2019 DLC

April 1 - 3 • St. Louis, MO

STAKEHOLDER MEETING

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Flicker metrics and other quandaries

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What is Flicker? CIE vs. IEEE

CIE 17.443 e-ILV:

Temporal light artifact (TLA): an *undesired change in visual perception* induced by a light stimulus (Temporal Light Modulation, TLM) whose luminance or spectral distribution fluctuates with time

- **Flicker**: Perception of *visual unsteadiness*… *for a static observer in a static environment. 3 - ~80 Hz*
- **Stroboscopic effect**: change of *motion perception*… for a *static observer in a non-static environment ~80 Hz - ~2000 Hz*
- **Phantom Array effect** (ghost effect): change in *perceived shape or spatial layout of objects*… for a *non-static observer in an otherwise static environment* (e.g. saccade, normal head movement, or while driving) ~80 Hz – ~2500 Hz

IEEE 1789-2015: "Variations in luminance over time" (temporal modulation of light)

- Encompasses all of the above
- Includes visual and non-visual effects, as measured by (e.g.) EEG testing

Image: Wikipedia.org

What does flicker (TLA) look like??

(ANYONE WITH A HISTORY OF SEIZURES, DO NOT WATCH)

Flicker

(Video)

Stroboscopic Effect
Effect

(PAR30 LED lamps Good-Meh-Bad)

Phantom Array

(Cheesy Light rope)

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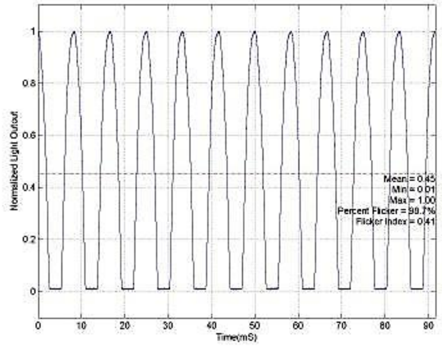
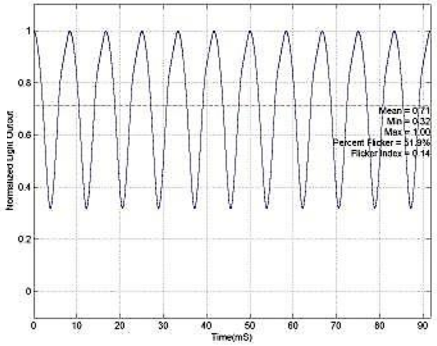
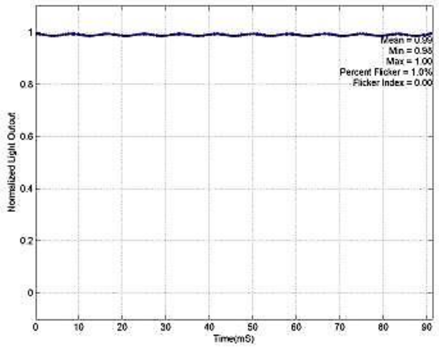
Important factors of flicker

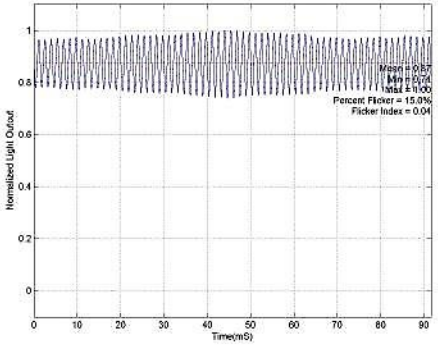
Primary factors of visibility and/or detection

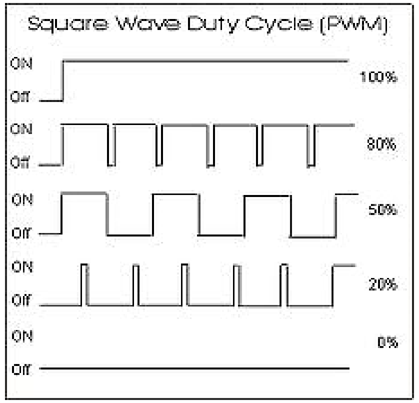
- **Frequency**, measured in cycles per second = Hertz (Hz)
- **Modulation depth** (% Flicker)
  = (max-min) ÷ (max+min)
- **Duty cycle** (for square waves): % of cycle time spent above a certain intensity (e.g. 10%)
- **Relative motion** of light source or illuminated objects, and eyes
- **Light intensity** and observer adaptation level
- **Shape of waveform** (sinusoidal, square, inconsistent)







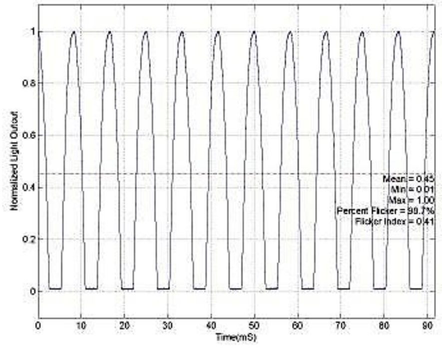


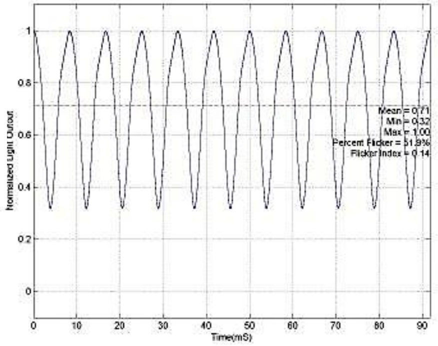


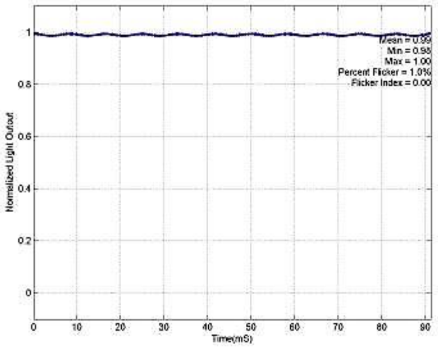
Important factors of flicker

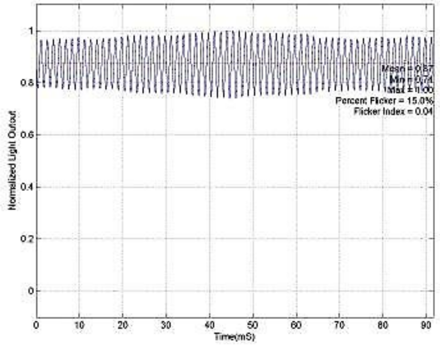
Other factors impacting health

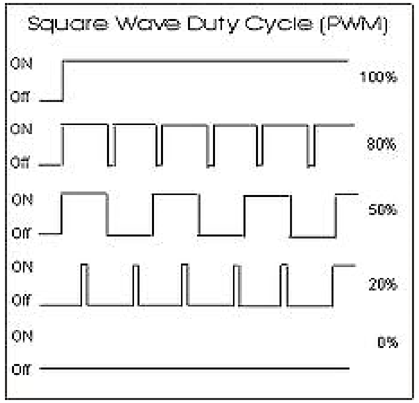
- **Duration of exposure –** longer is worse
- **Average luminous intensity (mean luminance) –** brighter is worse
- **Area of the visual field receiving stimulus** – more is worse
- **Whether both eyes are being stimulated –** both is worse
- **Position in the visual field –** central is worse than peripheral
- **Contrast with background –** more contrast is worse
- **Color and color contrast** of flash (deep red is worst)











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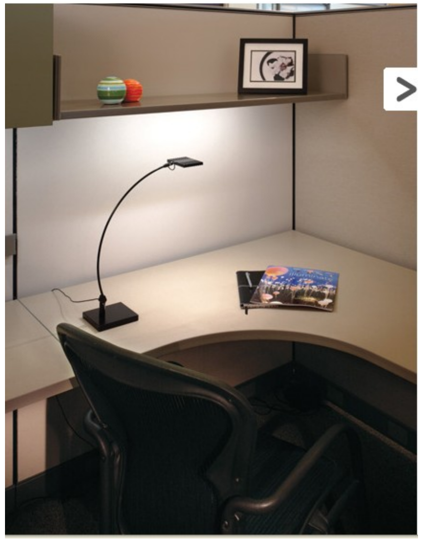
Why do we care? – Reported issues

- Photosensitivty epilepsy – flashing lights (and other repetitive patterns) stimulate epileptic seizures
- Stroboscopic effect – dangerous when working with rotating machinery
- Migraine or severe paroxysmal headache often associated with nausea and visual disturbances
- Increased repetitive behavior among persons with autism
- Asthenopia (eye strain), including fatigue, blurred vision, conventional headache, decreased performance on sight-related tasks, etc.
- Other: panic attacks, anxiety, increased heart rate, vertigo

- Also: interference with machine vision and imaging devices (video & security cameras, etc.)

Health.com

Where do we care?



Task lighting

General lighting

Industrial spaces

Hospitals/clinics

Video conference rooms

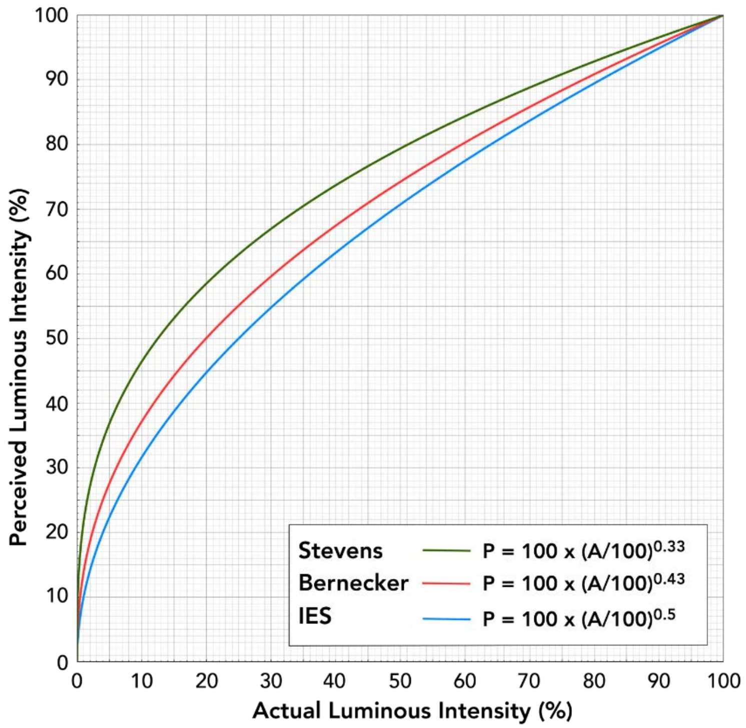
Classrooms

Offices

Why do we care, especially now?

