Threshold measurements of spectral sensitivity in a blue monocone monochromat

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Threshold measurements of spectral sensitivity were obtained from a blue monocone monochromat using a foveal fixation target. The dark-adapted spectral sensitivity function could be represented by the luminosity function of the rods (CIE C') weighted by xanthophyll. With a 6.2 troland (td) background the spectral sensitivity function was identical to that of the blue cones (Stiles \( \sigma_i \)) for wavelengths between 395 and 505 nm. With a 0.4-td background, a double-peaked function was obtained, representing the complete linear summation of the \( V' \) function and blue cones. It is suggested that the \( V' \) function obtained with a foveal fixation target is determined by cones and not rods.

Key words: blue monocone monochromat, spectral sensitivity, achromat, color vision, rod monochromacy, cone pigments.

In previous reports of the vision of the blue monocone monochromat,\(^1\)\(^-\)\(^3\) a brightness-matching technique was used to obtain the luminosity functions, with auxiliary methods such as dark adaptation, visual acuity,\(^4\) and increment thresholds\(^2\) to compare the absolute sensitivity of the blue monocone monochromat with that of the normal.

These studies demonstrate a spectral response similar to the blue cones of the normal response (Stiles \( \sigma_i \)) at high photopic levels and a spectral response similar to that of rods (CIE\( \sigma_t \)) at low photopic levels. At an intermediate luminance Blackwell and Blackwell\(^5\) were able to demonstrate a mixed function in which the blue cones and the \( V' \)\(_\lambda \) mechanism showed linear summation. Alpern, Lee, and Spivey\(^2\) were not able to obtain a mixed function on their blue monocone monochromat.

In studying spectral sensitivity, the threshold technique offers certain advantages: (1) At absolute threshold direct comparisons between observers can be made. (2) When more than one class of receptors is active in determining a threshold, it is possible to specify the outcome of various types of interactions between receptor mechanisms. (3) A small field can be used which, with reasonable fixation, places the stimulus well within the rod-free area of a normal fovea.
The present report gives details of spectral sensitivity obtained with a 12 minute field on a blue monocone monochromat using a threshold technique. Measurements were repeated at three adaptation levels: absolute threshold and against backgrounds of 0.4 and 6.2 trolands (td).

**Methods**

**Apparatus.** Fig. 1 shows a schematic representation of the optical system of the apparatus. Source $S_1$ is a 450 w xenon arc lamp. An image of the arc is produced on the input slit of a 500 mm. Bausch and Lomb grating monochromator, $MC$. The exit slit of the monochromator is imaged on the plane of the artificial pupil, $AP$. A coincidence shutter, $CS$, and field stop, $FS$, limiting the field of view to 12 minute visual angle, are placed adjacently in the converging beam. A compensating neutral density wedge, $W$, and filter box, $FB$, are available for manipulation of luminance. A second channel, at 90° to the main channel, is produced by a tungsten ribbon filament lamp, $S_2$, and opal glass, $OG$. A Corning 164 filter is placed next to the opal glass to produce a correlated color temperature of 6,000 K. The second channel is combined with the monochromator channel by means of a cube beam splitter, $BS$. For absolute threshold determinations, the second channel is used to provide a fixation target, $FT$. A plate with 4 one-minute apertures on a circle, 48 minutes in diameter, is centered in the channel. For increment threshold determinations, the plate is replaced by a glass slide bearing the photographic image of the outline of a circle, 36 minutes in diameter, on a 2.5° background.

The coincidence shutter is provided by a vane and rotating disc containing an aperture. By use of a tracking photosensitive device and associated logic, the vane may be removed from the optic axis for one revolution of the disc. The aperture size and rotation rate are set to give a stimulus flash of 12 msec. with 1 msec. rise and decay times.

**Calibrations.** The calibration procedure involved two steps: (1) The output of a photomultiplier was determined for an equal energy spectrum and (2) the photomultiplier was placed at the eyepiece to calibrate the instrument. A positive lens was placed near the plane of the shutter, forming a reduced image of source $S_1$ on the surface of a Reeder thermocouple. The output of the thermocouple was amplified with an Airpax magnetic amplifier and read on a voltmeter. Neutral density filters were inserted so as to give equal output at 10 nm. intervals from 395 to 695 nm. The thermocouple was then replaced by a RCA, 1P21 photomultiplier, whose output was measured with a Farrand microammeter. The output of the photomultiplier to the previously determined equal energy spectrum was noted. The lens was removed and the photomultiplier (sensitivity ×10) was placed on the subject’s side of the artificial pupil and neutral density filters were used to determine an equal energy spectrum at the eyepiece.

Inconal, neutral density filters were measured at 10 nm. steps between 400 and 700 nm. in a Beckman spectrophotometer. The linearity of the photomultiplier-microammeter unit was checked and used to calibrate the compensating wedge, in place, throughout its 2 log unit range at 50 nm. steps between 445 and 645 nm., and 10 nm. steps in the regions 395 to 445 nm. and 645 to 695 nm.

