TECHNICAL NOTE

Final Report

CIE Stakeholder Workshop for Temporal Light Modulation Standards for Lighting Systems

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This Technical Note has been prepared by CIE Reportership 3-32 of Division 3 "Interior Environment and Lighting Design". The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

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The Organizing Committee for the CIE Stakeholder Workshop on Temporal Light Modulation Standards for Lighting Systems was composed of the following members, and was responsible for the writing of this Technical Note.

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Summary

Contemporary lighting systems vary widely in the degree to which their light output shows temporal variations (temporal light modulation, TLM). TLM is known to affect human visual perception, neurobiology, and performance, sometimes in adverse ways. Many standards development organizations, regulators, and certification bodies have been active in seeking to address these issues. Some researchers are actively studying the effects of TLM. However, current activities are uncoordinated and risk being inefficient. The CIE, with the support of Natural Resources Canada – Office of Energy Efficiency, the National Electrical Manufacturers' Association, Philips Lighting, BC Hydro, and the National Research Council of Canada, convened a stakeholder workshop in Ottawa, Canada. February 8–9, 2017, to provide an impetus towards improved collaboration. The objective of this meeting was to develop a roadmap of research, recommendations, and standards activities related to temporal light modulation from lighting systems that are needed in order to speed up the process of developing international standards in an efficient way while preventing overlap and duplicate effort. The scope of the meeting was limited to developing the roadmap, establishing collaborations, and dividing the work amongst participants. The meeting was not intended to establish the content details for future standards documents. This report summarizes the current state of knowledge and standardisation concerning TLM, identifies gaps, and sets out the roadmap developed by the workshop participants. The roadmap leads, through collaborative effort, to evidence-based international standards intended to limit undesirable TLM from lighting products and systems. Lighting systems that meet these standards will thereby support the needs of lighting end-users, which will facilitate the market acceptance of new technologies and the achievement of energy-efficient targets.

1 Introduction

1.1 Background

The technological change in light sources and lighting systems since 2000 is unprecedented, with the luminous efficacy of individual solid-state lighting (SSL) packages moving rapidly towards what is thought to be a practical maximum on the order of 300 lumens per electrical watt (lm/W). In this period of rapid product development, it is not surprising that there is diversity among products in the driver designs for the electronics of these new light sources, resulting in wide variations in the temporal patterns of their light output (Poplawski et al. 2011). These temporal variations are known colloquially as flicker, and more precisely as temporal light modulation (TLM). In addition to the driver designs of the light source itself, dimming controls can add TLM even to light sources that do not exhibit TLM when operated at 100 % output. Many light-emitting diode (LED) systems use pulse-width modulation (PWM) dimming (100 % modulation at one frequency with varying duty cycles).

Temporal light modulation, whether from the design of the driver or through dimming control, can have adverse effects on visual function and health (Wilkins et al. 2010). Therefore, it is advisable for standards to be developed that will limit the possibility that new light sources and controls will produce light output with undesirable TLM characteristics. There is a liability risk for industry in possibly introducing products to market that may cause harm to consumers, and risks to public health for those who might experience these consequences.

The first industry recommendation on limiting light source flicker for the purpose of reducing the risk to viewers was IEEE 1789-2015, which was released in June 2015 (IEEE Power Electronics Society 2015). It has proved to be controversial, as several industry associations have issued press releases in response to it (e.g. National Electrical Manufacturers Association (NEMA) Lighting Systems Division 2015). Partly as a result of the publication of IEEE 1789-2015, and partly because of the general interest in TLM, several organizations, including CIE, have activities under way to address various aspects of the issue, including metrology, visual effects, and health effects. Some of these organizations write standards or recommendations, either at the national or international level; others generate information and research results.

CIE has recently published Technical Note TN 006:2016 (CIE 2016a) as an interim output of its Technical Committee (TC) 1-83 "Visual aspects of time-modulated lighting systems". This

document establishes definitions and proposes a measurement model for quantifying TLM for the purposes of predicting temporal light artefacts. TC 1-83 will proceed to complete its terms of reference to propose a predictive model based on data collected using this measurement model. In parallel, CIE Division 2 has a Reportership, DR 2-52, titled "Flicker measurement and flicker index study on solid state lighting".

All of this activity is healthy, but there is a possibility that different bodies may produce competing recommendations. The limited number of international experts in this field may be taxed to serve on the various committees and boards attempting to address light source flicker. A co-ordinated, harmonized approach would reduce duplication and speed the development of a reduced set of documents covering metrics, measurement, and criteria for protecting public health. CIE convened a stakeholder workshop, held in Ottawa, Canada, February 8–9, 2017, to open discussions towards such an approach. This document is the report of that workshop.

1.2 Workshop scope

The objective of this meeting was to develop a roadmap of research, recommendations, and standards activities related to temporal light modulation from lighting systems that are needed in order to speed up the process of developing international standards in an efficient way while preventing overlap and duplicate effort. The scope of the meeting was limited to developing the roadmap, establishing collaborations, and dividing the work amongst participants. The meeting was not intended to establish the content details for future standards documents.

The workshop scope was expressed as follows:

Temporal light modulation from lighting systems can affect people and equipment. Effects on equipment (e.g. interference with optical systems such as barcode readers and cameras) were out of scope. Effects on people were in scope for this workshop. Possible effects on people include the following:

- Visual perception effects (temporal light artefacts, TLA): flicker, stroboscopic effect, and phantom array

- Performance effects: eye movements changes, changes in visual performance, changes in cognitive task performance

- Neurobiological effects: headache, eyestrain, migraine, epilepsy, etc.

