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ABSTRACT Three experiments that measure the visibility of periodic flicker are presented. Temporal light modulations were presented to a large visual field to make the results valid for general lighting applications. In addition, the experiments were designed to control for flicker adaptation. In the first experiment, the sensitivity of human observers to light modulations with a sinusoidal waveform at several temporal frequencies up to 80 Hz was measured. The results showed that the sensitivity to flicker (that is, the inverse of the Michelson contrast) is as high as 500 for frequencies between 10 and 20 Hz, which is more than twice the maximum sensitivity reported in the literature. In the second experiment, the sensitivity to flicker for light modulations with complex waveforms, composed of two or three frequency components, was measured. Sensitivity to flicker was found to be higher than the sum of the sensitivities of the individual frequency components of the complex waveform. Based on these results, we defined the flicker visibility measure (FVM), predicting flicker visibility by a weighted summation of the relative energy of the frequency components of the waveform. In the third experiment, sensitivity to realistic waveforms (that is, waveforms of light emitting diode [LED] light sources available on the market) was measured. The flicker predictions of FVM showed a high correlation with the experimental data, in contrast to some other existing flicker measures, including flicker index and percent flicker, demonstrating the usefulness of the measure to objectively assess the visibility of periodic flicker for lighting applications.

KEYWORDS flicker, quality of light, temporal light artefacts, visibility threshold, visual perception

1. INTRODUCTION

In recent years, solid state lighting (SSL) sources, such as light emitting diodes (LEDs), have rapidly replaced traditional lighting, such as incandescent lightbulbs and fluorescent light tubes. This is because they offer a number of advantageous features, one of which is their fast response to changes in the driving current. This characteristic can be used to easily control the light output intensity and color, but it may also result in undesired changes in the perceived light output, called "temporal light artefacts." Unfortunately, many LEDs introduced on the market may have such temporal light artefacts. An exposure to such modulated light can have a number of negative consequences. It is commonly known that it can be irritating, but it can also result in visual discomfort [Stone 1992], can deteriorate task performance [Jaén and others 2011; Veitch and McColl 1995], and, for some

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people—for example, those suffering from photosensitive epilepsy—might cause negative health effects [Debney 1984]. In order to find the right balance between the cost of the light source and its light quality, it is important to better understand the occurrence and visibility of temporal light artefacts.

One of the visible artefacts that may occur in the light output of temporally modulated systems is flicker. Flicker can be periodic and aperiodic (like flashes and transient effects); the former is the focus of the current study. The CIE defines flicker as "the sensation of visual unsteadiness induced by a light stimulus whose luminance or spectral distribution fluctuates with time" [CIE 2011, term 17-443]. Because this definition can lead to ambiguity in the classification of other temporal artefacts, we define flicker in a manner consistent with recent work of CIE [2016] as "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." Fluctuations in the light stimulus with time include periodic and nonperiodic fluctuations and may be induced by the light source itself, the power source, or other influencing factors. "Static observer" is defined as an observer whose gaze is directed at a fixation point and therefore does not make *large* eye movements. Large eye movements exclude microsaccades, which are involuntary saccades that occur spontaneously during intended fixation. Microsaccades amplitudes vary between 2 and 30 min-arc in a variety of tasks [Engbert and Kliegl 2003], and an observer making such microsaccades is considered static. Other temporal light artefacts, like the stroboscopic effect and the phantom array effect (ghosting), only occur when either the observer or the environment is nonstatic [Frier and Henderson 1973; Hershberger and Jordan 1998].

Flicker visibility has been studied extensively in the past. It has been shown that it depends on many parameters, including the temporal frequency of the light modulation, the magnitude of the modulation, the shape of the waveform, and the light intensity [for example, Bullough and others 2011; De Lange 1958, 1961; Kelly 1961]. The relation between flicker visibility and temporal frequency is described by the temporal contrast sensitivity function (TCSF). It is obtained by measuring people's sensitivity to light that varies sinusoidally over time for a number of frequencies. The sensitivity corresponds to the reciprocal of the modulation depth at which flicker is just visible. Modulation depth is defined as the Michelson contrast:

$$MD = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}, \quad (1)$$

where $L_{\min}$ is the minimum luminance and $L_{\max}$ is the maximum luminance emitted by the light source in one cycle of the fluctuation. Modulation depth ranges between 0 and 1; sensitivity ranges between 1 and infinity. TCSFs have been measured, for instance, by De Lange [1958] and Kelly [1961] for several retinal illuminance levels. The curves measured by De Lange show that for illuminance levels higher than 3.75 trolands (that is, photopic vision) sensitivity increases with frequency and peaks around 8 Hz, after which it decreases to a minimum sensitivity of 1 at a frequency of 60 Hz, called the "critical fusion frequency" (CFF). The CFF depends on light level, and Kelly [1961] showed that it maximally reaches 80 Hz. Kelly's curves show that for illuminance levels higher than 7.1 trolands, there is a much steeper rise of sensitivity at low frequencies compared to De Lange's curves and the peak sensitivity occurs at higher frequencies (10–20 Hz). Kelly argued that these differences originated from employing different stimuli. De Lange used stimuli consisting of a 2° flickering test field in central vision, with a 60° surrounding field at the same average light level. Kelly used a flickering test field whose luminance was uniform in an area of about 50° and diminished to zero at 65°. Kelly concluded that the difference at low frequencies is an artefact resulting from the use of the sharp-edged, 2° field of the flickering stimulus [Kelly 1959]. It should be noted that in both De Lange's and Kelly's studies, visibility thresholds were obtained by the method of adjustment, with the observer encouraged to take as much time as necessary to reach the threshold. This means that the observer was increasing and decreasing the modulation depth of the stimulus at a given frequency until flicker was just not visible. However, similar to other visual percepts, flicker sensitivity is attenuated after prolonged exposure to a flickering stimulus, an effect known as "flicker adaptation" [Shady and others 2004]. This might have resulted in an underestimation of the sensitivity values in both studies and, hence, an overestimation of the visibility thresholds.

De Lange [1961] showed that flicker visibility also depends on the shape of the waveform of the light fluctuation. He measured the sensitivity to flicker for differently shaped waveforms, including a sinusoidal modulation and a square wave modulation. He showed that when sensitivity was expressed in terms of the amplitude of the fundamental Fourier component of the waveform, the sensitivity was independent of the wave shape. Therefore, given the modulation threshold for sine waveforms, it is possible to predict the modulation threshold for waveforms with other shapes. However, this only applies to periodic waveforms for which the amplitudes of the higher frequency components are much smaller than that of the fundamental frequency. Current LEDs can have complex waveforms, with high- and low-frequency components at any relative amplitude. Therefore, it is possible that not only the fundamental frequency but other frequency components significantly contribute to flicker visibility. The flicker perception for these types of waveforms was studied by Levinson [1960], who measured visibility of waveforms composed of two sinusoidal components at frequencies f and $2f$. First, he measured the modulation threshold of each of the components separately; then he summed these waveforms at their respective thresholds and measured the modulation threshold of the resulting composite waveform. Levinson [1960] showed that the amplitude of the composite waveform needed to be reduced by 30% on average to reach the visibility threshold. He concluded that the flicker visibility threshold depended on waveform and not on the energy in the fundamental frequency alone.