LEDs and dimming

- Inherently fast-responding devices
- No persistence in light output compared to incandescent or fluorescent sources
- Rely on the DRIVER to provide visibly continuous light
- Pairing the driver with a dimmer especially tricky, especially at very low dimming levels, especially if color or white tuning is involved
- Human visual perception is not linear – by a long shot!
- To get a light source to LOOK like it's dimmed to 10% output, actual output need to be <1% output. Differences between actual and perceived are particularly large at low relative intensity levels



Actual versus perceived dimming levels

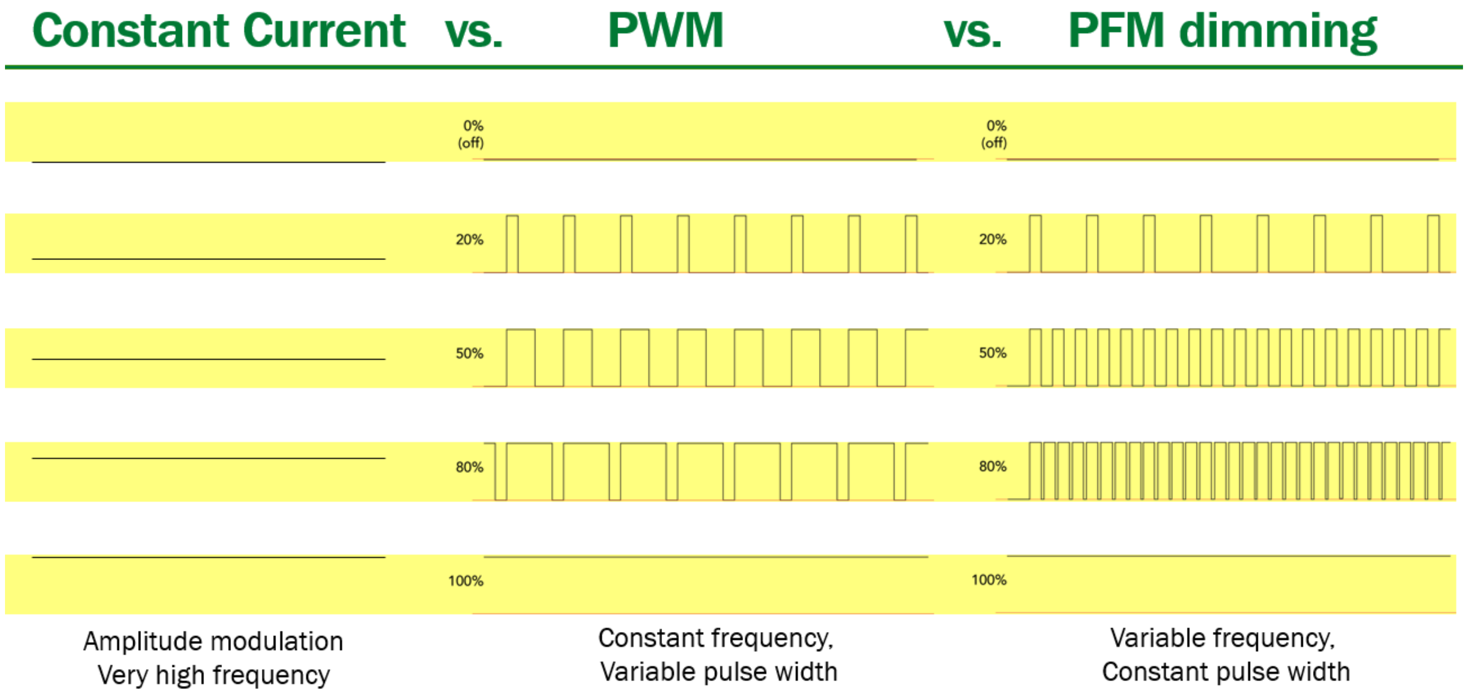
Don't blame the LEDs.
Blame the driver and the dimmer, knowing that this is NOT an easy problem to solve!

Dimming drivers

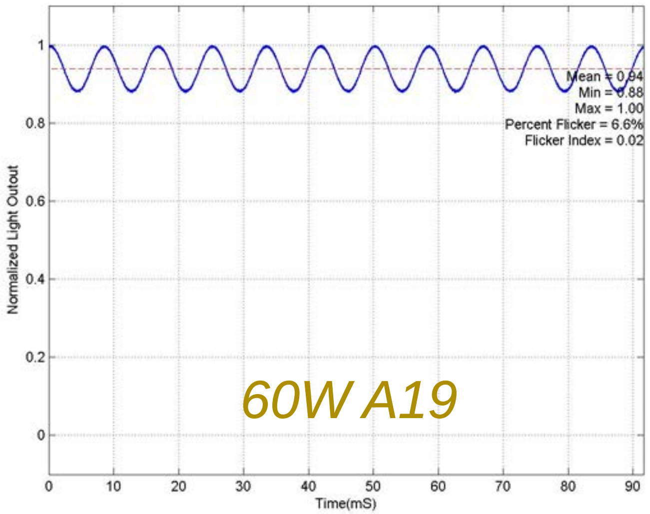
Ways for drivers to dim LEDs

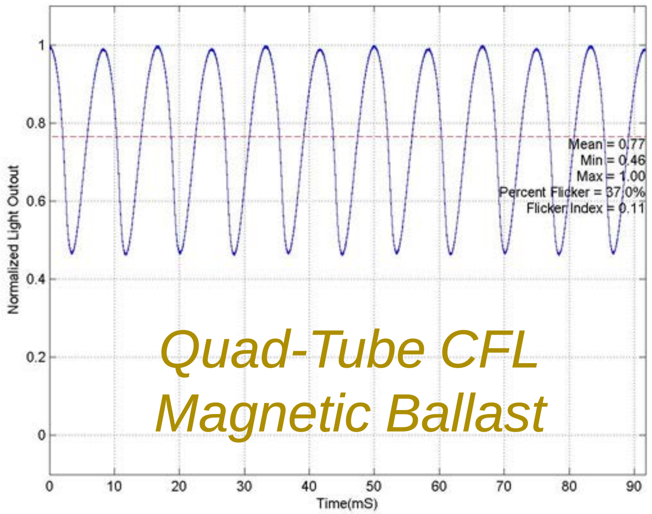
- Constant Current Reduction (CCR) *[Can introduce color shift]*
- Pulse Width Modulation (PWM)
- Pulse Frequency Modulation (PFM)

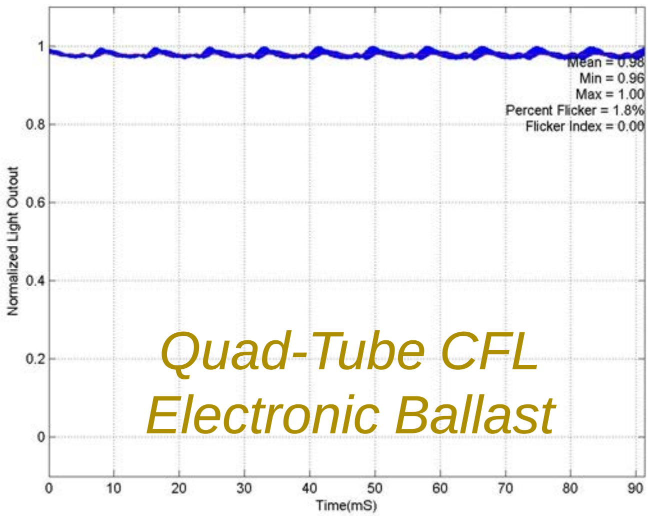
[These can be combined as a dimming strategy, but PWM and PFM can introduc temporal light artifacts (TLA)]

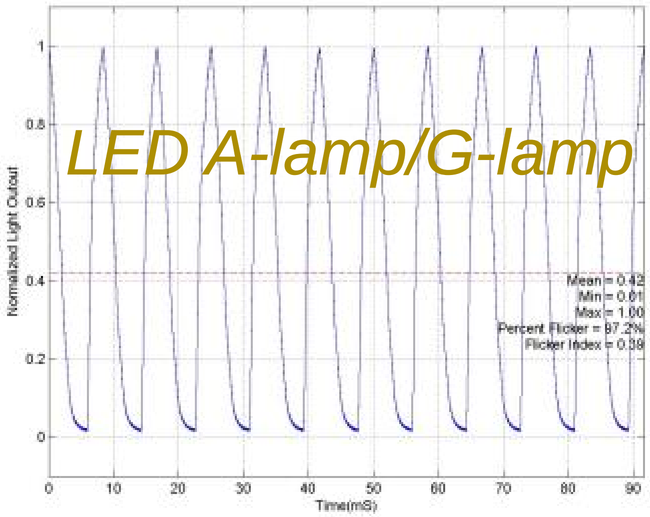


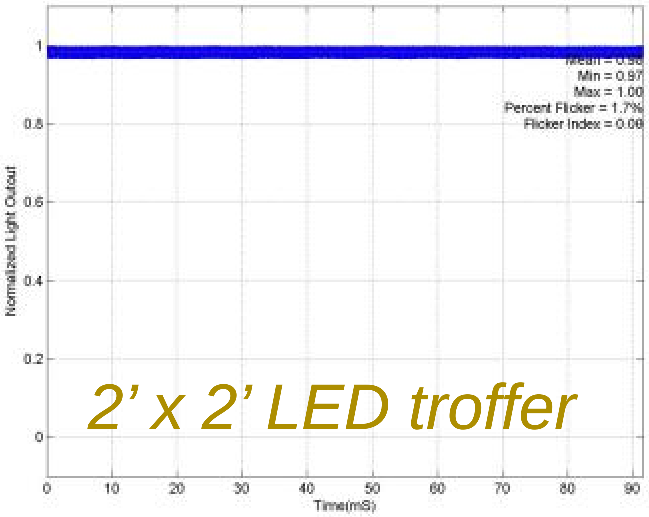
Nearly all light sources exhibit some flicker

