EFFECT OF BACKGROUND WAVELENGTH ON STEREOSCOPIC ACUITY AT SCOTOPIC AND PHOTOPIC ILLUMINATION LEVELS*

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ABSTRACT

Equidistance settings were made for a pair of black vertical rods viewed against several colored backgrounds presented over a wide range of scotopic and photopic retinal illuminance levels. The data were found to be consistent with expectations based on the duplicity theory of vision and on the scotopic luminosity function of the human eye. When matched for brightness, background wavelength has no effect on equidistance settings at photopic (cone) levels.

When visual functions are measured over a wide range of retinal illuminances, performance is characteristically poor at low intensity levels and progressively improves as intensity increases, i.e., as retinal illuminance is increased, the threshold measure in all cases progressively decreases to a final low value (Hecht[1]). The curves relating threshold and retinal illuminance show discontinuities in accordance with expectations based on the duplicity theory of vision: rods determine the function at low retinal illuminances, and cones determine the function at high retinal illuminances. For chromatic stimulation at various retinal illuminances, the rod portions of the curves are systematically displaced laterally toward the low end of the retinal-illuminance scale as stimulus wavelength decreases. These effects have been clearly demonstrated in studies on critical flicker frequency (Hecht and Shlaer[2]), intensity discrimination (Hecht, Peskin and Patt[3]), and visual acuity for red and blue light (Shlaer, Smith and Chase[4]).

Chromatic stimuli have also been used in the study of stereoscopic vision (see, for example, Johns and Sumner[5]; Karwoski and Lloyd[6]; Edwards[7]; Jonkers and Kylstra[8]; Mount, Case, Sanderson and Brenner[9]; Over[10]). No experiments in the literature could be found which deal systematically with the effects of target or background wavelength at many retinal illuminances. The present experiment was designed to provide new

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data on depth-discrimination thresholds for black targets on chromatic backgrounds presented over a wide range of retinal-illumi- nance levels.

METHOD

Subjects: Two undergraduate students served as observers. Each was emmetropic and had good binocular functioning and normal color vision. The interpupillary separation at the testing distance for one observer (A.F.) was 5.8 cm and that for the second (W.Z.) was 6.0 cm.

Apparatus: The apparatus[a], previously described in detail (Lit and Hyman[11]; Lit[12]), provides viewing conditions similar to those of the Howard-Dolman two-rod test apparatus (Howard[13]). The standard target is a vertical black rod, one-quarter inch in diameter, located in the upper half of the observer's visual field. It is located 100 cm in front of his eyes and 0.75^{o} to the right of his median plane. The comparison target is an identical rod located in the lower half of the observer's visual field. Its distance is adjustable by the observer along his median plane. The two targets are positioned so that the top edge of the lower target and the bottom edge of the upper target are in the observer's horizontal plane of fixation. The observer is seated in a dark-room and views the targets binocularly through a pair of eyepieces with artificial pupils 2.5 mm in diameter. His head is held in a fixed position by use of chin and forehead rests.

Homogeneous white background illumination is provided by nine 150-w frosted incandescent lamps mounted in a light box located in a frontal plane 250 cm from the observer. Screens provide the observer with a rectangular field of view, 22.07^{o} horizontally by 2.72^{o} vertically. At a viewing distance of 100 cm the width of each target subtends a visual angle of 20 min of arc. The intensity and wavelength of the background illumination are varied by Kodak Wratten neutral density and Kodak Wratten colored filters placed in filter boxes located on the outside wall of the darkroom in front of the eyepieces. The colored filters used were: red, No. 72B; yellow, No. 73; green, No. 74; and blue, No. 75. Their maximum transmittances occur at about 603, 572, 530, and 488 mm, respectively, as measured by a Beckman spectrophotometer.

