Visibility of temporal light artefact from flicker at 11 kHz

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A flickering light can be seen during a saccadic eye movement as a pattern of contours known as a phantom array. On repeated pairs of trials, observers made saccades across a narrow (1 arc minutes), bright (10^{-4} cd/m^2) source of flickering light and were required to detect the phantom array. On one of each pair of trials, chosen at random, the light flickered at 60 kHz and on the other at a frequency chosen in the range 1–11 kHz. In two such studies, a few observers were reliably able to discriminate 11 kHz from 60 kHz on the basis of the visibility of the phantom array. The average threshold at which the array was visible was about 6 kHz and therefore double that previously obtained with larger targets. Those observers who were able to see the phantom array tended reliably to report more symptoms of visual discomfort in everyday life.

1. Introduction

A flickering light can be seen during a rapid eye movement (saccade) as a pattern of contours known as a phantom array.[1] The phantom array is commonly seen in light emitting diode (LED) car tail lights at night: a trail of red dots across the visual field, sometimes called the 'bead string artefact'.[2] The phantom array is most visible at night, when there are few luminance contours to mask the effect.

Hershberger and Jordan[1] reported that the array was visible at the highest frequency they studied: 500 Hz. Roberts and Wilkins[3] showed that 1.98 kHz could reliably be discriminated from steady light. Wang *et al*.[4] reported that 50% of participants could perceive the phantom array at 2 kHz but not at 3 kHz. Lee *et al*.[5] have found similar limits but with large individual differences between observers.

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The upper spatial frequency limit at which a grating can just be seen varies between observers from about 30 to 60 cycles per degree and decreases with age.[6] Contrast sensitivity is only slightly reduced during a saccade.[7] The velocity of the eye during a saccade can reach up to 700 degrees per second, depending on the magnitude of the eye movement. These considerations would suggest that observers should sometimes be able to see the phantom array at frequencies of $700 \times 30 = 21\,000$ Hz, and that previous estimates of the frequency limits are too low. One of the factors restricting the visibility of the array is the spatial extent of the light source.[5] We therefore used a bright but narrow light source in the following studies.

2. Study 1

2.1. Method

2.1.1. Observers

Fourteen observers were recruited through advertisements at the University of Essex.

They were aged 21–50 years and had normal or corrected-to-normal vision with no history of neurological disorders.

2.1.2. Procedure

Observers were seated in a darkened room, 0.6 m from a black screen in which was a slit 0.2 mm wide (subtending 1.1 arc minutes at the observer) and 2 mm high, behind which was a white LED, luminance 10 000 cd/m^2. The room illumination was less than 1 lux, and the luminance of the black screen was <1 cd/m^2. The operation of the LED was controlled by an Arduino which was in turn controlled from a PC. Two white pins were positioned 29 degrees away from the target horizontally either side, their heads just visible under the low ambient illumination.

Trials were presented in pairs, and the observer was required to report in which of the two presentations they detected a pattern (phantom array), guessing if necessary. In each trial, the light was lit intermittently with square-wave temporal modulation for 1.5 seconds. In one trial in each pair, chosen at random, the frequency was 60 kHz. In the other trial, the light had one of the following frequencies: 3, 5, 7, 9, 11 and 13 kHz. Fifteen pairs of trials were given at each of the frequencies. Observers were required to saccade between the white markers repeatedly when the light appeared.

Observers were subsequently asked to complete a 21-item visual discomfort questionnaire devised by Conlon *et al.*[8] Examples of questions included: '*Do your eyes every feel watery, red, sore, strained, tired, dry or gritty, when working under fluorescent lights?*' and '*When you are reading a page that consists of black print on white letters, does the background ever appear to overtake the letters making them hard to read?*' The visual discomfort responses were given a numerical score based on how often participants reported a symptom occurring. As recommended by Conlon *et al.*,[8] a score of 0 was given if participants reported a symptom 'never' occurring. A score of 1 was given if participants reported a symptom occurring 'occasionally', a score of 2 was given if it was reported as 'often' and 3 if it was reported 'almost always'. The scores were summed.