To have simpler means than the TCSF to communicate the amount of perceived flicker of temporal light modulations, a number of measures have been developed in the past. For a measure to be useful for lighting applications it has to accurately describe the effect of frequency and waveform on flicker visibility, as described above. Eastman and Campbell [1952] introduced the flicker index (FI), which was adopted by the IESNA [Rea 2000], defined as the area above the average light output divided by its total area for a single cycle of a periodic modulation. The FI can vary between 0 and 1, and IESNA recommends that for good lighting quality it should remain below 0.1. FI is a widely used criterion in industry to predict flicker visibility. However, the calculation of FI is based on one cycle of light modulation, so it does not account for the effect of frequency. In addition, it is based on integration of the area above the waveform's average light output and its total area, so it only partially accounts for the effect of waveform. Another measure used to describe flicker perception is the percent flicker (PF). It describes the maximum percentage luminance difference within one cycle of a periodic light modulation with respect to the sum of its minimum and maximum luminance. The PF is also referred to as the peak-to-peak contrast, the Michelson contrast, or the modulation depth (MD), and its definition is given in (1). PF is based on one cycle of modulation, so it also does not account for the effect of frequency. Further, it is based on luminance peaks, so it does not account for the effect of waveform either. The International Electrotechnical Commission (IEC) has developed the flickermeter method, which predicts flicker visibility of light modulations caused by rapid voltage fluctuations in electrical power systems [IEC 2010, IEC 2015]. This method consists of a few blocks, one of which simulates the human visual system response to flickering light based on the TCSF of De Lange. The flickermeter method yields a short-term flicker indication, P_{st}, over a 10-min period and its associated limit $P_{st} = 1$ defines the threshold of irritability. The IEC model considers the incandescent lamp as the reference, but by removing the block that simulates the incandescent lamp, P_{st} can be used as a general measure to predict the visibility of luminance modulations. However, the basis of the flickermeter is the TCSF of De Lange, who used sharp-edged stimuli at a relatively small size of 2° visual field, which might not be suitable for general lighting applications, where the stimulus covers almost full visual field. Lehman and others [2011] recognized that it is common that a waveform of LED light source is composed of several frequencies, particularly when switching power supplies are used to drive LED strings. Similar to de Lange [1961], they analyzed individual components after decomposing a periodic time signal into its Fourier series components. In line with this approach, we recently developed another measure to evaluate flicker of LED light sources, the flicker visibility measure (FVM) [Perz and others 2013]. This measure is calculated as a Minkowski summation of the modulation of each frequency component, normalized by the modulation threshold of a sine wave at the corresponding frequency. A Minkowski summation corresponds to a nonlinear summation of components using a certain exponent. Bodington and others [2016] presented a similar measure, where a squared summation was used; that is, a Minkowski exponent of 2. The study by Bodington and others [2016] is a basis for the measure recommended by the Alliance for Solid-State Illumination Systems and Technologies [ASSIST 2015]. Bodington and others [2016] showed that the measure correctly predicted whether flicker was detected for five commercially available lamps. However, the quadratic exponent used for the summation was mathematically determined, based on the assumption of independence (orthogonality) of the frequency components of a waveform. Further, in Bodington and other's [2016] research, the participants directly observed the light sources that had an angular size of about 7°. The light source emitted about 600 lm, but the average luminance was not reported. Bodington and others [2016] also did not control for flicker adaptation, which, similar to the studies of De Lange and Kelly, might have resulted in overestimation of modulation threshold values.

The aim of the current article is to (1) quantify the visibility of periodic flicker by accounting for the effect of frequency, waveform, and flicker adaptation for a visual field applicable for general lighting and (2) evaluate the summation measures proposed by Perz and others [2013] and Bodington and others [2016]. Three perception experiments are reported, two of which were partially presented previously [Perz and others 2013]. In the first experiment, the visibility of light modulations with a simple sinusoidal waveform at different temporal frequencies was measured. This experiment was similar to the ones conducted by De Lange, Kelly, and Bodington and others, but it was designed to stimulate a visual field realistic for typical lighting applications and to prevent flicker adaptation. In the second experiment, light modulations with complex waveforms were generated. They consisted of a summation of two or three frequency components at a modulation depth corresponding to their respective visibility threshold. The results were used to determine the exponent of the Minkowski summation and to determine the accuracy of the summation measure. In the final experiment, flicker perception of realistic waveforms (that is, waveforms of LEDs available on the market) was evaluated and the new measure was validated with the obtained data.

2. EXPERIMENT 1: TEMPORAL CONTRAST SENSITIVITY FUNCTION

The experiment aimed at determining the temporal contrast sensitivity function for light covering a visual field characteristic for office application. Visibility thresholds for sinusoidally modulated light at nine temporal frequencies ranging between 1 and 80 Hz were measured. The light level that was chosen corresponds to the light level in a typical office, where it is recommended to have around 400 lux measured on the task area [European Committee for Standardization 2011].

2.1. Experimental Method

2.1.1. Design

The experiment used a mixed within-/between-subject design with flicker visibility threshold as the dependent variable and frequency as the independent variable. Visibility thresholds were expressed in terms of modulation depth (1).

2.1.2. Setup

The experimental setup is shown in Fig. 1. Two luminaires were equipped with LEDs. Each luminaire contained four rows of cool white LEDs (Lumileds, LUXEON Rebel, color temperature of 6500 K, Aachen, Germany) and four rows of warm white LEDs (Lumileds, LUXEON Rebel, color temperature of 2700 K). Only the cool LEDs were used in the experiments. The luminaires were mounted 0.8 m from each other in a frame at a height of 2.5 m from the floor, close to a white wall. The voltage of the LEDs was controlled by a programmable waveform generator via a laptop. Proper calibration of the setup was ensured by measuring and transforming the relation between voltage and illumination. During the perception experiment, a participant was sitting at a chair, 1 m away from the white wall, below the luminaires. In this way, the flickering stimuli comprised the intended visual field. There was a fixation cross on the wall, in front of participant's eyes. This particular experimental setup was chosen because it represents the worst-case conditions in a typical office environment; that is, where flicker would be the most problematic.

2.1.3. Stimuli

The LED lighting system was used to generate light temporally modulated with a sine wave at frequencies of 1, 2, 5, 10, 15, 20, 30, 50, 60, and 80 Hz. A pilot test was conducted in order to optimize the range of modulation depths per frequency. The modulation depth ranged between 0% and 10 % for 1, 2, and 50 Hz; between 0% and 2.5% for 5, 10, 15, 20, and 30 Hz; between 0% and 50% for 60 Hz; and between 0% and 100% for 80

Fig. 1 **Picture of the experimental setup.**

Hz. By doing so, the visibility thresholds could be measured with high accuracy. The average luminance level, measured at the wall, in front of participants' eyes was 209 cd/m^2. The color temperature of the light was 6500 K.

2.1.4. Procedure

Before the start of the experiment, participants read through and signed a consent form, confirming their eligibility for the study. Next, what light flicker is was explained to them, they were given oral instructions on the experimental procedure, and they were given a short demonstration of the experiment. Participants were instructed to look at the fixation cross at the wall and to indicate on a portable numerical keyboard whether the light was flickering or not. Each stimulus was presented until the participants made their decision, so they could take as much time as they needed to give the answer, but they were encouraged to give their answers fast. Pilot tests showed that prolonged time of the experiment did not result in increased accuracy. Participants were instructed to press the right arrow key when they observed flicker and the left arrow key otherwise. For each frequency, the visibility threshold was measured using a staircase method [Kaernbach 1991], meaning that the modulation depth that was presented for a stimulus with a given frequency depended on the response of the participant to the preceding stimulus with the same frequency. The starting modulation depth was set at a random value, well above the visibility threshold, within the range described above. The modulation depth was decreased if a participant indicated that flicker was visible and increased otherwise. The modulation depth at which the answer changed from yes to no or from no to yes was counted as a reversal point. Eight reversal points were measured for each frequency, and the visibility threshold was obtained as the arithmetic mean of the last four reversal points. As such, the visibility threshold represents the modulation for which the observer can detect flicker with a probability of 50% [Rose and others 1970]. In order to prevent flicker adaptation, light at a constant luminance and color temperature was presented after each stimulus for 4 s and the various staircase stimuli for all lighting conditions were intermingled and presented in a random order, different for each participant. The experiment took about half an hour per participant.