The luminance of the surround channel was

![Fig. 1. Schematic representation of apparatus.](downloadedfromjov.arvojournals.org on 11/14/2021)
checked at the eyepiece, using an Ilford SEI exposure photometer, previously calibrated against a MacBeth Illuminometer.

**Subjects.** Observer J. N. was obtained from a family examined by Dr. Alex Krill in the University of Chicago Hospitals and Clinics. The diagnosis of sex-linked, incomplete rod monochromacy was established through the family history, electroretinography, and clinical tests of acuity, dark adaptation, and color vision. A discussion of some clinical aspects of the vision of members of the family has appeared previously. In summary, observer J. N.'s visual acuity, measured with Snellen letters, was 20/80. On testing of dark adaptation, using the Goldmann-Weekers adaptometer, J. N. showed elevated cone thresholds and normal rod thresholds at a 15° eccentricity, in agreement with previous findings. Using the Nagel anomaloscope, J. N. could make matches over most of the R-G range, with Y brightness values like those of the rod monochromat. He missed all the red-green plates on the Ishihara and AO HRR tests, but read the blue-yellow plates on the HRR. He showed a diffuse red-green axis with many errors on the Farnsworth-Munsell 100 hue test. Observer J. N. had a minimal amount of nystagmus, detectable with magnification.

The normal data were obtained from five observers with normal color vision. All made fewer than 12 errors on the Farnsworth-Munsell 100 hue test.

**Procedure.** Thresholds were determined using a random alternating double-staircase procedure. In this procedure, the observer's response determines the energy level of the subsequent stimulus presentation. In a single staircase technique, the first stimulus flash occurs at an arbitrary energy level. If the observer reports "yes, I saw the flash," the energy level is decreased for the next trial (in steps of 0.1 log unit). If the observer responds "no, I did not see the flash," the next flash is presented at a higher energy level. This procedure is followed until there is a change in response (i.e., yes, yes, yes, no). The energy level at the change of response is repeated on the succeeding trial; and the response then determines the new stimulus energy as above. The threshold is defined as the average energy at the change of response for a minimum of ten changes.

![Fig. 2. Spectral sensitivity functions for observer J. N. The log relative energy at threshold is shown as a function of wavelength. Upper curve (●), dark adapted; middle curve (■), background of 0.4 td.; lower curve (▲), background of 6.2 td. The continuous and discontinuous lines fitting the data points are explained in the text.](image-url)
sponse. The random alternating double-staircase technique is a refinement of the staircase procedure which is used to eliminate subject bias. In this technique, two independent staircases are run with a random series determining which staircase is used on each trial.

A session started with 10 min. of dark adaptation. Initially, the method of constant stimuli was used and psychometric functions were obtained at 495 nm. When the psychometric function had stabilized, the staircase procedure was initiated. The staircase procedure was run for 10 changes of response for both the up- and the down-staircase. Thresholds were obtained for 495 nm. at the beginning and end of the session. Other wavelengths, at 10 nm. intervals between 395 and 605 nm., were sampled at random.

The normal controls were run for one-hour sessions. Typically, four or five wavelengths could be sampled in the hour. Thus, about 10 sessions were required for a full luminosity function. Subject J. N. served as an observer for three hour sessions, with 15 min. rest periods every hour.

The reported thresholds represent the average of both staircases (i.e., 20 changes of response at each wavelength).

Results

Fig. 2 shows the dark-adapted and increment thresholds obtained against 6,000 K. backgrounds of 0.4 and 6.2 td. The thresholds are plotted as a function of log relative energy. At absolute threshold, the spectral sensitivity function shows maximal sensitivity at 520 to 540 nm. and a shoulder between 460 and 500 nm. (upper curve). The increment threshold spectral sensitivity obtained against a 0.4 td. background is double peaked, showing maxima at 440 to 450 and 510 to 530 nm. (middle curve). With a background of 6.2 td., the increment spectral sensitivity of curve shows a single maximum at 440 to 450 nm. (lower curve).

The solid line fitted to the data points obtained against a 6,000 K., 6.2 td. background is the Stiles π₁ mechanism⁴ adjusted by eye for best fit. It appears that the Stiles π₁ function directly represents the activity of blue cones, at least over the range of our measurements.

