Energy - Docket Optical System

From: Wilkins, Arnold J [arnold@essex.ac.uk]
Sent: Tuesday, November 25, 2014 2:34 AM
To: Energy - Docket Optical System
Cc: Rider, Ken@Energy; Singh, Harinder@Energy; Saxton, Patrick@Energy; Taylor, Gabriel@Energy
Subject: Docket #14-AAER-1: LED Lamp Quality
Attachments: 2013-207.pdf; DesignFlicker_IEEEPEM9_14.pdf

Categories: Ready to Docket

Dear Colleagues
I have researched the effects of lighting flicker on headache and ocular motor control for the last 30 years. The standards that you are proposing are nowhere near stringent enough to reduce the symptoms induced by flicker. It is a major innovation, however, to insist on the measurement of flicker, and it can only be hoped that over time the criteria will become more stringent.
Under worst case conditions, flicker can be seen by most observers at frequencies of 2kHz. The perception can be made during a saccade, when the eye is moving extremely rapidly, and any intermittent illumination becomes a spatial illumination of the retina during the flight of the eye. It turns out that the conditions under which flicker is visible during a saccade closely resemble those at which symptoms are generally reported. I am attaching the relevant research papers.
Sincerely
Arnold Wilkins

Prof A J Wilkins
Department of Psychology
University of Essex
Colchester, UK

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Flicker can be perceived during saccades at frequencies in excess of 1 kHz

JE Roberts MSc and **AJ Wilkins** DPhil
Department of Psychology, University of Essex, Colchester, UK

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When driving at night, flickering automobile LED tail lights can appear as multiple images. The perception of a flickering source of light was therefore studied during rapid eye movements (saccades) of 20–40° amplitude in an otherwise dark room (<1 lux). The temporal modulation appeared as a spatial pattern known as a 'phantom array' during the saccade. The appearance of the pattern enabled the discrimination of flicker from steady light at frequencies that in 11 observers averaged 1.98 kHz. At a frequency of 120 Hz, the intrasaccadic pattern was perceptible when the contrast of the flicker exceeded 10%. It is possible that intrasaccadic stimulation interferes with ocular motor control.

1. Introduction

When driving at night behind a car with LED tail lights, it is possible to experience a trail of lights with each rapid movement of the eyes (saccade). The trail occurs because the LED lamps are lit intermittently to control heat build-up. The frequency of operation is above flicker fusion, varies from one manufacturer to another and may not be the same for both tail lamps, to judge from videos posted on the web.[1] Each flash of the lamp is imaged on a different part of the retina during the saccades, forming a pattern dubbed a 'phantom array' by Hershberger and Jordan.[2]

Normally, flicker is not perceived at frequencies greater than the so-called critical flicker fusion frequency. 'Classic data from Kelly for modulation of large (30° radius) visual fields at different light levels from $0.03\,cd{\cdot}m^{-2}$ to $5000\,cd{\cdot}m^{-2}$ showed that beyond 100 Hz, even flicker with 100% modulation was hardly ever directly visible, either centrally or peripherally.'[3] Critical flicker fusion frequency is, however, usually measured with a spatially unstructured field. It is rarely measured during eye movements, and when it is, estimates of the critical frequency increase.[4] When each flash of a spatially structured light source is imaged on a different part of the retina during a rapid eye movement, the light source forms a 'phantom array', and the above example of tail light flicker shows that the array is sometimes perceptible under everyday viewing conditions.

The chat forums contain complaints of discomfort from the 'phantom array' when driving at night. Some drivers are aware of the phenomenon, others are not. In an initial small-scale survey, respondents (20 students and staff at the University of Essex) were asked the following question verbatim: 'When you are driving at night and the car in front is a new one with long red lights, if you change the direction you are looking does anything happen?' Despite the deliberately non-specific wording of the question, three of the 20 respondents reported a 'trail of lights'. This paper shows that the perception of flicker as intrasaccadic patterns is possible at frequencies in the kilohertz range, more than 10 times

Address for correspondence: A Wilkins, Department of Psychology, University of Essex, Colchester CO4 3SQ, UK
E-mail: arnold@essex.ac.uk

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the typical estimates of critical flicker fusion frequency.

Normally, we are unaware of the retinal image during a saccade. Mechanisms of saccadic suppression thought to be largely central and cortical in origin[5,6] prevent the processing of the image during the saccade. The structured images before and after the saccade normally mask the intrasaccadic image. However, as the example of tail light flicker shows, there are circumstances in which the pre- and post-saccadic masking fails because at night the image before and after the saccade is spatially unstructured. It may then be difficult to distinguish intrasaccadic percepts such as the phantom array from those percepts that occur before and after the saccade.

During steady gaze (with microsaccades and drifts), spatially repetitive patterns can be distinguished at spatial frequencies as high as 40–50 cycle·deg^{-1} and can most readily be detected at spatial frequencies of around 4 cycle·deg^{-1}.[7] During a saccade, the angular velocity of the eye reaches a peak that can be as high as 700 deg·s^{-1} depending on the amplitude of the saccade.[8] It might therefore be possible in principle to distinguish flicker-induced intrasaccadic patterns at frequencies of up to $50 \times 700 = 35$ kHz. Two considerations make this unlikely. First, contrast sensitivity may be reduced to some extent during a saccade. Volkmann *et al.*[9] measured the ability to perceive the contrast of a grating during saccades. The gratings were flashed for 10 ms to the steadily fixating eye and also during 6° horizontal saccades. Contour masking before and after the saccade was minimised by a diffuse unpatterned field of view. Relative to contrast sensitivity during steady fixation, contrast sensitivity during the saccade was reduced by a factor of more than four. More recently, however, García-Pérez and Peli[10] have investigated contrast sensitivity for spatial patterns that appear only during a saccade and have shown that visual contrast processing is largely unaltered during saccades. Some of the reduction observed by Volkman *et al.*[9] may have occurred because the saccade trajectory was not perfectly aligned with the stripes of the grating, thereby reducing the contrast of the retinal image during the saccade. Indeed, this might explain why Volkmann *et al.* observed that the reduction in sensitivity increased as the spatial frequency of the gratings increased. Be that as it may, the physical reduction in contrast due to poorly aligned eye trajectories is irrelevant when flicker is perceived as an intrasaccadic pattern. If there is a reduction in contrast sensitivity during a saccade, it will reduce the maximum frequency at which flicker can be perceived. If contrast sensitivity is reduced by a factor of four, then, on the basis of the classic data from Campbell and Robson,[7] the maximum perceptible spatial frequency would be reduced from 48 cycle·deg^{-1} to 38 cycle·deg^{-1}, a relatively modest change.

The second consideration that might make a 35 kHz limit unlikely is the integration time of the retinal cells. Retinal cells integrate their signals over a period of time during which intensity and duration trade off against each other. Bloch's law of temporal summation states that $\Delta I \times \Delta T = \text{constant}$ where ΔI and ΔT are the light pulse intensity and temporal duration, respectively. At low light energy levels with large high-velocity saccades and high-frequency flicker, there may be insufficient variation in energy during the flight of the eye to stimulate the retina cells. However, Sam Berman in a memorandum to the IEEE PAR1789 committee dated 11 January 2011 combined data from Hart[11] with that from Fukuda[4] and showed that typical light sources can provide the luminance increment of sufficient magnitude such that temporal summation would not occur until ΔT was greater than approximately ½ msec, corresponding to 2 KHz flicker frequency.