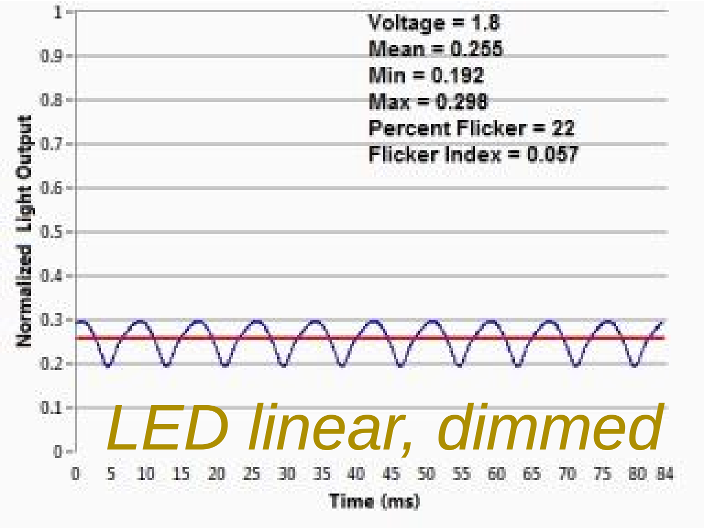












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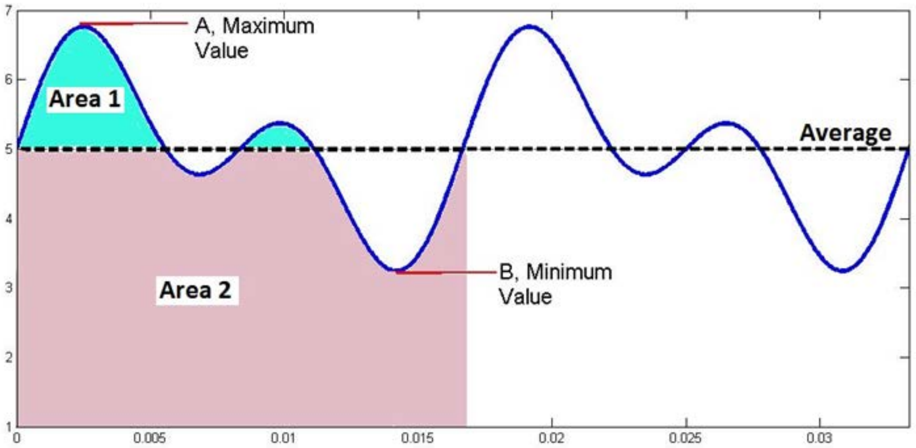
Flicker metrics over time

Illuminating Engineering Society

- Percent flicker (aka Modulation depth)
  - 0-100% scale
  - Older, but more well-known and more commonly used
  - Accounts for average, peak-to-peak amplitude
  - Does not account for shape, duty cycle, frequency
- Flicker index
  - 0-1.0 scale
  - Newer, but less well-known and rarely used
  - Accounts for average, peak-to-peak amplitude, shape, duty cycle
  - Does not account for frequency



Source: IES Lighting Handbook, 10th Edition

- Percent Flicker $= 100\% x \frac{A - B}{A + B}$
- Percent Flicker $\neq 100\% x \frac{A - B}{Average}$
- Flicker Index $= \frac{Area\,1}{Area\,1 + Area\,2}$

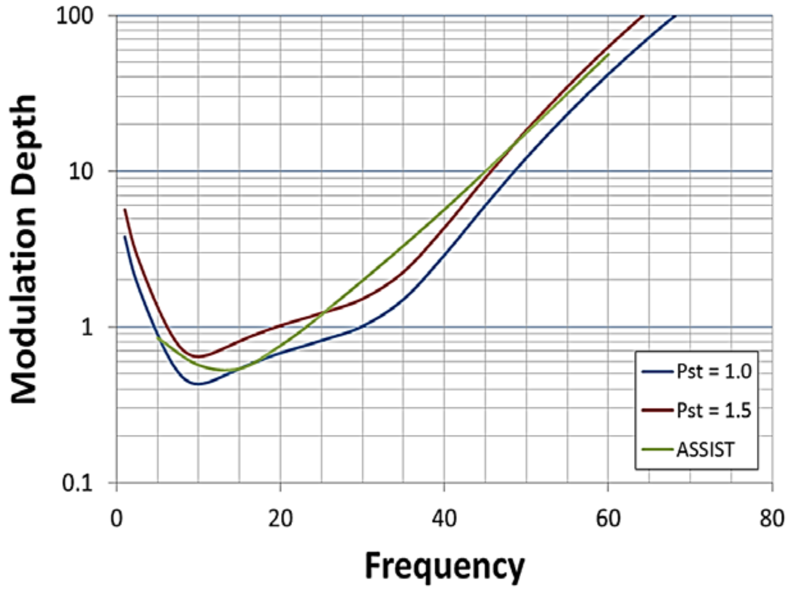
Flicker metrics over time (Thanks Jim Gaines & NEMA!)

IEC 61000-4-15

- "Flickermeter" – Functional and design specifications

IEC 61000-3-3

- "Limitation of voltage changes, voltage fluctuations and flicker" in public electric supply systems, up to 80 Hz
- Complex; originally developed to quantify power line quality



Plot of the visibility threshold (P_{st} = 1 and ASSIST), for visible flicker, expressed in terms of modulation depth, as a function of frequency. The curve is for a single sine wave modulation.

P_{st}

Limited to visible flicker up to 80 Hz
Values above 1.0 considered acceptable

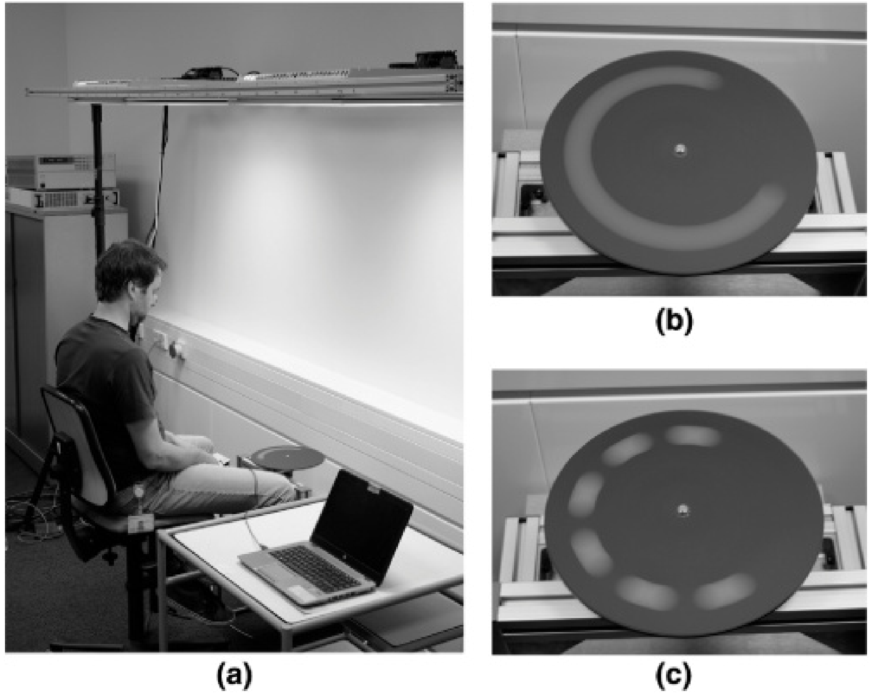
LRC ASSIST Flicker Perception Metric (M_P)

- Follows the IEC Flickermeter approach, but without the model of the incandescent lamp.
- Based on response of 10 subjects
- Covers frequencies from 5 Hz to 80 Hz

Flicker metrics over time

Stroboscopic Visibility Measure (SVM)

- Developed by Philips Eindhoven researchers based on human subjects testing, converted into a Standard Observer
- Predicts visibility of strobe effect based on wave shape and duty cycles, above 80 Hz.
- Uses Fourier analysis of waveform
- SVM value of 1 means for this waveform, standard observers will be able to see flicker 50% of the time. <1 is harder to see; >1 is easier to see.
- Less conservative than IEEE Standard P1789-2015

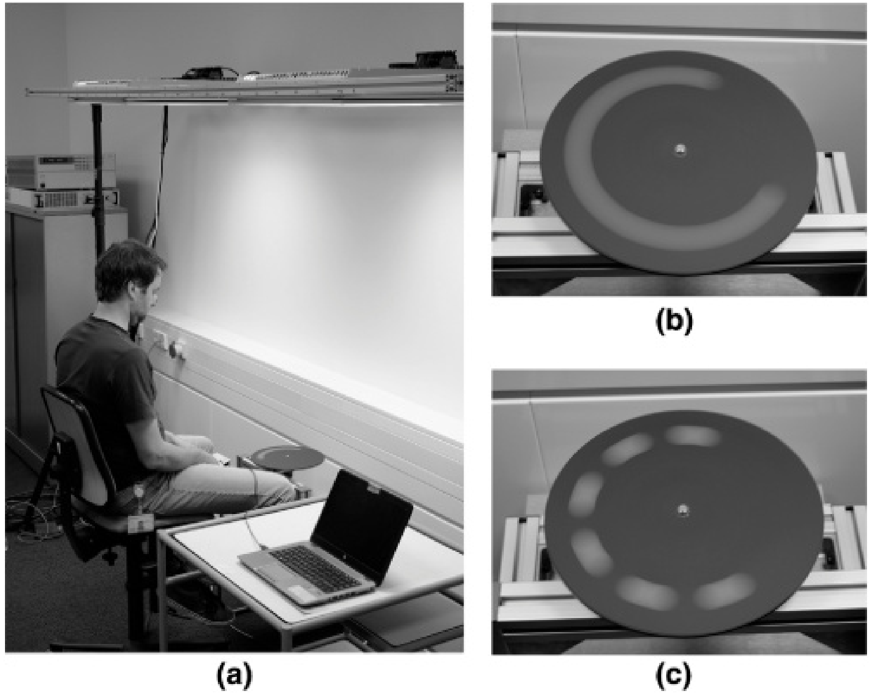


Perz et al, experimental setup for TLA

Flicker (or more accurately, Temporal Lighting Artifacts TLA)

The problems:

- SVM based on visibility, a fixed view of a rotating disk. No relative eye or head movement. For this reason SVM is likely to underestimate visibility of flicker
- Based on an average observer, not the most sensitive individuals, such as migraineurs and autists
- SVM of 1 = 50% of individuals will see flicker, 50% won't. This is a very loose threshold which doesn't protect the sensitive
- Are visibility and neurological response the same?
- Doesn't take the phantom array effect into account
- What threshold values are recommended for different applications?



