FINAL PUBLISHABLE REPORT

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RMG: -		

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1 Overview

LED-based lighting contributes to energy saving and the reduction of the environmental impact of lighting. However, LED lamps can show fluctuations in the light output known as temporal light modulation (TLM) which could, above certain limits and under certain conditions, impact the health, well-being and safety of people. Pursuant to the EU Directives 2009/125/EC, on Ecodesign requirements, Commission Regulation (EU) 2019/2020 sets limitations on TLM of light sources. The overall aim of this project was to create the metrology infrastructure for the measurement of TLM in LED lighting and the visual effects induced by TLM, known as temporal light artefacts (TLAs). This project developed and validated measurement methods for quantitative measurement of TLAs, such as flicker and the stroboscopic effect, and advanced the development of a metric for the phantom array effect. The project results underpinned the development of standardisation on TLM and provided the lighting industry, instrument manufacturers and market surveillance authorities with undisputable results of their TLM measurements. Following the guidance provided by the project, end users can now rely on traceable TLM measurement, and as a result, they have more trust in market surveillance.

2 Need

LED-based lighting is ever increasing, and the market is estimated to be worth more than 70 € billion in 2022. The ongoing transition to LED lighting is an important step in achieving the European goals on improved energy efficiency. However, LED lighting may show temporal variation of the light output, covering a large range of waveform shapes and frequencies. This temporal variation can often be perceived by humans. And as stated by the International Commission on Illumination (CIE) in TN 006:2016: "can lead to a decrease in performance, increased fatigue as well as acute health problems like epileptic seizures and migraine episodes". Also, distorted perception of moving objects could give rise to safety concerns, for instance, in traffic or work environments.

The three types of TLAs, caused by variations in light output, as defined in the TN 006:2016 by the CIE, are: i) flicker, which is the direct perception of temporal changes of the light output; ii) stroboscopic effect, which is observed as a discretised motion of moving objects resulting from illumination by a temporally modulated source; and iii) phantom array effect (or ghosting), which corresponds to a change in perceived shape or spatial position induced by saccadic eye movements across a temporally modulated light source. While metrics for flicker and the stroboscopic effect have been recommended by CIE, the metric for the phantom array effect is still missing due to a lack of the required research.

The need for worldwide harmonised TLM measurements has been recognised by the CIE. The European Commission has explicitly required the development of standards for the measurement of flicker and stroboscopic effect (Mandate M/519, Ares(2013)205169), and in 2021 the Commission Regulation (EU) 2019/2020 has entered into force. In view of public health and safety, the regulation has introduced limits on the allowed modulation of light sources for flicker and the stroboscopic effect. To demonstrate compliance with the regulation, lighting industry, measurement instrument manufacturers and market surveillance authorities need to be able to perform reliable, mutually comparable measurements of these TLAs. However, the metrology infrastructure to provide validated and SI-traceable measurements of TLM and TLAs is currently not available and international agreed standards do not exist.

Real scenes and life environments, such as offices and tunnels, are often illuminated with a combination of multiple light sources and daylight presenting an effective luminance pattern of high contrast and an inhomogeneous distribution of TLM parameters. Mapping the TLM of such environment would require multiple measurements with a single spot TLM measurement device. Such measurement procedures are inefficient and do not provide a full assessment regarding TLA perception. Multispectral cameras could map the spatially distributed TLM as seen from an observer's position. This provides a promising approach to map spatially resolved TLM and thereby to judge about the perception of TLAs in illuminated scenes. Although commercial state-of-the art image sensors, used in industrial cameras and imaging luminance measurement devices (ILMDs), already contain fast modes that provide the needed temporal resolution, methods for the evaluation of spatially resolved TLM are not yet available. Also, light sources comprised of multiple temporally modulated coloured LEDs potentially induce temporal colour modulation, often leading to the perception of colour-breakup in the phantom array effect. Although spectroradiometers have become widely available for spectral measurements, a framework for spectrally resolved TLM measurements is missing.

3 Objectives

The overall aim of this project was to create the metrology infrastructure required for the measurement of TLM and to contribute to the development of standardisation on the measurement of TLM. The specific objectives of the project were:

1. To establish methods for traceable TLM measurement of individual light sources and luminaires with a focus on flicker and stroboscopic effect. These would be based on IEC TR 61547-1 and IEC TR63158 and include: (i) methods for generating and measuring optical waveforms in the time-domain and power spectra in the frequency-domain, (ii) calibration and characterisation of TLM measurement devices and the evaluation of uncertainty budgets, (iii) quality metrics (e.g. frequency response, dynamic range of signal) for the classification of TLM measurement instruments.
2. To validate the traceable TLM measurement methods, developed in Objective 1, through an interlaboratory comparison between metrology institutes and industry, whilst ensuring compliance with the new EU Ecodesign 2019/2020 regulation. To develop a recommendation on associated standardised measurement conditions.
3. To develop novel methods for measuring TLM of the illuminated environment in extended scenes (e.g. offices, roads or tunnels) and for multispectral TLM measurement of light sources.
4. To develop a model for the visibility of the phantom array effect based on perception experiments that measure the visibility threshold for various lighting conditions (e.g. modulation frequency, amplitude, shape of the modulation and light level). This model would be shared with CIE TC 1-83 or its successor in a suitable format that enables its use in a future metric for the phantom array.
5. To facilitate the take up of methods, technology and measurement infrastructure developed in the project by the standards developing organisations (e.g. CIE) and end-users (e.g. regulatory bodies, lighting industry and instrument manufacturers). This should include providing input to CIE TC 2-89 and CIE TC 1-83 (or its successor) and support for a new CIE TC for addressing the measurement of spatially resolved TLM and colour TLM.

4 Results

These are the results of joint collaborative work.

4.1 *Methods for traceable and validated measurement of temporal light modulation (objective 1)*

Based on the models given in IEC TR 63158:2018 and IEC TR 61547-1:2020, uncertainty components, which affect TLM quantities for flicker and the stroboscopic effect, have been identified. To propagate uncertainties, from the time domain to PstLM and Mv, models have been built. Using these models, sensitivity coefficients for uncertainty propagation have been determined for various waveforms. This uncertainty analysis has been used for the calibration of TLM measurement devices. Further investigation into the models revealed shortcomings of the current definitions as well as of reference implementations of TLA metrics. In addition, the improved models have been implemented in a luminous flux measurement setup which has been used to measure a large number of light sources for TLM, in a market surveillance.

For validation of implementations of TLM models a dataset containing discretised mathematically generated waveforms, named "MetTLM TLM waveform set 1". The dataset is accompanied by a report guiding and exemplifying how the dataset can be used by laboratories in achieve measurement uncertainties below 0.05 on PstLM and Mv. The dataset and report have been released to the MetTLM community on Zenodo, an open access repository.

Typical performance of measurement devices can be expressed in quality indices, which characterise how a physical effect influences the instrument's reading. For TLM measurement devices, quality indices have been defined for frequency response and spectral mismatch. An LED-based facility has been built with the aim of characterising TLM measurement devices. A laser-based facility has been realised, and procedures to measure the frequency response of TLM measurement devices have been tested. The frequency response of various commercially available TLM measurement devices has been characterised and compared against the developed TLM models for flicker and the stroboscopic effect. An approach for a quality index for frequency response has been developed. Quality indices can be used for instrument classification, helping prospective instrument buyers selecting suitable TLM measurement equipment. Example uncertainty budgets for the measurement of PstLM and Mv are given in **Error! Reference source not found.** and Table 2. This uncertainty budget assumes a non-colour modulated source and takes into account uncertainties for: source stability, time scale of the digitizer, linearity of the digitizer, dark correction and noise of the measurements system. A typical example of a measurement setup is shown in Figure 1. The light source for which the uncertainty budgets are drawn up are shown in Figure 2.

Table 1: Overview of uncertainty for measurement of flicker for various light sources.

Source	U_PstLM_stab	U_pstlm_freq	U_PstLM_lin	U_dark_Dark	U_Noise	U_PstLM_exp_Total
Refrad - Wave 14	2.7E-02	2.8E-04	8.2E-06	1.4E-05	5.8E-06	2.7E-02
Refrad - Wave 24	1.6E-04	2.8E-02	2.5E-06	5.3E-05	4.5E-06	2.8E-02
Refrad - Wave 26	2.0E-02	1.2E-03	2.5E-05	1.1E-05	4.4E-06	2.0E-02
Refrad - Wave 9		2.3E-02	7.6E-05	3.6E-04	3.0E-06	2.3E-02
ART-2_1_ Crompton	2.9E-03	3.3E-03	9.2E-06	3.5E-06	3.1E-06	4.4E-03
ART-2_2_CALEX_250lm	2.2E-02	3.6E-02	1.4E-04	3.1E-05	2.7E-05	4.2E-02
ART-2_3_ECOMIN	6.3E-03	5.4E-03	1.1E-05	6.5E-04	1.0E-05	8.3E-03
ART-2_4_XG	4.2E-03	1.5E-03	1.9E-05	4.7E-05	1.6E-05	4.5E-03
ART-2_5_Calex_350lm	3.8E-03	6.0E-03	3.3E-05	1.8E-05	1.0E-05	7.1E-03
IKEA_Ledare_2	3.4E-02	3.1E-03	3.1E-05	1.7E-05	2.1E-05	3.4E-02