The workshop aimed to align efforts in standardisation and research within its scope, to identify overlap and knowledge gaps, to identify possible mismatches between research and standardisation projects, and to develop a roadmap for collaboration and co-operation leading to a useful set of appropriate standards in this domain. At the conclusion of the workshop, the goal was to achieve agreement on both the work that is needed and on who will undertake the various activities needed to fulfil the roadmap. Annex A shows the workshop agenda.

1.3 Workshop participants

Front row: Carl Bloomfield; John O'Hagan; Jennifer Veitch; Yoshi Ohno; Howard Wolfman; Naomi Miller; Terry McGowan. Second row: Robert Nachtrieb; Andrew Watson. Third row: Youngshin Kwak; Kathryn Nield; Joanne Zwinkels; Brad Lehman. Fourth row: Sandra Mancini; Li Qian (Cherry); Arnold Wilkins. Fifth row: Alex Baker; He Yang (Crane); Annette Steinbusch. Back row: Chan Su Lee; Jim Gaines; Aaron Miller; Dan Rogers; Malgorzata Perz; Norbert Wittig; Reinhard Lecheler; Christophe Martinsons

Figure 1 – Workshop participants

The organizing committee developed a list of nearly 50 invitees, comprising representatives of standards development organizations (SDOs), industry associations, researchers who are or were recently active in studying TLM, and regulators. The SDOs included were at both the regional and international levels, as were the industry associations. Every effort was made to include participation from all regions of the globe; despite this, there were no invitations issued to organizations representing South America or Africa. Some organizations chose to be represented by people who were also attending on behalf of another organization, and a few individuals were unable to attend because of illness. There were twenty-seven participants, all of whom were present for the entire workshop. The workshop was aided by a professional facilitator, Mr. Alain Rabeau of the Intersol Group, a consultancy based in Ottawa, Canada. Ms Sandra Mancini of the National Research Council of Canada assisted with recording and arrangements.

Participants were responsible for funding their travel and accommodation costs. There was no registration fee for the workshop; the sponsors' contributions covered the meeting and associated costs.

Table 1 lists the workshop participants and their affiliations. Where more than one affiliation is listed, the first is the primary affiliation for which the individual was a representative at the workshop. The second (and in one case, third) affiliation listed is the individual's employer, where that is different from the primary affiliation, to provide context for each individual's contributions to the workshop.

Table 1 – Workshop participants and affiliations

Name	Organization(s)	Country
Yoshi Ohno	CIE – President National Institute for Standards & Technology	USA
Kathryn Nield	CIE – General Secretary	Austria
Youngshin Kwak	CIE – Director, Division 1 Ulsan National Institute of Science and Technology	Republic of Korea
Joanne Zwinkels	CIE – Associate Director, Division 2 NRC Measurement Science & Standards	Canada
Jennifer Veitch	CIE – Director, Division 3 NRC Construction	Canada
John O'Hagan	CIE – Director, Division 6 Public Health England	United Kingdom
Pierre Gallant	Natural Resources Canada – Office of Energy Efficiency	Canada
Annette Steinbusch	LightingEurope Philips Lighting	Netherlands
Rob Nachtrieb	IEC/TC 23, IEC/TC 34, IEC/TC 23/SC 23B/JAHG 17 NEMA Lutron Electronics	USA
Jim Gaines	NEMA Philips Lighting	USA
Brad Lehman	IEEE P1789 Northeastern University	USA
Howard Wolfman	IEEE Power Electronics Society Study Group Lumispec Consulting	USA
Arnold Wilkins	University of Essex	United Kingdom
Malgorzata (Gosia) Perz	CIE TC 1-83 Philips Lighting	Netherlands
Norbert Wittig	IEC/TC 34/WG 5 Panasonic Europe	Germany
Naomi Miller	Illuminating Engineering Society [North America] Pacific Northwest National Laboratory	USA
Li (Cherry) Qian	China Lighting Standardization Committee TC 224 SC3 Everfine	China
Dan Rogers	Environmental Protection Agency / ENERGY STAR ICF International	USA
Reinhard Lecheler	ZVEI OSRAM	Germany
He (Crane) Yang	International SSL Alliance	China
Alex Baker	International SSL Alliance Lumileds	USA
Terry McGowan	American Lighting Association	USA
Andrew Watson	Apple	USA
Chan Su Lee	Yeungnam University	Republic of Korea
Aaron Miller	CSA Group	USA
Carl Bloomfield	Intertek	USA
Christophe Martinsons	IEA 4E SSL Annex Centre Scientifique et Technique du Bâtiment	France

2   Current state of research and standards

2.1   Parties active in TLM

As evidenced from the participation list, there are many players at both the international and regional levels active in developing standards, in applying them in various regulations or product certification schemes, and in commenting on all of these matters. Considering only the SDOs involved, Figure 2 shows a schematic of the inter-relationships, highlighting the divisions of work recognized between organizations. Note that at the regional and national levels, examples of relevant organizations are shown; this is not intended to be a complete listing. It is easy to see how, if these organizations proceed independently, there will be a high degree of duplication and the possibility for differing metrics, criteria, and recommendations.

The documents that these organizations publish are generally intended for use by regulatory bodies. They provide the technical detail by reference that is needed to support various national and local regulations. In some cases such regulations become mandatory, but they also may become part of voluntary certification programs. In both the United States and Canada, ENERGY STAR (a program of the U.S. Environmental Protection Agency) is an example of such a program; products that meet its criteria receive the ENERGY STAR label. This is an informative label for consumers that also can be used by incentive programs (e.g. those run by electric utility companies) to promote energy-efficient products. Within a few countries, local jurisdictions may also have chosen to make recommendations for low-flicker operation (e.g. California Title 20; CEC 2016a). In addition to product certification programs, some lighting standards are referenced in building energy certification programs such as BREEAM (http://www.breeam.com/).