Procedure: Prior to the experiment it was necessary to obtain a measure of the "equivalent brightness" of the different colored backgrounds. To accomplish this specification the "equivalent

* The apparatus was originally constructed in 1950 at Pupin Laboratories, Columbia University, partially through funds from a research grant-in-aid generously provided by the American Academy of Optometry.

neutral density" value of each colored filter was determined by the criterion of a constant critical flicker frequency (CFF) threshold at 30 cps. A CFF vs. log retinal-illuminance curve was obtained on a separate device for "white" light, using eight retinal-illuminance levels that gave flicker-fusion thresholds from about 10 to 45 cps. The retinal illuminance of the white light that yielded a threshold value of 30 cps was 1.40 log trolands. Similar CFF threshold determinations were obtained for each of the four colored filters by adding each filter to the same eight combinations of neutral density filters used in determining the threshold CFF vs. log retinal-illuminance curve for white light.

As expected, the additional density value contributed by the colored filter reduced the magnitude of the CFF threshold obtained at each of the eight retinal-illuminance levels. The extent of the reduction in CFF threshold varied with the colored filter used. The CFF threshold data for the four colored filters were plotted on the same eight abscissa values as those used for the white threshold data. The equivalent neutral density value of each colored filter was obtained graphically by measuring the lateral separation (in density units) between the curves for the white and colored data at the criterion level of 30 cps.

In effect, the equivalent neutral density value of any colored filter obtained by this graphical method of analysis specifies the magnitude of the neutral density filter which theoretically is required to replace the given colored filter in order to produce in both cases a constant (30 cps) CFF threshold response. The equivalent neutral density value obtained for each of the colored filters is given below:

Observer	Red (No. 72B)	Yellow (No. 73)	Green (no. 74)	Blue (No. 75)
A.F.	2.12	1.82	1.42	1.94
W.Z.	1.74	1.74	1.37	1.70

The equivalent neutral density values of the colored filters for both observers were also obtained by the method of direct brightness matching; the results were in good agreement with the values obtained above by the CFF-matching procedure.

In the main experiment on equidistance settings, the observer's task consisted of "bracketing" the lower target by the method of adjustment until it appeared to lie in the same frontal plane as that containing the upper standard target. Fixation was continuously maintained on the upper end of the comparison target. During each experimental session, 14 equidistance settings were made at each of 10 retinal-illuminance levels, presented in increasing order of magnitude from near threshold to about 2.00 log trolands. For each observer, a total of 16 sessions was held, four sessions for each of the four background wavelengths presented in the following counterbalanced order: R,Y,G,B B,G,Y,R R,Y,G,B B,G,Y,R. Each observer was dark adapted for 20 to 30 minutes before testing. An experimental session lasted about 60 minutes.

The equidistance settings were analyzed in terms of both the variable error and the constant error. As in earlier experiments (Lit[12]), the stereoscopic threshold angle, η_{AD}, is computed from the average deviation of the 14 equidistance settings made under each condition of illumination. The angular magnitude of the constant error, $\eta_{\Delta R}$, is based on the average depth difference between the standard and variable target for the corresponding groups of 14 equidistance settings. For a detailed discussion of response specification in stereoscopic vision, see Graham[14].

RESULTS AND DISCUSSION

The results for both observers are given in Table 1. Each entry for the constant and variable errors represents the average of the values obtained from the four replications under each testing condition. Fig. 1 and Fig. 2 show for each observer separately the relationship between the stereoscopic threshold angle, η_{AD}, and level of retinal illuminance, log E, corrected for equivalent neutral density value. The results indicate that, for all background wavelengths, eta-AD is large at low values of log E and decreases to the same final asymptotic value (about 10 sec of arc) at a retinal illuminance of approximately +0.5 log troland.

