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Detection and acceptability of stroboscopic effects from flicker

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Previous studies have demonstrated that the perception of stroboscopic effects from flickering light is strongly influenced by both the frequency and the amount of modulation (e.g. percent flicker). The relationship, if any, between these factors for the detection and acceptability of stroboscopic effects has not been elucidated under conditions corresponding to illuminating engineering practice. In a laboratory study, participants reported whether they could detect stroboscopic effects from flickering light with a range of frequencies and percent flicker values, and if detected, whether it was acceptable. The resulting data can provide functional relationships between frequency and percent flicker in terms of detection and acceptability of stroboscopic effects under conditions corresponding to those tested.

1. Introduction

Nearly all light sources produce flicker. For many conventional lighting technologies (e.g. incandescent, fluorescent and high intensity discharge lamps), flicker is a consequence of 50 Hz (in Europe, Asia, Africa and Australia) or 60 Hz (largely in the Americas) alternating current (AC) power line frequencies. Alternating polarity at these frequencies can result in flicker at twice the power line frequency (e.g. 100 Hz or 120 Hz), unless high-frequency driving circuitry (e.g. electronic ballasts) is used. The thermal mass of incandescent filaments and the decay characteristics of phosphors used in discharge lamps can reduce the flicker amplitude. This amplitude can be characterised in different ways, the most commonly used of which are percent flicker and flicker index. Percent flicker[1] is defined in terms of the difference between the minimum and maximum light output during a flicker waveform cycle:

$$\text{Percent flicker} = [(\text{maximum} - \text{minimum}) / (\text{maximum} + \text{minimum})] \times 100\% \qquad (1)$$

If a light source ever reaches zero light output during any portion of the cycle, the percent flicker is 100%. Flicker index[2] is defined with respect to a plot of the light output curve as a function of time. Flicker index is the area under the light output curve and above the time-averaged light output for the entire cycle, divided by the total area under the light output curve. For a given waveform shape and duty cycle (duty cycle is defined here as the percentage of time during a flicker cycle that the light output exceeds 10% of the maximum value), percent flicker and flicker index are proportional to each other.

With respect to solid-state light sources, the Institute of Electrical and Electronics Engineers (IEEE) is preparing a draft standard (P1789) on flicker from light-emitting diodes (LEDs). In addition to reviewing the literature on the visual and non-visual effects

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of flicker such as photosensitive epilepsy and headaches, the IEEE draft describes various methods for driving LED sources. These include full wave rectifiers and the use of parallel LED strings with opposite polarity. In addition, some residential dimming equipment can produce low-frequency flicker when used to dim LED sources.

Direct visual perception of flicker is negligible at frequencies of 100 Hz or more,[3–5] higher than the critical fusion frequency for most stimuli.[6] However, indirect perception of flicker is possible through stroboscopic effects at frequencies of 100 Hz and higher[5,7]and widespread perception of stroboscopic effects has been reported at 500 Hz.[8] The variety of methods by which LEDs can be driven means that various flicker frequencies and percent flicker values are possible in lighting systems using these sources. Perception of stroboscopic effects decreases as frequency increases[5,8]and as percent flicker (or flicker index) decreases[7]. Bullough *et al.*[5] found that detection of stroboscopic effects was greater for high-modulation flicker (100% flicker, 0.5 flicker index) at 300 Hz than for lower modulation flicker (33% flicker, 0.17 flicker index) at 120 Hz. However, the interaction between these factors is not well understood. This study was conducted to identify combinations of frequency and amount of modulation for rectangular-wave flicker that would result in similar detection and acceptability.