2.2. Results

The observers were required to choose in which of the two trials the phantom array appeared, guessing if they did not see the array. At each frequency, the average proportion of the 15 trials in which the lower frequency flicker was chosen, shown in Figure 1 (upper graph), were fitted by least squares to a cumulative normal distribution using the *solver* in *Excel* (solid curve). The frequency at which the group averaged 75% correct (half-way between chance and 100% correct) was 6.6 kHz. Seven of the 14 observers correctly chose the 3 kHz stimulus in all 15 trials. The individual 75% thresholds were obtained similarly by fitting a cumulative normal and ranged from 1.8 kHz to 12.4 kHz. The summed visual discomfort scores ranged from 3 to 33, with a mean of 13.8 (standard deviation (SD) 7.8).

The higher the individual frequency thresholds, the greater the visual discomfort[8] summed score, see Figure 1 (lower graph). The correlation was 0.43, $p < 0.06$ (t test).

2.3. Discussion

The mean threshold for the group was higher than that reported in previous studies, possibly because the dimensions of the light were small. The light was only 1.1 minutes arc wide and was on and off for equal durations with rapid rise and fall time. Given the integration time of phototransduction, the light captured by a retinal cell will have followed a profile that depended on both the frequency of the light modulation and the speed of the saccade. The spatial frequency of the waveform will have increased with flicker frequency and decreased with

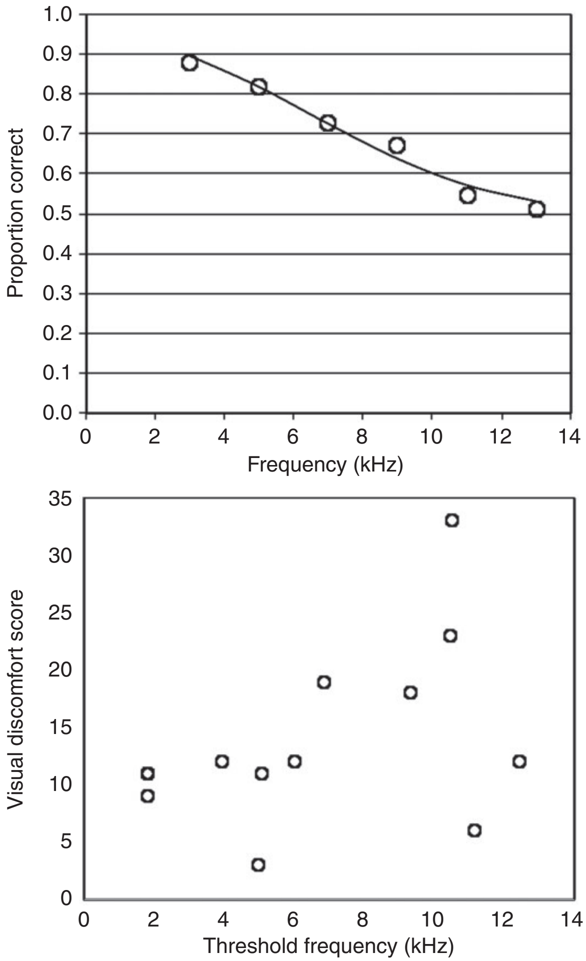

Figure 1. Upper: Proportion of correct responses for the group of observers in Study 1, shown as a function of the frequency of the light. Lower: Score on the Visual Discomfort Questionnaire of Conlon *et al.*,[8] as a function of the threshold frequency at which the phantom array could be seen

saccade velocity. The threshold should have been reached when the contrast at the spatial frequency of the phantom array was below the contrast sensitivity threshold for that spatial frequency, given that this threshold is little affected by the motion of the eye.[7] With a saccade of 58 degrees, a velocity of about 700 degrees per second would have been expected. The spatial frequency of the pattern formed from 18 kHz flicker would therefore have been about 26 cycles per degree, and the duty cycle of the pattern would have been close to the optimum of 50%. If the contrast was high, the phantom array should have been visible, although close to the acuity limit. The threshold of less than 18 kHz suggests that the effective contrast was reduced slightly by the eye movement.