In accordance with the duplicity theory of vision, the curves relating η_{AD} and log E for all but the red background wavelength reveal a marked discontinuity in response at about –1.0 log troland, reflecting the transition from rod to cone functioning. (A slight discontinuity is also to be noted in the curve for the red background light. Some rod activity at low retinal illuminances can be expected when a wide pass band filter such as the Wratten No. 72B is used.) As predicted from the scotopic luminosity function, the rod portions of the curves are progressively displaced toward the low end of the retinal-illuminance scale as background wavelength is decreased. The cone portions of the curves essentially overlap, particularly for observer A.F., indicating that, at equated photopic levels of illumination, background wavelength has no differential effect on the variability of the equidistance settings. These results on stereoscopic depth discrimination are in good quantitative agreement with the results reported earlier on other visual responses[2, 3, 4] obtained for colored stimuli presented over a wide range of illumination:

TABLE I

Variable error (η_{AD}) and constant error ($\eta_{\Delta R}$) of equidistance settings (in sec of arc) for two observers at each wavelength and level of background illumination, Log E, in trolands.

Red (No. 72B)					**OBSERVER A.F.**					
Log *E* (trol.)	−1.68	−1.46	−1.32	−1.22	−1.15	−0.92	−0.51	−0.04	0.60	1.61
η_{AD}	184.5	109.2	88.3	74.2	56.1	33.3	18.0	8.6	9.7	7.8
$\eta_{\Delta R}$	406.9	194.6	186.4	96.7	94.0	42.0	17.6	7.4	8.0	14.4
Yellow (No. 73)										
Log *E* (trol.)	−2.09	−1.84	−1.38	−1.02	−0.85	0.62	−0.21	0.26	0.90	1.91
η_{AD}	133.5	100.6	78.6	48.0	52.3	33.7	15.4	8.1	6.5	7.3
$\eta_{\Delta R}$	386.2	321.1	166.6	94.5	77.8	51.5	26.7	13.1	13.0	17.4
Green (No. 74)										
Log *E* (trol.)	−2.45	−2.00	−1.69	−1.52	−1.40	−1.17	−0.45	.19	1.30	2.31
η_{AD}	122.5	64.5	85.7	68.6	73.5	59.4	34.9	14.7	8.5	10.0
$\eta_{\Delta R}$	315.9	200.4	174.5	142.6	114.7	109.0	80.7	20.0	11.0	16.3
Blue (No. 75)										
Log *E* (trol.)	−2.96	−2.44	−1.92	−1.14	−0.97	−0.74	−0.33	0.14	0.78	1.79
η_{AD}	148.7	80.5	67.3	50.5	42.9	38.5	21.8	13.5	9.0	8.1
$\eta_{\Delta R}$	371.4	204.9	181.0	81.9	78.3	75.6	41.1	25.4	18.6	15.4
Red (No. 72B)					**OBSERVER W.Z.**					
Log *E* (trol.)	−1.61	−1.49	−1.30	−1.20	−0.94	−0.45	−0.13	0.34	0.98	1.99
η_{AD}	212.6	110.7	75.1	61.6	37.9	17.9	22.8	10.1	9.1	6.0
$\eta_{\Delta R}$	−87.4[a]	−67.6	−32.2	−21.5	−12.7	0.1	−1.1	−3.9	2.2	7.4
Yellow (No. 73)										
Log *E* (trol.)	−2.54	−2.01	−1.30	−1.08	−0.94	−0.65	−0.13	0.34	9.8	1.99
η_{AD}	301.6	74.0	35.9	31.7	24.3	18.6	11.5	0.98	6.0	5.60
$\eta_{\Delta R}$	−268.1	−70.6	−18.8	−27.0	-14.4	0.8	3.1	−4.5	0.9	−2.50
Green (No. 74)										
Log *E* (trol.)	−2.69	−2.17	−1.65	−1.47	−1.35	−1.12	−0.40	0.24	1.35	2.36
η_{AD}	113.5	48.4	31.0	36.3	31.1	25.8	16.6	6.9	5.0	8.2
$\eta_{\Delta R}$	−81.5	−37.9	−23.3	−15.5	−13.9	−3.2	16.3	6.6	10.1	2.7
Blue (No. 75)										
Log *E* (trol.)	−3.15	−2.51	−1.98	−1.81	−1.58	−1.38	−0.62	0.02	1.01	2.02
η_{AD}	145.0	46.9	31.1	31.4	25.2	20.3	17.8	10.3	6.1	6.1
$\eta_{\Delta R}$	−131.7	−55.2	−27.2	−12.6	−14.1	−12.0	5.7	9.9	8.3	9.7

[a]A negative value of $\eta_{\Delta R}$ indicates that the mean distance of the comparison rod from the observer's eyes was less than that of the fixed standard rod.

