Phantom Array and Stroboscopic Effect Visibility under Combinations of TLM Parameters

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Abstract

Solid-state light sources can be more prone to larger temporal light modulation (TLM) than conventional sources. TLM visibility depends on wave shape, frequency, modulation depth, and duty cycle, and is affected by the sensitivity of the observer. TLM can be visible well above the critical flicker fusion frequency (CFF), when there is relative movement between the observer's eyes and light source, lighted space, or moving objects in the field of view. This human subjects experiment explored visibility of the stroboscopic versus the phantom array effect with targeted tasks under 74 TLM waveforms. The results showed the stroboscopic effect visibility peaks between 90 and 120 Hz, while the phantom array effect visibility peaks between 500 and 1,000 Hz. The phantom array is visible to sensitive participants at 6,000 Hz. Both effects are more visible under rectangular versus sinusoidal TLM, higher modulation, and when duty cycles are 10% or 30% versus 50%. Higher-sensitivity participants, differentiated using the Leiden Visual Sensitivity Scale, rated TLM waveforms as more visible, especially those inherently harder to see. This work lays a foundation for a phantom array effect metric and guides driver and dimmer designers toward electronic circuits that minimize the visibility of TLM in LED products.

1. Introduction

Complaints of "flicker" accompanied the introduction of solid-state lighting in the early 2000s.[1] As was the case for magnetically ballasted fluorescent systems, not all observers could see the effects of temporal light modulation (TLM) or were bothered by it, but a subset of sensitive individuals could.[2] This has continued to be true for LED lighting, with detectability depending on the time-based pattern of current delivered by the driver/dimmer combination. Visible perceptions of TLM have been observed even at much higher frequencies than 100 Hz, [3,4,5,6,7,8,9,10] far above the critical flicker fusion frequency, from 90 Hz up to 11,000 Hz.[11,12,13] Investigation into TLM waveforms revealed non-sinusoidal shapes exhibiting deep modulation and low duty cycles not before seen in architectural lighting.[14] The electronics of the dimmer and driver are responsible for the TLM waveforms delivered by the LED, and these TLM waveforms can be highly variable.

The terminology for "flicker," a purely generic term for either the stimulus or response to light modulation, has evolved in recent years. This article will use the terms found in Appendix A, which includes descriptions of the four characteristics affecting the waveform's potential for producing visible perceptions of TLM: frequency, modulation depth, duty cycle, and the shape of the waveform. Sensitivity of the observer is also a critical variable: as an example, some will clearly see the phantom array effect even at 6,000 Hz under certain conditions, while others will see no pattern or distorted motion whatsoever.[10]

In the last 20 years, much research effort has gone into understanding the two visual responses to TLM that occur at frequencies above 100 Hz: the stroboscopic effect and the phantom array effect. The stroboscopic effect requires the movement of an object within the visual field, illuminated by the modulating light; the phantom array effect involves the interaction of the observer's eye saccade relative to the modulating light source or an object lighted by it.

Bullough *et al.*[3] examined TLM visibility from 50% duty cycle waveforms of 100, 300, 1,000, 3,000, and 10,000 Hz, and modulation depths from 5% up to 100%. Overall, they found that visibility increased as modulation increased, and decreased as fundamental frequency increased. However, a subsequent study[4] found an interaction between frequency and percent modulation in that it was more noticeable at 100% modulation at 300 Hz, versus 33% modulation at 120 Hz. Observers reported seeing the stroboscopic motion up to roughly 1,600 Hz with 100% modulation, and 1,000 Hz with 54% modulation. In their study that included a waving wand task, 300 Hz frequency was found to have the highest visibility. A final study[5] found improved task performance and visual comfort under higher frequencies and lower modulation depths.

Vogels *et al.*[6] presented a dark-colour rotating disk with a white spot to observers under different rectangular TLM waveforms from 50 Hz up to 400 Hz frequencies; duty cycles of 10, 30, 50, 70, and 90%; and multiple modulation depths. Visibility was greatest at lower frequencies, and at lower duty cycles of 30% and 50%. This was the first of many studies by this research team.[15,7] Cumulatively, 180 observers were tested with both sinusoidal and square TLM, at frequencies up to 1280 Hz. Square TLM proved to be more visible by a factor of 4/π than sinusoidal waveforms of equal frequency and modulation depth. Using Fourier analysis of the waveform and frequency summation, they proposed the Stroboscopic Visibility Measure (SVM) as a predictive tool for TLM visibility from frequencies from 80 to 2000 Hz.

Hershberger and Jordan[16] conducted an early study of the phantom array effect, finding that almost all participants could see the array in a darkened room, scanning across a 200 Hz frequency, 30% duty cycle, 100% modulation depth source of TLM. Roberts and Wilkins[17] used pulse-width modulation control of slit-aperture sources of 120 to 2,500 Hz in a dark room, with all observers able to discriminate the modulating light from steady light at frequencies averaging 1.98 kHz. Further work by Brown *et al.*[8]

with a similar lighted slit against a black background in a dark room increased the average maximum frequency for visibility up to 5.8 kHz, but this extended as high as 11 kHz in one individual. Wang *et al.*[9] used a higher adaptation luminance similar to that of a lighted office space, learning that the peak visibility was achieved at 600 Hz, but that although task polarity and contrast affected its visibility, detection of the phantom array did not vary with illuminance level. A subsequent study by the same research group[18] showed that, like the stroboscopic effect, the visibility of the phantom array was higher with rectangular waveforms than sinusoidal, so a Fourier summation could be used to characterize the response. Park *et al.*[10] showed that visibility of the phantom array increased linearly with logarithm luminance, that green, blue, and red lights were in descending order of visibility, and that narrower visual angles produced greater visibility. Notably, they documented considerable differences in response among their 26 participants to each stimulus.

Research efforts have focused on the stroboscopic effect and metrics to predict it[19] but to date, no approach has been proposed to quantify responses to a TLM waveform producing a phantom array effect short of a provisional model published by the Commission Internationale de l'Eclairage (CIE) in 2022[20]. One intention of this study was to differentiate the two responses, and document that they are separate responses that potentially require two different measures.

A pilot study was undertaken in October 2021 using 11 participants to explore responses to 65 TLM waveforms. That work led to the following hypotheses for the current study.

For both phantom array effect and stroboscopic effect:

1. The peak of the stroboscopic effect visibility ranges between 90 and 120 Hz, but the peak of the phantom array effect visibility occurs between 500 and 1,000 Hz. Thus, they are likely different visual responses.
2. Rectangular TLM waveforms with ≤50% duty cycles are more visible than sinusoidal waveforms at the same frequency and modulation depth.
3. Waveforms at 100% modulation depth are more visible than those at lower modulation depths (50% and 20%), given the same frequency and duty cycle.
4. Among rectangular TLM waveforms, those with duty cycle of 10% and 30% are more visible than waveforms with duty cycle of 50%, given the same frequencies and modulation depth.
5. Higher sensitivity participants are more likely to report higher visibility of TLM waveforms than lower sensitivity participants.

For the phantom array effect:

6. Phantom array effect visibility ratings at frequencies above 1,000 Hz are unlikely to be predicted by the stroboscopic visibility measure (SVM).

2. Method

This study asked participants to evaluate 74 TLM stimuli produced by a bare LED situated on a table in a dimly lit conference room. The participants evaluated the visibility of patterns in the light when scanning across the LED (*i.e.* phantom array effect), and the visibility of patterns produced by a rotating wand (*i.e.* stroboscopic effect).

2.1 Experiment space

The experiment was conducted in February 2022 in an unfurnished conference room, 2.5 m (W) x 5.2 m (L) x 2.7 m (H), in Portland, Oregon. An LED was set up on a draped cart located at the end of the room. The LED was at the participants' approximate eye height of 1.17 m. The participant was seated in a chair with a 3.0 m distance between eye and LED. Reading light for the clipboard materials during the experiment session was provided by a small 5 W halogen gooseneck task light directed toward the clipboard. Wall reflectances were approximately 60% light grey. A 2.2 m tall by 1.5 m wide, matte finish, solid grey screen was positioned behind the light source, with a reflectance of 52% to provide a neutral colour and unpatterned background for a rotating white wand. The 6 mm diameter wand extended 0.46 m on either side of the rotation point. Two 100 mm tall visual targets were located on walls flanking the light source at the 1.17 m eye height, each at a 22° visual angle to the left or the right of the LED. Figure 1 shows a plan and section of the room.

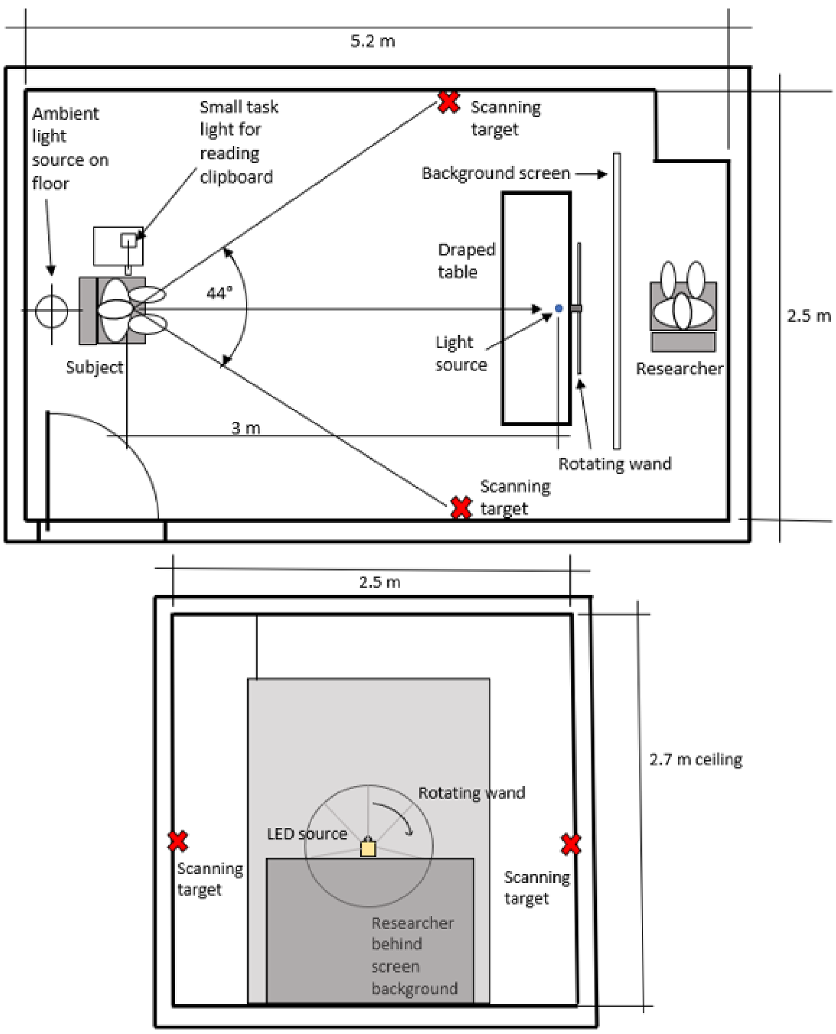
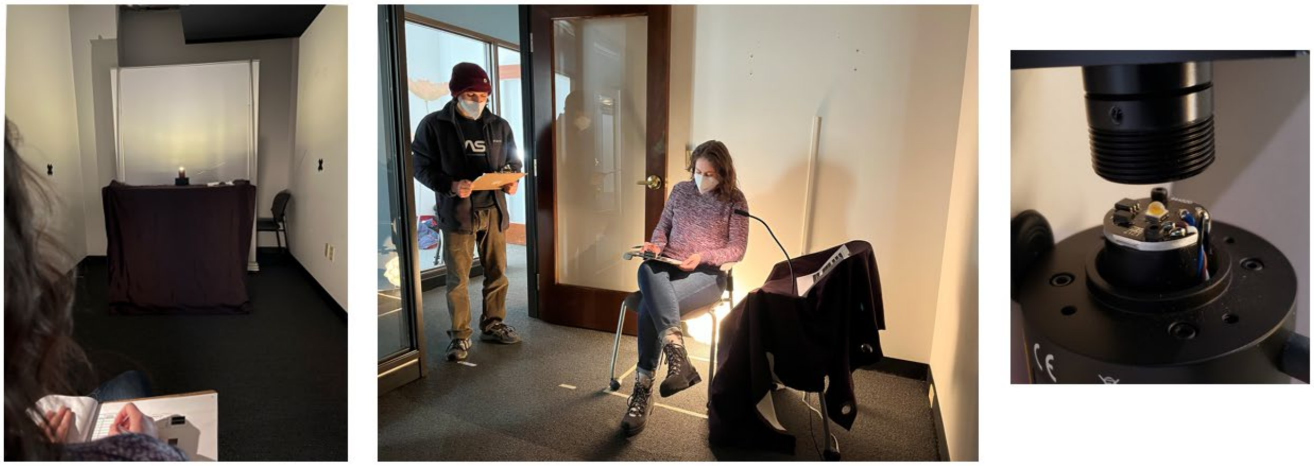


Figure 1. Plan and section of experiment room.