Most of the existing literature on the 'phantom array' has been concerned with issues surrounding the location of the intrasaccadic percepts in relation to the timing of the saccade,[12–15] although Hershberger *et al.*[12] reported that a phantom array was visible by most of their subjects even at 500 Hz, the maximum frequency they used. This observation raises the possibility of (1) visibility of the intrasaccadic percept at frequencies greater than 500 Hz and (2) individual differences in its perceptibility. The purpose of this study was, therefore, to investigate in a range of observers the upper frequency limits below which flicker can be perceived as a phantom array and above which no such perception is possible. We chose viewing conditions likely to enhance intrasaccadic perception in order to provide worst-case estimates of use to engineers responsible for designing signal lights.

2. Experiment 1: 40° saccades with 1, 2, 3 and 5 kHz flicker

2.1. Method

2.1.1. Apparatus

An analogue oscilloscope (ISO-TECH ISR620) was operated on its side so that when the time base was set at its maximum of 2 µs per sweep of the screen (0.5 MHz), a vertical green line was visible (CIE chromaticity $x = 0.307$, $y = 0.529$). The *z*-input of the oscilloscope controlled the brightness of the line and was connected to the output of a computer-controlled function generator (Velleman PCSU1000 2 MHz). The function generator was programmed to generate a sine wave at a frequency of 1, 2, 3 or 5 kHz or a steady signal with similar time-averaged voltage and luminance. The luminance of the line varied over time between a minimum of $0.02\,cd{\cdot}m^{-2}$ and a maximum of $310\,cd{\cdot}m^{-2}$. The oscilloscope display was visible through a circular aperture (diameter 50 mm) in a matt black screen (width 2 m) on which were two white discs that served as fixation points. These were positioned 600 mm horizontally to the left and right of the line and were visible as a result of the low ambient lighting of the room (<1 lux).

2.1.2. Participants

Participants, four males and seven females aged 22–65 years, mean 34 years, with normal or corrected to normal visual acuity were recruited from staff, students and acquaintances of the authors at the University of Essex. Three wore corrective lenses during the testing. One female, aged 26, used a green overlay when reading (but not for the experiment).

2.1.3. Procedure

Participants were seated 1.7 m from the display, which was at eye level. The line was illuminated for 3 s in two immediately successive trials, during which participants were required to make saccades back and forth between the targets, and then decide in which of the two presentations, a pattern of spatially periodic lines could be seen. On one of the trials selected at random, the function generator modulated the brightness of the line; on the other trial, the line was not modulated. Ten such pairs of trials, separated by a 3 s interval, were given at each frequency in a constant random order.

2.2. Results

The average data are presented in Figure 1. A cumulative normal was fitted to the data using least squares. The 75% threshold based on the fitted curve was 1.67 kHz (standard deviation 0.52 kHz). A cumulative normal was also fitted to each individual participant's data using least squares and the mean of the individual thresholds was 1.98 kHz (standard deviation 1.13 kHz).

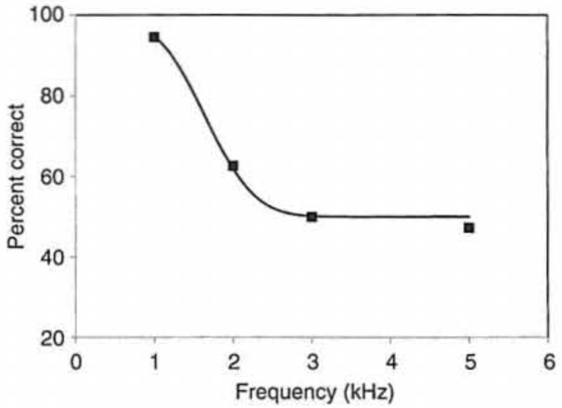

Figure 1 Experiment 1: Percentage of trials in which flicker was correctly detected, shown as a function of flicker frequency

3. Experiment 2: corroboration using different apparatus

Light from a 12 V tungsten halogen lamp controlled by a stabilised DC supply was directed via an optic fibre to the aperture of a Princeton Applied Research (Oak Ridge, TN, USA) light chopper (model 187). The end of the optic fibre measured 1 mm wide by 7 mm high and was observed by the authors from a distance of 1 m through the rotating shutter of the chopper in an otherwise darkened room (<1 lux). When the shutter was operated at 1 kHz, the intrasaccadic pattern was invariably perceived; at 2 kHz, it was occasionally perceived and at 3 kHz, the pattern could not be distinguished.

4. Interim discussion

Using the apparatus from Experiment 1, the authors estimated the spatial frequency of the intrasaccadic pattern by counting the number of lines in a known angular displacement at 100 Hz intervals between 100 Hz and 500 Hz. The data were used to estimate the spatial frequency at 1 kHz. The average estimate of 1.8 cycle·deg^{-1} agreed reasonably well with the estimate of 2 cycle·deg^{-1} based on (1) the temporal frequency of the line, (2) the amplitude of the saccade (40°) and (3) the peak velocity of 500 deg·s^{-1} for a saccade of this amplitude expected on the basis of the data quoted in Leigh and Zee.[16] Halving the amplitude of the saccade to 20° would be expected to change the velocity to 400 deg·s^{-1} and increase the spatial frequency of the intrasaccadic pattern from 2 cycle·deg^{-1} to 2.5 cycle·deg^{-1} at 1 kHz. At 2 kHz, the change would be from 4 cycle·deg^{-1} to 5 cycle·deg^{-1} and at 3 kHz from 6 cycle·deg^{-1} to 7.5 cycle·deg^{-1}. On the basis that the contrast sensitivity function peaks at about 4 cycle·deg^{-1} and the fact that the threshold was between 1 kHz and 2 kHz, one might anticipate that the threshold frequency at which the intrasaccadic pattern is perceptible would be little affected by reducing the saccade amplitude to 20°. On the other hand, the amount of saccadic suppression has been shown to increase monotonically with the size of a saccade.[17] Experiment 3 was therefore designed to determine the threshold for a saccade of 20° amplitude.

5. Experiment 3: 20° saccades with 1, 2, 3 and 5 kHz flicker

5.1. Method

The method was the same as for Experiment 1 except that the fixation points were repositioned 300 mm horizontally to the left and right of the light. Three participants from Experiment 1 aged 25–38 took part.

5.2. Results

Figure 2 shows mean data for the three participants. The 75% threshold based on the means of the group was 2.35 kHz (standard deviation 0.42 kHz). The mean of the individual thresholds was 2.47 kHz (standard deviation 0.57 kHz). The thresholds did not differ consistently or significantly from those in Experiment 1.

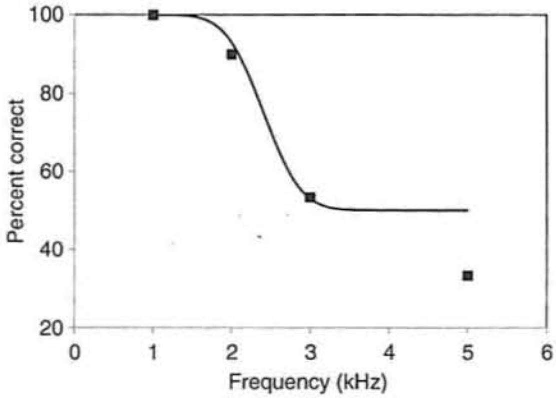

Figure 2 Experiment 3: Percentage of trials in which flicker was correctly detected, shown as a function of flicker frequency

6. Interim discussion

As anticipated on the basis of the spatial frequency of the intrasaccadic pattern, the amplitude of the saccade in the range 20–40° had little effect on the upper frequency limit at which the intrasaccadic pattern could be perceived.