Table 2: Overview of uncertainty of TLM meter for SVM of various light sources

Source	U_SVM_stab	U_SVM_freq	U_SVM_lin	U_SVM_Dark	U_Noise	U_SVM_exp_Total
Refrad - Wave 14	0.0E+00	5.5E-04	5.3E-07	4.6E-05	1.2E-08	5.5E-04
Refrad - Wave 24	3.8E-05	3.8E-06	1.9E-07	4.0E-07	2.4E-08	3.8E-05
Refrad - Wave 26	3.0E-04	4.1E-04	1.4E-05	7.7E-05	3.0E-08	5.1E-04
Refrad - Wave 9	1.5E-04	9.1E-04	1.3E-05	4.3E-05	2.3E-08	9.2E-04
ART-2_1_ Crompton	3.0E-04	1.8E-06	1.7E-07	1.3E-07	2.2E-08	3.0E-04
ART-2_2_CALEX_250lm	8.3E-03	1.3E-05	6.1E-07	1.4E-05	7.0E-08	8.3E-03
ART-2_3_ECOMIN	2.4E-03	4.3E-04	1.6E-06	5.1E-04	9.4E-08	2.5E-03
ART-2_4_XG	7.1E-03	2.6E-04	6.8E-06	4.0E-04	9.6E-08	7.1E-03
ART-2_5_Calex_350lm	6.1E-04	1.1E-04	8.5E-06	2.3E-05	3.3E-08	6.2E-04
IKEA_Ledare_2	1.7E-03	6.1E-04	8.4E-06	1.2E-04	7.2E-08	1.8E-03
V-light_36_4773_2	3.4E-03	4.9E-05	3.6E-06	2.2E-05	4.7E-08	3.4E-03

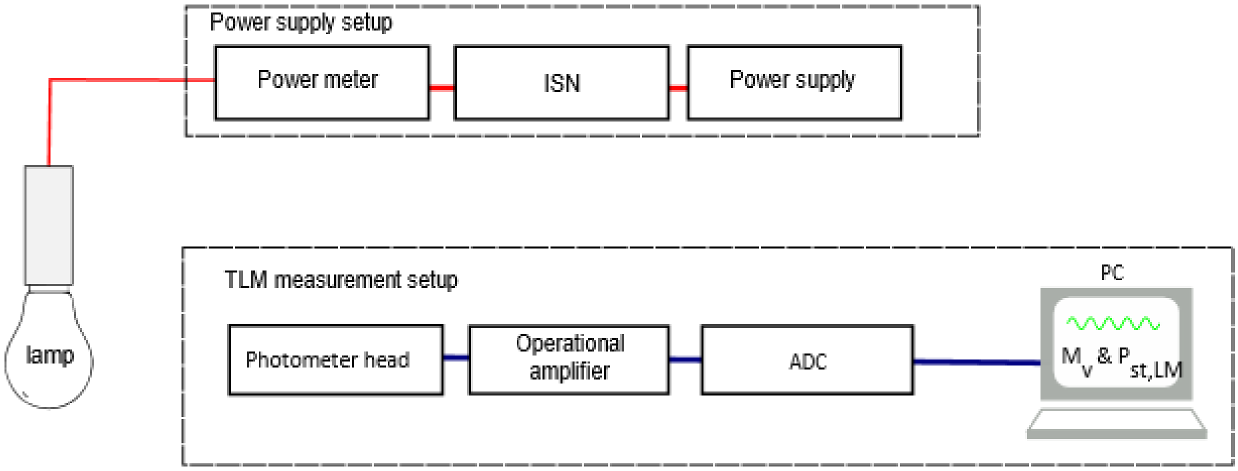

Figure 1: Typical setup used to measure the TLM of a light source.

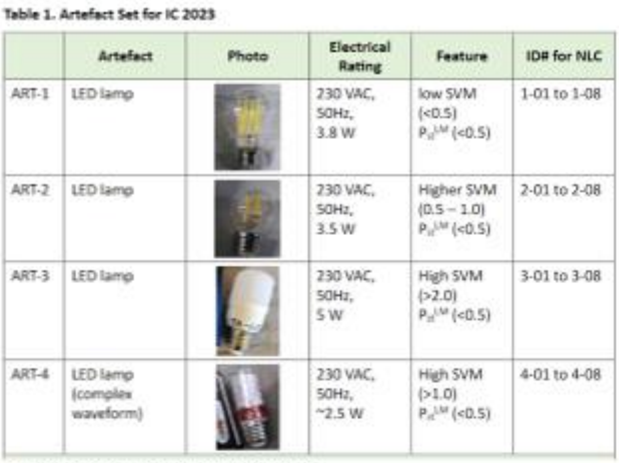

Table 1. Artefact Set for IC 2023

	Artefact	Photo	Electrical Rating	Feature	ID# for NLC
ART-1	LED lamp		230 VAC, 50Hz, 3.8 W	low SVM (<0.5) P_{st}^{LM} (<0.5)	1-01 to 1-08
ART-2	LED lamp		230 VAC, 50Hz, 3.5 W	Higher SVM (0.5 – 1.0) P_{st}^{LM} (<0.5)	2-01 to 2-08
ART-3	LED lamp		230 VAC, 50Hz, 5 W	High SVM (>2.0) P_{st}^{LM} (<0.5)	3-01 to 3-08
ART-4	LED lamp (complex waveform)		230 VAC, 50Hz, ~2.5 W	High SVM (>1.0) P_{st}^{LM} (<0.5)	4-01 to 4-08

Supplied by: IEA 4E SSL Annex

Figure 2: Overview of light sources used in uncertainty budgets, source of table 1 supplied by IEA AE SSL Annex.

Summary of the key outputs and conclusions

Multiple implementations of calculation models for flicker as well as for stroboscopic effect have been compared, which initially revealed discrepancies. Mutual improvements of the models led to consistent results. A data set of waveforms along with a guiding report is now available for end users to validate their own implementations of TLM calculations. Based on the improved models the measurement uncertainties have been propagated, leading to an example uncertainty budget for the measurement of TLM. Next to this uncertainty budget a method for the assessment of a frequency response quality metric and spectral mismatch quality metric have been developed.

The objective of establishing methods for traceable TLM measurement of individual light sources and luminaires with a focus on flicker and stroboscopic effect has been achieved.

4.2 Validation through interlaboratory comparison (objective 2)

To validate the traceable TLM measurement methods developed in Objective 1, an interlaboratory comparison has been carried out. In this comparison, eleven artefacts are measured: four waveforms of the TLA box and seven lamps of which four are also measured in the IEA 4E SSL Annex comparison.

Organization

During the interlaboratory comparison, VSL acted as pilot, carrying out the data analysis of the comparison results. RISE acted as copilot and performed lamp aging, pre- and post-comparison measurements and distributed the artefact sets to the participants. Four sets of artefacts have been sent around to the participants and each set was measured by two participants of the comparison. Participants to the comparison were DTU Electro, Signify, Aalto University, ICCS, VSL, LMT, Gigahertz Optik and RISE.

The copilot aged and measured all the artefacts before shipping them in November 2023. The participants finished their measurements around January 2024, after which the artefacts were returned to the copilot and remeasured by the copilot. The data was collected and send to the pilot, who analysed the data and wrote a report by May 2024.

Figure 3 shows the aging facility at RISE. In this facility, the artefacts were seasoned for 24 hours by continuously running the lamps using a stabilized power supply. The facility includes shielding from ambient light, base-up measurements at an ambient temperature of (25 ± 5) °C. The conditions and equipment of the electrical testing are specified as a supply voltage of 230 V AC (±0.5 %), 50 Hz and THD < 1.5 %. The power meter had a bandwidth >100 kHz and meets the requirements in CIE S 025. During a stability test of 63 minutes, the photometric and electrical quantities are measured every 5 minutes for Mv (5 s), PstLM (180 s), lamp current (and/or active power) and the relative luminous intensity or flux.

Figure 3: Aging facility at RISE.

Materials and methods

Artefacts

In the comparison, two types of artefacts were used. First, four different waveforms from the Signify TLA demo source were used: waveforms 9, 14, 24 and 26. The TLA box is a programmable LED source connected to the mains with preinstalled waveforms having various visibility and perception properties. The TLA box was stabilized for 15 minutes after turning on and 5 minutes while changing between waveforms. Second, lamps are measured. Of these lamps, the IKEA Ledare and IKEA V-light were selected by the MetTLM project, four lamps, Calex, Ecomin, XG and Crompton were taken from the IEA 4E SLL Annex comparison and the additional Calex was selected when was discovered that Calex lamps with two different lumen were included.

Method

Each of the participants measured the lamps according to their normal measurement procedures for flicker and stroboscopic visibility and determined an uncertainty budget. Some factors influencing the measurement uncertainty were the algorithm, stability, reproducibility, linearity, and the uncertainty of the photodetector. The quantities measured were the voltage, current, power, sampling rates, flicker, stroboscopic visibility measure, ambient temperature, humidity, stabilisation time and burning time.

Data analysis

The measurement results of the comparison are evaluated according to the "Guidelines for CCPR Key Comparison Report Preparation". The normalized ratio, degrees of equivalence and reference value are determined.

Results

Figure 4 shows the normalized ratio of the measurement of the participant compared to the before and after measurements of the copilot for two artefacts. Figure 4A shows the flicker results of waveform 26 of the TLA boxes, where the uncertainties overlap. Figure 4B shows the normalized ratios for the Crompton lamp. All artefacts neatly envelop the measurements with their uncertainties, showing good lamp stability during the comparison. Figure 4C shows good stability in the stroboscopic effect for waveform 26 and Figure 4D shows good artefact stability for the Crompton lamp.