2. Method

In a dark, windowless room at the Lighting Research Center, ten subjects (aged 23 to 52 years, mean 31 years, SD 9 years, 4 females) participated in a study to evaluate the detection and acceptability of stroboscopic effects produced by flickering light sources. The experimental setting and apparatus was the same as that used by Bullough *et al.*[5] to study various flicker parameters. In that study, subjects performed some arithmetic problems on a laptop computer and were asked whether they detected flicker while using the computer. Since there were no differences in responses to flicker between when the computer was used and when subjects were asked if they detected flicker when the computer display was turned off;[5] no computer was used in the present experiment. A high-powered LED [20 W, 4000 K correlated colour temperature (CCT)] was installed into a portable task luminaire, where it could be operated, through microprocessor control,[5] with a rectangular waveform to one of five frequencies (100 Hz, 300 Hz, 1000 Hz, 3000 Hz or 10 000 Hz) and one of four percent flicker values (100%, 54%, 25% or 5%, corresponding to flicker indices of 0.50, 0.27, 0.13 and 0.03, respectively). At 100% flicker, the duty cycle was 50%; for the remaining flicker conditions, the minimum and maximum light output were each produced 50% of the time. All light output waveforms were checked using an oscilloscope and a photopic detector.

Subjects were seated at a workstation equipped with the task luminaire, and experienced each combination of frequency and percent flicker in randomised order. All 20 lighting conditions produced equivalent horizontal illuminances (~400 lx) on the workstation desktop surface, which was covered with matte black cloth. Under each condition, subjects were asked to wave a white plastic rod (172-mm long, 6-mm diameter) back and forth underneath the luminaire and to report whether they could detect any flicker or stroboscopic effects, such as the presence of multiple or striated images of the rod as they waved it underneath the luminaire (experimenters were trained by the first author to demonstrate waving the rod underneath the luminaire to try to maintain consistent movement speed). If subjects responded that they detected stroboscopic effects, they were then requested to rate the acceptability of the effect they perceived, on a scale of −2 (very unacceptable) to +2 (very acceptable). It usually took less than 30 minutes for each subject to observe all 20 lighting conditions.

3. Results

A contour plot of the mean detection percentages is shown in Figure 1. Similarly, a contour plot of the mean acceptability ratings is illustrated in Figure 2. Figures 1 and 2 both illustrate the systematic influence of frequency and percent flicker on detection and acceptability of stroboscopic effects in the present experiment. Because of the systematic relationships apparent in Figures 1 and 2, empirical models for these responses were developed from the data.

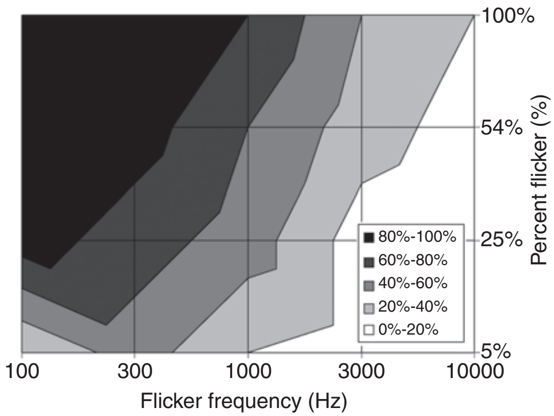

Figure 1 Contour plot of detection percentages, as a function of frequency and percent flicker

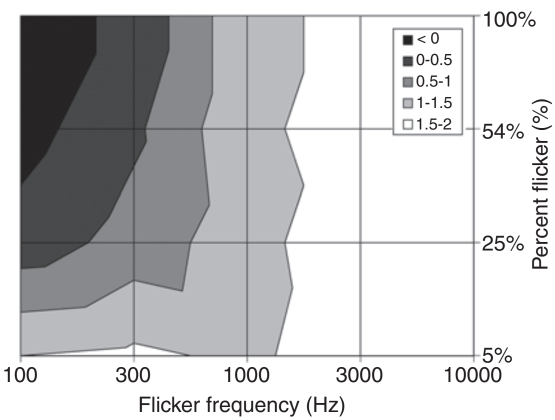

Figure 2 Contour plot of acceptability ratings, as a function of frequency and percent flicker