(a) (b) (c)

Figure 2 (a, b, c). Participant's view of the light source (a). Participant receiving instructions from researcher (b), and close-up view of the LED used in the experiment (c). Photo (c) shows the LED positioned for TLM waveform measurement.

Figures 2a and 2b show photos of the room. A low-height floor-mounted diffuse luminaire was positioned behind the observer's chair to provide a low level of ambient light. This source minimized any asymmetrical or distinct light patterns outside those emanating from the test light source, and was tested to ensure it emitted a constant light output (i.e. with no measurable modulation) so that it would not interfere with the programmed TLM waveforms. Ambient vertical illuminance at the participant's eye was approximately 0.95 lx, and the test light source provided 0.67 lx vertical at the participant's eye. The luminance of the LED was approximately 38,700 cd/m^2 from the point of view of the observer. It was measured from a 0.3 m distance so that the meter's capture angle (0.3°) most closely matched the LED package's (Figure 2c) apparent luminous size (3.2 mm dia. X 1.6 mm height). Although the room's luminances were not identical, the 1.5 m wide screen behind the light source and wand subtended a minimum 26° visual angle and its luminances ranged from 0.6 to 2.3 cd/m^2. Note that the screen's reflectance (52%) was intentionally selected as a neutral value so that it did not bias results.

2.2 Equipment

The following equipment was used to generate the TLM stimuli:

- A laptop computer running a Python script, which ran through the testing procedure for each participant. This included calling up TLM waveforms in a randomized order and recording the order.
- A Rigol DG800 arbitrary waveform generator (AWG) pre-programmed with waveforms having different shapes (rectangular, sine, and direct current), frequencies (ranging from 90 Hz to 6,000 Hz), modulation depths (ranging from 0% (*i.e.* direct current) to 100%), and duty cycles for rectangular waveforms (10%, 30%, and 50%).
- A ThorLabs DC2200 LED driver that converted the digital inputs from the AWG into analog current outputs.
- A ThorLabs MWWHLP1 LED (3000 K, 11.7 V_F, 750 mA, 3.5 mm dia. emitter) producing the TLM waveform viewed by participants. Its Spectral Power Distribution (SPD), colour characteristics, and melanopic Daylight Equivalent Ratio (DER) can be found in Appendix B.

Because there were differences between the ideal programmed waveforms and resulting patterns and luminance values, the light waveforms were measured using an Admesy Asteria flicker meter to document the delivered TLM waveform. As subsequently described, input parameters were modified using an iterative process to generate the desired output TLM waveforms as closely as possible.

2.3 TLM Waveforms

Seventy-four waveform combinations, listed in Supplementary Material Table S.1, were selected to explore the effect of frequency, modulation, duty cycle, and wave shape on the visibility of TLM. Not all combinations of factors could be presented in a limited 90-minute test session. Three “direct current” (*i.e.* constant output, non-modulating) waveforms were included as a control, because a constant light output should elicit no visibility of the phantom array or stroboscopic effects. These allowed a check on consistency of response. For the analysis, ratings from waveforms 53 and 55 were averaged since they were inadvertently programmed with identical characteristics.

Programming the waveforms was an iterative process because the waveform data input from the AWG to the driver and LED did not match the measured output. The waveforms were distorted by the limitations of the driver and, to some extent, the normal behaviour of the LED (such as the rising/falling time limitations, I-V curve, and Flux-I curve). Rectangular waves, especially, experienced some latency in ramp-up and ramp-down, affecting luminance. The LED had a minimum turn-on voltage, so maximum and minimum values delivered to the LED were increased by a constant value to achieve the desired modulation depth. For example, sinusoidal waves would turn off too soon because the driver was not able to maintain the minimum output voltage for a very low current output to achieve high-modulation sinusoidal waves, and thus the shape became trimmed flat at the bottom end. The correction to the AWG signal delivered to the driver compensated for the response time of the driver, but often meant the current through the LED never truly reached a zero value, especially when a high frequency meant that the current signal was on the rise before the LED had a chance to reach its minimum value.

At high frequencies, usually 2,000 Hz and above, the limitations of the LED driver created distortions to both rectangular and sine waves. As an example, Figure 3 (a) shows the rectangular output for a 120 Hz, 100% modulation, 10% duty cycle waveform, with the (c) plot showing 30% duty cycle, and the (e) plot showing the familiar sinusoidal output for a 120 Hz, 100% modulation waveform. However, when the frequency was high, the TLM waveform was distorted. Figure 3 (b) shows the output from a programmed rectangular, 6,000 Hz, 100% modulation, 10% duty cycle waveform, with the (d) plot showing 30% modulation. Figure 3 (f) shows the output waveform from a programmed sinusoidal, 6,000 Hz, 100% modulation waveform. The high frequency sinusoidal waveform (f) never quite achieves zero output in a cycle, because of driver and LED limitations. Similarly, the high frequency rectangular waveform (b) never achieves the desired rectangular shape.

All waveforms were intended to have identical luminance values. 73 of the 74 were within 7.4% of the maximum value (from 1.8% below, to 5.6% above the average). The one exception was #23 (rectangular, 6,000 Hz, 100% modulation, 10% duty cycle), where the closest achievable luminance value was 15.8% below the average. All were measured with a Photo Research Jadak PR670, calibration on 3 March 2021.

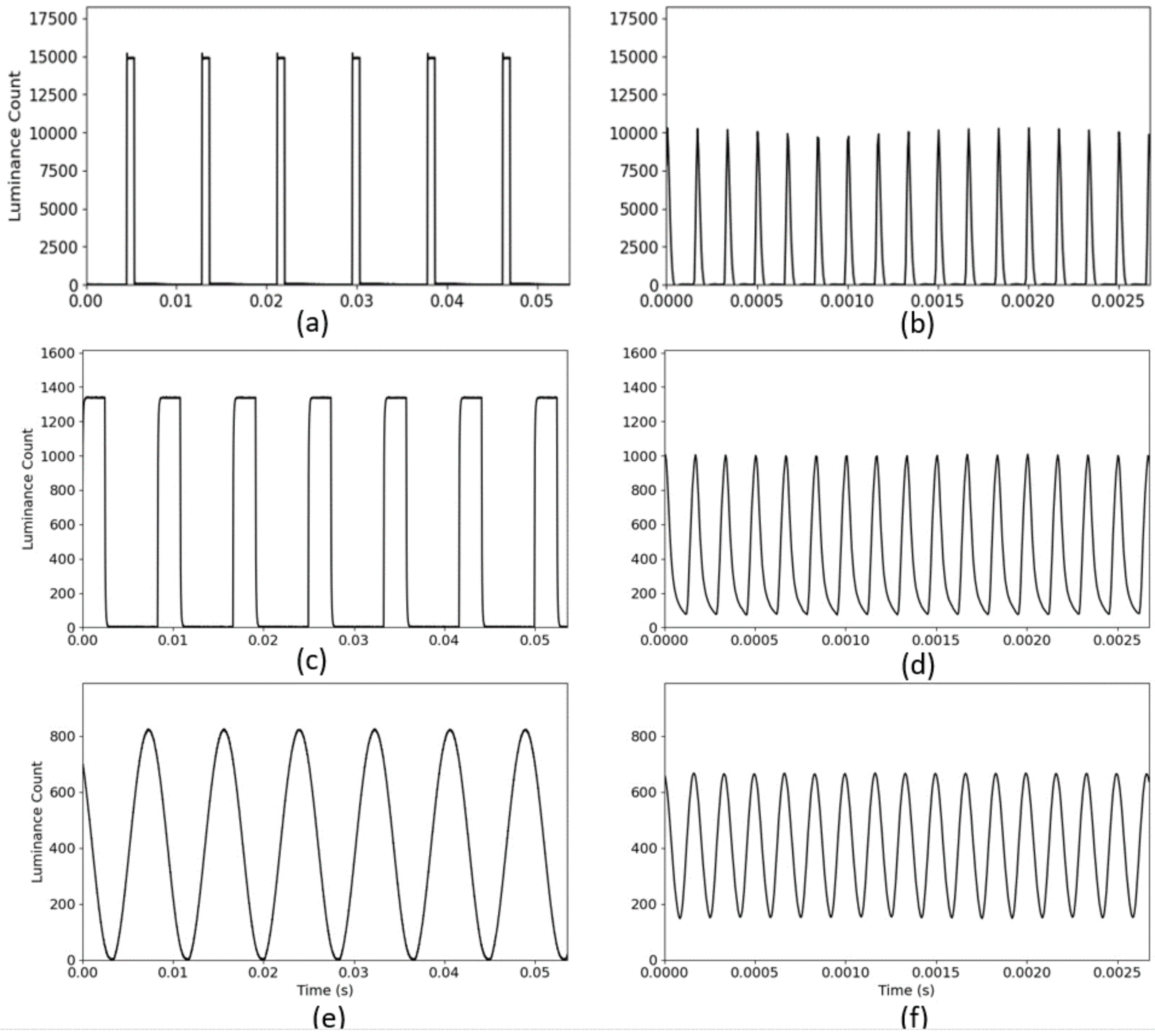


Figure 3 (a – f). Plots (a), (c), and (e) illustrate the output of three 120 Hz, 100% modulation waveforms, rectangular with 10% duty cycle in (a), 30% duty cycle in (c), and a recognizable sine wave in (e). Plots (b), (d), and (f) illustrate the output of three 6,000 Hz, 100% modulation waveforms, "rectangular" in (b) with 10% duty cycle, 30% duty cycle in (d), and sine wave in (f).

2.4 Participants

Participants were recruited from local colleges, an LED Facebook page, and word of mouth among friends, neighbours, and colleagues of the researchers. 30 were compensated with a gift card; 6 were compensated as employees of Pacific Northwest National Laboratory. The participants ranged in age from 19 to 76 years with a median of 41, with 15 identifying as female, 20 male, and 1 non-binary. Participants were pre-screened for migraines and excluded if they reported them. They read and signed Informed Consent Forms. The study was reviewed and approved by the Pacific Northwest National Laboratory Institutional Review Board.

One intent of the study was to be able to differentiate participants with greater visual sensitivity from those with lower sensitivity. The Leiden Visual Sensitivity Scale[21] is a questionnaire designed to quantify sensitivity to light and patterns (see Appendix C), and participants completed it along with consent and demographics forms. Question responses were scored for each participant, and the frequency of Leiden Scale scores is shown in Figure 4. Eighteen participants with scores of 8 and higher were deemed *higher* *sensitivity* and eighteen scoring 7 or below, *lower sensitivity* for the phantom array test; and 14 deemed *higher sensitivity*, 16 *lower sensitivity* for the stroboscopic effect test. The reason for the unequal participant numbers for the two tests is explained in Section 2.6. There was no significant correlation between the Leiden Scale sensitivities by age or gender.

