Flicker: A review of temporal light modulation stimulus, responses, and measures

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Abstract

Flicker has been an important lighting system consideration for over a century. More precise terms are temporal light modulation (TLM) as the stimulus, and responses to TLM as the unwanted visual, cognitive, or physiological consequences. As lighting technology evolved, different forms of TLM emerged and so did responses to them. Today, some LED systems—encompassing the LED, driver, and control—can result in TLM causing severe unwanted effects, while other LED systems produce no unwanted effects at all. LED systems can deliver a much wider range of luminous waveforms than conventional lighting systems, some exhibiting very high modulation depths. More than any light source before, they can elicit perceptions of the phantom array. Direct flicker effects at modulation frequencies less than about 80 Hz and the stroboscopic effect at frequencies greater than 80 Hz are fairly well understood, but the phantom array effect needs more exploration and characterization. This review focuses on the technology and research history that led to current metrics for quantifying TLM and human responses to TLM. Visually impaired individuals may exhibit alterations in their response to TLM, but such a discussion is beyond the intent of this review. Thus, the focus is individuals with normal visual function.

1. Introduction

Almost all lighting sources modulate light output over short periods, following a repetitive pattern. For some lighting systems, the temporal light modulation can be imperceptible and harmless, but in other cases, the modulation can cause effects ranging from annoyance to neurological disorders; the perceptibility and effects are dependent on the characteristics of the modulation, viewing conditions, and observer. Characterizing the waveform—defined as the pattern of light output over time—and crafting metrics to predict its effect on human observers has been a research topic for many decades. However, the existing metrics have limited value for predicting unwanted TLM or evaluating it on a job site. In fact, there are no prediction tools at all for the phantom array effect, which results from a waveform with deep modulation that was rarely seen before LEDs entered the marketplace. Also, there is little performance data or specification guidance available to design professionals and users of lighting, creating a risk for adverse effects and the potential for rejection of new, energy efficient lighting technologies.

This review article begins with a discussion of terminology. It then addresses the stimulus, beginning with an overview of light source development because this shaped the concerns and research needs. It then addresses the stimulus waveform characteristics, and then the response, providing an overview of potential effects of modulating light on humans and summarizing the critical concepts and human factors research that has led to temporal modulation measures and metrics for assessing and predicting adverse effects. It concludes with relevant regulations and guidelines and a discussion of potential next steps toward a future where temporal light modulation is easily measured, its effects well predicted, and this information widely available and appropriately applied.

1.1 Terms and definitions

The lighting industry, vision scientists, human factors researchers, and users have struggled with terms to describe modulating light and its effects on humans. Often the term *flicker* is used to mean either the stimulus or the response, irrespective of frequency or modulation of the light waveform. Despite efforts to standardize terminology, it remains fragmented and often researchers and practitioners default to terms such as *flicker waveform, light flicker, flicker detection*, or *flicker perception*.

For the purposes of this review, the critical terms are defined in Table 1, with each described in detail in Section 3. A note on the use of the term “static observer” used in several definitions. Observers are never completely static because they are experiencing involuntary microsaccades. A “non-static observer” is one experiencing larger saccades, often 40° of visual angle or more.

Table 1. Terms, definitions, and alternate terms for Temporal Light Modulation (TLM) quantities.

Preferred Term	Definition of Term	Alternate Term
Temporal Light Modulation (TLM)	Fluctuation in luminous quantity or spectral distribution of light with respect to time [CIE TN 012:2021].	None
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” (CIE 2021a). It is a grouping of unwanted visual responses, including direct flicker, the stroboscopic effect, and the	Temporal Light Artefacts (TLA), as defined by the CIE (CIE 2016).

Preferred Term	Definition of Term	Alternate Term
	phantom array effect, as described in CIE TN 006 2016 (CIE 2016).	
Responses to TLM	"The response to a TLM stimulus, which can either be conscious (i.e. visible) or subconscious (i.e. neurological)".[82] TLR 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.	Temporal Light Responses (TLR), as defined by the IES.[82]
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" (CIE 2021a). 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.	Flicker
Stroboscopic Effect	"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" (CIE 2021a). This is a visual response to a stimulus, but it requires a moving object in the field of view for detection.	Also called "Stroboscopic Motion"
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" (CIE 2016). 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.	Also called "Ghosting"

2. Stimulus

2.1 Lighting and display technology and its relationship to TLM and responses to TLM

The first, most compelling application of electricity was lighting, and the incandescent filament lamp was the first practical lighting technology. In North America, with a 60 Hz 120 V AC distribution system, the incandescent lamp produces a sinusoidal 120 Hz TLM waveform with a 6 to 10% modulation (see Section 2.3). In countries and regions with a 50 Hz AC distribution system, incandescent lamps exhibit a sinusoidal 100 Hz TLM waveform with around 15% modulation depth. Unless there is poor power quality that exaggerates the modulation, this is not commonly identified as noticeable or problematic, in part because the thermal persistence of the filament produces a continuous TLM waveform (*i.e.* no breaks or gaps), as opposed to a rectangular waveform that may exhibit ON/OFF behaviour or sudden changes in output.

Fluorescent lamps, which became widely available in the 1940s, initially required a magnetic device to deliver the needed voltage, and to limit the current delivered. Magnetic ballasts on 50 or 60 Hz AC power distribution systems produce sinusoidal modulation of the delivered light output at twice the mains frequency, 100 Hz or 120 Hz for 50 Hz or 60 Hz distribution, respectively. The dominant modulation stems from the sinusoidal AC waveform, but fluorescent phosphors persist in light output slightly beyond the duration of current to the lamp. The modulation in each cycle usually ranges between 20 and 45% (with some exceptions up to 100% modulation), depending on lamp type and luminophore.[1,2] There were complaints of headaches and migraines attributed to magnetically ballasted fluorescent light.[3]

In the late 1980s, electronic ballasts became available for fluorescent lamps, operating at a much higher frequency of 20,000 to 60,000 Hz. Anecdotal reports and scientific research found that this change reduced complaints. Wilkins *et al.*[3] studied headache/migraine frequency in an office building, comparing high-frequency electronic ballasts (32kHz frequency, <4% modulation [reported as 7% contrast using equation (max-min)/max] at 100 Hz) to a baseline of magnetic ballasts (100 Hz frequency, 30% modulation [reported as 46% contrast using equation (max-min)/max]). Among office worker subjects most sensitive to headaches, the frequency and severity of headaches was significantly reduced after the switch. In other work, Colman *et al.*[4] found TLM to be detrimental for autistic individuals, leading to recommendations to use daylight or incandescent lamps instead of fluorescent lamps for classrooms with autistic children.

There were also improvements in visual performance when magnetic ballasts in fluorescent luminaires were replaced with electronic ballasts. Wilkins[5] described how modulating light from visual display terminals and, separately, from fluorescent luminaires affected the saccades during reading. Veitch and McColl[6] identified lower visual performance from magnetically ballasted fluorescent lighting versus electronically ballasted fluorescent lighting. This was likely related to disrupted saccade size.

The proliferation of cathode ray tube (CRT) visual display terminals (VDTs) beginning in the 1980s presented additional challenges. Refresh rates on CRT terminals (usually 60 to 75 Hz) generated complaints from some users. Manufacturers responded by increasing refresh rates and interlacing the raster lines on screens.[7] Bauer *et al.* found that maximum detection of *flicker* in VDTs occurred not with on-axis viewing, but with off-axis viewing, peaking at 30 degrees eccentricity. They recommended that refresh rates exceed 100 Hz in order to reduce *flicker* perception among 95% of users. They reported that higher luminance displays of 320 cd/m^2 produced greater responses than those at 80 cd/m^2. Berman *et al.*[9] conducted experiments to evaluate interactions between fluorescent lighting and screen displays. Using EEG equipment, they determined that the brain was responding to undesirable TLM, even if the participant did not report visible artefacts, at frequencies of 164 Hz and higher.

In the 1980s, some specific types of halogen PAR30 and PAR38 lamps used a diode in series to reduce the voltage to the filament, providing an optically more compact light source. This reduced the frequency of the TLM from 120 to 60 Hz because it cut out the reverse phase of each AC cycle and deepened the modulation due to filament cooling. When combined with phase-cut dimmers, the modulation depth increased even more. Following complaints from the field, this design was replaced with one that did not use a diode.[10]

In the 2000s, LEDs arrived for architectural applications, and eventually led to intensified interest in responses to TLM, because the performance can be highly problematic and can vary widely from system to system. The TLM of an LED lighting system is based on the combination of the LED driver and control and requires accurate methods for measuring the TLM and predicting responses. In contrast, the TLM of incandescent filament, fluorescent, or metal halide lamps was fairly consistent in sinusoidal modulation, so it was easier to predict the TLM and any responses based on knowing the technology and whether a ballast was 50 or 60 Hz magnetic or high-frequency electronic. Figure 1 illustrates TLM waveforms for some conventional light sources and Figure 2 for LED sources.

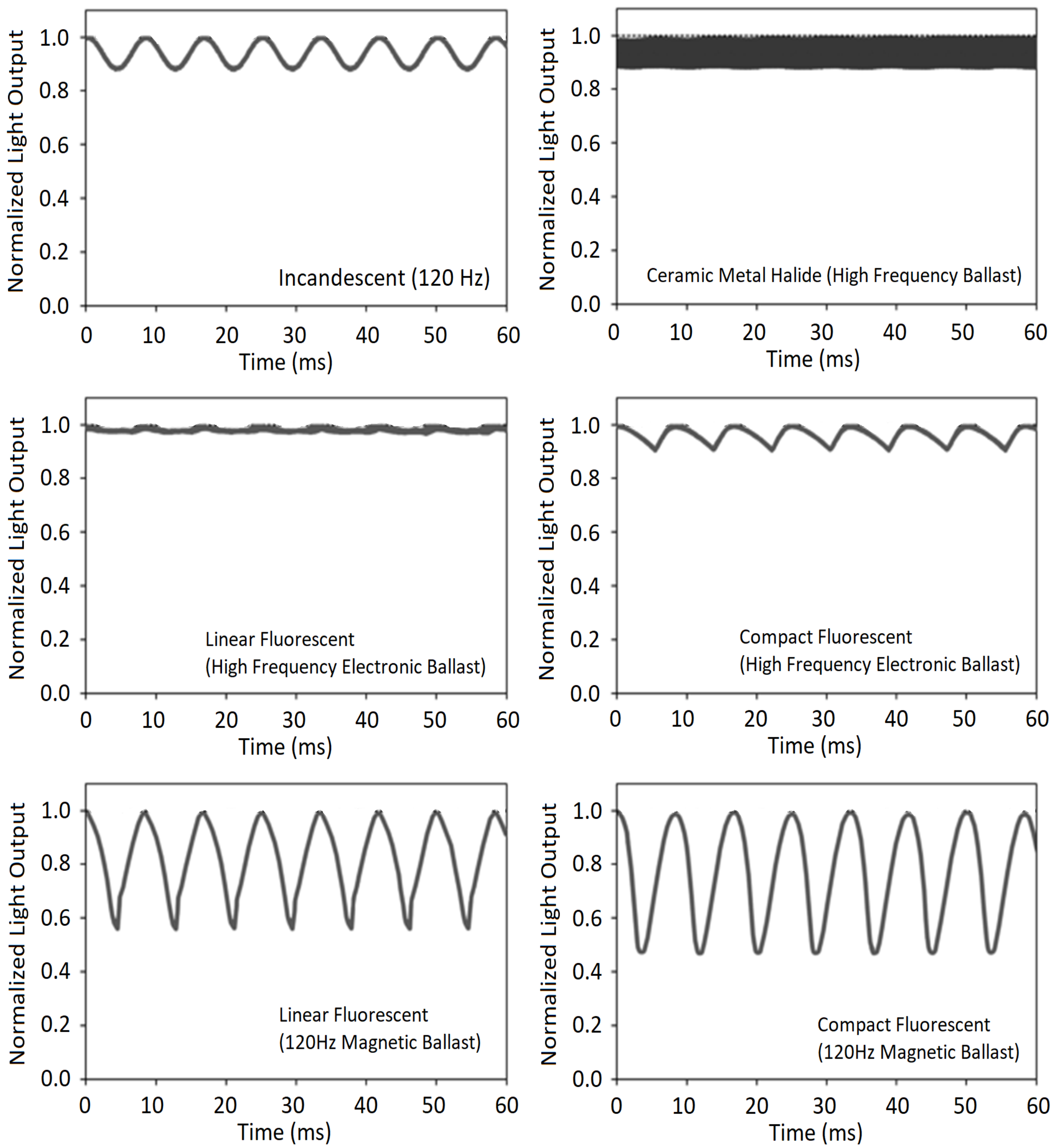

Figure 1. TLM waveforms from a variety of conventional lamps and ballasts. (Source PNNL).