2.1.5. Participants

Two groups of participants took part in the experiment. The first group measured all frequencies except 15 Hz. This group consisted of 18 participants: 11 males and 7 females, with ages ranging between 19 and 32 years. The second group measured only a frequency of 15 Hz and consisted of 10 participants: 7 males and 3 females, with ages ranging between 19 and 28 years. The second group was added after analyzing the data for the first group, which showed that the peak sensitivity could have been between 10 and 20 Hz. All participants were either Philips employees or interns at Philips Research. Participants were asked whether they suffered from epilepsy, had a family history of epilepsy, or suffered from migraines. If so, they were excluded from the experiment.

2.2. Results

Visibility thresholds, expressed in terms of modulation depth, were measured for each participant and frequency. First, the visibility thresholds were averaged across people and the 95% confidence intervals were calculated. Then the means and confidence intervals were converted into sensitivity values, by taking the inverse values. Figure 2 shows the log–log plot of the mean sensitivity as a function of frequency. The error bars in the figure represent the 95% confidence interval of the mean. The data points were interpolated, using shape-preserving cubic interpolation, in order to create a temporal contrast sensitivity

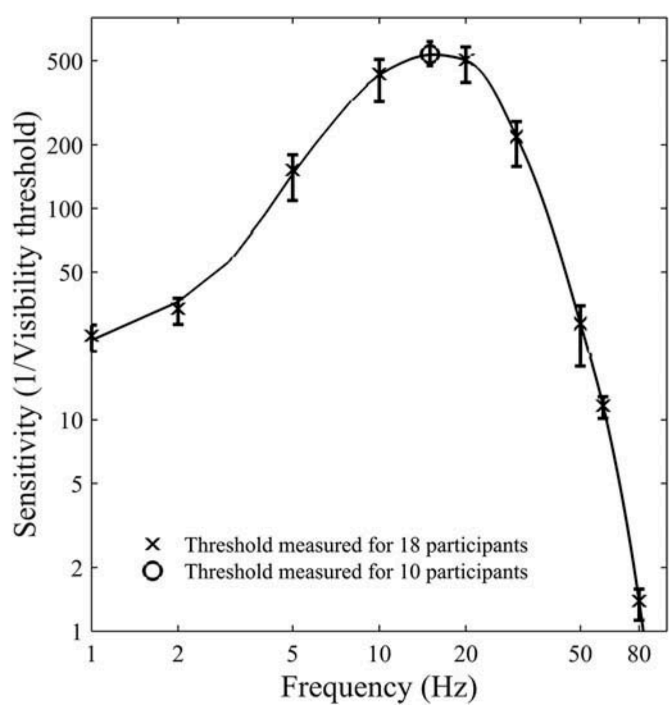

Fig. 2 **Visibility thresholds expressed as sensitivity (1/modulation depth) for sinusoidal waveforms as a function of frequency. Error bars correspond to the 95% confidence interval of the mean.**

curve for sinusoidal light modulations presented to the large visual field realistic for office application.

Figure 2 shows that the sensitivity increases with frequency for frequencies up to 10 Hz. The sensitivity reaches a peak value of about 500 at 15 Hz. This corresponds to a modulation threshold of 0.002. The sensitivity decreases for higher frequencies to a value of 1 at 80 Hz. The error bars are small, showing that the participants were consistent. The error bars of the 15 Hz stimulus, even though they were measured with a smaller number of participants (n = 10), are smaller than the error bars of other frequencies.

3. EXPERIMENT 2: FLICKER VISIBILITY MEASURE

The temporal contrast sensitivity curve developed in the first experiment can be used to predict flicker visibility of sinusoidally modulated light. However, it does not predict flicker visibility of all complex waveforms, because, as pointed out by Levinson [1960], all frequency components of a waveform, if sufficiently large, contribute to flicker perception. Earlier, we proposed a FVM that can be used to predict flicker visibility of such complex waveforms [Perz and others 2013]. It is described by a Minkowski summation of the Fourier frequency components, normalized by the modulation threshold of a sine wave at the corresponding frequency as shown in (2). The applicability of the Minkowski summation for predicting thresholds of complex visual stimuli has been demonstrated in several studies on visual perception. Typically, the Minkowski exponent was found to range between 2 and 4 [To and others 2008]. The measure is defined such that at visibility threshold its value is equal to 1.

$$\mathrm{FVM} = \sqrt[n]{\sum_{m=1}^{\infty}\left(\frac{C_m}{T_m}\right)^n} \begin{cases} < 1 \text{not visibile} \\ = 1 \text{ just visibile} \\ > 1 \text{ visible} \end{cases} \quad (2)$$

In (2), C_m is the absolute value of the amplitude (that is, energy) of the mth Fourier component of the light waveform and T_m is the visibility threshold of the sinusoidal waveform at the respective frequency. The visibility threshold, being the reciprocal of sensitivity, is expressed in terms of modulation depth, as measured in the first experiment. The ratio of C_m and T_m is also referred to as normalized energy. If the calculated FVM value for a given waveform is equal to 1, flicker is just visible; that is, it is visible with a probability of 0.5. If the value is larger than 1, flicker is visible with a probability larger than 0.5, and if it is smaller than 1, flicker is visible with a probability smaller than 0.5. It should be noted that the Minkowski summation is a generalized norm and by varying the exponent n, a number of different norms are produced. If n = 1, this corresponds to a Manhattan norm, which means that all frequency components are summed linearly. If n = 2, this corresponds to the standard Euclidean summation. If n approaches infinity, this corresponds to the Chebyshev summation, which means that only the frequency with the maximum visibility predicts flicker perception.

The goal of the second experiment is to validate the proposed flicker visibility measure and to determine the exponent of the summation, which satisfies the conditions of (2). It should be noted that in the study of Bodington and others [2016] the quadratic exponent was determined mathematically, assuming independence of the frequency components of a waveform. In order to experimentally determine the exponent, the visibility of both simple and complex waveforms was measured. The stimuli were constructed using the TCSF measured in the first experiment. Two simple sinusoidal waveforms at a frequency of 5 and 10 Hz were presented, and a number of complex waveforms, consisting of two or three frequency components. The modulation depth of each frequency component was equal to the modulation threshold of a simple sine at the corresponding frequency. This means that the normalized energy (that is, C_m/T_m) was equal for all frequency components. It is expected that at visibility threshold the normalized energy of a simple sinusoidal waveform is equal to 1. Because of the summation, the normalized energy of the frequency components of the complex waveform is expected to be smaller than 1.

3.1. Experimental Method

3.1.1. Design

The experiment used a mixed within-/between-subject design with the visibility threshold as dependent variable and the waveform as independent variable. In total 18 light conditions were tested. With every condition taking about 3–4 min to be executed, the full experiment would take about 1 h per participant. Such long experimental time can be tedious to the participants. Therefore, the light conditions were evaluated by two groups of participants, each group evaluating nine conditions (in a blocked way).

3.1.2. Setup and Procedure

The experimental setup and procedure were identical to that of experiment 1.