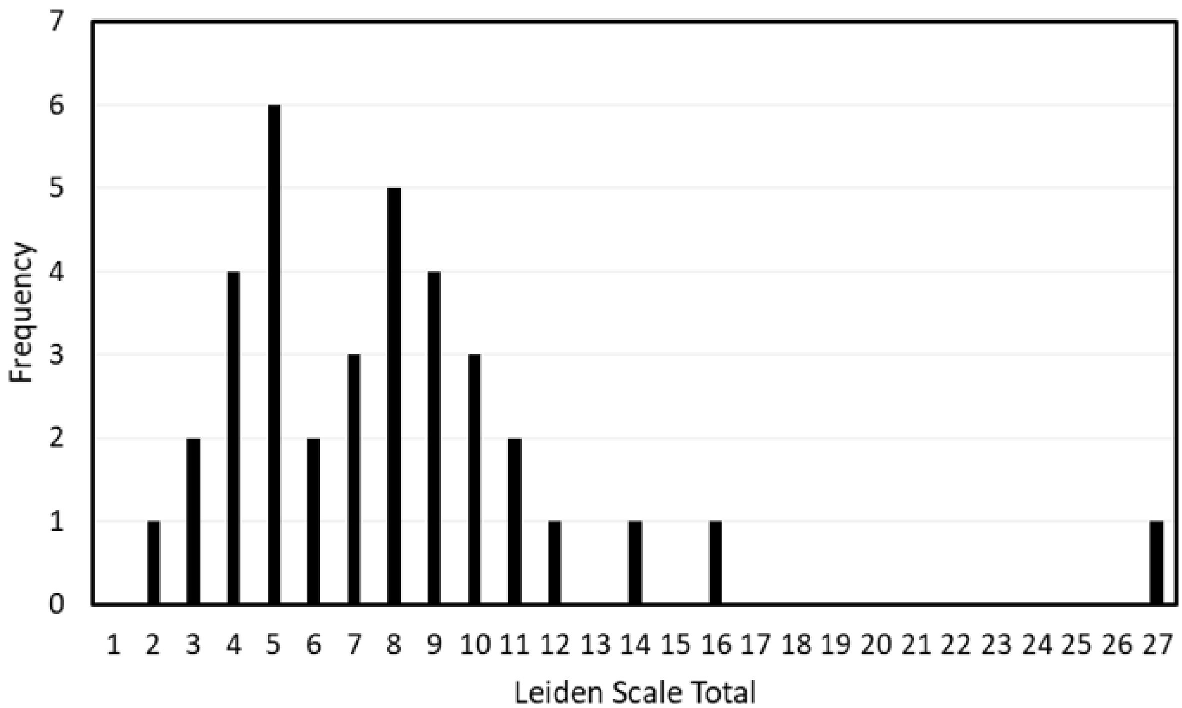


Figure 4. Distribution of Leiden Visual Sensitivity Scale scores for the 36 participants.

2.5 Visual tasks and dependent measures

There were two visual tasks. The first visual task tested for the phantom array effect. The participants were asked to fixate at the X on the left side wall, rapidly move their gaze to the X on the right side, and back again, scanning two or more times. The X's were separated by a 44° visual angle (Figure 1), and the task prompted the participant to engage in a voluntary large eye saccade, expected to exhibit a visual angle velocity around 500°/s.[22] Some waveforms had the potential to induce the phantom array effect, which when visible, appeared as a pattern of dots, dashes, or other repeated images across the retina.

For the second task, the researcher activated a motorized rotating white wand (stationary wand measured at the wand length centre and background luminances 19.5 and 1.4 cd/m^2, respectively) positioned behind the light source. Rotating at 84 rpm, the wand tip had a tangential velocity of 4 m/s to mimic the speed of typical arm motion,[15] which translates to a rotational velocity of 504°/s. Roughly half of the circular rotation was visible (Figure 1), and the full width of the wand arc subtended 17.4°of visual angle. Some waveforms had the potential to produce visible stroboscopic motion, a discrete or blurred pattern of wand images due to the modulated light. One example is shown in Figure 5 where only part of the wand pattern is visible in this photo because of the interaction of the shutter and wand speed.

Figure 5. Photo showing the visibility of the stroboscopic effect from the rotating wand from a high-modulation light source.

The participant was asked to rate the visibility of any repeating pattern in the scanning task on a scale of 0 (no pattern visible) up to 6 (highly visible repeating pattern). Similarly, they were asked to rate the pattern visible in the rotating wand task using a scale of 0 (no stripe pattern visible) up to 6 (highly visible stripe pattern). To minimize any confusion or introduced bias, the scale used no intermediate descriptive anchors, but the example illustrations provided showed an explicit example of a 0 and 6 rating for each task (Figure 6), as well as multiple images in no specific order presented as examples of patterns that might receive intermediate ratings.

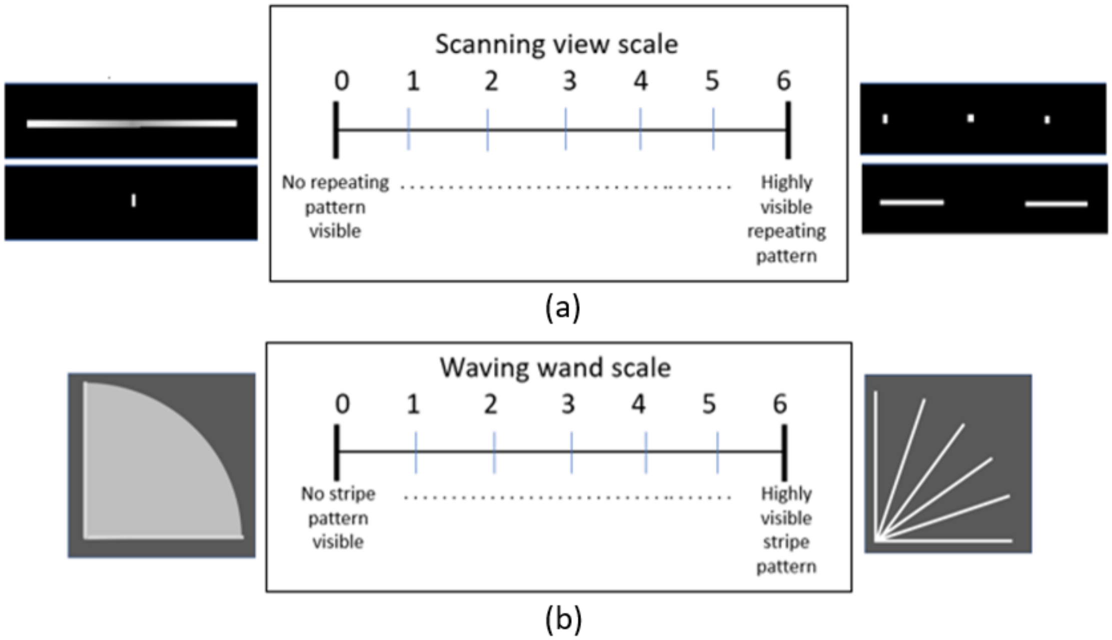


Figure 6 (a, b): Rating scales for experiment with graphical examples of 0 and 6 visibility images to help participants calibrate their ratings. Phantom array effect, (a); stroboscopic effect, (b).

2.6 Procedure

Participants were tested one at a time, seated with a lighted clipboard and forms on their laps in the experiment room. Each completed a brief set of demographic and pattern sensitivity questions, including the Leiden Visual Sensitivity Scale,[21] then read instructions with illustrations of what they might see as the stroboscopic effect or phantom array effect. The researcher in the room also verbally explained the two visual tasks to reinforce comprehension. The participants were presented with five practice light settings varying in frequency, waveshape, modulation depth and duty cycle. For each practice light setting, the participant gave ratings for the phantom array effect and stroboscopic effect (as described in Section 2.5). The instruction and practice sheets were then collected by the experimenter, but the illustrated instruction sheets were posted on an adjacent chair for reference during the trials. The orientation and instruction time comprised 10 minutes or longer, allowing the participant time to dark adapt to the room lighting.

The presentation order of the 74 waveforms was randomized for each participant and was also unknown to the experimenter. Participants were offered a 5-minute break after viewing the first and second sets of 25 waveforms and instructed that they could request a break at any time or stop the session altogether if they felt any discomfort. One participant reported slight “car-sickness-like” symptoms but elected to complete the session. After recording a rating for the phantom array effect first, followed by the stroboscopic effect, for all 74 TLM waveforms, the participants completed a follow-up set of questions soliciting comments or observations.

After the sixth participant, the researchers had heard feedback from a few participants that the rotating wand was difficult to see against the background because the background poster material was semi-specular, resulting in vertical areas that were uneven in luminance. The poster material was reversed to display a matte finish instead, and the poster luminance was remeasured. The luminance values were found to be almost identical, but the uneven shininess for the participant was eliminated. This background change did not affect the phantom array effect observations, but stroboscopic motion visibility data from the first six observers were discarded from the data set. Thus, data was collected from 36 observers for the phantom array effect, and 30 observers for the stroboscopic effect.

3. Results

The stroboscopic effect and phantom array effect visibility ratings for all observers (30 for stroboscopic effect and 36 for phantom array effect) were arithmetically averaged for each waveform and standard deviations were calculated. Rectangular and sine wave response data were plotted separately. This section begins with a data overview, followed in section 3.2 by statistical analyses of the six hypotheses. The hypotheses, statistical values, and results are summarized in Table 1.

3.1 Data overview

3.1.1 Phantom Array Effect - Observations

The arithmetic average phantom array effect visibility ratings for all 36 participants are plotted in Figure 7 for all rectangular waveforms (a) and all sinusoidal waveforms (b). The lines connect average visibility responses at different frequencies to a single combination of waveshape, duty cycle and modulation depth. In Figure 7 (b) all points represent 100% modulation depth except for the single open circle representing 120 Hz, 20% modulation depth.

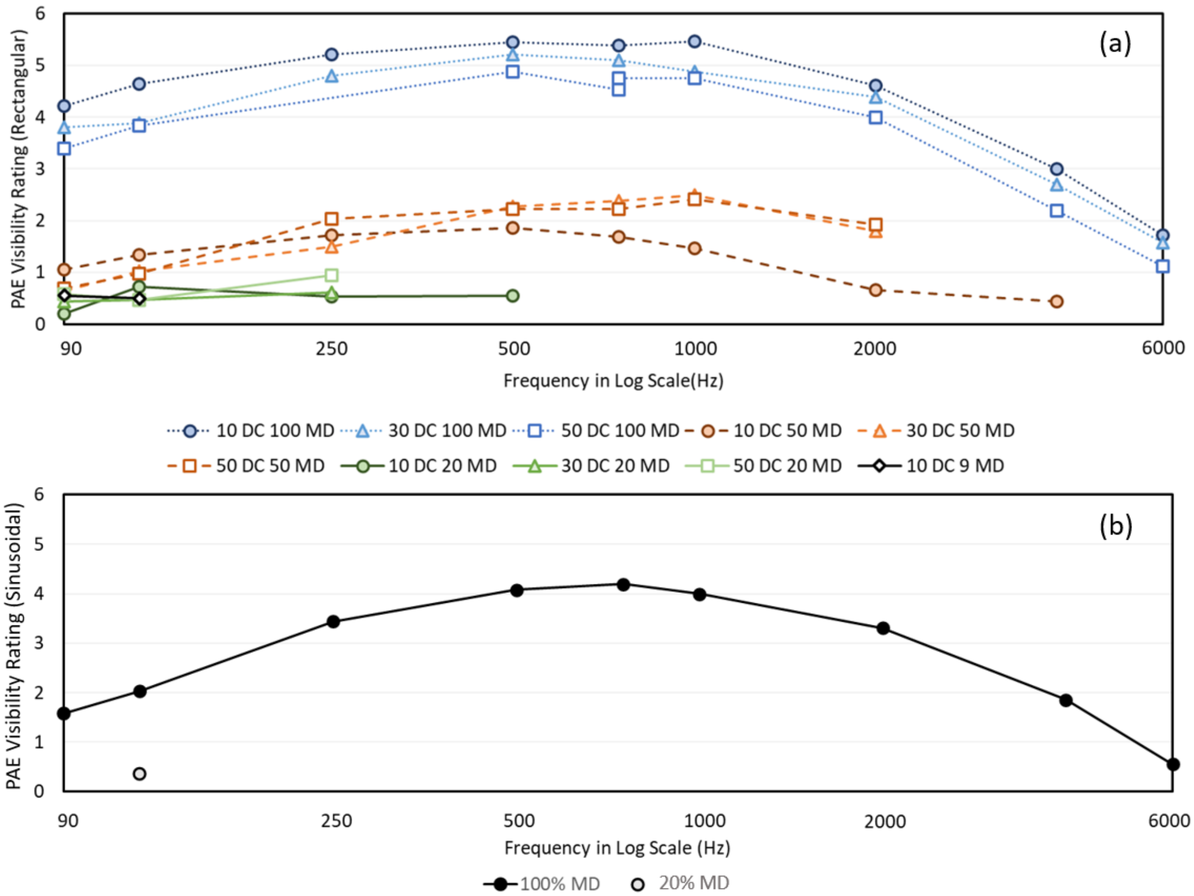


Figure 7 (a, b). Phantom array effect (PAE) visibility: Arithmetic average ratings for rectangular waveforms of different frequency, modulation depth (MD), and duty cycle (DC) (a); and sinusoidal waveforms of different frequencies (b).