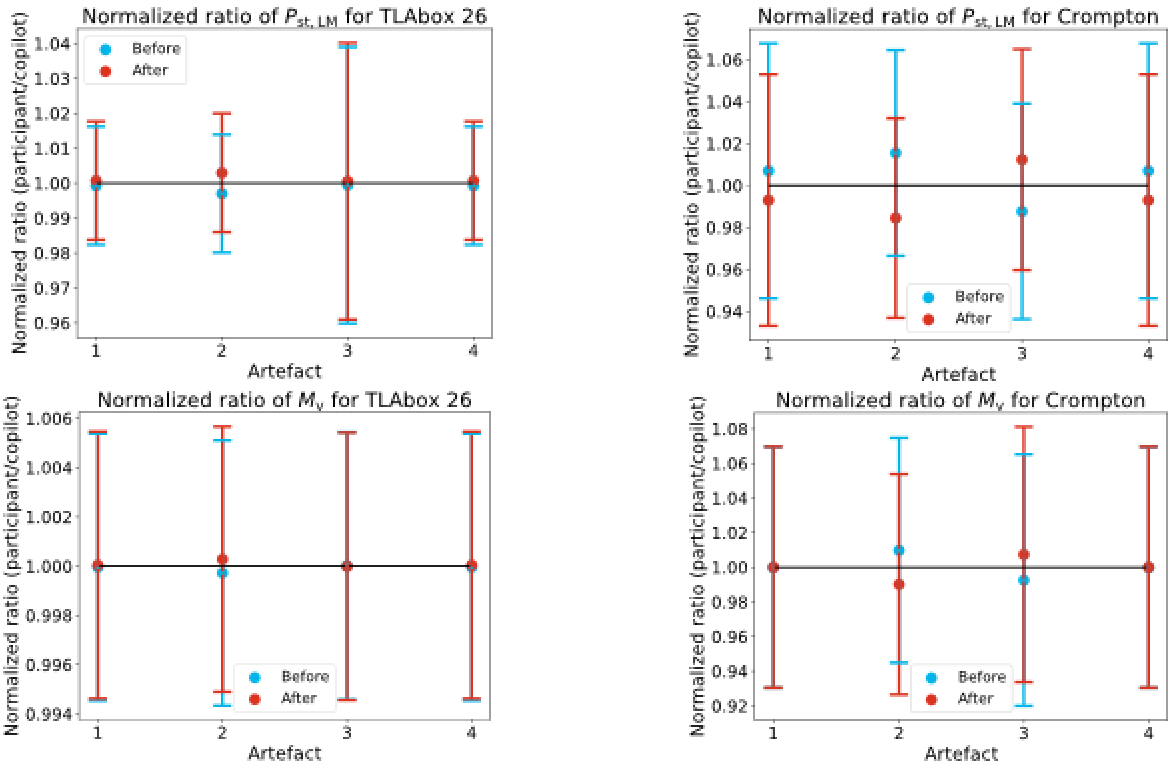

Figure 4: The normalized ratio of the flicker (PstLM) measurements for artefacts A) waveform 26 of the temporal light artefact (TLA) box and B) the Crompton lamp. The normalized ratio of the stroboscopic effect (Mv) measurements for artefacts B) waveform 26 of the temporal light artefact (TLA) box and D) the Crompton lamp.

Figure 5A shows the results of the degrees of equivalence of waveform 26, where only participants 5 and 7 might be equivalent. This is confirmed by Figure 5B, where the uncertainties of these participants are overlapping. Figure 5B also shows that participant 3 measured a value significantly higher than the other participants. Figure 5C shows that for the Crompton artefact all participants are equivalent. Figure 5D confirms this, with participants 4 and 5 even enveloping both measurement and reference value.

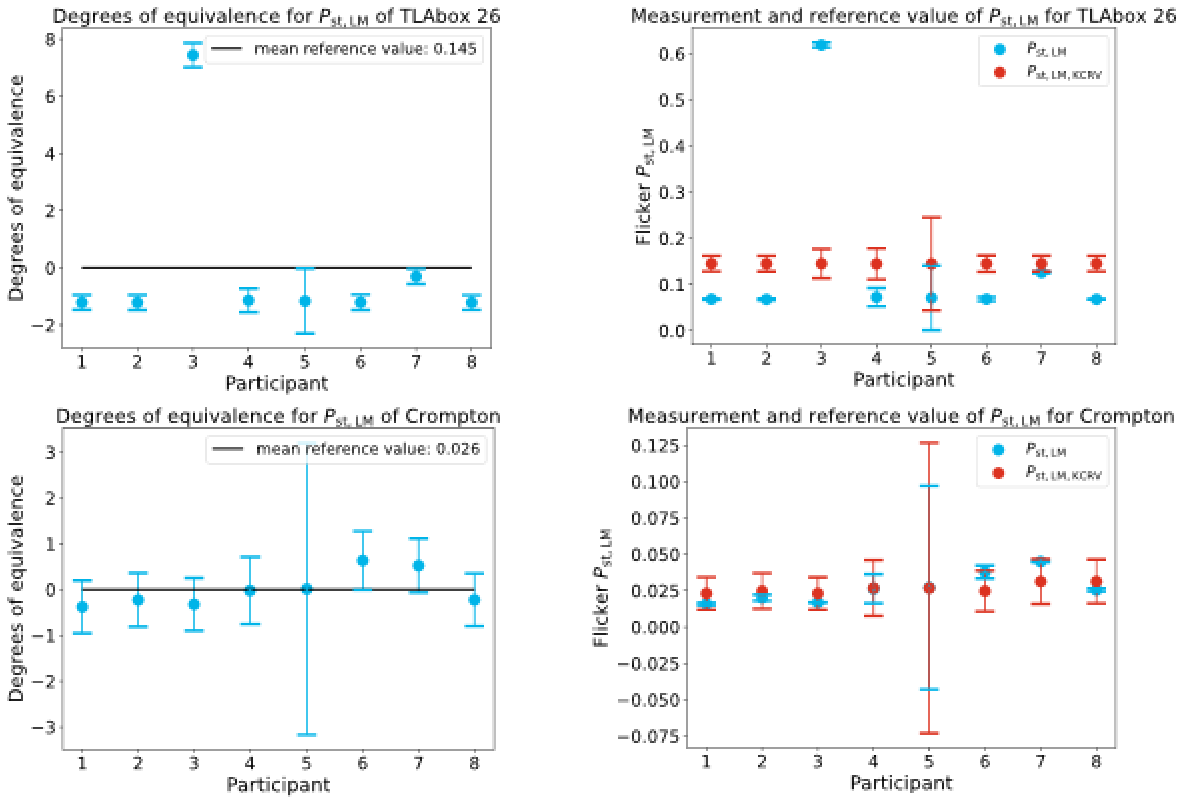

Figure 5: Degrees of equivalence of the flicker (PstLM) measurements for A) the temporal light artefact (TLA) box waveform 26 and C) the Crompton lamp. The flicker measurements and their reference value (KCRV) of B) waveform 26 and D) the Crompton lamp.

Figure 6A shows that all participants are equivalent for waveform 26. Figure 6B shows the enveloping of the reference values for participants 1, 2, 4, 5, 6, and 7 while measuring waveform 26. Figure 6C shows that for the Crompton artefacts only participant 1 is equivalent. Figure 6D shows, however, that participant 5 has their measurement and reference value enveloped by the uncertainties.

