Critical fusion frequency as a function of stimulus intensity and wavelength composition*

ALAN J. WILSON and DAVID L. KOHFELD
Southern Illinois University, Edwardsville, Illinois 62025

Critical fusion frequency (CFF) values for a white and three colored targets were obtained on five Ss over a wide range of scotopic and photopic luminance levels. All the target intensity values were taken from a decibel (dB) scale of luminance whose reference level was set at 10^{-10} L [10^{-6} trolands (Tr)] of white light. The major findings indicated that (a) the obtained curves relating CFF and stimulus intensity showed discontinuities at about 47 dB (.05 Tr), the approximate value of the photopic threshold, and (b) the CFF-intensity functions for the white and colored stimuli were coincident above the photopic threshold, while in the scotopic range the blue curve exhibited marked lateral displacement over decreasing luminance values, the red function showed no displacement from the photopic functions, and the green and white curves were intermediate between those for blue and red. The results were compared on the same intensity scale with the findings of two other CFF studies and with recent reaction time research which provided similar support for the predictions of the duplicity theory of vision.

A variety of different procedures and response measures have been used to demonstrate the differential functioning of the human duplex retina at scotopic and photopic levels of stimulus intensity. For example, the classic studies of Hecht and Shlaer (1936) and Crozier, Wolf, and Zerrahn-Wolf (1937) have shown that the critical fusion frequency (CFF) curve consists of scotopic and photopic segments. More recently, Kohfeld (1971) and Lit (1971) obtained comparable results using simple reaction time (RT) measures. Specifically, Kohfeld utilized a decibel (dB) scale of luminance (suggested by Stevens, 1955) because of its utility in permitting comparisons between simple auditory and simple visual RT measures on the same scale, and found that RT was inversely related to signal intensity over luminance levels ranging from 30 to 90 dB re 10^{-10} L of white light. Between 50 and 46 dB, however, there was a sudden increase of around 30 msec in the visual RT function, a finding which was consistent with the interpretation that the photopic threshold is about 47 dB. In Lit's RT experiment, the rod-cone break was apparent at about .5 troland (Tr), a value which corresponds to 47 dB. When the RT data of Kohfeld (1971) and Lit (1971) and the CFF data of Crozier et al (1937; luminance scaled in millilamberts) are compared on the decibel, millilambert, or troland scale, it is clear that the change from photopic to scotopic vision occurs at a luminance of around 47 dB. However, a conversion of Hecht and Shlaer's (1936) data from trolands to decibels yields a photopic threshold figure which is

approximately $2\frac{1}{2}$ log units higher than the 47-dB estimate.¹

In addition to noting the point of transition between scotopic and photopic visual functions, another primary purpose of Crozier et al's and Hecht and Shlaer's research was to investigate the differential effects of target wavelength on CFF. Both studies reported that the photopic segments of the curves were the same for all colors, but that the scotopic portions exhibited progressive lateral displacement on the intensity axis with decreasing wavelength. Lit (1971) also employed several colored stimuli in his RT experiment and obtained results analogous to those of the CFF studies.

The purpose of the present study was to obtain CFF-intensity functions which were consistent with those reported in the CFF and RT experiments previously cited. CFF-intensity curves were obtained for white, blue, green, and red targets, which were presented over a wide range of scotopic and photopic luminance levels. Since the decibel scale was employed, it was hypothesized that discontinuities in the functions would be apparent at approximately 47 dB. Based on the previous CFF and RT data, it was hypothesized further that the photopic functions would be independent of wavelength, while the scotopic segments would diverge, exhibiting increasing lateral displacement along the stimulus intensity axis with decreasing wavelength. Finally, the studies previously cited were evaluated with the present data in terms of common intensity units in order to compare the locations of the rod-cone break obtained in five different investigations.

METHOD

Subjects

Five undergraduate students (four males and one female) at

*Both authors contributed equally to the study. The article was based on an undergraduate honor's thesis conducted by the first author. The research was supported in part by Research Grant 020457 to the second author from the Office of Research and Projects, Southern Illinois University, Edwardsville.

Fig. 1. The relation between critical fusion frequency in cycles (flashes) per second and luminance level in decibels (log mL; log Tr) for white light and three different chromatic stimuli.

Southern Illinois University, Edwardsville, served as Ss. Each S's visual acuity was either normal or fully corrected.

