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16. Abstract

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SUMMARY

Peripheral visual response time was measured in seven volunteer, dark-adapted subjects to the onset of small (45′ arc diam), brief (50 msec), colored (blue, yellow, green, red) and white stimuli imaged at 72 locations within their binocular field of view. The blue, yellow, and green stimuli were matched for brightness at about 2.6 $\log_{10}$ units above their absolute light threshold, and they appeared at an unexpected time and location. These data were obtained to provide response time and no-response data for use in various design disciplines involving instrument panel layout. The results indicated that the retina possesses relatively concentric regions within each of which mean response time can be expected to be of approximately the same duration. These regions are centered near the fovea and extend farther horizontally than vertically. Mean foveal response time was fastest for yellow (288 msec) and slowest for blue (341 msec). Three and one-half percent of the total 56,410 trials presented resulted in no-responses. Regardless of stimulus color, the lowest percentage of no-responses occurred within 30° arc from the fovea and the highest within 40°–80° arc below the fovea. These data are discussed in relation to findings by other investigators and are related to several hypothetical instrument panel/cockpit design problems.

INTRODUCTION

Many investigators have quantified simple visual response time (RT) to colored stimuli imaged upon or near the fovea (refs. 1-11). Others have measured simple and choice RT in various applied settings using colored stimuli (refs. 12-15). Very little data is available on how long a person takes to respond to colored stimuli imaged in the *peripheral* visual field. This is particularly unfortunate since such data could be useful to equipment designers in several fields, for example, instrument panel designers who must locate warning lights where they are most likely to elicit the fastest manual response.

In 1968 it was reported (ref. 1) that red (Kodak filter no. 70) and blue (Kodak filter no. 49b) stimuli at each of three luminances produced quite different RTs depending upon where they were imaged upon the retina. A 21′-arc-diam stimulus was imaged on the fovea and at 12° arc on the temporal retina. It was found that (1) foveal RT was significantly faster for red for both onset and offset stimulation, (2) peripheral RT was fastest for blue for the lowest luminance studied (viz. 0.0043 ml), (3) mean RT increased as stimulus luminance decreased, (4) onset RT was not significantly different from offset RT at the fovea for either color, and (5) onset RT was signficantly faster than offset RT in the periphery.

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Response time to white and to blue (Kodak filter no. 48) stimuli was determined in reference 10 for nine retinal locations across the horizontal retinal meridian,[1] each separated by 10° arc and including the fovea and one position 5° arc from the fovea. The stimulus in each case was extremely small (4′ arc diam) and was flashed onto the dark-adapted retina of one eye for 23 msec. Two photopic and one scotopic (0.11 ml) luminances were investigated. The dimmest stimulus condition was the blue; no comparable RTs are given for a white stimulus of the same scotopic luminance. The results of reference 10 showed that (l) for photopic stimuli, foveal RT was fastest, (2) the slowest RT occurred to stimuli imaged at 30° arc on the temporal retina for both photopic and scotopic stimuli, and (3) the fastest RT for the scotopic stimulus was found to occur to stimuli imaged at 20° arc on the nasal retina.

A preliminary investigation was conducted in this laboratory to gain a better understanding of how simple visual RT to colored stimuli varies across the light- and dark-adapted retina (ref. 2). Red (631 nm), green (525 nm), and blue (463 nm dominant wavelength) stimuli at equal brightnesses were imaged at 10° arc separation across the horizontal meridian from 80° arc left to 90° arc right. Each stimulus was approximately 0.5 $\log_{10}$ unit above the subject's absolute forced choice light threshold. These data indicated that (1) RT is significantly slower to red than to blue, which is, in turn, slower to green, (2) RT is significantly faster at the fovea than at the periphery, (3) mean RT at the fovea for red was 360 msec and 470 msec at the extreme periphery of the visual field, (4) mean RT for a foveally imaged green stimulus was 301 msec (this value increased to 350 msec at 80° arc from the fovea), and (5) mean RT for a foveally imaged blue stimulus was 326 msec which increased to 346 msec at 80° arc from the fovea. Thus, mean RT for red increased more rapidly with increasing angular separation from the fovea than did RT for either green or blue.

Although the above three investigations provide useful information concerning the mechanisms that mediate RT in the normal dark-adapted retina, it was felt that more knowledge could be gained about visual RT by increasing the number of retinal locations investigated and the sample size.

In a majority of applied contexts a no-response (NR) to the appearance of a visual stimulus is more important than a delayed response. Consequently, the proportion of NRs was also analyzed in the previous study from this laboratory (ref. 2). Within the first 250 trials following dark-adaptation each day, it was found that a NR occurred to only about 1–5 percent of the total number of stimuli presented, regardless of their color, as long as they were imaged within about 60° arc from the fovea. Beyond 60° arc, however, the proportion of NRs increased rapidly for the red stimulus, reaching nearly 100 percent at the extreme periphery of the visual field. Such was not the case for green or blue stimuli; the proportion of NRs for these colors remained between 1 and 5 percent across the entire horizontal meridian. Within the first 250 trials immediately following light-adaptation, which consisted of a 3-min exposure of the full visual field at 3.73 $\log_{10}$ units ml, the proportion of NRs was particularly high for all three colors within about 30° arc from the fovea. This emphasizes the important influence of white light-adaptation upon subsequent reduction of color detection capability.