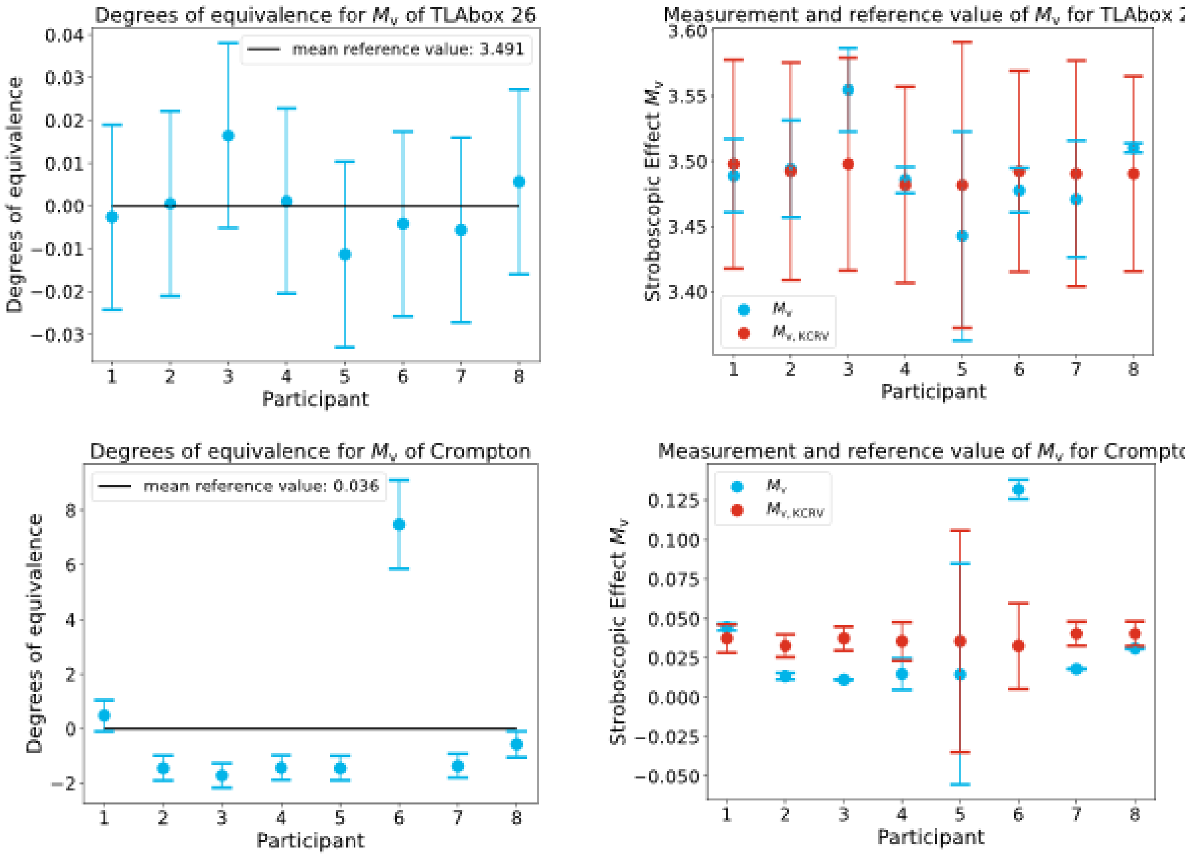

Figure 6: Degrees of equivalence and their uncertainty of the stroboscopic effect (Mv) measurements for the artefacts A) waveform 26 and C) Crompton. The Mv measurements, their reference value (KCRV) and corresponding uncertainties for artefacts B) waveform 26 and D) Crompton.

Summary of the key outputs and conclusions

The aim of the interlaboratory comparison was to validate the capabilities of each of the participants regarding measurements of the flicker and stroboscopic effect as produced by different types of artefacts. However, there were still some artefacts where the participants were not in agreement. These differences can be caused by differences in each of the participants set-ups and uncertainty calculations, hence it is important to find out the source of the differences. Participants with lower uncertainties might have missed some factors affecting their uncertainty budget such as the influence of zero-padding, resulting in non-equivalence, etc. Besides, this non-equivalence can be caused by outliers in the measurements. These outliers affect the equivalence because in this comparison the assumption was made that each of the participants were equally skilled at measuring the TLM effects.

The objective of developing traceable TLM measurement capabilities and to validate them in an interlaboratory comparison, has been achieved.

4.3 Novel methods for TLM measurement (Objective 3)

To probe individual light sources inside complex field scenes a luminance TLM meter based on a fast photocurrent flicker-meter, including an anti-aliasing filter, and a luminance photometer head was set up. This luminance TLM meter has been verified inside the lab and thereafter used in field measurements. To enable a multi-channel TLM meter with synchronized acquisition, a trigger extension for this fast photocurrent meter was initiated in this project. Using an adopted software development kit a multi-channel configuration has been set up which was verified and used to demonstrate the advantages of parallel TLM measurements. The first results have been disseminated in a conference presentation and a training session. Both the luminance TLM meter and the multi-channel TLM meter are now available as a commercial product.

In laboratory-based measurements, a set of three TLM luminance sources with patterned transmissive filters have been used to generate luminance contrast patterns which are then measured by using cameras. Doing so, limitations identified regarding the sampling theorem, resulting from the charge accumulating principle as used in most pixel-based detectors, has been addressed. The linearity of the TLM luminance source in constant luminance mode and during transient operation (regarding the actual TLM waveform compared to the nominal one) was investigated by illuminance photometers, see Figure 7. This revealed issues regarding modulation depth (offset) and small deviations resulting from internal decay time constants of the electrical circuit of the TLM luminance source, in addition to the well-known droop effects attributed to the included LED strains itself. Such information is a prerequisite for facilitating these sources in a characterization of TLM measurement devices.

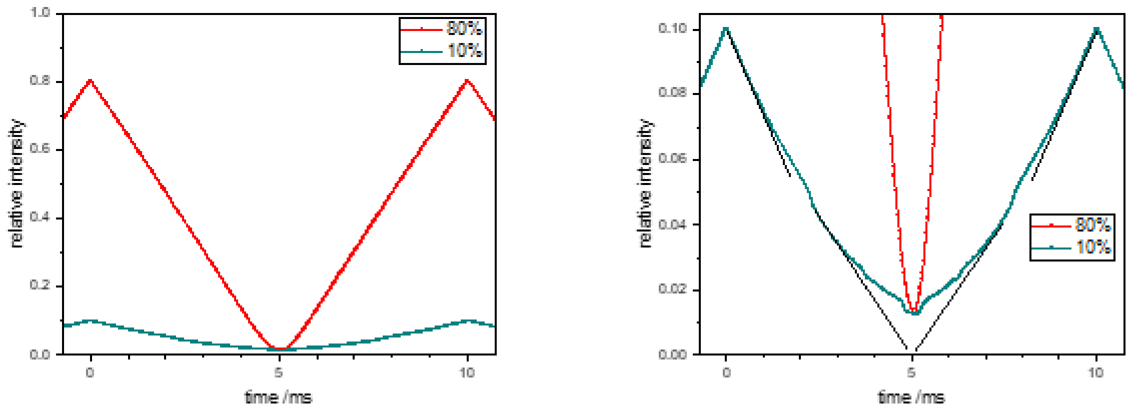

Figure 7: relative waveform of the TLM luminance source for a triangular TLM with 80% and 10% of the maximum luminance (left) visualizing the offset and non-linearity of the waveform below 10% (right).

An installation of TLM and of temporal colour modulation from smart lighting products (RGB and tuneable white LED lamps, see Figure 8) and display for outdoor advertisement was assembled for visualizing TLM by the rolling shutter of camera sensors and gave evidence of limitations regarding reliable measurements and assessments of TLM metrics. These examples also demonstrated the needs and advantages regarding measurement of TLM and temporal colour modulation, i.e. regarding spectral mismatch of flicker meters.

Figure 8: photo of smart LED-based lamps rendering TLM artefacts by the rolling shutter.

An accurate method for the measurement of temporal colour modulation was developed by setting up a 4-channel tristimulus detector head and four of the fast photocurrent meters, coupled by a common trigger signal. This creates a unique tristimulus-TLM meter that allows high-speed measurement of the tristimulus waveforms and temporal evolution of colour coordinates and demonstrated the advantages regarding measurement of TLM and temporal colour modulation. An example for the tristimulus waveform and the variation of the chromaticity coordinate of a tuneable-white LED-based lamp is presented in Figure 9. For a measurement of faster modulations, i.e. with components above 10 kHz, a photocurrent meter with a low-pass filter of 100 kHz was used, which can also be used in a triggered mode to enable a synchronized acquisition for multi-channel measurement of RGB LEDs at short PWM duty cycles of just a few 10 µs.

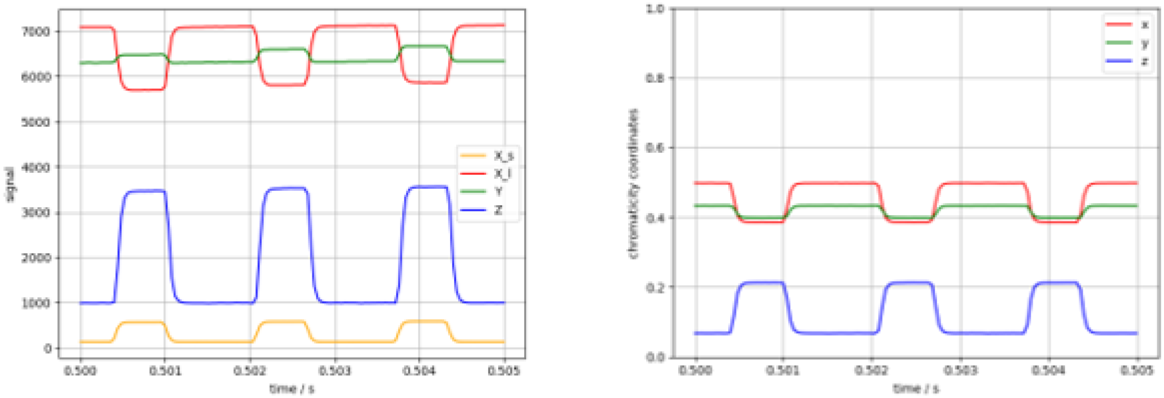

Figure 9: waveform signal of the tristimulus-TLM-meter channels (left) and calculated chromaticity coordinates (right) of the tuneable-white LED-based lamp from Figure 8 centre.

In an experimental study, conducted in an environment illuminated with multiple light sources, image sequences at frame rates of 8 kHz and 4 kHz have been taken with RGB cameras. For each colour channel of the cameras, (namely, red, green, and blue) the TLM waveforms have been extracted for a region of interest marked in the image sequences, see Figure 10. The results reveal the operation principle of tuneable white LED-based lamps, which consist of various types of white LEDs or RGB-LEDs. The study underlined the need to evaluate TLM by (multi-)spectral and spatially resolved measurements. Vivid examples have been obtained by imaging TLM measurements of field scenes: a Christmas tree with different fairy lights; car headlights and daytime running lights; road lighting; a car dashboard with head-up display; E27 socketed LED-based lamps providing RGB and tuneable white light. Heat maps have been generated for relevant TLM metrics, see Figure 11.