3.1.3. Stimuli

The simple sinusoidal and complex waveforms were generated using the average modulation threshold measured in experiment 1. We decided to use the average modulation threshold and not the modulation threshold for each participant individually for two reasons. First, experiment 1 showed that the differences between participants were quite small, as indicated by the small error bars in Fig. 2. Second, in a study on modeling the visibility of related visual percept, the stroboscopic effect, this approach was found to produce significantly equal errors [Perz and others 2014]. Therefore, measuring the sensitivity curve for each of the participants separately was not needed. To obtain the complex waveforms, the sinusoidal waveforms were summed at their respective modulation thresholds, which means that for each frequency component the normalized energy was equal to 1. In order to measure the visibility threshold of the simple and complex waveforms, the amplitude of the waveforms with a normalized energy of 1 were multiplied by a gain factor, ranging between 0 and 4, with a total of 100 steps. Table 1 shows the conditions evaluated with the two groups of participants.

3.1.4. Participants

In the first group, 17 participants took part: 10 males and 7 females, with ages ranging between 19 and 33 years. In the second group, 20 participants took part: 14 males and 6 females, with ages ranging between 19 and 34 years. Participants' exclusion criteria were the same as in the first experiment.

3.2. Results

Visibility thresholds were measured for each participant and light condition. Visibility thresholds were expressed in terms of the normalized energy of the frequency components, which corresponds to the gain factor that was varied in the experiment. This threshold is referred to as normalized visibility threshold, to make a distinction from the visibility threshold in terms of modulation depth, as measured in experiment 1. Figure 3 shows the mean normalized visibility threshold averaged across participants of the first group (top) and the second group (bottom) including the 95% confidence intervals of the mean as error bars and the violin plots showing density estimation.

First, the data of the waveforms with a single sinusoidal frequency at 5 and 10 Hz were analyzed with a t test to check whether the normalized visibility threshold significantly differed from 1. A value different from 1 means that the visibility thresholds measured in experiment 2 were different from the average visibility threshold measured in experiment 1. A t test was performed for each group of participants separately. In the first group, the analysis showed that the normalized visibility threshold was not significantly different from 1, $t(16) = 1.21$, $P = 0.24$, whereas in the second group the threshold was found to be significantly different from 1 at a significance level of 0.05, $t(19) = 2.09$, $P = 0.04$. An additional test was performed to test whether the distribution of visibility thresholds of the simple sines measured in experiment 2 differed from the distribution of visibility thresholds measured in experiment 1, instead of the average visibility threshold. A two-sample t test was not significant in both groups, $t(33)) = 0.60$, $P = 0.55$; $t(33) = 0.63$, $P = 0.54$, respectively. Therefore, it was concluded that the visibility thresholds of single sinusoidal waveforms are the same in experiment 1 and experiment 2.

For the complex waveforms (that is, with multiple frequency components), a t test showed that on average their normalized visibility threshold significantly differed from 1 in group 1, $t(143) = 14.66$, $P < 0.01$, and in group 2, $t(170) = 5.56$, $P < 0.01$, as is also clear from Fig. 3. A value of 1 means that the frequency components are independent and their respective modulation thresholds are sufficient to predict flicker visibility. This would mean that the summation exponent is equal to 1. The normalized visibility thresholds of the complex waveforms, averaged across the participants of the first group, ranged between 0.61 and 0.89, with a mean of 0.71. For the second group, the average thresholds of the complex

TABLE 1 Frequency components of composite waveforms evaluated in experiment 2

	Frequency components (Hz)								
Group 1	10	10,20	20,30	50,60	1,2	2,5	2,5,10	2,50	2,10,50
Group 2	5	2,15	5,2	5,10	5,15	5,25	5,35	5,50	5,80

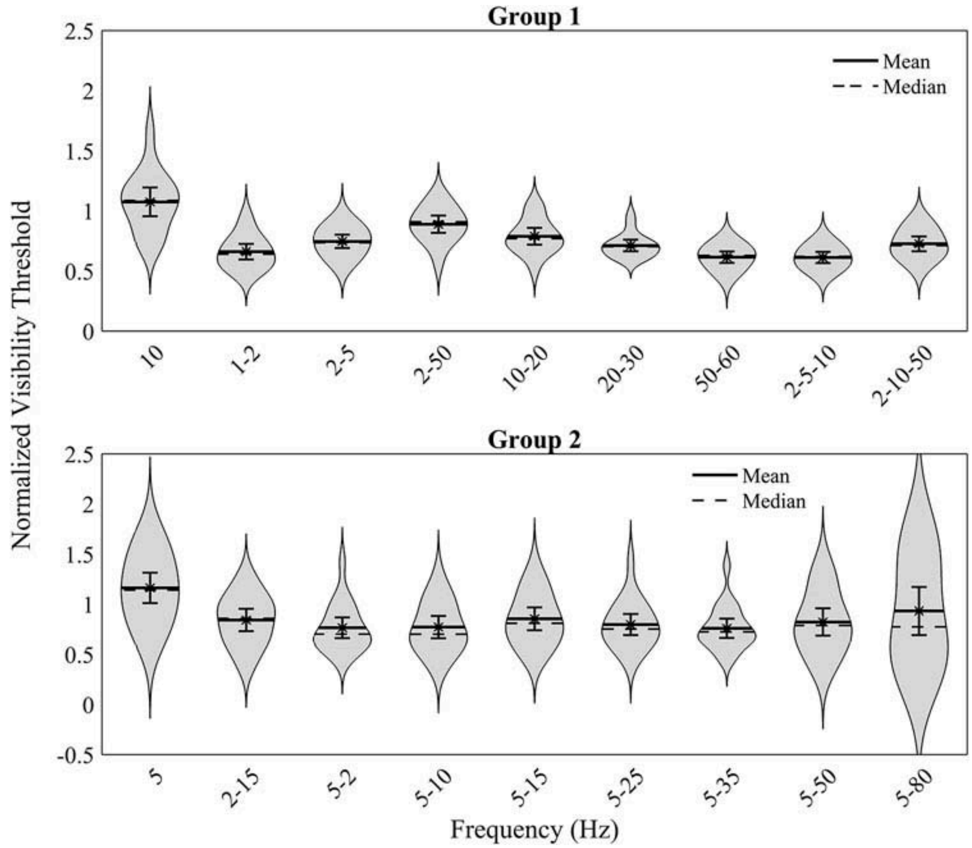

Fig. 3 **Error bars and violin plots of the mean normalized visibility threshold for various complex waveforms measured in the first (top) and second (bottom) group of participants of experiment 2; the error bars correspond to the 95% confidence interval of the mean.**

waveforms ranged between 0.76 and 0.93, with a mean of 0.82. Thus, the modulation of the waveforms composed of sinusoidal frequencies at their respective modulation threshold had to be decreased on average by 29% and 28% in order to become just not visible. This result is consistent with the study of Levinson [1960], who showed that the amplitude of the composite waveform needed to be reduced by 30% on average to reach the visibility threshold.

Figure 3 shows that the variance in the visibility threshold was larger for participants in the second group compared to the participants in the first group. The size of the error bars of the second group was twice the size of the first group. In addition, the violin plots were much larger for the second group of participants and appeared to be less normal. In particular, for the complex waveform consisting of the sinusoidal components of 5 and 80 Hz the spread was very large with a substantial difference between the mean and the median of the distribution. Therefore, a hierarchical clustering was performed to analyze the dissimilarity in scores between the participants of the two groups. Figure 4 shows the dendrogram of the cluster analysis for group 1 (left) and group 2 (right), where each leaf corresponds to one participant. To construct a dendrogram, the Euclidean distance was calculated between pairs of all participants. Then, the participants who were the closest in proximity were linked. Because participants were linked into binary clusters, the newly formed clusters were further linked into larger clusters until a hierarchical tree was formed. In the final step, a Euclidean distance larger than 1 was used to define different subgroups of participants.