Flicker at frequencies of 100 Hz and 120 Hz (above flicker fusion) is known to interfere with the control of eye movements.[18,19] Flicker from fluorescent lighting at 100 Hz and 120 Hz is known to impair visual performance[20] and cause headaches in some individuals.[20,21] Brundrett[22] showed that individuals who complained of discomfort from fluorescent lighting had a higher critical flicker fusion frequency than those who did not, and corroborated these observations electrophysiologically. One of the participants in Experiment 1 used a green overlay to treat visual stress when reading. This participant had a threshold of 4.9 kHz, well above that of the other observers. The intrasaccadic perception of flicker as an anomalous pattern in the form of a phantom array provides a putative mechanism for the interference with eye movements, and the possibly consequent disruption of visual performance and headache. If so, the conditions known to have these untoward effects (e.g. fluorescent lighting) might be those that sustain the intrasaccadic percept and those not so associated (e.g. incandescent lighting) be those that fail to sustain the intrasaccadic percept. This possibility was investigated in the next study.

Both fluorescent and incandescent lighting flicker at twice the frequency of the electricity supply, but the modulation depth of the variation in light from an incandescent lamp (defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$) is usually less than 10%. The modulation from fluorescent lighting varies between about 5% and 100% depending on the control circuitry and the phosphors[23] and was typically between 30% and 50% until high-frequency electronic ballasts became widespread. The following experiment was designed to determine the modulation depth at which the intrasaccadic pattern from flicker at 120 Hz becomes perceptible.

7. Experiment 4: modulation thresholds at 120 Hz

7.1. Method

The method was the same as in Experiment 1 except that the *z*-modulation of the oscilloscope had a square-wave luminance profile and a frequency of 120 Hz. The modulation depth defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$ was 5%, 10%, 20% or 40%. A total of 40 trials were presented, 10 for each modulation depth, selected in random order. Four participants from Experiment 1 aged 25–65, mean 40, took part.

7.2. Results

The average data are presented in Figure 3. A cumulative normal was fitted to the data using least squares. The 75% threshold based on the fitted curve was 10% (standard deviation 7.2%). A cumulative normal was also fitted to each individual participant's data

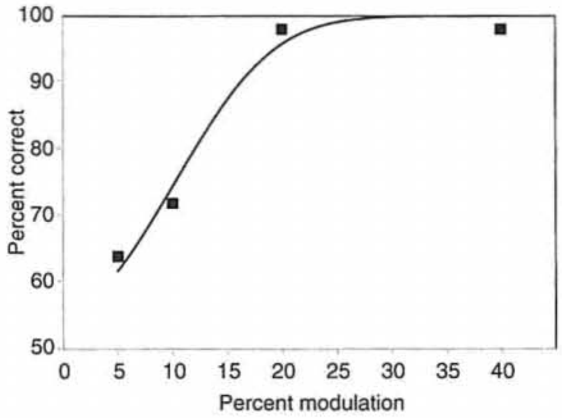

Figure 3 Experiment 4: Percentage of trials in which flicker at 120 Hz was correctly detected, shown as a function of the modulation of the flicker

using least squares and the mean of the individual thresholds ranged between 3% and 14% with a mean of 9% (standard deviation 4%).

8. Interim discussion

The average modulation depth at which flicker at 120 Hz gave rise to a perceptible intrasaccadic pattern was 10% and therefore greater than the modulation depth of incandescent lighting and lower than the modulation depth typical of gas discharge lighting and some LED lighting. The modulation was square-wave. The abrupt change in brightness may have made the pattern more perceptible than it would have been had the modulation been sinusoidal. Gas discharge lighting and LED lighting can have abrupt transitions reminiscent of those in a square wave.

With a saccade of 40° amplitude and velocity of about $500\,\mathrm{deg{\cdot}s^{-1}}$, the spatial frequency of the intrasaccadic pattern at a frequency of 120 Hz is only about $0.24\ \mathrm{cycle{\cdot}deg^{-1}}$, well below the peak of the contrast sensitivity function at ~4 $\mathrm{cycle{\cdot}deg^{-1}}$.[7] It is therefore possible that the intrasaccadic pattern would be perceived at lower modulation with a smaller and therefore slower saccade because the spatial frequency would then be higher and closer to the peak of the contrast sensitivity function. The smallest saccades are the involuntary microsaccades that have velocities of about $50\,\mathrm{deg{\cdot}s^{-1}}$.[24] and the smallest voluntary saccades are probably those that occur during reading, which are typically 1–2° in amplitude with a velocity that ranges from $80\,\mathrm{deg{\cdot}s^{-1}}$ to $120\,\mathrm{deg{\cdot}s^{-1}}$ (S. Jainte, personal communication). With velocities such as these, only about one cycle of a pattern would be available during the saccade, and the visibility of a grating is known to decrease when fewer bars are present.[25] When the authors used a 1° saccade, they were unable to see any periodic intrasaccadic pattern at 120 Hz even when the modulation was 100%.

9. General discussion

The neurological effects of saccadic suppression appear in motion-sensitive neurons.[26] The flashed presentation during a saccade might be expected to have little effect on any mechanisms of suppression that are due to image motion. This may be one reason why the intrasaccadic stimulation was clearly perceived.

The above experiments were undertaken looking at a light source in a darkened room. The measurements, therefore, apply to conditions in which light sources such as signal lamps are visible in low ambient lighting. One example of such conditions is that with which this paper began: driving at night behind tail lights of cars. These are conditions in which the apparent displacement of the location of the lights due to intrasaccadic perception can be a distraction – one that may or may not impact on road safety.

Recently, it has been shown that the horizontal spatial periodicity of words interferes with reading by prolonging the time taken for vergence movements.[27] It is possible that the intrasaccadic simulation of spatial periodicity may interfere further with this process and help to explain the effect of high-frequency flicker in disturbing eye movement control, particularly during reading.[18,19] The measurements obtained here reflect the conscious perception of spatial periodicity, and it is possible that non-conscious effects occur at parameter ranges beyond those explored here.

The perception of the phantom array would appear to be predictable from considerations of the spatial frequency, contrast and extent (number of cycles) of the intrasaccadic stimulation. With this in mind, it is of interest that the contrast limit for perception of the array at twice the electricity supply frequency (120 Hz) averaged 10%, which is above the modulation typical of incandescent lighting but below that typical for gas discharge and LED lighting. In other words, even under conditions in which the intrasaccadic stimulation ('phantom array') is maximally visible, as here, a modulation depth of 10% is insufficient for its reliable perception. It remains to be seen whether the complaints of discomfort from gas discharge lighting can be attributed to the 'phantom array' (perceptible or otherwise) and any resultant interference with saccadic control.