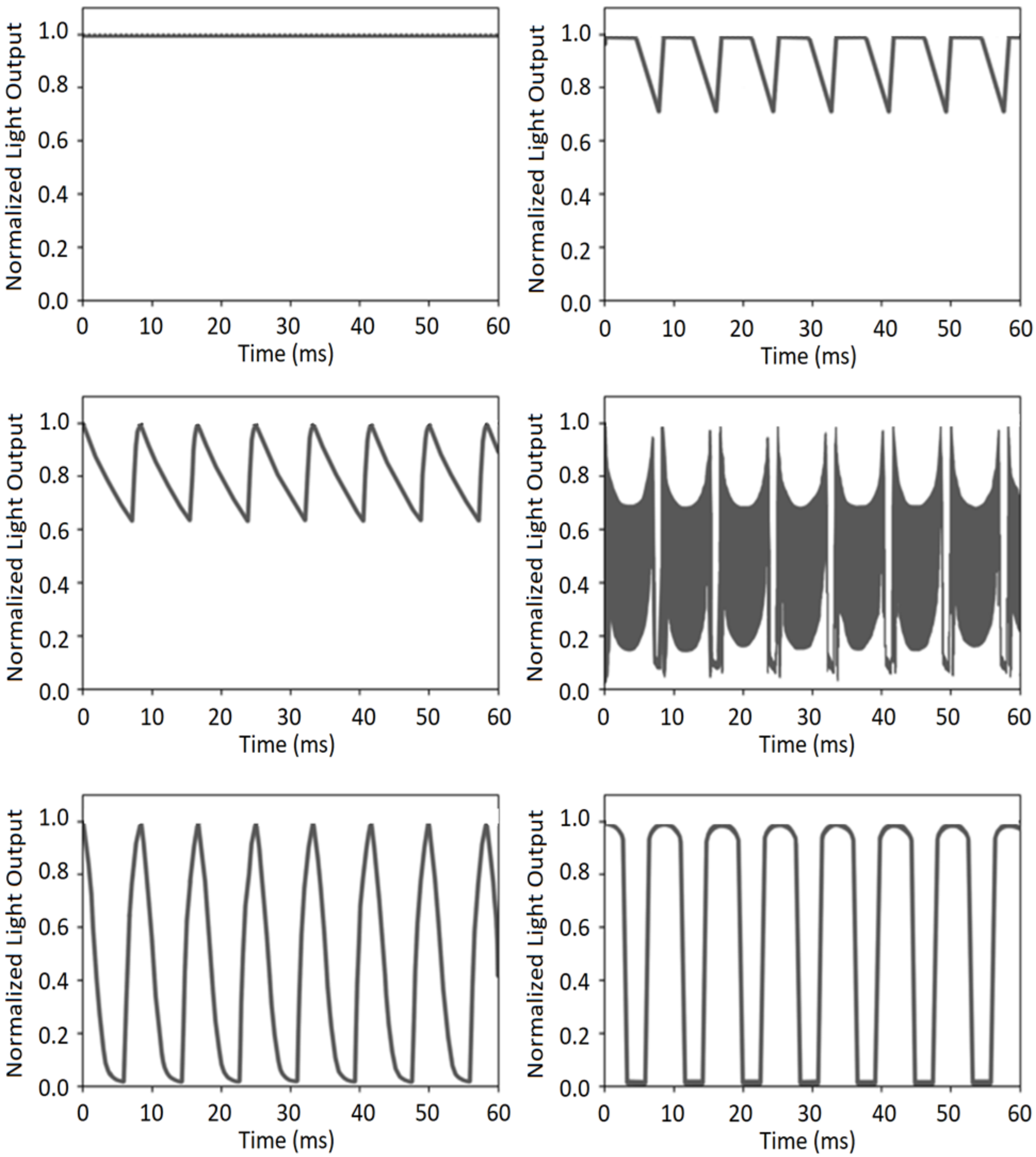

Figure 2. TLM waveforms from a variety of LED systems, showing the wide variation. (Source PNNL).

LED drivers can turn current to the LED on and off rapidly in response to a control signal, and this characteristic can also be used to adjust the light output with a technique called pulse width modulation (PWM). PWM applies 100% modulation and varying duty cycle to reduce the output of the LED.

Although LEDs usually utilize a luminophore, the persistence is substantially less than with fluorescent or incandescent lamps, and thus the modulation depth can be greater. The first LEDs were difficult to dim and using them with conventional phase-cut dimmers often introduced undesirable TLM even though it was not present at full output. At the common modulation frequency of 120 Hz in North America, stroboscopic and phantom array effects, depending on the driver circuitry, were very noticeable.[11]

In some products, LEDs are modulated at frequencies of 400 to 2,000 Hz using PWM. Roberts and Wilkins[12] found this introduced visibility of TLM when existing stroboscopic effect and direct flicker models did not predict perceptibility. Since the effect was most noticeable during a large eye saccade, it was recognized as the phantom array effect, which is most visible for TLM with higher modulation depths and at frequencies at the extremes in that range.[13] LED taillights can become a problem at night because they are brake lights at full output, but dimmed using PWM to operate as the lower-luminance taillights. The phantom array is increasingly seen on streets and roadways due to the interaction of normal eye saccades of drivers or pedestrians with modulating vehicle taillights, marker lights, daytime running lights, and even headlights.[12]

Early generation, low-cost driverless LEDs operate on rectified AC power or with diodes that filter out all negative AC current. Often called AC-LEDs, they can produce noticeable 120 Hz and 60 Hz modulation in North America (Figure 3. Waveform for an early AC-LED source, producing 120 Hz modulation. (Source: PNNL)). Note that the waveform is asymmetric because the trough duration is longer than the peak interval. (Fortunately, improved AC-LED technology is available.)

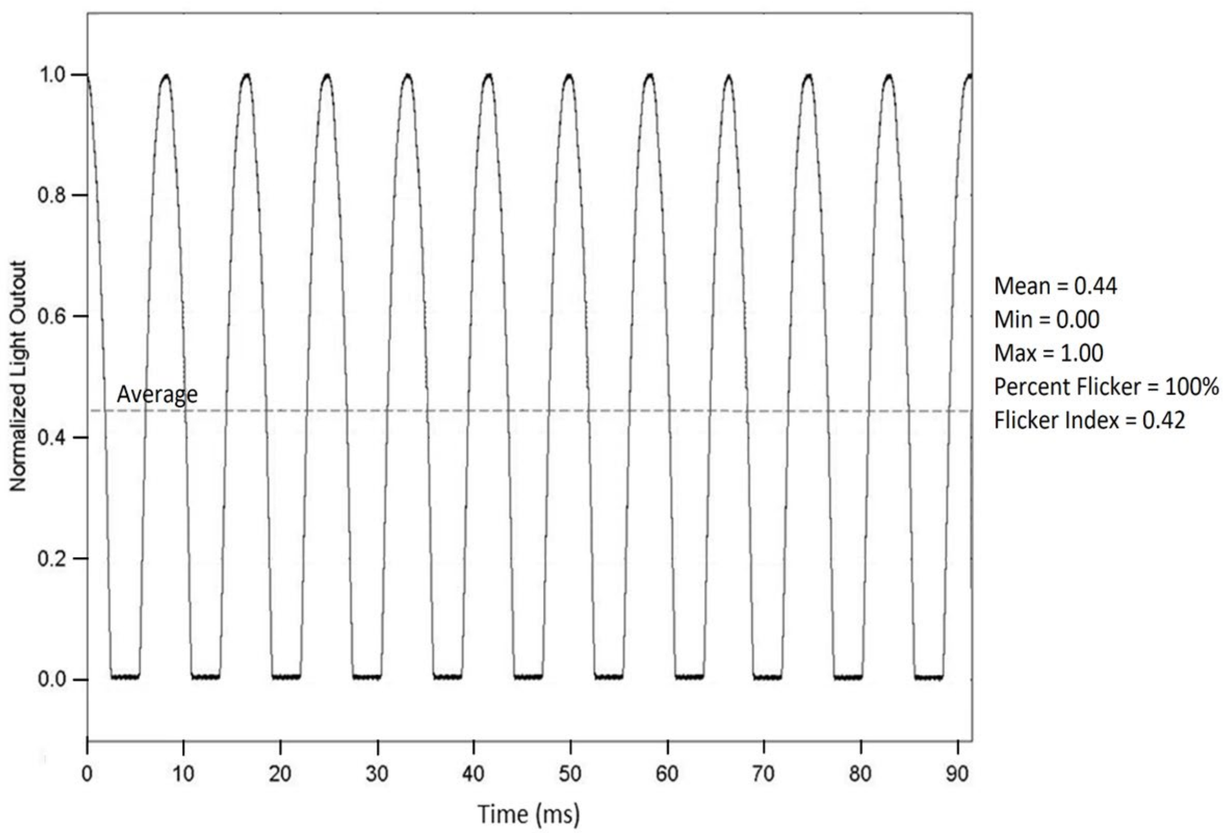

Figure 3. Waveform for an early AC-LED source, producing 120 Hz modulation. (Source: PNNL)

2.2 The TLM waveform

Understanding how TLM is detected and how the visual (*i.e.* eye-brain) system processes the information to produce a response is critical to creating models of perception. These psychophysical models in turn lead to measures for quantifying potential responses and their severity for a range of observers with normal vision. The TLM characteristics that affect responses include source luminance and luminance modulation depth, the fundamental frequency and any harmonic frequencies that contribute to the time-based waveform, the wave shape (such as sinusoidal versus rectangular waves), the duty cycle (the percent of time over a single cycle at which the light amplitude is high compared to the amplitude over the rest of the cycle), the contrast of the luminance compared to its background, and the sensitivity of the observer.[14] The average or mean luminance over a single cycle is sometimes called the DC component. One other significant factor is relative movement: direct flicker is based on a steady gaze, but the stroboscopic effect requires movement of an object in the modulating light (like a ball on a tennis court), and the phantom array effect requires a saccade by the eyes of the observer while the modulating light source or lighted scene remains stationary.[14] The phantom array has also been observed when both the eyes and the light source are moving.[15]

The TLM waveform can be expressed in the time domain, or a Fourier analysis can be applied to the waveform to convert it to the frequency domain (Figure 4). Multiple researchers[16,17,18] suggested applying a Fourier analysis to the TLM waveform to convert from a time domain to a frequency domain. A Fourier analysis identifies frequency harmonics that add to the perception of visual instability. (Fourier analysis assumes that the waveform is continuous and periodic, but sampling the waveform is usually performed for a fixed time period. The abrupt onset and offset of the waveform can introduce high frequency temporal transients, which alters the shape of the waveform.)