Figure 10: photo of a night-time outdoor scene including a car and a HID-based luminaire (left), still image of the high-speed camera indicating the area of interest covering 1184 · 584 pixels for which a sequence at 8000 fps with an integration time of 122 µs was captured (centre), and extracted waveform signal corresponding to the HID-based luminaire (right).

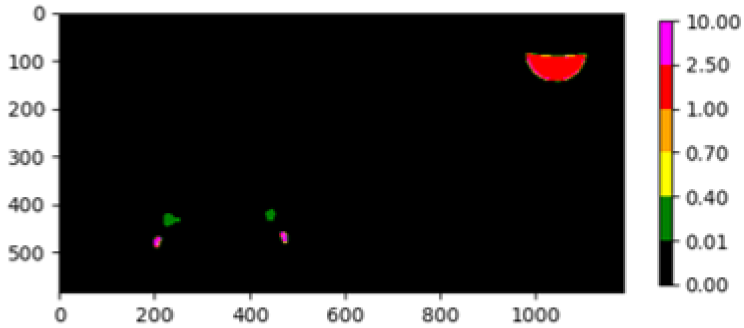

Figure 11: map of the SVM obtained by the high-speed image sequence, from the scene shown in Figure 10 rendering the HID-based luminaire (SVM ≈ 2.3), the PWM-dimmed running lights (SVM ≈ 5.1), and the headlamps based on an incandescent lamp (insignificant SVM).

A commercial high-speed RGB camera was used for multi-spectral TLM imaging measurements in lab-based and field scenes using real time sampling and equivalent time sampling. For multi- and hyper-spectral TLM measurement, a hyperspectral camera was used to measure LED luminaires in office scenes.

Measurements taken with an imaging luminance measurement device (ILMD), on different lamps and luminaires, demonstrated the feasibility of TLM measurements with such devices. Results from this feasibility demonstration resulted in an improvement of the TLM measurement modes: The use of the ILMD to implement a TLM imaging measurement was hindered by issues which had been reported to the manufacturer and were fixed in a revised version of the control software and the device-internal firmware. This solution was successfully verified during the project but not yet picked up by means of demonstrating TLM imaging measurement by an ILMD. Instead, industrial machine-vision cameras (monochrome and RGB) were used to implement and demonstrate also an Equivalent-Time-Sampling (ETS) mode for spatially resolved TLM measurements well above the aliasing frequency. The industrial cameras lack a V(λ) matching, but their lenses allow a change of the aperture (in contrast to many ILMDs that use a fixed aperture) to adjust the device responsivity to the luminance level of the scene. The implemented ETS measurement mode successfully demonstrated the possibility to determine the waveforms and metrics of TLM inside complex scenes with cameras, see Figure 12. Because the parameter range for the integration time is limited by the required frequency resolution, the adaptation to the luminance of the scene is mainly done by adjusting the lens aperture and applying neutral density filters. The main issue that limits the TLM measurement by cameras is the low dynamic range compared to traditional systems, i.e. using a photometer head and a fast photocurrent meter. For scenes with sufficiently low dynamic range contrast, these measurements can be executed automatically. The method of generating the phase shift for the ETS measurement, i.e. by synchronizing it to the mains frequency by a delay trigger or by a continuous sampling, determines whether the waveform measurement is done for the full scene at once or sequentially for recognized TLM regions. The latter requires to analyse the scene for finding regions showing TLM, grouping them by waveform properties to virtual luminaires, and determine the individual base frequency (modulation period) of these regions in a scene image under the condition, that the measured signal is not band-limited, which complicates the signal analysis. The ETS-mode was successfully demonstrated by waveforms for typical light sources, i.e. of a many hundred Hz and PWM duty cycles above 10%, which present significant TLA. Using the ETS-mode with an industrial RGB camera also the measurement of temporal colour modulation from smart lighting products (RGB and tuneable white LED lamps) was successfully demonstrated.

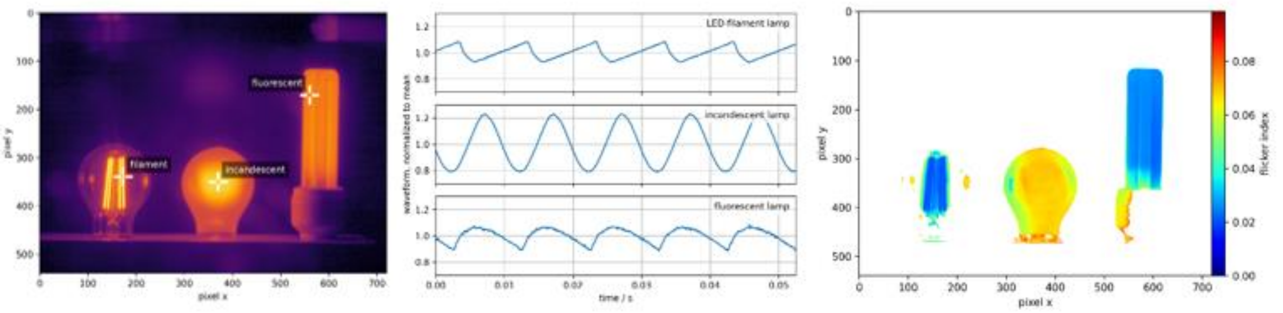

Figure 12: average image of an ETS measurement of a scene with three mains-modulated lamps presenting different peak luminance levels (left), normalized waveform for the three regions of 49 pixels marked in the image (centre), and map of the Flicker-Index rendering also reflections at neighbour lamps (right).

Also, the impact of TLM on ILMD measurements of the average luminance and measurements of spectral irradiance by array-spectroradiometers was demonstrated. Errors as encountered during luminance measurement for glare assessment from artificial light at night caused by high-intensity discharge lamps (HID-lamps), or pulse-width-modulated LEDs have been studied. In addition, the possibility of using conventional cameras that provide a high frame rate mode of up to 1000 Hz, such as compact cameras or smartphone cameras dedicated for slow motion recordings, were investigated. In contrast to these, photos obtained with a long integration time of i.e. 0.05 s or 0.1 s captured during a camera pan can give visual evidence for the phantom array effect, see Figure 13. As such cameras are widely used, this is expected to increase the uptake of results.

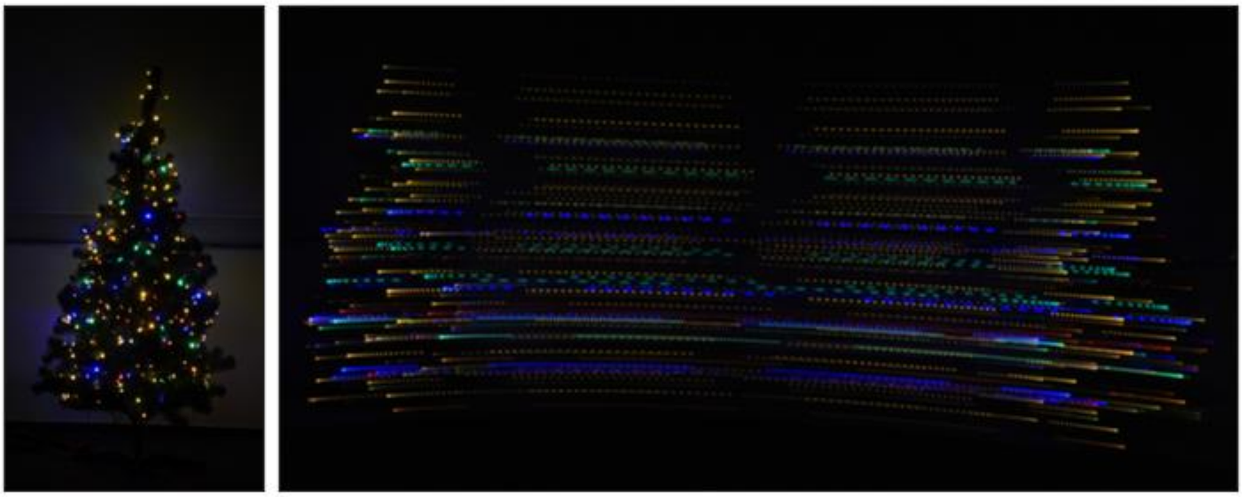

Figure 13: photo of a Christmas tree with different LED-based fairy lights (left) and overlay of a sequence of four images captured with an integration time 100ms during a camera pan (right)

Summary of the key outputs and conclusions

An accurate method for the measurement of temporal colour modulation has been developed. This key output has been picked up by a manufacturer in the development of a 4-channel tristimulus detector head, now available as commercial product. Furthermore, methods have been developed that enable the use of cameras for measurement of spatial resolved TLM, e.g. to generate an SVM heat map. Limitations of latter method e.g., regarding sampling theorem, have been identified, to provide guidance to future users of such methods.

The objective of development of novel methods for measuring TLM of the illuminated environment in extended scenes and for multispectral TLM measurement of light sources has thus been achieved.

