



Temporal Light Modulation (aka Flicker) and how to fix it....

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Driving Vision News Workshop

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Photo: Vinny Tennis

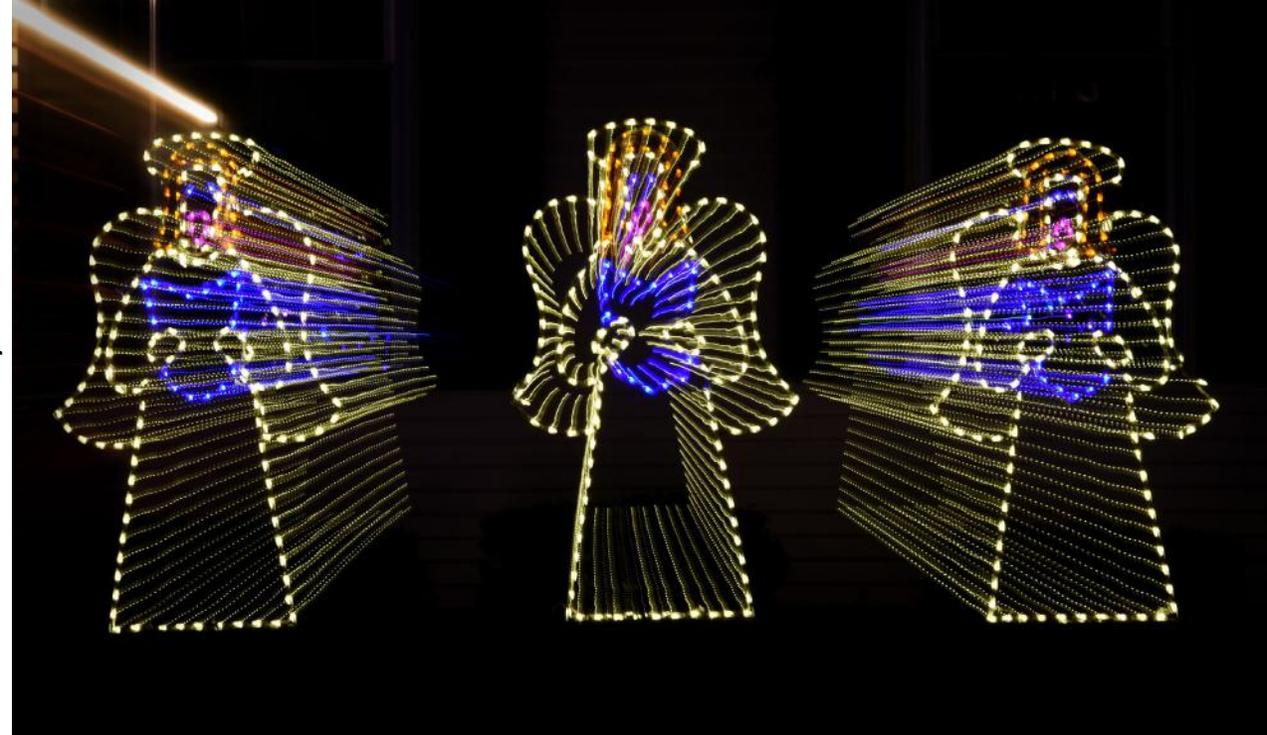


Photo: Tom Emerson



“Flicker” definitions (informal):



“**Flicker**” is a generic term for modulating light over time, either stimulus or response

Temporal light modulation (TLM): The fluctuating light stimulus (illustrated by its waveform)

Visual perceptions from TLM: an *undesired change in visual perception* induced by a light stimulus (TLM) whose luminance or spectral distribution fluctuates with time

- **Direct Flicker:** Perception of *visual unsteadiness*... for an observer with fixed gaze. 3 - ~80 Hz
- **Stroboscopic motion:** Change of *motion perception*... for an observer with fixed gaze, but movement of object in visual field ~80 Hz - ~1000 Hz
- **Phantom array effect** (ghost effect): A spatial effect across the retina of multiple, separate images of an edge or bright object, resulting from an eye saccade relative to the modulating light source. ~80 Hz – ~15,000 Hz



Jems.com

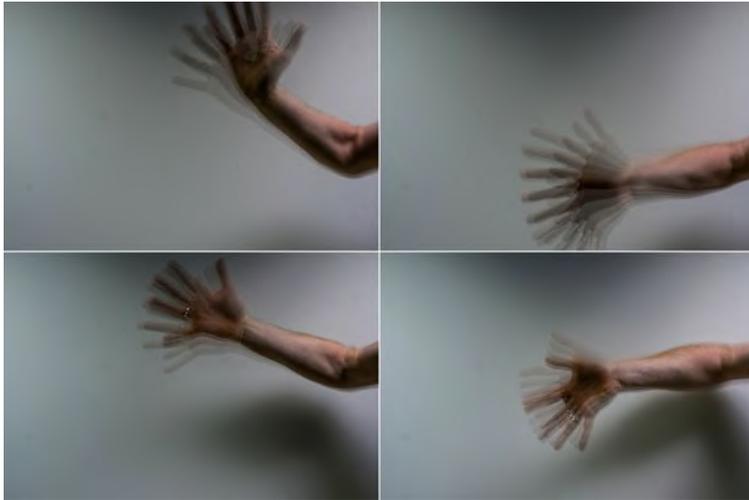


Image: Gosia Perz



Demonstration of Temporal Light Modulation (TLM)



Photo: Lee Sonko



Direct flicker

Stroboscopic Effect

Phantom Array Effect



Saccades 2-3 every second

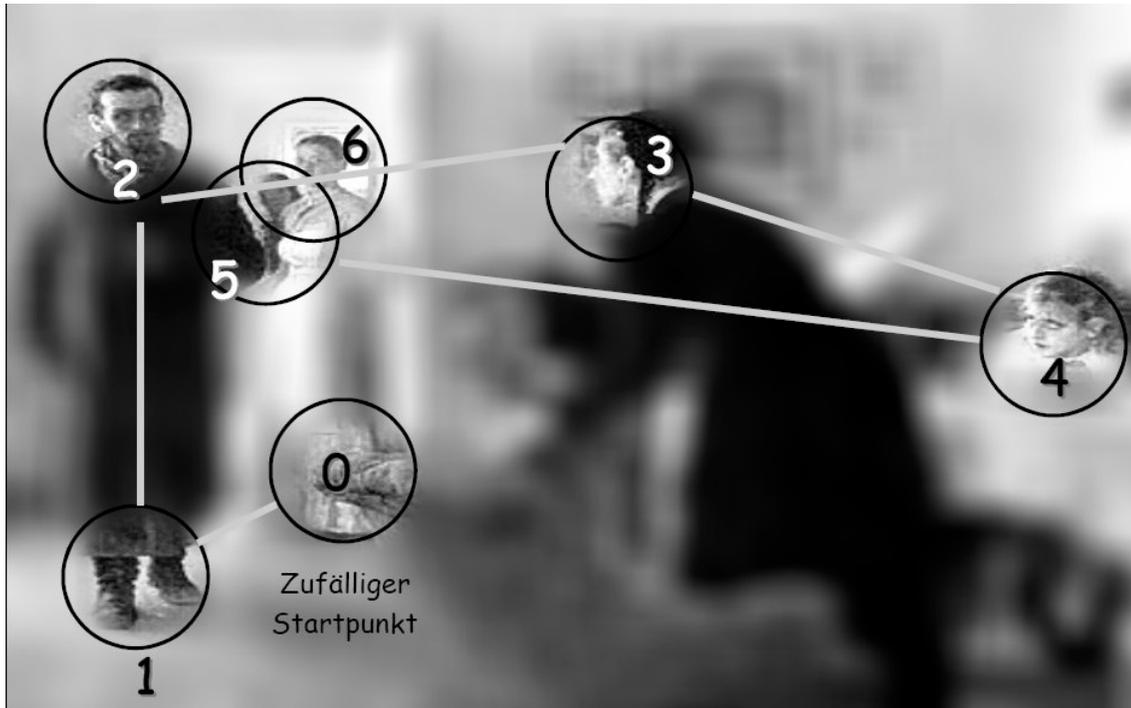
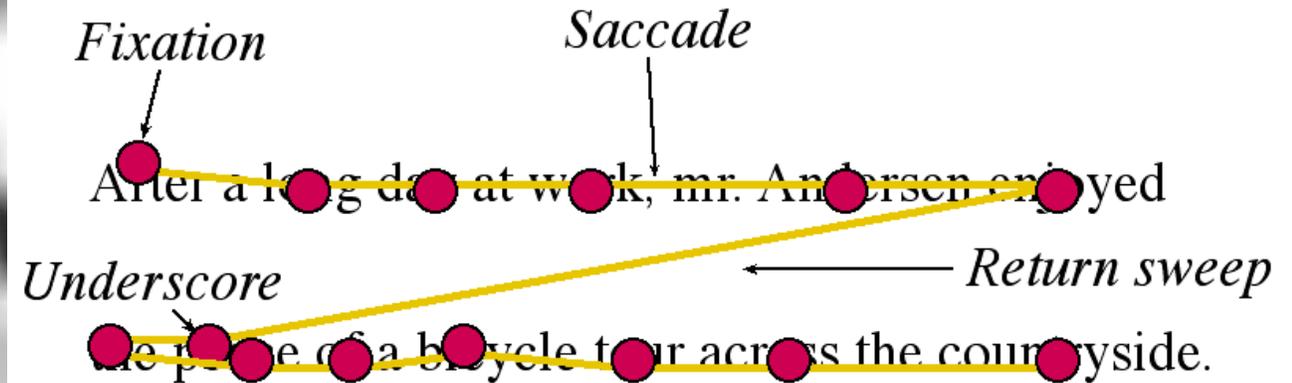