The experimental conditions used in this study might be expected to enhance the perceptibility of the intrasaccadic pattern, because after the retina was exposed to a flash, little further light reached the stimulated location on the retina. In a well-lit room, the contrast of the image of each flash would presumably be reduced by the additional light reaching the part of the retina stimulated by the flash later in the saccade. The perceptibility of the intrasaccadic pattern might, therefore, be less when a dark line is viewed on a white background that flickers. Bullough *et al.*[3] have reported the perceptibility of flicker when subjects observed a minimally contoured wall of a room lit with flickering light from an LED luminaire and made a 40° saccade between two distant targets; 30% were able to detect flicker at 300 Hz. In a subsequent study,[28] participants were required to wave a white rod and report any stroboscopic effects. Under these conditions, the upper frequency limit was still higher. The participants in the original study[3] did not include those with migraine or epilepsy, and it is possible that the greater cortical hyperexcitability in these participants[29] would render the flicker more visible. Our observation that an observer who used coloured overlays for reading was able to perceive the intrasaccadic pattern at higher frequencies than those for the remainder of the sample is of interest because coloured filters have been shown to reduce cortical hyperactivation in migraine.[30]

In summary, temporally modulating lighting can result in intrasaccadic perception of spatial periodicity for parameter ranges in which the lighting has been associated with impaired ocular motor control, impaired visual performance, discomfort and headaches. The upper frequency limit of such effects is well above the frequency at which the modulation can be appreciated as flicker.

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Designing to Mitigate the Effects of Flicker in LED Lighting

Reducing risks to health and safety

by Brad Lehman and Arnold J. Wilkins

How often has this scenario happened? You are driving at night behind a car that has bright light-emitting diode (LED) taillights. When looking directly at the taillights, the light is not blurry, but when glancing at other objects, a trail of lights appears, known as a *phantom array*. The reason for this trail of lights might not be what you expected: it is not due to glare, degradation of eyesight, or astigmatism. The culprit may be the flickering of the LED lights caused by pulse-width modulating (PWM) drive circuitry. Actually, many LED taillights flicker on and off at frequencies between 200 and 500 Hz, which is too fast to notice when the eye is not in rapid motion. However, during a rapid eye movement (saccade), the images of the LED lights appear in different positions on the retina, causing a trail of images to be perceived (Figure 1). This disturbance of vision may not occur with all LED taillights because some taillights keep a constant current through the LEDs. However, when there is a PWM current through the LEDs, the biological effect of the light flicker may become noticeable during the eye saccade.

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Human Biological Effects of Light Flicker

Flicker can be defined as a rapid repetitive change in brightness [1]. At a minimum, flicker is a distraction. However, it can also become a hazard to health, provoking an increased incidence of headaches [2], [3] and even epileptic seizures [4]–[6]. The hazard depends on the area of retina exposed to the flicker and the way in which the light changes with time (frequency and modulation depth), among other factors. When flicker occurs at frequencies between 3 and 70 Hz with a sufficient peak-to-peak amplitude, the dangers can be the most catastrophic: a small percentage of the population may suffer an epileptic seizure [4]–[6].

Fortunately, almost all flicker in lighting occurs at or above a frequency twice that of the ac input power line: 100 Hz in Europe and 120 Hz in North America [2]. So in normal operation, commercial lighting may not increase the incidence of photosensitive seizures. Indeed, flicker cannot usually be seen when its frequency is greater than the so-called critical flicker fusion frequency (CFF), which is usually between ~60 and 90 Hz, although the frequency varies with the characteristics of the light and the observer. Above the CFF, the light appears continuous, but this does not mean that it is innocuous. In fact, the flicker can still be seen under certain circumstances, as in the case of the LED taillights. Even when it cannot be seen, however, flicker can remain hazardous to humans [2]. We know this because of experience with fluorescent lighting. When fluorescent lamps are controlled by line-frequency magnetic ballasts, a discharge occurs twice with each cycle of the electricity supply. The flicker cannot usually be seen, but it doubles the average incidence of headaches in office workers [3], triggers migraines in some individuals [7], [8], and impairs the performance of visual tasks [9]. The twofold increase in headache incidence is due to a small proportion of the population who experience relatively frequent headaches [3], [10].

When looking directly at the taillights, the light is not blurry, but when glancing at other objects, a trail of lights appears, known as a phantom array.

An increased hazard also occurs in fluorescent lamps with low-frequency magnetic ballasts as they age. Sometimes, the discharge may be brighter when the ac flows in one direction more efficiently than in the other, resulting in brightness variation at the frequency of electricity supply. The flicker can then sometimes be seen, and, generally speaking, when flicker can be seen, there is a risk of seizures. When the lamp is operating normally, however, and the flicker cannot be seen, there may be little risk of seizures, but the possibility of other neurological consequences, such as headaches, remains. There are important lessons to be learned from fluorescent lighting, e.g., the negative health effects from flicker should be mitigated in all possible life cycle operations for any lamp technology.

FIG 1 When a person's eyes move quickly from side to side, multiple images are observed in some LED car taillights.

The eye is continually in motion, moving the retinal image in a succession of drifts and jerks (saccades), even when we gaze directly at something [10]. These movements are necessary for vision for, without them, the image fades. When the gaze is redirected from one point of regard to another, the eyes make a large saccade, and the flight of the eye during such a saccade can be extremely rapid, reaching more than 400°/s for the largest saccades. Although the eyes are open and the retinal cells are functional, we are usually unaware of what we see during a saccade. This lack of awareness, called *saccadic suppression*, arises partly because what we see before and after the rapid eye movements are relatively stable images, which mask the moving image that occurs during the saccade. When the image is illuminated intermittently by flickering light, the image during the flight of the eye is not a moving image but a succession of discrete images, and these can get confused with the images before and after the flight of the eye. You become aware of flickering LED taillights because each saccade is accompanied by a disconcerting trail of images [11]–[13]. At night, there is nothing to see before and after the saccade to mask the intrasaccadic image. The frequency of flicker at which such intrasaccadic images are visible can be as high as 2 kHz [14]. During a saccade, the image on the eye is moved as the eye moves. On the other hand, when the eye is relatively stable and the objects themselves move rapidly, we may again notice a similar succession of images. This is known as the *stroboscopic effect*, and it occurs at frequencies that are similarly high [15].

Driving LED Lamps May Lead to Flicker

Figure 2 shows the light output of typical commercially available LED Edison socket bulbs with A19 size, all of which are marketed as 60-W incandescent replacement bulbs and have about 800 lumens of light output. Most LED bulbs will demonstrate modulating light output that is periodic at twice the line frequency, which, in this case, is 120 Hz. However, as can be seen from one bulb, it is possible to design a driver that exhibits virtually no flicker. High-frequency measurement noise may be ignored because it is due to the low-cost Texas Instruments OPT101 photodiode and transimpedance amplifier. To eliminate the measurement noise, the more elaborate experimental measurement setup described in [2] and [16] may be utilized. The flickering levels of the LED bulbs depend on the type of driving method that is utilized to convert the ac input to the required dc through the LED.

Incandescent bulbs do not require these power electronic drivers since it is possible to send the positive and negative cycle current directly through their tungsten filaments. The thermal time response for the filament is so slow that the flicker is naturally filtered to a lower level. On the other hand, LEDs are unidirectional devices and require ac–dc conversion. The response time for LEDs is almost instantaneous, and it is commonly assumed that the luminous intensity of an LED is approximately linearly proportional to the current through the LED. As a result, LED current ripple instantaneously becomes light flicker ripple. This has caused flicker to reemerge as an important issue in the design process, even giving rise to new standards groups such as IEEE PAR1789 that study safe levels [17].

