

International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

TECHNICAL NOTE

Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models

CIE TN 006:2016

CIE Technical Notes (TN) are short technical papers summarizing information of fundamental importance to CIE Members and other stakeholders, which either have been prepared by a TC, in which case they will usually form only a part of the outputs from that TC, or through the auspices of a Reportership established for the purpose in response to a need identified by a Division or Divisions.

This Technical Note has been prepared by CIE Technical Committee 1-83 of Division 1 "Vision and Colour" and has been approved by the Board of Administration as well as by Division 1 of the Commission Internationale de l'Eclairage. 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.

Any mention of organizations or products does not imply endorsement by the CIE. Whilst every care has been taken in the compilation of any lists, up to the time of going to press, these may not be comprehensive.

© CIE 2016 - All rights reserved

The following members of TC 1-83 "Visual Aspects of Time-Modulated Lighting Systems" took part in the preparation of this Technical Note. The committee comes under Division 1 "Vision and Colour".

Sekulovski, D. (Chair)	Netherlands
Chou, P.-T.	Chinese Taipei
Couzin, D.	Germany
Dakin, J.	USA
Itoh, N.	Japan
Lee, C.-S.	Korea
Lee, T.-X.	Chinese Taipei
Perz, M.	Netherlands
Pong, A.B.-J.	Chinese Taipei
Poplawski, M.	USA
Vogels, I.	Netherlands
Wang, L.	China
Whitehead, L.	Canada
Wilkins, A.	United Kingdom
Yamauchi, Y.	Japan

CONTENTS

Summary	1
1 Introduction	2
1.1 Background	2
1.2 Scope	3
1.3 Structure of the document	4
2 Terms, definitions and fundamentals	5
2.1 Introduction	5
2.2 Physical characteristics of time-modulated lighting systems	5
2.2.1 Waveform	5
2.2.2 Time characteristics	5
2.2.3 Intensity characteristics	6
2.2.4 Spatial characteristics	6
2.3 Visibility aspects of time-modulated light	7
2.4 General definitions	7
3 Literature overview	8
3.1 Fundamental studies and models	8
3.2 Standardized measures to predict visibility of temporal light artefacts	9
4 Methodologies for quantification of visibility of temporal light artefacts	11
4.1 Introduction	11
4.2 Capturing the waveform	11
4.2.1 Linearity and sensitivity	11
4.2.2 Sampling frequency and sample duration	11
4.2.3 Measurement resolution	11
4.2.4 Normalization of the data	12
4.3 Frequency domain analysis	12
4.3.1 Discrete Fourier transform	12
4.3.2 Sensitivity normalization	12
4.3.3 Visibility measure	12
4.3.4 Example embodiments	13
4.4 Time domain analysis	15
4.4.1 Introduction	15
4.4.2 Temporal filtering	16
4.4.3 Computing short-term variance and adjustment	16
4.4.4 Statistical processing	16
4.4.5 Example embodiment	16
5 Recommendations and future work	17
References	17

Summary

The fast rate at which solid state light sources can change their intensity is one of the main drivers behind the revolution in the lighting world and applications of lighting. Linked to the fast rate of the intensity change is a direct transfer of the modulation of the driving current, both intended and unintended, to a modulation of the luminous output. In turn, the light modulation can give rise to changes in the perception of the environment. While in some very specific entertainment applications a change of perception due to light modulation is desired, for most everyday applications and activities the change is detrimental and undesired. These changes in the perception of the environment are called "temporal light artefacts" (TLAs) and can have a large influence on the judgment of the light quality. Moreover, the visible modulation of light can lead to a decrease in performance, increased fatigue as well as acute health problems like epileptic seizures and migraine episodes.

The potential negative impact of temporal light artefacts has prompted lighting manufacturers, lighting application specialists, universities and governments to look for ways to measure the impact and come to a better understanding of the temporal quality aspects of lighting systems. In this context, the CIE formed Technical Committee (TC) 1-83 "Visual Aspects of Time-Modulated Lighting Systems".