The collected data showed the visibility of the phantom array effect:

- Peaked between 500 – 1,000 Hz.
- Was higher at 100% and 50% modulation, compared to 20% modulation.
- Was maximized at lower duty cycles (10% and 30%) compared to 50% duty cycle at 100% modulation, but that result was less consistent at lower modulation depths.
- Was visible to participants on average at 6,000 Hz, 100% modulation, 10% duty cycle.
- Was greater in rectangular compared to sinusoidal wave shapes at equal modulation depths.

Figure 8 shows two plots of arithmetic average phantom array visibility ratings with standard deviation for three families of 100% modulation waveforms: rectangular with 30% duty cycle (a), 50% duty cycle (b), and sinusoidal (c). Note the large standard deviation in individual responses. The dashed line in both plots is the arithmetic average rating for three constant current TLM waveforms, intended to produce a 0-visibility rating for the both effects.

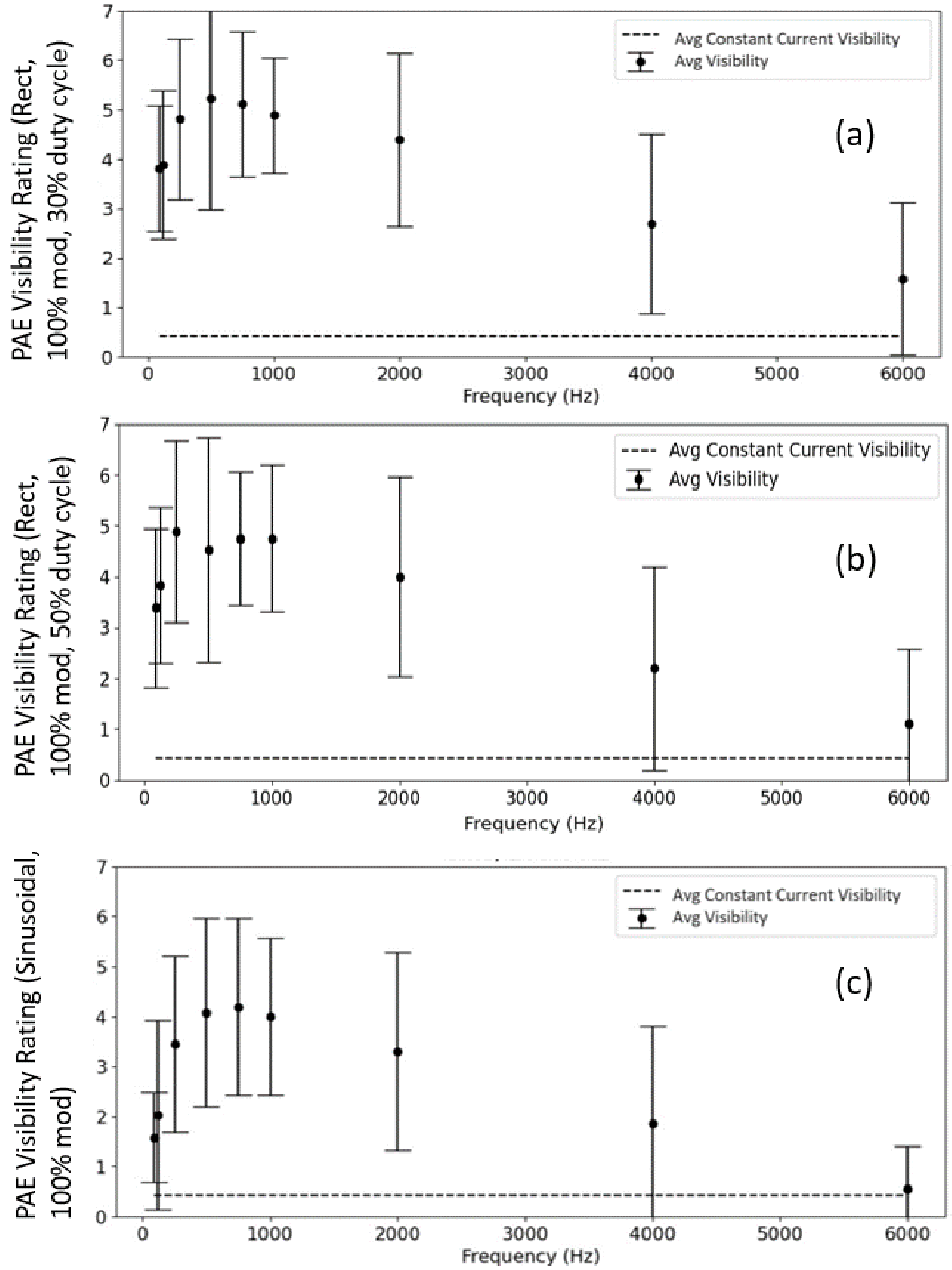


Figure 8 (a, b, c): Plots of arithmetic average phantom array effect visibility ratings with standard deviation by frequency for two families of 100% modulation waveforms: rectangular with 30% duty cycle (a), rectangular with 50% duty cycle (b), and sinusoidal (c).

3.1.2 Stroboscopic Effect - Observations

The arithmetic average stroboscopic effect visibility ratings for all 30 participants are plotted in Figure 9 (a) for rectangular waveforms, and Figure 9 (b) for sinusoidal waveforms. All points in the sinusoidal plot represent 100% modulation depth except for the single dot representing 120 Hz, 20% modulation depth.

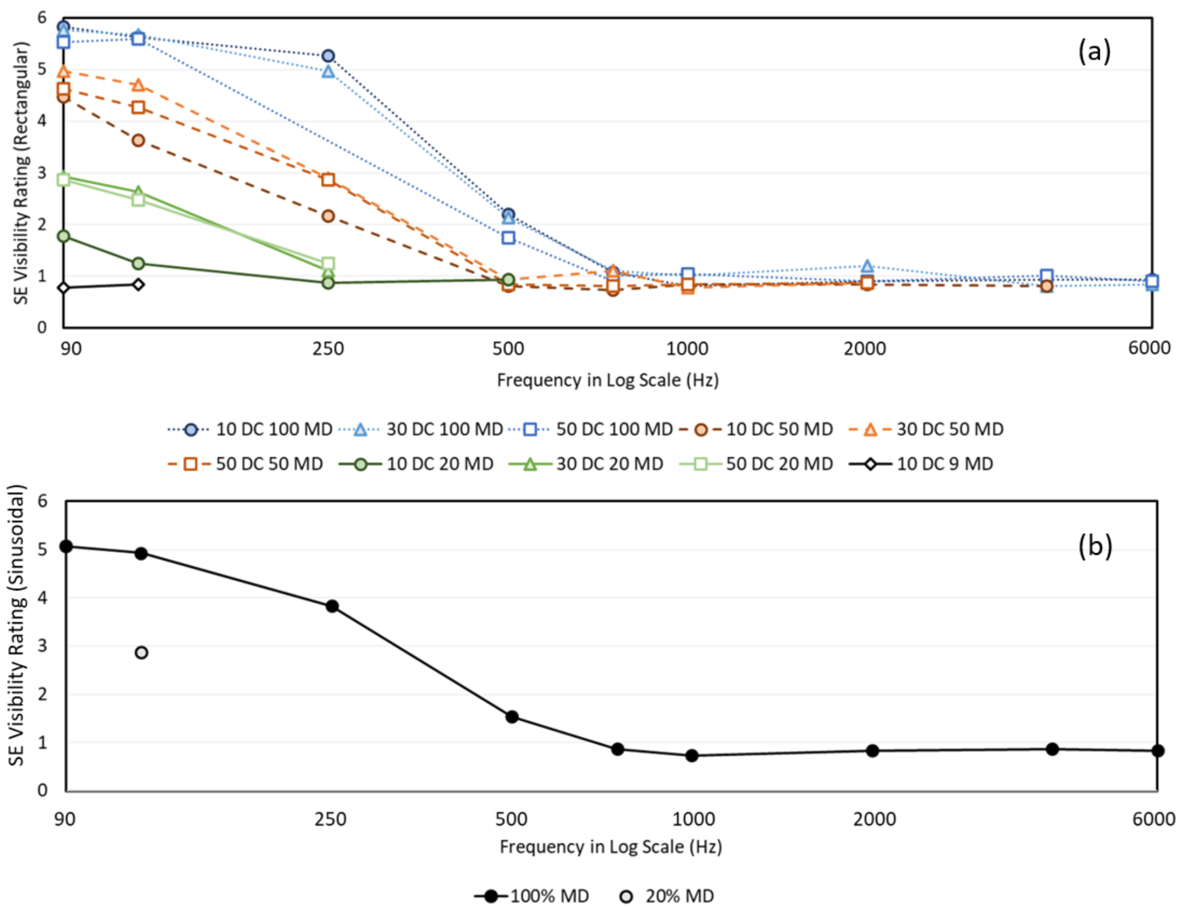


Figure 9 (a, b). Plot of arithmetic average participant stroboscopic effect (SE) visibility ratings for 30 observers for all 61 rectangular TLM waveforms (a) and all 10 sinusoidal TLM waveforms (b).

The data showed the visibility of the stroboscopic effect:

- Peaked between 90 Hz and 120 Hz, declining rapidly at frequencies ≥500 Hz.
- Was highest at 100% and 50% modulation depth in rectangular wave shapes.
- Was maximized at 10% and 30% duty cycle for rectangular TLM waveforms.
- Was higher for rectangular waves than for sine waves at equal modulation depth.

Figure 10 illustrates the standard deviations for two shapes of waveforms with 100% modulation: one plot for 30% duty cycle rectangular waveforms (a), one for sinusoidal (b). The responses to three constant current waveforms were averaged and shown as a dashed line.