Bild 11: Foveale Ergänzung durch die ersten 6 Fixationen (nach Daten von Yarbus, 1967)



Saccades speed up with large visual angles (500 – 700°/s for >40° visual angle (*think driving...*))



We can see during a saccade



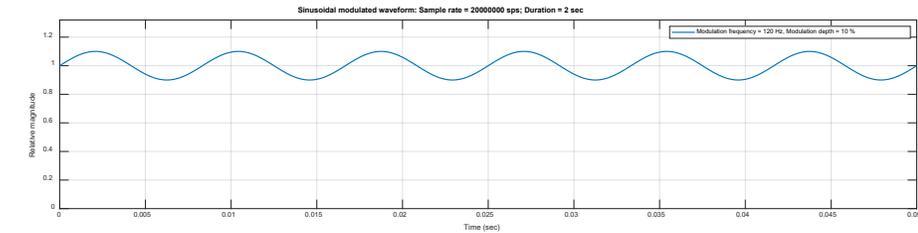
“phantom array”

Why is “flicker” (TLM) an issue, especially now?

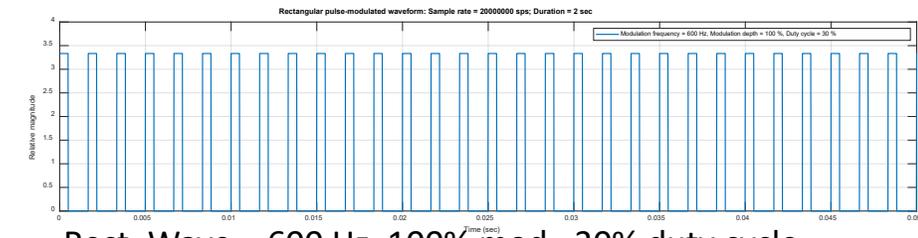


Solid-state lighting sources new to architectural lighting

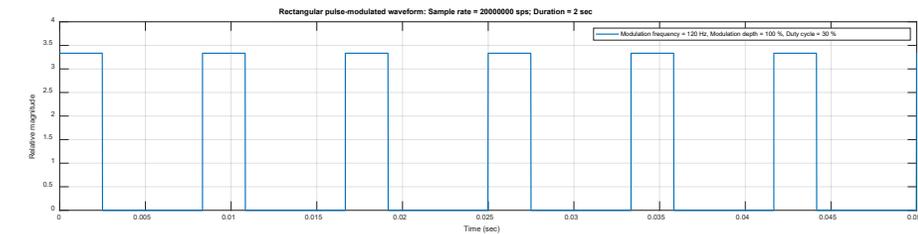
- Previous lighting systems usually sine waves and twice mains frequency
- Some flicker complaints about fluorescent, fixed with high-frequency electronic ballasts.
- SSL systems – fast-responding devices
 - Little thermal or temporal persistence
 - LED TLM dependent on current from driver and dimmer.
- PWM circuits are an easy way to dim LEDs, producing ON/OFF output ... But are especially visible!
- LED system waveforms can take any shape, frequency, modulation



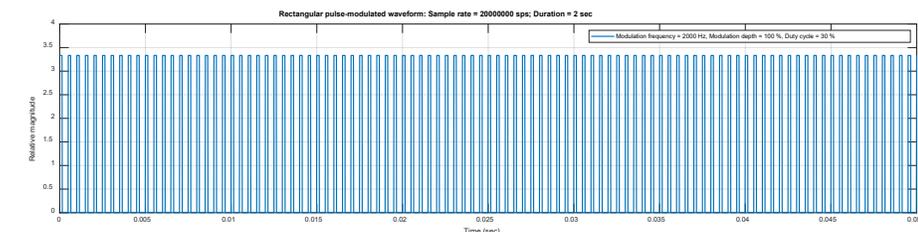
Sine Wave – 120 Hz, 10% mod., sim to incandescent



Rect. Wave – 600 Hz, 100% mod., 30% duty cycle



Rect. Wave – 120 Hz, 100% mod., 30% duty cycle



Rect. Wave – 2000 Hz, 100% mod., 30% duty cycle

TLM

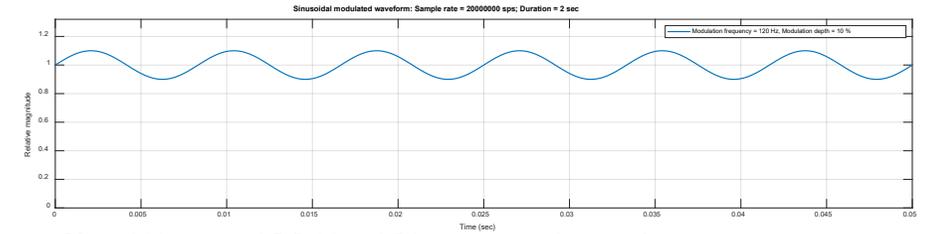
Responses to TLM:

20-30% of population may experience visual and *non-visual* responses (e.g., cognitive, behavioral, physiological, and psychological), including

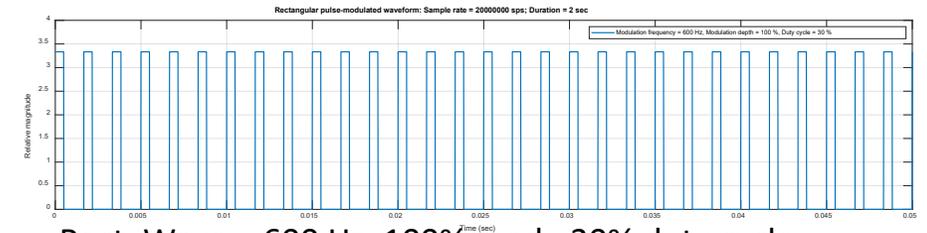
- Headaches
- Migraines
- Nausea
- Seizures (primarily 3-65 Hz frequencies)
- Autistic behaviors
- Distraction, disorientation
- Slowed reading, etc.

Factors that affect the visual perception

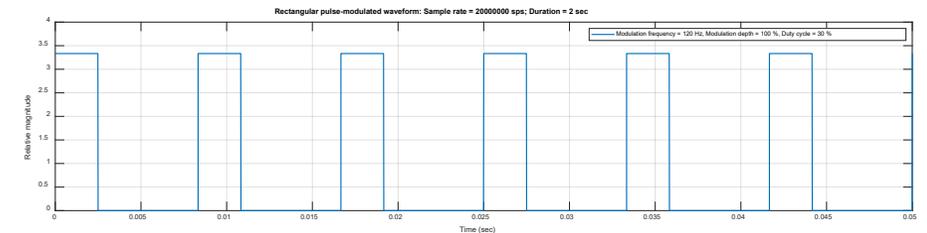
- Waveform shape (such as sine vs. rectangular waves)
- Frequency
- Duty cycle
- Modulation depth (also called % flicker, % modulation)
- ***Sensitivity and characteristics of the observer***
- Size of light source (i.e. width in visual degrees)
- Background luminance and relative contrast