Figure 2 – A schematic illustration of international, regional, and national standardization bodies related to light and lighting, showing particularly those interested in TLM

2.2   Existing and in-progress standards and recommendations

2.2.1   Definitions

There are few definitions specifically related to TLM in, for example, the International Lighting Vocabulary (CIE 2011), although there is an existing definition for flicker. Steps towards official definitions were taken with the publication of CIE TN 006:2016 – Definitions for

temporal light artefacts, which is the initial output of CIE Technical Committee 1-83. Temporal light artefacts (TLA) comprise the visual perceptual phenomena flicker, stroboscopic effect, and phantom array. The definitions proposed in TN 006:2016 for these phenomena are:

flicker: perception of visual unsteadiness induced by a light stimulus the luminance or spectral distribution of which fluctuates with time, for a static observer in a static environment (CIE 2016a, 2.4.2).

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 2016a, 2.4.3).

phantom array effect [ghosting]: 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 2016a, 2.4.4).

For flicker, TN 006 has proposed the metric P_{st} (IEC 2010, 2013) as being predictive of when flicker will be perceived. For the stroboscopic effect TN 006 has proposed the Stroboscopic Visibility Metric (SVM) as the predictor. There is no suggested metric for the phantom array. The document also includes suggested measurement and reporting procedures to facilitate further research.

Since the workshop, the German industry association ZVEI has published a guidance document in German for a national audience: "Temporal Light Artefacts – TLA, Flimmern und Stroboskopeffekt" (ZVEI 2017). ZVEI has adopted the definitions proposed in CIE TN 006:2016 and its recommended measurement methods, but made a first attempt at an acceptance criterion based on the IEC metric P_{st}^{LM} (IEC 2015), where the superscript ^{LM} denotes that the variation is luminous and not electrical.

2.2.2 Measurement standards and recommendations

Any metric will require a measurement scheme and calculation standards.

In the realm of electrical standards, the IEC has long had its P_{st} metric (IEC 2010, 2013) to limit line-voltage fluctuations, and this is being adapted for application to temporal light modulation, known as P_{st}^{LM} (IEC 2015). IEC is also engaged in developing similar documents related to the stroboscopic effect. The relevant electrical standards currently available are:

- IEC 61000-3-3, "Electromagnetic compatibility (EMC) – Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection", 3rd edition, 2013 (IEC 2013).

- IEC 61000-4-15, "Electromagnetic compatibility (EMC) – Part 4-15: Testing and measurement techniques – Flickermeter – Functional and design specifications", 2nd edition, 2010 (IEC 2010).

- IEC TR 61547-1, "Equipment for general lighting purposes – EMC immunity requirements – Part 1: An objective voltage fluctuation immunity test method", 1st edition, 2015 (IEC 2015).

As noted above, CIE TN 006:2016 includes suggested measurement methods for capturing the time-varying light output. Additional guidance concerning accurate measurement is available from Pacific Northwest National Laboratory (PNNL) (Perrin et al. 2016).

Since the workshop, CIE has approved the formation of a new technical committee titled "Measurement of Temporal Light Modulation of Light Sources and Lighting Systems". The committee is tasked with the development of a measurement protocol, followed by standardized test methods for metrics developed by CIE TC 1-83 "Visual Aspects of Time-Modulated Lighting Systems".

In addition, the U.S. National Electrical Manufacturers' Association (NEMA) published its *Standard for Temporal Light Artifacts* (NEMA 2017) in April 2017, which includes measurement details as well as suggested general criteria for limits on the metrics (or "acceptance criteria" in NEMA terminology).

Prior to the workshop, IEEE had formed a Study Group to determine whether IEEE 1789 requires maintenance. The recommendation of this Study Group is expected in late summer 2017.

2.2.3   Recommendations for limits

The first publication that proposed limits on TLM was the IEEE standard 1789:2015, *Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers*. This document includes an extensive literature review and hazard analysis, as well as proposing limits for no-risk and low-risk ranges for operation of lighting systems, expressed in relation to modulation frequency and modulation depth (%). Lehman and Wilkins (2014) described the recommendations in an article. PNNL has produced an informative document about IEEE 1789:2015 (Miller and Lehman 2015).

The IEEE 1789:2015 recommendations have been adopted in two Chinese documents. CQC 1601-2016 (CQC 2016a) establishes certification criteria for table lamps, and CQC 31-465318-2016 (CQC 2016b) covers certification criteria for lighting in schools.

The International Energy Agency (IEA) 4E Solid State Lighting (SSL) Annex (IEA 2016) has proposed performance categories for SSL products. These include criteria for flicker among other parameters. The recommendations are based on the IEEE 1789:2015 limits applied to the dominant frequency of the temporal light modulation. For Tier 1, the recommendation is based on the low risk limit of IEEE 1789:2015. For Tiers 2 and 3, the limits are more stringent below 90 Hz and are based on the no risk limits of IEEE 1789:2015.

Since the workshop, NEMA (2017) has proposed recommended limits (acceptance criteria) for the metrics P_{st}^{LM} and SVM. There are separate recommendations for indoor and outdoor applications,

2.2.4   Regulations

As of the time of writing, few jurisdictions have enacted flicker requirements for lighting systems, and those that have done so apply them only to products that are intended to be dimmed. The US EPA has included a requirement to report the frequency, highest modulation depth, and IES flicker index, but only for lamps marketed as dimmable, as part of its ENERGY STAR Lamps V2.0 specifications (US EPA 2015). The proposed revision, which will be Lamps V2.1 (US EPA 2017a), would add to this reporting a metric developed by the Lighting Research Center (LRC), known as the ASSIST metric (LRC 2015), to predict flicker (see also US EPA 2017b) as well as the flicker and SVM metrics from the NEMA 77 Standard (NEMA 2017). Both the existing and proposed requirements are part of the ENERGY STAR voluntary product certification program.