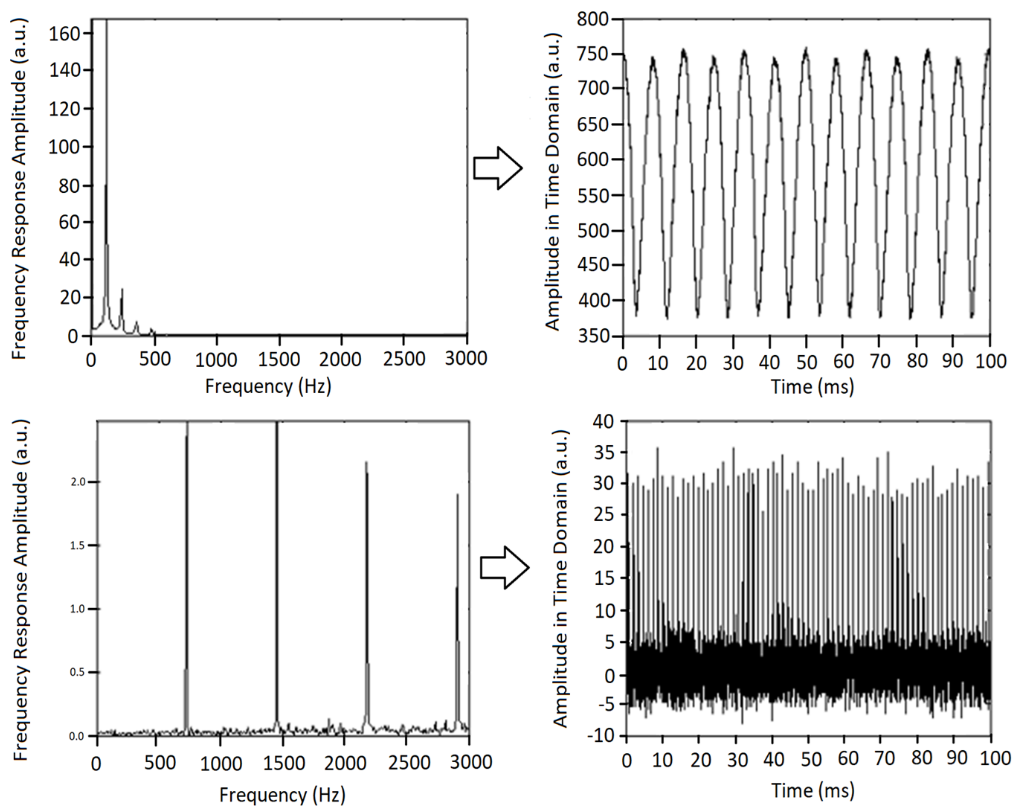

Figure 4. Two TLM waveforms plotted in the frequency domain (left) and the time domain (right). Images courtesy PNNL.

2.3 Measuring the stimulus

TLM begins with the waveform. The modulation can be described by parameters consisting of its frequency, modulation depth, duty cycle (in the case of rectangular waveforms), and shape. Figure 5 illustrates the following two basic equations to characterize a periodic waveform:

Percent Flicker = Percent Modulation = 100% x (Max – Min) / (Max + Min) (1)

Flicker Index = (Area A) / (Area A + Area B) (2)

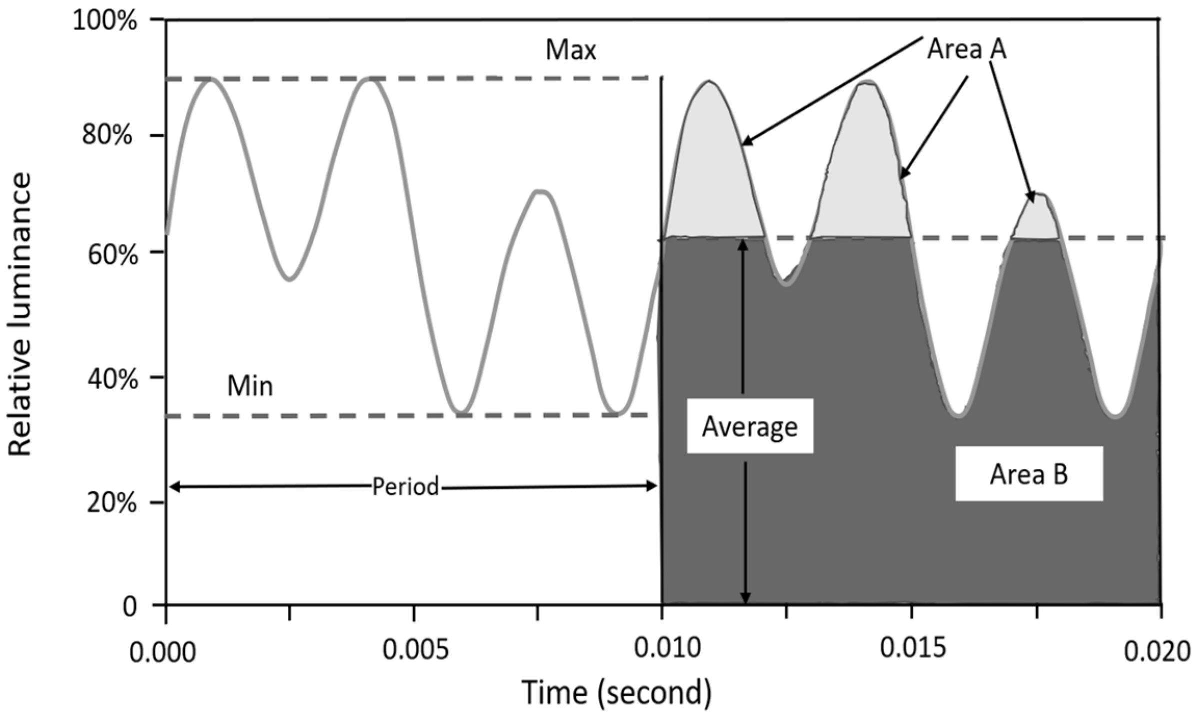

Figure 5. A periodic TLM waveform illustrating period, frequency, and values critical for calculating percent flicker and flicker index.

2.3.1 IES Percent Flicker

IES percent flicker is a relative measure of the cyclic variation in the luminance waveform. Also known as modulation depth or percent modulation, it was previously used as means to compare systems exhibiting 120 Hz modulation. IES percent flicker is calculated from the measured TLM, based on Michelson contrast, using Equation 1. Percent flicker has limited value as a measure of response because it does not take the wave shape, duty cycle, or frequency of the TLM into account.

2.3.2 IES Flicker Index

Like IES percent flicker, the flicker index was developed as a means of comparing systems exhibiting 120 Hz modulation and was not directly targeted for addressing visual responses. When examining the area under the curve emitted over a single cycle of luminous output, the flicker index is the area above the average value relative to the total area under the curve (Equation 2). It is sometimes expressed as a decimal value between 0 and 1, and sometimes as a percentage from 0 to 100%. It can be used as a comparative metric for sources all operating at a single frequency, but modern ballasts and LED drivers are not consistent in their driving frequency.

Poplawski and Miller[19] recommended flicker index as a superior metric to percent flicker because it works for non-continuous waveforms, taking duty cycle into account, for example. It is not sufficient as a standalone metric for characterizing stroboscopic motion potential but could be useful when combined with fundamental frequency. Its drawback is that it does not account for the increased visibility of a waveform due to higher frequency components in the waveform. That is, the flicker index cannot distinguish between the visibility of a rectangular wave and a sine wave if they both have the same percentage of light emission above the waveform average.

The response metrics described in the next section all require the measurement of the TLM waveform, but some have different stipulations on the duration and resolution of that measurement. The IES has standardized a method for measuring the TLM waveform[20], as has the CIE.[21] These will not be discussed further in this article.

3. Response

There are three key concepts related to how the human visual system processes TLM: spatial contrast sensitivity and its relationship to temporal contrast, TLM sensitivity curves, and the Critical Flicker Fusion Frequency (CFF). Each of these deal with observer responses to different parameters of the TLM.

3.1 Spatial contrast sensitivity

Contrast sensitivity functions (CSF) are a fundamental tenet of vision science that describe the human visual response to two-dimensional gratings of varying spatial contrasts, sizes, and frequencies expressed in terms of visual angle.[22] Campbell and Robson[23] explored contrast thresholds of two-dimensional oscilloscope-displayed grating patterns over a range of contrast values and spatial frequencies. Examining sine, square, rectangular or saw-tooth waves in the pattern, they learned that visibility of an image projected on the retina could be explained by Fourier theory. They established a relationship between contrast sensitivity and frequency in cycles per degree (cpd), shown in Figure 6. Specifically, they found a 50% duty cycle, 100% modulation spatial waveform to be more visible than an equivalent sinusoidal spatial waveform by a factor of $4/\pi$ at the same frequency—a similar value was confirmed by Levinson (1960).[24] Additional harmonics were found to add to the visibility, supporting a Fourier series approach to calculating visibility of a static image.

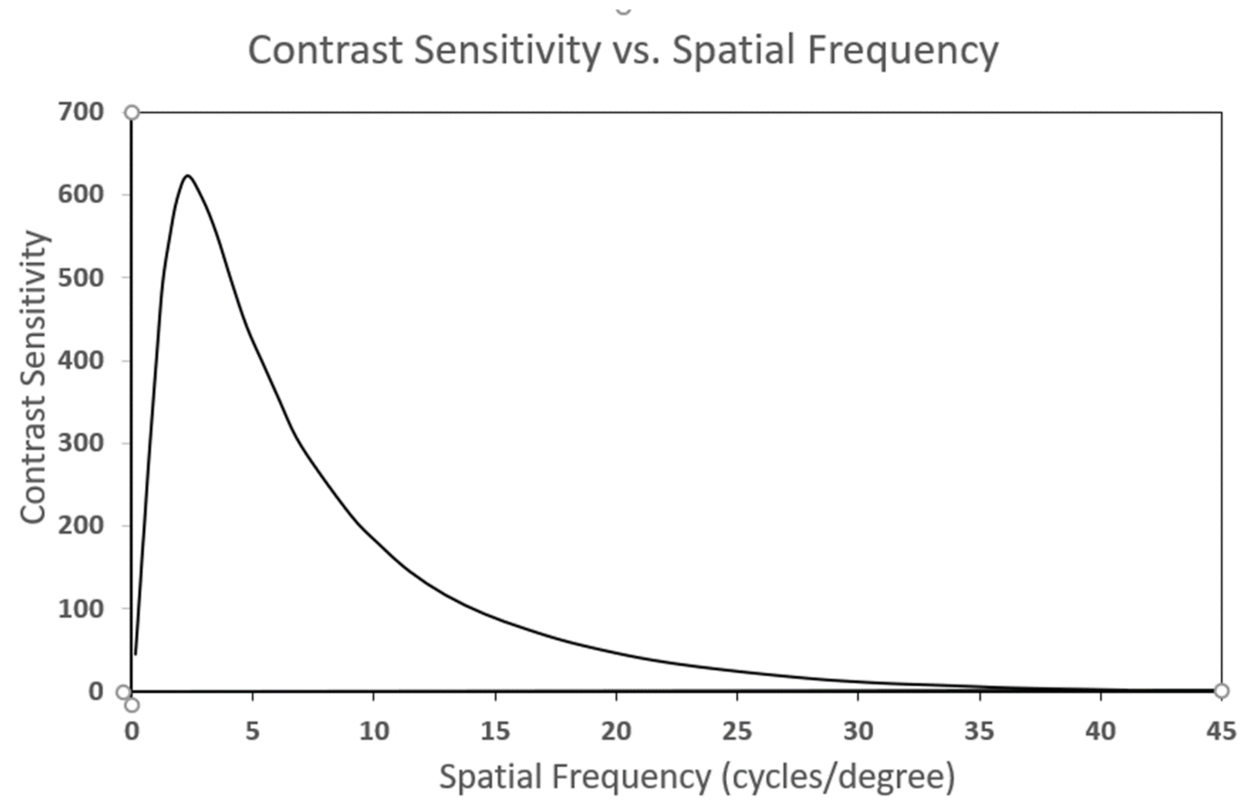

Figure 6. Spatial contrast sensitivity plotted on a linear scale, showing maximum sensitivity at 3-4 cpd. Replotted from Legge 1981.