From the experimental plots of luminous intensity in Figure 2, it is possible to define [2], [18]

$$\text{Percent Flicker or Mod\%} = 100\,(\text{Max} - \text{Min})/(\text{Max}+\text{Min}),$$

where Max/Min represent the maximum/minimum measured light intensity from the lamp. It is interesting to note that there is no dependence on flicker frequency in this definition, although it is known to be an important parameter in human safety for lighting. From the definition, it can be seen that Mod% will always be a value between 0% and 100%. A summary of the Mod% of the tested commercially available A19 LED Edison socket bulbs is presented in Table 1. For reference, compact fluorescent lamps with high-frequency ballasts normally have a Mod% of less than of 10%, while that of fluorescent lamps with magnetic ballasts is 25–50% [2], [16]. Outdoor lighting with high- or low-pressure sodium lamps may have up to 100% modulation.

In the following sections, we present a few of the basic methods to create the required dc whereby unwanted flicker may be introduced in LED lighting [2], [19]. There are many variations of the presented methods.

Full-Wave Rectifier Connected to LED String

In this approach, shown in Figure 3(a), the ac input source is sent into a full-wave rectifier, causing the (approximate) absolute value of the input voltage to be sent to the load. In

Table 1. Philips and Maxlite are within the measurement error of the flicker.

LED Bulbs	Mod%
60-W incandescent	7.62%
Cree	21.27%
Philips	~1%
Utilitech	48.39%
Ecosmart	16.96%
GE	19.63%
MaxLite	~1%
Sylvania	29.41%

this case, the current through the LEDs has a waveform shape similar to a scaled absolute value of a sine wave. That is, the rectified sine wave may be of the form $|V_p \sin(\omega t)|$, where V_p is the amplitude of the sine wave, ω is the angular frequency in radians $\omega = 2^* \pi^* f_{ac}$, and f_{ac} is the ac mains power line frequency. Similarly, it is possible to use the so-called ac-LED approach, as shown in Figure 3(b). Two strings of LEDs are powered in parallel, with the anode of one paralleled string connected to the cathode of the other parallel string. When the ac line voltage is positive, energy drives one of the LED strings. When the ac line voltage is negative, the other paralleled LED string is driven. At most, one of the LED strings has a current through it. The combined LED current would, therefore, in both cases have a shape as in Figure 3(c), which has Mod% = 100% with flicker frequency $f_{Flicker}$ equal to twice the ac mains frequency, i.e., $f_{Flicker} = 120$ Hz (North America) or $f_{Flicker} = 100$ Hz (Europe).

The benefits of the ac-LED approach are the minimal part count and the elimination of high-frequency power electronic drivers, but this comes at a cost of extremely high ripple—much higher than in line-frequency magnetic ballast for fluorescent lamps. Alterations on the ac-LED approach may include ac stacking, which varies the number of conducting LEDs depending on the voltage level of the input source [19]–[21]. Then, it may be possible to add holdup capacitors of reasonable size to subsequently provide energy to the LEDs, even when the input voltage becomes low. Such approaches can partially reduce the flicker modulation percentage [22].

Simple Dimming PWM Circuits

It is common to dim LEDs by pulsing the current through them, as shown in Figure 4. The average luminous intensity of the LED can be adjusted by varying the length of time that the LED current is high and low. Thus, PWM dimming circuits may be designed to operate at any frequency. This is true whether the input source is ac or dc power, although Figure 4 assumes a dc input source, perhaps coming from a prior ac–dc conversion. In Figure 4(a), the switch is in series so that when it is on, the current will flow through the LED. When the switch is off, no current flows through the LEDs. In Figure 4(b), the current flows through the

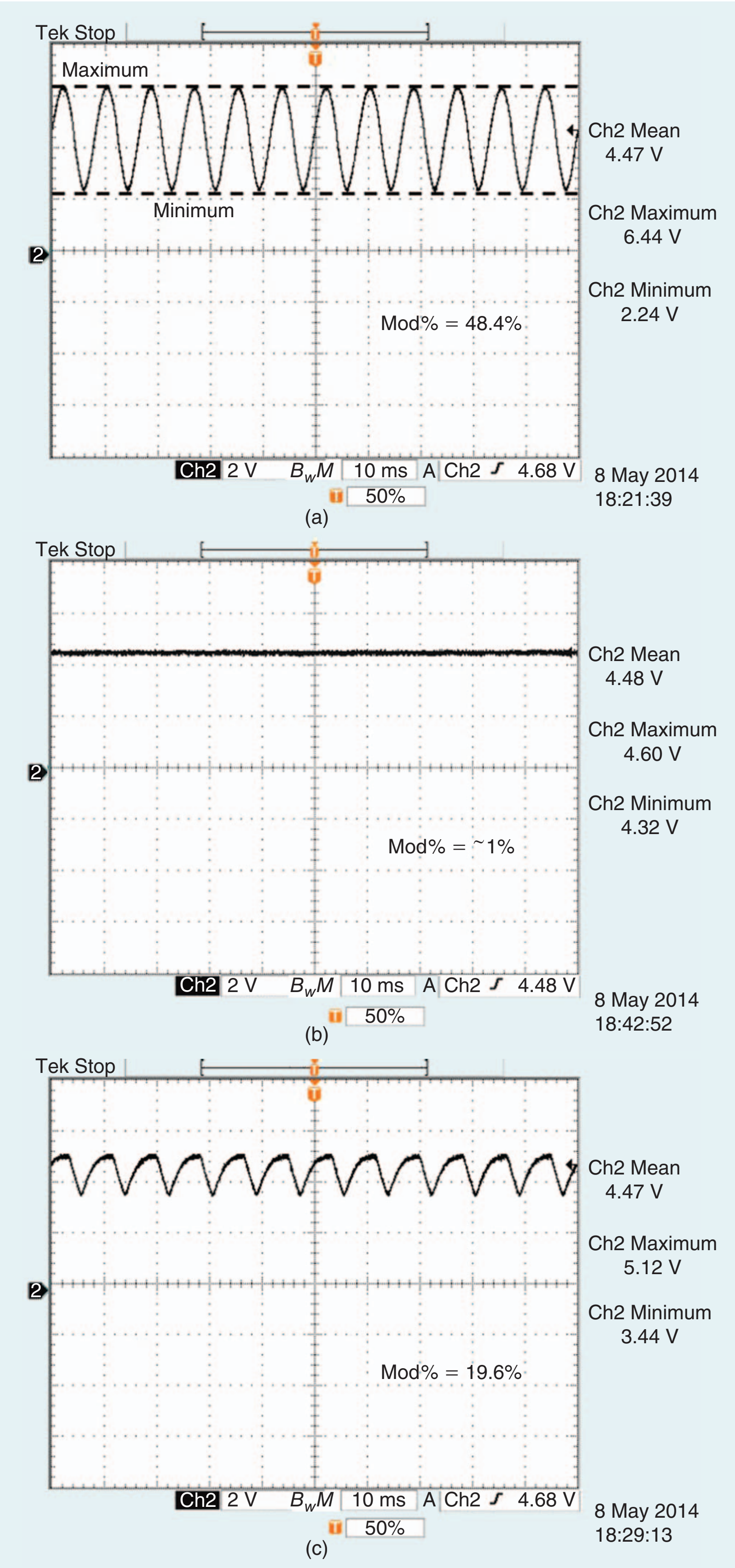

FIG 2 The typical plots of luminance light flicker in commercial LED A19 bulbs (60-W incandescent replacement bulbs). Mod% = (Max luminance – Min luminance)/(Max luminance + Min luminance). Mod% for the three bulbs are (a) Utilitech, 48.4%; (b) Philips, <1%; and (c) GE, 19.6%.