4. Empirical model development

4.1. Detection of stroboscopic effects

The detection data are plotted for each percent flicker value in Figure 3. With the exception of the detection percentage for the 100 Hz, 5% flicker condition, Figure 3 seems to illustrate a consistent pattern whereby detection of stroboscopic effects decreases along an S-shaped function as frequency increases (the resolution of the measurement is relatively low, 10%, with 10 subjects). Setting the 100 Hz/5% flicker data point aside for now (an *a posteriori* explanation of this data point is given in Section 5), the detection percentage (d) for each percent flicker value is reasonably well described by a sigmoid function of frequency, having the form:

$$d = 1/(1 + f/\alpha) \times 100\% \qquad (2)$$

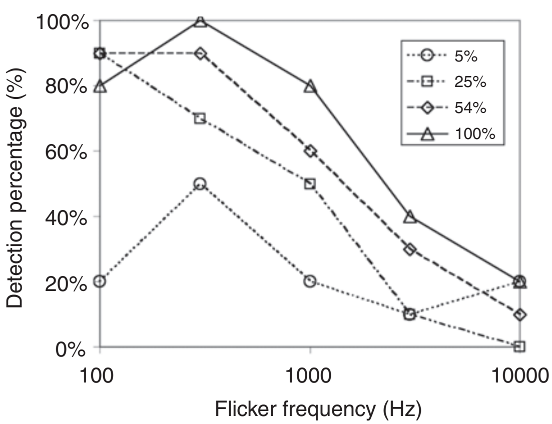

Figure 3 Detection percentages for each frequency and percent flicker value

where f is the frequency (in Hz) and α a value resulting in the best fit with the data for each percent flicker value. There is a strong linear correlation ($r^2 = 0.99$) between the percent flicker values and best-fitting values for coefficient α, according to the following equation:

$$\alpha = 25p + 140 \quad (3)$$

where p is the percent flicker. Combining Equations (2) and (3) and rearranging terms, an empirical formulation for the detection of stroboscopic effects (d) as a function of frequency (f) and percent flicker (p) is:

$$d = [(25p + 140)/(f + 25p + 140)] \times 100\% \quad (4)$$

4.2. Acceptability of stroboscopic effects

Figure 4 illustrates the mean acceptability ratings for each condition (for clarity, the standard error of the mean (SEM) values, averaging about 0.3 units, are not displayed, and the y-axis is truncated). The trends are different for these data than for the detection percentages in Figure 3. Acceptability was always relatively high for the 5% flicker conditions, regardless of the frequency. For the higher flicker percentages, acceptability increased between 100 Hz and 1000 Hz and then remained relatively high.

Using a similar curve-fitting strategy as for the detection data, the acceptability ratings (a) in Figure 4 were fitted to sigmoid functions ranging from −2 to +2 having the form:

$$a = 2 - 4(1 + f/\beta) \quad (5)$$

where f is the flicker frequency (in Hz) and β a value resulting in the best fit with the data. The relationship between the percent flicker

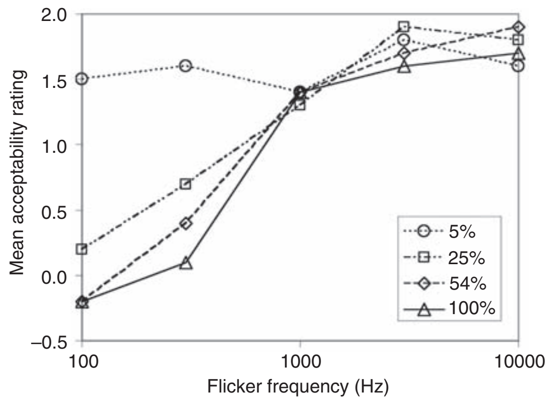

Figure 4 Mean acceptability ratings for each frequency and percent flicker value. For improved clarity, SEM error bars (typically about 0.3 units) are not shown, and the y-axis is scaled to include only the range of measured acceptability ratings (possible values ranged from −2 to +2)

values and β closely ($r^2 = 0.99$) follow a logarithmic function of the form:

