# Evaluating Flicker Performance of UL Type B LED Products for Campus Energy Projects

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# Temporal Light Modulation (TLM)

Fluctuation in luminous quantity or spectral distribution of light with respect to time [1], which can cause flicker (visible or invisible) and a range of perceptual or physiological responses.

https://www.lighttherapyinsiders.com/light-flicker-and-health/

[1] Commission Internationale De L'Eclairage. Guidance on the measurement of temporal light modulation of light sources and lighting systems. CIE TN 012:2021. Vienna, Austria: CIE, 2021.

# Why Does Flicker Matter?

https://medlineplus.gov/

1. TLM might cause discomfort (e.g., headaches, migraine, nausea, eye strain) and reduce visual task performance.

2. Old metrics have limited predictability, and new metrics are not widely adopted yet.

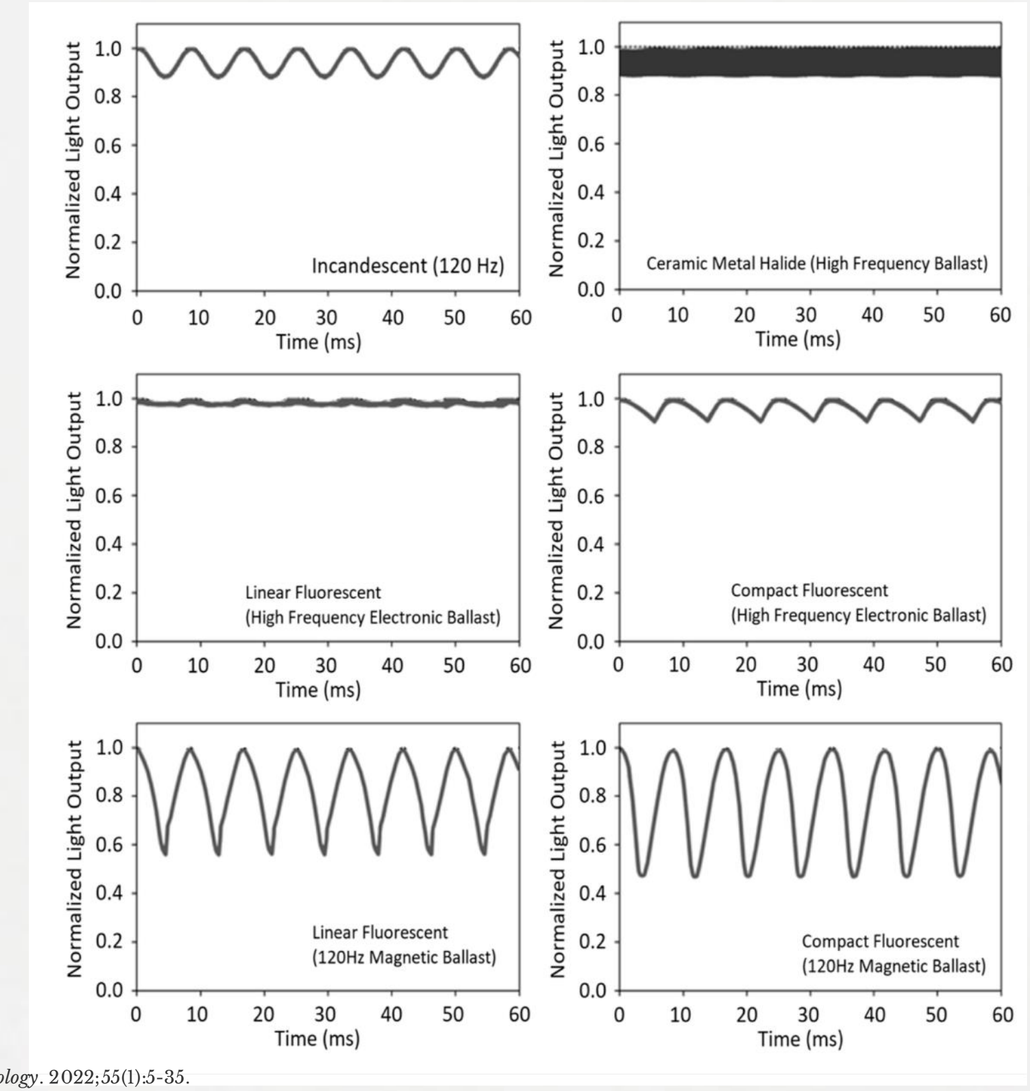
3. There is little “real-world” performance data available.

# Lighting Technology and TLM

TLM varies with lighting technology.