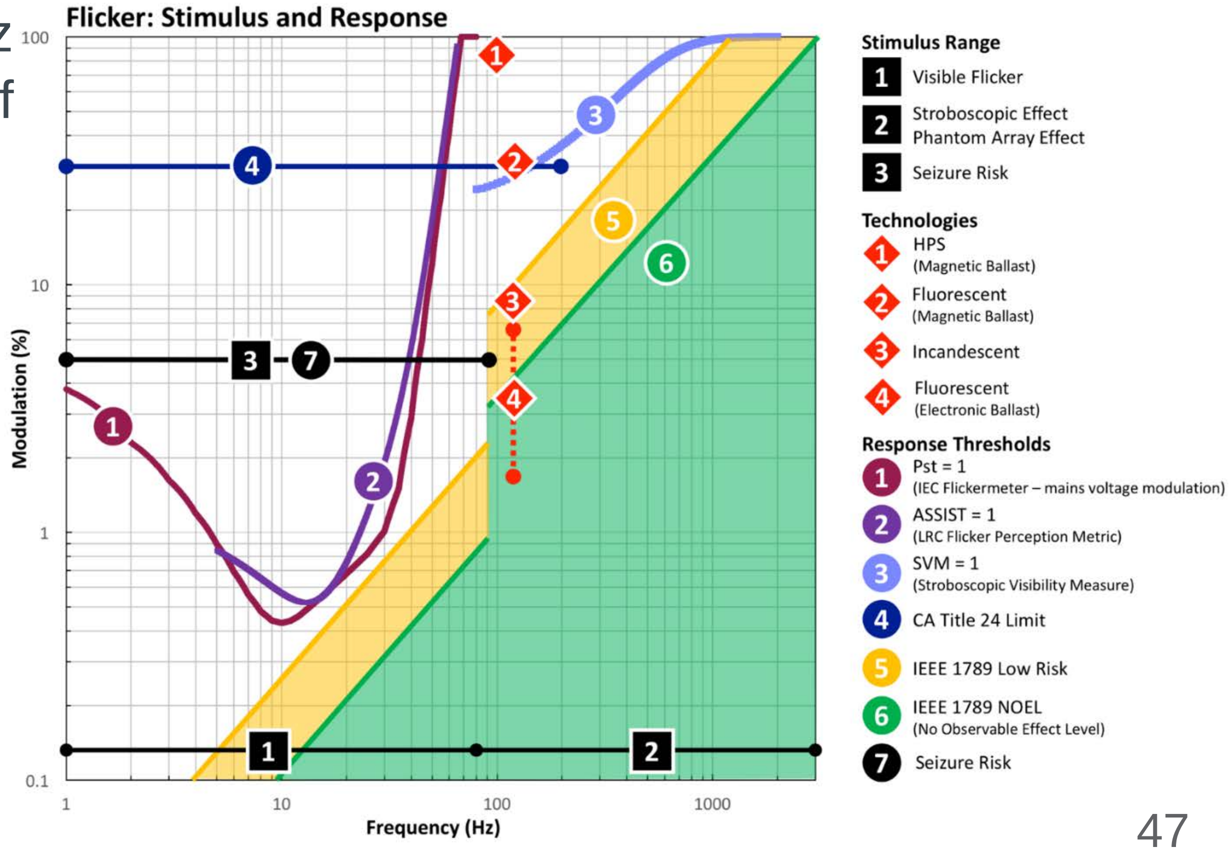
Perz et al, experimental setup for TLA

Flicker metrics over time

NEMA 77-2017 Temporal Light Artifacts (Pst + SVM)

- Based on flicker visibility.
- Uses Pst standard (flickermeter) below 80Hz
- Uses SVM above 80 Hz, with a max value of 1.6, because products performing at that level have been on the market for years without complaints
- Strength: a group of manufacturers has signed on to this standard. The numbers need to be tweaked based on application and experience
- Weakness: Not complete. Fixed gaze only. No differentiation between “standard observer” and sensitive individuals. Doesn’t account for phantom array effect. Assumes flicker visibility = neurological effect.

Plots of all metrics using frequency and % Flicker, but NOT duty cycle



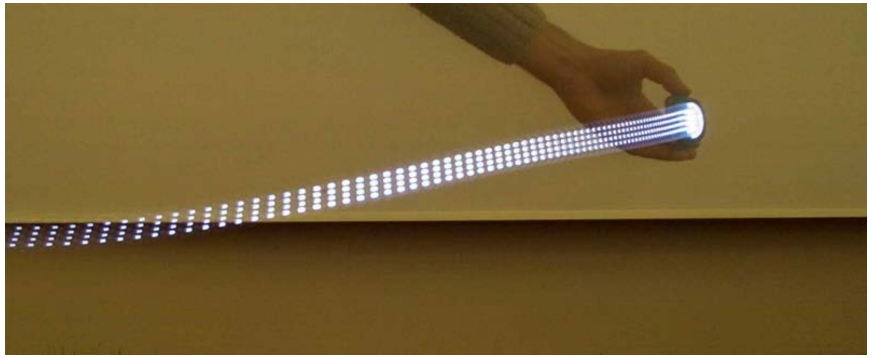
Background

Two prominent TLA measures for stroboscopic effect and, perhaps, phantom array effect:

- **Stroboscopic Visibility Measure (SVM)**
- **IEEE 1789-2015** which limits %flicker based on fundamental flicker frequency

The problems:

- Neither of these works consistently to predict visibility of, or responses to, modulating light
- We have waited too many years for confirmation by the neurological community that this predicts seizures, EEG response, headaches, migraines, autistic behaviors, task performance reduction, etc.



https://www.led-professional.com/resources-1/articles/lighting-with-leds-2013-more-than-just-illuminating-objects

SVM TLA recommendation based on Veitch and Martinsons 2019 study interim report

SVM study to determine ranges for A-lamp sales in Europe

Proposed SVM values

- 1.6 proposed by NEMA 77-2015 is higher than flicker from magnetically-ballast fluorescent lamps
- 0.9 means 25% of population will see flicker 63% of the time (normal applications)
- 0.4 means most sensitive 25% of population will see flicker only 10% of the time (more stringent applications)

Photo from Veitch and Martinsons 2019 study of stroboscopic effect visibility

So, taking things into my own hands…..

I have a superpower:

- Not strength, not flying, not stretchy, not spidey-sense, not turning green and hulky….
- I can visually detect flicker, stroboscopic effect, and phantom array effect, even at very high frequencies (>1500 Hz)
- And I have a flicker meter (UPRTek MF250N)

I've measured flicker from hundreds of luminaires:

- Some visible
- Some not visible
- Some only visible under certain conditions

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Informal data collection

Included

- Philips TLA generator settings (Thank you, Philips!)
- Products measured in DOE/PNNL sphere testing
- Field measurements (in offices, on planes, in restaurants, in hotels, at home…)
- Looked at waveforms as well as calculated flicker metrics (% flicker, Flicker Index, Frequency, SVM)
- Logged personal visibility of each product or setting

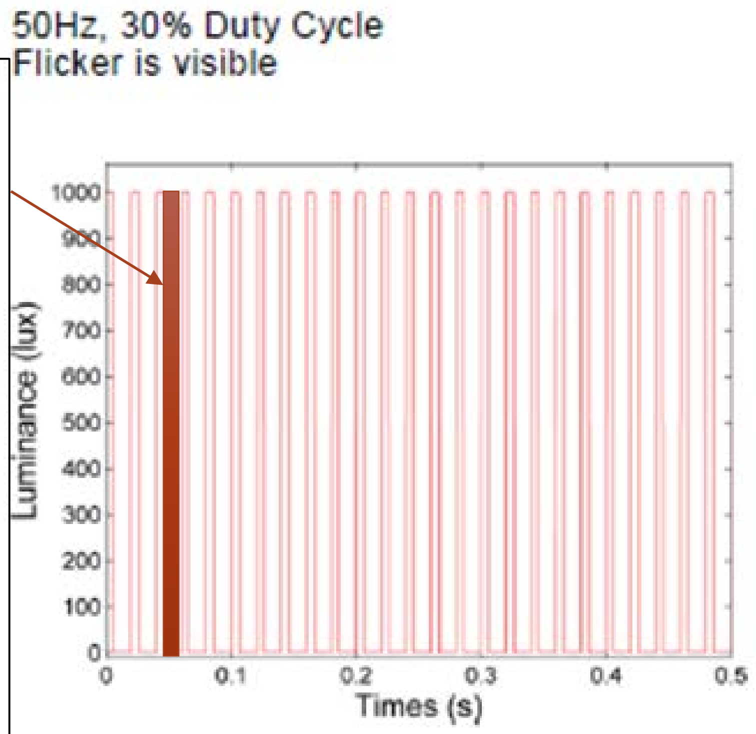
	A	B	C	D	E	F	G	H	I	J
1	TLA Demo Unit ID	Shape	Modulation Frequency (Hz)	Duty Cycle (%)	MD (%)	FI	PstLM	SVM	Description /Name	Visible to Naomi? (Yes-Maybe-No)
21	WF20	Square	100	95	100	0.05	0.01	0.45	Effect of duty cycle on the stroboscopic effect	N
22	WF21	Sine	100	50	35	0.111	0.03	1.36	Typical LED	M
23	WF22	Sine	100	50	10	0.032	0.01	0.39	Typical 60W incandescent bulb	N
24	WF23	Square	8.8	50	0.342	0	0.99	0	Typical waves with $P_{st}^{LM} = 1$; IEC TR 61547-1	N
25	WF24	Square	33.3	50	1.001	0.005	1	0.02	Typical waves with $P_{st}^{LM} = 1$; IEC TR 61547-1	N
26	WF25	Square	0.33	50	1.269	0.005	0.97	0	Typical waves with $P_{st}^{LM} = 1$; IEC TR 61547-1	N
27	WF26	Square	100	50	100	0.252	0.13	3.52	Typical TL-D (without storage)	Y
28	iLumens T8 LED tube, full output	Square wave	505		98.7	0.487		1.647	PNNL sample	Y
29	iLumens T8 LED tube, 50% output	Square wave	1015		98.4	0.806		1.647	PNNL sample	Y
30	Delta airline cabin LED lighting	Square	450		98	0.3		1.075	White light	Y