Apparatus

A standard Lafayette Instrument Company Model 1202D flicker fusion control unit was used in conjunction with a modified version of the Lafayette Model 1202E viewing chamber. The latter unit's filter wheel was fitted with neutral density filters (Kodak Wratten No. 96), which, along with a "slide" arrangement providing for insertion of additional neutral or colored filters between the glow modulator tube (Sylvania R1166) and the target aperture, permitted coverage of a wide range of intensities and wavelengths. Three Kodak Wratten colored filters were used: No. 98 (blue), No. 99 (green), and No. 70 (red), with respective peak transmittances at 451, 554, and 677 nm. The highest obtainable luminance of the glow modulator tube was 85 dB re 10^{-10} L. A dark-adapted O calibrated this level by placing a Macbeth illuminometer directly against the target aperture of the viewing chamber and achieving a match. All stimulus intensities were obtained by attenuating the 85-dB source with appropriate combinations of neutral and/or colored filters, thus yielding intensity values in decibels above threshold for white light. Only the right side of the viewing chamber was used, and the target aperture had a small black dot at its center to provide a fixation point for S. The visual angle subtended by the circular target was 2.3 deg. The ratio of light time to dark time in a flash cycle was 1.0.

Procedure

Each S participated in four experimental sessions one each

for white, blue, green, and red CFF determinations. S was seated facing the viewing chamber and allowed to dark adapt for approximately 20 min before measurements began. A trial consisted of having S look into the viewing chamber and report to E whether the target was flickering or fused, and then to indicate when it changed states as E varied the frequency. A series of trials consisted of eight measurements, obtained on each S at each intensity, for a given color. In order to control the error of habituation, each of the series included, in random order, four flicker-to-fused thresholds and four fused-to-flicker thresholds. Four trials were "long" adjustments (8-10 sec) and four were "short" adjustments (4-5 sec) in order to cancel the error of expectation. The interval between trials was approximately 20 sec. During each session, measurements were begun at the highest intensity and continued until the target could no longer be seen by S. Both S and E were in a totally dark room during the experimental session and were separated by a barrier which permitted E to record threshold values with a shielded narrow-beam penlight.

RESULTS

Each data point in Fig. 1 represents the mean CFF for all Ss as a function of target color and target intensity. The photopic and scotopic portions of the CFF-intensity curves depicted here are readily apparent, with the photopic-scotopic shift occurring at approximately 47 dB. In the photopic intensity range, the four functions are nearly coincident, whereas in the scotopic

range, the curves diverge considerably, exhibiting an increasing lateral displacement on the intensity axis with decreasing wavelength. The blue function remains almost horizontal to the 20-dB point, the green drops more rapidly, while the red falls precipitously from the 47-dB point and approximates an extension of the photopic segment. At first, the white scotopic function falls below the blue and green, but at approximately 20 dB, it assumes values intermediate to the blue and green curves. All Ss reported that, although the blue and green targets became gray or white below the 47-dB point, the red stimulus retained its hue so long as it was visible.

Figure 1 also makes possible an evaluation of the three different intensity measures employed in five different investigations, as compared in common intensity units. An arrow marks the approximate location on the abscissa of the point where previous investigators reported the rod-cone break in their respective units of measurement. It is obvious that four studies, including the present one, obtained a photopic threshold value in the vicinity of 47 dB. It is also apparent that the value reported by Hecht and Shlaer is about $2\frac{1}{2}$ log units higher than that reported by the other investigators.

Further analysis of the results indicated that no error of expectation was present, with "long" and "short" adjustments yielding similar CFF thresholds. An error of habituation was evident with fused-to-flicker adjustments yielding lower thresholds than flicker-to-fused adjustments. This effect was most pronounced in the scotopic range for the colored stimuli, although it held for all luminance levels.

DISCUSSION

The 47-dB scotopic-photopic shift found in the present experiment is in substantial agreement with the value reported by Crozier et al (1937) in their CFF investigation and with the data obtained by Kohfeld (1971) and Lit (1971) in their RT work. Thus, it would seem that this value is accurate, and that the relatively high value reported by Hecht and Shlaer (1936) for CFF may have reflected an error of about $2\frac{1}{2}$ log units in the calculation of the intensity units used to plot the data in their study. Somewhat surprisingly, the possible error in their plotting procedures has persisted in the popular citations of this famous work (see, e.g., Geldard, 1953, p. 88; Brown, 1965, p. 263; Riggs, 1971, p. 312).