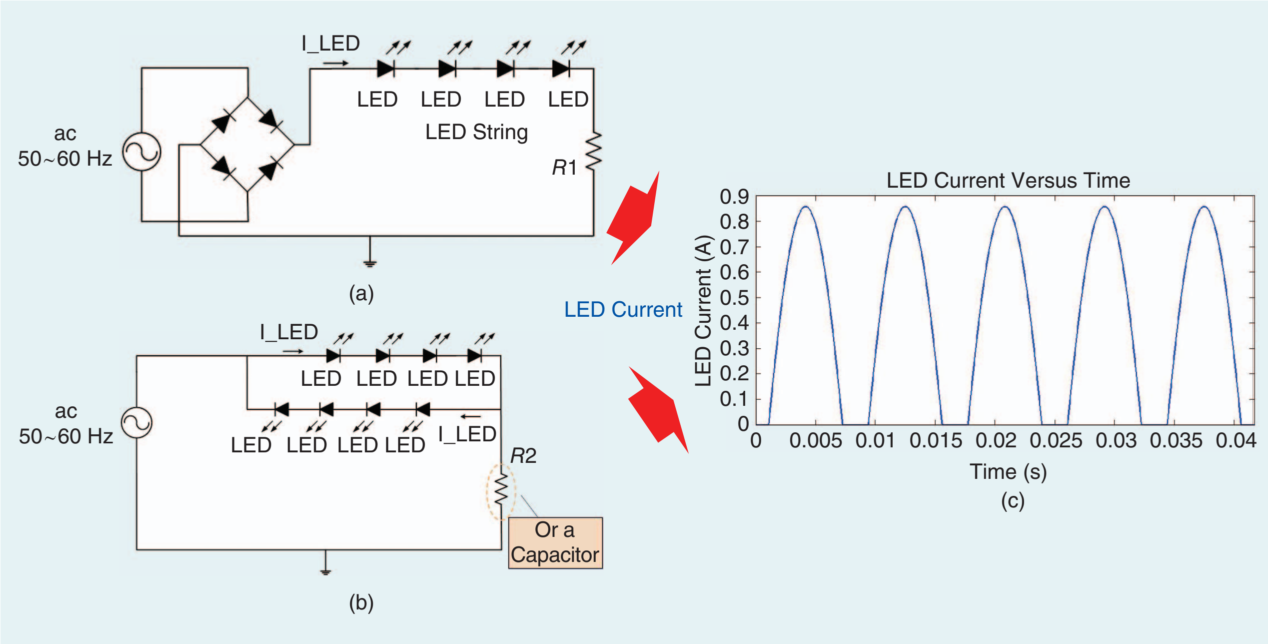

FIG 3 The two methods to drive LEDs at twice the line frequency. (a) A full-bridge rectification: rectify ac and send to the LED string. (b) The opposite connected parallel strings: directly power two LED strings with opposite anode/cathode connections. (c) The current/luminous output in the LEDs for both approaches: simulation of current through HB LEDs. The luminous intensity is proportional to the current, causing the lamp to flicker at twice the line frequency (shown periodically every 1/120 s) [2].

LEDs when the switch is off, while there is no current in the LED when the switch is on. In either case, the LED current looks similar to Figure 4(c) and has a flicker frequency of $f = 1/T$, where T is the period of the PWM. The flicker frequency for PWM dimming in commercial LED lamps typically varies from 120 to 480 Hz [16], but it is also possible to perform high-frequency dimming [23].

It should be mentioned that there are alternative approaches to dimming, such as amplitude dimming, in which the current through the LED is continuous and not pulsing. By reducing the value of this continuous current (amplitude), the luminance is dimmed. This approach can avoid flicker.

Power Factor Correction Circuitry

Even when more sophisticated high-frequency switching power supplies with power factor correction (PFC) circuits are used to drive LEDs from ac mains, such as in Figure 5, there is often flicker at twice the line frequency. Depending on the design of the circuitry, the harmonic content of this flicker may vary from being small and unnoticeable to significant in magnitude. The percent flicker depends on the controller design, the circuitry being used, and filter component values, among other factors.

Figure 5 shows a typical circuitry that may be used in driving the LEDs in a bulb. A two-stage approach [19], [24]–[26] is illustrated because this can have a reduced flicker Mod%. The first stage may be used to achieve PFC to meet typical requirements, such as a power factor greater than 0.7 given by EnergyStar requirements [27]. The second stage can be used to reduce the percent flicker. An energy buffer, such as a dc-link reservoir capacitor, is usually used to absorb the ripple between

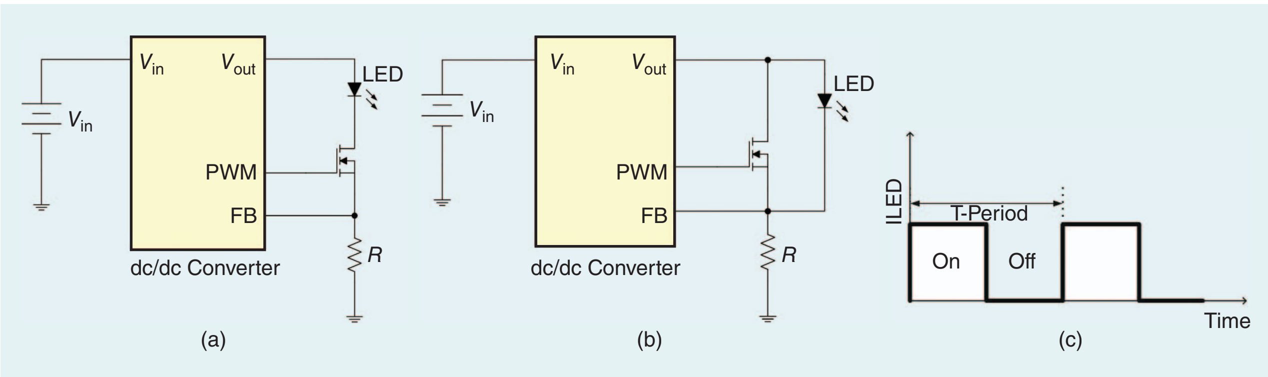

FIG 4 Sending a PWM current through LEDs: (a) series PWM dimming, (b) parallel PWM dimming, and (c) the PWM current through the LED in either method.

the two stages. To reduce the value of the dc-link capacitance, some designs sacrifice the performance. On the other hand, some vendors may utilize only a single-stage ac-dc approach and only keep the PFC portion of Figure 5 [28]–[31]. In this case, it is likely that the percent flicker may significantly increase, but there is a benefit of lower cost as a result of the lower parts count. A compromise between the two- and single-stage approaches is the single switch converters that integrate two topologies [32]. Finally, it should be mentioned that linear regulators may be inserted in series with the LEDs to regulate constant dc so that no flicker appears [33]. This comes at the disadvantage of additional power loss.

Developing Levels of Flicker That Have Minimal Human Biological Effects

This section presents flicker criteria that can mitigate the human biological effects. The focus of the results concerns flicker at frequencies above 90 Hz since this is the dominant location of flicker for commercial LED driving methods. However, it is important to mention the following known criterion to prevent photosensitive epileptic seizures: to reduce the risk of seizures to individuals susceptible to photosensitive epilepsy, all flicker at frequencies below 90 Hz must satisfy Mod% $\leq$ 5%.