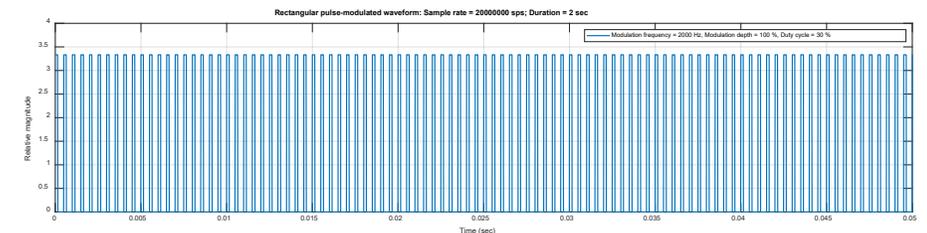
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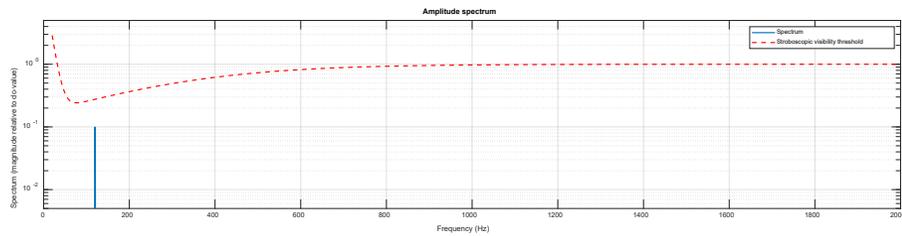
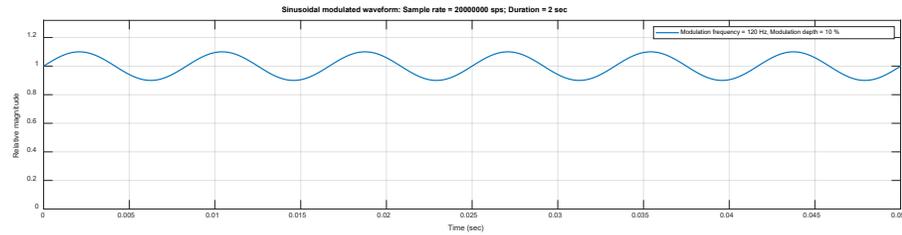


Show and Tell

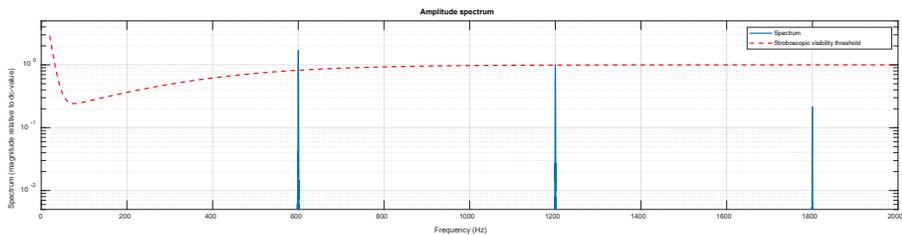
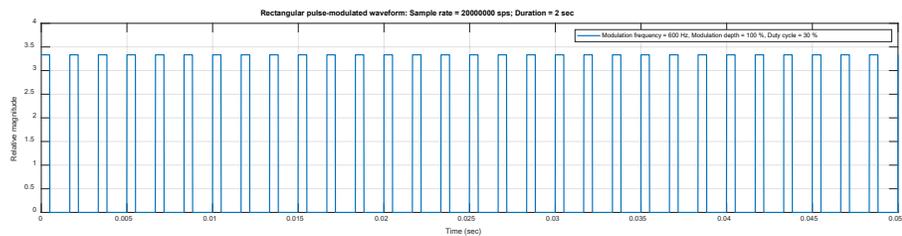
Showing range of waveforms and demonstration in real time to audience



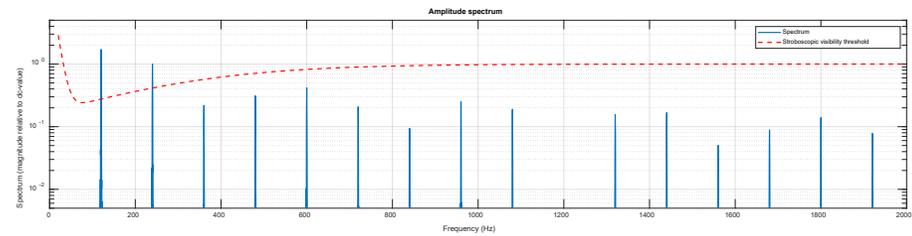
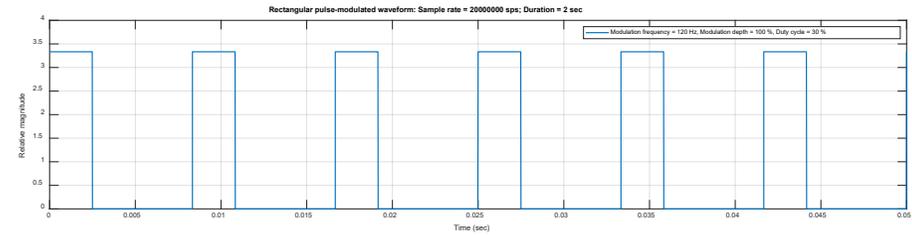
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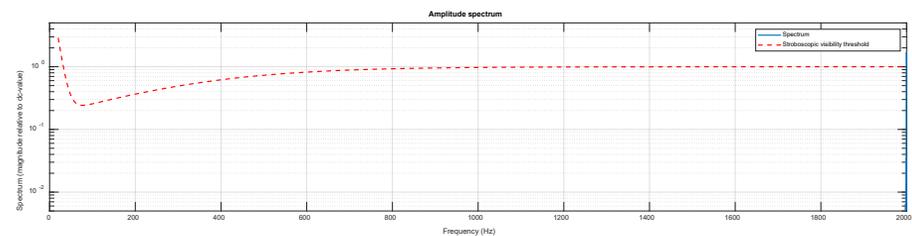
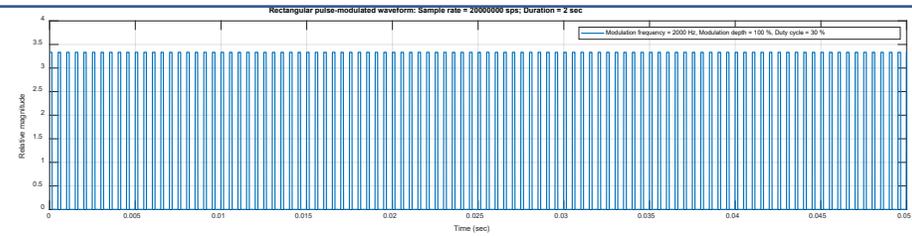
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Rect. Wave – 120 Hz, 100% mod., 30% duty cycle



Rect. Wave – 2000 Hz, 100% mod., 30% duty cycle

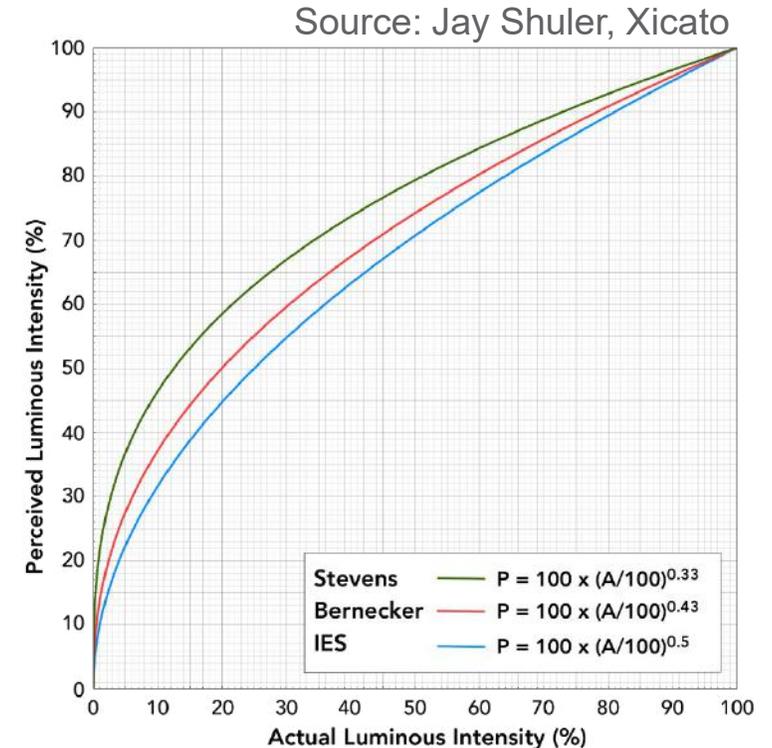




Why is this a concern? Why now???

LEDs

- 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 vs perceived dimming levels



Where does that leave us?

