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A Review of Contemporary Issues with Temporal Light Modulation of Lighting Systems

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***Abstract*— Temporal light modulation (TLM) is defined as a temporal change in luminous or color quantities of a light source, resulting from fluctuations of the power supply. Research studies published during the past decade helped define new metrics describing well-known visual effects of TLM such as flicker and the stroboscopic effect. Other visual artifacts induced by TLM such as the phantom array effect are still under investigation to better understand their occurrence and visibility, especially when viewing modern types of LED modules and power supplies, used for instance in automotive lighting and in color-tunable decorative or entertainment lighting. With the advent of solid-state lighting, high levels of temporal light modulation and new types of waveforms exhibited by some LED lamps and luminaires have generated concerns among users and regulators, thereby motivating the establishment of new research, metrics, and standards. Limits have been set in regulations to protect people from undesirable effects. Below these limits, TLM can be used as a useful optical signature to facilitate remote sensing measurements of lighting systems and their obtrusive light components by lock-in detection techniques.**

Keywords—lighting, power systems, temporal light modulation, flicker, temporal light artifacts, stroboscopic effect, phantom array effect, visual performance, health, remote sensing.

I. INTRODUCTION

Temporal light modulation (TLM) is defined as a change in the luminous output or spectral distribution of light with respect to time of a light source. These changes arise because of the electrical design of the light source power supply, including ballasts, drivers and control gears, and because of fluctuations in the electrical distribution network [1].

The term "temporal light artefact" (TLA) is used for the human visual perception of temporal light modulation [2]. Temporal light artifacts can have a detrimental influence in the judgment of artificial lighting as they can be a cause of annoyance and distraction. In addition, the exposure to temporal light modulation may cause unwanted effects on visual performance and health [3].

The importance of temporal light modulation in the design of lighting installations motivated the IEEE Standards Association to include a specific clause in the Recommended Practice for the design of power systems supplying lighting systems in commercial and industrial facilities. A joint working group was created between the IEEE Industrial Applications Society and the Illuminating Engineering Society (IES) to review the existing knowledge guidelines, and recommendations about TLM and its effects. The survey of the working group was incorporated into the IEEE 3001.9/IES RP-48-2023 Recommended Practice published in May 2023 [4]. This paper is authored by members of the joint IES / IEEE working group. It presents useful information about TLM, updated after the publication of the IEEE 3001.9/IES RP-48-2023 Recommended Practice, that should be considered for the improved design of lighting systems and their power supply.

The initial version of this paper was presented at the 11th International Conference on Energy Efficiency in Domestic Appliances and Lighting & 17th International Symposium on the Science and Technology of Lighting (EEDAL/LS:17), 01-03 June 2022, Toulouse, France [5]. This article is an augmented and updated version of the conference paper.

II. ORIGINS OF TEMPORAL LIGHT MODULATION IN LIGHTING PRODUCTS

In general lighting products, temporal light modulation is the result of AC or transient currents flowing through the light source, creating fluctuations in the light output. In lighting devices connected to AC mains power sources, imperfect rectifying causes ripple currents at the output of the driver or the ballast, inducing temporal light modulation [4].

A. Common types of TLM

The common types of luminous waveform in general lighting are listed below.

1) Periodic modulation at twice the mains frequency

Fluorescent lamps and high intensity discharge lamps powered by magnetic ballasts exhibit temporal light modulation at twice the mains frequency (100 Hz, or 120 Hz). This is also the case of LED lamps and luminaires used with an AC/DC converter. The amount of this modulation depends on the electrical design of the ballast or driver.

2) Periodic modulation at high frequencies

Light sources powered by high frequency electronic ballasts or drivers usually operate in the 20 kHz to 100 kHz range, inducing temporal light modulation at these frequencies. These high frequency components are often superimposed to a residual 100 Hz, or 120 Hz, component.

3) Pulse-width modulation (PWM)

Pulse-width modulation (PWM) is associated with a square wave modulation profile with constant frequency, usually of a few hundred Hz, and 100% modulation depth. The duty cycle is variable between 0% and 100%, according to the desired average light level. PWM is used in many dimmable LED lighting systems.

4) Modulation introduced by phase-cut dimmers

Phase-cut dimmers are a common type of equipment used to dim lamps. Phase-cut dimmers operate by interrupting the mains voltage to the light source twice each line cycle. Proper operation of the dimmer determines the phase angle, which in turn determines the root mean square voltage applied to the light source and its average light output.

