

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

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Abstract

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 degrees amplitude in an otherwise dark room (<1lux). 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 1.98kHz. At a frequency of 120Hz the intrasaccadic pattern was perceptible when the contrast of the flicker exceeded 10%. It is possible that intrasaccadic stimulation interferes with ocular motor control.

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 [e.g. 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 to 5000cd.m⁻² showed that beyond 100Hz 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 (saccade) 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”. The present paper shows that the perception of flicker as intrasaccadic patterns is possible at frequencies in the kilohertz range, more than ten times 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 (“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 50x700=35kHz. Two considerations make this unlikely. First, contrast sensitivity may be reduced to some extent during a saccade. Volkman *et al.* [9] measured the ability to perceive the contrast of a grating during saccades. The gratings were flashed for 10ms to the steadily fixating eye and also during 6 degree 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 4. More recently, however, Garcia-Perez and Peli [10] have investigate 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 may have occurred because the saccade trajectory was not perfectly aligned with the stripes of the grating, reducing the contrast of the retinal image during the saccade. Indeed, this might explain why Volkman *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; p.554], the maximum perceptible spatial frequency would be reduced from 48 to 38 cycle.deg⁻¹, a relatively modest change.

The second consideration that might make a 35kHz 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 memo to the IEEE PAR1789 committee dated 11th January 2011 combined data from Hart [11] with that from Fukuda [4] and showed that typical light sources can provide a 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, 13, 14, 15], although Hershberger Jordan and Lucas [12] reported that a phantom array was visible by most of their subjects even at 500Hz, the maximum frequency they used. This observation raises the possibility of (1) visibility of the intrasaccadic percept at frequencies greater than 500Hz and (2) individual differences in its perceptibility. The purpose of the present 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.

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

Methods

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

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).

Procedure. Participants were seated 1.7m from the display, which was at eye level. The line was illuminated for 3s 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 3s interval, were given at each frequency in a constant random order.

INSERT FIGURE 1 ABOUT HERE

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 1.67kHz (SD

0.52kHz). A cumulative normal was also fitted to each individual participant's data using least squares and the mean of the individual thresholds was 1.98kHz (SD 1.13kHz).

Experiment 2: Corroboration using different apparatus

Light from a 12v 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 1mm wide by 7mm high and was observed by the authors from a distance of 1m through the rotating shutter of the chopper in an otherwise darkened room (<1lux). When the shutter was operated at 1kHz the intrasaccadic pattern was invariably perceived; at 2kHz it was occasionally perceived and at 3kHz the pattern could not be distinguished.

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 100Hz intervals between 100Hz and 500Hz. The data were used to estimate the spatial frequency at 1kHz. 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 degrees) 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; p.92]. Halving the amplitude of the saccade to 20 degrees would be expected to change the velocity to 400 deg.s⁻¹ and increase the spatial frequency of the intrasaccadic pattern from 2 to 2.5 cycle.deg⁻¹ at 1kHz. At 2kHz the change would be from 4 to 5 and at 3kHz from 6 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 and 2kHz, 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 degrees. 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 degrees amplitude.

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

Methods

The methods were the same as for Experiment 1 except that the fixation points were repositioned 300mm horizontally to the left and right of the light.

Three participants from Experiment 1 aged 25 - 38 took part.

INSERT FIGURE 2 ABOUT HERE

Results

Figure 2 shows mean data for the 3 participants.

The threshold based on the means of the group was 2.35kHz (SD 0.42kHz). The mean of the individual thresholds was 2.47kHz (SD 0.57kHz). The thresholds did not differ consistently or significantly from those in Experiment 1.

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 degrees had little effect on the upper frequency limit at which the intrasaccadic pattern could be perceived.

Flicker at frequencies of 100Hz and 120Hz (above flicker fusion) is known to interfere with the control of eye movements [18, 19]. Flicker from fluorescent lighting at 100Hz and 120Hz 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 4.9kHz, well above that of the other

observers. The intrasaccadic perception of flicker as an anomalous pattern (“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 [21] and was typically between 30 and 50% until high frequency electronic ballast became widespread. The following experiment was designed to determine the modulation depth at which the intrasaccadic pattern from flicker at 120Hz becomes perceptible.

Experiment 4: Modulation thresholds at 120Hz

Methods

The methods were the same as in Experiment 1 except that the z-modulation of the oscilloscope had a square-wave luminance profile and a frequency of 120Hz. The modulation depth defined as $(L_{\max} - L_{\min}) / (L_{\max} + L_{\min})$ was 5%, 10%, 20% or 40%. 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.

INSERT FIGURE 3 ABOUT HERE

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% (SD 7.2%). A cumulative normal was also fitted to each individual participant's data using least squares and the mean of the individual thresholds ranged between 3% and 14% with a mean of 9% (SD 4%).