4.4 Model for the visibility of the phantom array effect (Objective 4)

Based on an initial literature review, five psychophysical experiments were designed to study the effect of temporal frequency, colour of the light source, saccade amplitude and velocity, and ambient illumination on the visibility of the phantom array effect. The experimental protocols for experiments 1-4 were approved by the Ethical Review Board (ERB) at Eindhoven University of Technology, and for experiment 5, by the Swedish Ethical Review Authority. The following experimental studies have been conducted:

1. Effect of Frequency and Chromaticity (Naïve Observers)
2. Effect of Frequency and Contrast (Naïve Observers)
3. Effect of Frequency and Saccade Amplitude (Naïve Observers)
4. Effect of Frequency and Adaptation Level (Expert Observers)
5. Visibility of the Phantom array effect in real-life applications (Naïve and Expert Observers)

All five experiments used a two-interval forced-choice (2IFC) task for the observers, in which observers need to indicate in which of the two sequentially presented stimuli the phantom array effect is visible to them. Changing the modulation depth in the pair of stimuli in combination with the QUEST+ method (a Bayesian adaptive psychometric testing method), enables adaptive collection of data, thus reducing the number of perceptual experiments needed. By doing so, the visibility threshold of the phantom array effect could be determined for the various lighting conditions.

Experiments

Experiment 1 focused on the effect of temporal frequency and the chromaticity of the light source on the visibility of the phantom array effect. The results of Experiment 1 show an inverted U-shaped bandpass sensitivity function for the phantom array effect as a function of temporal frequency for all three chromaticities (i.e., red, green, and warm white) used in the experiment. The 3rd-order polynomial fit indicates a peak sensitivity at a temporal modulation of 600 Hz in all three cases. This finding is in line with earlier results in literature. However, the experimental peak differs from the provisional model presented in CIE 249:2022, in which the sensitivity peaks around 1000 Hz for an averaged luminance of 1000 cd/m^2. In our study, the luminance is 50 cd/m^2, which might partially explain the discrepancy. There are also substantial individual differences in sensitivity to the phantom array effect. The fitted curves look similar across the three chromaticities used. However, the peak sensitivity is higher for red than for green and white. The MD (Modulation Depth) visibility threshold is about 3% for red, whereas it is 6-7% for green and white. In addition, the low-frequency slope is not as steep for the red colour, compared with the green and warm white colours. This indicates the phantom array effect is more visible at low frequencies for the red colour than for green and white colours. To test the overall effect of colour and frequency on the visibility of the phantom array effect, a linear mixed model (LMM) analysis was performed showing a significant effect of both colour and frequency as well as a significant interaction between them. The viewing scene for a participant is shown in Figure 6.

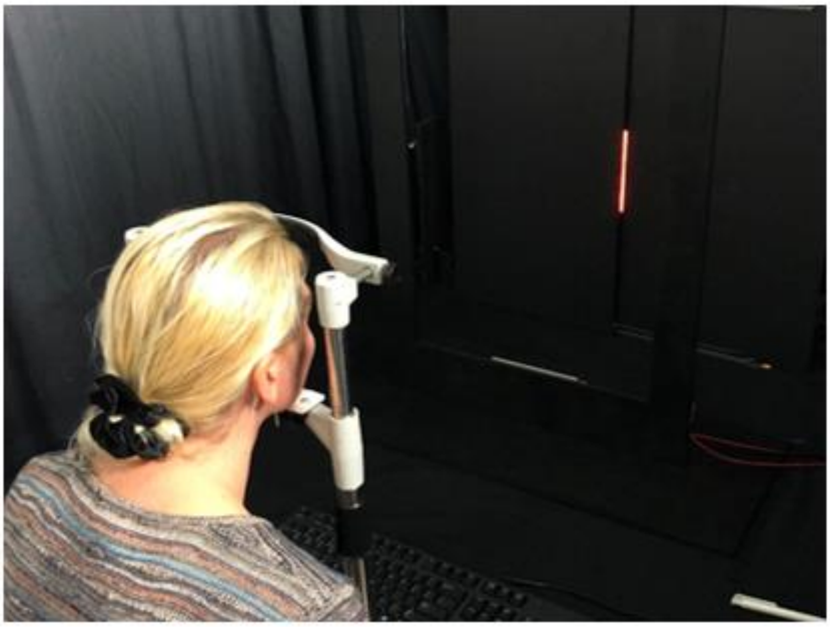

Figure 14: The viewing scene for experiment 1.

In experiment 2, 3 and 4, a narrow slit white light source was used. **Experiment 2** focused on modelling the temporal contrast sensitivity function to the phantom array effect. In this experiment 22 participants were included, and 10 different frequencies were tested. The participants were instructed to view two sequentially presented stimuli (i.e., a reference stimulus that was driven with a direct current (DC), and a test stimulus that was temporally modulated with a sinusoidal waveform) and indicate in which of the two stimuli the phantom array effect was observed. A Bayesian adaptive psychophysical procedure named QUEST+ implemented as a MATLAB Toolbox was used to change the modulation depth of the sinusoidal waveform in the next stimuli pair based on the participant's previous response(s). The resulting data were fitted to determine the visibility threshold (expressed as modulation depth varying between 0 (i.e., DC light) and 100 %). The resulting sensitivity as a function of frequency, averaged over all participants shows that the sensitivity is clearly higher at the medium frequencies, with the maximum at 600 Hz and the sensitivities are substantially lower at the two far ends of the measured frequency range.

A description of the setup (for Experiment 1 and 2) and methods were presented at the CIE Expert Tutorial and Symposium on the Measurement of Temporal Light Modulation in Athens, Greece, October 2022. The results of Experiment 1 were presented at the 30th Quadrennial Session of the CIE (CIE 2023 conference) in Ljubljana, Slovenia, September 2023.

In **Experiment 3** we investigated the effect of saccade amplitude on the visibility of the phantom array effect for one light condition (i.e., in the dark). The visibility threshold was determined at seven temporal frequencies:

80 Hz, 160 Hz, 300 Hz, 400 Hz, 600 Hz, 900 Hz, and 1800 Hz. These frequencies were distributed over the expected range of visibility of the phantom array effect based on results from the first two experiments. Hence, the experiment consisted of a 2 (saccade amplitudes) × 7 (frequencies) × 1 (ambient lighting condition) within-subject design.

The data collection consisted of two sessions, with each session corresponding to one saccade amplitude. The order of the saccade amplitude was counterbalanced, such that half of the participants started with a 20-degrees saccade, while the other half of the participants started with a 40-degrees saccade. The collected data in each session were based on 24 pairs of stimuli (the modulation depth of which was determined with the QUEST+ method) for each of the seven temporal frequencies. Thus, each participant had to assess 168 (= 24 × 7) pairs of stimuli for each saccade amplitude.

The results show that there is a large individual variation in the sensitivity to observe the Phantom Array effect. Comparing the visibility thresholds as a function of frequency for the two different saccade amplitudes, the sensitivity is higher for 40 degrees saccades than for 20 degrees saccades at frequencies below the sensitivity peak at 600 Hz.

In **Experiment 4** we investigated the visibility of the Phantom Array effect under two different ambient conditions (i.e., a rather dark environment vs. a typical office setting). The first part used the same conditions as in Experiment 3, but the participants only made 40 degrees saccades. For the second part, the luminaires in the ceiling of the laboratory were uncovered yielding a vertical luminance at the position of the slit in the black board between 2.5 to 4 cd/m^2, resulting in a contrast of approximately 0.9 with respect to the TLM light source of 50 cd/m^2. Results from Experiment 4 show that the sensitivity is frequency dependent, and that the ambient light level has a substantial effect on the visibility of the Phantom Array effect. It is much more difficult to observe when the contrast is lower.

In **Experiment 5** the objective was to verify the results of the controlled laboratory experiments (1-4) conducted at TU/E and CSTB, in a real-life scenario. One of the most common situations where the Phantom Array effect is reported is when driving at night behind a car with modulated taillights. Therefore, in this study, we conducted a psychophysical experiment where the visibility of the phantom array effect was determined in a real-life context using commercially available taillights. In the laboratory, a setup was constructed simulating viewing conditions closely resembling the real-life situation. The set-up used taillights from a Volvo XC60 modulated with square waves with 50% duty cycle. The modulated light output of the two taillights was temporally synchronized. The experimental setup is shown in Figure 6.

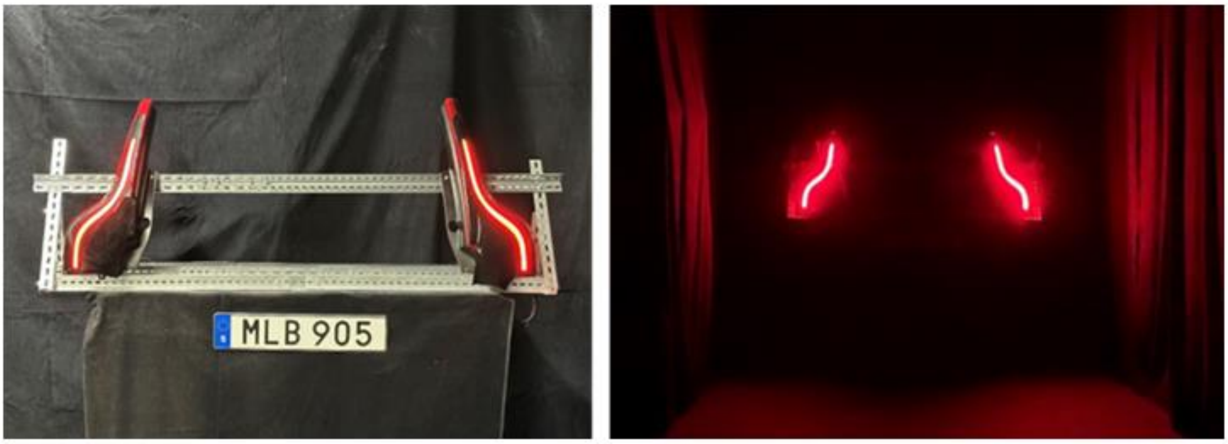

Figure 15: The viewing scene for experiment 5.