Example of collected data table

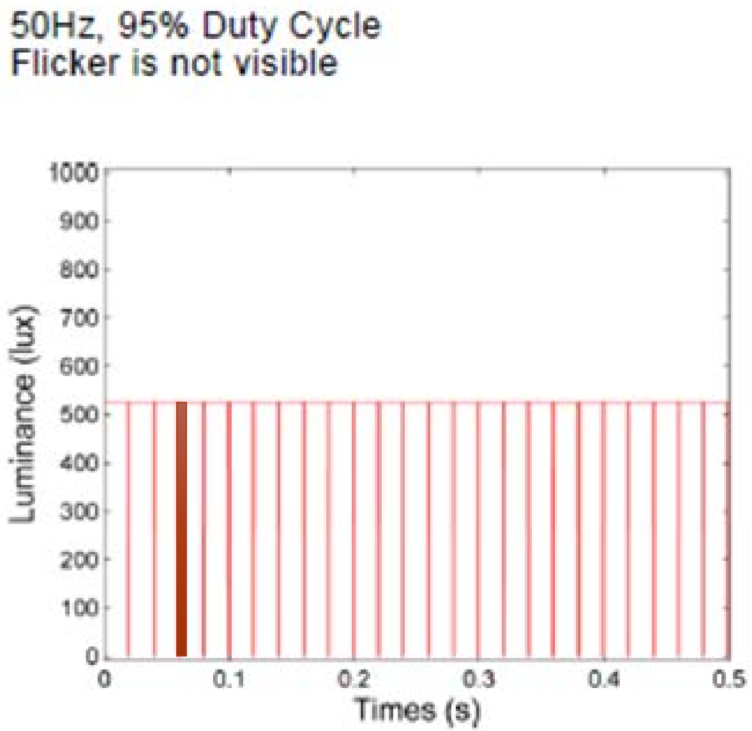
Results

Visibility depends on size of area “missing” from waveform due to duty cycle

Note: Red highlighted area illustrates area “missing” from waveform cycle. The more area missing, the higher the flicker index.



Visible (0.699 FI)



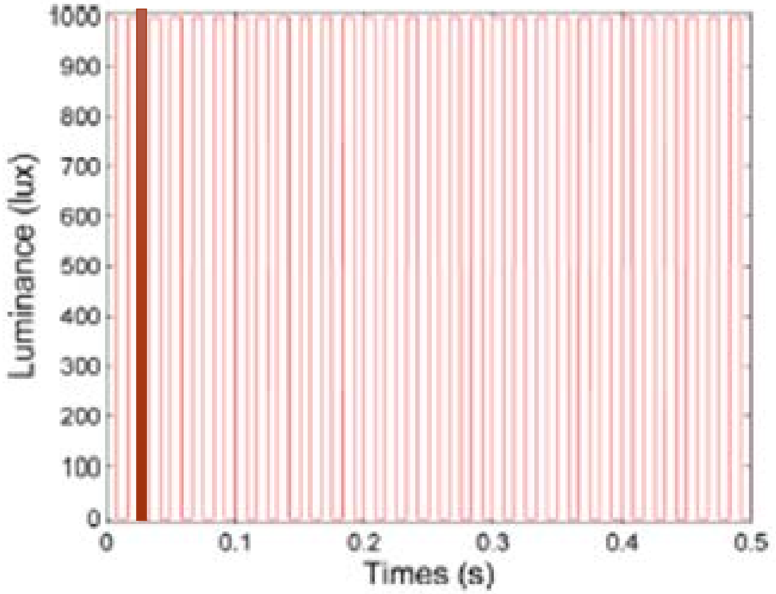
Not visible (0.05 FI)

Plots from Philips Research

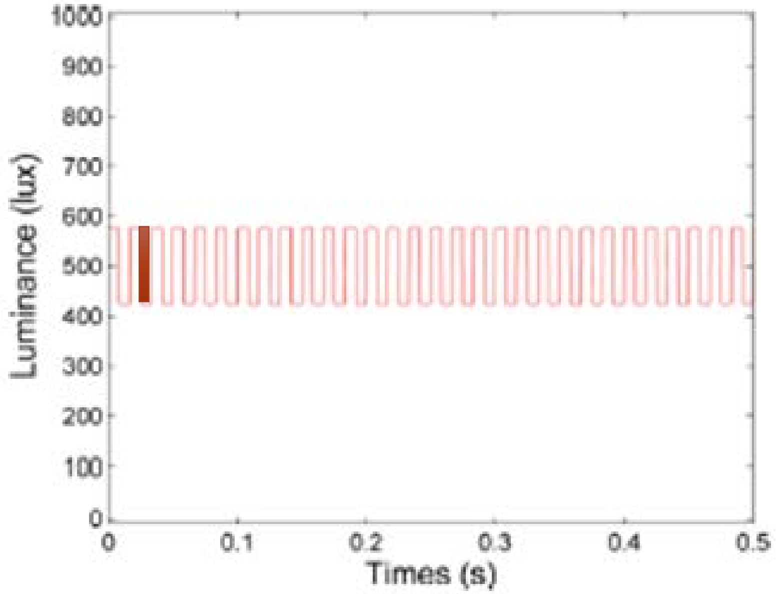
Results

Visibility also depends on depth of modulation (i.e., % flicker)

60Hz, 100% Modulation Depth (full), flicker is visible



60Hz, 15% Modulation Depth, flicker is NOT visible

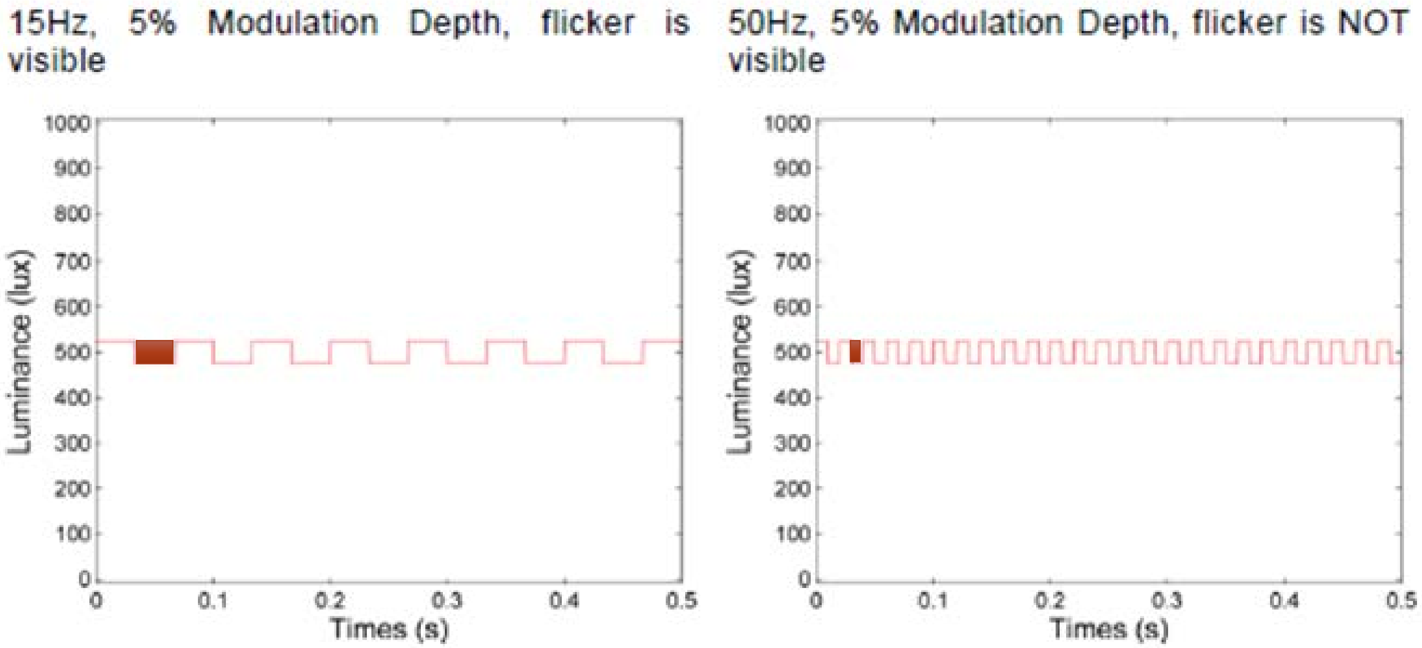


Plots from Philips Research

- Area “missing” from waveform is roughly modulation depth x (100 - duty cycle) and is related to Flicker Index

Results

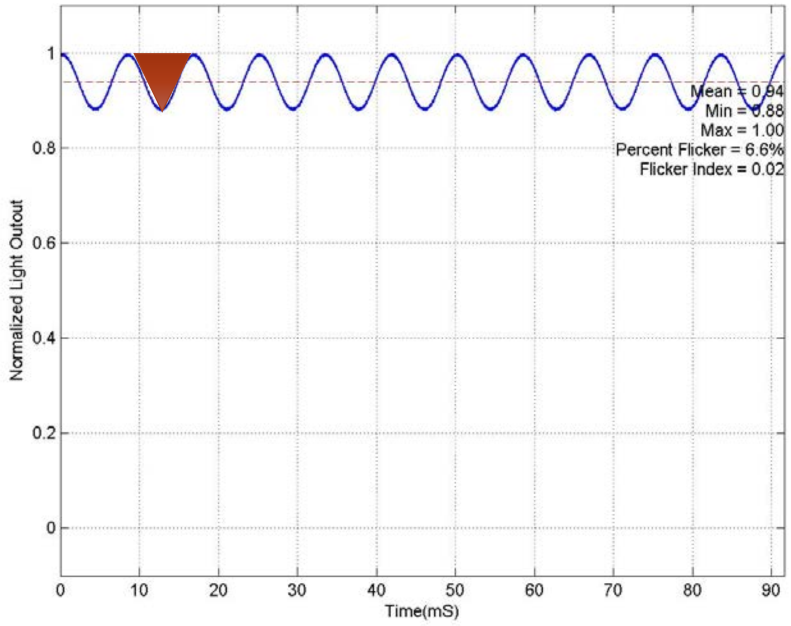
Visibility also depends frequency of modulation