There is a significant amount of research from medical and vision science to support the necessity for keeping flicker below 5% modulation for flicker frequencies below 90 Hz [4]–[6]. It seems reasonable to avoid designing drivers that cause flicker below 90 Hz. This would, in effect, forbid the half-bridge rectified ac power line from being directly used to drive LED strings, but it would also mean that the bulb should not flicker in this low frequency even when connected to a dimmer switch. It has already been well documented that some LED bulbs fail on residential dimmer switches, and these flicker at low frequencies that may induce photosensitive seizures in some individuals [34].

Note that the 5% modulation criterion does not prevent discomfort from flicker but only implies that it would not induce photosensitive seizures. In fact, it is well understood that in the 1–35-Hz range, a 5% modulation may be detected by observers since the eye is sensitive to flicker in the very low frequency range [35]–[39]. IEEE PAR1789 Standards Working Group [17], as well as other groups [27], [35], [36], may shortly provide recommended practices to limit the detectability of flicker below the CFF in these lower frequency ranges below 90 Hz. However, these flicker frequencies would occur because of poor power line harmonics rather than the LED driving method. Instead, this research considers the more common flicker frequencies observed in LED lighting that occur at or above twice the ac line frequency. For flicker frequencies, $f_{Flicker}$, above 90 Hz, Mod% should satisfy the following:

- low-risk level: Mod% $\leq 0.08^* f_{Flicker}$ will mitigate any distractions or negative biological effects caused from flicker
- no-observable-effect level: Mod% $\leq 0.0333^* f_{Flicker}$.

Note that the Mod% has a maximum of 100%.

Example Calculations

Normally, in lighting, the flicker frequency will have a fundamental component at twice the ac line frequency, i.e., $f_{Flicker} = 2^* f_{ac}$ and that $f_{Flicker} > \text{CFF}$.

- Example 1: In the United States, $f_{ac} = 60$ Hz
  - The low-risk level leads to Mod% $< 0.08^*$ 120 Hz = 10% (rounded to the nearest percent).
  - The no-effect level leads to Mod% $< 0.0333^*$ 120 Hz = 4% (rounded to the nearest percent).

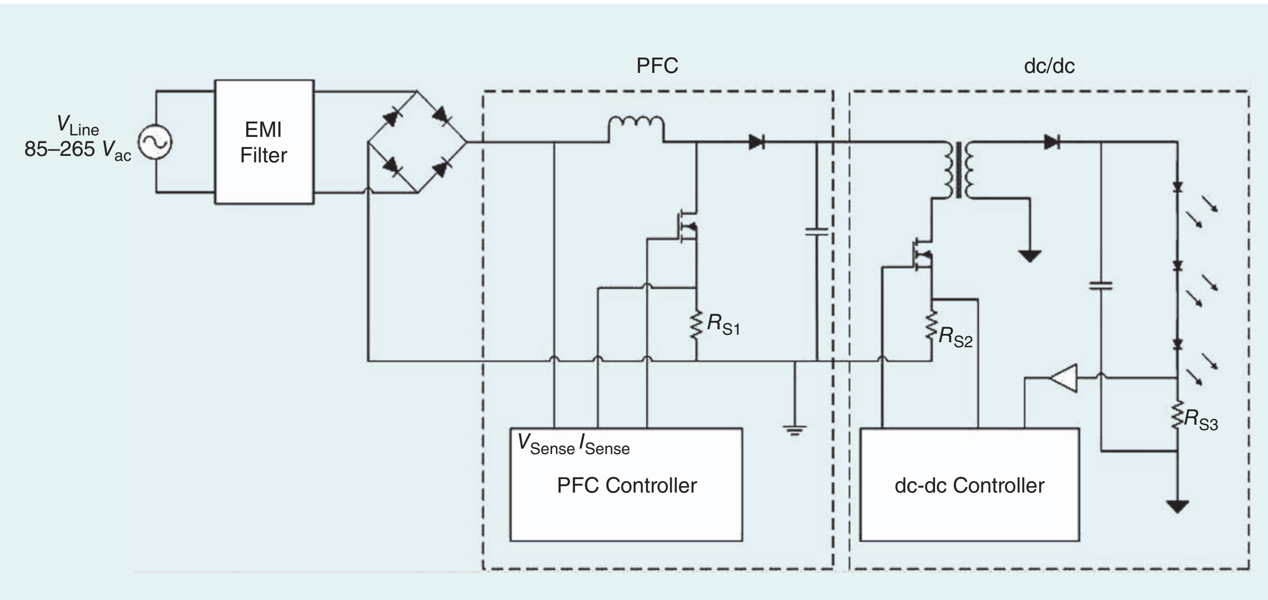

FIG 5 The typical active PFC circuitry for an ac line input will normally have some flicker frequency at twice the ac line frequency.

- Similarly, in Europe, $f_{ac} = 50$ Hz. The low-risk level leads to Mod% $< 0.08^*$ 100 Hz = 8% (rounded to the nearest percent), and no-effect level leads to Mod% $< 0.0333^*$ 100 Hz = 3% (rounded to the nearest percent).

■ Example 2: PWM dimming

- The low-risk level for PWM dimming at 100% modulation can be derived by solving $100\% = 0.08^* f_{\text{Flicker}}$. This means that keeping $f_{\text{Flicker}} > 1.25$ kHz would minimize the visual distractions such as the phantom array effects. The no-observable-effect level flicker is $f_{\text{Flicker}} > 3$ kHz, which can be derived by solving $100\% = 0.0333^* f_{\text{Flicker}}$.

Remembering that the maximum value of Mod%= 100%, Example 2 implies that flicker above 1.25 kHz is low risk and flicker above 3 kHz can be considered to have no human biological effects, independent of the Mod%.

How Were the Low-Risk and No-Effect Regions Derived?

The derivation of the low-risk and no-observable-effect level can be seen from Figure 6. Data from several independent lab studies on flicker are superimposed to first derive the no-observable-effect line Mod% $= 0.0333^* f_{\text{Flicker}}$. The low-risk region Mod% $\leq 0.08^* f_{\text{Flicker}}$ is then derived by multiplying the no-effect line by a factor of 2.5 and then comparing it with the data from [40], incandescent lighting experiments [14], and the results of a U.S. Department of Energy/Pacific Northwest National Laboratory (DOE/PNNL) case study, as we discuss next.

Roberts and Wilkins [14] (the triangles in Figure 6) measured the ability to see a flickering light during a saccade. They showed that during a saccade, the flicker could be seen as a trail of lights even when the frequency of the flicker was as high as 2 kHz. The data from [14] were obtained when making horizontal saccades across a vertical bar that was either steady or intermittently illuminated (time-averaged luminance 150 cd.m^{-2}) in an otherwise dark room (<1 lux). On the basis of their perception of a phantom array, participants were forced to choose on which of the two immediately successive trials the vertical bar was intermittently illuminated. The forced-choice procedure ensured veridical limits on perception that were not contaminated by a predisposition to report flicker when none was visible.

The data from [14] were then combined with those from other independent studies in which flicker was detected not as a direct result of eye movement but from the movement of a target—the so-called stroboscopic effect. First, the data from [14] and [15] (the squares in Figure 6) are combined to provide data to create the no-observable-effect limit. In [15], participants were asked to report the stroboscopic perception of a white rod that they held in their hand and waved. The data in Figure 6 show the frequency at which flicker was reported on 50% of occasions. A 50% criterion was used because there was no control for the reporting of flicker when none was visible. The participants had the ability to alter the speed of the white rod that they waved until they noticed any flicker (if ever). This freedom to change the speed of the wand motion suggests a worst-case analysis suitable for no-effect levels. The data from [14] and [15] are curve fit to create a line Mod% of approximately $0.0333^* f_{\text{Flicker}}$ and are shown in Figure 6 on log–log axes.