The observer was seated at a distance of 7,5 m from the set-up in line with the centre between the two lamps. Since the experiments should resemble a real-life situation, no chin rest was used. Except for the light from the taillights the room was kept dark. The visibility threshold was determined at six temporal frequencies: 100 Hz, 200 Hz, 600 Hz, 1000 Hz, and 1800 Hz.

A total of 20 participants were included in experiment 5. Each participant was presented with pairs of consecutive stimuli, one constant DC and the other modulated, and was instructed to indicate in which of the two cases the phantom array effect was visible. Instead of using an adaptive procedure, fixed levels of MDs for each frequency were used. The settings were selected based on pilot experiments. Each participant went through 186 pairwise comparisons and the stimuli for the different frequencies and MDs were intermixed and presented in a randomized order.

Data showed individual variations in the threshold values for the visibility of the phantom array effect, but the frequency dependence was consistent among most participants. The mean percentage of correct answers for the selected MDs at the frequencies 100 Hz and 600 Hz are shown in Figure 6. We chose the Weibull cumulative distribution function as the psychometric function to fit our data across all six frequencies. The visibility threshold at each frequency was chosen as the modulation depth where the probability of answering correctly is 74% (i.e., midway between 50% (guessing) and 98% (certainty, accounting for a 2% keystroke error rate)).

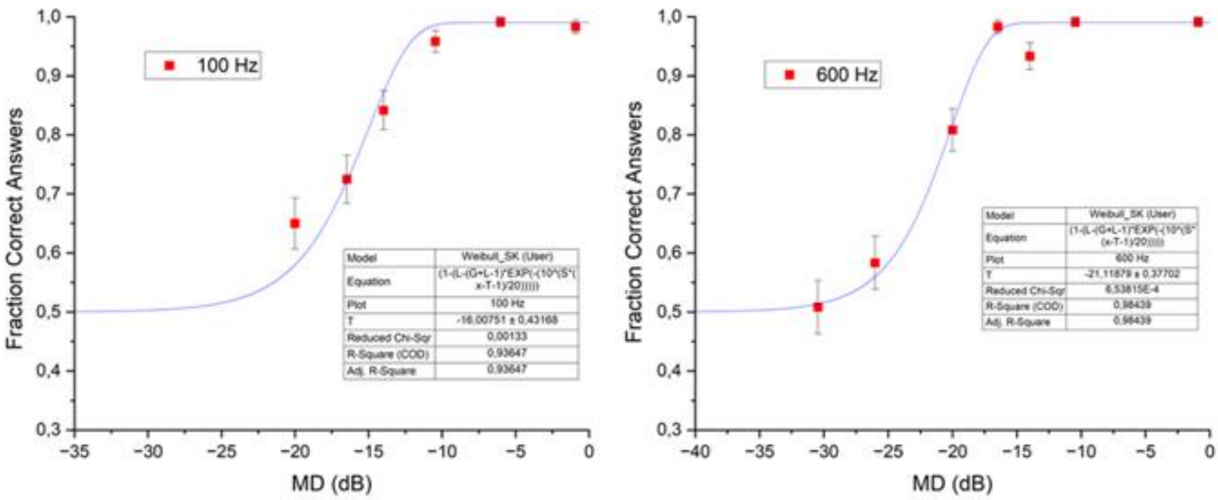

Figure 16: Fraction of correct answers at different MDs for two different frequencies.

The sensitivity curve exhibits a similar bandpass shape to that found in other studies, albeit with a higher peak frequency and a flatter appearance. This may be partially attributed to the use of square wave modulation instead of sine wave modulation. In this experiment, we utilized two light sources with a curved design, whereas many other studies used one single source (often a narrow slit). Additionally, no chin rest was used in this study, allowing the observers to move their eyes more freely. Consequently, this experiment brings new insights into the visibility of the phantom array in real-life situations.

Model development

There are three layers in the model development, which are described below.

1. Practical models (simple numeric fits)

   In the multiple psychophysical experiments that we conducted, variables such as temporal frequency, chromaticity of the light source, saccade amplitude, and ambient illumination were examined. The psychophysical data (the log(Sensitivity) as a function of log(frequency)) were fit with 3-order polynomial equations, and the chi-square values for those fits indicate that all three fits pass the criterion for goodness of fit at the 0.05 significance level. Although the coefficients of those fits differ significantly from each other, those practical functions provide valuable insights into the visibility of the phantom array effect under various conditions, which can give us a good estimation of whether the phantom array effect is visible for an average observer.

2. Development of a visibility measure

   The practical models can be useful in some scenarios. However, only sinusoidal waveforms were used in all the experiments that collected the visibility threshold data (*The square waveform was used in the validation experiment). To develop a measure that quantifies the visibility of the phantom array effect of any kind of waveform, a more complete set of stimuli (i.e., square waveforms and other arbitrary waveforms) should be used in future experiments. This new set of stimuli can help determine a Minkowski norm parameter, following a similar approach to how the stroboscopic visibility measure (SVM) was developed.

3. Development of a model that reflects the underlying visual mechanisms

   In the above two layers, the visibility model is expressed as a function of temporal frequency. Since the phantom array effect is a spatiotemporal visual phenomenon, modelling its sensitivity as a function of temporal frequency alone clearly has its limitations; expressing the sensitivity as a function of a spatially transformed variable (i.e., when the saccade speed is known) seems more appropriate.

<u>Summary of the key outputs and conclusions</u>

The sensitivity curves obtained for the conducted experiments allow the visibility of the phantom array to be accurately predicted for targets and environments similar to the experimental conditions: sinusoidal temporal waveforms and very fine slit in high luminance contrast with the background. With a spatially extended modulated light source, the phantom images created by high modulation frequencies are wider and tend to merge above a certain temporal frequency, creating an effective high frequency cut-off in the visibility curve.

In the case of other waveforms, our results provide a very useful lower bound for the visibility of the phantom array. Our sensitivity curves can be applied to the relative amplitude of the dominant Fourier component of the waveform, as historically suggested by De Lange in 1954 in the case of flicker assessment based on the “ripple ratio” (Lange Dzn, H. de. “Relationship between Critical Flicker-Frequency and a Set of Low-Frequency Characteristics of the Eye.” Journal of the Optical Society of America 44, no. 5 (May 1, 1954): 380. https://doi.org/10.1364/JOSA.44.000380.). It is useful to emphasize that any additional harmonic Fourier components present in the waveform cannot lower the visibility of the phantom array but can only increase it.

A more general model for the visibility of the Phantom Array effect can be built using a formula similar to the model of the stroboscopic visibility measure (SVM). This type of formula is a Minkowski sum of the weighted harmonic components. However, the determination of the Minkowski component would require performing a new set of experiments using temporal waveforms featuring two or more harmonic components, such as a square wave for instance.

A new Technical Committee should be formed at the CIE with the objective of building a unified sensitivity curve and a general visibility measure to describe the phantom array effect. This TC should have members of the teams that have carried out research in this field, including the MetTLM partnership (RISE, TU-e and CSTB). The objective would be to compare the respective results obtained by the different research groups and reach a consensus on a set of sensitivity curves and Minkowski exponents applicable to the most relevant luminous environments. Transferring the results of MetTLM to the CIE is therefore of primary importance to build the currently missing and eagerly expected standard on the phantom array effect. With the new knowledge about this undesirable effect of temporal light modulation, more informed decisions about limit values in different settings can be made, thereby improving the safety, comfort, and overall quality of LED-based lighting systems.

The objective of developing a model for the visibility of the phantom array effect based on perception experiments that measure the visibility threshold for various lighting conditions e.g. modulation frequency, amplitude, shape of the modulation and light level, has been achieved.

5 Impact

The first results of the project, related to calibration of TLM measurement devices, were presented at the CIE Midterm Meeting hosted by MyCIE, the Malaysian CIE committee, in 2021. The project contributed to the CIE Expert Tutorial on the Measurement of Temporal Light Modulation in Athens, Greece, October 2022. The attendees were trained in measurement of TLM, estimation of measurement uncertainties and uncertainties in calculation of predictors of TLAs. The tutorial was followed by a project stakeholder meeting, which was attended by about fifty participants. After the presentations, the consortium and stakeholders engaged in open discussion. Stakeholders endorsed the need for guidance on implementation of TLM models as well as on the propagation of uncertainties. In addition, stakeholders endorsed the need for spectrally resolved TLM measurements, referring to colour-breakup perceived in light sources comprised of multiple temporally modulated coloured LEDs. At the CIE quadrennial session, held in Ljubljana, Slovenia, in September 2023, results of the MetTLM project have been presented by four members of the consortium in a dedicated session on temporal light modulation. Linked to this event, in a meeting of the CIE research forum on matters relating to temporal light modulation, project results have been presented and discussed. In conjunction with the final project meeting at PTB in April 2024 a training session was held, focusing on measurements, measurement uncertainty as well as verification and validation. Using an RGB-based smart lighting product also technical aspects of handheld flicker-meters that cover a huge price range, namely sampling rate and duration, aliasing, signal ringing at steep slopes, offset, and time constants and their dependence on the measurement range as well as digital low-pass filtering, had been demonstrated in the training.