Driving (and crossing streets) are inherently dynamic head movement activities. Flicker studies up to now:

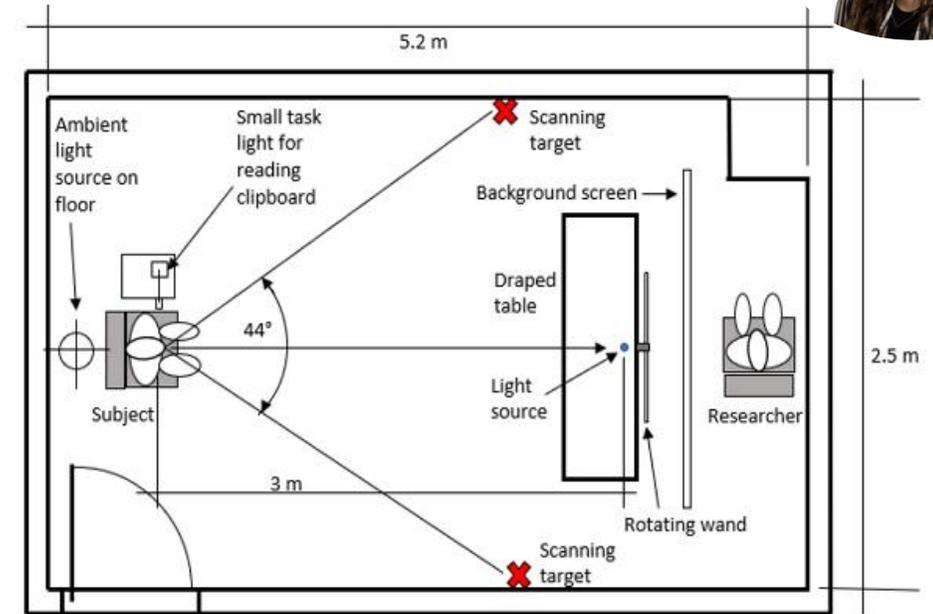
- Base visibility results to the ‘average person’, leaving a lot of people behind
- Too often restrict head movement, use constrained laboratory conditions, avoid interactions between multiple moving sources, and use very short exposures
- Some organizations’ ethics rules preclude studying sensitive populations – thankfully, others have informed consent procedures that allow for this
- PNNL would like to start filling these research gaps



PNNL Test Goals and Setup

Goals of this study: Investigate visibility of stroboscopic and phantom array effect with respect to wave shape, frequency, modulation depth and duty cycle.

Test Room
8'-2" x 17' x
9' ceiling
10' viewing
distance
from
subject eye
to LED
1.5 – 2 lux
at eye,
including
0.6 lx
ambient
light



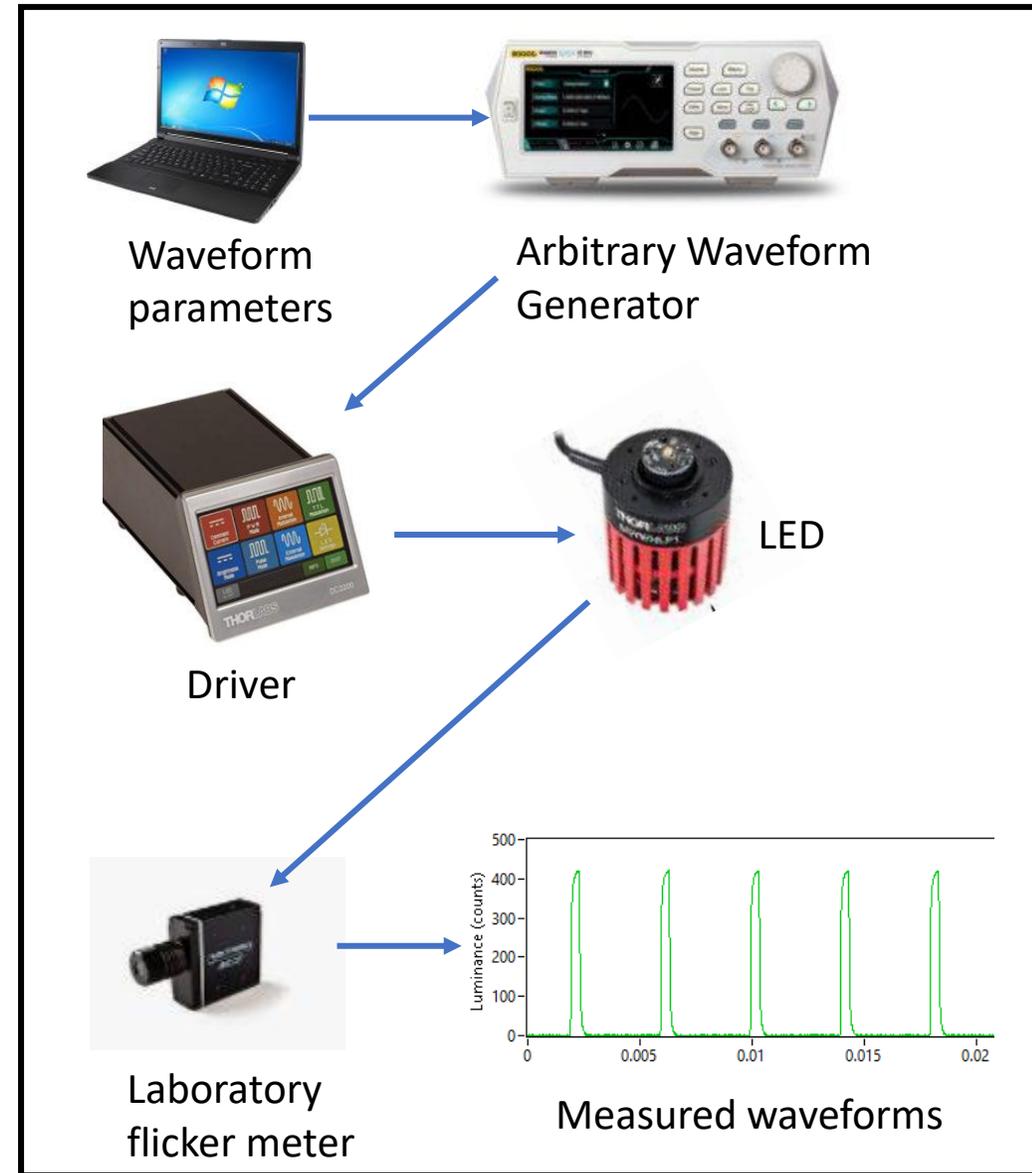
Closeup of rotating wand, in horizontal position.



PNNL Subjects, and Test Setup

Subjects: 36

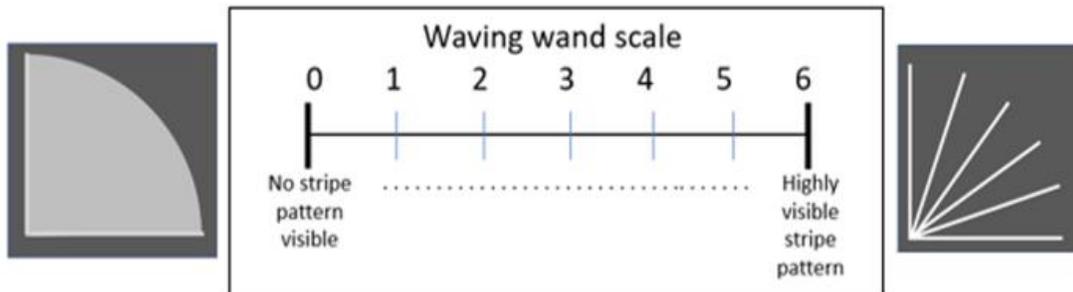
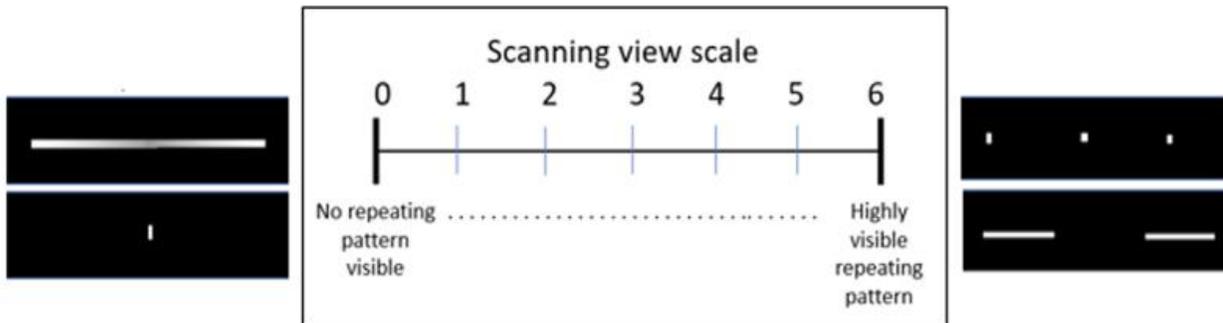
- Gender identity:
 - 15 female
 - 20 male
 - 1 non-binary
- Age range: 19 to 76 years
- Equipment used to display waveforms



Experiment protocols and rating scales



- Participants completed the Leiden Visual Sensitivity Scale questionnaire
- Participants “calibrated” with sample waveforms showing examples of 0-6 for both PAE and SE



Leiden Visual Sensitivity Scale

([Perenboom et al., 2018](#))

- 1 To what extent does sunlight bother you when you are not wearing sunglasses?
- 2 To what extent are you bothered by electric lighting?
- 3 To what extent are you bothered by flickering lights (e.g. a flickering lamp, during films, or at the discotheque)?
- 4 When you look at a bright light, is your eyesight worse afterwards (e.g. blurred or distorted vision)?
- 5 To what extent does looking at patterns bother you? (e.g. patterns in clothing, materials, window blinds)?
- 6 When you look at everyday patterns, do you experience afterimages? (Seeing an image of the pattern elsewhere, for instance, on a white wall)
- 7 When you look at patterns, is your eyesight worse? (e.g. blurred or distorted vision)
- 8 When you look at a computer or TV screen, do you see afterimages? (Seeing an image of the pattern elsewhere, such as on a white wall)
- 9 When you look at a computer or TV screen, is your eyesight worse? (e.g. blurred or distorted vision)

Scored from 0-4:

“not at all” (0 points), “slightly” (1 point), “moderately” (2 points), “severely” (3 points), and “very severely” (4 points).