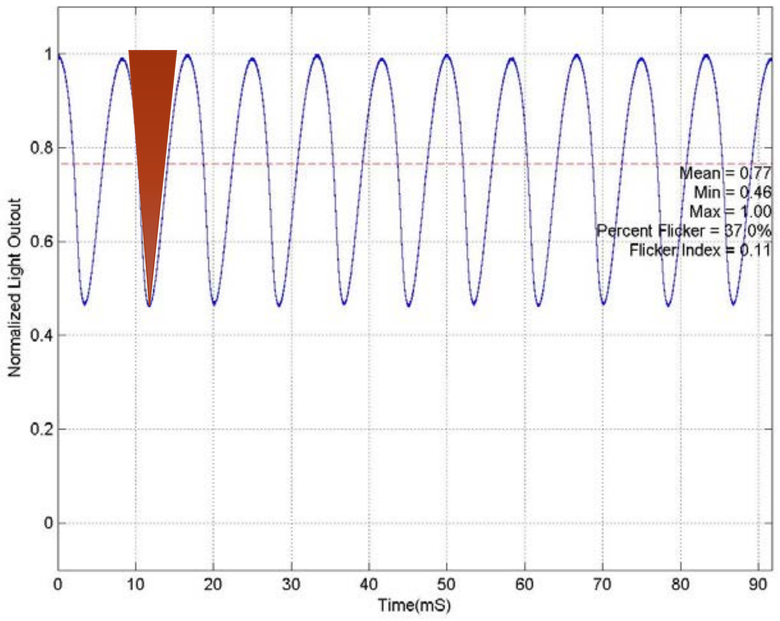
Very Visible! (0.025 FI)   Not visible (0.025 FI)

Plots from Philips Research

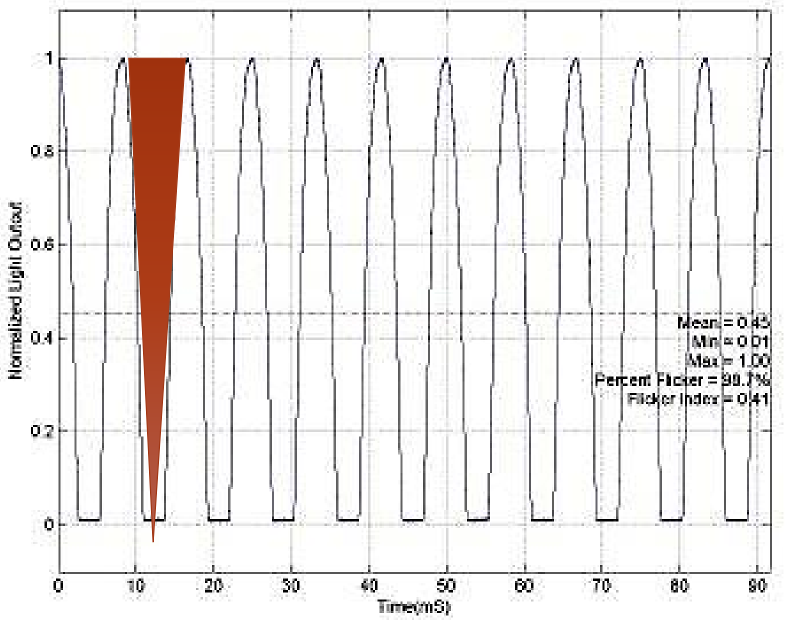
Examples of Flicker Index, Frequency, Visibility



60W A19
120 Hz
Flicker Index = 0.02
Not visible



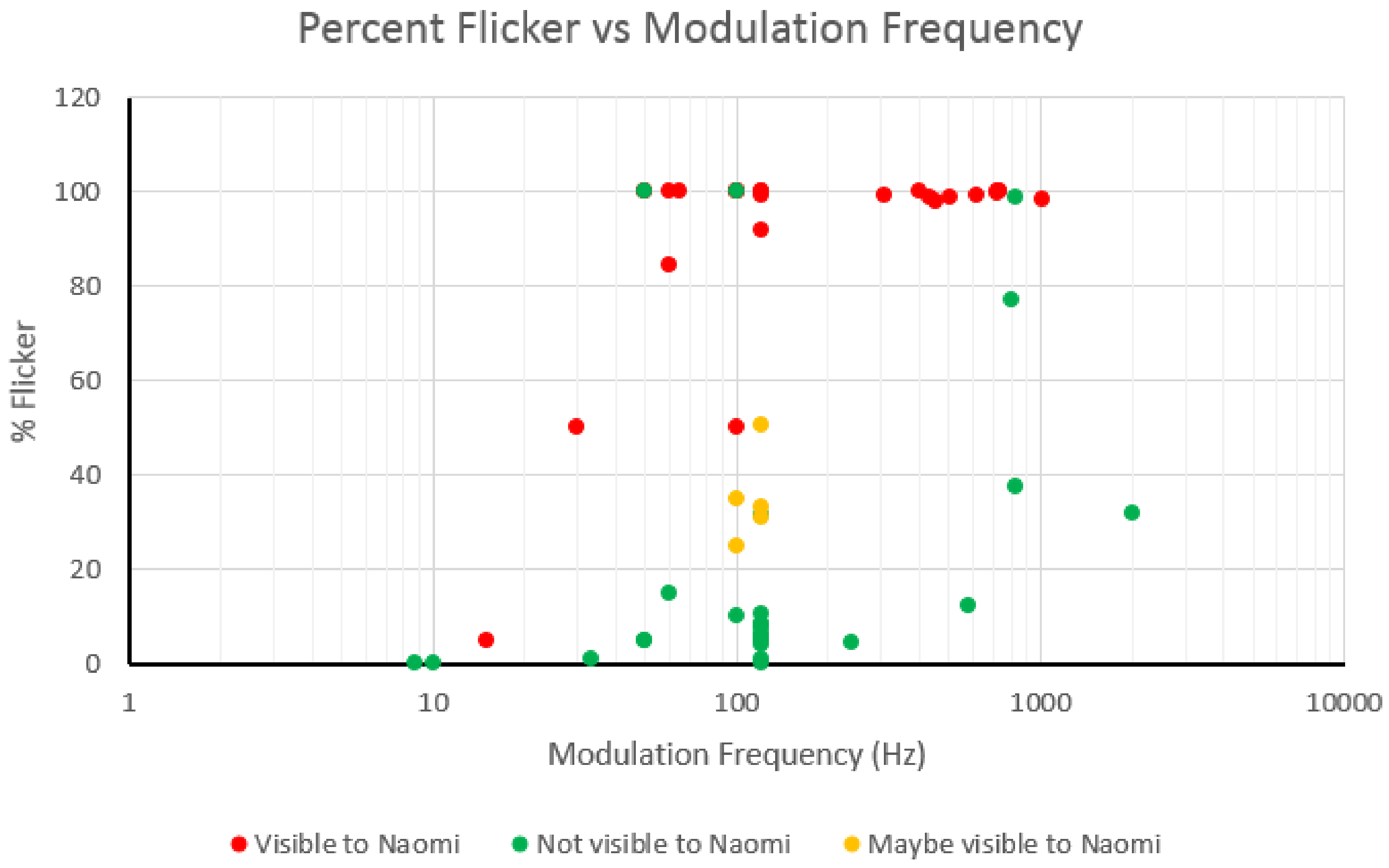
Quad-Tube CFL
Magnetic Ballast
120 Hz
Flicker Index = 0.11
Visible



AC LED
120 Hz
Flicker Index = 0.41
Dreadfully Visible!