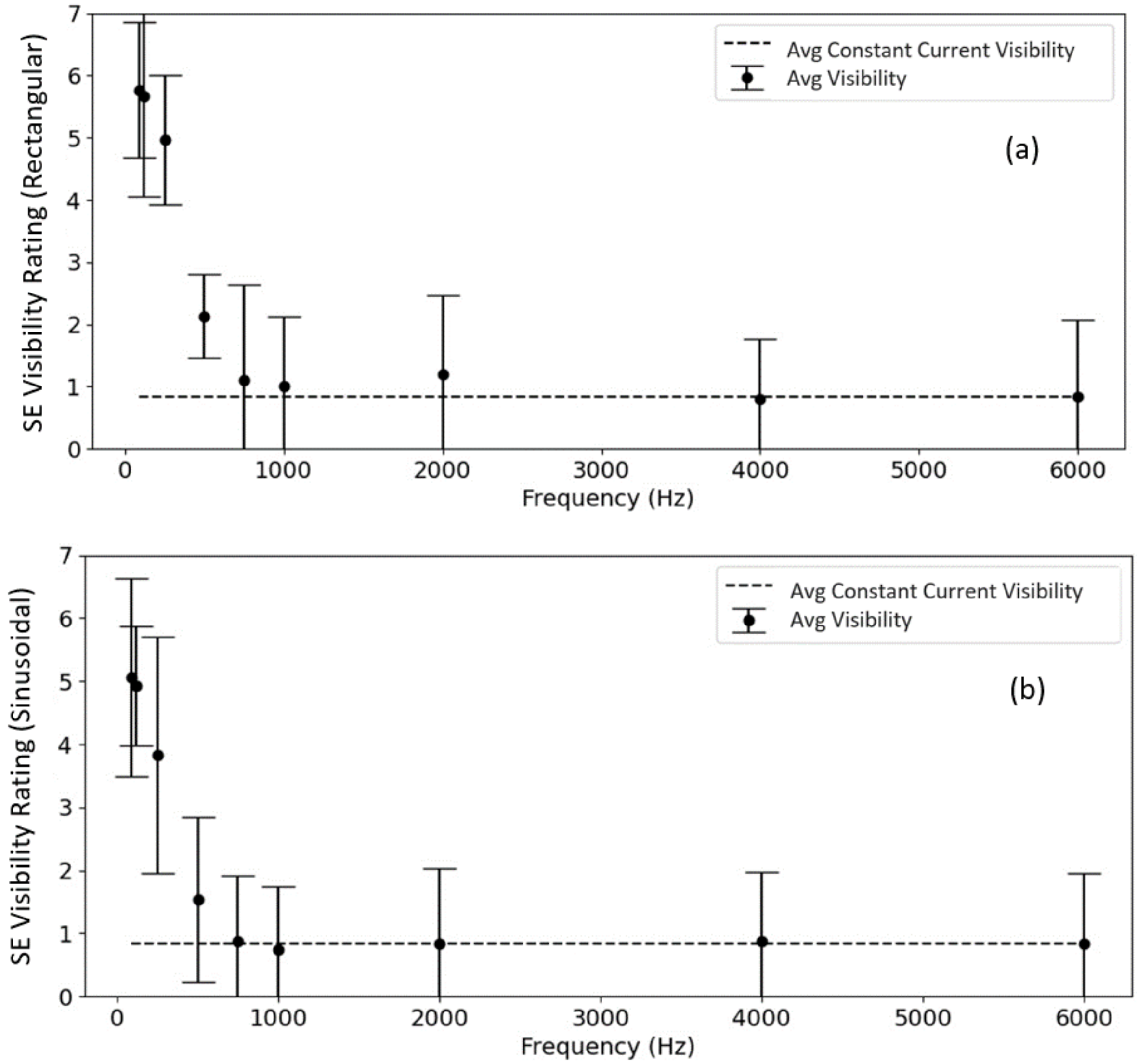


Figure 10 (a, b): Plot of arithmetic average stroboscopic effect visibility ratings with standard deviation by frequency for two families of 100% modulation waveforms: rectangular with 30% duty cycle (a), and sinusoidal (b).

Note that the lowest average stroboscopic effect visibility rating for both shapes of waveforms was very similar to the average visibility rating of the constant current waveforms. That is, visibility ratings of waveforms with no measurable modulation never reached zero. Feedback from participants confirmed researcher observations that a shortcoming of the rotating wand task was that although the tip of the wand was traveling at the specified rate, the wand was rotating too slowly to exhibit the completely smeared fan pattern illustrated in the instructions for no stroboscopic motion visibility. Thus, the shaft of the wand could be seen rotating even when there was no spoke-like stroboscopic effect to be observed. Consequently, it is possible many participants chose a rating of 1 rather than 0, as their minimum visibility.

It is important to note that this exploration of the stroboscopic effect was limited to visibility of a moving wand or hand movements, not that of moving or rotating machinery, wheels, etc. As such, there may be no upper frequency to the stroboscopic effect as long as the speed of the object can be very fast.

3.2 Analysis of hypotheses

Details of statistical analyses are found in Supplementary Material Table S.2.

3.2.1 Hypothesis 1

The peak of the stroboscopic effect visibility ranges between 90 and 120 Hz, but the peak of the phantom array effect visibility occurs between 500 and 1000 Hz, and thus they are likely due to different visual sensitivities.

Figure 11 shows the mean visibility ratings and standard error for all TLM stimuli for the phantom array effect and the stroboscopic effect. The two effects show distinctly different peaks. The hypothesis is supported. The shape of each curve is not smooth, and this may be attributed to the fact that stimuli aggregated by frequency did not have identical waveform counts or waveform combinations.

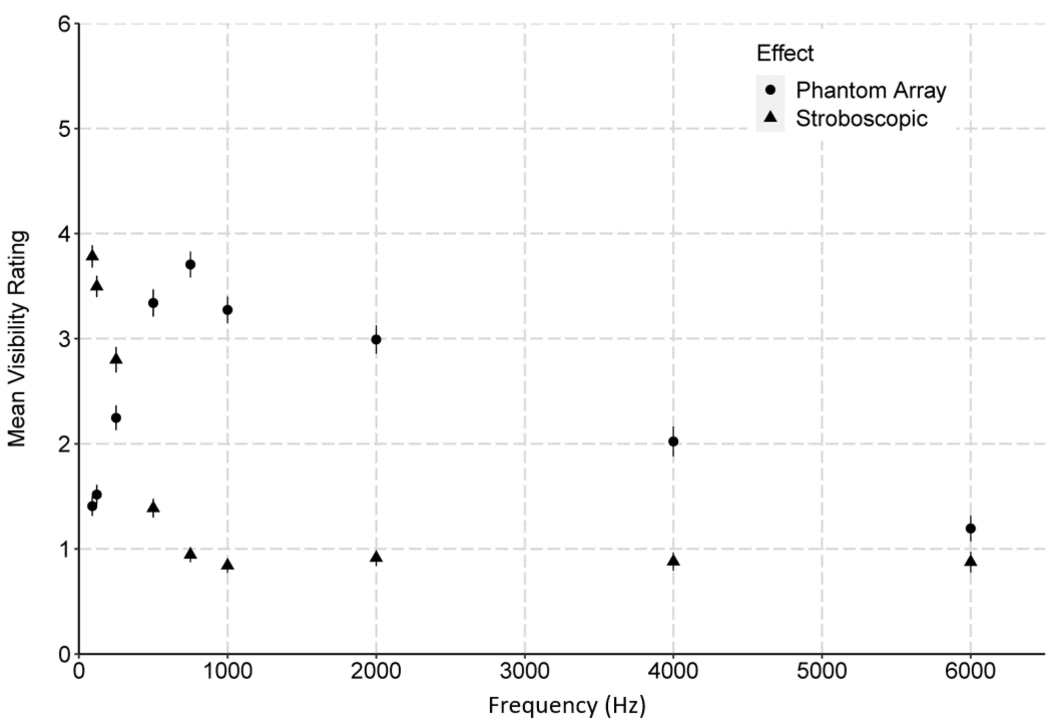


Figure 11. Mean visibility ratings and standard error (vertical bars) for the phantom array and stroboscopic effects, combining all TLM waveforms for each effect by frequency.

3.2.2 Hypothesis 2

Rectangular TLM waveforms with ≤50% duty cycle are more visible than sinusoidal waveforms at the same frequency and modulation depth.

The analysis compared sinusoidal and rectangular waveforms at the same frequencies and 100% modulation. 10%, 30%, and 50% duty cycle was selected for the rectangular waveforms. Vogels et al. identified the 30% duty cycle for peak visibility.6 Thus, this was a comparison of each of three rectangular waveforms to a single sinusoidal waveform, at each level of frequency. The distribution was not normal in the underlying groups, so a paired Wilcoxon signed rank test with continuity correction was implemented. Assumptions of random selection of participants, that rating scores are interval data, and that distribution of difference ratings are symmetrical about the mean, were tested and met.

Phantom array effect and stroboscopic effect: These tests confirmed that the rectangular waveform had a higher visibility rating compared to the sinusoidal waveform. Figure 12 (a) shows a box plot of visibility ratings for the three rectangular and the sinusoidal wave shapes for the phantom array; Figure 12 (b) shows the same for the stroboscopic effect. The analysis supports the hypothesis that rectangular were more visible than sinusoidal waveforms at the same frequency and modulation depth.

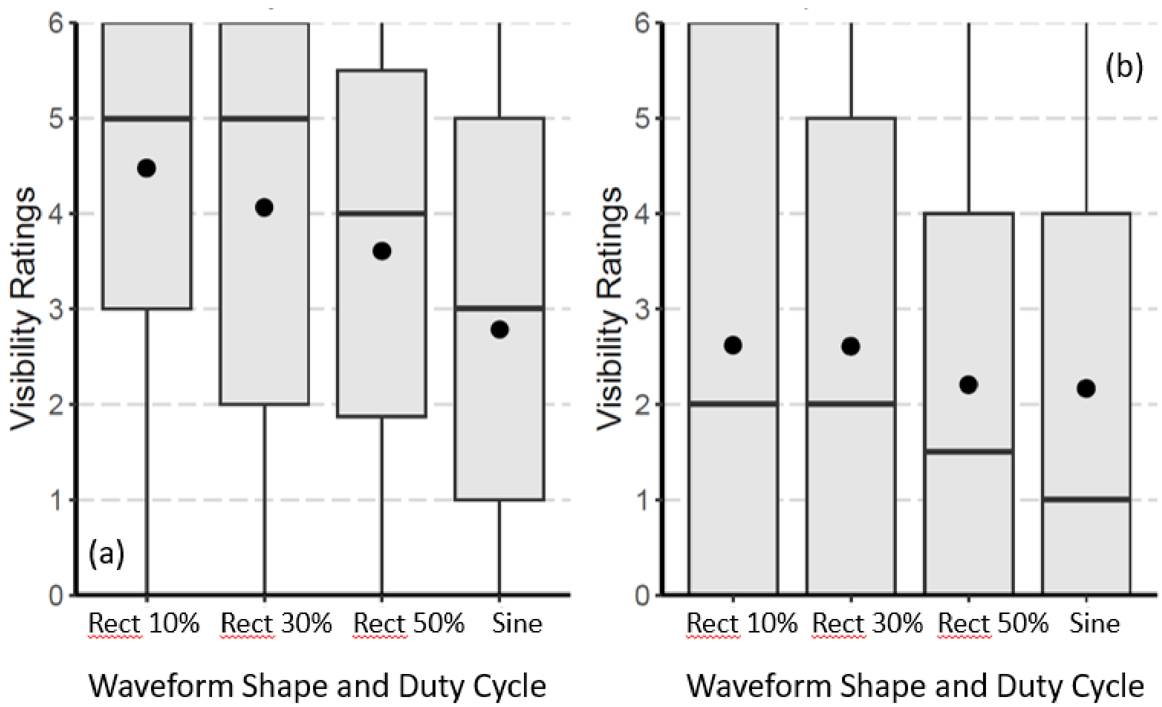


Figure 12 (a, b). Box plots with medians and quartiles of the visibility ratings of rectangular waveforms at three duty cycles, versus sinusoidal TLM waveforms at the same frequency and % modulation. (a) is the phantom array effect; (b) is the stroboscopic effect. Although the data set is not normally distributed, dots representing approximate arithmetic means are shown for reference.

3.2.3 Hypothesis 3

100% modulation rectangular waveforms are more visible than those at lower modulation depths (50% and 20%), given the same frequency and duty cycle.

Phantom array and stroboscopic effects: To test with paired comparisons, sinusoidal and constant waveforms were excluded because they did not include conditions with 50% and 20% modulation; stimuli with frequencies > 500 Hz were excluded because they were not tested with 20% modulation; and frequency and duty cycle combinations of 500 Hz with 30% and 50% duty cycles, and 250 Hz with 50% duty cycle were omitted because identical waveform characteristics were not tested for all three modulation depths.

For both the phantom array and stroboscopic effects, a Friedman test showed a significant difference among the three modulation depths. The Wilcoxon signed rank test showed that 100% modulation waveforms were more visible than those with 50% or 20% modulation depth. See Figure 13 (a for phantom array; b for stroboscopic effect). Thus, for both effects, the hypothesis was supported, with the proviso that the complete set of modulation depths could only be studied at 90, 120, 250, and 500 Hz. Thus, this hypothesis was not tested at frequencies of 750 Hz and higher.