Score is sum of the 9 items, possible range 0 – 36

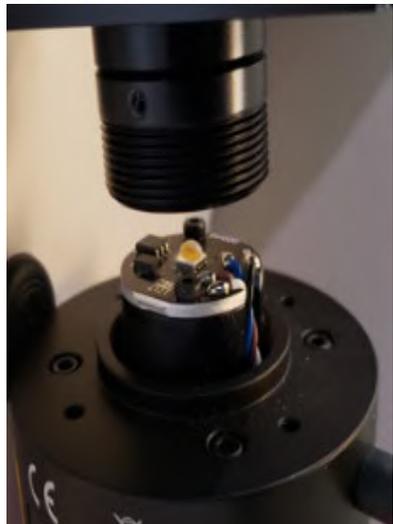
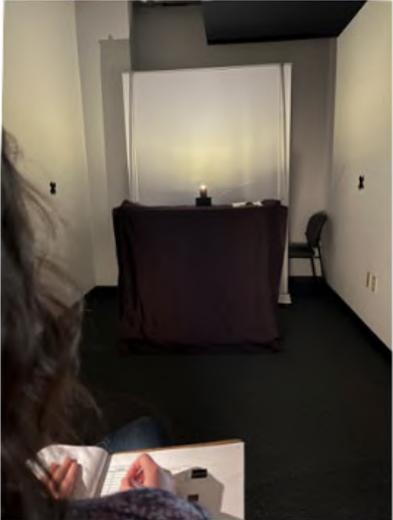
TLM Waveforms presented



Waveform characteristics presented, although not all combinations used (total was 74)

Wave Shape	Frequency (Hz)	Modulation %	Duty Cycle (%)
Sine	90	11	10
Rectangular	120	20	30
Continuous	250	50	50
	500	100	
	750		
	1000		
	2000		
	4000		
	6000		

All waveforms produced the same luminance within 7% variation except one at 6000 Hz



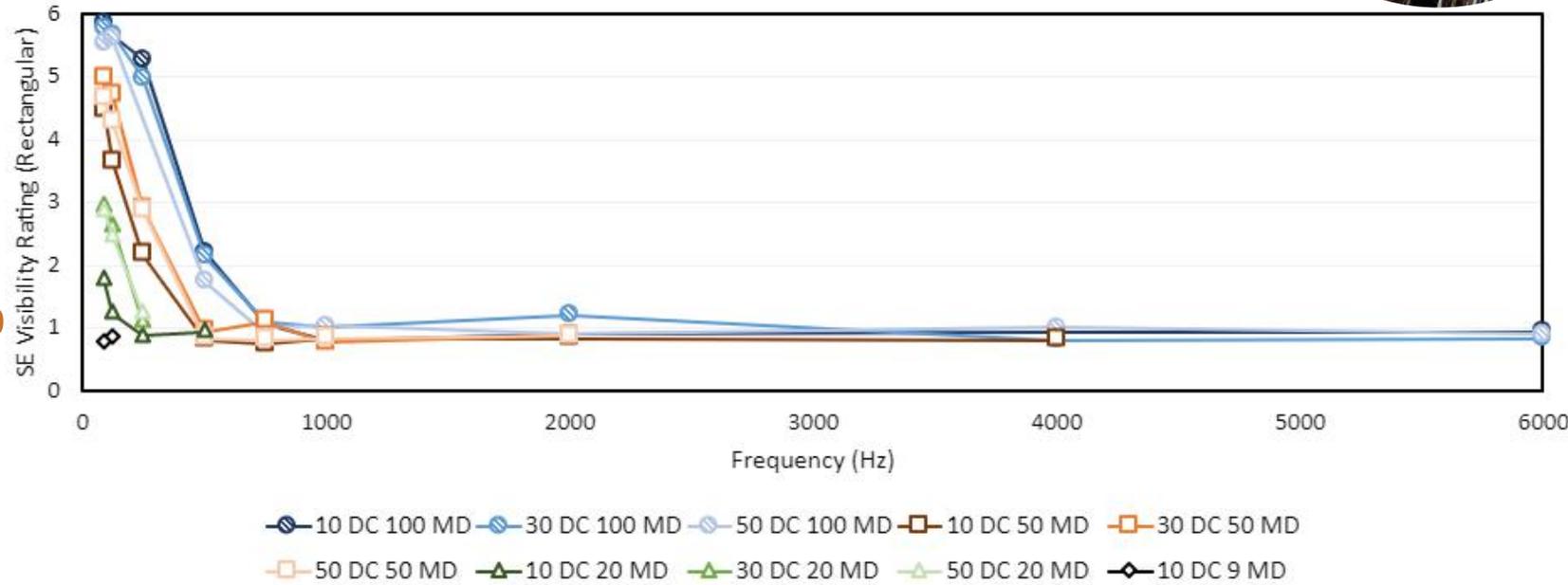
Results: Stroboscopic Effect Visibility Rating vs. Frequency



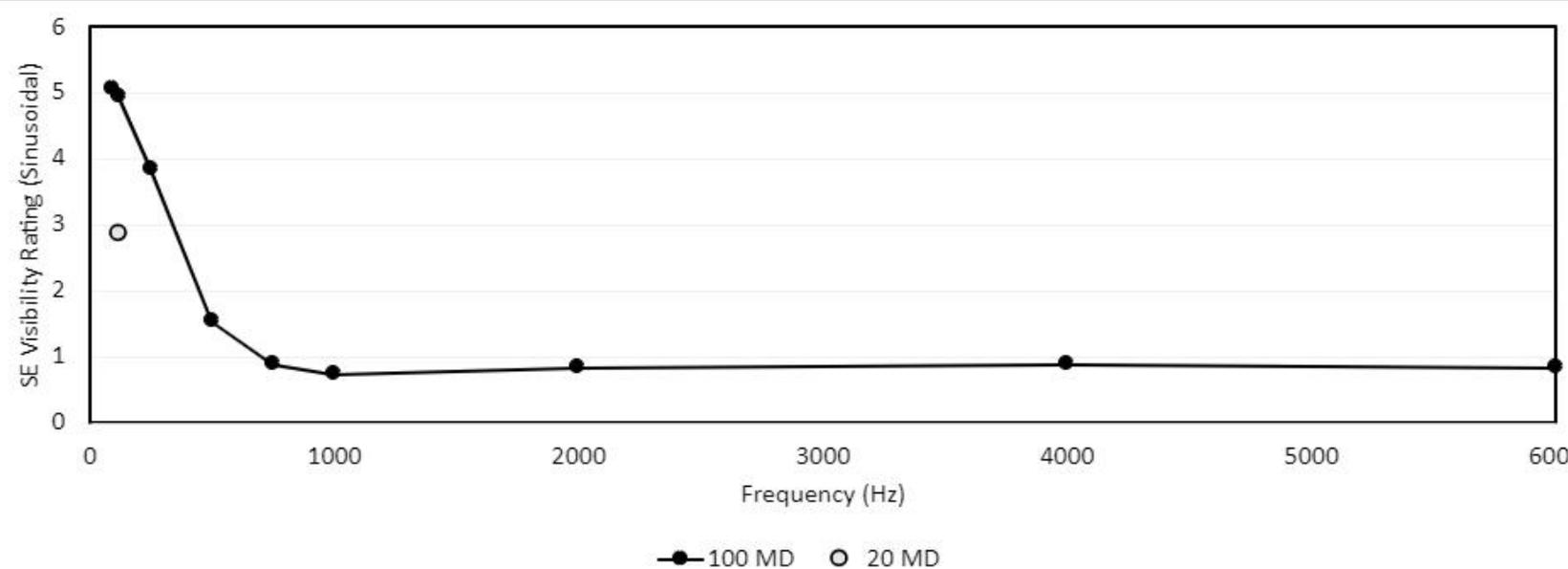
Average visibility of the stroboscopic effect from TLM waveforms:

- Peaks at 90 – 120 Hz, but declines rapidly with frequency
- Greatest at 100% and 50% modulation
- Maximized at 10% and 30% duty cycle (for rectangular TLM), compared to 50%
- Rectangular waves more visible than sine waves at equal frequency and modulation depth