The hierarchical cluster analysis showed no participant effect in group 1. However, in group 2, two distinct subgroups of participants were found: subgroup 1, depicted with black lines in Fig. 4, and subgroup 2, depicted with grey lines. Therefore, the normalized visibility threshold obtained in group 2 was calculated separately for each subgroup, as shown in Fig. 5. The error bars with crosses in Fig. 5 show the results of subgroup 1 (depicted with black lines in Fig. 4), and the error bars with circles shows the results of subgroup 2 (depicted with the grey lines in Fig. 4). It is apparent that the two groups of participants are differently sensitive to flicker. The

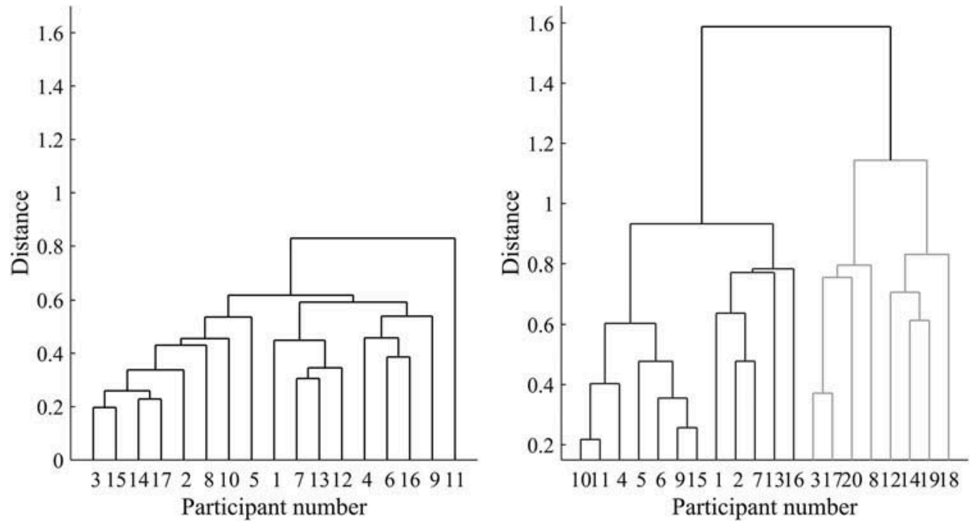

Fig. 4 **Dendrogram of the participants for group 1 (left) and group 2 (right). Group 2 shows two subgroups of people with different sensitivities to flicker.**

sensitivity of the first subgroup was as expected: the normalized visibility threshold of the waveform with a frequency of 5 Hz was equal to 0.96 and the visibility threshold of the complex waveforms was 0.69 on average, ranging between 0.52 and 0.76. Subgroup 2 was less sensitive to flicker, with a visibility threshold of 1.45 for the simple sine wave at 5 Hz and an average threshold of 1.1 for the complex waveforms, ranging between 0.87 and 1.54.

A two-sample *t* test showed that the visibility threshold for a sinusoidal waveform at 5 Hz did not differ from the visibility threshold of the participants in experiment 1, $t(28) = 0.28$ $P = 0.78$, for the participants of subgroup 1 but it did for the people of subgroup 2, $t(24) = 2.37$, $P = 0.02$. In addition, a *t* test showed that on average the normalized visibility threshold of the complex waveforms significantly differed from 1 in subgroup 1, $t(95) = 17.1$, $P < 0.0$, but it did not significantly differ from 1 in subgroup 2, $t(63) = 1.19$, $P < 0.24$.

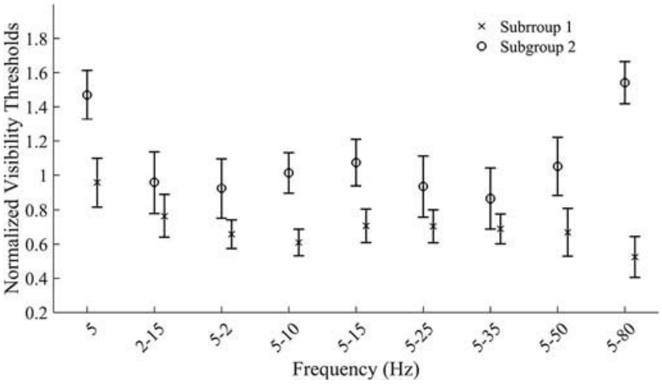

Fig. 5 **Mean normalized visibility threshold for various complex waveforms for the two subgroups of participants from group 2: subgroup 1 (crosses) corresponds to participants with sensitivity to flicker as expected, whereas subgroup 2 (circles) corresponds to participants with decreased sensitivity to flicker. The error bars correspond to the 95% confidence interval of the mean.**

Interestingly, a large difference in visibility threshold for the complex waveform consisting of 5- and 80-Hz frequency components can be observed between the two subgroups. The mean visibility threshold for this condition was 0.52 for subgroup 1, whereas it was 1.54 for subgroup 2. This threshold was significantly different from the threshold of the sinusoidal waveform at 5 Hz for subgroup 1, $t(11) = 6.15$, $P < 0.01$, but not for subgroup 2, $t(7) = 0.59$, $P = 0.58$. Thus, the participants in subgroup 2 are much less sensitive to flicker and apparently cannot perceive the 80 Hz component in the complex waveform, because their normalized visibility threshold for the complex waveform was not significantly different from the threshold of the 5-Hz simple sinusoidal waveform. This suggests that their CFF was below 80 Hz.

The observation of having two subgroups of participants with different sensitivities to flicker indicates clear individual differences in flicker perception between people. Despite the importance of the individual differences, it is also beneficial for the LED industry to define a standard observer to flicker. The results of the people of subgroup 2 do not match the TCSF measured in experiment 1. Apparently most people have a similar sensitivity (that is, 29 people out of the 37 measured), and this sensitivity is hence considered the standard observer sensitivity. Therefore, the results of people from subgroup 2 are excluded from further analysis. Hence, the rest of the analysis could be considered as results for a standard observer based on the results of the people of subgroup 1.

3.3. Parameter Estimation for the Visibility Measure

In order to fit the Minkowski exponent of the FVM, the following procedure was used. First, the normalized energy of the Fourier components of the 16 complex waveforms at visibility threshold was calculated—that is, C_m/T_m—in (2). This corresponds to the normalized visibility threshold of experiment 2. This was done for every waveform and every participant. It should be noted that the visibility thresholds of the simple sinusoidal waveforms (T_m) were the same for every participant, because, as mentioned before, we decided to use the average TCSF measured in experiment 1. Next, the normalized energy was summed over the contributing Fourier components using a Minkowski summation (given by 2) with the exponent n ranging between 1 and 4, in steps of 0.5. This was also done for every participant and every waveform. Finally, the resulting values of the FVM were averaged across the participants for each waveform, resulting in 16 FVM values per exponent. Figure 6 shows the mean FVM value averaged across the waveform and its 95% confidence interval. According to the definition of the measure, FVM should have a value of 1 at visibility threshold. Figure 6 shows that this value is reached with a Minkowski exponent of around 2.

To assess the difference between the values predicted by FVM and the values measured in experiment 2, the relative root mean square (RMS) error (also referred to as coefficient of variation) was calculated. First, the value of the FVM was calculated per participant and per complex waveform for Minkowski exponents ranging between 0.5 and 5 in steps of 0.1. Then, for each waveform the RMS error was calculated with a predicted value of 1. Next, it was divided by the mean observed FVM value of the corresponding waveform, such that the resulting value was unitless and varied between 0 and 1. Finally, the relative RMS errors were averaged across the waveforms. Figure 7 shows the mean relative RMS error as a function of the Minkowski summation exponent. It illustrates that the minimum error is equal to 0.075, which is considered small; this minimum error is found with a Minkowski exponent of 2.