The US state of California has a mandatory building energy efficiency standard known as Title 24. The requirements given in this standard apply to construction of new and renovated buildings, both residential and commercial. The current version (CEC 2016b) has requirements to limit TLM for dimmable lighting products, expressed as a fixed 30 % limit on modulation depth at frequencies below 200 Hz. A test method unique to California accompanies this requirement.

The European Union is drafting its "One Single Lighting Regulation", which combines three existing regulations into one. The current draft version of this regulation contains a requirement for flicker (P_{st}^{LM}).

2.2.5   Measurement support

Several companies offer characterization of TLM in lighting products and systems, for example testing related to flicker index, modulation depth, ENERGY STAR's requirements for

dimmable lamps, and California's Title 24 flicker test (CEC 2016b). Several equipment makers are adding the capability to report SVM, P_{st}^{LM} and other metrics based on measurements using their handheld optical equipment.

2.3 Current knowledge

Given the focus on developing the standards roadmap, the workshop did not set out to create a comprehensive review of the literature, but to quickly summarize the state of knowledge against the framework set out in 1.2, for the purpose of identifying significant gaps. However, one interesting consequence of the broad participant base was the identification of areas of knowledge that have gone largely unnoticed by the lighting research community.

2.3.1 Visual perception effects

As noted above, temporal light artefacts (TLA) are visual phenomena that arise when the luminous environment includes TLM. TLA include flicker, in which a static observer views a static light source; the stroboscopic effect, which is an interaction of the TLM with a moving object, and the phantom array, which is an interaction between the observer's eye movements and TLM.

Flicker is relatively well understood. IEEE 1789:2015 (IEEE 2015) summarized the literature up to late 2014. Subsequently, Bodington et al. (2016) proposed a modification of the IEC P_{ST} metric to predict flicker. This new metric is the one proposed for use in the ENERGY STAR lamps specification (EPA 2017). Most recently, Perz et al. (2017) have proposed a new, empirically-derived metric to predict flicker based on experimental studies with complex waveforms, attempting to reconcile differences between previously published models.

Developments in fundamental vision science that seek to explain contrast sensitivity (e.g. Watson, 1986; 2013) appear to have had little uptake by applied lighting researchers. Most recently Watson and Ahumada have proposed an integrated model of human spatial and temporal contrast sensitivity (Watson and Ahumada 2016).

Stroboscopic effects have also been extensively studied, to the point at which CIE TN 006 (CIE 2016a) has proposed the use of the Stroboscopic Visibility Metric (SVM) to predict its occurrence. Phantom array effects are known to occur (Roberts and Wilkins 2013), but have not been extensively studied to date; no metric has been proposed to predict the phenomenon. One examination of the phantom array found greater sensitivity to the effect for red than for blue light sources, higher luminances, and narrower viewing angles (Lee et al. 2016); however, individual differences in response were also large. Furthermore, Lee et al. (2017, in press) have studied the combined effects of the stroboscopic and phantom array effects together to better understand how automobile passengers might perceive the rear lights of vehicles ahead of them.

2.3.2 Performance and neurophysiological effects

There is good evidence, summarized in IEEE 1789:2015 and by Wilkins et al. (2010), that exposure to TLM at frequencies of 100 Hz to 120 Hz and modulation depths of ~35 % disrupts saccadic eye movements and reduces visual performance as compared to light sources operating at frequencies > 40 kHz and with modulation depth < 4 % (electronically ballasted fluorescent lighting systems) and DC systems. Emotions may also be affected: Knez (2014) compared the effects of exposure to TLM from magnetic and electronic ballasts for fluorescent lighting, and reported that the magnetic ballast condition was associated with reductions in both activated (excited, enthusiastic) and unactivated (content, serene) positive emotions as compared to the electronic ballast condition.

Few studies as yet have examined the health or neurophysiological effects associated with the TLM conditions that LED lighting systems may create. One study has examined variations in modulation depth with 100 Hz TLM: Olsen et al. (2014) found that 0 % and 29 % modulation depth were acceptable to office workers who experienced the conditions for a full workday, but 100 % modulation depth was not. One experiment compared the effects of 0 Hz, 100 Hz, and 500 Hz at 100 % modulation while examining brain activation, eye movements, and cognitive task performance. Preliminary results presented in 2014 showed that brain

activation at 100 Hz and 500 Hz was greater than at 0 Hz; unexpectedly, one measure of cognitive performance indicated an improvement at 500 Hz relative to 100 Hz (Van Roon et al. 2014). Eye movement data and more refined analyses have not yet been published.

IEEE 1789:2015 includes an extensive review of neurophysiological effects of varying severity that have been associated with TLM, including eyestrain, headache, and epilepsy. There are broad individual differences in sensitivity to these problems. The review includes a systematic hazard analysis and a decision scheme for determining circumstances in which special attention to TLM is warranted.

3 Desired state

3.1 Knowledge gaps

Through breakout groups and plenary summary discussions, workshop participants evaluated the areas where the scientific literature is lacking. Although (as is to be expected) there remained some areas of disagreement between individuals at the conclusion of the workshop, consensus formed concerning the following high-priority points[1].

1) Waveform measurement: Measurement and reporting protocols for TLM waveform measurements that are consistently applied by all researchers would greatly improve the ability to compare research results. Metrological principles of precision need to be applied here. It is inadequate only to report frequency, modulation depth, simple waveform, and duty cycle. Reporting the power spectrum in a standard way would enable the calculation of various metrics and speed the testing of different metrics as predictors of any behavioural effect. Notably, there is no controversy about using fast Fourier transforms to characterize power and phase spectra, only variation in the metrics derived from FFT results.