The primary source of temporal light modulation that occurs from a lamp connected to a phase-cut dimmer does not occur at harmonics of the mains voltage, because most LED lamps with integral drivers also include some degree of energy storage. Rather, the primary component of temporal light modulation is low frequency and broad band. If there are instabilities in the power supply of the dimmer, then the phase angle is unstable. Therefore, the RMS voltage applied to the lamp is not stable. Consequently, the light output modulates at low frequency, resulting in visible flicker.

The power supplied to the phase-cut dimmer typically passes through the light source. Therefore, a design interface requirement exists between phase-cut dimmers and dimmable LED lamps with integral drivers. Such an interface requirement has been described in two IEC technical reports [6] and [7]. Methods of measurement for compliance of the dimmer and light source were published by the NEMA [8] and [9] to ensure their proper mutual compatibility.

5) Transient modulation

Transient fluctuations of the light output may be caused by electrical disturbances in the power supply but also by electromagnetic perturbations. The voltage may be distorted and may fluctuate for several reasons, such as:

- Insufficient available instantaneous power for the load
- Sudden load changes associated with inrush current (e.g., turn on of air conditioner, refrigerator, coffee maker, hair dryer)
- Powerline communications superimposed on the mains waveform
- Environmental effects (e.g., lightning and strong winds)
- Distributed power generation (e.g., wind and solar) may create fluctuations because of changes in wind or sunlight.

Equipment connected to the mains may be adversely affected by the presence of voltage fluctuations if the equipment has insufficient immunity to those fluctuations. In the case of lighting equipment, voltage fluctuations can potentially increase TLM, depending on their severity. The IEC TR 61547-1 technical report [10] provides a description of an objective light flickermeter and a method for measuring the intrinsic flicker of lighting equipment as well as testing the immunity of lighting equipment against mains voltage fluctuations. IEC TR 61547-1 also describes testing to determine compatibility with external light regulation equipment (i.e., dimmers).

The NEMA 77 standard [9] advises manufacturers to consider the immunity of their products to variations in mains voltage during the design process and advises the manufacturer to choose representative distorted waveforms to evaluate product immunity.

6) Erratic modulation

An erratic modulation may be associated with certain non-compatible associations of dimmers and luminaires.

B. Frequency content of temporal light modulation

Unless the luminous waveform is purely sinusoidal and stationary, it is not possible to identify a single frequency characterizing temporal light modulation. In the general case, there are several frequencies present in the luminous waveform: fundamental frequency, dominant frequency, harmonic frequencies, sub-harmonic frequencies, inter-harmonic frequencies.

In the case of a periodic modulation, the dominant frequency corresponds to the Fourier component of highest magnitude in the power spectrum of the luminous waveform. The fundamental frequency is the lowest non-zero frequency among all the Fourier components. Harmonic frequencies are multiples of the fundamental frequency. In the presence of harmonic frequencies, the luminous waveform is not a pure sine wave and presents harmonic distortion.

Sub-harmonic and inter-harmonic frequencies may come from dysfunctional light sources or power circuits. These frequencies are unwanted components in the luminous waveform, often responsible for instabilities in the light output.

III. TEMPORAL LIGHT ARTIFACTS PERCEIVED BY THE HUMAN VISUAL SYSTEM

Three types of TLAs are commonly reported in general lighting applications: flicker, the stroboscopic effect, and the phantom array. A description of these effects can be found in [11] and a literature review has been recently published [12]. Other types of temporal light artifacts have been studied but are more rarely encountered in general lighting applications. For instance, chromatic flicker [13] and color break-up phenomena [14] may be perceived when the spectral distribution of the light changes with time.

A. Flicker

The term “flicker” was formerly used as a generic term for both temporal light modulation and temporal light artifacts. Flicker is now precisely defined as being a specific type of TLA: the perception of visual unsteadiness induced by temporal light modulation for a static observer in a static environment. Flicker may be perceived as periodic, aperiodic, random, or transient fluctuations of the light level, according to the characteristics of the luminous waveform.

B. *The stroboscopic effect*

The stroboscopic effect is defined by a 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. This effect may be visible when a moving or rotating object is illuminated by modulated light. It may also be visible when the observer moves under modulated light. In this case, the stroboscopic effect may alter the perceived motion of limbs (hands, arms, etc.). With the stroboscopic effect, moving objects are perceived to move discretely rather than continuously.

In the context of machines and tools, if the frequency of a periodic temporal light modulation coincides with the frequency of a rotating object, the rotating object may be perceived as static. More generally, the stroboscopic effect can change the perceived motion of rotating or reciprocating machines. In this context, it must be assessed and reduced to avoid potentially dangerous situations.