Interim Discussion

The average modulation depth at which flicker at 120Hz 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 degrees amplitude and velocity of about 500 deg.s^{-1} , the spatial frequency of the intrasaccadic pattern at a frequency of 120Hz is only about $0.24 \text{ cycle.deg}^{-1}$, well below the peak of the contrast sensitivity function at $\sim 4 \text{ cycle.deg}^{-1}$ [7]. It is therefore possible that the intrasaccadic pattern would be perceived at lower contrast 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 deg.s^{-1} [24] and the smallest voluntary saccades are probably those that occur during reading, which are typically 1-2 deg in amplitude with a velocity that ranges from 80-120 deg.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 one degree saccade they were unable to see any periodic intrasaccadic pattern at 120Hz even when the contrast was 100%.

General Discussion

The neurological effects of saccadic suppression appear in motion-sensitive neurons [25]. The flashed presentation during a saccade might be expected to interfere little with 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 lamps of cars. These are conditions in which the apparent displacement of the location of the lamps 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 (120Hz) ranged from 3% -14%, 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 40deg saccade between two distant targets. 30% were able to detect flicker at 300Hz. 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 (see [29] for review) 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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Declaration of conflicting interests

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Figure Legends

Figure 1. Percentage of trials on which flicker was correctly detected, shown as a function of flicker frequency.

Figure 2. Percentage of trials on which flicker was correctly detected, shown as a function of flicker frequency.

Figure 3. Percentage of trials on which flicker at 120Hz was correctly detected, shown as a function of the contrast of the flicker.

Figure 1

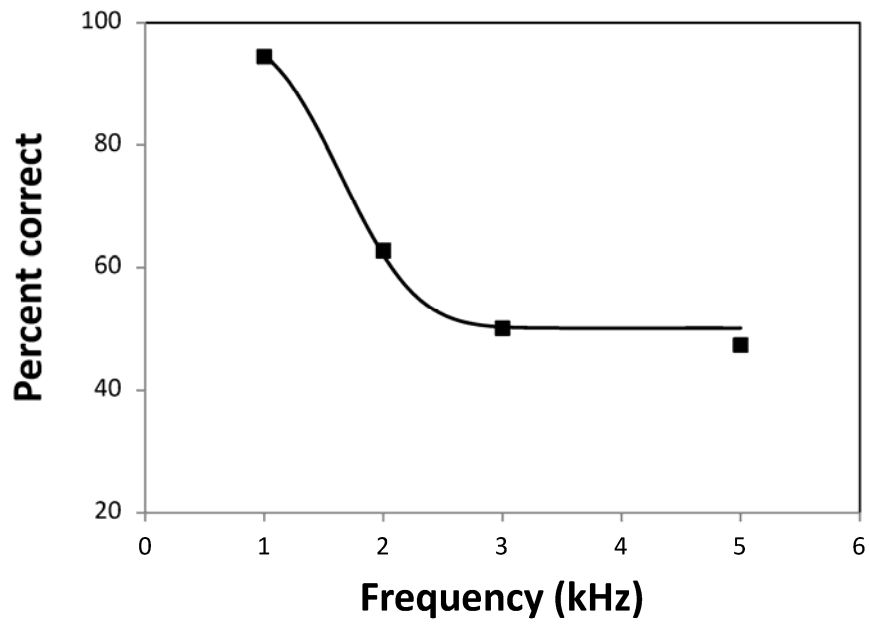


Figure 2

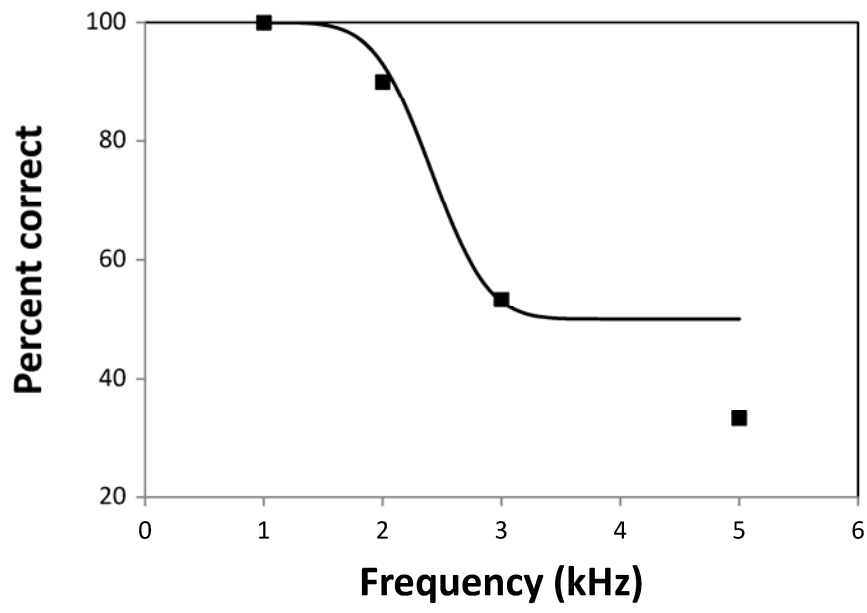


Figure 3