2) Vision models: There is an unrealized opportunity to test whether existing models of spatial and temporal sensitivity from vision science (e.g., Watson and Ahumada 2016) might parsimoniously explain TLA effects such as flicker, the stroboscopic effect, or the phantom array effect.

3) Individual differences: Larger sample sizes and a better understanding of the range of sensitivity to all TLM effects in the population are needed. The use of a standard observer according to CIE definitions is questionable when it is clear that individual differences are large, and for some individuals the consequences of certain conditions may be serious.

4) Context effects: Most investigations have taken place in highly controlled laboratory conditions over relatively short exposures that are not typical of the settings where lighting systems are used. Experiments in more realistic environments, with naturalistic viewing conditions, multiple light sources, long-term exposures (hours, days, weeks), typical spectral content, etc. are required for the establishment of practical acceptability criteria. Greater attention is needed to the possibility of chromatic (spectral) as well as luminance variation, the effect of adaptation luminance, the size of the retinal area being stimulated by TLM, and the viewing geometry. For studies of moving targets, position in the visual field and speed of movement are critical variables.

Many other gaps in knowledge also appeared evident to workshop participants, although it was more difficult to establish the priority ranking:

− Among TLA, the phantom array effect is least well understood and deserving of greater attention. Both the spatial arrangement of light sources and the TLM of those sources seemed to be possible sources of the phenomenon.

− A question arose as to whether there exists a fourth category of TLA in which both the viewer and the target are moving, and what that combined stroboscopic-phantom array effect might be called. Given that all viewers' eyes are always in motion, there was disagreement on this point.

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[1] CIE had previously identified knowledge gaps related to TLM as part of its *Research Roadmap for Healthful Interior Lighting Applications* (CIE 2016b). By reference the topic is also among the high-priority research topics in the CIE Research Strategy, issued summer 2016. The gaps identified in this workshop provide greater detail.

– Alternatively, are the stroboscopic and phantom array effects two manifestations of the same process in which there is a spatial pattern to retinal stimulation?

– Another point of view held that the spatial pattern to retinal stimulation is less important, whereas understanding differences in eye movements is critical. In this view, the phantom array occurs as a result of saccades, and, when large, the saccades can have very high velocity. In consequence the phantom array TLA can occur at very high frequencies. In contrast, the stroboscopic effect usually involves a complex mixture of smooth pursuit movements sometimes broken up with small low speed saccades. The nature and velocity of the eye movement is completely different, and so is the resulting pattern on the retina. This view gave rise to the suggestion that another approach would be to develop TLA visibility models based on the nature of the eye movements involved in the task.

– Development of visibility models based on eye movements will require that researchers examine TLAs systematically in relation to the size and speed of saccades. Common experimental protocols for recording eye movements and reporting results would facilitate better communication.

– Might there be a general model that could explain all TLA with a single metric?

– Another point of view held that a single metric for various TLA phenomena is unlikely because eye movements differ greatly when targets are stationary versus moving.

– Effects on visual performance, cognition, emotion, and related consequences of TLM will require greater evidence than is currently available before TLM limiting criteria can be set. It seemed unlikely to some workshop participants, but likely to other participants, that metrics that predict TLA would also predict outcomes beyond visual perception; but this is a topic for further investigation.

– Greater understanding of neurophysiological effects is needed, including focused clinical studies of sensitive individuals, leading to dose-effect relationships where one of the determinants is exposure time. Knowledge of the underlying mechanisms by which adverse effects might arise would aid in the design of means to avoid them. This will require active collaboration with specialists in fields such as ophthalmology, medicine, and epidemiology.

– Understanding how individual differences occur on a population level is a challenge, but important to understanding risk; similarly, it would be valuable to know the occurrence of different TLM conditions in various environments. Given a measurement protocol, it would be valuable to survey a variety of places to determine common exposures to TLM. These waveform data could be used to calculate any predictive metrics that have been developed (e.g. P_{st}^{LM}, SVM) and to estimate the likely occurrence of adverse effects in those spaces. This could be combined with occupant surveys to determine what, if any, effects have occurred in that place; or conversely, these real conditions could be simulated in a laboratory setting and the occurrence of TLA or other behavioural changes measured in response to those conditions over varying exposure times.

3.2 Standards

The desired end state for standards documents is a set of international standards that is straightforward for manufacturers and practitioners, and in which consumers may have confidence. Regional or local variations on these may follow, depending on local conditions and local consensus.

The highest-priority gap in TLM standards mirrored the list of research gaps. These may be considered fundamental lighting standards:

1) Definitions for TLM, TLA, and related phenomena should be established as for other official lighting vocabulary terms, and incorporated as quickly as possible into the *International Lighting Vocabulary* and the *International Electrotechnical Vocabulary*.

2) There is an urgent need for a standard measurement protocol that can apply to the measurement and reporting of TLM waveforms. Whatever metric is applied to power spectrum measurements, it is critical that the data be accurate, repeatable, and reproducible in the same manner as other photometric data.

3) CIE TC 1-83 is tasked with examining the evidence for predictive metrics of TLA, and to "build a model for the visibility of temporal artefacts and their dependence on environmental, demographical and lighting parameters". Its output is to be a Technical Report. If successful, measurement and calculation of such visibility metrics could be standardized relatively quickly.

As concerns application standards, there was considerable debate at the workshop. Although all present agreed with the need for application standards, there was not agreement on the best way to structure such standards. The original agenda, as set by the organizing committee, proposed a framework in which application standards were organized by setting (e.g. schools, hospitals, offices). During the workshop, the possibility of organizing TLM application standards by task or user group emerged. In this alternative framework, there would be application standards for different adaptation ranges (e.g. scotopic, mesopic, photopic), or different task types (e.g. target size, motion rates, contrasts, colour contrasts, exposure times), or populations (e.g. identified by age group or sensitivity). This possibility was seen as a useful simplification that would speed the work greatly, but requiring further discussion to identify the categories in which such standards might be developed.