This Technical Note (TN) is an intermediate product of the work of the TC. In the first part of the TN, new definitions for the perceptual effects modulated light can produce are given. In the second part, an overview of the relevant literature is given as well as an overview of the parameters that influence the visibility of the different TLAs. The last part gives a description of two methods, one in the time domain and one in the frequency domain, which can be used to quantify TLAs. Furthermore, three implementations of the general methods into specific visibility measures are given as an example.

1 Introduction

1.1 Background

Solid state lighting has revolutionized the world of lighting and lighting applications. The introduction of small, bright light sources which can change intensity at a very high rate and which have an almost arbitrary spectrum has profound influence on lighting quality (Schubert & Kim, 2005; Schubert et al., 2006). While in traditional lighting, the search for optimal light was limited to the capabilities of the technology, the almost limitless capabilities of solid state lighting call for a more fundamental approach, starting from human perception, and not from the hardware limitations.

Some of the technological advantages can introduce perceptible side effects that were either absent or less prominent in traditional lighting systems. One such advantage is the fast reaction of solid state light sources to the driving current. The response time can be as short as a couple of nanoseconds and results in an almost instantaneous translation of the driving current to the luminous output. As the driving current of most electric light sources is modulated, so is the light output intensity and colour. The simplest and most common source of modulation is unintended and results from the supply of the lighting equipment with mains power, usually modulated at 50 Hz or 60 Hz or twice these frequencies through a rectifier. Further modulation can originate from interactions between the driver and dimmer electronics or as a result of disturbances in the mains power induced by other loads on the network.

The fast reaction of solid state light sources is in sharp contrast to the reaction times of previous generations of electric light sources. Incandescent and halogen sources have emissions based on thermal process that are slower than electrical processes. This is evident in the so-called “afterglow” effect of an incandescent lamp being switched off. Fluorescent sources typically use phosphorescent materials with time constants in the order of 200 ms to transfer the UV radiation produced by the mercury vapour into visible radiation. In this case, the slow phosphor acts as an optical low-pass filter on the output of the fluorescent lamp. Metal halide lamps are well known for their inability with respect to temporal modulation. Many of them need more than 30 min after switching off before they can be switched on again.

Temporal light modulation can also be intended and is used for control of intensity and colour. Using temporal modulation ensures that the solid state light sources are always driven in a similar operating range and results in simpler, usually linear, models of their behaviour (Pousset et al., 2010). Examples of such driving schemes are pulse width and pulse density modulation, often used in colour-tuneable light sources. Figure 1 below and Figure 2 in Clause 2 depict examples of time-modulated light signals, from unintended modulation arising from AC mains and from intended modulation produced by a system that uses a pulse width modulation scheme, respectively.