Veranda.com

https://science.howstuffworks.com

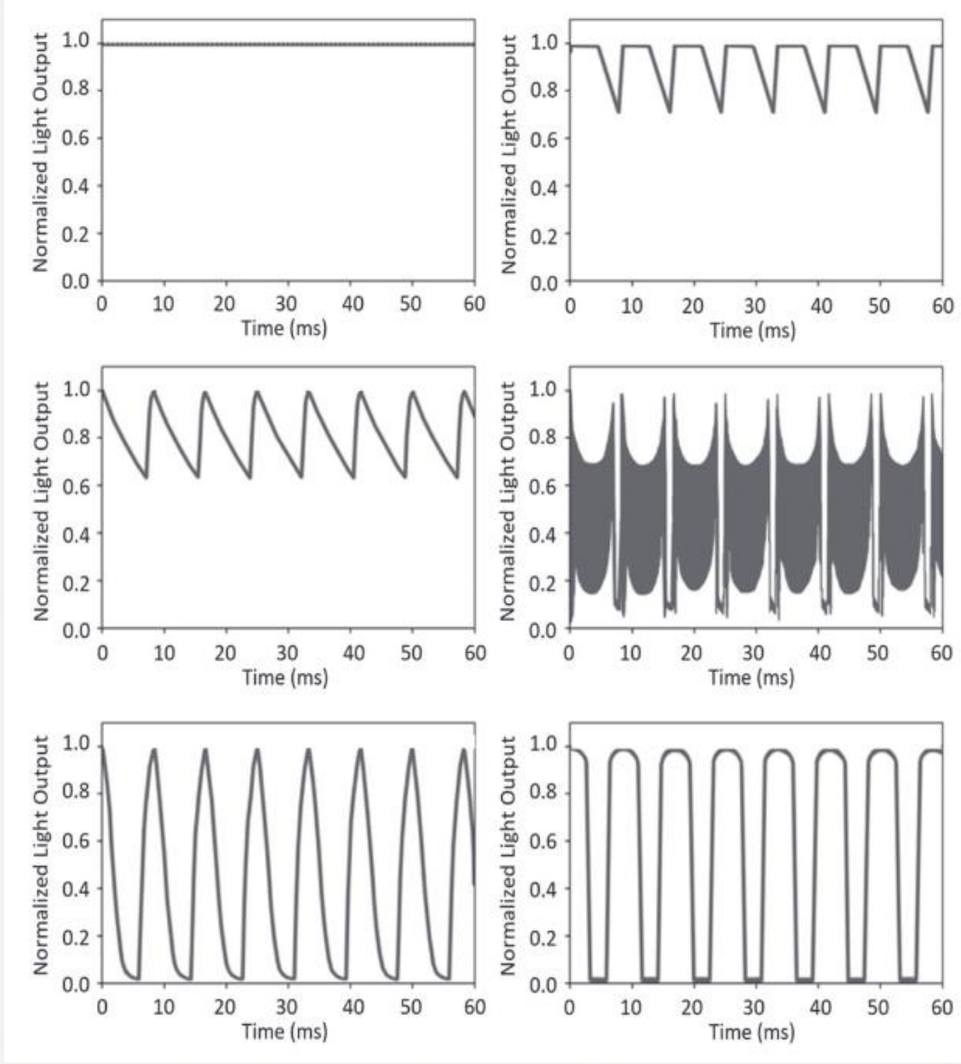



Miller N, Leon F, Tan J, Irvin L. Flicker: A review of temporal light modulation stimulus, responses, and measures. *Lighting Research & Technology*. 2022;*55*(1):5-35.

# Lighting Technology and TLM

LEDs can create waveforms with widely varying shapes, modulation depths, and duty cycles.

Ikea.com




Miller N, Leon F, Tan J, Irvin L. Flicker: A review of temporal light modulation stimulus, responses, and measures. *Lighting Research & Technology*. 2022;*55*(1):*5-35*.

# Types of TLM

**Visible Direct Flicker**

Direct perception of brightness fluctuations — light visibly “flickers.”

**Stroboscopic Effect**

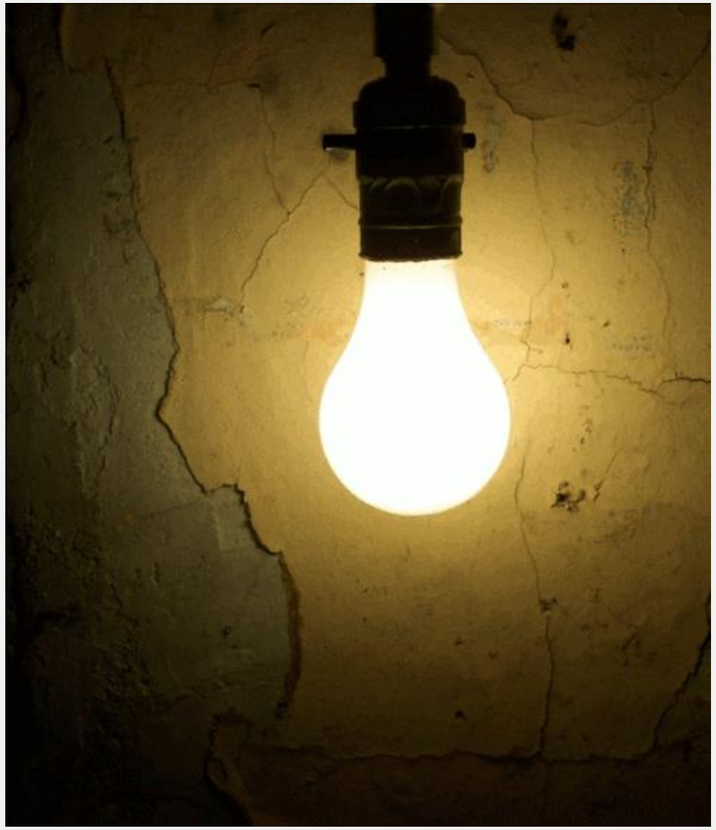
Moving objects appear to move discontinuously or blur unevenly.

**Phantom Array Effect**

Multiple stationary “images” appear when the eye moves rapidly (saccadic motion).

# Direct Flicker Effect / Perceived Flicker

Direct flicker is detected during **steady gaze** and refers to the visible fluctuation of a light source when its output varies due to inconsistent electrical power. It typically occurs between **3 and 90 Hz**, with peak sensitivity around 10–15 Hz.



https://ledtest.vestum.ua/wp-content/uploads/2021/07/%D0%BB%D0%B0%D0%BC%D0%BF%D1%8B.gif

Miller N, Leon F, Tan J, Irvin L. Flicker: A review of temporal light modulation stimulus, responses, and measures. *Lighting Research & Technology*. 2022;*55*(1):*5-35*.

# Findings

| Author | Year | Independent variable | Dependent variable | Findings |
|---|---|---|---|---|
| Sanae Y. et al. [1] | 2020 | Flicker contrast (modulation depth), mean light level, flicker frequency | Pupil size, discomfort, contrast threshold, naturalness evaluation | • Discomfort increases with mean light level increases<br>• Stronger modulation (higher contrast) leads to more discomfort<br>• Bright flicker is more uncomfortable than dim flicker<br>• Peak discomfort at 10–20 Hz (mid temporal frequencies). |
| Jaén, E.M. et al. [2] | 2011 | 4 light boxes with two fluorescent lamps, 2 light box | Discrimination task (Landolt task), visual search task [measure speed and errors) | • Flicker can affect the visual system at a non-conscious level<br>• Better performance in low TM condition than in high TM condition |
| Bullough, J. D., et al.[3] | 2011 | 3 LED sources | Perform arithmetic problems and questionnaire [measure flicker frequency, amount of modulation, duty cycle, waveform shape and CCT) | • At frequencies of 100 Hz and higher, perception of flicker was negligible<br>• Direct perception of flicker at frequencies of 60 Hz and lower was rated as unacceptable<br>• Lower comfort under the lower duty cycle |

[1] Yoshimoto, S., Jiang, F., Takeuchi, T., Wilkins, A.J. and Webster, M.A., 2020. Visual discomfort from flicker: Effects of mean light level and contrast. *Vision research*, *173*, pp.50-60.
[2] Jaén, E.M., Colombo, E.M. and Kirschbaum, C.F., 2011. A simple visual task to assess flicker effects on visual performance. *Lighting Research & Technology*, *43*(4), pp.457-471.
[3] Bullough, J.D., Sweater Hickcox, K., Klein, T.R. and Narendran, N., 2011. Effects of flicker characteristics from solid-state lighting on detection, acceptability and comfort. *Lighting Research & Technology*, *43*(3), pp.337-348.