Rectangular Waves



Sine Waves



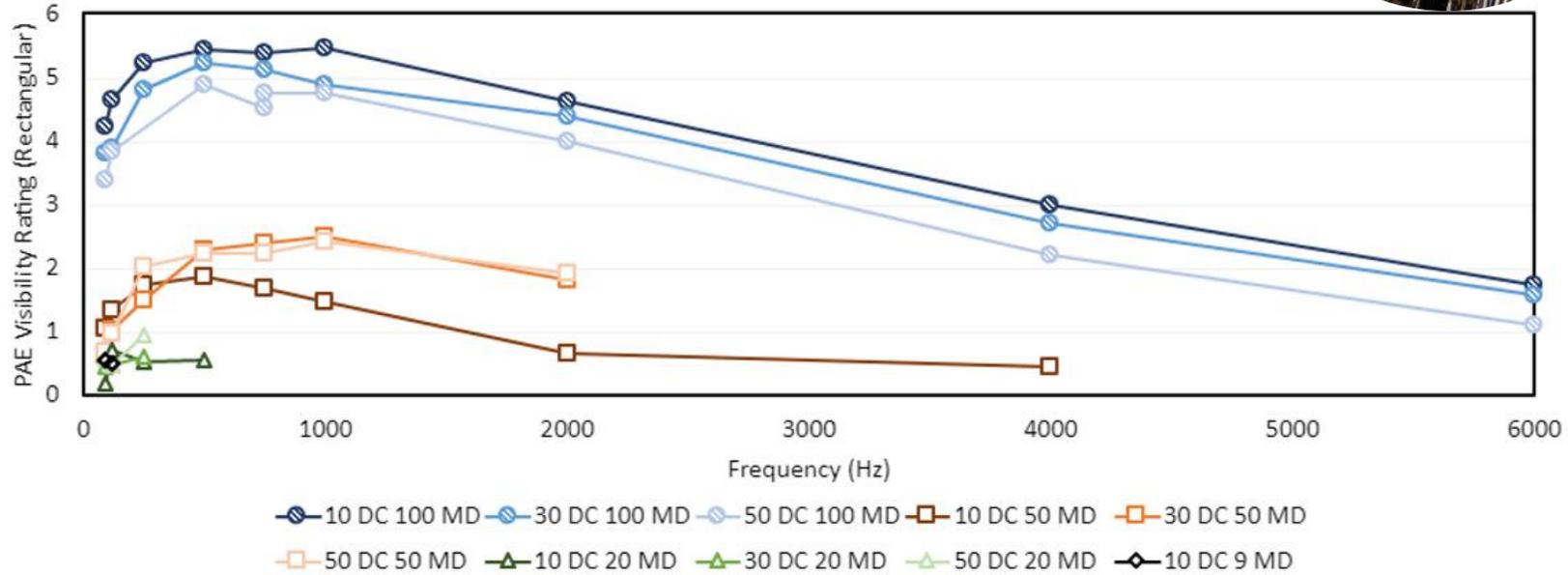
Results: Phantom Array Effect Visibility Rating vs. Frequency



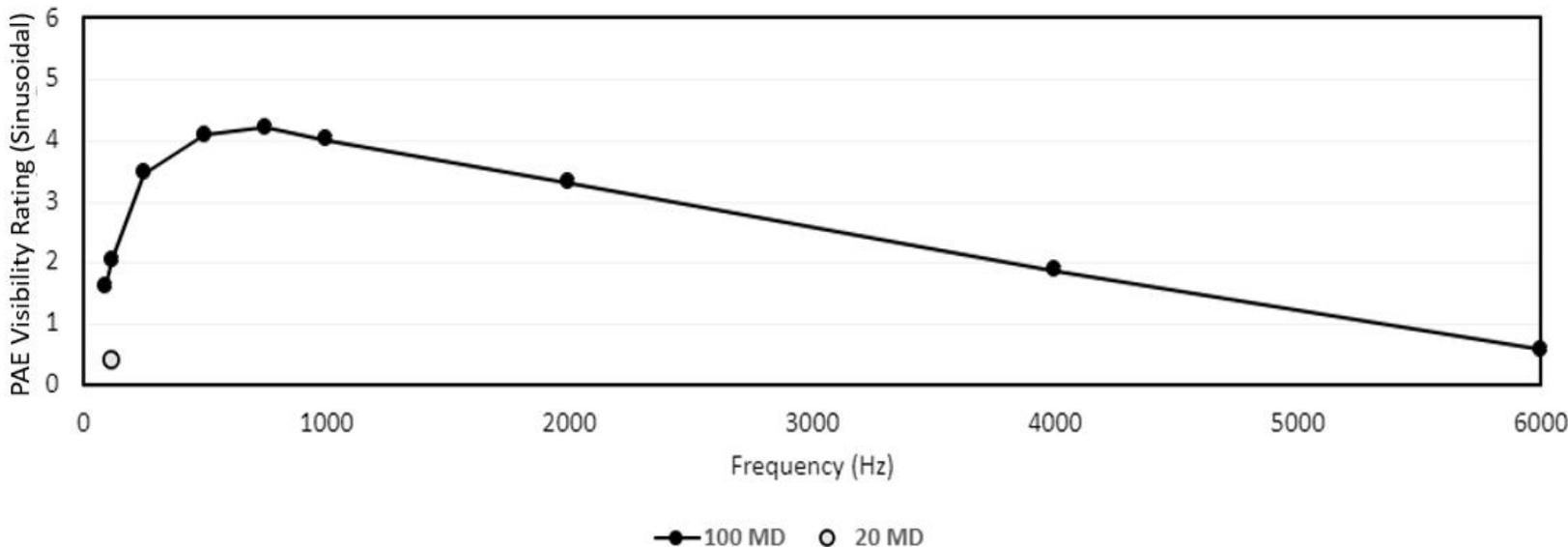
Average visibility of the phantom array

- Peaks at 500 – 1000 Hz.
- Greatest at 100% and 50% modulation
- Maximized at lower duty cycles (10% and 30%)
- Visible *on average* at 6000 Hz at 100% mod, 10% duty cycle
- Rectangular waves more visible than sine waves at equal frequency and modulation depth