C. *The phantom array effect*

The phantom array effect, also known as ghosting, is defined as a 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 (i.e., an observer moving her eyes) in a static environment [11].

When making an eye saccade over a light source exhibiting TLM, the light source is perceived as a series of spatially extended ghost images, the so-called phantom array [15]. The phantom array is aligned with the saccade trajectory but appears to be entirely displaced on one side of the light source, towards the end point of the saccade. The tail end of the array is virtually coincident with the light source. The multiple ghost images appear sequentially in the reverse direction of the saccade [16]. The multiple images will blur together in different degrees, depending on details of the TLM (modulation depth, duty cycle, frequency, etc.).

IV. Temporal Light Artifacts Observed on Electronic Devices

Temporal light modulation can interfere with electronic image sensors used in cameras and electronic devices. Several types of undesirable artifacts may be produced on captured images and videos: dark bands (banding), missing part of an object, edge distortion, color artifacts, etc. The exact nature of these artifacts depends on technical parameters of the sensors themselves, such as the type of shutter (rolling shutter, global shutter), the integration time, the frame rate, etc.

High speed cameras are used in a variety of applications to capture fast phenomena: filming sport events, research, testing, high resolution imaging, etc. They usually operate at frame rates between 300 fps and 600 fps. When lighting systems are used with such cameras, the undesirable visual artifacts can be controlled by:

- Reducing the modulation depth of the luminous output at all frequencies, typically down to a few percent
- Using high-frequency electronic ballasts or drivers to avoid modulations at lower frequencies (especially the mains frequency and its first harmonics)
- Avoiding using pulse-width modulation to control the light level

The operation of bar-code scanners can also be potentially affected by the temporal light modulation of the general artificial lighting.

V. Neurophysiological and Health Effects of Temporal Light Modulation

Neurophysiological and health effects associated with TLM were initially revealed by research carried out using fluorescent tubes and cathodic display units from the 1960s up to the 1990s. Research on biological effects of TLM associated with LED lighting and displays confirmed the existence of similar effects. The IEEE 1789 standard published in 2015 included a review of the scientific literature available at the time as well as a risk analysis based on the severity of the effects and the probability of their occurrence under given exposure scenarios [17]. However, the ubiquity of solid-state lighting and solid-state display technologies profoundly changed the characteristics of human exposure to TLM. Longer exposures to an increasing number of modulated light sources are becoming the norm. The human response to these repeated stimuli is still unclear but some recently published results are now available [18]. The case of sensitive people is worth considering because a significant fraction of the general population is known to suffer from symptoms associated with the exposure to TLM.

A. *Neurophysiological effects*

The known neurophysiological effects of TLM are the modifications of ocular movements and alterations of visual performance. These effects were revealed during common visual tasks such as reading or performing tests. TLM at 100 Hz or 120 Hz can disrupt eye movements and reduce visual performance compared to higher modulation frequencies, or to constant light [19], [20].

Recent studies using electro-encephalography (EEG) and pupillometry revealed that TLM influences brain activity and arousal. Accomplishing visual tasks under light with TLM frequencies around 100 Hz leads to greater physiological arousal [21] and a general increase in brain activity, particularly in the right hemisphere [22], in comparison with TLM with higher modulation frequencies, or with constant light.

B. *Health effects*

The known health effects of TLM are eyestrain (asthenopia), headaches [23], migraine [24], and photosensitive epilepsy [25]. Eyestrain, headaches, and migraine happen during, or after, prolonged exposures to TLM, typically of one or several hours. The delay in the onset of these effects makes it difficult to identify TLM as a critical factor of lighting systems. This is not the case of photosensitive epileptic seizures which can be triggered after a few seconds of exposure to flickering lights.

C. *Sensitive populations*

An unknown fraction of the general population is particularly sensitive to temporal light modulation. This population is not well understood but includes migraineurs and people suffering from headaches induced by flickering lights, those suffering from pre-existing conditions such as photosensitive epilepsy, and some people who have suffered head injuries such as traumatic brain injuries [26].

Safe TLM levels were defined for photosensitive epilepsy [25], [17], but there is insufficient data to define safe levels for other categories of sensitive people.

Table I summarizes the different effects of temporal light modulation in the range of modulation frequencies where they have a probability to occur [4].

