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The Society of Light and Lighting

Temporal light modulation (TLM) is a change in the luminous quantity or spectral distribution of light with respect to time of either a light source or a lighting system. These changes arise because of the device or system design, including drivers and control gear, and because of fluctuations in the electrical supply. In former times, families of lighting products all exhibited the same (or approximately the same) TLM characteristics: For example, AC-powered incandescent lamps shared the property of TLM in a sinusoidal wave at twice the mains frequency and 4%–10% modulation depth. T8 fluorescent lighting systems with electronic ballasts operated with a dominant frequency between 20 kHz and 40 kHz and little modulation depth. Previously, knowing the lighting technology provided sufficient information about the TLM properties of a lighting system; today, this is impossible without measuring the system directly.

Light-emitting diode (LED) light sources and lighting systems exhibit a very wide variety of TLM characteristics because of the variety of ways in which the products can be designed and because LEDs inherently respond very quickly to the driving current.[1,2] Moreover, TLM is sometimes deliberately introduced to LED lighting systems through the use of pulse-width modulation (PWM) to control the light intensity. When using PWM, the light output exhibits a 100% modulation depth at constant frequency but with variable duty cycle depending on the desired intensity. Most systems of which we are aware use PWM at frequencies higher than twice the mains frequencies (e.g., 300–400 Hz).

The importance of this phenomenon rests in the fact that TLM can be a cause of adverse visual, behavioural and health effects on viewers.[2–4] The undesirable visual perceptions are flicker, the stroboscopic effect and the phantom array effect; these are collectively known as temporal light artefacts.[1] Among the unanswered questions is the relative importance of the visual effects of TLM, as compared to effects on health or task performance.[5] Some argue that the visual effects in common interiors are little more than an annoyance provided that the light source does not exhibit flicker; others argue that these visual perceptions relate to more serious phenomena, at least for some sensitive people.[6]

In 2015, the IEEE published a recommended practice that included an in-depth risk assessment of possible heath and behavioural outcomes, taking into account both the severity of the outcome and the probability of its occurrence.[2] The risk assessment component of the hazard analysis took into account the strength of the evidence; notably, many of the outcomes were judged to be in need of more evidence to support evidence-based guidance on limits for TLM. This also was the conclusion drawn by the 2017 CIE stakeholder workshop[3] and the 2019 ANSES report.[4]

Researchers have risen to these challenges with several recent publications in this journal and others, which is most welcome; nonetheless, there remains disagreement concerning the meaning of these findings for recommendations and regulations. We comment here,

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very briefly, on the state of knowledge, focusing primarily on publications from *Lighting Research and Technology*, and propose a few priority topics for research attention.

It has long been the case that the visual effects of TLM receive the most research attention, and these were the basis for the limits in the only institutional recommended practice on the topic to date.[2] These effects occur after very short exposures and are therefore easy to test.[1] For example, Perz et al. developed the Stroboscopic Visibility Measure[7] to predict the stroboscopic effect from a metric derived from the measured light source TLM. This metric is founded on the principle of threshold visibility and is normalized so that the value of the SVM for threshold visibility (50% likelihood of seeing the stroboscopic effect) of the average person is 1.0.[5,7]

According to Scopus, the eighth-most-cited paper from this journal (cited 141 times as of this writing) is the 1989 paper by Wilkins, Nimmo-Smith, Slater and Bedocs[8] in which fluorescent lighting in an office was changed between magnetic ballasts and high-frequency ballasts. Complaints of headaches and eyestrain were reduced by the high-frequency operation of the linear fluorescent lamps, but the effect was pronounced only for those with a tendency to experience headaches and eyestrain. That is, on average across the whole sample the effects were marginal, but there appears to have been a subpopulation of sensitive individuals who experienced the adverse effects of the TLM more powerfully. This outcome occurred despite the large windows in the offices, which would have the effect of reducing the influence of the electric lighting conditions during daylight hours.

That is, in the general population it can be difficult to detect the effects of TLM. Veitch and McColl[9] observed an effect of TLM (also manipulated using fluorescent lighting ballasts) only on a visually difficult task in a repeated-measures experiment under restrictive viewing conditions, and with young adult participants. Sekulovski *et al.*[10] conducted a field intervention study with conceptual similarity to the original Wilkins *et al.*[8] paper, but did not find that there was any difference in headache incidence between LED lighting with an SVM value of nominally 1.34 and one of 0.47. They appear not to have had data concerning the participants' individual differences in sensitivity, so it is unknown whether the most-sensitive individuals might have had a different experience than the group overall. Moreover, the experimental space had large windows and included desks at varying distances from the window, so that there was considerable variability in the effective SVM of the conditions to which participants were exposed both across the space and during the day as well as an unknown additional variability in the SVM experience of individuals as they moved throughout the space during the day. Thus, there are several reasons why the expected effect of SVM on headache incidence was not observed.

Veitch and Martinsons[11] studied stroboscopic visibility and the acceptability of conditions for a set of commercially available lamps varying in SVM, focusing on young adults (thought to be more sensitive) and including a measure of sensitivity to visual discomfort. The relationship between the light source's SVM value and participants' reporting of stroboscopic visibility (namely, a rapid, non-linear increase in stroboscopic visibility as SVM increased above 0.4) were the same for groups high and low in sensitivity to visual discomfort, but the high-sensitivity group did report that the conditions were more annoying than the low-sensitivity group when the SVM value of the light source was 1.4 or 3.0. Given the very short exposures, Veitch and Martinsons argued that this finding merits a greater focus in future research upon more sensitive individuals. Individuals who are more sensitive to visual discomfort also have a higher TLM frequency threshold for detecting the phantom array effect than those who are less sensitive (up to 11 kHz, vs. the 6 kHz average threshold).[12]

The renewed focus on effects beyond visual perception seen in Sekulovski *et al*.[10] is important. Zhao *et al*.,[13] with a small sample size, examined brain activity, eye movement, the stroboscopic effect and cognitive performance in a repeated-measures experiment with nine TLM conditions chosen in relation to the IEEE 1789-2015 recommendations.[2] They found that the conditions identified as being high-risk conditions in IEEE 1789-2015 caused greater cortical arousal and, in some cases, higher ratings of task difficulty even when cognitive performance was unaffected.

The rapid adoption of LED lighting has created pressure to develop recommendations to limit the risk of such adverse effects. Whether in the form of recommendations[2] or regulations,[14] these are invariably controversial.[5,15] Debate and discussion of these various approaches to establishing the suitable metrics and the limit values on them are important and necessary, of course; but more and better information on which to base these discussions would prevent a continual revisiting of old disagreements. Specifically, the world would benefit from more information to address the following open questions, among others:

- What are the effects of TLM in the population subgroup of people who are susceptible to visual stress?
- What are the effects of varying TLM conditions on outcomes beyond visual perception (i.e., physiological, behavioural and health effects)?
- Given that much emphasis has been placed on dominant frequency and modulation depth as predictors of outcomes, what are the effects of other possibly influential parameters, such as duty cycle and waveform?

It should go without saying that strong research designs, adequate sample sizes, and clean measurements of both stimulus conditions and outcome measures will be required to provide the strong evidence base upon which to build future recommendations, standards and regulations. Exactly what those documents ought to say will be the result of consensus processes in various communities,[3] but more and better research is needed as inputs to the discussions.

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