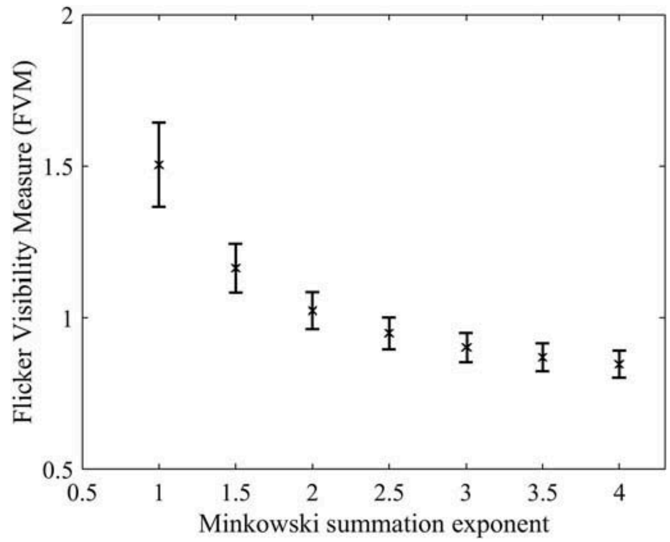

Fig. 6 **Mean FVM, as defined in (2), as a function of the Minkowski summation exponent *n*. The error bars correspond to the 95% confidence interval of the mean.**

Therefore, the measure to predict visibility of periodic flicker for the large visual field, realistic for an office application, called the FVM is computed as follows:

$$\mathrm{FVM} = \sqrt[2]{\sum_{m=1}^{\infty}\left(\frac{C_m}{T_m}\right)^2} \begin{cases} < 1 \text{not visibile} \\ = 1 \text{ just visibile} \\ > 1 \text{ visible} \end{cases}. \quad (3)$$

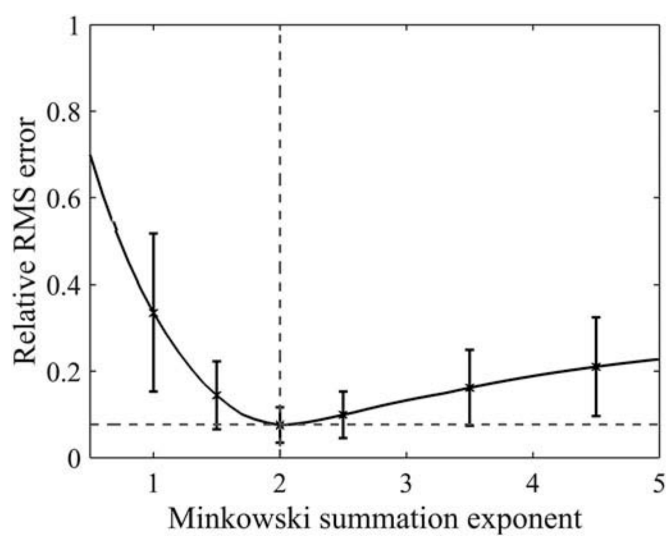

Fig. 7 **Relative RMS error of the FVM prediction averaged over the complex waveforms of experiment 2, calculated against the estimated value of 1, for different values of the Minkowski summation coefficient.**

4. EXPERIMENT 3: FLICKER VISIBILITY OF REALISTIC WAVEFORMS

The third experiment aimed at comparing FVM with several flicker measures, explained in the Introduction—that is, FI, PF, and P_{st}—for their capability to predict perceived flicker of light modulations with realistic waveforms.

4.1. Experimental Method

4.1.1. Design

The experiment used a within-subject design with standard scores as the dependent variable and waveform as the independent variable. A forced-choice paired comparison procedure was used. In total 11 light conditions were tested, which resulted in 55 different pairs of stimuli.

4.1.2. Setup

In addition to the setup used in the previous two experiments, a white cardboard was mounted in between the two luminaires, perpendicular to the wall. By doing so, different waveforms could be simulated in each of the two luminaires and the light patterns generated by the luminaires did not overlap.

4.1.3. Stimuli

The luminance, varied over time, of 42 LED light sources available on the market was measured using a photodiode and an oscilloscope. The measurements were 50 s long and had a sampling frequency of 10 kS/s. The light output of all light sources was visually examined by the experimenter and, based on this, 11 light sources were selected. For some of these light sources the temporal light quality was evaluated by the experimenter as good (that is, flicker was not perceived), and for some the light quality was evaluated as poor (that is, flicker was perceived). The temporal fluctuation of these waveforms could be either periodic or aperiodic. Two examples of these waveforms are shown in Fig. 8 (all waveforms are available on request from the authors). The light output of the 11 selected light sources was simulated in the experimental setup.

4.1.4. Procedure

Participants were seated 1 m away from the wall at the end of the cardboard. In each of the luminaires a different waveform was presented and the participants' task was to indicate on a portable numerical keyboard which of the two stimuli, presented on the left or on the right side of the cardboard, flickered most. Participants were instructed to look at each side of the cardboard; they could freely move their head and they could look to each side of the cardboard for as long as necessary in order to make their decision. Participants were instructed to press the right arrow key when the stimulus on the right side flickered most and otherwise the left arrow key. All combinations of lighting conditions were presented in a random order, different for each participant. The experiment took about half an hour per participant.

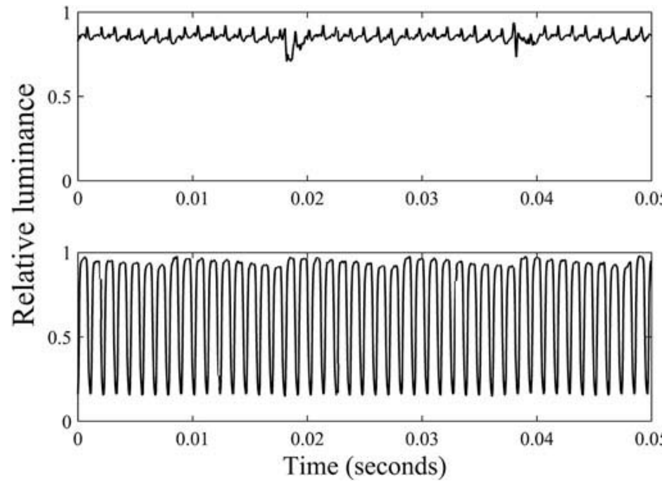

Fig. 8 Relative luminance as a function of time of realistic waveforms evaluated in experiment 3.

4.1.5. Participants

In total 18 participants took part in the experiment: 10 males and 8 females, with ages ranging between 19 and 36 years. The exclusion criteria were the same as in experiments 1 and 2.

4.2. Results

The percentage of the responses given by participants to every waveform in each pair of stimuli was recorded and translated to standard scores [Rajae-Joordens and Engel 2005]. In addition, the value of the different flicker measures was calculated for the 11 light sources. The values of MD and FI were calculated for all cycles of each light waveform and the average value was used. Figure 9 shows the standard scores of the light sources against the values of the flicker measures. A linear equation was fitted through the data points using the least squares method, and the best fit for every flicker measure is depicted in Fig. 9 as a solid line. Figure 9 clearly illustrates that the fit for the MD and FI is poor compared to the fit for P_{st} and FVM.