TABLE I. SUMMARY OF THE VISUAL AND NON-VISUAL EFFECTS OF TEMPORAL LIGHT MODULATION

<table>
<tr><th>Modulation frequency of luminous waveform (Hz)</th><th>1 Hz</th><th>100-120 Hz
2 × mains frequency</th><th>10 kHz</th></tr>
<tr><td rowspan="2">Temporal light artifacts (TLA)</td><td rowspan="2">Flicker
(peaks at about 8 Hz)</td><td>Stroboscopic effect with moderate speed hand motion (peaks at 80 Hz)</td><td></td></tr>
<tr><td colspan="2">Phantom array effect
(peaks at 600 Hz in dark conditions)</td></tr>
<tr><td rowspan="2">Neuro-physiological effects</td><td colspan="2">Influence on brain activity and eye movements during visual tasks</td><td rowspan="3">Unknown boundary</td></tr>
<tr><td colspan="2">Modification of visual performance</td></tr>
<tr><td>Psychological effects</td><td colspan="2">Effects on emotions, mood, and cognition
(unclear)</td></tr>
<tr><td rowspan="3">Health effects</td><td>Photosensitive seizures
(1 Hz to 65 Hz)</td><td colspan="2"></td></tr>
<tr><td>Eyestrain</td><td rowspan="2">Unknown boundary</td><td rowspan="2"></td></tr>
<tr><td>Migraines
Headaches</td></tr>
</table>

VI. METRICS DESCRIBING TEMPORAL LIGHT ARTIFACTS

Before 2015, three parameters were widely used by the lighting community to characterize temporal light modulation: the modulation frequency, the modulation percent, and the flicker index [27]. These parameters were not always able to catch the complexity of the different types of waveforms associated with TLM: transient phenomena, presence of multiple frequencies, variable duty-cycle, etc. Furthermore, they were loosely correlated to the temporal light artifacts perceived by human vision. For this reason, several standards and scientific organizations including the CIE, the IEC, the IEEE, the IES, and the NEMA have formed various joint groups to introduce and improve of a new set of metrics dedicated to better quantify temporal light artifacts.

A. *Short term flicker visibility index*

The short-term flicker visibility index P_{st}^{LM} was defined by the IEC in [10]. It is a measure of the visibility of flicker evaluated over a short duration of at least 3 min, typically 10 min. Its calculation is performed in the time domain from the luminous waveform using an algorithm, called the IEC light flickermeter. The calculation uses a standard human visual response function to temporal contrasts. This function has a maximum sensitivity at about 8 Hz and the critical fusion frequency (maximum frequency above which a modulated light source appears steady when the observer is fixed) is about 60 Hz. The human response function used in the calculation of P_{st}^{LM} was originally derived using a small size luminous stimulus with sharp edges, seen in central vision in well-lit conditions. However, P_{st}^{LM} can be assessed, and is now used, outside its original range of lighting conditions, included in dim environments (mesopic conditions).

The short-term visibility index P_{st}^{LM} has been extensively used to test the immunity of lighting systems to voltage fluctuations. It is now the standard metric for testing flicker at the product level in normal (stable) power supply conditions. This metric has the advantage of being applicable to all types of luminous waveforms: transient, periodic, highly distorted, variable duty-cycle, etc.

The mathematical procedure to determine P_{st}^{LM} is described in [9] and [10]. By definition, when P_{st}^{LM} equals 1, an average observer has a 50% chance to perceive flicker. The P_{st}^{LM} value of 1 is now consensually accepted as a limit value below which flicker is acceptable. It is specified in most standards and regulations as the upper limit for flicker, throughout the world.

B. Stroboscopic visibility measure

The stroboscopic visibility measure (SVM) was defined by the CIE in [1] and by IEC in [28]. It is a measure of the visibility of the stroboscopic effect perceived with movements of the hand or the arm of moderate speed (less than 4 m/s) under modulated light. It is evaluated over a short duration of at least 1s. Its calculation is performed in the frequency domain using the Fourier transform of the luminous waveform, weighed by a sensitivity curve having a maximum at about 80 Hz. The calculation of SVM is precisely detailed in [28] and [9]. The upper frequency limit is 2000 Hz. By definition, an average observer has a 50% chance to perceive the stroboscopic effect when SVM equals 1.

The SVM metric is used to quantify the visibility of the stroboscopic in applications where speeds of the order of human motion is dominant and the illuminance level is greater than 100 lx. It is not applicable in dark environments, nor with outdoor lighting.

It is important to notice that SVM is not adapted to assess the stroboscopic effects observed on high-speed rotating or reciprocating machinery under modulated light, where motion may be considerably faster than 4 m/s.

Unlike the flicker metric P_{st}^{LM}, there is currently no consensus on an acceptable upper limit for SVM. The European eco-design regulation EU 2019/2020 defined the limit at 0.4, following an interim two-year period during which the accepted limit had first been set at 0.9. The NEMA specifies a maximum SVM of 1.6 [9], which is considerably higher than the EU limit.