The intermediate background illuminance of 0.4 td. was chosen by determining that background illuminance at which the thresholds for 425 and 535 nm. were equal. This background luminance level enables us to investigate the interactions of the 445 and 505 nm. mechanisms (top and lower curves of Fig. 1), when both are of similar sensitivity. In the normal trichromat, a wide variety of interactions, ranging from inhibition to full summation, have been demonstrated both between the various cone mechanisms and between cones and rods.⁸⁻¹⁰

The solid line fitted to the data points was obtained by summing the sensitivities of the CIE V₃ function weighted by xanthophyll and the Stiles π₁ function (complete linear summation). The dot-dashed line was obtained by calculating sensitivities based on probability summation between the two mechanisms, assuming their independence.⁴ The dashed line was obtained by assuming the thresholds to be determined by the more sensitive of the two mechanisms (no summation). All three theoretical functions were adjusted to give equal sensitivities at 425 and 535 nm. and fitted by eye to data points at 425 nm. and between 505 and 595 nm. Below 440 nm. the thresholds are not greatly influenced by the mode of interaction, but for wavelengths between 440 and 505 nm. the prediction of complete linear summation of both mechanisms provides the best fit to the data points. Therefore, both for a brightness-matching task and for increment thresholds, complete linear summation is observed for the mechanisms of the blue monocone monochromat.

Fig. 3 shows a comparison of J. N.'s data with those of normal observers, both at absolute threshold and with a 6.3 td background. At absolute threshold the spectral
Fig. 3. A comparison of the spectral sensitivity functions of observer J. N. (○) with those obtained from normal observers (solid line). (A), dark-adapted functions, (B), background of 6.2 td.

Sensitivity of the normal observers has the same shape as that determined by Hsia and Graham.11 With a 6.3 td background, the spectral sensitivity function for the normal observers is essentially parallel to that obtained at absolute threshold, requiring approximately 250 per cent more energy at all wavelengths.

At absolute threshold the energy required at the peak sensitivity is about the same for both subject J. N. and the normal observers. Observer J. N. has greater sensitivity at absolute threshold for wavelengths between 420 and 530 nm. and is less sensitive for wavelengths above 540 nm. With a 6.3 td background, J. N.’s thresholds lie on the curve for the normal observers for wavelengths below 430 nm.

Discussion

The absolute threshold function was obtained within the macular area, as evi-
denced by the necessity of applying the xanthophyll connection to the CIE scotopic luminosity function. A similar result was obtained by Blackwell and Blackwell\textsuperscript{1} using brightness matching with a 1° field at 0.08 td. The absolute threshold function was mediated by either (1) normal parafoveal rods or (2) parafoveal cones or foveal cones containing a 505 nm cone pigment, with a spectral response like that of rhodopsin.

Two lines of reasoning suggest that the absolute threshold function is not mediated by rods. (1) The threshold at 505 nm did not change with continued dark adaptation on three consecutive days. Thresholds obtained after one hour of dark adaptation differed from those obtained after seven minutes of dark adaptation by 0.03 log unit. Stiles\textsuperscript{12} has shown that when a small test light (10 minutes square) of wavelength 475 nm is moved across the normal fovea, a sizeable change in threshold results as the rods mediate the threshold. This drop in threshold occurs for eccentricities of 1½° and greater. Since previous studies indicated normal rod function in J. N.,\textsuperscript{5} a drop in threshold during the hour session would be expected if parafoveal rods were mediating the thresholds. (2) By use of a visuscope, it was possible to establish that observer J. N. did fixate bright test objects on the foveal pit.

It has long been recognized that rod monochromats possess more than one receptor mechanism. A variety of hypotheses have been suggested concerning the nature of the other mechanism. The history of the concept of the day rod, first suggested by von Kries, is summarized by Walls and Heath,\textsuperscript{13} although they themselves rejected such a hypothesis in favor of the notion that rod monochromats possess blue cones. More recent psychophysical data counter the generality of their hypothesis. Sloan\textsuperscript{14} has demonstrated that the fast-adapting, high-intensity receptors of typical total monochromats have a spectral response like that of rhodopsin. She suggested that typical monochromats possess rhodopsin receptors in both fovea and parafovea which behave more like cones than rods. Alpern, Falls, and Lee\textsuperscript{15} have shown that these receptors demonstrate a Stiles-Crawford effect similar in magnitude to that of normal cones.

Thus, it appears that for typical monochromacy, two mechanisms are operative: normal rods and cones peaking at 505 nm. with a spectral response like that of rhodopsin (von Kries' day rods). The presence of blue cones, as suggested by Walls and Heath,\textsuperscript{13} is observed only for members of pedigrees of the sex-linked form of atypical rod monochromacy (e.g., J. N.) and in this case appears in conjunction with the 505 nm. mechanism observed for typical rod monochromats. Our measurements on observer J. N. demonstrate two receptor mechanisms with foveal fixation. At a luminance level where both were active, complete linear summation was observed. The sensitivity of the 505 nm. receptor approximates that of normal cones at absolute threshold (Fig. 3) but, with increasing light intensity, the changes in increment sensitivity (Fig. 2) closely resemble measurements made on rods.\textsuperscript{16, 17}

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REFERENCES
Spectral sensitivity in a blue monocone monochromat