The fundamental standards are those that establish predictive metrics, which are mathematical constructs based on photometric measurements that have been shown to be related to some phenomenon (e.g. flicker perception, headache). Standards will set limiting values for these metrics, just as for interior light level recommendations we use target illuminance values tailored to the task (and, in some documents, modifications for task and viewer characteristics). Consensus recommendations are not only a matter of evidence, but of value judgements between competing interests (Boyce 1996). Workshop participants expressed a range of opinions concerning how values ought to be applied to TLM recommendations, which application standards committees will need to reconcile:

− The precautionary principle: This is a conservative view in which strict limits are set to prevent adverse effects in a broad range of circumstances for the broadest range of individuals.

− Societal risk tolerance varies depending on the severity of the outcome and on local factors (Baybutt 2014). In some circumstances, it is not permitted to create conditions that might adversely affect 1 in 1000 people. Others argue that if even 1 in 4000 individuals might be harmed catastrophically, the risk is too great. There appears to have been little public discussion to date about risk tolerance in relation to lighting systems and their possible effects.

− There are cost consequences to any limiting criteria that might be set. Manufacturers will pass those costs to consumers, not all of whom might feel that the reduced risk is valuable to them. Moreover, if the increased cost slows the adoption of an energy-efficient product, there are other associated environmental costs. In some countries, regulators (e.g. in the U.S., the Consumer Product Safety Commission and the Department of Energy) are obliged to conduct an impact analysis, which is subjected to public review, prior to a new regulation, to balance the intended benefits with the anticipated costs.

− In safety analysis, the "as low as reasonably practical" (ALARP) principle is often applied. This principle seeks to set the criteria for risk reduction such that any further reductions would add disproportionate cost in relation to the risk reduction gained.

− Conversely, failing to set criteria risks the creation of lighting systems that prove unacceptable to some individuals or in certain circumstances. This could result in slower adoption of the new technologies, with associated environmental and health consequences.

3.3 Barriers to advancement

Workshop participants also discussed the factors that may limit success in achieving the desired set of research knowledge and standards. Some of these are relatively straightforward to overcome, but others will require ingenuity and creativity:

− Intellectual openness, honest communication, and data sharing are required to achieve the desired outcomes. Researchers, laboratories, and companies will need to set aside

individual and organizational interests to engage in thoughtful, respectful debate. As the successful two-day workshop demonstrated, it is possible to take this approach and to achieve good results.

− All standards, whether fundamental or applied, should be based on research findings that have been replicated and validated more than once, and by independent laboratories. Just as in fundamental metrology, laboratory inter-comparisons are the basis for both standards and their realization, so too should independent confirmation of results be the basis for TLM standards. This could easily be a principle that is widely adopted.

− All areas of TLM research and standardisation would benefit from greater participation of a broader range of scientists, including experts who have not typically interacted with the light and lighting or international standardisation communities. Although there may be individuals from each of these disciplines among those known to the participants, greater participation from vision scientists, psychologists, neuroscientists, medical doctors, physiologists, occupational hygienists, and related fields would strengthen both the knowledge base and the related standards. Engaging these disciplines is an ongoing challenge.

− There are ethical challenges to studying the most severe consequences: No one would wish to, and no ethics review system would permit, the induction of a potentially fatal seizure or even a severe headache. This precludes much direct experimental work into these effects and will require careful case study and epidemiological approaches to infer causation without direct causal tests.

4 Activity roadmap

4.1 Summary of activities

The workshop developed an extensive set of activities that are required to achieve the goals of evidence-based, international standards. Figure 3 summarizes the end state. Measurement standards that characterize TLM have two purposes: They are necessary as a starting point for all research activities, where they are applied to enable the development of solid predictive metrics for effects of interest, whether they are visual (TLA), performance and cognition, or neurobiological and whether they are limited to specific populations, tasks or settings. The interrelationships between visual, neurobiological, and performance/cognition effects also remain to be determined. This body of research (within the large dotted rectangle) will be the starting point for the development of application standards that set criteria for those metrics. As noted above, the application standards also require consensus to establish the criteria. The same measurement standards will also apply to performance verification for compliance with the application standards.
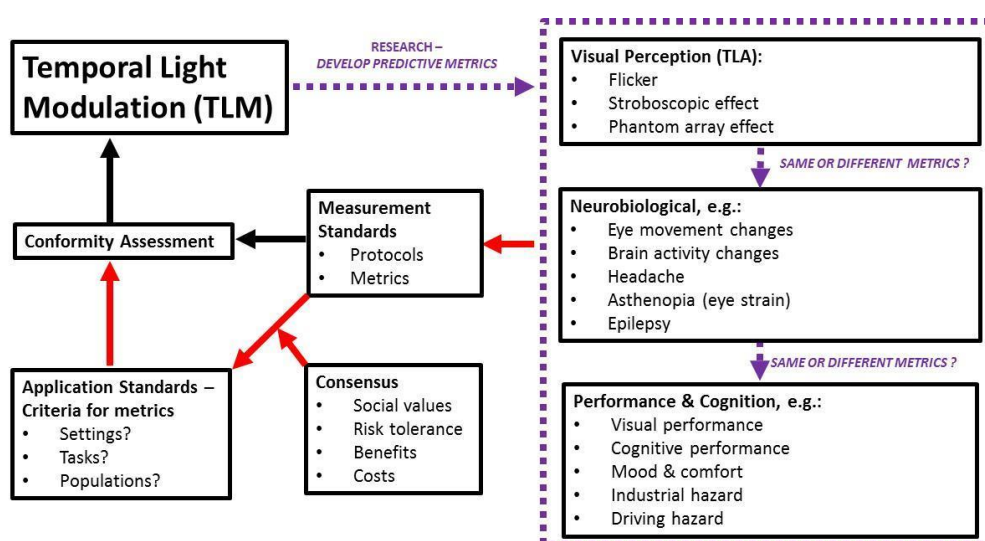
Figure 3 – Schematic display of needed activities, with research activities denoted in purple dotted lines and standards activities shown with red arrows; black arrows mark the application of these standards

The roadmap shown below in Table 2 focuses on a highly collaborative effort among all stakeholders to achieve the goal as expressed in Figure 3. It does not preclude any individual activity by one of the parties, but seeks to maximize joint activities wherever possible. Success in achieving the goal will depend on founding principles described in 4.2.