# Direct Flicker Effect Metric ($M_P$)

The total perceived modulation is calculated as:

$$M_P = \sqrt{\sum_k (M_{P_k})^2}$$

$$k = 1, 2, 3, \ldots$$

If $M_k$ is higher than the detection threshold, the ratio is >1 (flicker likely visible).
If $M_k$ is lower than the threshold, the ratio is <1 (flicker likely not visible).

where the physical modulation of a frequency component is divided by the modulation detection threshold (M DTH) value for that frequency.

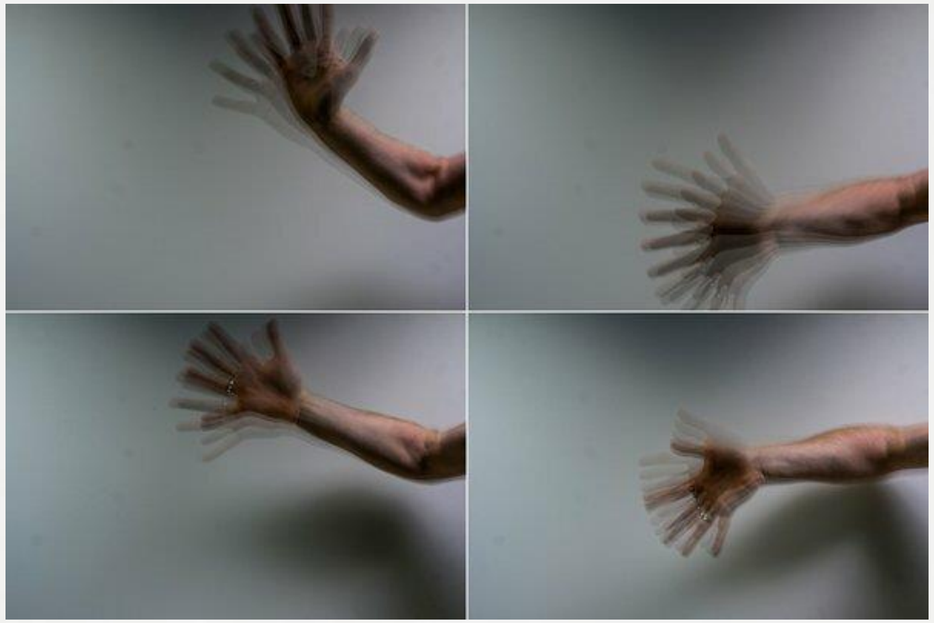
$$M_{P_k} = \frac{M_k}{M_{DTH_k}}$$

Bodington, D., Bierman, A., & Narendran, N. (2016). A flicker perception metric. *Lighting Research & Technology, 48*(5), 624-641.

# Stroboscopic Effect

Stroboscopic effect is the idea that when certain **TLM** interact with **moving objects** the object appears to be **blurred** or ‘jumping’ rather than smoothly gliding.

At TLM frequencies between 90 and 750 Hz, Stroboscopic Effect may be visible.



[1] Unknown author, 2019. *Stroboscopic effect image*. [image] Available at: <https://scx2.b-cdn.net/gfx/news/2019/stroboscopic.jpg> [Accessed 20 Oct. 2025]

# Findings

| Author | Year | Independent variable | Dependent variable | Findings |
|---|---|---|---|---|
| Matej Bernard Kobav, Matjaz Colaric [1] | 2018 | Frequency, modulation depth, waveform, spectrum | Visibility, discomfort, thresholds, and visual performance | LED lights with low modulation frequency oscillations cause stroboscopic effects |
| Malgorzata P, et al. [3] | 2018 | Illumination level, light waveforms, frequency, modulation depth | Contrast thresholds, perceived stroboscopic visibility | Stroboscopic effect is not detectable above 750 Hz |
| Mark Alexander Henney, et al | 2024 | heterochromatic light combinations, illuminance level | EEG response, Response Amplitude, Spectral Sensitivity | Amber and Red produced the strongest SSVEP (Steady-state visually evoked potentials) response<br><br>Heterochromatic flicker could be less invasive then stroboscopic on Alzheimer's disease |

[1] Kobav, M.B. and Colarič, M., 2018. Flicker experimental set-up and visual perception of flicker. In: *2018 IEEE International Conference on Lighting and Photometry*. IEEE. https://doi.org/10.1109/LS2463127.2018.XXXXX
[2] Kuiper, M., Mantela, V., Madias, E.-N., Källberg, S., Thorseth, A., Reiners, T., Klej, A., Zuber, R. and Dekker, P., 2024. Interlaboratory comparison on traceable flicker and stroboscopic effect measurements of light sources. In: *2024 IEEE Sustainable Smart Lighting World Conference & Expo (LS24)*. IEEE. https://doi.org/10.1109/LS2463127.2024.10881444
[3] Perz, M., Sekulovski, D., Vogels, I. and Heynderickx, I., 2018. *Stroboscopic effect: contrast threshold function and dependence on illumination level*. Journal of the Optical Society of America A, 35(2), pp.309–319. https://doi.org/10.1364/JOSAA.35.000309

# Stroboscopic Visibility Measure (SVM)

Ranges between 0 and 9. 1 represents a greater than 50% chance of detecting an effect.