The correlation between the threshold frequency at which the phantom array was visible and symptoms of discomfort, though marginal, was consistent with previous reports of a correlation between complaints from fluorescent lighting (with magnetic ballast) and the ability to discern flicker.[9]

3. Study 2

In Study 1, observers were free to make several saccades to and fro across the light. The afterimage obtained on the first saccade will have interfered with the pattern that resulted from the second saccade to some uncontrolled extent. In Study 2, eye movements were recorded while observers made a single saccade rightwards on each trial from one lit fixation point to another across the flickering light source. This permitted control of the eye movement made across the flickering stimuli and examination of any differences in saccade dynamics between observers. It reduced the number of saccades per trial to only one and thus made the task more difficult.

3.1. Method

3.1.1. Observers

Nineteen women and 19 men aged 21–48 years with normal or corrected-to-normal visual acuity were recruited from students and staff at the University of Essex.

3.1.2. Procedure

A black screen 0.83 m wide and 0.58 m high was mounted vertically at a distance of 0.74 m from a headrest. A white LED was mounted behind a central slot 0.2 mm wide (subtending 0.9 minutes arc at the observer) and 2 mm high. Green LEDs were mounted horizontally in line with the white LED and 0.15 m to the left and to the right. A red LED was placed 0.4 m above the white LED. Each coloured LED was therefore at the apices of an isosceles triangle. An EyeLink 1000 remote eye tracker recorded the observer's eye movements. The tracker was calibrated by asking the observer to fixate each coloured LED in turn. The room illumination and screen luminance were as in Study 1.

Between trials, observers were asked to look at the top (red) LED. A trial began when the red LED was extinguished and the left green LED illuminated for 1 second. The left green LED was then extinguished and the right green LED illuminated immediately; 100 milliseconds after the left green LED was extinguished, the white LED was illuminated for 500 milliseconds. The right green LED remained on for 1.0 second and was then extinguished and the red LED turned on. The observers' task was to fixate the green LEDs in turn and finally the red LED. The green LEDs were separated by 22.9 degrees. The white LED flickered with a square wave luminance profile either at 60 kHz or at one of the following frequencies: 1, 3, 5, 7, 9 or 11 kHz. The trials were presented in pairs, one of which, chosen at random, presented 60 kHz flicker while the other presented flicker at one of the lower frequencies. The observers' task was to follow the coloured LEDs and observe any pattern from the white LED. They indicated verbally and by pressing a button which of the two trials gave rise to a pattern (phantom array). The button press identified the response on the eye tracker. Ten trials were given at each frequency, in an order randomised across frequencies.

3.2. Results

As before, the function relating the average proportion of correct trials to flicker frequency was fitted to a cumulative normal distribution using least squares and is shown in Figure 2. Twenty-four of the 35 observers for whom data were available (63%) identified at least 9 of the 10 trials at 1 kHz correctly and were considered separately as 'good observers' (shown by crossed points in the upper graph of Figure 2). It was clear that