Table 2 – Activity roadmap

Activity	Mechanism – Lead	Start
Establishment of a network and the opening of communications between stakeholders, both as a continuation from the workshop itself and with the addition of parties not present in Ottawa. • Use platform to share existing publications (courtesy copies) between forum members for standards development purposes. • Outreach to parties not present.	CIE Research Forum[2] – CIE to initiate, voluntary leader to maintain.	Q2 2017
Establish protocols for power spectrum measurement and reporting.	CIE Division 2 TC – CIE	Q2 2017
Support completion of CIE TC 1-83 Technical Report, including the development of a model for the visibility of TLAs; ask TC to consider whether to add a TLA category for non-static observer in non-static environment (conceptualized at the workshop as a combination of phantom array and stroboscopic effects).	Expand TC membership with members drawn from this group	Q2 2017
Establish mechanisms for collaborative standards development where those do not yet exist (e.g. CIE-IEEE; CIE-NEMA), and review existing arrangements (renew if needed).	Memoranda of Understanding – SDO leaders from workshop	Q2 2017
Issue joint position statement from international (CIE, IEC, ISO, IEEE) and interested regional (IES, NEMA, SAC) SDOs, industry associations, and other willing stakeholders, to raise awareness of need for research funds from relevant agencies.[3] Leverage all media avenues to promote this.	Position statement & media push – SDO leaders from workshop	Q3 2017
Promote this workshop report	Social media, lighting magazines, networks – All	Q3 2017 (after publication of TN)
Establish provisional definitions, starting from CIE TN 006:2016, and pass to relevant committees in CIE and IEC for official vocabulary consideration	Seminar at CIE 2017 – CIE lead	Q4 2017
Further public discussion in lighting community, especially to promote high-quality research (measurement; reporting; replication)	Conferences & seminars, etc. – All	Q4 2017 & ongoing
Refine categories for application standards	CIE Research Forum discussion – All	Ongoing
Research project to test vision science models against proposed predictive metrics for flicker, stroboscopic effect.	Research project – Workshop participants	Q1 2017
Expert meeting to discuss new knowledge	CIE Expert Symposium – CIE D1/D2/D3/D6	Q3 2019

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[2] A CIE Research Forum is an open discussion group for information exchange. As an official entity, it is entitled to secure space in the CIE Collaboration Tool, use of the CIE WebEx platform, and access to meeting space at CIE events where committee meetings are held.

[3] Relevant agencies can include governmental science research funding agencies, private foundations, regulatory agencies, industry.

Table 2 – continued

Activity	Mechanism – Lead	Start
Review state of knowledge to determine feasibility of standards development; • When judged feasible, engage in discussions concerning the appropriate mechanism for the development of the given standard; proceed then to international standards development.	CIE Research Forum discussion – All	Ongoing

4.2 Principles for further activities

Participants in the workshop agreed that the success of this collaborative approach will depend on principled participation based on:

– honesty;

– humility;

– objectivity;

– open-mindedness;

– true collaboration aimed at a collectively beneficial result for participants and society;

– a shared sense of urgency;

– shared effort towards agreed-upon objectives and schedule.

Many, if not all, of the participating organizations have established codes of conduct and ethics; participants affirm these as the basis for their future actions together.

5 Next steps

This Technical Note with its roadmap is a freely available CIE publication. In parallel with the CIE document approval process, CIE will take the lead in creating a Research Forum, open to interested stakeholders, as the first outward-facing step towards the realization of the roadmap. CIE will also pursue its assigned tasks as shown in Table 2. Workshop participants left Ottawa enthusiastic to continue this collaboration. The Workshop Organizing Committee invites all interested stakeholders to join with us in pursuing this work so that together we will efficiently and quickly develop guidance to facilitate the development of new lighting technologies and systems that support the adoption of energy-efficient, high-quality lighting with appropriate limitations on TLM to support human needs.

Annex A
Workshop Agenda

CIE Stakeholder Workshop for
Temporal Light Modulation Standards for Lighting Systems

February 8th and 9th, 2017

National Research Council of Canada, 1200 Montreal Road, Ottawa, Ontario
Building M-36, Kelvin Room

Purpose and Scope:
The objective of this meeting is to develop a roadmap of research, recommendations, and standards activities related to temporal light modulation from lighting systems that are needed in order to speed up the process of developing international standards in an efficient way while preventing overlap and duplicate effort. The scope of the meeting is limited to developing the roadmap, establishing collaborations, and dividing the work amongst participants. The meeting is not intended to establish the content details for future standards documents.

Scope of the workshop:
Temporal light modulation from lighting systems can affect people and equipment. Effects on equipment (e.g., interference with optical systems such as barcode readers and cameras) are out of scope. Effects on people are in scope for this workshop. Possible effects on people include the following:

- Visual perception effects (temporal light artefacts, TLA): flicker, stroboscopic effect and phantom array
- Performance effects: eye movements changes, changes in visual performance, changes in cognitive task performance
- Neurobiological effects: headache, eyestrain, migraine, epilepsy, etc.