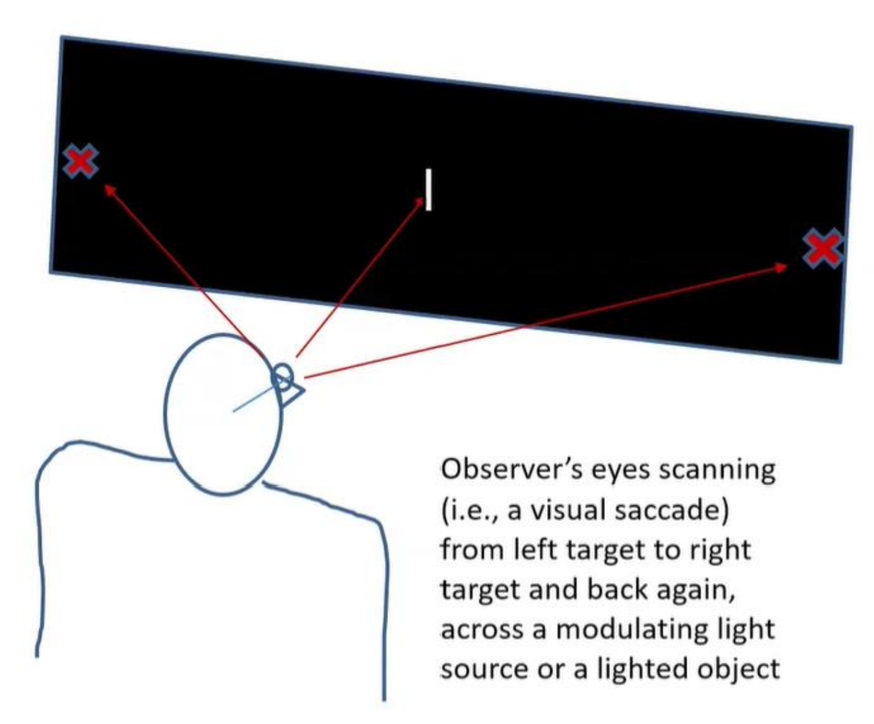
$$\mathrm{SVM} = \sqrt[3.7]{\sum_{m=1}^{\infty}\left(\frac{C_m}{T_m}\right)3.7}\begin{cases} < 1 \mathrm{not visibile} \\ = 1 \mathrm{just visibile} \\ > 1 \mathrm{visible} \end{cases}$$

where $C_{\mathrm{m}}$ is the amplitude of the $m$-th Fourier component and $T_{\mathrm{m}}$ is the visibility threshold for the stroboscopic effect for a sine wave at the frequency of the $m$-th Fourier component.

Perz, M., Vogels, I. M. L. C., Sekulovski, D., Wang, L., Tu, Y., & Heynderickx, I. E. J. (2015). Modeling the visibility of the stroboscopic effect occurring in temporally modulated light systems. *Lighting Research & Technology*, *47*(3), 281-300.

# Phantom Array Effect

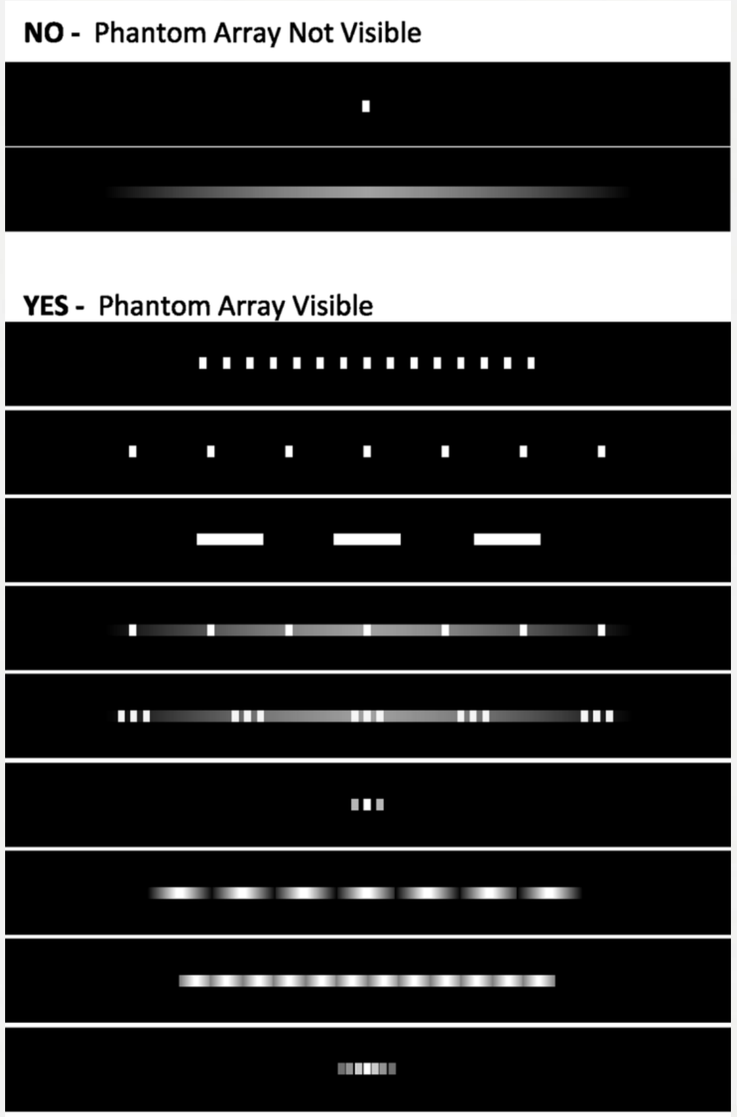
At TLM frequencies between 80 and 20,000 Hz observes may perceive the PAE




[1]

Involves the interaction of an observer's eye saccade relative to a modulating light source

The rapidly modulating light sources create the illusion of multiple images or light "trails" during saccadic eye movements




[2]

[1] Miller N. "Flicker: It's Not Just Annoying. New Results of Work on the Phantom Array Effect. Pacific Northwest National Laboratory, March 2025.
[2] Miller N, Irvin L, Royer M, Strachan C. Visibility and annoyance of the phantom array effect varies with age and history of migraine. Lighting Research & Technology. 2024;56:676-706.