C. Metric for the phantom array effect

There is currently no metric to quantify the visibility threshold or the sensitivity function to the phantom array effect. The latest CIE technical report on TLM, published in 2022 [11], informs that the phantom array effect is more visible with small light sources in high contrast with their background (dark environments) at modulation frequencies from about 100 Hz to 10 kHz. This report contains a tentative visibility model which has not been experimentally validated yet.

An experimental study published in 2023 [15] showed that the visibility of the phantom array effect peaked between 500 Hz and 1000 Hz, confirming observations made in 2018 [29]. A recent experimental study, also published in 2023 [30], found that the phantom array was the most visible at 600 Hz, with a visibility threshold, expressed in terms of modulation depth for a pure sine wave, of 7% for a white-light stimulus observed in dark conditions. For a red-light stimulus under dark conditions, the visibility threshold was about 3% at 600 Hz. The visibility of the phantom array was found to be significant at modulation frequencies as low as 80 Hz. At such frequencies, the phantom array was visible at a threshold of 10% for red light, but only at a threshold of 35% for white lights.

Noticeable differences in the perception of the phantom array effect according to the color of the modulated light source were also shown in [31] when assessing the high frequency limit of the phantom array visibility range (threshold frequency).

In real-life application, the phantom array is best seen in indoor and outdoor luminaires (and displays) using PWM dimming at low illuminance levels. It is also noticeable in automotive headlights and rear lights. The effect is more visible under rectangular versus sinusoidal TLM and when duty cycles are low (typically 10% or 30%, versus 50%) [15].

D. Metrics applicable to temporal light artifacts produced by image sensors and visible on electronic displays

The metrics SVM and P_{st}^{LM} were designed to predict the visibility of flicker and the stroboscopic effect on humans. These metrics are not applicable to artifacts created by image sensors on electronic displays. There is currently no standard metric associated with TLAs observed on electronic devices. The imaging/display industry uses luminous waveform parameters such as the modulation percent and the dominant modulation frequency.

VII. Measurement methods

A. Laboratory measurements

The luminous waveform and the TLA metrics can be measured at the product level in a photometry laboratory. The documents describing the test methods and test conditions are listed in a CIE technical note [2]. The IES and the ANSI jointly published in 2020 the LM-90-20 standard to describe the procedures to perform measurements of the luminous waveform for use in temporal light artifact calculations under standard conditions, covering modulation frequencies 1 Hz and 3 kHz, and providing data reporting formats based on the XML language [32].

B. On-site measurements

Portable instruments are now available to perform on site TLM waveform measurements and return TLM and TLA metrics. However, there is no standard covering the field measurement of these parameters.

In-situ testing is much more prone to measurement uncertainties due to daylight, stray light from other light sources and displays, motions of people or object during the measurement. Temporal light modulation parameters should be measured without daylight, without any unwanted light from another lighting/display installation nearby and without any moving objects or people in the field of view of the measurement device.

The temporal light modulation in a real-world application, consisting of multiple light sources is generally lower than the TLM performance of a single light source due to the averaging out of the light modulation from the different light sources. The combination of luminous waveforms of individual sources is not additive but could, in principle, lead to beat frequencies if the frequencies slightly differ between luminaires [33].

C. Remote sensing measurements of lighting systems facilitated by TLM

When light sources exhibit temporal light modulation, it has been shown [34] that lock-in detection techniques can be used to improve remote sensing measurements of lighting systems.

Traditional illuminance and luminance meters can be connected to a lock-in amplifier to detect TLM while rejecting strong background lights, such as daylight and other light sources. Using a lock-in amplifier, the illuminance given by a

LED lamp exhibiting TLM was reliably measured by a sensor placed in the direct sun, under an illuminance level about 500 000 times higher than the lamp illuminance [35].

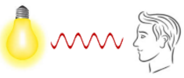
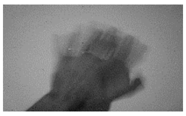
A new type of parallel multi-wavelength optical lock-in spectrometer [36] was designed to measure the spectral distributions of the modulated light emitted by lamps and luminaires. The outputs of the optical lock-in spectrometer are the amplitude and phase spectral distributions which are free of background lights.

The proper operation of lock-in amplifiers and lock-in spectrometers requires a reference signal synchronized with the TLM of light source of interest. This can be achieved by remotely sensing the light source using an astronomical telescope fitted with a photodetector and a synchronization circuit [35].