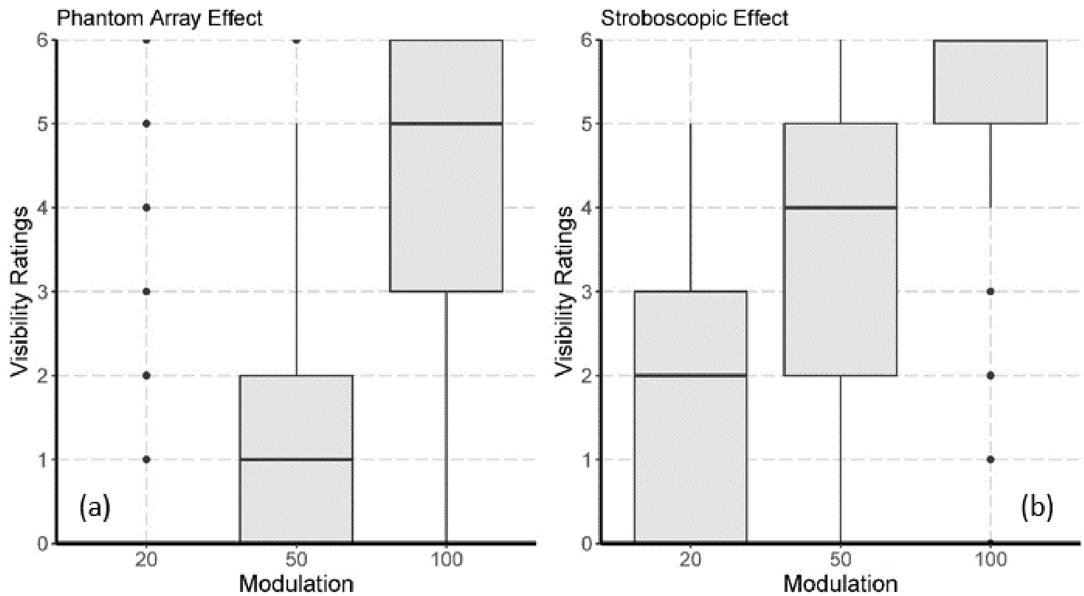


Figure 13 (a, b). Box plot of visibility rating medians and quartiles of 20%, 50%, and 100% modulation from rectangular TLM waveforms, phantom array (a) and stroboscopic effect (b). The phantom array effect visibility responses for 20% modulation collapsed to zero, so no box or whiskers are visible.

3.2.4 Hypothesis 4

Among rectangular TLM waveforms, those with 10% and 30% duty cycle are more visible than 50% duty cycle waveforms at the same frequencies and modulation depth.

Phantom array and stroboscopic effects: Waveforms excluded because not all combinations were tested at the three duty cycles were: combinations of 250 Hz with 100% modulation, 500 Hz/20% modulation, 4000 Hz/50% modulation, and all with 9% modulation. A Friedman rank sum test showed a significant difference among the three duty cycles.

For the phantom array and the stroboscopic effects, the Wilcoxon signed rank test showed that 10% duty cycle waveforms were more visible than those with 50% duty cycle, and waveforms with 30% duty cycle were more visible than 50% duty cycle.

Hypothesis 4 is supported for the phantom array effect visibility, but the medians of differences between samples from the three duty cycles were small and ranged between 9.2×10^{-6} to 3.5×10^{-6}. For the stroboscopic effect, the hypothesis is supported for the 30% duty cycle compared to the 50% duty cycle (median of difference= 8.1×10^{-5}), but not for the 10% duty cycle.

The results are not completely consistent, which suggests that there may be an interaction among duty cycle and modulation depth which merits further research.

3.2.5 Hypothesis 5

Higher sensitivity participants are more likely to report higher visibility of TLM waveforms than lower sensitivity participants.

When the data were analysed, the difference of arithmetic average phantom array visibility ratings between the higher sensitivity and lower sensitivity groups above 500 Hz was lower for 100% modulation rectangular waveforms than for the 50% modulation waveforms (Figure 14). This shows a greater response difference between higher and lower sensitivity participants when the TLM stimulus is harder to see (*i.e*. lower modulation depths, higher duty cycles, higher frequencies). The arithmetic average difference plotted in the dashed line of Figure 14 shows that higher sensitivity participants found the TLM waveforms to be more visible.

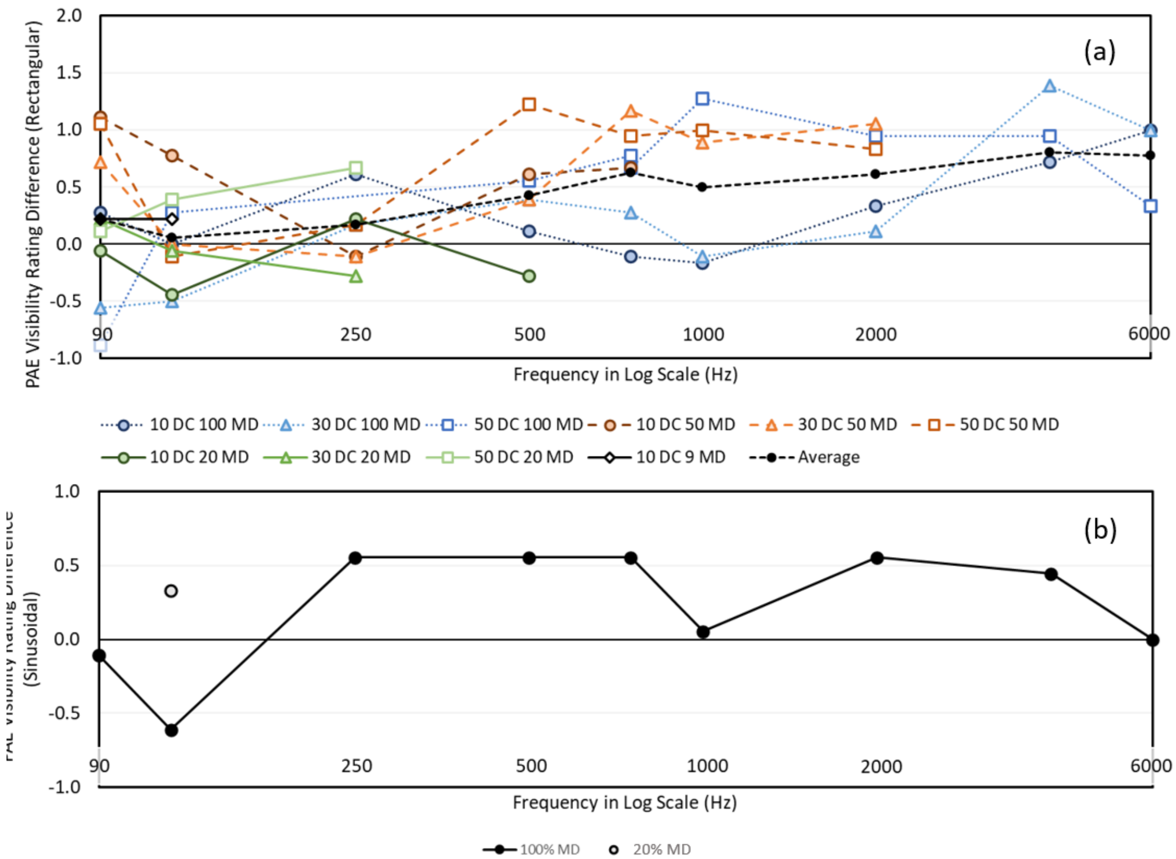


Figure 14 (a, b). Differences between higher and lower sensitivity participant phantom array effect (PAE) visibility ratings for rectangular waveforms (a) and sinusoidal waveforms (b).

For the stroboscopic effect test, on average the higher sensitivity group scored rectangular TLM waveforms as more visible than did the lower sensitivity group (Figure 15 (a)). The same was true for sinusoidal waveforms (Figure 15 (b)) except that the average differences were smaller. For the phantom array effect, the visibility ratings of the lower sensitivity participants exceeded those of higher sensitivity participants at the two lowest frequencies. Note that higher sensitivity participants rated the single 20% modulation sinusoidal waveform, a condition "harder to see," as more visible for both effects.

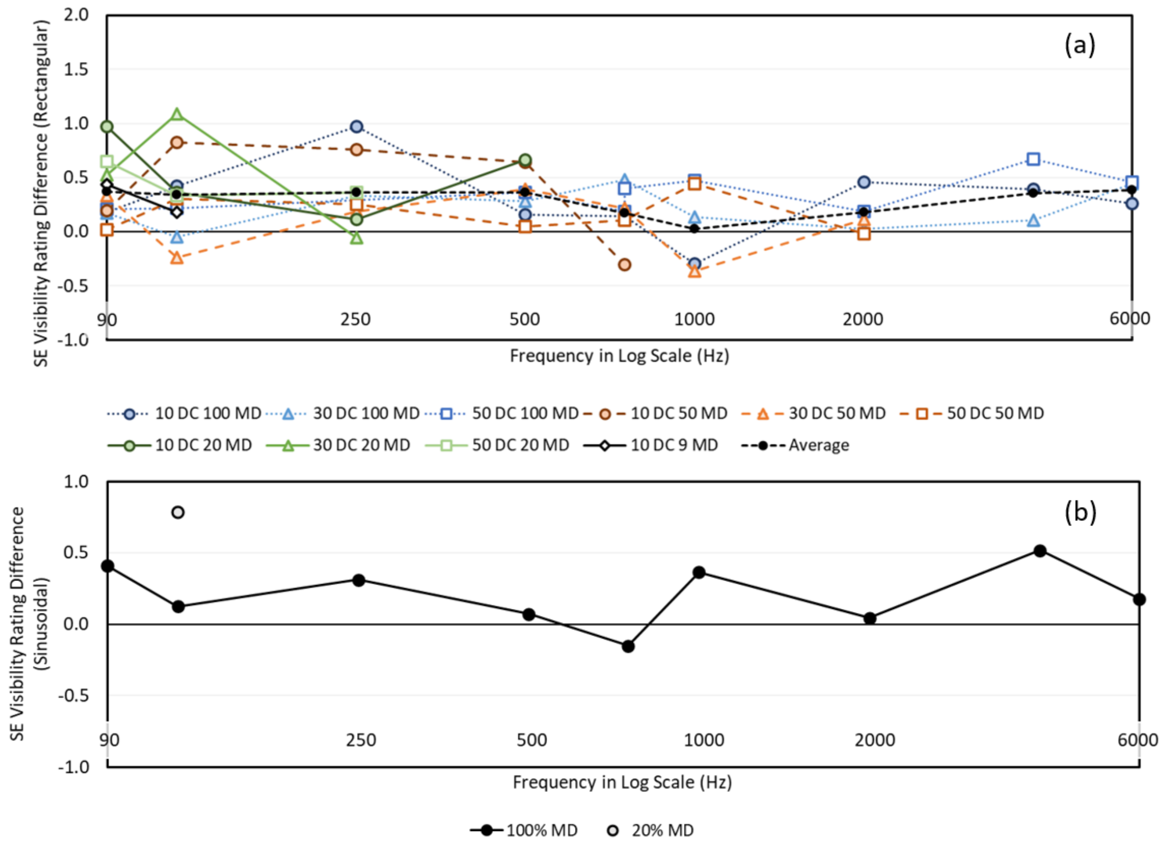


Figure 15 (a, b). Differences between higher and lower sensitivity participant stroboscopic effect (SE) visibility ratings for rectangular waveforms (a) and sinusoidal waveforms (b).

Phantom array effect - A statistical analysis of the data between the two groups of participants as identified through the Leiden Scale was performed. A parametric test was not appropriate because the data were not normally distributed within each group, so the non-parametric Mann-Whitney test was used. Assumptions of random selection from population, independence of samples, and continuous nature of dependent variables were tested and met. The hypothesis was supported.

Stroboscopic Effect - Data were not normally distributed for sensitive and non-sensitive groups. Assumptions were tested and met. The Mann-Whitney test supported the hypothesis.

Figure 16 shows the Leiden Scale differentiated higher sensitivity from lower sensitivity participants in their visibility ratings for the phantom array effect (a), and the stroboscopic effect (b). The Leiden Scale has potential in future work to establish metrics or standards based on protecting more sensitive populations.