That the photopic function is independent of wavelength while the scotopic function shifts laterally along the intensity axis with decreasing wavelength is in agreement with previous CFF data and with Lit's RT findings. This phenomenon probably results from the arbitrary specification of all intensities of the chromatic stimuli in reference to photopic sensitivity for white light. The direction of the shifts of the scotopic CFF functions is to be expected, because the rod system exhibits luminosity functions which are different from

those of the cone system. In comparison with the cones, the rods show a greater relative increase in sensitivity for the short wavelengths than for the long (Boynton, 1966, p. 286). The 677-nm (red) stimuli used in the present study evidently fell in the range where rod and cone sensitivity is nearly identical, as there was no lateral displacement of the red function below 47 dB and the target retained its hue even at its lowest intensity, thus indicating a predominantly cone response.

In the discussion of his RT data, Lit (1971) suggested that if his photometric matches had been made at scotopic rather than at photopic luminance levels, the resulting curves would have exhibited overlapping scotopic functions for all target wavelengths. Since CFF- and RT-luminosity functions seem to identify the same visual events, it seems reasonable to make a similar prediction for scotopic CFF functions. Thus, it is appropriate to predict that if the intensities of the chromatic stimuli were specified in decibels above each of their respective absolute thresholds, the resulting scotopic CFF functions would be independent of wavelength while the photopic segments should now exhibit progressive lateral displacement along the intensity axis with decreasing wavelength.

REFERENCES

- Boynton, R. Vision. In J. Sidowski (Ed.), *Experimental methods and instrumentation in psychology*. New York: McGraw-Hill, 1966.
- Brown, J. Flicker and intermittent stimulation. In C. Graham (Ed.), *Vision and visual perception*. New York: Wiley, 1965.
- Crozier, W., Wolf, E., & Zerrahn-Wolf, G. Intensity and critical frequency for visual flicker. *Journal of General Physiology*, 1937, 21, 203-221.
- Geldard, F. *The human senses*. New York: Wiley, 1953.
- Hecht, S., & Shlaer, S. Intermittent stimulation by light: V. The relation between intensity and critical frequency for different parts of the spectrum. *Journal of General Physiology*, 1936, 19, 965-979.
- Kohfeld, D. Simple reaction time as a function of stimulus intensity in decibels of light and sound. *Journal of Experimental Psychology*, 1971, 88, 251-257.
- Lit, A. Simple time reaction as a function of luminance for various wavelengths. *Perception & Psychophysics*, 1971, 10, 397-399.
- Riggs, L. Vision. In J. Kling and L. Riggs (Eds.), *Woodworth and Schlosberg's Experimental psychology*. (3rd ed.) New York: Holt, Rinehart, & Winston, 1971.
- Stevens, S. Decibels of light and sound. *Physics Today*, 1955, 8, 12-17.

NOTES

1. In order to convert luminance units (millilamberts) to retinal illuminance units (trolands), the formula $Tr = [(pupil\ diam\ in\ mm)^2 \times 2.5] \text{ mL}$ should be utilized (Boynton, 1966, pp. 284-285). Similarly, Hecht and Shlaer (1936, p. 969) used the equivalent conversion factor of Tr (or photons) = $[10(pupil\ area)/\pi] \text{ mL}$. For a pupil diameter of 2 mm, both expressions yield a conversion factor of $1 \text{ mL} \approx 10 \text{ Tr}$. Since $1 \text{ mL} \approx 70 \text{ dB}$ (Stevens, 1955; Kohfeld, 1971), $1 \text{ mL} \approx 10 \text{ Tr} \approx 70 \text{ dB}$. It is to be noted that Hecht and Shlaer (1936) and Lit (1971) used artificial pupil diameters of 2.0 and 2.5 mm, respectively, whereas Crozier et al (1937), Kohfeld (1971), and the present

authors utilized relatively large visual fields, as did Hecht and Schlaer, and natural pupils. Despite the probable differences in the effective pupillary areas employed in the studies under consideration, the 10:1 (Tr to mL) conversion factor suggested by Boynton will be utilized in the present comparisons. It is also noteworthy that the ratio of light to dark time in a flash cycle

was 1.0 in the three CFF studies compared in the present investigation.

(Received March 15, 1972;
revision received September 21, 1972.)