The low-risk region Mod% $< 0.08^* f_{\text{Flicker}}$ is then derived by multiplying the no-effect line by a factor of 2.5. This is further validated by noticing that the line curve fits the data from [40], which collected data for noticing stroboscopic effect, more suitable for the low-risk region. Specifically, the data from [40] (circular points) relate to the perception of the stroboscopic flicker of a white dot on a black rotating turntable, rotating at a certain fixed speed quickly enough to make saccadic eye movements likely. The data were those from the third experiment in [40, Figure 5]. The observer reported the presence or the absence of the stroboscopic effect, and a 50% threshold was obtained by increasing the frequency in interleaved staircases within the initial dc standard for comparison. The lower limits of the thresholds were given (shown in Figure 6). The threshold data excluded outliers (a substantial proportion of the data). Because outlier data have been excluded, the experiments are taken as suggesting a low-risk level but not a no-effect level.

Roberts and Wilkins [14] also measured the modulation depth at which the flicker could be seen when the frequency was 120 Hz. They showed that the flicker became visible at modulation depths greater than 9% and suggested that this might explain the tolerance of incandescent lighting, which

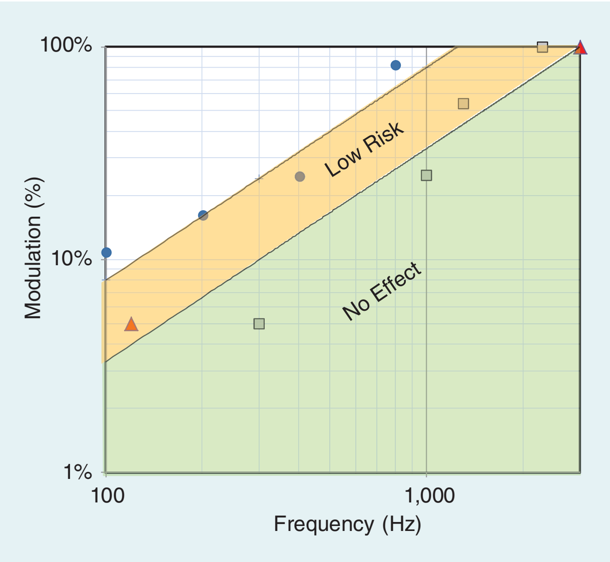

FIG 6 The low-risk (orange) and no-observable-effect (green) regions for flicker as a function of the frequency and modulation percentage. The line Mod% $= 0.0333^* f_{\text{Flicker}}$ separates the no-observable-effect and low-risk regions, and the upper margin of the low-risk region is given by the line Mod%$= 0.08^* f_{\text{Flicker}}$. (Data taken from Figure 3 of [14] and [15].)

has a modulation that is usually less than this, versus the intolerance of gas-discharge lighting, which can often have a modulation greater than 9%. Their observations are consistent with creating a low-effect level line that multiplies the no-observable-effect line by a factor of 2.5 to obtain Mod% $< 0.08^{*} f_{\text{Flicker}}$.

The conservativeness of the low-risk level line Mod% $\leq 0.08^{*} f_{\text{Flicker}}$ can be examined by comparing it with data from a study by the U.S. DOE/PNNL, which measured the detection of flicker in LED troffers in real-world lighting situations [41]. The LED lamps tested by the U.S. government lab had a flicker frequency ranging from 120 to 480 Hz. At full output, none of the observers was able to reliably detect flicker, even when the percent modulation reached ~24%. However, when dimmed, some of the lamps had flicker that was noticeable either by the stroboscopic effect produced by hand motion or pencil movement in the troffer area, or, in some cases, several observers detected flicker with normal eye motion only. The study introduces a numerical perceived flicker rating on a scale from 1 to 5. Flicker "scores" below ~2.6 might lead to observer distractions.

Although the eyes are open and the retinal cells are functional, we are usually unaware of what we see during a saccade.

Several items should be noted from the DOE/PNNL study [41].

- Each of the seven luminaires with a flicker score below 2.6 would violate the condition that Mod% $< 0.08^{*} f_{\text{Flicker}}$.
- All 21 luminaires tested by PNNL that satisfied the condition Mod% $\leq 0.08^{*} f_{\text{Flicker}}$ had satisfactory flicker ratings, whether dimmed or not.
- Two LED luminaires at full output and one at dimmed level did not satisfy the condition that Mod% $\leq 0.08^{*} f_{\text{Flicker}}$, but they had flicker ratings above 2.6, which suggested that, in the conditions tested, the flicker was not regularly detected.

It can be inferred, therefore, that for flicker frequencies above 90 Hz, Mod% $< 0.08^{*} f_{\text{Flicker}}$ should contain the low-risk level, but with proper design of specific lighting circumstances (glare, brightness, spectral content, etc.), it may be possible to operate outside the region and still be acceptable. In any case, the DOE/PNNL experiments suggest that the low-risk region %Mod $< 0.08^{*} f_{\text{Flicker}}$ is not overly conservative.

Conclusions

This article presents criteria that can mitigate the biological effects of light flicker. The results were derived for LED lighting, but they can be applied to all general illumination technologies. LED lighting, however, has been the focus of more attention recently because its driving methods may introduce more flicker than other lamp technologies. The flicker depends on the drivers selected for the LED bulb, as described in this article. In addition, flicker health risks depend upon a variety of lighting applications and exposure factors. For example, outdoor lighting with high-pressure sodium lamps on magnetic ballasts and low-pressure sodium lamps sometimes has nearly 100% modulation. They are often used without health incident, perhaps because the light is not being used for prolonged reading, studying, or other more difficult visual tasks. According to DOE/PNNL researchers [16], a lighting situation may determine the case-by-case tolerance of flicker. They conjecture that flicker matters most in 1) general lighting, 2) spaces where children or susceptible populations spend time (e.g., hospitals), 3) task lighting, and 4) industrial spaces with moving machinery. Even in other lighting applications, prudence should be used when designing the amount of light flicker. This article creates generalized low-risk and no-effect flicker regions that would be both task and lighting application independent.

A low-risk criterion of Mod% $\leq 0.08^{*} f_{\text{Flicker}}$ for flicker frequencies above 90 Hz may be a reasonable target for flicker design for LED bulb manufacturers. Some bulb manufacturers have already met the criterion, while others are close to meeting it. In fact, two of the seven tested LED bulbs actually satisfy the no-effect level criteria, Mod% $\leq 0.0333^{*} f_{\text{Flicker}}$. It, therefore, seems possible that commercial LED luminaires may be able to reduce their Mod% with small changes in their controllers or software, or even by changing a few filter component values (perhaps without altering the package size) if they desire to meet the low-risk level criterion for flicker.

About the Authors

Brad Lehman (lehman@ece.neu.edu) is a professor in the Department of Electrical and Computer Engineering, Northeastern University, Boston, Massachusetts. He is also the editor-in-chief of *IEEE Transactions on Power Electronics*. He is a Senior Member of the IEEE.

Arnold J. Wilkins (arnold@essex.ac.uk) is a professor in the Department of Psychology, University of Essex, Colchester, United Kingdom.

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