VIII. Summary of Standards and Guidelines

Table II summarizes the different standards and guidelines covering temporal light modulation and its effects.

TABLE II. Standards and Guidelines on Temporal Light Modulation and Its Effects

	Illustration	**Definition**	**Metric**	**Measurement method**	**Limit values**
TLM waveform		CIE S 017:2020 NEMA 77-2017 IES Lighting Handbook	Frequency (f) Flicker percent (PF) Modulation depth (MD or D^M) Flicker index (FI)	CIE TN 012:2021 ANSI/IES LM-90-20	IEEE 1789
Flicker		CIE TN 006:2016 CIE 249:2022 NEMA 77-2017	Short-term flicker index P_{st}^{LM} Perceptual modulation M_P	P_{st}^{LM} : CIE TN 012:2021 IEC TR 61547-1 NEMA 77-2017 M_P : ASSIST 2015	EU Ecodesign 2019/2020 NEMA 77-2017
Stroboscopic effect with hand and body motions		CIE TN 006:2016 CIE 249:2022 NEMA 77-2017	Stroboscopic visibility measure (SVM)	CIE TN 012:2021 IEC TR 63158 NEMA 77-2017	
Stroboscopic effects with machines and tools		CIE TN 006:2016	Nonexistent		
Phantom array effect		CIE TN 006:2016 CIE 249:2022	Nonexistent		
Photosensitive seizures		IEEE 1789 ITU-R BT.1702	Critical range of frequency, modulation depth, color and angular subtense values	Web, cinema, and television contents: ITU-R BT.1702 Lighting products: IEEE 1789	IEEE 1789 ITU-R BT.1702
Eyestrain Migraines Headaches Other neuro-physiological effects		IEEE 1789	Normalized modulation (NM)	Nonexistent	IEEE 1789

IX. Conclusions

Temporal light modulation has become an important aspect of the quality of lighting installations. Impacts on visual comfort and visual performances are now better understood and can be predicted in many standard situations. Flicker and stroboscopic effects can be assessed using the P_{st}^{LM} and SVM metrics, even if their use is limited to certain luminous environments and specific visual adaptation conditions. The case of the phantom array effect is currently under investigation by several teams of researchers whose preliminary results seem to converge towards a unified visibility curve, with a dependence on the spectral power distribution of the modulated light source. Overall, the three most common temporal light artifacts may appear in a very wide range of modulation frequencies, from about 1 Hz to about 60 Hz for flicker (maximum visibility at about 8 Hz), 60 Hz to about 2 kHz for the stroboscopic effect associated with hand motion (maximum visibility at 80 Hz), and from about 100 Hz to about 10 kHz for the phantom array effect (maximum visibility at 600 Hz). The electrical design of power supplies, drivers and dimmers should minimize the occurrence of undesired effects of temporal light modulation in this wide frequency range.

Beside visual discomfort, there are health effects associated with the exposure to temporal light modulation. Headaches, migraines, and eyestrain have been commonly reported, studied, and confirmed in the scientific literature. However, these negative symptoms seem to occur more frequently and more intensely for a fraction of the general population which is yet to be rigorously identified [37]. For these well-known effects, more research should be done to provide dose-response relationships to be able to improve health and safety requirements for sensitive people.

Temporal light modulation is also known as a powerful trigger of epileptic seizures in subjects suffering from photosensitive epilepsy. Other conditions, such as traumatic brain injuries, require specific protective measures against exposure to modulated light sources.

International standards and regional regulations now include requirements providing a certain degree of protection against undesired visual effects of temporal light modulation that may occur at high levels.

This topic has an evolving knowledge base with more and more research being published annually and should be revisited every couple of years to stay abreast of the state of the art. New research on the phantom array effect may translate into a metric to help compare lighting products.

The CIE technical committee TC-89 is currently working on new measurement guidelines dealing with signal processing and computational aspects to ensure the reproducibility and reliability of standard metrics and their uncertainties. A working group of the IES Vision Science Committee is also elaborating a technical memorandum devoted to temporal light modulation to specify the best practices for lighting design.

Compliant low levels of temporal light modulation can have a useful purpose as an optical signature associated with a particular light source or with a lighting installation. Lock-in detection techniques can take advantage of this optical footprint to improve photometric and spectral measurements by rejecting noise and background light, including daylight. This feature can significantly improve remote sensing measurements of lighting systems, as well as their obtrusive light components found at long distances at very low levels.

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REFERENCES

[1] *Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models*, CIE TN 006, Commission Internationale de l'Eclairage (CIE), Vienna, 2016.