# Findings

| Author | Year | Independent variable | Dependent variable | Findings |
|---|---|---|---|---|
| NJ Miller, et al. [1] | 2023 | TLM waveforms varying by frequency, waveform shape, modulation depth, duty cycle | Perceived visibility | • PAE visibility peaks between 500 -1000 Hz<br>• Waveforms with rectangular shape, high modulation depth, and lower duty cycles produce higher visibility for phantom array effects |
| HR Kang, et al. [2] | 2022 | LED color temp/spectral LED type (blue, red, green, warm white, cool white), temporal modulation frequency | Perceived visibility | • Spectrum and color matters: PAE remained visible at high frequencies for green and red LEDs<br>• Phantom array effect was visible up to 11 kHz |
| NJ Miller, et al. [3] | 2024 | Age group, migraine history, modulation frequency and waveform type | Perceived visibility<br>Annoyance | • Migraine group was more sensitive and more annoyed<br>• Peak visibility between 400 – 1,200 Hz of PAE<br>• More Modulation (full on to full off), there was more visibility |

[1] Miller N, Bermudez E, Irvin L, Tan J. Phantom array and stroboscopic effect visibility under combinations of TLM parameters. *Lighting Research & Technology.* 2024;56:707-733.
[2] Kang HR, Kim JG, Park SW, Lee C-S, Pak H. Visibility of the phantom array effect at different LED colour temperatures under high-frequency temporal light modulation. *Lighting Research & Technology.* 2023;55:36-46.
[3] Miller N, Irvin L, Royer M, Strachan C. Visibility and annoyance of the phantom array effect varies with age and history of migraine. *Lighting Research & Technology.* 2024;56:676-706.

# Phantom Array Visibility Measure (PAVM)

PAVM predicts visibility and annoyance from the waveforms

$$\mathrm{PAVM} = \sqrt[2.1]{\sum_{m=1}^{\infty} (C_m \cdot S_m)^{2.1}} \begin{cases} <1, \text{ not visible} \\ =1, \text{ just visible} \\ >1, \text{ visible} \end{cases}$$

where

$C_m$: Normalized amplitude of the $m$-th Fourier component (modulation strength)

$S_m$: Sensitivity of visual system at frequency

$n$ = 2.1 (Minkowski exponent scaling visibility)

Miller N, Royer M, Tan J, Irvin L. Temporal light modulation: A phantom array visibility measure. *Lighting Research & Technology*. 2024;56:772-789.

# Phantom Array Visibility Measure

| PAVM Value | Interpretation | % of People Likely to See it |
|---|---|---|
| < 0.5 | Very low visibility | Most people won't perceive it |
| 0.7 | Threshold for sensitive populations | About 50% of sensitive viewers detect it |
| 1.0 | Group Threshold | About 50% of general population detects it |
| > 4 | Strong PAE | Unacceptable in practice |

[1]

[ Miller N, Royer M, Tan J, Irvin L. Temporal light modulation: A phantom array visibility measure. *Lighting Research & Technology*. 2024;56:772-789.

**Table 11-1. Summary of Guidelines for Reducing Human Responses to TLM**

| | MINIMUM | GOOD | BETTER |
|---|---|---|---|
| **Metric Method** Direct Flicker | $M_p \leq 1.0$ | $M_p \leq 0.9$ | $M_p \leq 0.4$ For 6 Hz ≤ f ≤ 30 Hz, modulation ≤ 0.1% |
| Stroboscopic Effect | SVM≤1.6 | SVM≤0.9 | SVM≤0.4 |
| Phantom Array Effect | PAVM≤1.6 | PAVM≤0.9 | PAVM≤0.4 |
| **Alternate Frequency Method** | | | $f \geq 10.000$Hz for sinusoidal waveforms $f \leq 20.000$Hz all other or DC Waveform |

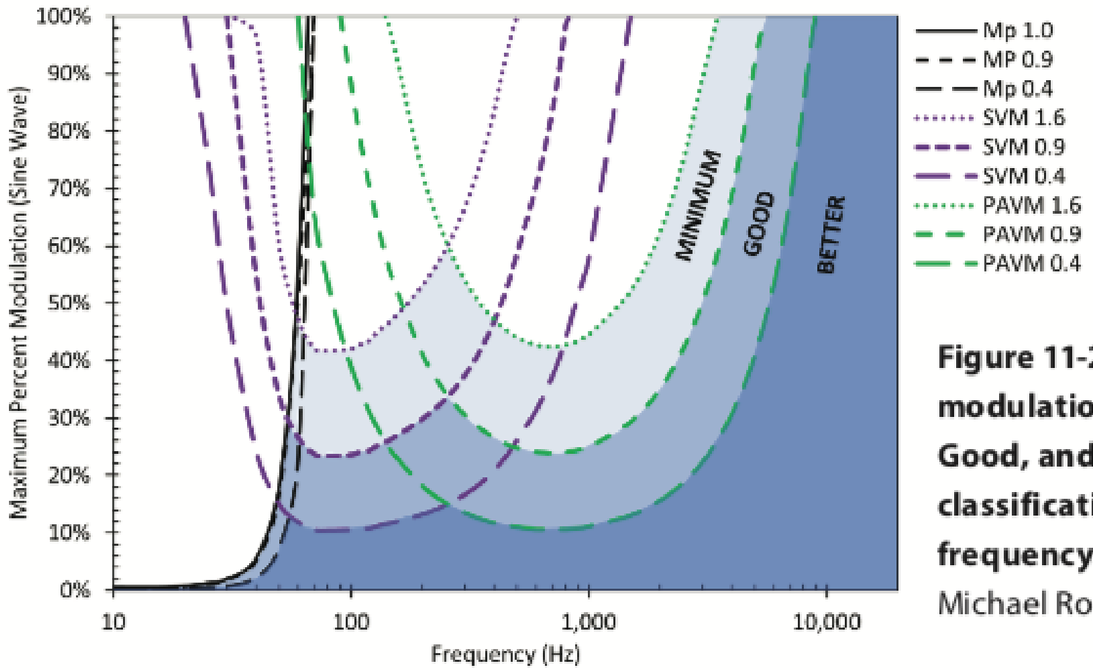
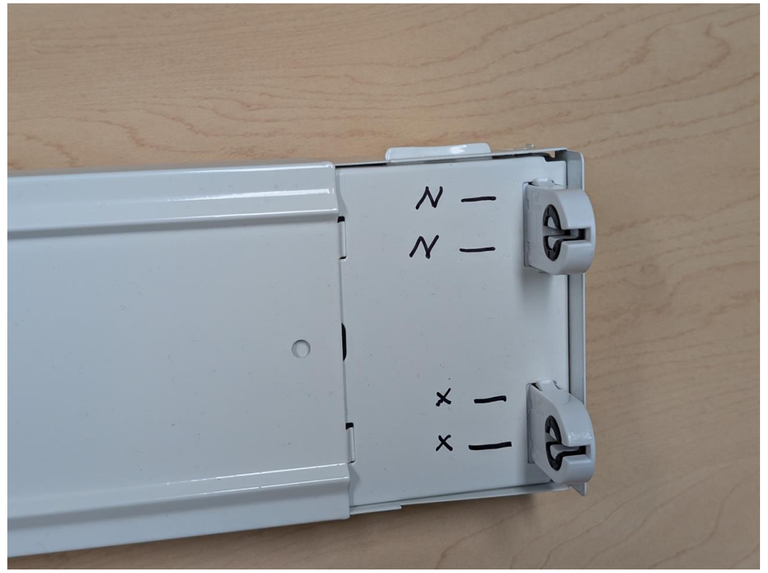