Because retinal images have some persistence, and both stroboscopic effects and phantom array images are spread spatially across the retina when there is relative movement between light source, head, eyes, and object, the concept of spatial contrast sensitivity, which generally applies to a static retinal image, was applied to temporal contrast sensitivity.[25] Thus, the concept was applied to a retinal image that is built up on the retina over time.[12,26]

3.2 Temporal contrast sensitivity functions

Multiple researchers have investigated temporal variation by testing the sensitivity of observers to modulating light, identifying the combinations of frequency, modulation depth, waveform shape, luminance, and adaptation level under which the time-based modulation is most and least visible to the average observer. The seminal studies are described in the paragraphs that follow. From this data, temporal contrast sensitivity functions (TCSF) have been derived. A TCSF is the reciprocal of the temporal visibility threshold and is defined as the modulation depth at which an average observer can detect modulation with a probability of 75%. (A detection modulation with a probability of 50% is chance performance.) Some plots illustrate a maximum response or sensitivity, while others show the same data as a minimum value in the threshold conditions for detection.

De Lange[27] studied small field photopic sensitivity to TLM, with modulation in the center 2° field of view only, and a steady luminance in the 60° field around it. He found the maximum temporal sensitivity occurred around 8-9 Hz with a modulation of 0.8%, but this was only for a small retinal area around the fovea. Subsequent research concluded that the direct flicker visibility was dependent on the fundamental frequency of the modulation.[28] Kelly[17] followed this work with a larger 68° diameter field of view, with a uniformly modulating field using sinusoidal waves. He developed a TCSF over a range of 1 to

80 Hz, as shown in Figure 7. These plots illustrate that at higher retinal illuminances (measured in Trolands, which takes pupil size into account), direct flicker can be visible even at small modulation depths when the frequency ranges from approximately 5 to 65 Hz.

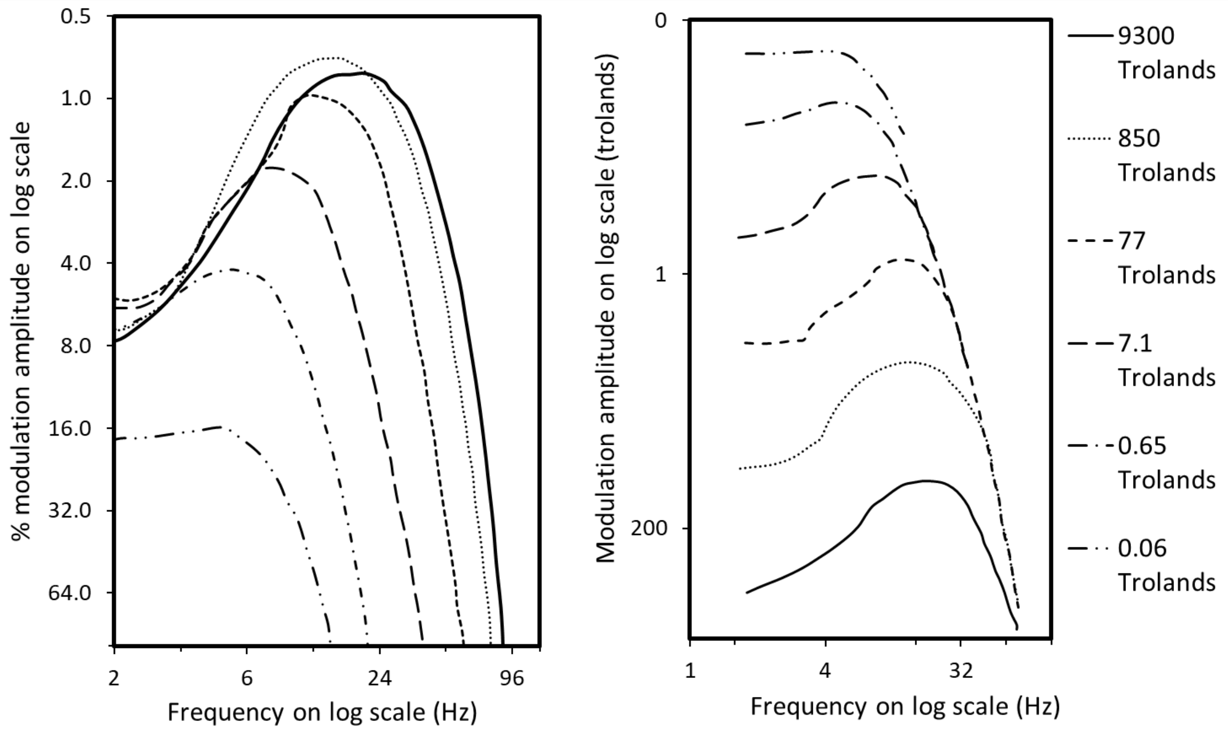

Figure 7. Temporal contrast sensitivity curve derived from Kelly (1961) showing direct flicker thresholds for a large visual field at different retinal illuminances. The modulation is expressed as percentage modulation in the left plot and absolute modulation in the right plot (after Boyce 2014 and Kelly 1961).

Levinson[24] expanded De Lange's initial finding by demonstrating that for waveforms that were described using a Fourier series frequency spectrum, those with more than one frequency (*e.g.* a rectangular wave) added to the visual perception of TLM. He found that when there was a fundamental frequency and a harmonic in the waveform, the second harmonic increased the modulation sensitivity by a factor of 30%.

Henger[29] continued with Kelly's work, creating an eye-brain frequency response function in the frequency domain, known as the Kelly-Henger response. It peaks at 10 Hz (shown in Figure 8) with maximum sensitivity of 1.0 and drops to less than 0.005 at 80 Hz, and 0.001 at 99 Hz. The Kelly-Henger weighting function is shown beside similar sensitivity functions by Bodington *et al.*[18] and the International Electrotechnical Commission's (IEC's) Flickermeter sensitivity function[30] derived from De Lange's 1961 TCSF.[28] The Flickermeter is described further in Section 3.4.2.

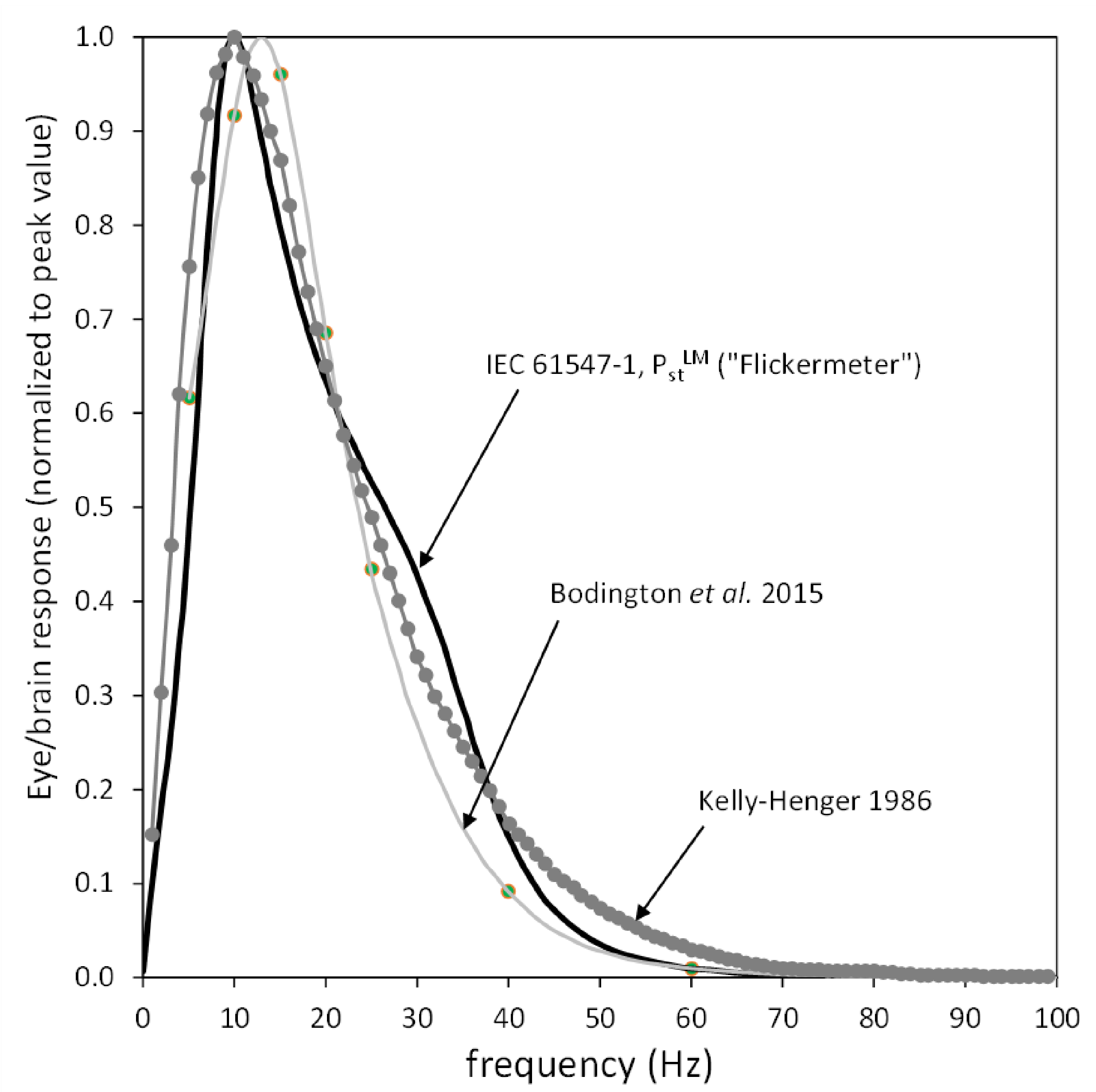

Figure 8. Sensitivity curves for direct flicker, one by Kelly-Henger (1986), one by Bodington et al. (2015), and one for the IEC's "Flickermeter" measure (De Lange 1961). Plot after Garner 2020.

3.3 Critical Flicker Fusion Frequency (CFF)

The Critical Flicker Fusion Frequency (CFF) is the frequency threshold above which a periodically modulated light source appears as steady in output when viewed with a fixed gaze. This is the point where the TCSF has a value of zero. Originally identified by Porter,[31] his and subsequent work by De Lange[27] identified the following factors as affecting the CFF: average luminance of the modulating light, adaptation level of the eye, background illumination of the environment, size and position of the modulating spot on the retina, and subject age. De Lange concluded that chromaticity did not affect CFF if the luminance was held constant. According to past work, CFF values range from 50 Hz up to 90 Hz as long as subjects are viewing a high luminance modulating source or area with a steady gaze.