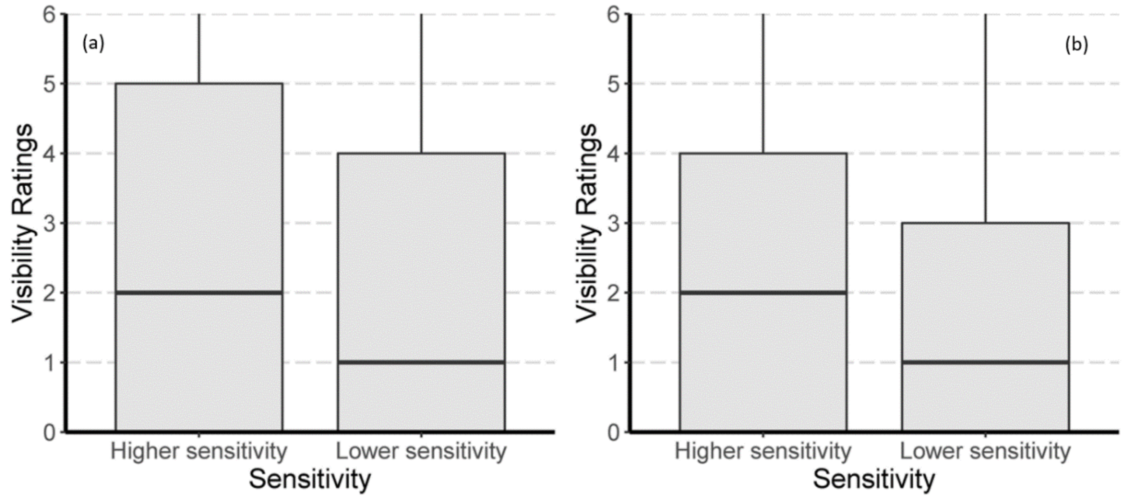


Figure 16 (a, b). Box plots of the median, 25% and 75% quartiles of visibility ratings by participant sensitivity for phantom array effect (a) and stroboscopic effect (b). The whiskers represent the highest value no greater than 1.5 times the inter-quartile range.

3.2.6 Hypothesis 6

Phantom array effect visibility ratings at frequencies above 1000 Hz are unlikely to be predicted by SVM metrics.

SVM is a metric designed to predict the stroboscopic effect, intended for conditions where the illuminance on the object of interest exceeds 100 lx. For this hypothesis, the data were analysed to see how well SVM predicted the stroboscopic visibility irrespective of the lower illuminance. The data were also analysed to see whether SVM could predict the phantom array effect, obviating the need for an additional "flicker" metric. Output waveforms were collected and calculated using the original Admesy Asteria meter sampling rates of 186,567 samples/s (Supplementary Material, Table S.1). Some captured waveforms at frequencies ≥ 2000 Hz were too short in duration for the MATLAB© SVM code, so ideal (*i.e.* target) waveforms were evaluated, also using 186,567 samples/s, for those TLM waveforms only. Figure 17 plots the mean phantom array visibility ratings against SVM; Figure 18 plots the stroboscopic effect visibility ratings against SVM.

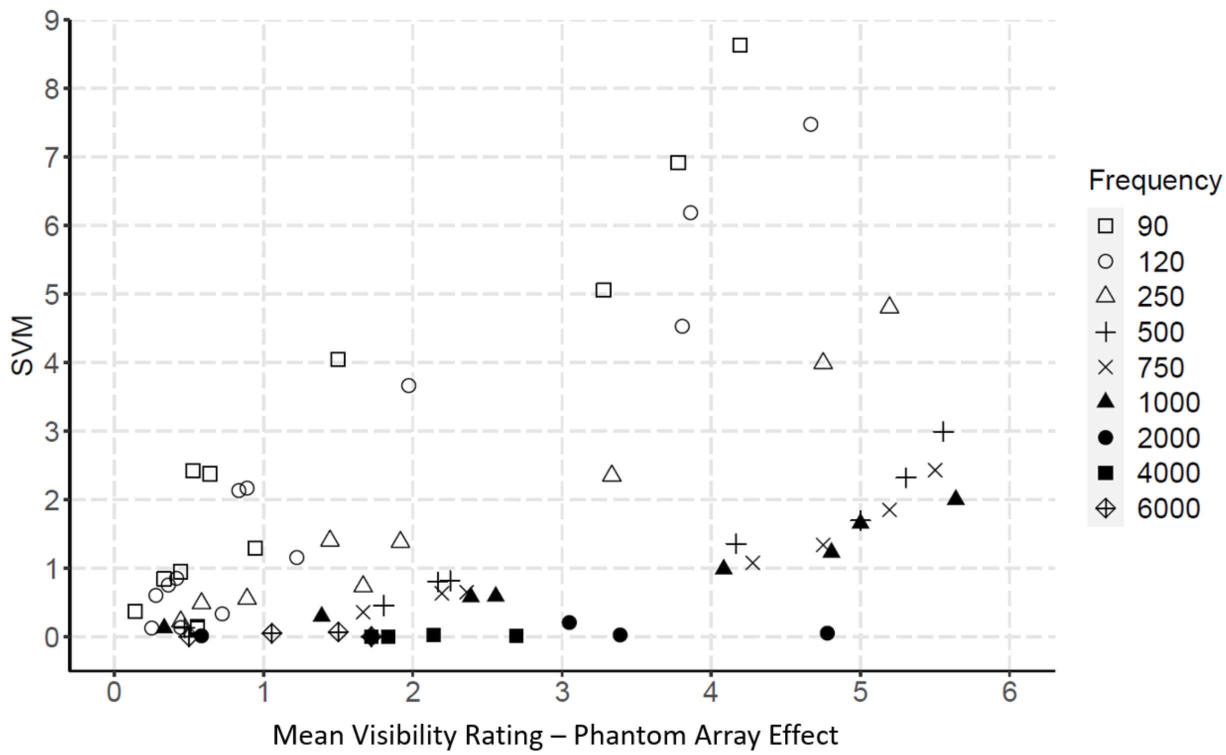


Figure 17. Mean phantom array visibility ratings plotted against SVM values for each TLM waveform.

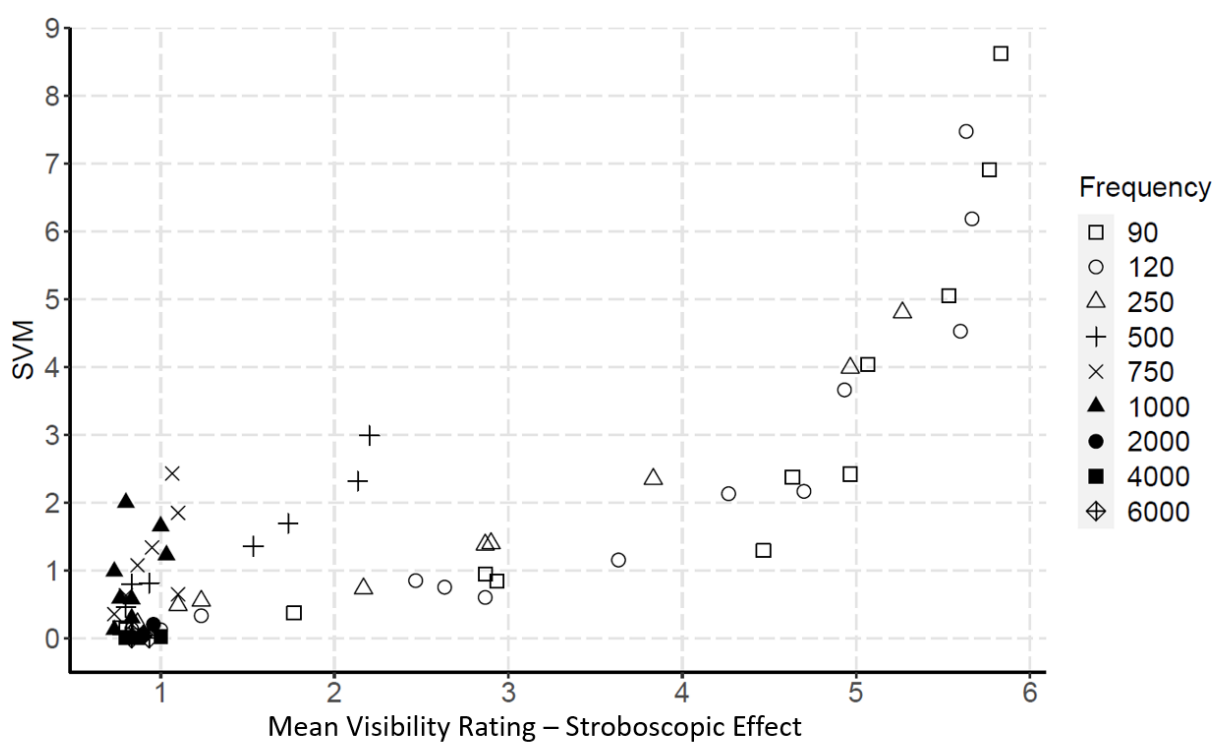


Figure 18. Mean stroboscopic effect visibility ratings plotted against SVM for each TLM waveform.

Phantom array effect

The Kendall's correlation tau test comparing individual responses versus SVM showed the hypothesis was partially supported. The phantom array effect was poorly explained by SVM at or above 2,000 Hz, since the tau value was low (Table 1) and the data points for those frequencies tended to lie on a horizontal line (Figure 17). This suggests that even though visibility ratings were high from some high frequency TLM waveforms, SVM was predicting the visibility to be far lower. However, at 1000 Hz, the tau value was 0.65, suggesting that SVM is better at predicting the phantom array than the stroboscopic effect at that frequency.

Stroboscopic effect

Using the same test, the correlation was high for the lower frequencies of 90 to 250Hz where the stroboscopic effect visibility peaks, as would be expected given the sensitivity normalization curve developed for SVM.[7] Table 1 shows that the correlation between stroboscopic visibility ratings and SVM declined at frequencies ≥500 Hz, where SVM was predicting higher visibility than participants reported, as plotted in Figure 18.

Table 1: Kendall's tau correlations between SVM and individual visibility ratings by frequency for phantom array effect and stroboscopic effect.

	PAE		SE	
Frequency	**n**	**tau**	**n**	**tau**
90	432	0.46**	360	0.70**
120	468	0.49**	390	0.67**
250	324	0.58**	270	0.59**
500	288	0.63**	240	0.29**
750	252	0.56**	210	0.08^{NS}
1000	288	0.65**	240	0.05^{NS}
2000	252	0.14**	210	0.06^{NS}
4000	180	0.11^{NS}	150	0.04^{NS}
6000	144	0.16*	120	-0.02^{NS}

* represents p<0.05; ** represents p<0.01. NS represents non-significance.

4. Discussion

4.1 Findings from this study

The analysis of participant visibility rating data yielded some clear patterns, given the experimental conditions. The results show that visibility of TLM at frequencies above 90 Hz is higher than would have been expected just a decade ago when this issue was identified and the first metrics to mitigate it proposed.[1] Improvements in the design of driver and dimmer electronics for solid-state lighting systems are needed, as well as corresponding performance standards.

4.1.1 Stroboscopic effect and phantom array effect may be due to different responses

The peaks of the visual responses to stroboscopic motion and the phantom array have been shown to occur at different frequencies and may be due to different visual mechanisms. If so, a metric for one likely cannot accurately predict the other. The shapes of the visibility rating curves at higher frequencies showed that the stroboscopic effect visibility drops to very low levels at and above 1000 Hz, confirming the research findings of Perz *et al.*[7] while the phantom array effect remains visible into frequencies from 1000 Hz up to 6000 Hz. This confirms the findings of Roberts and Wilkins;[17] Brown *et al*.;[8] Yu *et al.*;[18] and Wang *et al*.[9] The practical impacts of this for electronics designers are significant: much higher fundamental frequencies, perhaps well above 11,000 Hz, may be needed if pulse-width modulation techniques are employed. The phantom array effect is more pronounced when high modulation depth and low duty cycles are used to dim LEDs to very low output in dim or dark applications.

It is also possible that both effects are due to spatial frequency sensitivity, the stroboscopic effect being a spatial displacement of the retinal image when a viewer has a fixed gaze of an object (or arm) moving within modulating light; or the phantom array effect being retinal spatial displacement resulting from rapid eye movement relative to a fixed modulating source. An initial test of this was performed by calculating the peak visibility of each at 4 cpd:[23]

Stroboscopic effect. The wand rotates at 84 rpm or 1.4 revolutions per second, and its radius is 0.46 m. Assuming the observer's gaze is most sensitive to motion midway along the wand length, the area of maximum visibility occurs along the circle subtending a visual angle that is 8.7° wide. Converting that into units of visual angle, the circumference of that revolution is 8.7° of visual angle x pi = 27.3°/rev. The visual angle traversed by the wand midpoint in one second is 27.3°x 1.4 rps = 38.3°/s. Maximum visibility of 4 cpd would then be 4 x 38.3° = 153 Hz. [Compare this value to the 90 – 120 Hz maximum visibility found in this experiment.]

Phantom array effect. At 44°of visual angle between the X's on the side walls of the experiment room, the saccade speed is approximately 500°/s. Maximum visibility of the pattern should then occur at 500°/s x 4 cpd = 2000 Hz.[24] [Compare this value to the maximum visibility frequency of 500 to 1000 Hz found in this experiment.]