A project website was regularly updated: https://www.mettlm.eu/. All told, 74 people registered on the website to receive periodic project updates via email. Registrants included EU Member State representatives, government experts, test organisations, manufacturers of measurement instruments, NGOs and other associations. As a result of direct engagement with stakeholders, 7 stakeholders confirmed the need for standardized measurement methods for TLM. Results have been presented at meetings of CIE, DIN, IEA SSL Annex and EURAMET TC-PR, which generated further awareness of the project. A YouTube video has been released aimed at explaining definitions related to TLM to the general public, as well as a longer video on the subject of TLM contains an interview with a prominent researcher.

Impact on industrial and other user communities

The availability of reliable TLM measurements and related temporal light artefacts is important for the lighting industry, because the Ecodesign Commission Regulation (EU) 2019/2020 sets limits for flicker and the stroboscopic effect of the light sources and luminaires they bring to the market. The project outcomes have supported the lighting industry in its efforts to demonstrate compliance of lighting products with the regulation. Similarly, market surveillance authorities have benefited from the availability of metrological methods and calibrated TLM measurement instruments, which is required for them to fulfil their role to enforce compliance with the regulation.

The project provided novel methods using multispectral imaging measurement devices to measure TLM of extended scenes or large area luminaires and displays. The findings have already initiated an improvement of the TLM measurement mode implemented in a commercial imaging luminance measurement device (ILMD). The initiated luminance, multichannel, and tristimulus TLM meters were demonstrated regarding their advantages compared to illuminance TLM meters. These results are especially relevant to end users who want to measure the quality of lighting in field installations e.g., in an office space under mixed lighting conditions or on a building façade. The research on the visibility of the phantom array effect of car taillights could provide the automotive industry and lighting manufacturers with a quantitative measure for the visibility of this effect. This could enable them to improve lighting products such that the visibility threshold for the phantom array effect is not exceeded, enhancing the safety and consumer appreciation of their products.

To promote the uptake of the project’s outcomes by the lighting industry and instrument manufacturers, the consortium invited stakeholders from these sectors to participate in the interlaboratory comparison. To increase the number of participants the comparison was joined with the IEA 4E SSL Annex comparison.

The consortium built up LED- and laser-based facilities to characterise and calibrate TLM measurement devices. The first commercially available TLM measurement devices have been tested against the facilities. Further characterisation and calibration of TLM measurement devices supports regulatory compliance assessments. Preliminary tests were conducted on several (commercially available) TLM sources, using a variety of imaging devices, demonstrating the benefit of imaging TLM measurement modes.

In collaboration with stakeholder LightingEurope the project conducted at webinar on “Measurement of lighting with temporal light modulation and EcoDesign”. The webinar was attended by at least 150 participants, with 300 signing up beforehand. A LinkedIn announcement of the webinar gained more than 1000 impressions on the platform.

Impact on the metrology and scientific communities

The project has strengthened the knowledge and measurement capabilities of national metrology institutes on the characterisation and calibration of TLM measurement devices and TLM sources. This has enabled NMIs to establish calibration services of TLM measurement devices and/or reference sources for their stakeholders. The project has published a set of representative computer-generated and real-life waveforms and the corresponding values and measurement uncertainties for flicker and the stroboscopic effect. This has allowed scientists and metrologists involved in TLM measurement to validate their models and uncertainty calculations. Within the project, novel techniques for measuring temporal light modulation of complete scenes have been investigated, based on high-resolution time-resolved and spatially resolved imaging. The development of metrology for this type of measurement, was new and challenging and has not only impacted the field of TLM measurement, but also the wider field of metrology for time and spatially resolved photometry. The project has impacted the research field of human perception of TLM. In particular, it has progressed scientific knowledge on the phantom array effect with the work on the development of a metric for this TLA. More generally, the developed metrology on TLM measurement supported ongoing research on health, performance and safety effects of TLM.

To promote the uptake of the project results by the metrology community, two presentations have been given at the CIE midterm meeting (2021). In the first presentation, a laser-based TLM calibration facility was evaluated for characterisation of TLM measurement devices, in relation to the Ecodesign Commission Regulation (EU) 2019/2020. In the second presentation, the findings of sensitivity analyses of TLM measurements to noise and sampling frequency have been shown. The findings of both presentations have been taken into account in the technical report on measurement of TLM, by CIE 2-89.

At the CIE Expert Symposium on the Measurement of Temporal Light Modulation in Athens, Greece, October 2022, the setup to determine the visibility of the phantom array effect was presented. The first results have been presented as well as an outline of methods that will be used to evaluate the data.

At Lux junior 2023 in Dörnfeld bei Ilmenau, Germany, June 2023, arranged by LitTG and Technische Universität Ilmenau two presentations were given on the characterization of TLM in scenes using imaging devices.

The results of the first phantom array sensitivity experiments, uncertainty propagation and the camera based TLM methods have been presented at the CIE 2023 conference in Ljubljana, Slovenia, September 2023. The results of the 5th phantom array sensitivity experiment will be presented at the IES conference in New York, USA, August 2024.

To facilitate impact a Zenodo community has been established: mettlm20nrm01, where data items related to TLM in general and MetTLM specifically will be curated and collected. So far, the dataset posted there has been viewed 320 times and downloaded 120 times.

Impact on relevant standards

The project has contributed to the work of the technical committee under the CIE, TC 2-89 “Measurement of Temporal Light Modulation of Light Sources and Lighting Systems”. One of the project deliverables is a GPG on metrological methods, instrumentation and conditions for calibration of TLM measurement devices, which has contributed to an international CIE standard on TLM measurement. CIE was the Chief Stakeholder of the project and the involvement of TC 2-89 in the stakeholder board of the project ensured that the needs of CIE were met and that project results were taken up effectively. Since CIE and CEN have a formal agreement on technical cooperation, it is expected that CEN will adapt the CIE standard once available. This will help CEN to respond to the mandate issued by the European Commission (Ares(2013)205169), requiring the development of standardisation on LED lighting and the development of standards for flicker and the stroboscopic effect. This project delivered a significant contribution to scientific data on the sensitivity for the phantom array effect and the development of a metric for this TLA. This will contribute to the work of CIE continuing work with visual aspects of time-modulated lighting systems. Other standards and guidelines that are likely to be impacted by this work are IEC TR 63158:2018 and 61547-1:2020.

Over the 36 months duration of the project, the consortium was actively involved in the following international standardisation committees: CIE TC 2-89, CIE TC 2-96, CIE TC 2-97, CIE RF-02, CEN TC 169, ISO TC 274 JWG1, and the national standardisation committees DIN- NA058-00-03AA, IEA 4E SSL Annex and DS-061. On behalf of the consortium direct input has been provided to the draft technical report of CIE TC 2-89, to ISO/CIE 19476:2024 "Characterisation of the performance of illuminance meters and luminance meters", which should be published in 2024 and falls under the responsibility of CIE TC 2-96, and to CIE S 025/E:2015 Test Method for LED Lamps, LED Luminaires and LED Modules, which should be published in 2024 and is being prepared by CIE TC 2-97.

Longer-term economic, social and environmental impacts

The project outcomes have supported the execution of the EU Ecodesign Commission Regulation (EU) 2019/2020, which protects EU citizens against potentially negative health, performance and safety effects resulting from modulated light sources like LED lighting. Having only compliant light sources on the market protects people against these potentially negative effects like decrease of performance, fatigue, eye strain or more severe effects like migraine episodes or epileptic seizures.

This EU regulation currently focuses on light sources that produce flicker and/or the stroboscopic effect and will be revised in 2024. Requirements on dimmable light sources, known for exhibiting TLM, will probably also be included in the revision.

The project indirectly contributed to energy saving and reduction of the environmental impact of lighting by supporting regulations that put limits on the allowed TLM of light sources. The ability to enforce compliance with regulations, based on appropriate standardisation, supported the adaption of LED lighting by the public and the phase-out of incandescent lighting. This supports European and international goals on energy saving and reduction of the emission of greenhouse gasses. End users such as building owners and governmental organisations benefited from the outcomes of the project, since it supports them in their efforts to save energy and cost by using efficient lighting.

6 List of publications

- Dekker, P.R., van Bloois, A.L. (2023) 'Facility for calibration of photometers for measurement of temporal light modulation', *Lighting Research & Technology* p. 1.4771535231e+14. Available at https://doi.org/10.1177/14771535231159289
- Ikonen, E. et al (2023) 'Digital implementations for determination of temporal light artefacts of LED luminaires', *Lighting Research & Technology*(0) p. 0-12. Available at https://doi.org/10.1177/14771535231212404
- Nordlund, R. (2022) 'Validation for measurement of Temporal Light Artefacts on LED light sources', Aalto University. School of Electrical Engineering. Available at https://aaltodoc.aalto.fi/handle/123456789/113709
- Stein, A., Wiswesser, P., Ledig, J. (2023) 'Auswertung der zeitliche Lichtmodulation unter Verwendung von bildauflösenden Messgeräten', *Lux Junior*, 2023 p. 10.22032/dbt.55787. Available at https://www.db-thueringen.de/receive/dbt_mods_00058613

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