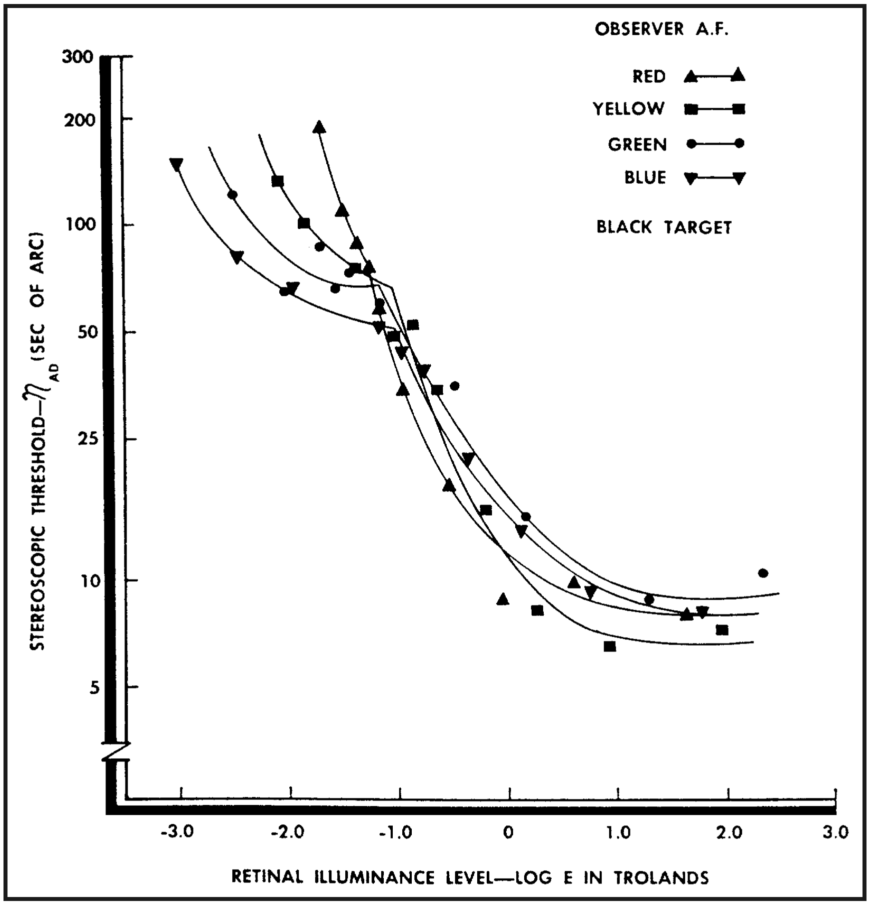

Fig. 1. Stereoscopic threshold angle, η_{AD}, in logarithmic scale, as a function of retinal illuminance, log E, in trolands. Each data point for observer A.F. is based on the mean value of the average deviation of four groups of 14 equidistance settings.

as in the present experiment, the reported visual thresholds were initially high at low retinal illuminance and progressively decreased to a final low asymptotic value as retinal illuminance was increased. Also, the reported curves exhibited discontinuities in function at retinal-illuminance levels comparable to that obtained in the present experiment, and similar lateral displacements were obtained at scotopic levels for the different stimulus wavelengths.