$$\beta = 130 \log p - 73 \quad (6)$$

where p is the percent flicker. Combining Equations (5) and (6), the mean acceptability ratings (a) were predicted by the following equation:

$$a = 2 - 4[1 + f/(130 \log p - 73)] \quad (7)$$

5. Discussion

5.1. Predictive ability of empirical model

Figures 5(a) and (b) illustrate the ability of the empirical models to predict the detection percentages and mean acceptability ratings, respectively, for stroboscopic effects from flicker. Except for a single point in Figure 5(a), which corresponds to the 100 Hz, 5% flicker condition (and which was excluded from the empirical model development), the models yield reasonable goodness of fit to the

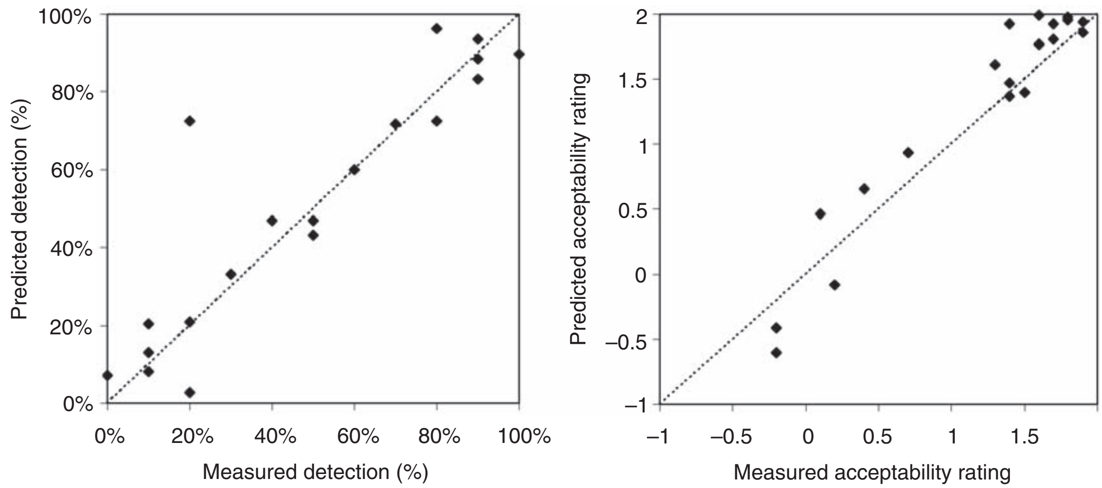

Figure 5 Agreement between the measured and modelled detection percentages (a) and acceptability ratings (b)

$y = x$ lines shown in each panel of Figure 5 [$r^2 = 0.81$ for detection ($r^2 = 0.94$ if the outlying point is excluded) and $r^2 = 0.91$ for acceptability].

Why was the detection of stroboscopic effects under the 100 Hz, 5% flicker condition so much lower than predicted by the empirical model in Equation (4)? A visual inspection of this condition yielded the observation that when waving the plastic rod underneath the luminaire under this condition, the perception of stroboscopic effects was indeed more difficult than under, for example, the same percent flicker value at 300 Hz. The stroboscopic perception was manifested primarily through striations in the blurred image of the rod as it was waved back and forth, resulting in a virtual, low-contrast grating. The spatial frequency of this grating would depend upon the speed and distance travelled by the rod, which could obviously be different for each subject in the study, although as described above, experimenters were trained by the first author to attempt to maintain a consistent speed of movement. Measurements of the speed and distance travelled by the rod when waved by this individual were as follows:

- Waving frequency: 12 times (back and forth) in 5 seconds, ~2.4 Hz
- Distance travelled by rod per wave (back and forth): 50 cm
- Distance travelled by rod per flicker cycle (at 100 Hz): 0.5 cm (2 light/dark cycles per cm)
- Viewing distance to rod from subjects' seating position: 60 cm
- Spatial frequency of light/dark pattern (from 60 cm, at 100 Hz): 2 cycles/degree

With the same geometry and waving characteristics, the spatial frequency of the light/dark pattern at 300 Hz would have been about 6 cycles/degree. In the mesopic and photopic adaptation regions, contrast sensitivity is higher at 6 cycles/degree than at 2 cycles/degree.[9] This is consistent with the observation that the perception of stroboscopic effects under the 100% Hz, 5% flicker condition was more difficult than at 300 Hz. It must be recognised, however, that this is a very limited *post hoc* analysis that must be confirmed experimentally under conditions with much greater control over the speed of the stimulus used to assess stroboscopic perception than in this study.

