering* 47: 27-35.

- Hershberger, W.A., S.S. Jordan, and D.R. Lucas. 1998. Visualizing the perisaccadic shift of spatiotopic coordinates. *Perception and Psychophysics* 60: 82-88.
- Institute of Electrical and Electronics Engineers. 2015. *IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers*, IEEE Standard 1789. New York: Institute of Electrical and Electronics Engineers.
- Jaén, E. M., E. M. Colombo and C. F. Kirschbaum. 2011. A simple visual task to assess flicker effects on visual performance. *Lighting Research and Technology* 43: 457-471.
- Kelly, D.H. 1961. Visual responses to time-dependent stimuli: I. Amplitude sensitivity measurements. *Journal of the Optical Society of America* 51: 422-429.
- Küller, R. and T. Laike. 1998. The impact of flicker from fluorescent lighting on well-being, performance and physiological arousal. *Ergonomics* 41: 433-437.
- Lehman, B. and A. J. Wilkins. 2014. Designing to mitigate the effects of flicker in LED lighting. *IEEE Power Electronics Magazine* 1: 18-26.
- Miller N. J., M. P. Royer and M. E. Poplawski. 2013. *CALiPER Exploratory Study: Recessed Troffer Lighting*. Richland, WA: Pacific Northwest National Laboratory.
- Navigant Consulting. 2012. *2010 U.S. Lighting Market Characterization*. Washington, DC: U.S. Department of Energy.
- Perz, M., I. M. L. C. Vogels, D. Sekulovski, L. Wang, Y. Tu and I. E. J. Heynderickx. 2014. Modeling the visibility of the stroboscopic effect occurring in temporally modulated light systems. *Lighting Research and Technology* 47: 281-300.
- Poplawski, M. E. and N. J. Miller. 2013. Flicker in solid state lighting: Measurement techniques, and proposed reporting and application criteria. *Proceedings of the Commission Internationale de l'Éclairage Centenary Conference*, Paris, France, April 15-16.
- Rea, M.S. (editor). 2000. *IESNA Lighting Handbook: Reference and Application*, 9th edition. New York: Illuminating Engineering Society.
- Rea, M.S., and M.J. Ouellette. 1988. Table-tennis under high intensity discharge lighting. *Journal of the Illuminating Engineering Society* 17: 29-35.
- Roberts, J. E. and A. J. Wilkins. 2013. Flicker can be perceived during saccades at frequencies in excess of 1 kHz. *Lighting Research and Technology* 45: 124-132.
- Veitch, J. A. and S. L. McColl. 1995. Modulation of fluorescent light: Flicker rate and light source effects on visual performance and visual comfort. *Lighting Research and Technology* 27: 243-256.
- Wilkins, A. J., I. Nimmo-Smith, A. I. Slater and L. Bedocs. 1989. Fluorescent lighting, headaches and eyestrain. *Lighting Research and Technology* 21: 11-18.



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## **About ASSIST**

The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) was established in 2002 by the Lighting Research Center as a collaboration among researchers, manufacturers, and government organizations. ASSIST's mission is to enable the broad adoption of solid-state lighting by providing factual information based on applied research and by visualizing future applications.