The Pearson correlation was computed to assess the relationship between the standard scores and the values of the different flicker measures. There was no significant correlation of the standard scores with MD or FI (MD: $R^2 = 0.33$, $P = 0.32$, FI: $R^2 = 0.06$, $P = 0.87$), but there was a positive significant correlation with P_{st} and FVM (P_{st}: $R^2 = 0.84$, $P < 0.001$, FVM: $R^2 = 0.77$, $P = 0.005$). This means that both P_{st} and FVM appear to be good measures to predict flicker visibility. The visibility threshold for both P_{st} and FVM equals 1, meaning that if the value of the measure is larger than 1, flicker is visible and if the value of the measure is smaller than 1, flicker is not visible. Figure 9 shows that three out of 11 waveforms have a P_{st} larger than 1, whereas seven waveforms have an FVM above 1. Participants reported afterwards that the majority of the presented stimuli were flickering. This suggests that P_{st} might be underestimating absolute flicker visibility.

5. DISCUSSION

In the first experiment of the current study, a temporal contrast sensitivity curve for simple sine waves was developed. Similar curves have been measured by De Lange [1958], Kelly [1961], and Bodington and others [2016]. Figure 10 shows a comparison of these curves. Both Kelly and De Lange measured several illumination levels and the level closest to the illumination level of our study (that is, 209 cd/m^2 measured at the wall) was chosen for the comparison (De Lange: 10,000 photons, Kelly: 9300 td). Bodington measured a TCSF for a light source emitting 600 lm.

There are several differences and similarities between our curve and the other three curves. For frequencies below 20 Hz, the shape of the curve measured in the current study is quite similar to the shape of the curve measured by Kelly, but the absolute sensitivity is a factor of 3 higher for frequencies between 1 and 5 Hz and a factor of 5 higher between 5 and 20 Hz. Between 20 and 50 Hz the curve we measured is falling off much more rapidly than Kelly's curve. Above 50 Hz the two curves overlap. Our result is consistent with the study by Kelly [1961], showing that for relatively high luminance levels the CFF corresponds to about 80 Hz. The difference between the two curves could be attributed to flicker adaptation, which was controlled for in the current study, by showing a reference of constant light after each

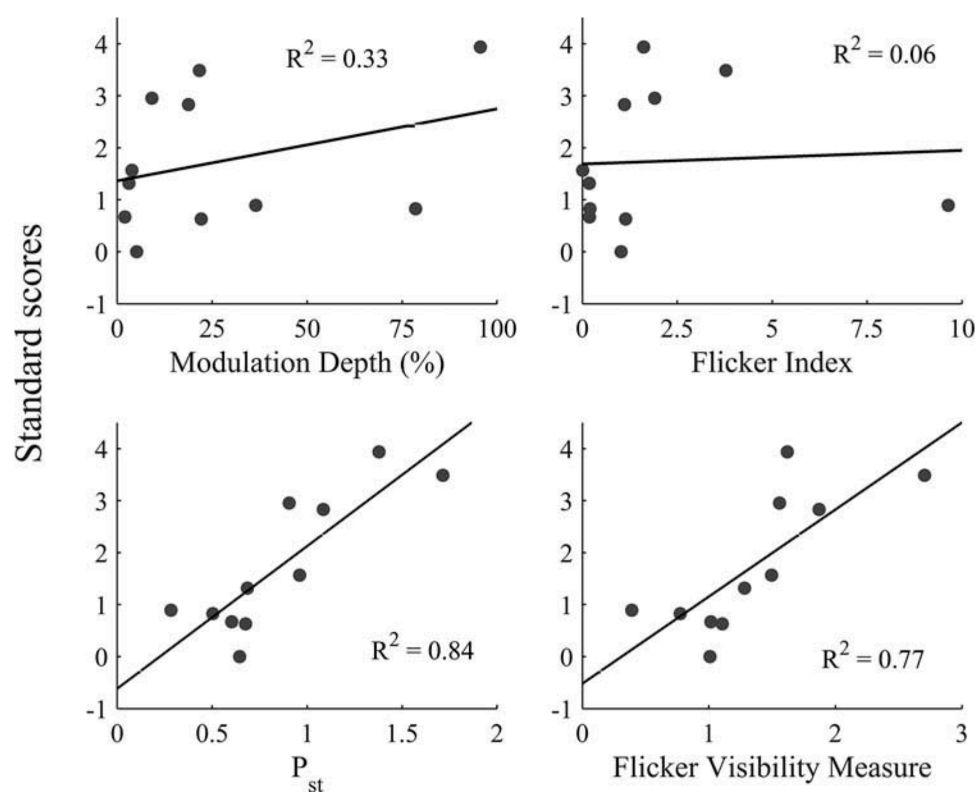

Fig. 9 Standard scores as a function of different measures predicting flicker visibility. The solid line shows the best linear fit.

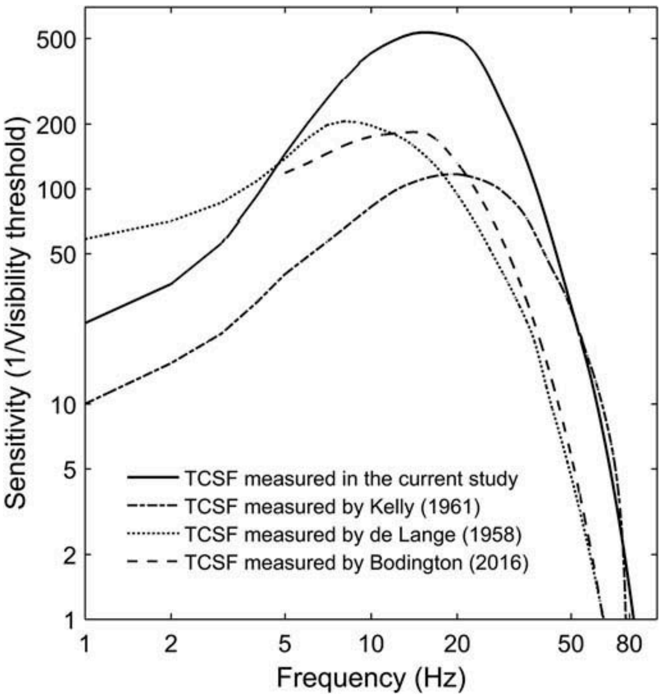

Fig. 10 **Flicker sensitivity curves measured by Kelly [1961] (dash–dot line), by De Lange [1958] (dotted line), by Bodington and others [2016] (dashed line), and in our study (solid line).**

stimulus of modulated light and by using interleaved staircases that randomized the subsequently observed frequencies. Kelly used a tuning method to obtain visibility thresholds, which means that participants might have been adapting to flicker over time, which in turn might have resulted in an underestimation of the sensitivity. The curves measured by De Lange [1958] and Bodington and others [2016] have a different shape. Above 5 Hz the sensitivities are lower than what we measured in the current study. This difference can also be attributed to differences in methodology. De Lange used a tuning method, similar to Kelly. Bodington and others used a staircase method, similar to the current study. However, Bodington and others presented the stimuli directly after each other, without breaks, a reference with constant light, or interleaving different frequencies, which means that during this study, participants might have been adapting to flicker over the course of the experiment. Not all sensitivities found in the three previous studies are lower than what was measured in the current study. The sensitivity measured by de Lange is higher than what we measured in the low-frequency region, between 1 and 5 Hz. This difference is attributed to the shape of the stimuli employed in the different studies. De Lange used a 2° visual field with sharp edges, whereas an almost full visual field with a smooth gradient was used in the current study. It was argued by Kelly [1959] that the behavior of de Lange's curve in the low-frequency range is an artefact of using sharp-edged stimuli.

In the second experiment, the FVM was evaluated. The exponent in the FVM that best described the data of the complex waveforms was experimentally found to be 2. In the study by Bodington and others [2016], the summation exponent was mathematically determined to also be 2. Therefore, we found the same exponent even though the two studies used different methodologies and were based on a different TCSF.