Rectangular waves



Sine Waves

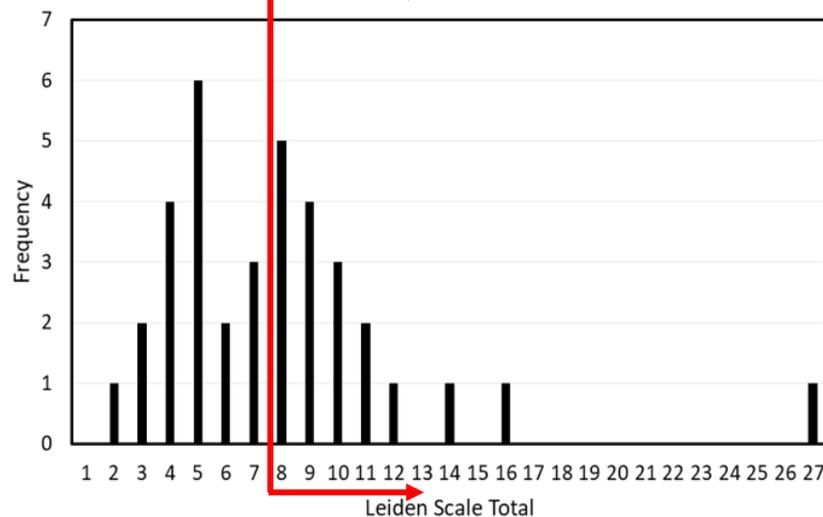


Difference between higher and lower sensitivity responses

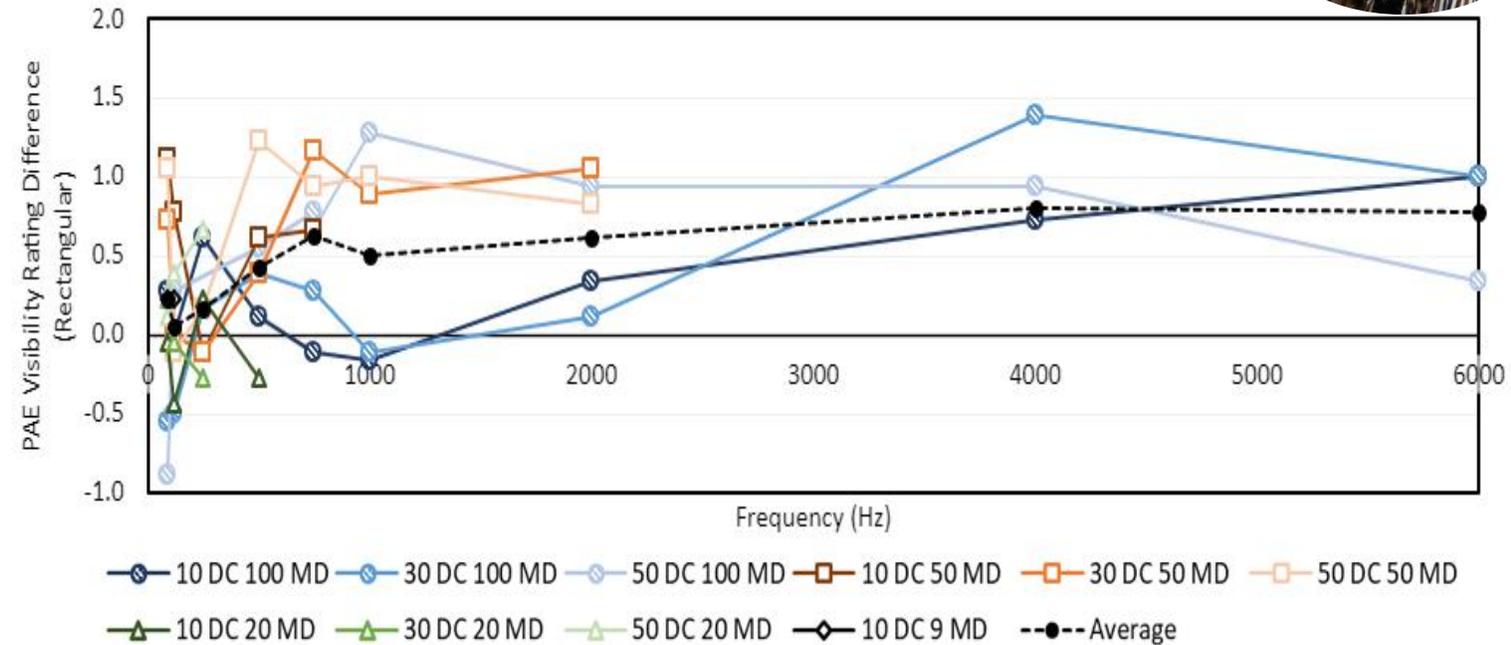


Visibility of the phantom array

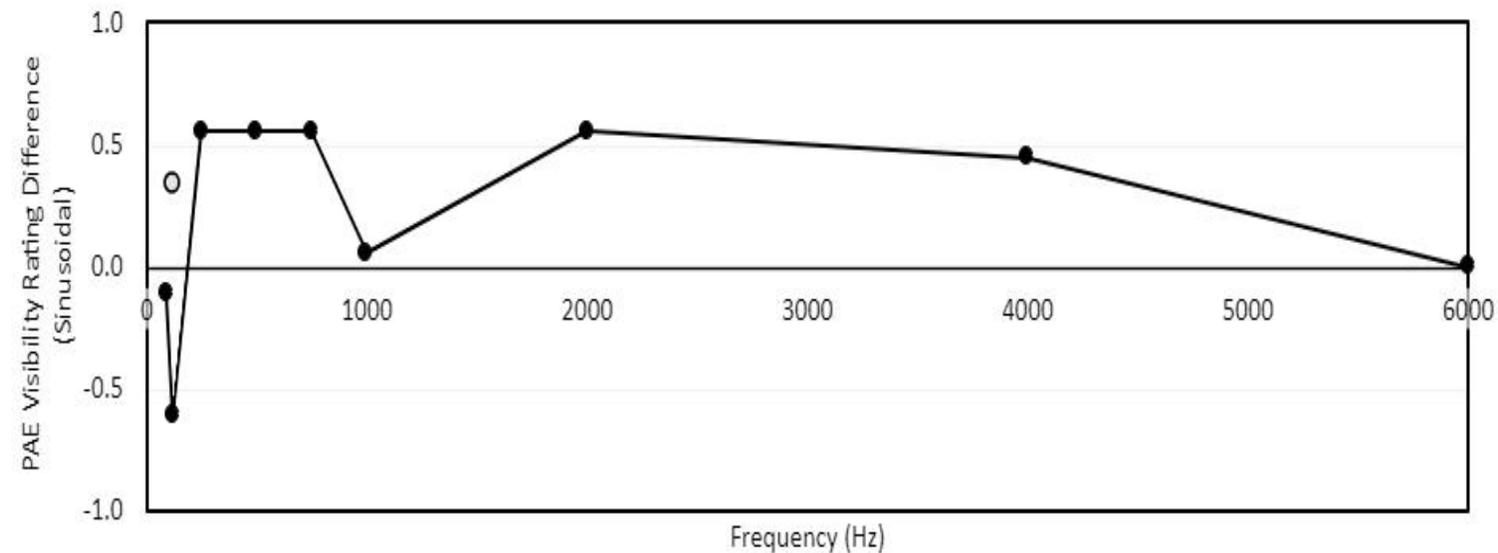
- Leiden visual sensitivity scale used to separate higher vs. lower sensitivity subjects
- Significant differences between groups
- Differences were greatest when the waveforms were “harder to see” (lower modulation depths, higher duty cycles, higher



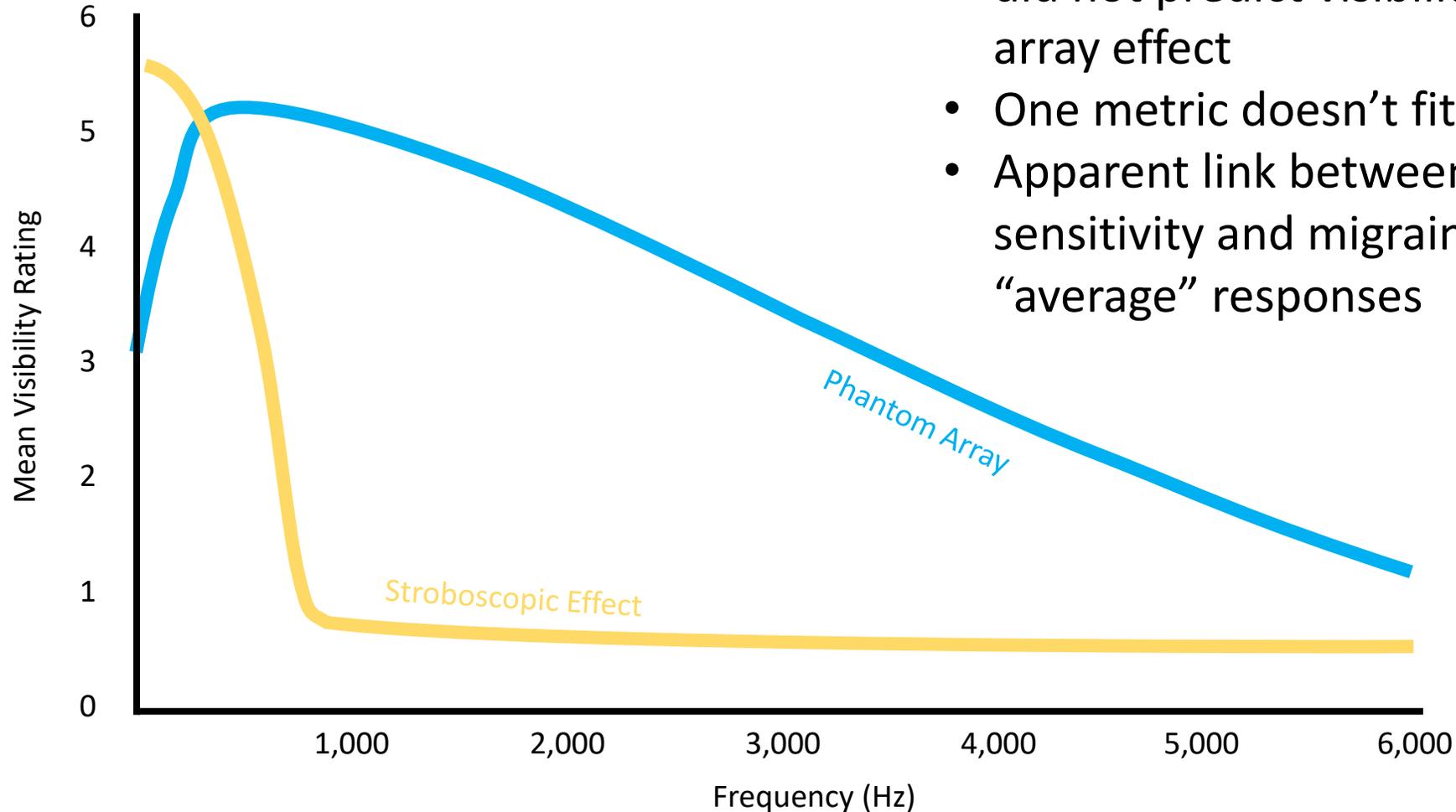
Rectangular waves



Sine Waves



Stroboscopic and Phantom Array Effects are different responses



- Stroboscopic Visibility Measure (SVM) did not predict visibility of phantom array effect
- One metric doesn't fit all
- Apparent link between flicker sensitivity and migraines – may skew “average” responses

Do we design flicker standards for the average population or the sensitive population?



What do we right now?