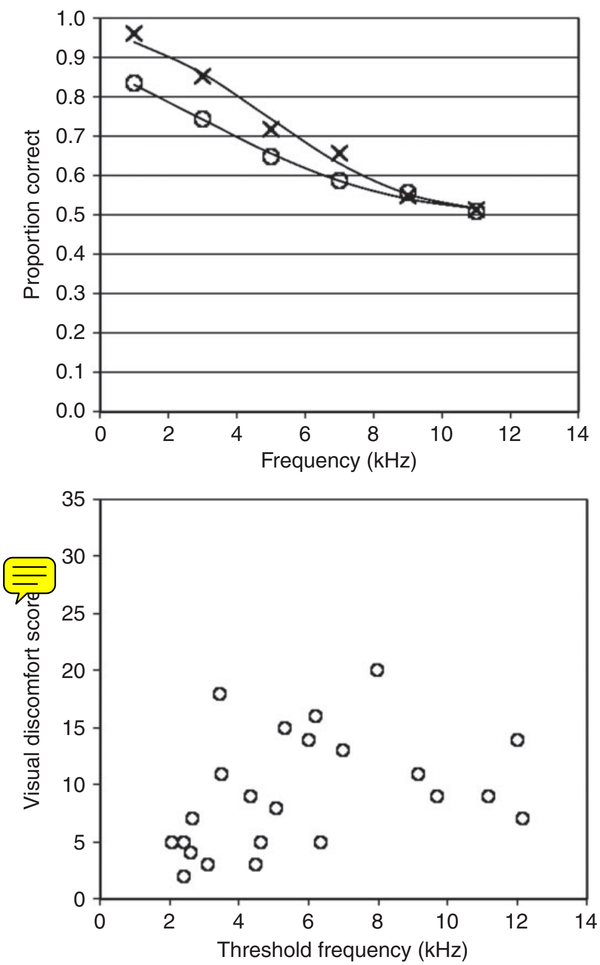

Figure 2. Upper: Circular points: proportion of correct responses for the group of observers in Study 2, shown as a function of the frequency of the light. Crossed points: data for the 'good observers'. Lower: Score on the Visual Discomfort Questionnaire of Conlon *et al.*,[8] as a function of the threshold frequency at which the phantom array could be seen.

they could perceive the phantom array and understood the task. One observer correctly perceived the phantom array at every frequency from 1 to 11 kHz, although he scored at chance when the frequency was increased to 13 kHz. For the remaining 23/24 'good observers' the thresholds ranged from 2.1 kHz to 12.1 kHz, with an average of 5.8 kHz (SD 3.1 kHz). For the 'poor observers' the estimates of thresholds did not reflect the data, due to the variability.

The saccades showed a stereotypical velocity profile, so it was of interest to see whether the individual differences in flicker thresholds were related to differences in eye movement dynamics. For each participant, the function relating saccade size and saccade peak velocity (main sequence) was fitted with the equation from Baloh *et al.*[10] using least squares. There was little correlation between the threshold frequency and the saccade peak velocity, the median velocity or the parameters of the exponential fit to the main sequence (all correlations less than 0.25 regardless of whether the data for the participants who performed poorly at 1 kHz were included).

As in the previous study, there was a weak positive correlation between the threshold frequency at which the phantom array was reported and the score on Conlon *et al.*'s[8] Visual Discomfort Questionnaire ($r = 0.36$, $N = 23$, $p = .045$), see Figure 2 (lower graph).

4. Discussion

Previous literature[3–5] suggests an upper frequency limit of the phantom array in the range 1–3 kHz. In both the present studies, a few observers were well able to see the phantom array at far higher frequencies, some at 11 kHz. The reasons for the large differences in threshold between observers are yet to be determined, but there appears to be no simple explanation in terms of saccade velocity. Instead, the individual differences appear to relate to health. In both studies, there was a weak ~~but consistent~~ correlation between the frequency limit and reports of symptoms of discomfort ~~such that t~~hose who reported discomfort ~~were~~ better able to perceive the phantom array. The symptoms of discomfort were reported in response to a variety of everyday situations, most of which involved reading, and none of which concerned the phantom array as such. The correlation therefore suggests that, as in the case of fluorescent lighting,[9] the high-frequency flicker is associated with a cost in terms of health. Here, we have not shown that the association is causal, although causality has been demonstrated at lower frequencies in the case of fluorescent lighting with magnetic ballasts.[9,11,12]

The phantom array was seen at low-lighting levels, and the findings may have implications for night-time lighting practice with LEDs and in such places as movie theatres.

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