Two distinct groups of participants were found, differing in their sensitivity to flicker. The flicker sensitivity of one group of participants was the same as that measured in experiment 1 and the other group of participants was significantly less sensitive to flicker. This result is not surprising, because literature on flicker visibility indicates that it varies between people. Sensitivity to modulated light might be affected by several factors, both internal, such as gender and age, and external, such as time of the day [Johansson and Sandström 2003]. We strived to develop a measure for a standard observer and therefore the data for participants whose sensitivity substantially deviated from the average sensitivity were excluded from the analysis.

In the last experiment it was shown that P_{st} might be underestimating flicker visibility. The weighting filter used in P_{st} is based on the TCSF measured by De Lange [1958] for a 2° visual field. As shown above, the sensitivity of De Lange at frequencies above 5 Hz is lower compared to the sensitivities measured in the current study for light presented to the large visual field, used in typical lighting application. This could explain why P_{st} cannot accurately predict the absolute visibility of flicker of the stimuli used in this experiment. A more detailed analysis of the experiment showed that P_{st} better predicts the visibility of aperiodic flicker compared to FVM. Such aperiodic fluctuations are not uncommon in the lighting domain. One of the waveforms used in the third experiment contained a single transient effect, a flash. After removing this waveform from the analysis, the correlation of FVM with perceived flicker was slightly higher than the correlation of P_{st} with perceived flicker ($r = 0.86$, $P < 0.001$ for FVM and $r = 0.82$, $P < 0.001$ for P_{st}). Ideally, a flicker measure should predict both periodic and aperiodic flicker (for example, single flashes and pulses). Because P_{st} is calculated in the time domain, it is better able to account for both types of flicker. The summation exponent of FVM is equal to 2 and therefore Parseval's theorem can be used, which states that the sum of the square of a waveform $x(t)$ in the time domain is equal to the sum of the square of the Fourier transform $X(f)$ in the frequency domain. Therefore, FVM can also be calculated in the time domain. By doing so, similar to P_{st}, it has the potential to account for both periodic as well as aperiodic flicker.

There are some limitations in the usability of the results. FVM was determined under typical office conditions, which means with an illuminance of about 500 lux, measured on the task area. Therefore, the measure is valid for applications with comparable light levels; that is, office, hospitality, home, and retail. It is known that flicker visibility depends on adaptation level [Kelly 1961]. To what extent the same approach is able to accurately predict perceived flicker in applications with other light levels, such as outdoors, should be investigated.

In this study, complex waveforms were used to develop FVM, but there was no phase difference between the different frequency components. In order to generalize the validity of the established FVM, additional experiments with complex waveforms including phase shifts between the components should be performed.

In the second experiment, the less "sensitive" observers were excluded from the general analysis and consequently only the average sensitivity was used to validate the visibility measure. This was because the sensitivity curve used in the flicker visibility measure was based on the average sensitivity obtained in experiment 1 and the less sensitive observers significantly deviated from the average in the case of a single frequency (5 Hz). It should be noted that using only the average sensitivity might not be sufficient for defining good quality lighting for all people; for example, people with still higher sensitivity to temporal light modulations. The current study does not propose any specific sensitivity curve that can cover all uses; one should realize that the focus of the current study was on flicker visibility at one particular illuminance level, covering a large part of the visual field. Having a sensitivity curve for all uses would undoubtedly be beneficial for lighting communities, but we did not have access to enough sensitive observers. Conversely, the two groups of participants in the second experiment might not have differing sensitivities, but they could be using different strategies while executing the experiment. Due to hardware limitations, a 2AFC-based experiment could not be conducted and it is known that yes–no methodologies can have innate biases that are also participant dependent. The second group of participants can in fact be less sensitive compared to an average observer, but it can also be due to the use of a different strategy. How the sensitivity of the observers varies with differing methodologies should be studied in the future.

The task of the participants in the current study was to look at a white, spatially unstructured wall. This is similar to the most critical case in a typical office, when workers look at white walls. Other cases include situations when spatial patterns are present in the workers' field of view. How the temporal sensitivity changes with addition of spatial patterns has been previously studied. Robson [1966] measured temporal visibility thresholds for a number of spatial frequencies (square-wave gratings). He showed that the fall-off in sensitivity at high temporal frequencies is independent of the spatial frequency of the pattern. In addition, a fall-off in sensitivity at low temporal frequencies occurs only when the spatial frequency is also low (0.5 cpd). Finally, for higher spatial frequencies (4, 16, and 22 cpd), the absolute temporal contrast sensitivity decreases with increasing spatial frequency. Kelly [1979] also measured sensitivity to temporal frequencies at a number of spatial frequencies. By plotting sensitivity as a function of both spatial and temporal frequency he constructed a complete spatiotemporal threshold surface. The results were very similar to those of Robson [1966]. The results of Robson and Kelly can be used to determine how the temporal contrast sensitivity changes when spatial patterns are present in workers' fields of view. In most cases, the addition of a spatial pattern results in attenuation of human temporal sensitivity. This confirms the assumption that by using the current experimental setup, the worst-case spatial structure for an office application was probed.

A last point of consideration is the influence of saccades. The task of the participants in the current study was to indicate whether flicker was visible or not while fixating on a cross marked on the wall in front of them. This means that they were not making large eye saccades. This, in combination with the fact that the wall was white and spatially unstructured, means that the phantom array effect was not visible during the experiment [Roberts and Wilkins 2013]. However, normal vision is accompanied by microsaccades, and it can be argued that this might have influenced the flicker visibility thresholds. Kelly [1977] conducted an experiment in which he measured spatiotemporal contrast sensitivity by stabilizing the image on the retina. The results showed that normal (unstabilized) and stabilized threshold surfaces have essentially the same shape for frequencies higher than 0.1 Hz. This means that though participants were constantly making microsaccades during the experiment, it did not affect their visibility thresholds.

6. CONCLUSIONS

The light output of LED light sources introduced on the market is often temporally modulated with different kinds of irregular waveforms and at various temporal frequencies. To ensure that the light has a high perceptual quality, it is important to accurately quantify the visibility of temporal light artifacts. In the current study, three experiments were conducted with the general aim of developing a measure that predicts flicker visibility of periodically modulated waveforms of light presented to the large visual field and at an illumination level typically used in office applications. In the first experiment, the TCSF for simple sine waves was developed. The shape of the TCSF was comparable to earlier studies; however, the maximum sensitivity was more than twice the sensitivity reported in the literature. In the second experiment, a measure for predicting flicker visibility of periodic waveforms with different shapes and frequency components was evaluated. The measure, called the flicker visibility measure, consists of a Minkowski summation of the Fourier frequency components in the light modulation normalized by the modulation threshold of a sine wave at the corresponding frequency. In order to determine the Minkowski exponent, the visibility threshold of complex waveforms, consisting of two or three frequency components, was measured. The TCSF, measured in experiment 1, was used for normalization. The best fitting exponent was found to be 2. In the last experiment different flicker measures, including FI, PF, P_{st}, and FVM, were evaluated based on their capability to predict flicker visibility of realistic waveforms. The results showed that the commonly used measures, FI and PF, are not suitable measures to accurately quantify flicker visibility. The correlation of FVM and P_{st} with perceived flicker was high, with P_{st} showing a slightly higher correlation than FVM. However, it was also shown that FVM predicts the absolute flicker visibility better, whereas P_{st} might be underestimating flicker visibility.

Finally, it was shown that the measure has the potential to be calculated in the time domain. This means that the measure could be extended and be applicable for aperiodic flicker as well. Future work should focus on validating such a measure.

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