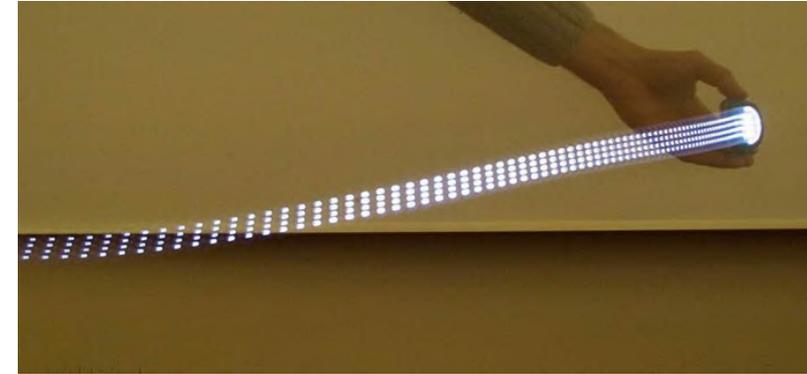
Metrics that are promising for the 2 or 3 flavours of visible perceptions of TLM

- Direct flicker –
 - Use Assist M_p or P_{st}^{LM} , metrics for 3 - 80 Hz. Values should be <1.0 for both metrics
- Stroboscopic motion –
 - Stroboscopic Visibility Measure (SVM) where values should be arguably ≤ 0.9 for normal populations, or <0.4 for very sensitive observers
- Phantom array effect – No metric yet exists, but stay tuned. In the meantime, use rules like:
 - Avoid $> 50\%$ modulation TLM
 - Avoid duty cycles $\leq 50\%$
 - Avoid rectangular waveforms
 - If possible, increase frequency to $\geq 25,000$ Hz

Guidelines for LED/driver/dimmer manufacturers



- Metrics for lower frequency waveforms may not apply to vehicular applications
- Sinusoidal waveforms better than square waveforms
- Avoid 100% modulation. <50% is much better. <10% better still
- Avoid low duty cycles. 90% duty cycle is hardly visible. 10% - 30% duty cycle is VERY visible
- Consider tradeoffs between and combinations of CCR, PWM, and PFM for very low dimming
- Be cautious with any frequency lower than 80 Hz. Risky.
- Higher frequencies needed if you must dim to less than 1% or 0.1%, using low duty cycles. But phantom array effect is very visible at 500 -1000 Hz. Higher frequencies better.
- For applications with very dark ambient levels and high needs for dimming (like roadways), consider frequencies >25,000 Hz



How to identify TLM in the field: simple tricks



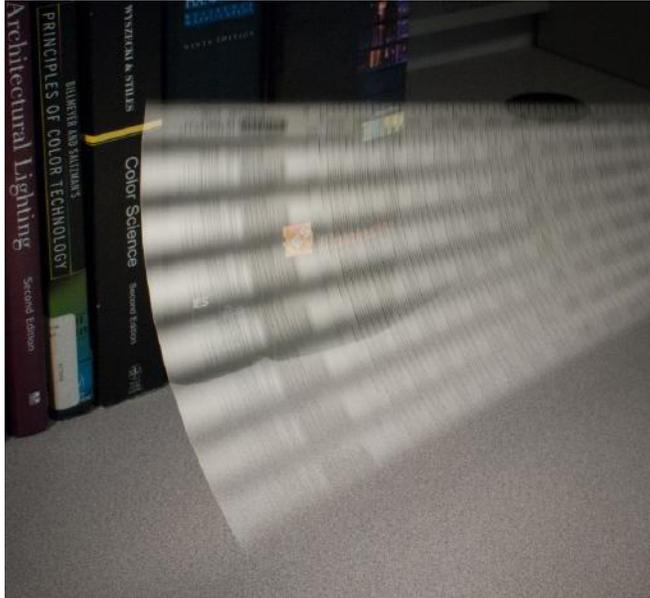
Easy tests:

One of the best methods to test for flicker is the waving wand or hand test, which can be seen in flicker videos. Wave the wand or your hand *as fast as you can* in a fan shape and look for multiple wands or multiple fingers under the light, rather than a smooth blurred image of the wand or fingers. If the frequency is high, between 2000 Hz and 4000 Hz, for example, the image you see from the waving image may look like the teeth of a comb. If this is visible, sensitive individuals may still be able to detect it, especially when the background condition is very dark.

Video:

If you suspect flicker from light source, take a cell phone and set it on 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**

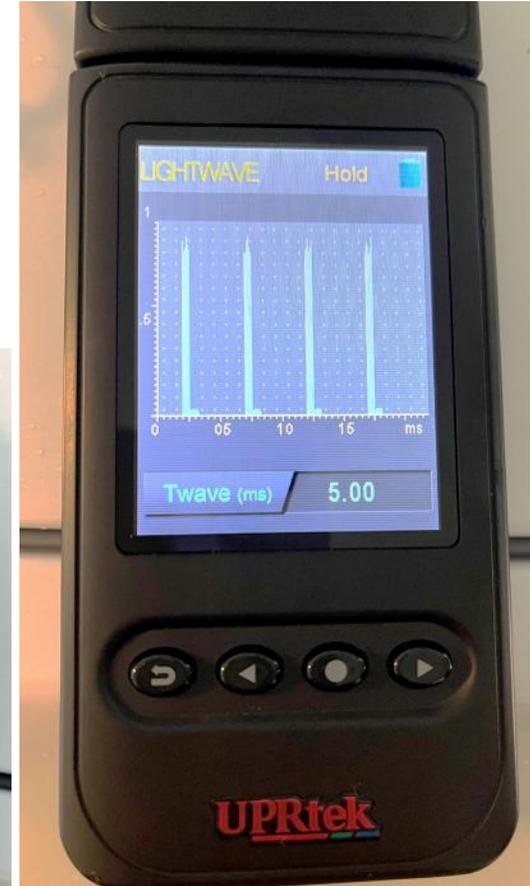
INDICATOR, AND IT'S FUN.



TLM (Flicker) from Tesla 2023 Y DRL



200 Hz, 100% modulation
< 10% Duty cycle
SVM > 4
Video at 240 fps



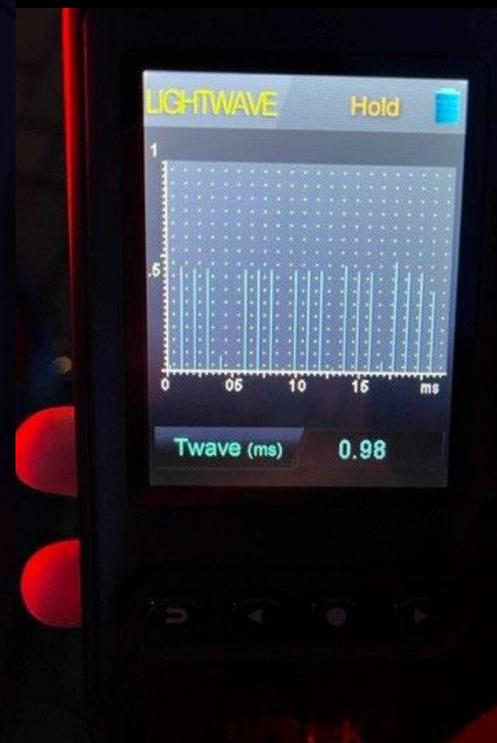


TLM from Kia Soul 2023 taillights

1025 Hz, 100% modulation

< 10% Duty cycle

SVM = 2.4





Implications for Auto Industry

- Modulating taillights, DRLs, parking lights, turn signals, interior spots, and dashboards can be distracting or annoying, with potential safety consequences.
- Metrics and guidelines should protect higher sensitivity populations
- **Cameras in vehicles interact with TLM in lighting**
- LED electronics should combine CCR, PWM and high frequencies to reduce perceived stroboscopic and phantom array effect
 - We fixed fluorescent flicker with high frequency ballasts – we can fix LED flicker with high frequency drivers (> 25,000 Hz ?)
- TLM is a human health, safety, and a perception issue



Photo: Lee Sonko



Why do we care?

“If I am crossing a street at night, I scan left and right to spot oncoming traffic. Looking back and forth with rapid head and eye movement, the “flickering” daytime running lights and taillights superimpose phantom arrays on my field of view, making it very difficult to gauge speed and distance of the oncoming cars. I go through a double-take, because I am unable to interpret the series of phantom array afterimages that do not correlate to the motion of the cars. This is very distracting and disorienting, causing a slight loss of balance, sense of nausea, and real danger.”



"Crossroad" by [halfrain](#) is licensed under [CC BY-SA 2.0](#).



What's the proof?

- Do we have crash statistics?
- How do you collect crash statistics from drivers who were disoriented by lighting from other cars?
- Do we have neurologists up in arms because there are pedestrians being injured?
- Does the auto industry recognize health complications from lighting frequencies above 120 Hz?

The research community is slowly accumulating data associating TLM with disorientation, nausea, headaches, migraines.

Slo-Mo video of Honda Dashboard – Lee Sonko



*What have you learned?
What would help?
Talk to us.*

Thank you!



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