In their study on the effects of chromatic aberration of the eye on depth-discrimination thresholds, Karwoski and Lloyd[6] found that the variability of equidistance settings under a photopic level of illumination was least for the red and yellow targets and greatest for the green and blue targets. Baker[15] reported similar effects for vernier thresholds obtained at optical infinity. Because of the long viewing distances used in both experiments, these wavelength effects can be readily accounted for in terms of the blurred retinal images formed by the green and blue

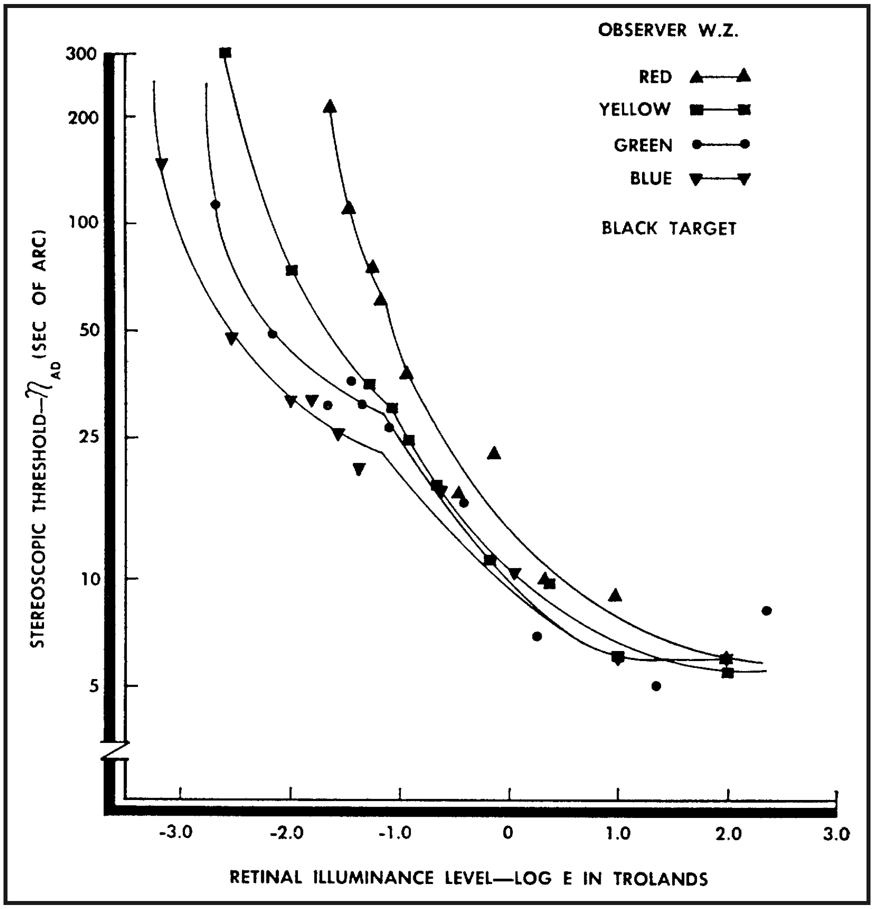

Fig. 2. Stereoscopic threshold angle, η_{AD}, in logarithmic scale, as a function of retinal illuminance, log E, in trolands. Each data point for observer W.Z. is based on the mean value of the average deviation of four groups of 14 equidistance settings.

targets as a result of the chromatic aberration of the eye. Thus, improved acuities for blue targets were obtained by these investigators when concave lenses were used to correct for the effects of chromatic aberration. For equidistance settings performed at near distances, as in the present experiment, the detrimental effect of chromatic aberration was overcome because the observers were able to relax their accommodation to obtain clear retinal images under all background wavelengths.