5.2. Caveats

Many of the same caveats apply to the results of this study as to an earlier study conducted using similar experimental methods. In particular, the conditions employed probably nearly maximised the subjects' ability to perceive stroboscopic effects by using a single-task luminaire and a light-coloured rod viewed against a dark background in an otherwise dark, unlighted room. The presence of other light sources, especially daylight, could substantially reduce the amount of resulting flicker modulation, and the stroboscopic effects would have been more difficult to see against a light-coloured background. The light level used, 400 lx on the work surface, is representative of illuminances for interior applications,[1] but contrast sensitivity could differ for large deviations from this light level.[9] Therefore, sensitivity to stroboscopic effects for the task used in this study could differ from the model predictions in Equations (4) and (7) under very different conditions.

As described earlier, the speed of movement of the rod was likely different for each subject, and this speed obviously interacts with flicker frequency. The present experiment used human movements and showed little sensitivity to stroboscopic effects at frequencies of 1000 Hz or higher, but for very rapidly rotating machines or fans, vivid stroboscopic effects might be visible at very high frequencies exceeding thousands of hertz. Perhaps future work should use controlled stimuli with fixed movement speeds to avoid possible confounding from having subjects perform the movement themselves.

The flicker conditions all used rectangular waveforms, although the shape of the flicker waveform (rectangular versus a chopped sine wave shape) was not found in an earlier study to reliably affect stroboscopic effect perception at 120 Hz.[5] Observations in the test laboratory under illumination provided by a 60-W incandescent lamp (producing about 8% flicker[1] with a sinusoidal waveform at 120 Hz) confirmed that stroboscopic effects under this lamp could be readily seen, albeit faintly, using the same stimulus protocol. Application of Equation (4) would suggest that stroboscopic effects from a 60-W incandescent lamp could be detected 74% of the time, even though incandescent lamps used in general service are not usually considered problematic in terms of flicker. Thus, the model predictions may be more indicative of a worst-case scenario than of the actual likelihood that a lighting system might be objectionable in practice. They might be useful in making relative comparisons among light sources with different flicker characteristics, however.

The present experiment assessed short-term perceptions of stroboscopic effects from flicker only. A previous investigation[5] suggested that comfort is reduced when the duty cycle of flicker is low. Duty cycle (or the percentage of time the waveform's high level was produced) was always 50% in this study, and the duration of each experimental trial was relatively short. It is possible that under longer durations of exposure, feelings of comfort or discomfort could affect perceptions of stroboscopic effects from flicker.

5.3. Conclusions

The results of this study suggest that indirect flicker perception, through stroboscopic effects, is systematically affected by both frequency and the amount of modulation of flicker. The contours of equal detection in Figure 1 and of equal acceptability in Figure 2 indicate that these characteristics interact, providing a basis for comparing the relative impacts of changing either, or both, of these characteristics while holding others constant.

Although the trends for detection and acceptability are somewhat consistent, they differ in one important way. Once the flicker frequency was about 1000 Hz or higher, differences in flicker modulation amount were unimportant for acceptability of stroboscopic effects (Figure 4), but the amount of modulation had a large impact on detection of the stroboscopic effects of flicker (Figure 3). In other words, even when many subjects were able to detect stroboscopic effects, most of them did not necessarily find the flicker unacceptable on this basis. Such data might be helpful in the design of solid-state lighting systems, many of which can use pulse-width modulation and other modes of driving that produce flicker and stroboscopic effects.

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