**Figure 11-2. Maximum percent modulation for Minimum, Good, and Better TLM visibility classifications as a function of frequency.** (Graphic courtesy of Michael Royer)

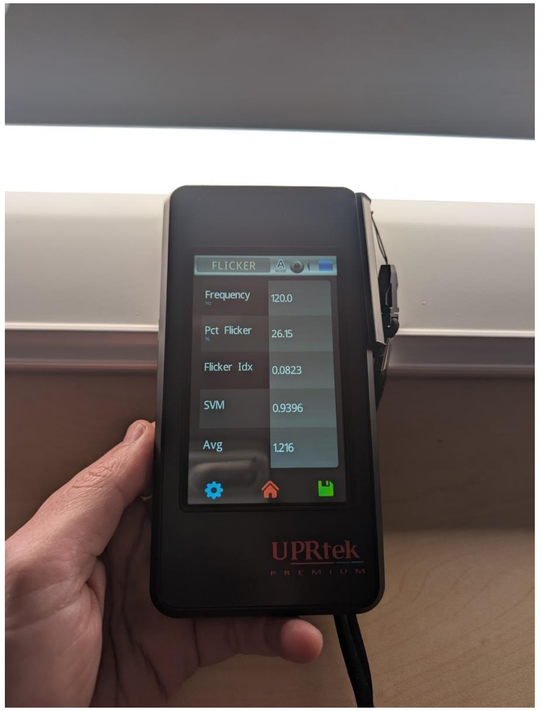
**IES TM-39**: Quantification and Specification of Flicker