These initial calculations using rotational visual angle for the stroboscopic effect overpredict the maximum sensitivity frequency, but by less than a factor of 2. However, the phantom array effect visibility calculation overpredicts the peak frequency visibility by a factor of 2 to 4. Whether these effects are evoked by the same visual response based on the human visual system's spatial frequency sensitivity has yet to be determined. It is possible the two are related by the speed of the saccade, but more exploratory work is needed.

4.1.2 TLM waveform shape and characteristics affect visibility

Both the phantom array and stroboscopic effects were more visible from rectangular waveforms than sinusoidal waveforms at the same frequencies and modulation depth. This agrees with the results of Campbell and Robson,[23] Levinson,[25] and Perz *et al.*[15] The high-frequency Fourier content in rectangular waveforms increases visibility of both stroboscopic and phantom array effects, so reducing the rapid level change in current delivery to the LED through more continuous wave shapes can help reduce the visibility for both the phantom array and stroboscopic effects.

LED electronics designers should avoid deep modulation delivered to the light source. At any frequency, TLM waveforms with 100% modulation produce greater stroboscopic or phantom array effect visibility than 50% modulation, which in turn is more visible than 20% modulation. This confirms the results of Kelly,[26] Bullough *et al*.,[3] and Vogels *et al*.[6] The higher the modulation, the more visible is the waveform; but higher frequencies can help compensate for this. For example, modulation of 20% is visible to some participants at 90 Hz, but at 2000 Hz and above, higher modulations of 50 to 100% are needed for visibility.

For both effects, rectangular TLM waveforms with duty cycle of 10% and 30% were shown to be more visible than waveforms with duty cycle of 50%, given the same frequencies and modulation depth. However, the data analysis does not clearly point to 10% being more visible than 30% duty cycle, so it may support the results of Vogels *et al.* 2011[6] which found 30% duty cycle to exhibit maximum visibility.

The results of this work can inform improved dimmer and driver electronics design for solid-state lighting, especially deep dimming applications. Using duty cycle reduction alone may introduce annoying and potentially unhealthy responses to TLM. Combinations of constant current reduction (CCR), pulse frequency modulation (PFM) and pulse width modulation (PWM) dimming techniques are likely to mitigate visibility of unwanted effects.

4.1.3 Higher versus lower sensitivity participants

Participants exhibited considerable variation in rating the visibility of each individual TLM condition, and on average the degree of visibility was related to their scoring as higher or lower sensitivity on the Leiden Visual Sensitivity Scale. Whether this scale or similar tests are used, the significant difference between higher and lower sensitivity participant responses allows for development of a metric quantifying perceptions of TLM based on sensitive participants, thus establishing guidelines that protect more sensitive populations and making LED-lighted environments inviting to a wider population. Ideally, this work could be continued by qualified medical researchers with migraineurs as participants to test higher levels of sensitivity.

4.1.4 The phantom array effect visibility cannot be predicted by the SVM metric.

Because SVM was developed for higher ambient illuminances and because the stroboscopic and the phantom array effects exhibit different peak visibilities and ranges of visibilities, phantom array effect visibility did not highly correlate with SVM metrics at frequencies ≥2000 Hz. As frequency increased, there was more of a flat line of SVM values compared to lower frequencies (Figure 17), showing that SVM was not predicting the high phantom array visibility from many high-frequency waveforms, although the correlations were moderately high at frequencies between 250 and 1000 Hz.

As one might expect, SVM exhibited a higher correlation with stroboscopic visibility ratings than phantom array (Figure 18), but only up to 250 Hz. SVM tended to overpredict visibility of the waving wand at TLM frequencies ≥500 Hz. A possible explanation is that the Perz *et al*. studies' participants were only tested for visibility of stroboscopic motion and may not have understood that any discontinuity of visual images could be due to the phantom array effect. If there was any saccadic eye movement, the induced pattern could have been attributed to stroboscopic motion, and thus the visibility would have been recorded as higher. (It's very difficult to distinguish the two effects without training and experience.)

Given that SVM cannot be used to reliably predict the visibility of the phantom array effect under these ambient conditions, a separate metric is needed to reduce potential health, cognitive, and behaviour effects from LED lighting systems. Basing it on a Fourier analysis of the waveform is a promising approach because rectangular waves with similar high-frequency Fourier components are more visible than sinusoidal waves at the same modulation depth, suggesting that the additional visibility is created by the high-frequency components. This is the same approach used by Perz *et al*.[7] in the development of SVM.

4.2 Future work, improvements, and limitations

One of the experiment participants explained why the phantom array effect is a personally serious health concern.

> *"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*."

It should be noted that multiple researchers[8,27,28] posit that TLM may contribute to non-visual health-related responses such as headache, migraine, malaise, etc., but there is little neurological evidence to date. For the study reported here, the exploration of responses to TLM at frequencies at or above 90 Hz was limited to visibility. Migraineurs were excluded as participants to prevent unintended health consequences of exposure to modulating light in recognition of the potential relationship.

This experimental work was performed with a 3.0 m viewing distance and a low adaptation level of approximately 2 lx at the observer's eye. A longer or shorter viewing distance may increase or decrease the visibility of the phantom array effect because the saccade will spread repeated images of a given frequency farther apart or closer together in terms of visual angle. The change in visibility will depend on the change in spatial frequency toward or away from the peak human sensitivity of 3-4 cycles per degree.

A higher ambient light level may reduce the visibility of both effects if it reduces the contrast between the light source or lighted object with its background; conversely, a lower ambient level is likely to increase the visibility if it increases the object/background contrast. This experiment used a 52%-reflectance neutral grey background. A darker or lighter reflectance background will affect the visibility and conspicuity of the target. The visual angle subtended by the moving target and its speed will also affect visibility of the stroboscopic motion of the target.

This work was unable to test all possible combinations of frequency, wave shape, duty cycle, and modulation depth. High frequency waveforms, in particular, were challenging to achieve. Research examining frequencies above 6,000 Hz is especially needed.

5. Conclusions

This study of temporal light modulation (TLM) found that:

- The stroboscopic and phantom array effects were different perceptual responses, and that metrics for one may not predict visibility of the other.
- For the frequencies studied, these effects were more visible from TLM waveforms with higher modulation depths, given the same frequency, shape, and duty cycle.
- The effects were more visible from rectangular TLM waveforms than sinusoidal shape waveforms.
- TLM waveforms with lower duty cycles increased the visibility of the phantom array effect compared to 50% duty cycle.
- There was wide variability among participants, demonstrating that a metric based on average visibility may not be appropriate for protecting more sensitive populations from unwanted visual perceptions. There was a significant different between visibility ratings according to whether they categorized as higher or lower sensitivity.

Overall, the results of this work are largely confirmatory of prior research findings regarding visibility of the stroboscopic effect. The work expands upon past research by simultaneously examining visibility of the stroboscopic and phantom array effects, and examining visual responses to more combinations of TLM shape, modulation, duty cycle, and frequency.

Although only a subset of solid-state lighting systems "flicker" at the time of this writing, they are sufficiently common that there is a growing set of complaints from individuals experiencing discomfort, distraction, annoyance, and potentially unwanted health effects. This may be a consequence of unwanted TLM in their homes, vehicles, workspaces, schools, and even from their mobile phones or their holiday lighting.

The authors hope that this research can contribute to improved lighting products for automotive, architectural, and electronic device applications.

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Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this paper.

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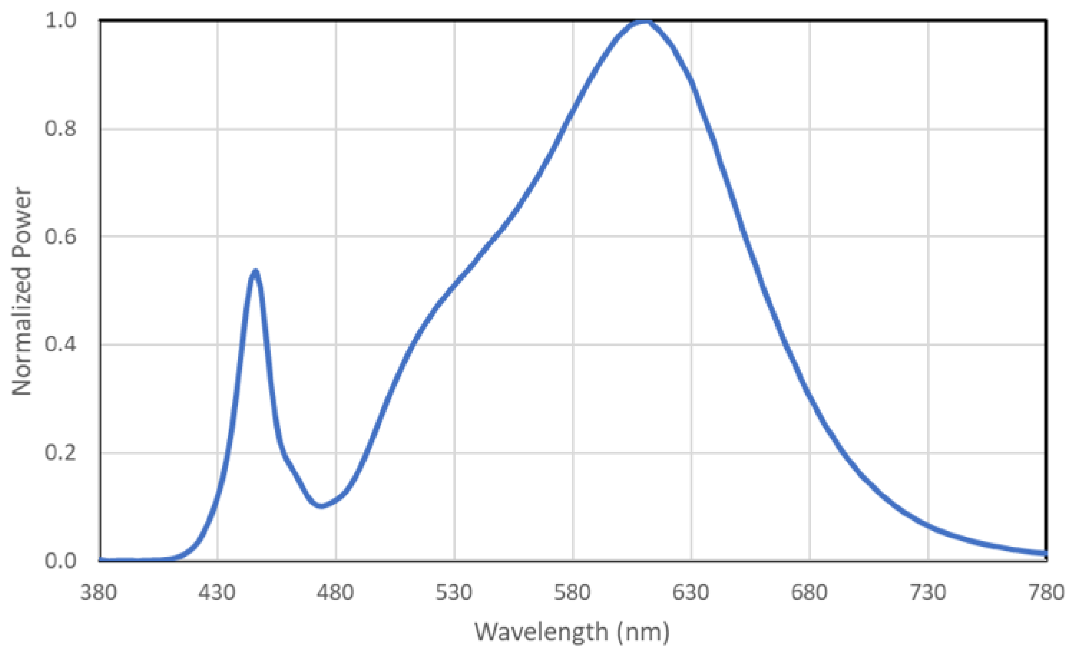
Appendix A

Table A.1 Terms and definitions for TLM quantities and factors affecting TLM visibility

Term	**Definition**
Temporal Light Modulation (TLM)	Fluctuation in luminous quantity or spectral distribution of light with respect to time (CIE TN 012:2021)29.
Visual Perceptions of TLM	“Change in visual perception, induced by a light stimulus, the luminance or spectral distribution of which fluctuates with time, for a human observer in a specified environment.”29 It is a grouping of unwanted visual responses, including direct flicker, the stroboscopic effect, and the phantom array effect, as described in CIE TN 006 2016.31 Previously called Temporal Light Artefact (TLA).
Responses to TLM	“The response to a TLM stimulus, which can either be conscious (i.e. visible) or subconscious (i.e. neurological).”30 This response does not differentiate among visible and non-visible responses. A non-visual response such as headache or blurred vision is not necessarily solely caused by the TLM.
Direct Flicker Effect	“Perception of visual unsteadiness induced by a light stimulus, the luminance or spectral distribution of which fluctuates with time [i.e. TLM], for a static observer in a static environment.”29 The modifier direct has been added here to differentiate directly visible light fluctuations (on or off-axis view) from the generic term which is generally used to refer to either stimulus or response, and to differentiate it from the stroboscopic effect that is detected indirectly.
Stroboscopic Effect (or Stroboscopic Motion)	“Change in motion perception induced by a light stimulus, the luminance or spectral distribution of which fluctuates with time, for a static observer in a non-static environment.”29 This is a visual response to a stimulus, but it requires a moving object in the field of view for detection.
Phantom Array Effect	“Change in perceived shape or spatial positions of objects, induced by a light stimulus the luminance or spectral distribution of which fluctuates with time, for a non-static observer in a static environment.”31 CIE TN 006:2016 indicates the non-static observer is one who moves their eyes in large saccades across a light source or a scene.
Frequency	Number of cycles of modulation per second (Hz)
% Modulation (= % flicker = Modulation depth)	Michaelson contrast calculated from one cycle of the TLM waveform = (max – min) / (max + min) x 100%.
% Duty cycle	Percent of time per cycle when TLM waveform is at high output, compared to the rest of the cycle at lower or 0 output.
Wave shape	Descriptive shape of TLM waveform: sinusoidal, rectangular, constant, or more complex patterns

Appendix B



CCT = 2871 K

D_{uv} = 0.0007

Melanopic DER = 0.45

R_a = 83

R_f = 83

Figure B1. Experiment light source colour characteristics, including plot of SPD.

Appendix C

Leiden Visual Sensitivity Scale
(Perenboom *et al.*[21])

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