[2] *Guidance on the Measurement of Temporal Light Modulation of Light Sources and Lighting Systems*, CIE TN 012, Commission Internationale de l'Eclairage (CIE), Vienna, 2021.

[3] C. Martinsons *et al.*, "Correspondence: An appraisal of the effects on human health and the environment of using light-emitting diodes," *Lighting Research & Technology*, vol. 51, no. 8, pp. 1275–1276, Dec. 2019.

[4] *Recommended Practice for the Design of Power Systems Supplying Lighting Systems in Commercial and Industrial Facilities*, IEEE 3001.9/IES RP-48:2023, IEEE Standards Association, New York NY, 2023.

[5] C. Martinsons, J. Gaines, J. Vollers, R. Nachtrieb, H. Wolfman, and G. Zissis, "Contemporary issues with temporal light modulation of lighting systems," in *2021 Joint Conference - 11th International Conference on Energy Efficiency in Domestic Appliances and Lighting & 17th International Symposium on the Science and Technology of Lighting (EEDAL/LS:17)*, Jun. 2022, pp. 1–7.

[6] *Electrical interface specifications for self ballasted lamps and control gear in phase-cut dimmed lighting systems*, IEC TR 63037 ed.2.0, International Electrotechnical Commission, Geneva, 2019.

[7] *Electrical interface specification for phase-cut dimmer in phase-cut dimmed lighting systems*, IEC TR 63036, International Electrotechnical Commission, Geneva, 2016.

[8] *Phase-cut dimming for solid-state lighting: basic compatibility*, NEMA SSL-7A-2015, National Electrical Manufacturers Association Standards Publication, Arlington VA, 2015.

[9] *Temporal Light Artifacts: Test Methods and Guidance for Acceptance Criteria*, NEMA 77-2017, National Electrical Manufacturers Association Standards Publication, Arlington VA, 2017.

[10] *Flickermeter Part 0 : Evaluation of flicker Severity*, IEC 868-0, International Electrotechnical Commission, Geneva, 1991.

[11] *Visual Aspects of Time-Modulated Lighting Systems*, CIE 249:2022, Commission Internationale de l'Eclairage (CIE), Vienna, 2022.

[12] N. Miller, F. Leon, J. Tan, and L. Irvin, "Flicker: A review of temporal light modulation stimulus, responses, and measures," *Lighting Research & Technology*, vol.55 , no.1, 2023, doi: 10.1177/14771535211069482.

[13] W. H. Swanson, T. Ueno, V. C. Smith, and J. Pokorny, "Temporal modulation sensitivity and pulse-detection thresholds for chromatic and luminance perturbations," *J. Opt. Soc. Am. A, JOSAA*, vol. 4, no. 10, pp. 1992–2005, Oct. 1987, doi: 10.1364/JOSAA.4.001992.

[14] P. V. Johnson, J. Kim, and M. S. Banks, "The visibility of color breakup and a means to reduce it," *J Vis*, vol. 14, no. 14, p. 10, Dec. 2014, doi: 10.1167/14.14.10.

[15] N. Miller, E. Rodriguez-Feo Bermudez, L. Irvin, and J. Tan, "Phantom array and stroboscopic effect visibility under combinations of TLM parameters," *Lighting Research & Technology*, Jun. 2023, early access, doi: 10.1177/14771535231169904.

[16] W. A. Hershberger and J. S. Jordan, "The Phantom Array: A Perisaccadic Illusion of Visual Direction," *Psychol Rec*, vol. 48, no. 1, pp. 21–32, Jan. 1998, doi: 10.1007/BF03395256.

[17] *Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers*, IEEE 1789-2015, IEEE Standards Association, New York NY, 2015.

[18] D. Sekulovski, S. Poort, M. Perz, and L. Waumans, "Effects of long-term exposure to stroboscopic effect from moderate-level modulated light," *Lighting Research & Technology*, vol. 52, no. 5, 2020.

[19] J. Veitch, "Cognitive and eye movement effects on viewers of temporal light modulation from solid-state lighting," in *Proceedings of the 29th Quadrennial Session of the CIE*, Washington DC, USA: International Commission on Illumination, CIE, Jun. 2019, pp. 22–31. doi: 10.25039/x46.2019.OP04.

[20] J. A. Veitch and S. L. McColl, "Modulation of fluorescent light: Flicker rate and light source effects on visual performance and visual comfort," *International Journal of Lighting Research and Technology*, vol. 27, no. 4, pp. 243–256, Dec. 1995.

[21] X. Zhao, D. Hou, Y. Lin, and W. Xu, "The effect of stroboscopic effect on human health indicators," *Lighting Research & Technology*, vol. 52, no. 3, Sep. 2019.