CFF values can vary for a single individual, depending on the overall central nervous system arousal state, or wakefulness and vigilance, which is correlated with higher CFF values.[32] CFF also increases (that is, the TLM is visible at higher frequencies before it fuses into steadiness) as the luminance of the flashing target increases;[17] the Ferry-Porter law describes the linear relationship between CFF and log luminance, as long as the stimulus is sinusoidal and the waveform contains no harmonics lower than its repetition rate.[17].

Tyler and Hamer[33] found that CFF also increases as the fixation point moves off-axis, up to a value of 35°, suggesting faster processing in the periphery. They found the maximum CFF at 90 Hz, at log illuminance of 4 Trolands, an eccentricity of 35°, and a source size of 5.7°. The mid-periphery, peaking at around 50° from the axis of view, had the best temporal resolution. Rather than source size, this may be related to the number of ganglion cells stimulated.[34] So, the larger the number of retinal ganglion cells (RGCs) stimulated, the higher the CFF value, being related by the log of the number of stimulated RGCs.

In 2015, Davis *et al.*[7] explored the perception of TLM on Digital Light Processing (DLP) displays from square wave temporal modulations, investigating 20 Hz up to 1,000 Hz, with low and high frequency spatial edges. Although the CFF followed earlier findings of a maximum CFF of 65 to 70 Hz when showing low contrast edges,[35,28,17] the high contrast edge increased CFF on average from 65 Hz to over 200 Hz for all observers, and as high as 800 Hz for some. Importantly, each subject's gaze was not fixed, and the researchers postulated that the unexpected sensitivity to high frequencies compared to previous work was likely due to saccades. Thus, the methodology was flawed, but illustrates that an unrestrained observer gaze means this study was effectively measuring a CFF for a saccadic response across the target, and therefore, detecting the phantom array.

3.4 Responses from TLM and related metrics

Human responses to TLM can be divided into visual and nonvisual types. As previously noted, the visual perception of TLM (also called TLA) includes the following: direct flicker effect, stroboscopic effect, and the phantom array effect. It is possible for an observer to experience both stroboscopic motion and the phantom array at the same time,[15] and some research suggests it is possible to experience visual perceptions from TLM without being conscious of it,[9] Considerable research effort has been dedicated to identifying parameters for visibility and other responses to TLM, to establish measures to quantify health risks, task performance, distraction, or otherwise unwanted consequences of TLM. In some cases, acceptability of these responses was also investigated.

Visual responses require an observer, and it is important to note that individuals vary widely in their sensitivity to temporal light variation both visually and in their non-visual responses. Although much research collapses the wide variation into a "normal" or average response, some researchers[36,37] are becoming aware that more sensitive individuals are more likely to be annoyed, distracted, or their health affected by the TLM, and standards may need to be tightened to protect the more vulnerable populations.

3.4.1 Direct flicker effect

Direct flicker is typically said to occur at frequencies between 3 and 90 Hz. This direct flicker is annoying for many, but also could lead to recognized health effects, as described in Section 3.3.4. Research into direct flicker was performed in response to the visibility of incandescent lighting systems that fluctuated in output when electrical power distribution was inconsistent. As detailed in Section 3.2, De Lange[16,27,28] and Kelly[17] identified parameters of direct flicker visibility: fundamental frequency, modulation depth, waveform shape, and light intensity. Peak sensitivity was found at approximately 10-15 Hz, where modulations of less than 1% are visible to an average observer. De Lange modeled the visual system as a series of curves of threshold visibility based on modulation depth and fundamental frequency. This was expanded by Rashbass (as reported in the IEC 1453-2015[38]) who developed a quantification of TLM, which led to the IEC Flickermeter metric (see Section 3.4.2).

Direct flicker is observed with a steady gaze, even if the modulating source is off axis. In computer displays, direct flicker is more easily detected at 30° off-axis, and the CFF is known to reach maximum at 35° off-axis.[8]

3.4.2 Metrics of the direct flicker effect

In response to early concern over direct flicker, and to perform voltage fluctuation immunity tests, the flickermeter was developed, a device designed to detect and analyze electrical waveforms on power networks. Once measurable, maximum limits could be applied through standards to reduce it. Originally, the flickermeter was a piece of equipment but was converted through a series of "blocks" into a software simulator. It is now called the IEC's Flickermeter metric, P_{st}^{LM}.[39] The subscript *st* stands for short-term direct flicker, and the superscript *LM* means light measurement, as opposed to electrical measurement. P_{st}, for short, takes instantaneous, non-periodic fluctuation in output into account, and importantly the metric builds in a test of electrical instability and noise. The context for the metric is general indoor applications where the average light level exceeds 100 lux, where the stimulus subtends a small visual angle (~2°), has a sharp edge, and a fully adapted observer views the stimulus with central vision.[14] Consequently, the metric may underestimate the response to an off-axis view of the modulation. P_{st} requires a 10-minute collection of the waveform and can be applied to transient waveforms. See IEC TR61547-1 (2020)[30] for details.

Bodington *et al.*[18] proposed a metric, Perceived Modulation (M_p), for characterizing direct flicker up to 90 Hz. Measured TLM is separated into component frequencies up to 90 Hz, treated independently, with modulation (contrast calculated using (max – min)/max) weighted by detection sensitivity. These results are combined in quadrature (*i.e.* the square root of a sum of squares), thus it follows the familiar form of a modulation perception equation.

Bodington *et al.*[18] concluded that the total perceived modulation was a sum of the squares of the normalized modulation at each frequency. They also determined that waveform components above the CFF can be neglected for M_p and there was not any sub- or super- additive combining of frequency components involved with direct flicker detection. This indicates that if direct flicker is not present in an individual lamp, combining multiple lamps will not produce direct flicker. M_p and P_{st}^{LM} are highly correlated and return similar values in the case of periodic waveforms. P_{st}^{LM} is the more established metric, but it requires a longer TLM collection period.[40]

3.4.3 The stroboscopic effect

Stroboscopic motion is detected as an object moves in the visual field for an observer with a fixed gaze—the modulation of the light is not observed directly. It is generally recognized as occurring between approximately 80 and 2,000 Hz. Negative consequences include headaches;[3] migraine or severe paroxysmal headache potentially accompanied by nausea and visual disturbances;[41] and eyestrain, malaise, and reduced performance on visual tasks.[42] The stroboscopic effect is also responsible for rotating or translating machinery appearing to stop or move at a different rate, posing an industrial hazard,[43] although the relevant range of frequency will depend on the speed of the machine.

Bullough *et al.*[44] explored factors contributing to the visibility of stroboscopic motion and found that detection was greater for high-modulation TLM (100% modulation depth, 0.5 flicker index, see Section 3.4.4) at 300 Hz than for lower modulation TLM (33% modulation depth, 0.17) at 120 Hz. Visibility increased when percent modulation increased and decreased as fundamental frequency increased. Bullough *et al.*[45] further studied the interaction between frequency and percent modulation, investigating the visibility and acceptability of the stroboscopic effect from a waving white wand illuminated by square wave modulating light in front of a black background. Observer gaze was not fixed, which may have contributed to higher frequencies of TLM being visible. Variables were modulation frequency, from 100 Hz up to 10,000 Hz, and modulation depth from 5% up to 100%. If stroboscopic motion was detected, subjects were asked about its acceptability. More than 60% of study participants reported seeing stroboscopic motion up to approximately 1,600 Hz with 100% modulation, and at 1,000 Hz with 54% modulation. However, visibility of stroboscopic motion did not always equate to the TLM's being unacceptable.

For three out of the four modulation depths tested by Bullough *et al.,*[44] detection was maximized at 300 Hz, although acceptability was quite high at that frequency and higher. Acceptability dropped at 100 Hz. TLM with 5% modulation depth produced both low detection values and high acceptability values. The authors proposed both a detection equation and an acceptability equation, although these have limited value in lighting practice since only 50% duty cycle waveforms were tested.

Later, Bullough *et al.*[46] explored visual performance in six subjects in the presence of modulating light. Using a numerical verification task and TLM with frequencies of 100 to 1,000 Hz and modulation of 25% or 100%, they found statistically lower error rates and somewhat higher visual comfort under higher frequency and lower modulation depth, even when task illuminance was reduced to approximately half, compared to 100% modulated light at 100 Hz.

Vogels *et al.*[47] published data on the visibility of a rotating disc under rectangular wave modulating light at fundamental frequencies of 50 up to 400 Hz; duty cycles of 10, 30, 50, 70, and 90%; and varying modulation depths. They showed that flicker index (see Section 3.2.2) alone was not a good predictor of visibility. However, modulation visibility threshold values were consistently lower at lower fundamental frequencies, and lower at 30% and 50% duty cycles than the other duty cycles. Observers were also more sensitive to stroboscopic motion when the rotating object was moving faster.

Figure 9 shows the modulation sensitivity curve developed by Perz *et al.*[48] for the stroboscopic effect frequencies. It is extrapolated up to 2000 Hz, although the experimental data did not extend up to that frequency.[48]

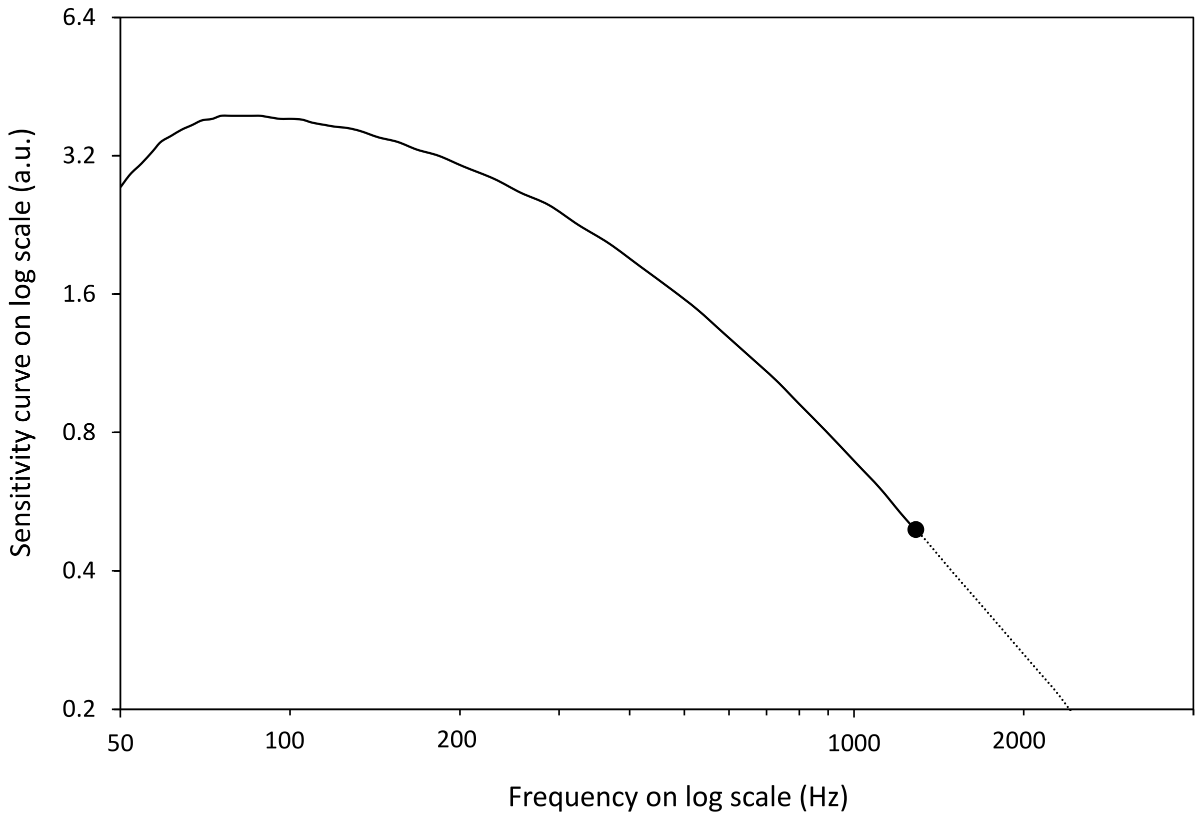

Figure 9. Sensitivity curve for sine waves at different frequencies, used to normalize the Fourier frequency amplitudes in the SVM calculation, plotted on log scales. The black dot indicates the highest frequency at which there was a datapoint. Plot after CIE 2016.