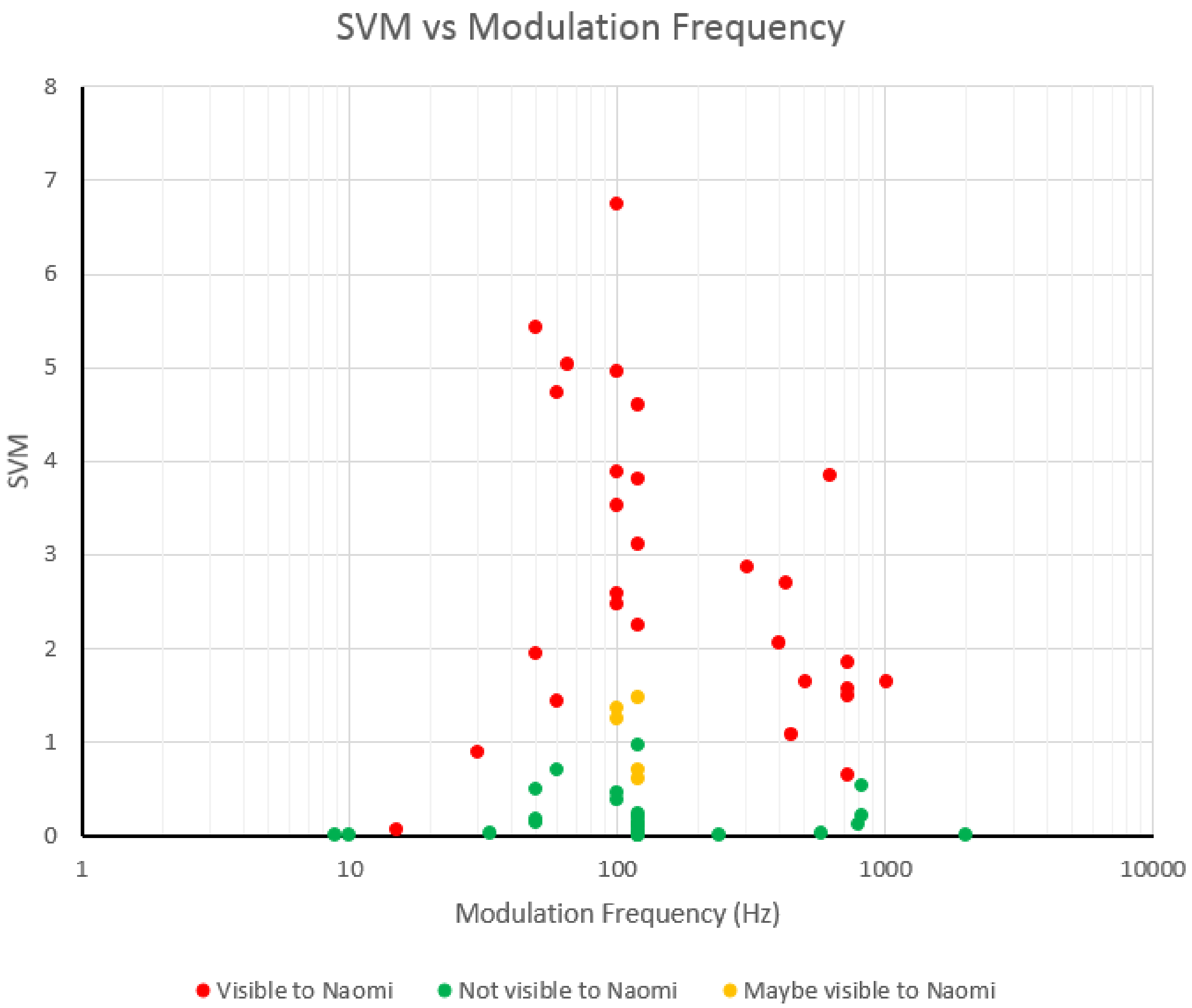
Results - %Flicker vs. Frequency

Not good



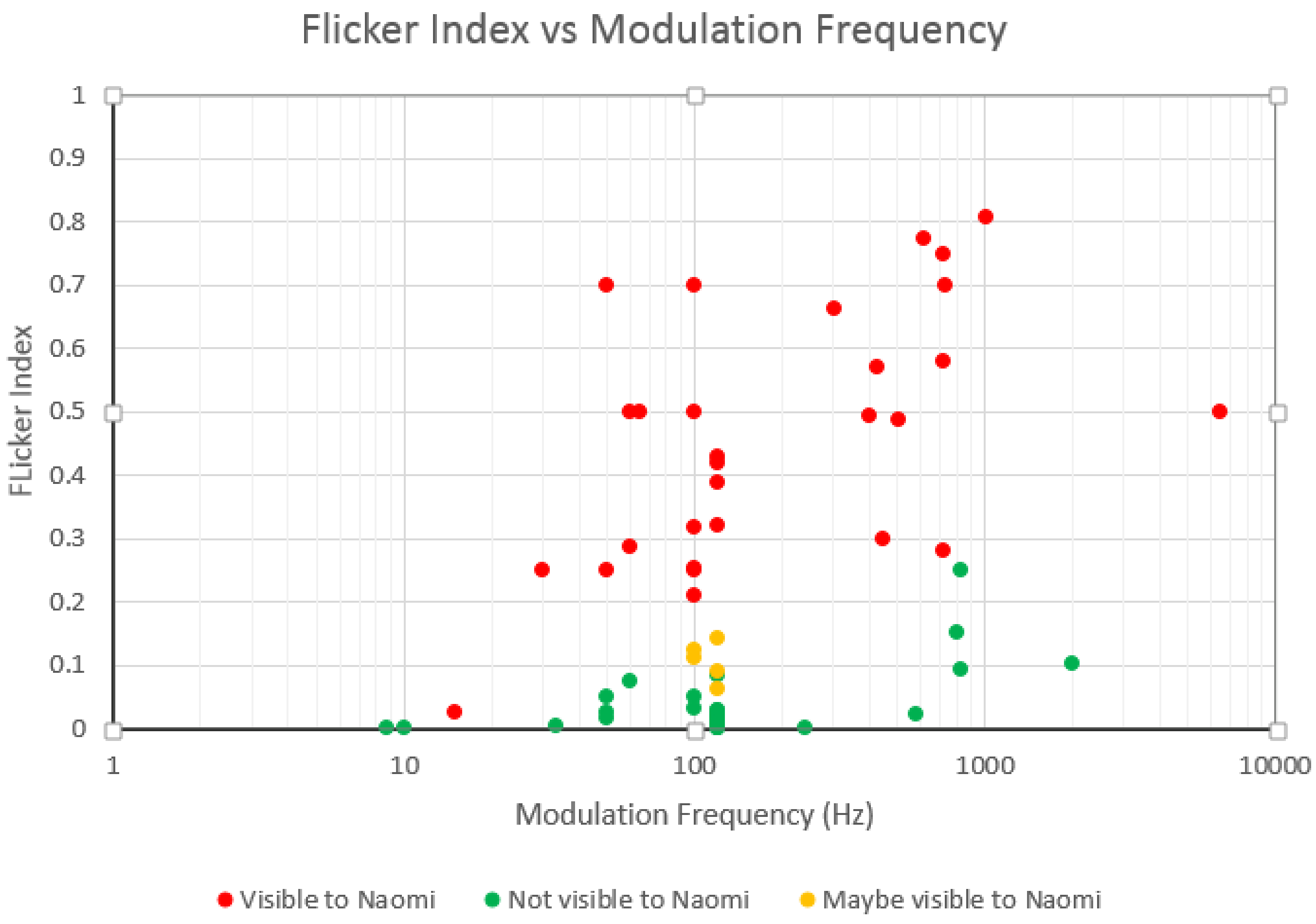
Results: SVM vs Frequency

Better



Results

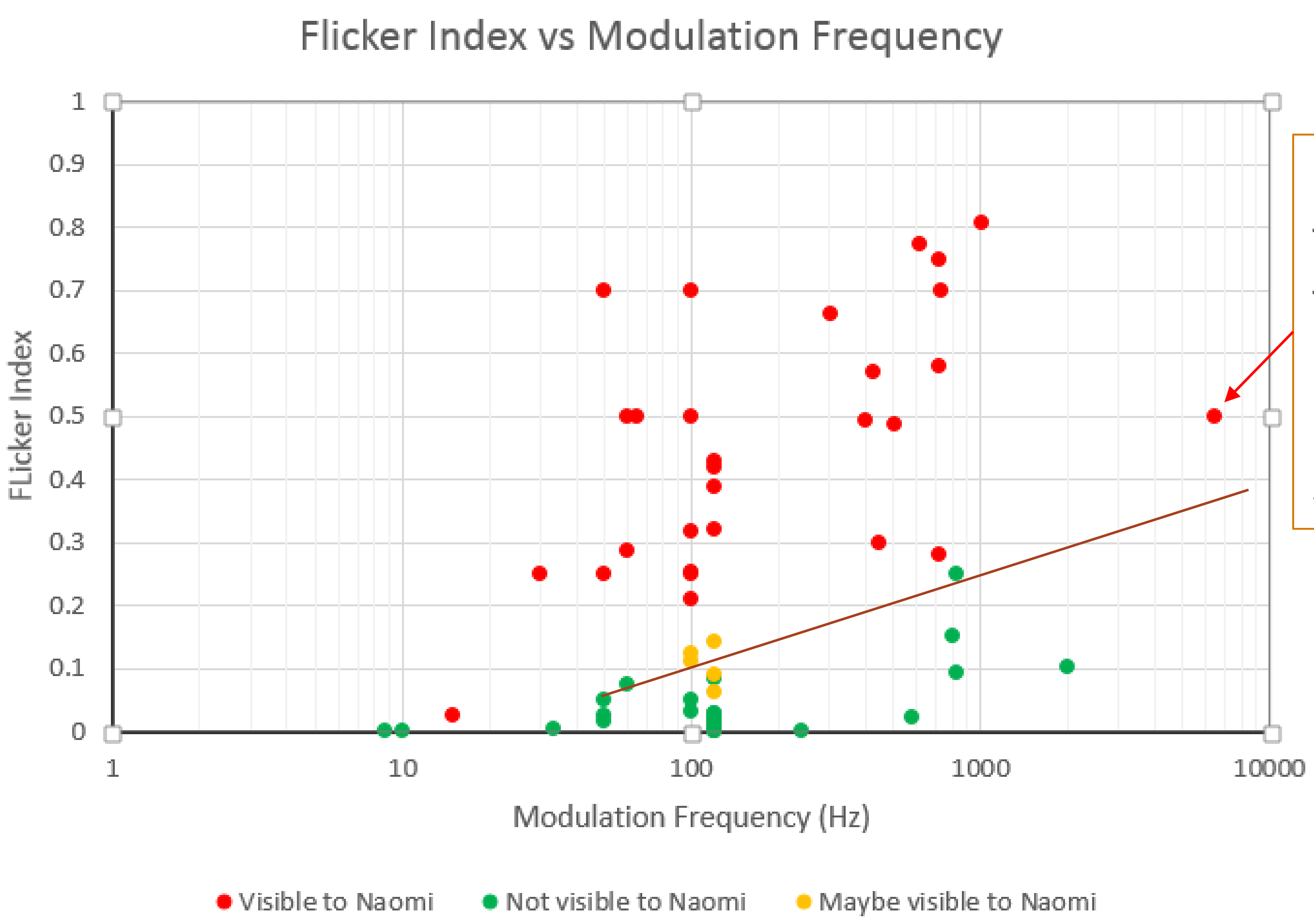
Best



Suggested Flicker Index values for testing

Can we draw a line through these points?

- Less than 0.03 below 60 Hz for epilepsy (US incand is 0.02)?
- Less than 0.06 at 100 Hz (EU incand lamp is 0.05)?
- Less than 0.1 at 120 Hz (magnetic ballast linear fluor is 0.09-0.11)?
- A constant multiplier of frequency above 120 Hz?

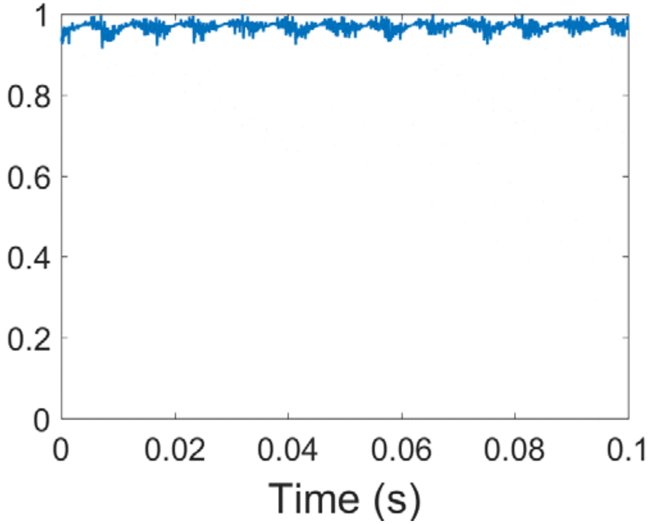


Datapoint from Wilkins for visibility of phantom array from square wave

Does this work solve the flicker metric problem??