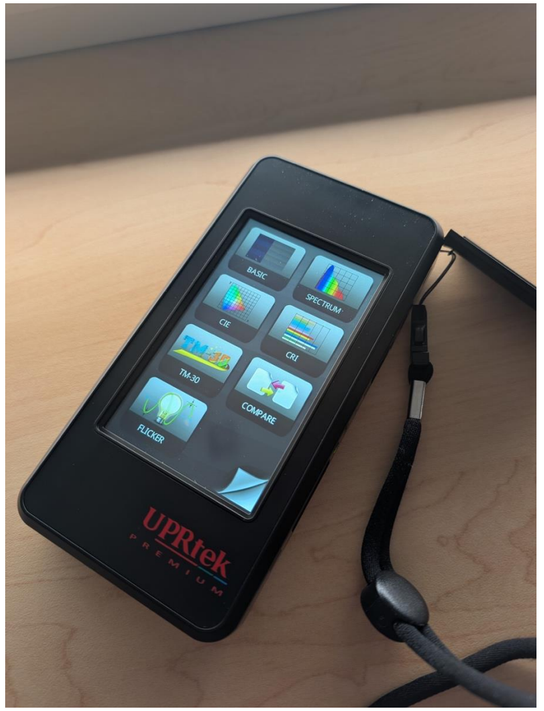
# Methods

12 UL type B LED luminaires has been tested in PSU OPP facilities.



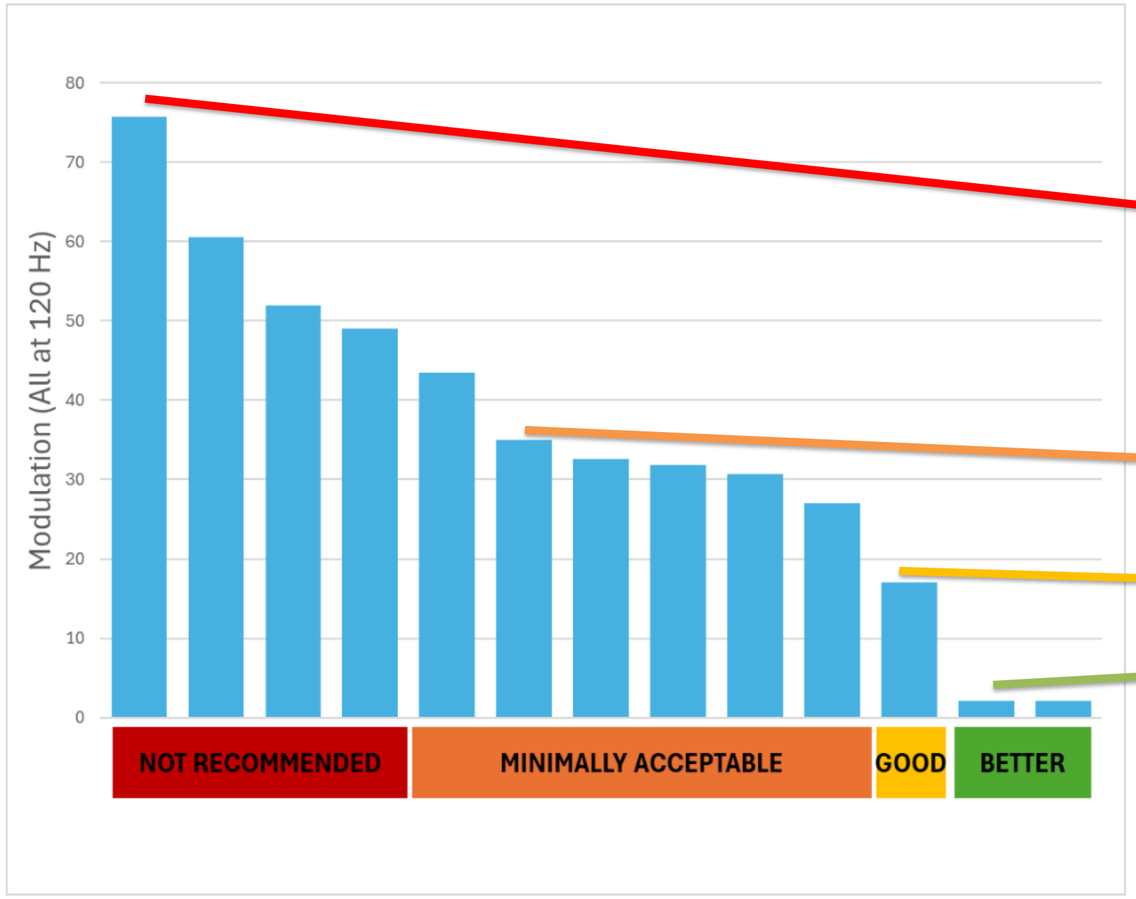

# Methods


https://www.uprtek.com/en/product/spectrometers/mk350s-premium

# Results




**IES TM-39:** Quantification and Specification of Flicker

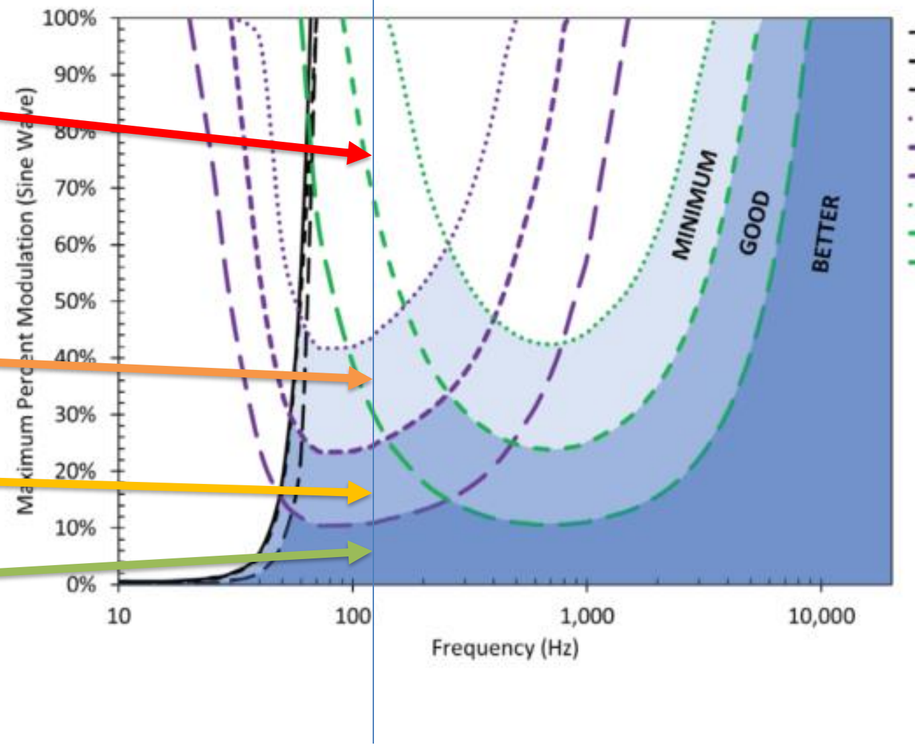
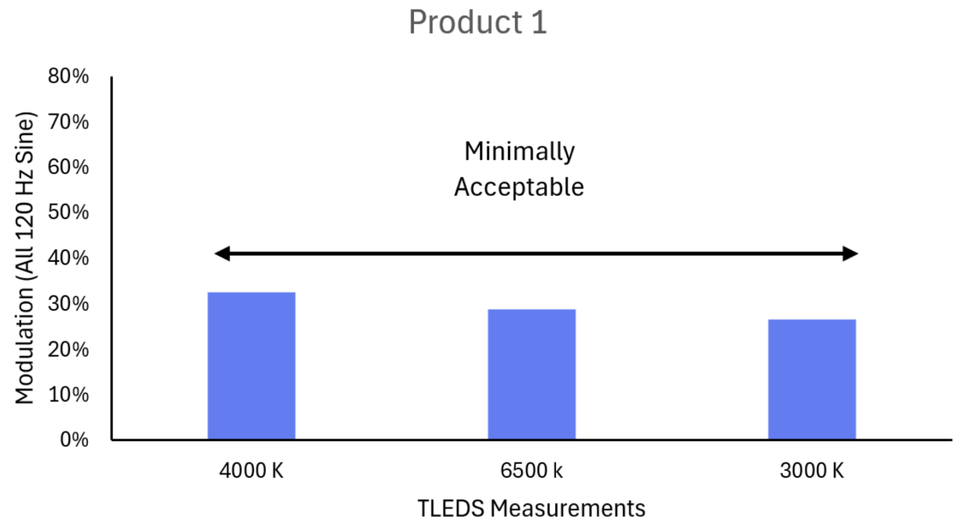
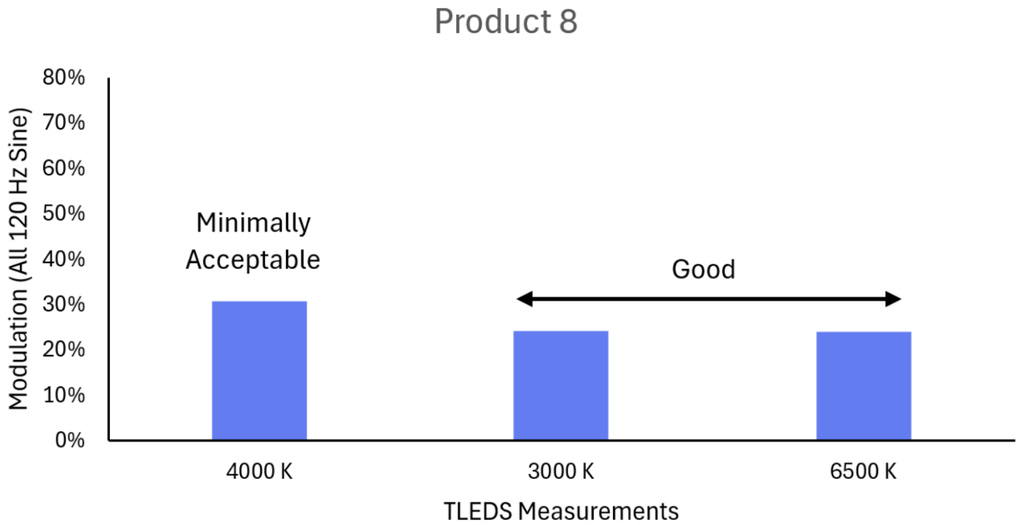
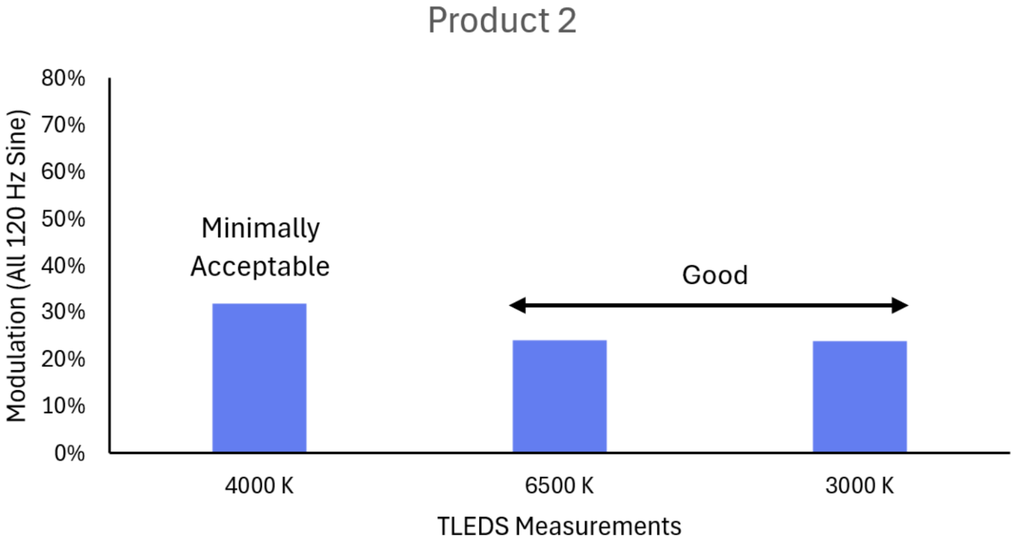