Perz *et al.*[26] continued the experimental work of Vogels to develop the Stroboscopic Visibility Measure (SVM), which is described further in Section 4.2.7. Their experiments cumulatively used over 180 subjects who were asked to observe a rotating black disc (approximately 15° visual angle) with one white dot near the perimeter. The disc was rotated at speeds of 4 m/s to mimic the speed of a gesturing hand in office applications. The disc was illuminated from overhead with a modulating light having a rectangular-wave or a sine wave shape of variable frequency and modulation depth. The rectangular waveforms produced lower thresholds than sine waveforms at all tested frequencies up to 400 Hz. The last experiment was designed to test the concept of frequency summation, based on the work of De Lange[28] and Levinson.[24] A Fourier analysis of the waveform separated it into its frequency components. Each component was weighted by a stroboscopic effect sensitivity curve (see Figure 9 based on the experimental results of their work. Summing the values of each Fourier frequency component together yielded better prediction than the fundamental frequency alone, even when accounting for the 4/π difference in response predicted by Campbell and Robson.[23] Responses from the multiple groups of observers were averaged to define a Standard Observer, so the more highly sensitive observers were balanced out by the least sensitive.

The Bullough *et al.,*[44,45] Vogels *et al.,*[47] and Perz *et al.*[26] studies all showed similar trends: stroboscopic motion visibility declined monotonically as fundamental frequency was increased, and as modulation depth decreased. The Bullough studies showed greater visibility than those of Vogels and Perz, likely because the Bullough studies' moving task subtended a larger visual angle and thus involved a larger portion of the retina. Also, the moving wand task may have introduced faster movement than the

Vogels and Perz *et al.* rotating disc task, plus the Bullough *et al.*[45] head and eye positions were not fixed. Neither group identified the distinctive behavior of the phantom array effect at frequencies of 600 Hz and higher, possibly because although there was minor eye and head movement, neither involved large eye saccades.

Veitch and Martinsons[49] studied stroboscopic motion visibility using an experimental setup and rotating disk task similar to those used in SVM studies and a metronome oscillating at 208 beats per minute. Test light sources ranged between SVM values of 0 and 3.0. Using a pattern glare test for subjects, they found that the more sensitive subset of the subjects had similar stroboscopic detection scores as the larger population, but exhibited more annoyance at conditions with SVM values of 1.4 and 3.0. In a followup report on state of the knowledge of TLM,[36] the authors argued that the results from the 2020 study based on very short exposure times point to more emphasis in future studies on sensitive subjects.

3.4.4 Metrics of the stroboscopic effect

Two metrics of stroboscopic effect are Physiological Percent Flicker (PPF) and Stroboscopic Visibility Measure (SVM). Price[50] proposed Physiological Percent Flicker (F'_P) as a characterization of stroboscopic effect, combining percent modulation and IES flicker index. It is expressed as a percentage, and similar to IES percent flicker, Michelson contrast is used to calculate the percent modulation. The maximum and minimum values of the original TLM waveform are smoothed by averaging the values occurring in the previous 3 ms, a value based on cone response decay. This effectively reduces the amplitude(s) of the modulation over time, and accounts for the frequency by averaging values over time. The proposed target value is <3.5% PPF, equivalent to incandescent lamp modulation or lower. PPF may be unable to take the phantom array effect into account because that effect does not monotonically decrease with increased frequency.

The most widely cited metric for the stroboscopic effect is SVM (M_v). As described in 3.3.2, Perz *et al.*[26] continued the experimental work of Vogels,[47] with the result used to extend the sensitivity curve to higher frequencies. Using frequency summation, an equation was developed using a Minkowski norm exponent to fit the data.

SVM has evolved over time and is now being documented through the CIE as one means to describe and quantify the stroboscopic effect.[14] Figure 9 illustrates the sensitivity curve for the stroboscopic effect used in SVM.[51] This is the inverse of the curve used to normalize the Fourier frequencies in the stimulus waveform. Notably, the sensitivity of SVM to frequency declines with higher frequencies above 80 Hz, until visibility is predicted to be very low at frequencies above 2,000 Hz.

The user of SVM should be aware of its limitations. It was defined for a static observer with fixed gaze in a non-static environment,[14] so it is most applicable for similar situations of fixed gaze and may not be a useful predictor of other types of TLM responses (e.g. the phantom array). Furthermore, the static observer condition does not apply to many situations because the eyes, head, and body of an observer are almost always moving. Realistic animated conditions may not match the experimental conditions as a result, and clearly the addition of the large eye saccade related to the phantom array effect introduces a different condition that is unlikely to be characterized with SVM. This metric was designed to mimic the speed of moving hands and arms in the visual field (at approximately 4 m/s), not moving machinery. As acknowledged by the developers, SVM is not appropriate for industrial predictions of stroboscopic hazard.

An SVM value of 1 is at the threshold of visibility, or the condition when the standard observer has only a 50:50 chance of being able to detect the modulation under threshold conditions. Situations producing a higher SVM are more reliably visible; those below 1 are less so. An industry group[52] provisionally recommended a threshold value of 1.6 for indoor applications, contending that TLM visibility does not equate to unacceptability, but deferring to the IES for further recommendations. Reports by Veitch and Martinsons[36,49] examined stroboscopic motion visibility among young people observing a rotating disk illuminated by commercially available general purpose lamps. They suggested an SVM limit value of 0.9 for normal observers based on one quarter of the population being able to detect stroboscopic motion more than 63% of the time; and an SVM limit value of 0.4 to reduce the detection rate to 10% for the most sensitive quarter of the population.

3.4.5 Phantom array effect

The phantom array effect involves a large eye saccade by the observer. Normally, the eyes will fixate on a point where the view is steady, and then jump to another point where the view is steady. Although the visual system seems to process the blurred scenes between these two points,[53] the awareness of them is diminished through saccadic suppression, a perceptual function that keeps the visual image steady relative to the surrounding scene and helps the viewer locate their gaze in space.[54] Recent work has implicated smeared, intrasaccadic vision in guiding eye movements following the saccade.[53] However, if there is a flashing light or a high-contrast object lighted with modulating light appearing in the space between the take-off and landing spots, the normally smooth smear is suppressed. The repeating, spatially-displaced images of the flashing light remain very visible because of high contrast with its background and because the resulting spatial frequency on the retina can approach 3-4 cpd, near the peak of the human contrast sensitivity function.[55] Or stated another way, the flashing source or flashed object creates the retinal pattern that is highly visible in spite of saccadic suppression, producing a discontinuous trail of dots or dashes, or repeated images of the object[12] (Figure 10). This effect may interfere with the visual system's ability to track its trajectory.[53]. TLM conditions under which the phantom array is observed are still being established, but visibility likely occurs between frequencies of 80 Hz and 11,000 Hz.[13,56] It is generally more visible when modulation depth is high and when there is a distinct edge to the luminance of the flashing (or flashed) object. In their study on the phantom array effect, Brown *et al.*[56] found that observers highly sensitive to the phantom array effect were more likely to experience headaches and migraines in their daily lives, so there may be a link between health and visibility of this effect.

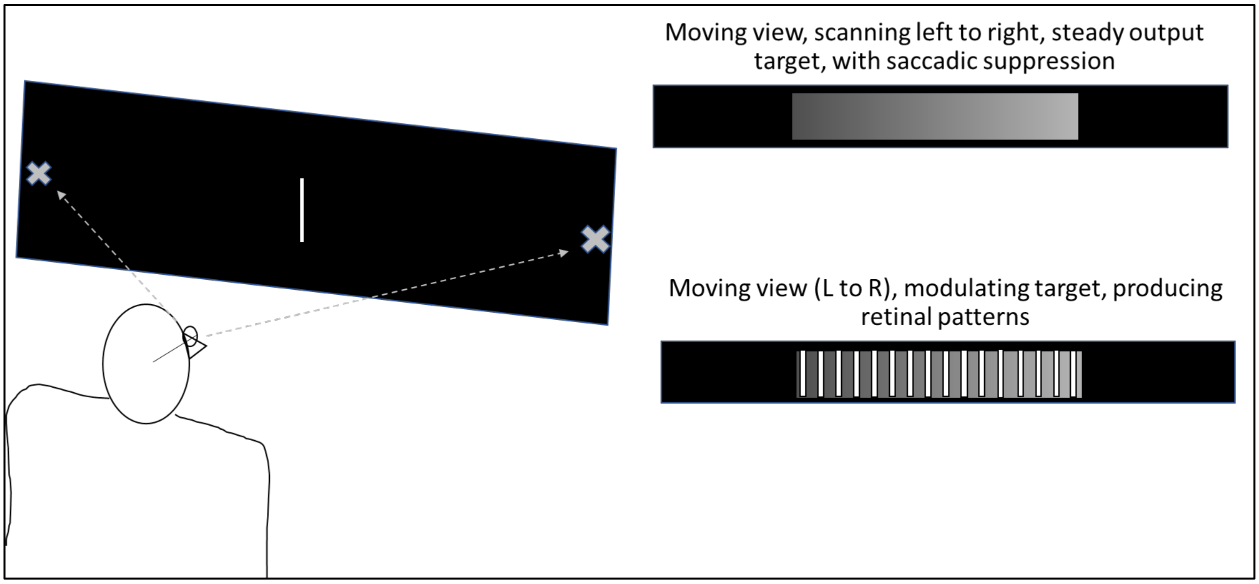

Figure 10. An illustration of the phantom array effect resulting from a saccade across a vertical target with either steady or modulating luminance. The repeated pattern from the modulating target is visible because of the target's high contrast and because the pattern on the retina is close to maximum contrast sensitivity.

The phantom array effect involves an interaction between the saccade of the eye which reaches velocities of up to 500° of arc per second[57] and the modulation of a light source. Hershberger and Jordan[58] studied phantom array visibility among subjects in a darkened room, scanning with a 40° horizontal saccade across a light source of 200 Hz frequency, 30% duty cycle, 100% modulation depth TLM. Almost all subjects saw the array. The first point of the array is located on the retina before the saccade takes place and can be a single point reinforced with multiple images of the modulating source over time. The series of dots or images appears to move in a direction opposite that of the saccade direction, appears on the side adjacent to the landing position of the saccade, and remains fixed in space and on the retina until the image fades.[58]

Roberts and Wilkins[12] described that when driving at night, PWM-modulated auto taillights can appear as multiple images, spaced across the retina. Their study was performed in a dark room with the test source modulation varying from 120 to 2500 Hz. Observers could discriminate the modulating light from steady light at frequencies averaging 1.98 kHz. They posited that the modulation interfered with steadiness of a scene during the saccade, making the trail of dots across the retina visible. Further work by Brown *et al.*[56] found that observers in a darkened room viewing a lighted slit against a black surround were able to identify the phantom array under modulations varying from 3 to 11 kHz. The average maximum frequency occurred at 5.8 kHz, but one individual was able to identify the effect up to 11 kHz.