Not likely.

- Subject pool: n=1
- Does visibility = neurological response?
- Does visibility predict physiological risk levels?
- Other waveform factors may contribute to visibility
- But this is a simple metric, similar to IEEE P1789 standard, using frequency and Flicker Index that are calculated already
- It may be a hypothesis worth testing.



Results of frequency from 8 different flicker meters

120 Hz
68 Hz
566 Hz
120 Hz
120 Hz
71 Hz
120 Hz
44 Hz

AND!!! Turns out flicker frequency is VERY difficult to measure reliably.

What you can do, starting today

Specifiers:

1. Insist on seeing an LED luminaire or lamp in operation before specifying it. See it in dimmed operation. Use the waving finger/waving wand test.
2. Buy a good quality hand-held flicker meter that measures AT LEAST up to 2000 Hz and learn to use it.
3. Become familiar with flicker metrics. Encourage manufacturers to publish flicker metrics on their cut sheets
4. Ask your clients about sensitivity to flicker
5. Decide which applications need careful attention to flicker
6. Write flicker language into your specification
7. If you suspect flicker in a sample or on a job site, set your cell phone to SLO-MO video (240 frames per second). This slows down the flicker rate by a factor of 8, making it more visible. Film for 5 seconds. Play back the video on the phone. Flashing, stripes, or other artifacts *may* indicate flicker or strobe or phantom array effect. **NO GUARANTEE, BUT IT'S A GOOD INDICATOR, AND IT'S FUN.**

Demo: Flicker effects from Slo-Mo video

120 Hz, 100%Flicker
SVM>4
Video at 30 fps
(not Slo-Mo)

120 Hz, 100%Flicker
SVM>4
Video at 240 fps

30,000 Hz, 2%Flicker
Video at 240 fps
SVM 0.02

120 Hz, 70%Flicker
Video at 240 fps
SVM 2.0

How do you measure flicker?

Bench top flicker meters available, reliable, and expensive.

https://www.energy.gov/eere/ssl/downloads/characterizing-photometric-flicker

Handheld flicker meters now available, less expensive, and mostly reliable for calculated metrics.

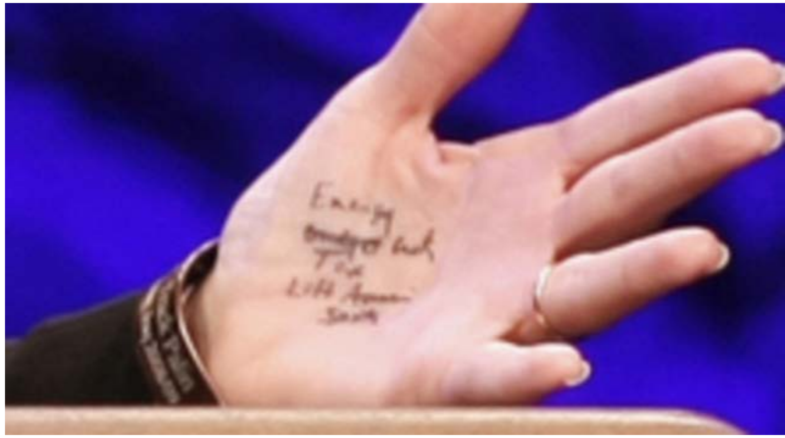
https://www.energy.gov/sites/prod/files/2019/01/f58/characterizing-photometric-flicker_nov2018.pdf

Manufacturers' To Do List:

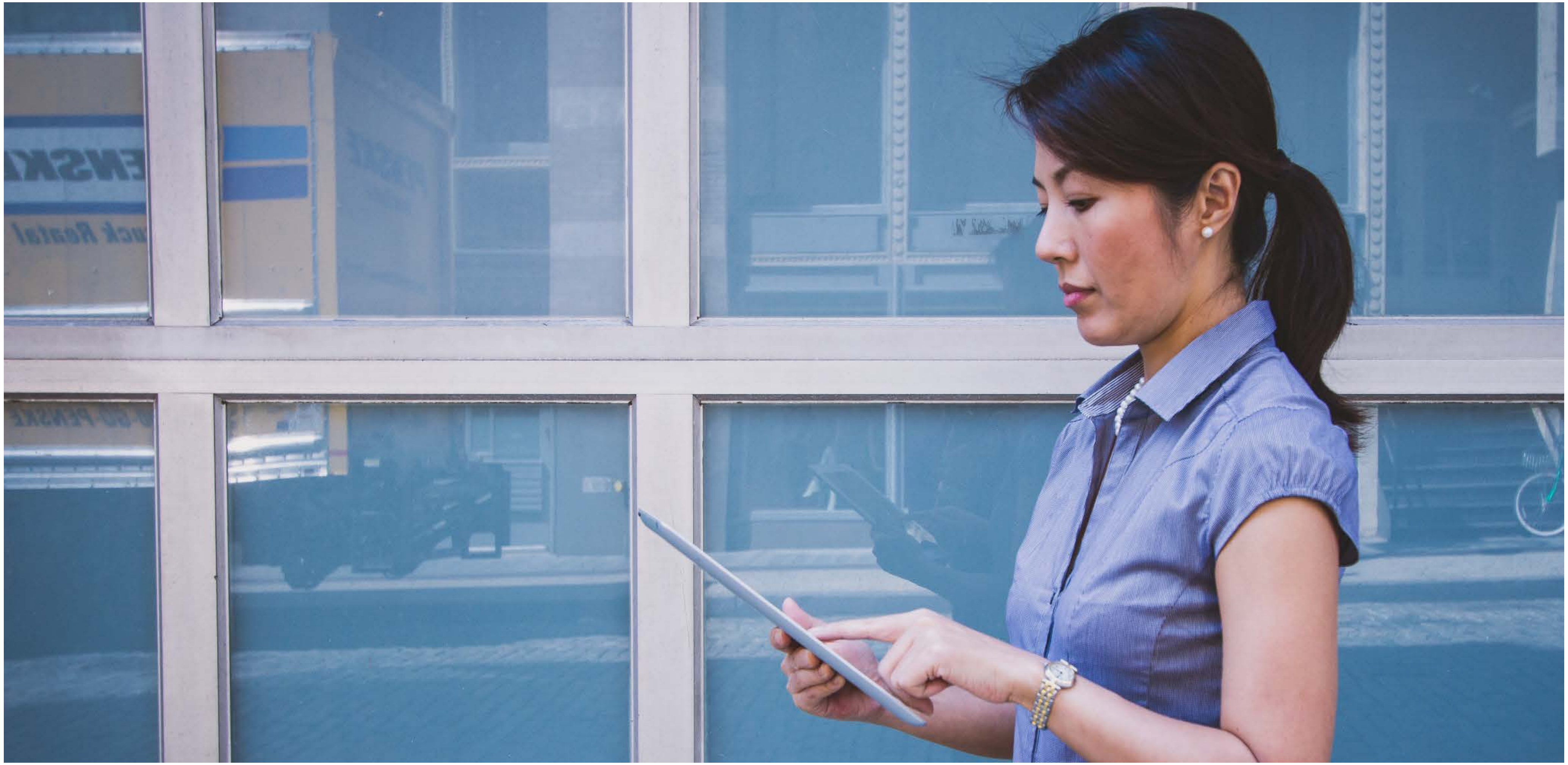
1. Buy a flicker meter that measures *at least* up to 2000 Hz
2. Test for flicker over full dimming range.
3. Use/Demand drivers that meet high standards of low flicker
4. Use/Publish flicker metrics on datasheets
   - %Flicker (i.e., modulation depth)
   - Flicker Index
   - Flicker Frequency
   - SVM, Pst or Mp

Crib notes for the pop quiz on TLM, TLA, aka flicker

- Almost all light sources flicker to some extent
- Modulation depth, frequency, duty cycle, waveform over time are factors
- LEDs aren't the problem. The driver/electronics are.
- Interaction with a dimmer can make flicker worse, especially at low levels
- ALL flicker metrics are imperfect
- W-i-d-e individual variation in sensitivity to flicker
- Responses can range from none to migraines to risky seizures
- Setting safe levels is difficult because we have so little neurological data



NashvilleScene.com



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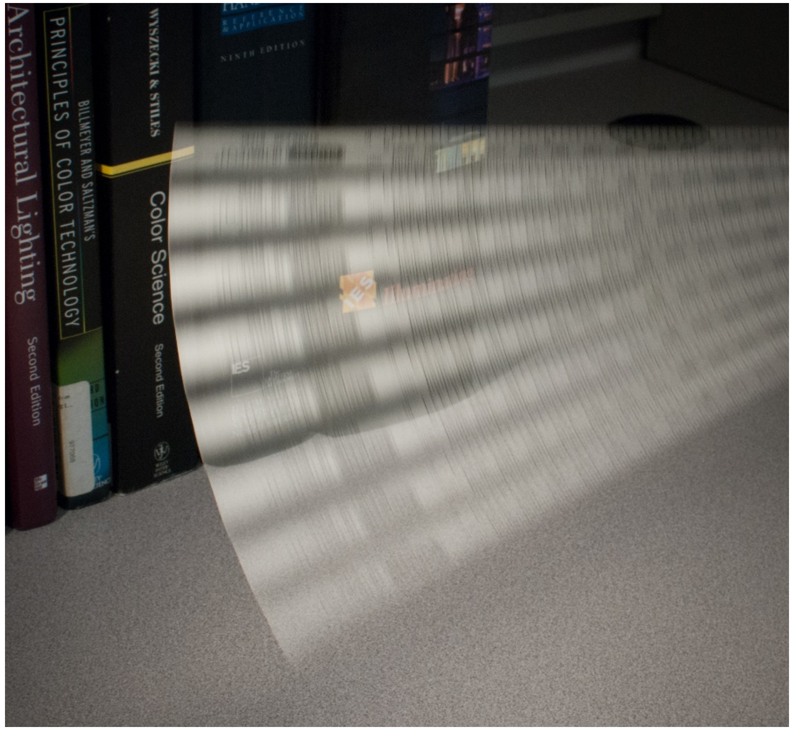
Thank you for listening! Questions? Comments? Complaints?



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