[22] J. A. Veitch *et al.*, "Effects of Temporal Light Modulation on Cognitive Performance, Eye Movements, and Brain Function," *LEUKOS*, vol. 20, no. 1, pp. 67–106, 2024.

[23] A. J. Wilkins, I. Nimmo-Smith, A. I. Slater, and L. Bedocs, "Fluorescent lighting, headaches and eyestrain," *Lighting Research & Technology*, vol. 21, no. 1, pp. 11–18, Mar. 1989.

[24] A. Albilali and E. Dilli, "Photophobia: When Light Hurts, a Review," *Curr Neurol Neurosci Rep*, vol. 18, no. 9, p. 62, Sep. 2018.

[25] G. Harding, A. J. Wilkins, G. Erba, G. L. Barkley, R. S. Fisher, and Epilepsy Foundation of America Working Group, "Photic- and pattern-induced seizures: expert consensus of the Epilepsy Foundation of America Working Group," *Epilepsia*, vol. 46, no. 9, pp. 1423–1425, Sep. 2005.

[26] T. T.-L. Chang, K. J. Ciuffreda, and N. Kapoor, "Critical flicker frequency and related symptoms in mild traumatic brain injury," *Brain Inj*, vol. 21, no. 10, pp. 1055–1062, Sep. 2007.

[27] D. L. DiLaura, K. W. Houser, R. G. Mistrick, and G. R. Steffy, *The Lighting Handbook (10th edition): Reference and Application*. New York, NY: Illuminating Engineering Society, 2011.

[28] *Equipment for general lighting purposes - Objective test method for stroboscopic effects of lighting equipment*, IEC TR 63158, International Electrotechnical Commission, Geneva, 2018.

[29] X. Yu, L. Wang, Y. Tu, M. Perz, and D. Sekulovski, "Influence of frequency, waveform and colour on the visibility of the phantom array effect," in *proceedings of CIE 2018 topical conference on smart lighting*, Taipei, Chinese Taipei: CIE, Apr. 2018, p. 146. doi: 10.25039/x45.2018.OP23.

[30] X. Kong, R. Vogels, C. Martinsons, M. Tengelin, and I. Heynderickx, "Dependence of temporal frequency and chromaticity on the visibility of the phantom array effect," in *Proceedings of the 30th Quadrennial Session of the CIE*, Ljubljana, Slovenia: CIE, Sep. 2023. doi: 10.25039/x50.2023.OP060.

[31] H. Kang, J. Kim, S. Park, C.-S. Lee, and H. Pak, "Visibility of the phantom array effect at different LED colour temperatures under high-frequency temporal light modulation," *Lighting Research & Technology*, vol. 55, no.1, 2023.

[32] *Approved method: measuring luminous flux waveforms for use in temporal light artifact (TLA) calculations*, ANSI/IES LM-90-20, American National Standard and Illuminating Engineering Society, New York NY, 2020.

[33] J. Lindén, C. Dam-Hansen, and A. Thorseth, "Beat flicker - a temporal light artefact due to multiple sources of time modulated light," in *Proceedings of the 29th quadrennial session of the CIE*, Washington DC, USA: International Commission on Illumination, CIE, Jun. 2019, pp. 1179–1186. doi: 10.25039/x46.2019.PO079.

[34] C. Martinsons, N. Picard, and S. Carré, "A Fiber-Optic Array Spectrometer With Parallel Multichannel Optical Lock-in Detection and its Application to in Situ Lighting Measurements," *Journal of Lightwave Technology*, vol. 41, no. 13, pp. 4489–4495, Jul. 2023, doi: 10.1109/JLT.2023.3244652.

[35] C. Martinsons, "Untangling Light In 'Noisy' Luminous Environments," in *Proceedings of the 30th Quadrennial Session of the CIE*, Ljubljana, Slovenia: CIE, Sep. 2023. doi: DOI 10.25039/x50.2023.OP012.

[36] C. Martinsons, "Implementing lock-in detection in photometry and spectroradiometry using temporal light modulation," in *Proceedings of the CIE Symposium on Advances on the Measurement of Temporal Light Modulation*, International Commission on Illumination (CIE), Oct. 2022. doi: 10.25039/x49.2022.P05.

[37] J. A. Veitch, C. Martinsons, S. Coyne, and C. Dam-Hansen, "Correspondence: On the state of knowledge concerning the effects of temporal light modulation," *Lighting Research & Technology*, vol. 53, no. 1, pp. 89–92, Jan. 2021.