The workshop will align efforts in standardization and research within its scope, will identify overlap and knowledge gaps, will identify possible mismatches between research and standardization projects, and will develop a roadmap for collaboration and co-operation leading to a useful set of appropriate standards in this domain. At the conclusion of the workshop, there should be agreement on both the work that is needed and on who will undertake the various activities needed to fulfil the roadmap.

Research Required for Standard Setting and Determining Acceptability Limits
Facilitated discussion will lead participants to complete the tables below, to identify where additional information or research is required.

Discussion:
- What elements in the tables require additional clarification / definition?
- Are there additional effects that ought to be added?
- Are there additional predictors or measurement methods to be added?
- Does a suitable measurement / metric exist? Is a new measurement required?
- How do we develop consensus among all the organizations / bodies on measurement?

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Table 1.

Effects of TLM on People		Definition	Measure of light	Measurement Method
Category	**Effect**			
Visual Perception (TLA)	Flicker	CIE TN 006:2016	P_{st}^{LM}	IEC TR 61547-1
	Stroboscopic effect - safety		not defined	
	Stroboscopic effect - ergonomics	CIE TN 006:2016	SVM, proposed	
	Phantom array	CIE TN 006:2016		
Performance	Eye movement changes			
	Changes in visual performance			
	Changes in cognitive task performance			
Neurobiological	Headache			
	Asthenopia [eyestrain]			
	Migraine			
	Epilepsy			
	Other			

- Do we have sufficient information and research to determine acceptability limits in application standards? If not, what's missing?
- Are the degrees of specificity to acceptability limits appropriate? Are there other applications for which we might require separate limits? Alternatively, could some categories be combined?

Table 2.

Category	Effect	Knowledge Exists to Support Acceptability Limit for Measure					
		Office	Industry	Hospitals	Schools	Roads	Home
Visual Perception (TLA)	Flicker						
	Stroboscopic effect - safety						
	Stroboscopic effect - ergonomics						
	Phantom array						
Performance	Eye movement changes						
	Changes in visual performance						
	Changes in cognitive task performance						
Neurobiological	Headache						
	Asthenopia [eyestrain]						
	Migraine						
	Epilepsy						
	Other						

<u>Standards and Guidance Required: The Roadmap</u>
Facilitated discussion will lead participants to answer the following:

- What are the next steps required to ensure that all organizations can contribute to the establishment (creation?) of fundamental and application standards and related guidance documents?
- Which documents could be developed based on knowledge available now?
    - Which organizations will lead, and which will collaborate, in developing these documents?
- Who will commit to conducting or supporting research required to fill in gaps identified in Tables 1 and 2?

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CIE TN 008:2017

AGENDA

W E D N E S D A Y ,   F E B R U A R Y   8 ^{T H} ,   2 0 1 7

Coach transport will depart the Lord Elgin Hotel at 9:15 a.m.

10:00   **Arrival, Registration, Coffee**

10:30   **Meeting Host Welcome** ....NRC (TBD)

10:35   **Opening Remarks** .... Yoshi Ohno, CIE / Jennifer Veitch
- Purpose of the meeting;
- Desired outcomes;
- Subsequent steps for CIE and others;
- Review of safety measures relevant to the building.

10:50   **Review of the Agenda and Introductions**...Alain Rabeau, The Intersol Group
- Review of the agenda;
- Approach to the workshop;
- Participation ground rules for the workshop.

11:00   **Part 1: Familiarising Ourselves with the Expertise Assembled in this Workshop**................................. All
Purpose: To provide participants with an opportunity to introduce themselves following a pre-determined format.

12:30   Lunch

13:00   **Part 2: Developing a Shared Understanding of the Current State** .... All
Purpose: To provide participants with relevant information concerning research and emerging from various Technical Committees.

Presentation #1 – Update on the Work of SDOs... Organizing Committee, TBD
- Presentation;
- Questions of clarification;
- Discussion: "What are the implications for our work?"

13:45   **Presentation #2 – Update on the Work of Researchers** .... Organizing Committee, TBD
- Presentation;
- Questions of clarification;
- Discussion: "What are the implications for our work?"

14:30 Break

14:45   **Presentation #3 – Update on the Work of Other Actors** .... Organizing Committee, TBD
- Presentation;
- Questions of clarification;
- Discussion: "What are the implications for our work?"

15:30   **Part 3: Identifying the Gaps** .... All
Purpose: Working from the tables in the scope statement, determine areas where additional information / research is required.

16:30   **Recap, Taking Stock of Our Progress** .... Alain / All

16:45   **Adjourn**

Coach transport will leave NRC at 17:00. Dinner on your own.

THURSDAY, FEBRUARY 9TH, 2017

Coach transport will depart the Lord Elgin Hotel at 7:30 a.m.
A light breakfast will be available at the meeting.

08:30   **Review Agenda** .... Alain

08:45   **Part 3: Identifying the Gaps (Continued)** .... All
Purpose: Working from the tables in the scope statement, determine areas where additional information / research is required.

11:00   **Part 4: Determining Priorities** .... All

12:00   Lunch

12:30   **Part 5: Next Steps – Roadmap to the Publication of Standards and Guidance** .... All
Purpose: To identify the steps required that will lead to the publication of standards and other documents.

14:15   **Closing Remarks** .... CIE / Jennifer Veitch
Confirmation of Workshop Output ....
- Workshop report;
- Balloting process;
- Publication of workshop report;
- Follow-up actions.

14:30   Adjourn

Coach transport will depart the NRC at 15:30 for the hotel. Other transportation may be arranged.

A limited number of places are available for tours of NRC metrology and applied research facilities following the workshop. Depending on interest, the coach departure time might be delayed until after tours are completed.

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