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

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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 $0.03\,\mathrm{cd{\cdot}m^{-2}}$ to $5000\,\mathrm{cd{\cdot}m^{-2}}$ 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

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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 $0.02\,\mathrm{cd{\cdot}m^{-2}}$ and a maximum of $310\,\mathrm{cd{\cdot}m^{-2}}$. 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).

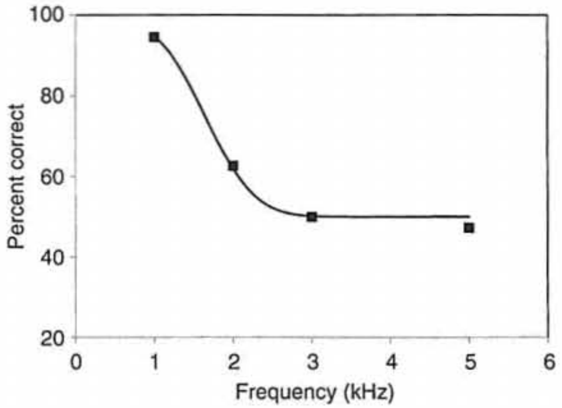

Figure 1 Experiment 1: Percentage of trials in which flicker was correctly detected, shown as a function of flicker frequency

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.

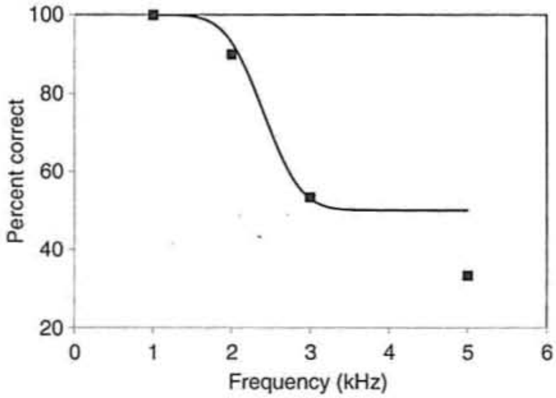

Figure 2 Experiment 3: Percentage of trials in which flicker was correctly detected, shown as a function of flicker frequency

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

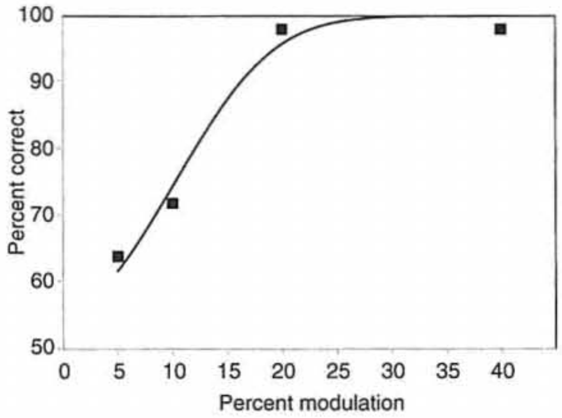

Figure 3 Experiment 4: Percentage of trials in which flicker at 120 Hz was correctly detected, shown as a function of the modulation of the flicker

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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