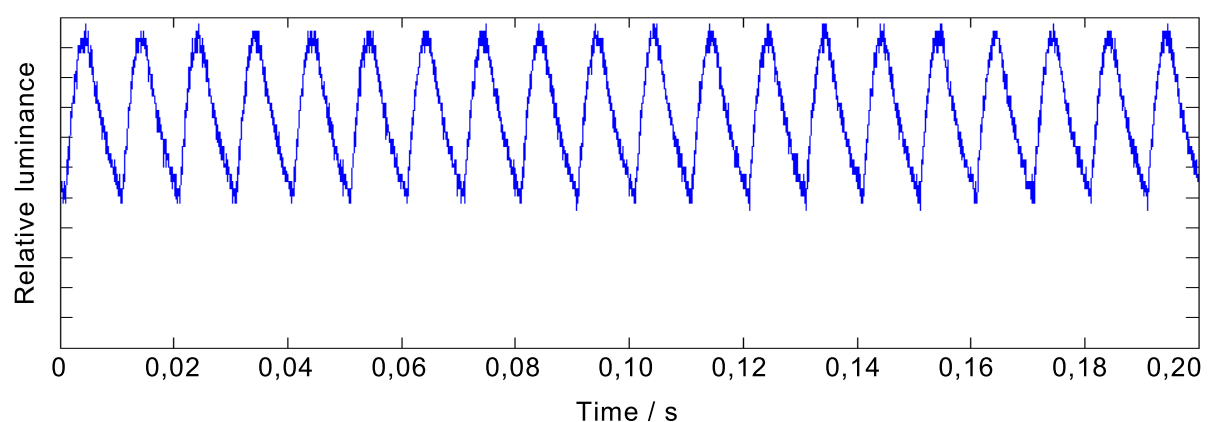


Figure 1 – Example of a time-modulated light output (unintended light modulation over time caused by AC mains)

Both intended and unintended sources of light modulation can give rise to changes in the perception of the environment. While in some very specific entertainment applications a change of perception due to light modulation is desired, for most everyday applications and activities the change is detrimental and undesirable. These unwanted changes in the perception of the environment are called “temporal light artefacts” and can dramatically change the visual environment as compared to natural light and previous generations of light sources. Moreover, the modulation of light can lead to a decrease in visual performance, an increase in fatigue, and acute health problems such as epileptic seizures and migraine episodes (Wilkins et al., 2010). Understanding the way that light modulation influences perception and the influence of the technological parameters on light modulation is therefore very important in the application of solid state lighting.

The need for understanding the perception of temporal light artefacts is increased by the fact that limiting the temporal modulation of light sources introduces compromises to the cost, features, or lifetime of the source, for both intended and unintended modulation. In the case of intentional modulation, lowering the visibility of temporal light artefacts can be achieved by increasing the driving frequency of the system, which can lead to higher material costs, a decrease in efficiency (Mulligan et al., 2007) and a decrease of the capabilities of the system. Examples of such decreases of capabilities are the loss of the possibility for dimming below a given level or observing visible steps between the intensity levels (Sekulovski et al., 2011). A driving frequency within a given range can also introduce other problems like audible noise (Garcia et al., 2011). To limit the influence of the unintentional sources of modulation on the light output, additional measures have to be implemented. These additional measures may result in increased material cost, increased size, lower efficiency, and lower lifetime of the light sources (Arias et al., 2012). As the main cause of this type of modulation is the lack of power in part of the AC cycle, the usual remedy is to provide power storage in the form of electrolytic capacitors. Their use is the main cause of the increase in cost and size, and consequently in the decrease of lifetime of the drivers (Arias et al., 2012). All the above mentioned issues are aggravated in the presence of legacy dimmers (Rand, 2007). Thus, the design of LED driving electronics entails trade-off between lowering the visibility of temporal light artefacts, efficiency of the produced light, and the features, lifetime, cost, and size of the light sources (Arias et al., 2012).

The potential negative impact of temporal light artefacts has prompted lighting manufacturers, lighting application specialists, universities, other standardization bodies (IEEE, 2015), and governments to look for ways to quantify the impact and to come to a better understanding of the temporal quality aspects of lighting systems (Poplawski & Miller, 2013). For this reason, in 2011 the CIE formed TC 1-83 “Visual Aspects of Time-Modulated Lighting Systems” to address this issue.

The terms of reference of the TC are

1. To investigate and report on current research on the perception of visual artefacts of temporally modulated lighting systems, including flicker, the stroboscopic effect, and the phantom array effect.
2. Design methodology and gather data on the visibility of temporal artefacts.
3. Build a model for the visibility of temporal artefacts and their dependence on environmental, demographical and lighting parameters.

This document is an overview of the current understanding of the methods to quantify the visibility of temporal light artefacts.

1.2 Scope

In line with the terms of reference of the TC, the scope of this document covers the visible effects of time-modulated lighting systems. Almost all effects that can be directly perceived by a human observer in an environment that includes time-modulated light sources is in the scope of the TC and this TN. This includes both direct observation of the temporal modulation (flicker and flashes) and interactions with the movement of the observer or objects within the environment.