Wang *et al.*[13] employed a non-luminous high-contrast slit task, lighted to office-level illuminances, with sinusoidal TLM of five modulation depths and frequencies from 100 to 1200 Hz. Their results showed the phantom array visibility peaking at 600 Hz, more visible at higher modulation depths, and detection did not vary with illuminance level. Task polarity and contrast affected visibility.

In 2020, this investigation was continued by the same research group[59] where subjects used 40° saccades between two fixation points on either side of a pair of LEDs in a dark room. They confirmed their original conclusion that the phantom array's threshold visibility has a U-shaped relationship with fundamental frequency, with the lowest threshold at 600 Hz, and sinusoidal waveforms having higher thresholds than square waveforms. Their data suggested that the higher frequency content (*i.e.* higher harmonics) in the waveform may contribute to the visibility of the phantom array in addition to the fundamental frequency. This was evidence that a Fourier summation may characterize the response just as it has been used for the stroboscopic effect. They further tested the spatial CSF as a predictor of the visibility of the phantom array. Using an equation as provided by Barten[60] they found that although the calculated visibility curve was the correct shape, it was not sufficient to explain their experimental results.

Park *et al.*[15] explored the phantom array visibility when the parameters of luminance, chromaticity and angular field of view are modified. The experiment presented vertically stacked LEDs to observers, either driven by a DC input or a square wave input but delivering the same luminance (25 up to 400 cd/m^2) and chromaticity. Subjects used a 45° scan width, and modulation frequencies ranged from 500 to 3500 Hz, in steps of 200 Hz. Results showed phantom array visibility at higher threshold frequencies for higher luminances (increasing linearly with logarithm luminance), for color (green, blue, red in descending order of visibility), and the narrower visual angle width. They noted considerable individual differences in response among the 26 subjects.

To summarize: the phantom array effect is visible under extreme conditions of a lighted object with discrete edges and dim surroundings up to an average of 1.98 kHz[12] or 5.8 kHz,[56] depending on parameters. It is most visible when the target is high luminance against a dark background, when the light source exhibits high modulation depths, and the fundamental frequency is approximately 600 Hz.[13] It is visible at higher frequencies when the luminous source is small, such as a point source or a narrow vertical slit.[13] On average, the phantom array from a white or red source produce similar visibility, while blue visibility is lower.[59] The threshold frequency of the visibility of the phantom array increases in proportion to the logarithm of the light source luminance; so the brighter the source, the higher the frequency at which it will be visible.[15] Yu *et al.*[59] found that the phantom array has a U-shaped visibility threshold, with the lowest threshold occurring close to 600 Hz when the modulation depth is 100% and the waveform shape is rectangular rather than sinusoidal. Their evidence reinforces that the summed visibility of Fourier frequencies in the waveform would be more predictive of visibility than that of the fundamental frequency alone. Park *et al.*[15] noted that in real situations, view, source, and environment are rarely static, so the phantom array effect that involves relative movement may be more prevalent and occurs at higher frequencies than recognized in earlier research exploring direct flicker and the stroboscopic effect.

3.4.6 Metrics of the phantom array effect

Although some researchers contend there is a U-shaped phantom array visibility threshold when plotted against frequency[15,59] with a minimum threshold between 600 and 1000 Hz, a metric that predicts the perceptibility of the phantom array effect has not yet been proposed.

3.4.7 Physiological, health, and cognitive responses to TLM

There are several effects that TLM might have, from mild to severe, beyond the basic visual perception or awareness of the TLM. Non-visual responses may include health issues such as seizures, headaches and migraines, malaise, fatigue, autistic behaviours, and task performance changes. However, it is not clear whether visible modulation is always associated with these, or whether the response can occur without visual perception of the TLM. Electroretinogram techniques have shown that photoreceptors can exhibit a response to TLM at frequencies up to 200 Hz, well above the human Critical Flicker Fusion (CFF) frequency value.[61] The same work showed that the response is not due to the fundamental frequency alone, but also to subsequent harmonics in the waveform.

Veitch[62] conducted a study in which subjects were asked about visibility of effects from TLM, as well as discomfort, defined as overall comfort; smarting, itchy, or aching eyes; sensitivity to light; teary eyes; dry eyes; sore back, wrist or arms; excessive fatigue; headache. The results followed expectations that lower modulation depths produced better comfort compared to 100% modulation. However, a surprising reduction in visual discomfort from 100% modulation compared to 30% modulation in 500 Hz TLM conditions was reported.

The most commonly reported health effects from modulating light are migraine and headaches. There are many anecdotal reports from migraineurs that TLM from fluorescent lights (at 120 Hz modulation in North America) and television screens can cause discomfort.[63] A survey of migraineurs and control subjects by Shepherd[64] on triggers for migraine and headache found light flicker to be the most cited trigger; it was chosen by 45% of the migraine group compared to only 6% of the control group. The same migraine group also identified other visual triggers, such as computer screens, glare, abrupt transitions in light conditions, or patterns of stripes.

Chorlton and Kane[65] measured the EEG response of migraineurs and a control group to flashes of light at frequencies between 6 and 24 Hz, which as previously discussed is in the Direct Flicker range. The migraineurs had a response deemed positive in a ratio of 19:3, while the control group's ratio was 1:39. A similar study was conducted by Gentile and Aguirre,[66] in which subjects were asked to rate their discomfort as they looked at a modulating stimulus between 1.625 and 30 Hz, while their neural responses (specifically, steady-state visually evoked potentials from the early visual cortex) were measured. There was a direct linear correlation between the discomfort ratings given and the neural responses, linking increased visual cortical activation with the experience of discomfort. Although this study examined both migraineurs and headache-free subjects, it found no significant difference between the two groups. Stovner *et al.*[67] studied global migraine epidemiology, reviewing 107 national and international studies on the topic. They estimated that 11% of people worldwide have active migraine disorders, with 46% of the population with an active headache disorder. This puts headaches high in the ranking causes of disability internationally.

Photosensitive epileptic seizures are a rare but serious response to direct flicker;[68]; they are most common at frequencies between 15 and 25 Hz.[69] Consequently, the Epilepsy Foundation recommends low modulation depth, no higher than 5%, for light sources and screens modulating from 3 to 65 Hz.[69] Unfortunately, it is now recognized that 5% modulation depth is very visible at 15 Hz, so more stringent recommendations may be necessary.

Several studies have found a reduction in task performance associated with undesirable TLM. Veitch and McColl[6] found reduced reading speeds and comprehension under magnetically-ballasted fluorescent lighting (120 Hz) compared to high-frequency electronically-ballasted lighting (between 20 and 60 kHz). Jaén *et al.*[70,71] identified reduced speed of visual search under 100 Hz, (32% modulation) magnetically-ballasted fluorescent lighting compared to 60 kHz (3% modulation at 100 Hz) electronic ballasts, even when subjects observed no discernable difference between the two conditions. Wilkins[5] identified enlarged saccades over text from fluorescent lighting operating at 100 Hz compared to high-frequency electronic ballasts. Küller and Laike[72] found that subjects with high CFF values performed a proof-reading task more quickly, but with more errors under light from magnetically-ballasted fluorescent lamps modulating at 100 Hz, compared with high-frequency electronic ballasted systems (no reported frequency or modulation values). They observed a marked difference in performance among subjects with lower CFF values (57% of the subjects), who exhibited no significant reduction in performance.

3.4.8 Metrics related to the physiological, health, and cognitive responses to TLM

At this time, investigations into and quantification of non-visual responses are on-going.

4. Standards, Recommendations, Specifications and Regulations

4.1 Standards regarding measurement conditions

Laboratory conditions have been established for specific measures as shown in Table 2.

Table 2. Documents for laboratory measurement standards of TLM and response metrics.

Document / Source	TLM waveform	Percent flicker	Flicker index	M_P	P_{st}^{LM}	SVM	CA T24 JA-10
CIE TN 012: 2021[21] Guidance on the Measurement of Temporal Light Modulation of Light Sources and Lighting Systems	✓	✓	✓		✓	✓	
IES LM-90-20 (2020)[20] Measuring luminous flux waveforms for use in temporal light artifact (TLA) calculations.	✓	✓	✓	✓	✓	✓	✓
NEMA 77-2017[52] Temporal Light Artifacts: Test methods and guidance for acceptance criteria.	✓	✓	✓		✓	✓	
IEC 61547-1 2020[30] Equipment for general lighting purposes – EMC immunity requirements – Part 1: Objective light flickermeter and voltage fluctuation immunity test method; IEC TR 63158:2018[79] Equipment for general lighting purposes – Objective test method for stroboscopic effects of lighting equipment	✓				✓	✓	
ASSIST Recommends[80] Vol. 11 Iss. 3, 2015 Recommended metric for assessing the direct perception of light source flicker				✓			
ENERGY STAR 2016[81] Method of measurement for light source flicker		✓	✓	✓			

Laboratory measurements and protocols for calculating metrics and measures from waveforms, while documented, do not always produce consistent values for different waveforms and metrics. Phase, offset, sampling rates, and other factors add complexity;[73] different measurement instruments can yield different values from the same waveform.[40]

4.2 Recommendations and specifications of limits

4.2.1 IEEE 1789-2015

IEEE 1789-2015[74] was the first published recommended practice aiming to reduce the health risk induced by TLM from solid state lighting systems. Based on data from a variety of studies, it quantified risk using a combination of percent flicker and fundamental frequency to establish limits. It is controversial because it is too strict in some areas (such as limits that would not include incandescent lamp modulation in the low-risk category), and not strict enough in others (especially at frequencies above 400 Hz where the phantom array visibility is likely highest[59]). The reference for human sensitivity at different frequencies is based on sinusoidal waveforms, so it does not take duty cycle into account, but it is now known that duty cycle affects the visibility of both the stroboscopic motion and the phantom array.[26] This recommended practice was published in 2015, before the combination of dimming and drivers in producing choppy TLM waveforms was well recognized.

IEEE 1789-2015 identifies three levels of risk based on percent modulation and fundamental frequency. These regions are plotted in Figure 11. The low risk level is based on minimizing visual discomfort or annoyance as well as ensuring low risk for headaches and photosensitive epileptic seizures. The *No observable effect level (NOEL)* is a 2.5 times reduction in risk compared to the low risk criteria. For seizure prevention, all frequencies below 90 Hz must exhibit modulation less than 5%.