The data on the constant errors of the equidistance settings, $\eta_{\Delta R}$, are shown in Fig. 3 for each observer; $\eta_{\Delta R}$ is initially high (positive for one observer and negative for the other) at low retinal illuminances and progressively decreases in absolute magnitude to a final asymptotic vaIue near zero as the level is increased about +0.5 log troland. The discontinuity in response between the rod and cone levels of retinal illuminance is less evident for $\eta_{\Delta R}$ than for η_{AD}, especially for observer W.Z. As in the case of η_{AD}, the scotopic segments of the curves relating $\eta_{\Delta R}$

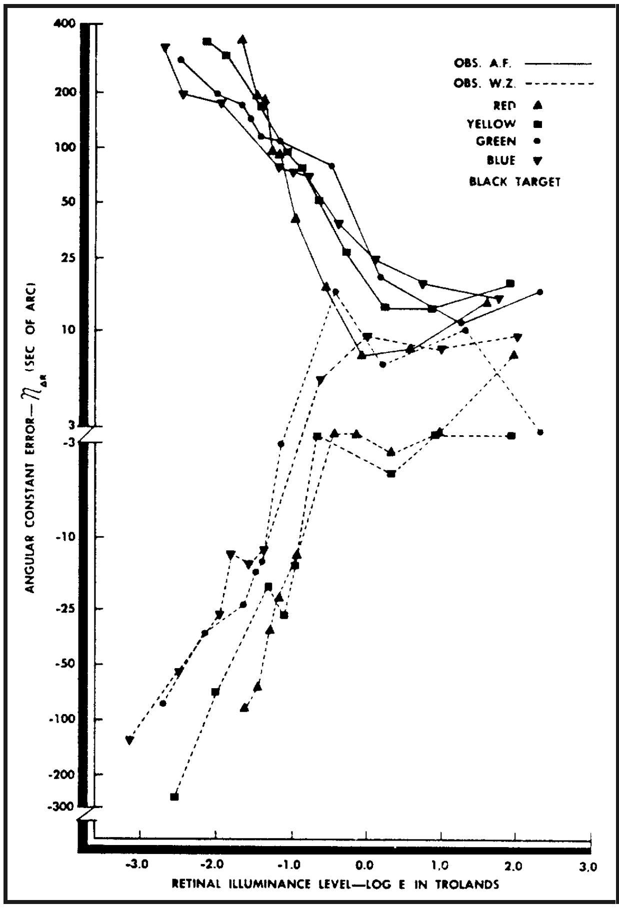

Fig. 3. Angular constant error, $\eta_{\Delta R}$, in logarithmic scale, as a function of retinal illuminance, log E, in trolands. Each data point for the two observers is based on the average value of the mean of four groups of 14 equidistance settings.

and log E are displaced toward the low end of the intensity axis as background wavelength is decreased.

Finally, it should be emphasized that the data of the present experiment show that different wavelengths matched for equal brightness at a high intensity level result in equal stereoscopic acuities over the entire range of photopic retinal-illuminance levels. To demonstrate that this relationship also holds for lower levels of illumination, an extension of the present experiment requires that equidistance settings be obtained for colored backgrounds which have been calibrated on the basis of brightness matches performed at scotopic and mesopic retinal illuminances (Bridgman[16]).

SUMMARY

Two observers made equidistance settings for a pair of black vertical rods viewed against several colored backgrounds presented over a

retinal-illuminance range of about 5 log units. The data for all background wavelengths show that at low levels of retinal illuminance the stereoscopic threshold angle is initially high. As retinal illuminance is increased, the thresholds for all background wavelengths decrease to the same low asymptotic value. Discontinuities obtained in the threshold vs. retinal-illuminance curves are interpreted to reflect rod-cone functioning in accordance with expectations based on the duplicity theory of vision. The cone segments of the curves overlap, indicating that background wavelengths have no differential effect on equidistance settings when the backgrounds are photometrically matched at a high retinal-illuminance level. The relative separations of the rod segments of the curves are consistent with predictions based on the scotopic luminosity function of the human eye. The data also demonstrate that the absolute magnitude of the constant error for each background wavelength progressively decreases as retinal illuminance is increased.

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