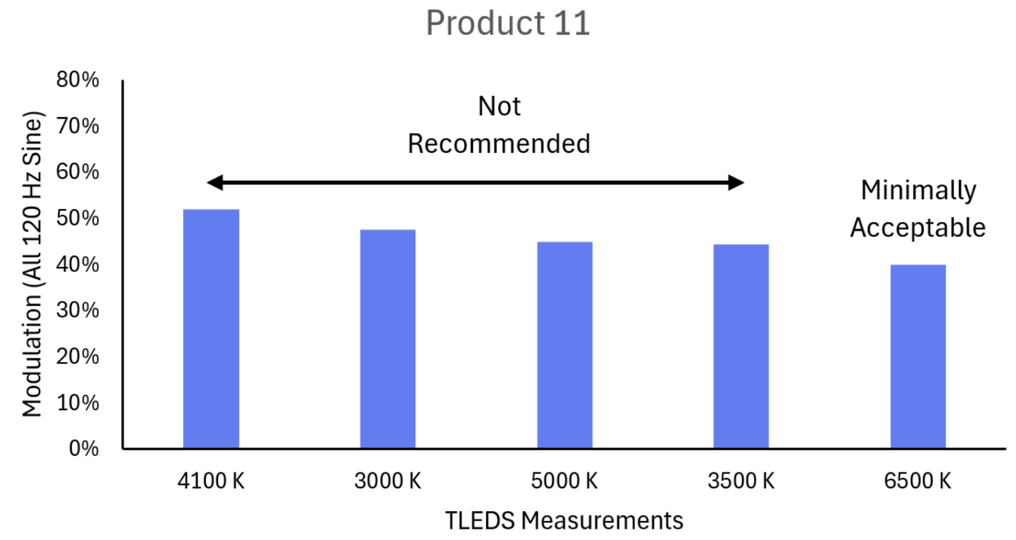

**Figure 11-2. modulation Good, and B classificatio frequency.** ( Michael Roye

# Results


Product 1
Modulation (All 120 Hz Sine)
80%
70%
60%
50%
40%
30%
20%
10%
0%
Minimally Acceptable
4000 K
6500 k
3000 K
TLEDS Measurements


Product 8
Modulation (All 120 Hz Sine)
80%
70%
60%
50%
40%
30%
20%
10%
0%
Minimally Acceptable
Good
4000 K
3000 K
6500 K
TLEDS Measurements


Product 2
Modulation (All 120 Hz Sine)
80%
70%
60%
50%
40%
30%
20%
10%
0%
Minimally Acceptable
Good
4000 K
6500 K
3000 K
TLEDS Measurements


Product 11
Modulation (All 120 Hz Sine)
80%
70%
60%
50%
40%
30%
20%
10%
0%
Not Recommended
Minimally Acceptable
4100 K
3000 K
5000 K
3500 K
6500 K
TLEDS Measurements

# Summary & Takeaways

- TLM has negative health impact, 3 categories
- TLM metrics are underused in real world performance data
- Real world data shows wide range of TLM performance
- Manufactures typically do not publish flicker information

https://retrofitcompanies.com/flicker-effect-with-led-lights/

# Thank you!

Questions?