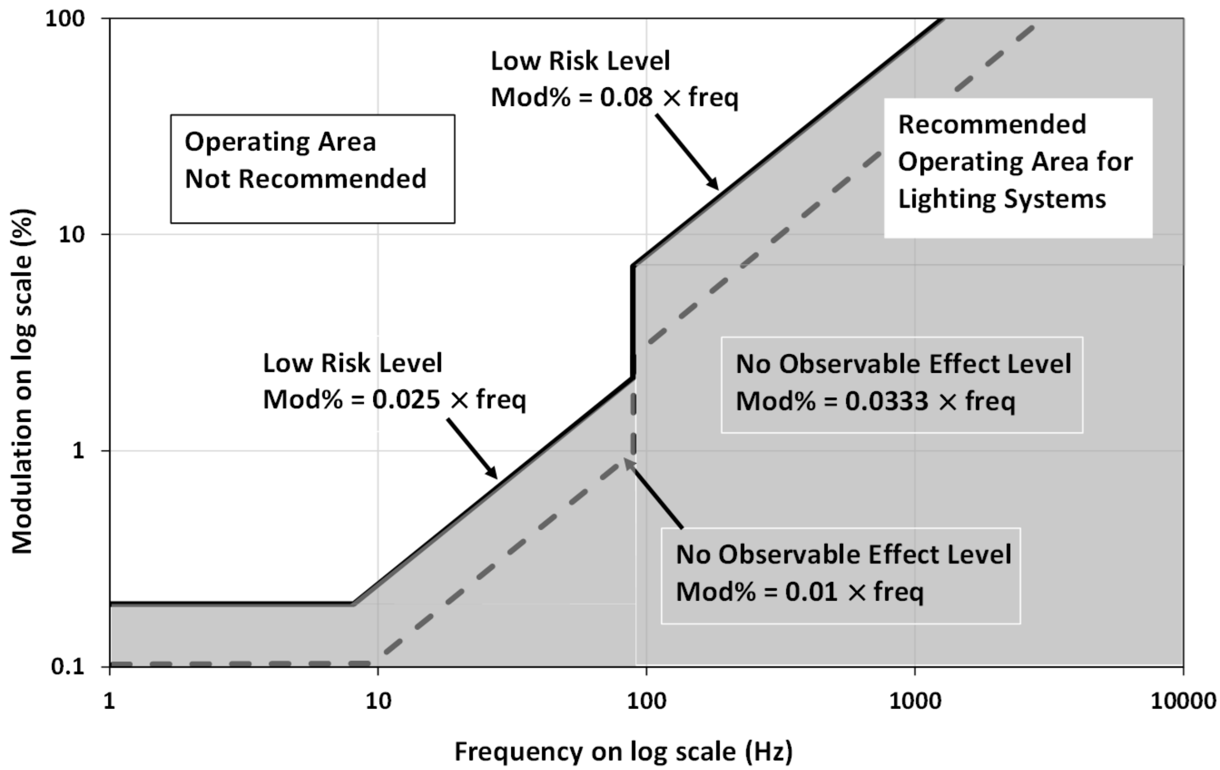

Figure 11. IEEE 1789-2015 recommended operating area to reduce visual discomfort, annoyance, and health effects of modulating light. Combinations of Percent Flicker (Modulation (%)) and fundamental frequency at the Low-Risk and No Observable Effects Levels fall in the shaded area. (Figure adapted from IEEE 1789-2015.)

4.2.2 NEMA 77-2017 Temporal Light Artifacts

With this document,[52] this lighting industry association established TLM testing standards, but also a recommended limit of P_{st}^{LM} ≤1.0 and SVM ≤1.6.

4.2.3 Well-Building Standard V2, Q3 2021

This evolving certification program[75] is aimed at health and well-being of building occupants. Its lighting category includes specifications on light levels, daylight access, visual comfort, etc. Its TLM requirements allow demonstrating lighting system compliance using California Title 24 JA-10[76] (See section 4.3.1), complying with the IEEE 1789-2015 recommended practice,[74] or demonstrating P_{st}^{LM} ≤1.0 and SVM value ≤0.6 [sic] per NEMA 77-2017.[52]

4.2.4 IEA 4E SSL Annex 2021

In an effort to promote international adoption of energy efficient solid-state sighting (SSL), the International Energy Agency's Annex on LED lighting product quality performance[77] recommended an SVM value ≤0.4 for all product types.

4.3 Regulations

4.3.1 California Title 24 JA10

The 2016 Title 24 Joint Appendix JA10, *Test Method for Measuring Flicker of Lighting Systems and Reporting Requirements*[76] includes a calculation for quantifying TLM. Using Fourier analysis, the TLM is filtered for all frequency components above a specified cut-off, and then the percent modulation below each cut-off frequency of 40, 90, 200, 400, and 1,000 Hz is calculated for three dimming levels of 100%, 20%, and the minimum dimmed level. Thus, for each cut-off frequency and dimmed level, a percent modulation is calculated. Unlike the SVM and M_P approaches, no sensitivity function is applied to the frequency domain. Acceptable TLM is defined as a percent modulation at each cut-off frequency range of the Fourier analysis that does not exceed the IEEE 1789-2015 recommended value of 0.08 times the lowest frequency in the range, on the assumption that those limits apply to all wave shapes, irrespective of duty cycle.

4.3.2 Regulation on ecodesign requirements for light sources (EU) 2019/2020

Effective in Sept 2021, this document[78] sets minimum standards for lighting products used in buildings in the EU. The TLM limits for interior lighting are PstLM ≤1.0 and SVM value ≤0.4, with an exception for industrial and other applications where color rendering is <80 CRI.

4.4 TLM waveforms and metrics

Table S1 (see Supplementary Material) shows a set of theoretical waveforms, their frequency spectra, and their calculated metrics. Not all metrics are intended for all frequencies, but the table is an illustration of the numbers generated by the TLM metrics and where the values may not be predictive. Threshold or recommended values for the metrics are as follows:

- IES Percent Flicker (aka Modulation %): <10%
- IES Flicker Index: <0.10 at 120 Hz [designed to evaluate only waveform frequencies of 120 Hz]
- P_{st}^{LM}: <1.0 [not designed to evaluate waveform frequencies above approx. 90 Hz]
- M_P and probability of direct flicker perception: <1.0 [not designed to evaluate waveform frequencies above approx. 90 Hz]

- IEEE 1789-2015: Low Risk (% Flicker <0.08 x Fundamental Freq); No Observable Effect (% Flicker <0.025 x Fundamental Frequency); The Seizure Prevention Region (<5% Flicker at all frequencies below 90 Hz)
- JA10: <30% flicker below 200 Hz; <IEEE standard percent flicker at set frequencies
- SVM: <1.0 threshold value; recommended values vary. [SVM not designed to evaluate waveform frequencies below 80 Hz.] Some organizations recommend maximum value of 0.4 for all lamp types and populations.
- PPF: <3.5%

Note, however, that none of the metrics may be predictive of phantom array visibility

5. Discussion

Undesirable TLM has been recognized as potentially affecting human health, performance, and comfort for over a century, but the proliferation of LEDs has renewed interest in this field.

Today it is recognized that direct flicker, stroboscopic motion, and the phantom array are different visual responses, with different sensitivity curves, different viewing conditions, and potentially different physiological/cognitive mechanisms. However, this has not always been the case and past research has not always effectively targeted a specific response. This can make interpreting and comparing the results of past studies more difficult. Nonetheless, some fundamental concepts are broadly applicable, and have served as the basis for proposed metrics for all three types of visual perceptions of TLM. At the same time, there is insufficient research into the broader range of physiological responses to TLM, and therefore no metrics have been proposed that specifically address consequences such as migraines or headaches; it remains unknown if reducing directly visible effects can have other physical benefits.

Two of the measures quantifying the response to TLM use a consistent approach derived from De Lange[28] and others. That is, they apply Fourier frequency analysis to the TLM waveform, normalize the amplitude of each resulting frequency with a sensitivity curve, and sum the responses with a set of empirically derived exponents and constants. The measures using this approach include M_p, and SVM.

With SVM, Perz *et al.*[26] tested the responses of almost 200 observers to sinusoidal waveforms of varying frequency and modulation depth, building a model following the De Lange approach of creating a sensitivity curve in the frequencies of the stroboscopic effect, from 80 Hz up to 1280 Hz, the highest frequency at which the stroboscopic effect was visible. For M_p, Bodington *et al.*[18] developed a different sensitivity curve based on their own human subject research in the direct flicker frequency ranges, but the curve and calculated metric values are quite similar to that of De Lange.

The direct flicker effect is well studied and characterized using metrics of IEC P_{st}^{LM} and M_p. While TLM that is directly visible can have severe consequences (*e.g.* seizures) these quantifications are somewhat less relevant to lighting practice because typical lighting products have a modulation frequency of 100 Hz or higher. However, P_{st}^{LM} remains the standard method for testing the immunity of lighting products to mains voltage fluctuations.

The stroboscopic effect is also well researched and characterized. Although there is always room for improvement in existing metrics, SVM is a logical approach provided it is not expected or used to quantify responses to TLM other than that of the stroboscopic effect. Any future work on characterizing the stroboscopic effect should target any gaps in the SVM measure. This may include, for example, experiments with more realistic relative movement among eyes, head, light source, and object(s), and expanding the minimum fixation conditions for which the stroboscopic effect is defined. Studying stroboscopic effect using a waving rod or arm instead of the rotating disc may show more sensitivity to TLM because it can be off-axis for potentially greater visibility, and the moving object tracks along a larger area of the retina than the rotating disc.

The phantom array effect is less studied, with no proposed metrics. Phantom array visibility is not monotonically related to frequency as stroboscopic motion appears to be; thus, a different measure is needed. The phantom array may be visible at frequencies up to 11 kHz under high-contrast conditions. This may have implications for LED driver and dimming system designers, since the undesirable TLM could not be eliminated through a tradeoff between duty cycle and frequency. The peak sensitivity seems to occur between 600 Hz and 1,000 Hz, although further investigation is warranted. Perhaps "safer" frequencies can be identified outside of that range.

6. Conclusions

Research has led to a better understanding of the direct flicker effect, the stroboscopic effect, and the phantom array effect as visual responses to TLM, particularly in applying the spatial contrast sensitivity function to temporal patterns. This review examined technological and perceptual developments related to TLM and responses to TLM, including the metrics developed to characterize the different responses. Critical areas for research include:

1. Humans exhibit wide variations in sensitivity to temporal light modulation, and it is important to learn how many are vulnerable to discomfort, health effects, or reduced productivity caused by undesirable TLM, and to what degree. Research into the neurological pathways that relate TLM (visible or not) to physiological responses such as autistic behaviors, headaches, malaise, migraines, distraction, or annoyance is scarce. Once more is known, lighting standards organizations should establish criteria for metrics to promote comfort and health, balancing those outcomes with cost and functionality implications for lighting products.
2. Research into responses to TLM should address the needs of more sensitive observers. SVM and other metrics are based on the "normal" (or average) observer. The average observer is unlikely to represent the response of the most sensitive people, and observers sensitive to unwanted responses to TLM seem to experience greater annoyance, headaches, migraines, and eyestrain. Furthermore, most studies have excluded individuals with a direct or family history of headaches and migraines from the subject pool, and as a result the "average" response may be somewhat skewed. How to screen potential subjects to identify sensitive viewers without risking health consequences is an issue for discussion.
3. Most studies of responses to TLM have been carefully controlled to fix subject gaze on a target, or otherwise control relative movement among head, eyes, light source, and/or lighted object. While this is important for isolating the specific type of response (*i.e.* the direct flicker or stroboscopic effects), it is unrealistic in application. More work is needed with more naturalistic relative movement by observers to simulate real environments with off-axis and moving views.
4. Studies of the phantom array effect are limited, even though this may be the most likely cause of visibility and health responses to TLM generated by LED systems in both interior and exterior luminous environments. Existing evidence suggests the phantom array is most readily perceived when the frequency is high (*e.g.* 400 - 1,000 Hz), the luminance of the source or object is high relative to its background, there are high spatial contrasts and edges, the modulation depth is close to 100%, and the duty cycle is low (usually ≤ 50%). Parametric investigations into frequency, modulation depth, duty cycle, luminance of target and background, visual angle of

target, and observer sensitivity will yield data that can be used to generate logical, practical metrics and associated guidance.

These developments can be achieved through new psychophysical research, metric development, testing new measures with earlier data sets, and consensus-building on application-based standards.

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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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