The distribution pattern of mean RT within the visual field is of theoretical interest as well. Since it is well known that the proportion of cone-to-rod receptors varies with retinal location

[1] A meridian is an imaginary reference line on the retina which passes through the fovea. The horizontal meridian, designated as $\varphi = 90°–270°$, may be visualized as the image of the horizon when the head is held vertically erect and fixation is upon the horizon. Meridians are labeled from the point of view of the subject with 0° at the top progressing clockwise.

(refs. 16-18), and that the normal human retina possesses relatively well defined color-sensitive zones when the characteristics of the stimulus are held constant and the level of adaptation has stabilized (refs. 19-23), the question may be raised whether the distribution pattern of RTs over the retina might reflect the distribution of different color-sensitive cone receptors (ref. 6). From the extensive series of investigations cited above, it is clear that the limits of color sensitivity are affected by almost every stimulus variable known. The most influential of these is stimulus intensity. Ferree and Rand (ref. 21, p. 245) point out that, "With very high intensities the limits of red, yellow, and blue are coincident with the limits of white light vision. Green cannot be made to have so wide an extent." When these colors are presented at lower intensities, but of equal energy, the color boundaries criss-cross each other with the limit for green remaining the most narrow. These findings form the basis for comparisons between the retina's color-threshold response and RT.

METHOD

Experimental Design

The present investigation can be characterized as an 18 by 8 by 3 by 7 by 2 factorial design with the following parameters: 18 *stimulus positions*[2] (as described in the apparatus section); 8 *meridians*; 3 *stimulus colors* (blue, yellow, and green) plus a lower luminance red and white as described in the apparatus section; and 7 *subjects* (*S*). The last parameter was subject *sex*.

Presentation order of the *stimulus position*, *meridian*, and *color* variables was randomized with the following restrictions: (1) no stimulus position was presented twice in a row, (2) no two *S*s could receive the same stimulus color presentation order or meridian presentation order, and (3) all eight meridians were presented for a given color for each *S* before the next color was tested.

Apparatus

The apparatus used is shown in figure 1 and is described in detail elsewhere (ref. 24). Briefly, a black metal, semicircular ring supported and aligned the 18 stimulus sources each of which was an 8-mm-diam (45′ arc diam), diffuse, molded acrylic, hemisphere lens.[3] These stimulus sources were located at 10° arc separations from $\theta = 80°$ arc on one side to $\theta = 90°$ arc on the opposite side of the fovea.

Each stimulus source lens received light from the exit end of a fiber optic bundle[4] and transmitted it as a diverging cone of light toward the subject's eyes. All testing was binocular with the subject in a supine position.

After dark-adapting for 15 min, each subject set the brightness of the fixation cross to be just foveally visible by adjusting a variac which, in turn, regulated the current to an ultraviolet projector that was shown upon the fixation cross. This cross consisted of yellow-green fluorescent tape on a

[2] Hereafter the symbol θ will be used to designate the angle along the given meridian between the line of sight and the stimulus position.

[3] Edmunds Scientific Co., No. P-41,232.

[4] Du Pont CROFON 1610X, 64 fiber.

Figure 1.– Photograph of subject lying beneath semicircular stimulus support ring holding the response button in his right hand and the variac in his left.

diffuse black background. Each cross-arm subtended a 17′ arc width and an 8° 27′ arc length and was oriented normal to each other. In order that the $\theta = 0°$ stimulus would be at the intersection of the two arms, the cross was broken at its center with an angular separation of 1° 19′ arc. The subject's eyes were directly below and 0.61 m distant from the cross. The subject responded by depressing a normally open, spring-loaded button with the thumb of his right hand.

The light source for all 18 stimuli was a fluorescent, cold cathode flash tube[5] with approximately 1 μsec rise time. Each stimulus remained on for 50 msec. The different stimulus colors were produced by inserting Kodak Wratten chromatic filters (table 1) with Kodak neutral density filters

[5]G. E. F4T5-CW.

between the flash tube and the input end of each fiber optic bundle. The luminances of the blue, yellow, and green stimuli were approximately matched as indicated in table 1.

TABLE 1.– PHOTOMETRY DETAILS AND RESULTS

	Stimulus color				
	Blue	Yellow	Green	Red	White
Kodak filter no. used[a]	47	16	60	29	–
Dominant wavelength (nm)	463.7	582.7	525.7	631.6	–
Percent transmission	2.8	57.7	26.1	6.3	–
Luminance[b] at point of brightness match					
(cd/cm^2)	2.501×10^{-5}	2.501×10^{-5}	1.610×10^{-5}	8.565×10^{-6}	2.295×10^{-5}
(ft.-L)	7.3×10^{-2}	7.3×10^{-2}	4.7×10^{-2}	2.5×10^{-2}	6.7×10^{-2}
Approx. amount stimulus was above absolute light threshold (in $\log_{10}$ units)	2.6	2.6	2.6	1.0	1.3

[a] Transmission values in 10-nm increments for each filter are given elsewhere (ref. 31).
[b] The availability of neutral density filters in only 0.1 $\log_{10}$ unit steps precluded a closer brightness match for the red and white condition.

The photometric calibration measurements presented in table 1 were performed in two different ways. In the first, a Pritchard Spectra photometer with a 6′ arc diam aperture was used in conjunction with a newly calibrated 100-ft-L, Gamma Scientific standard source (2854° K) to measure the luminance at each θ position. In the second method, Kodak Wratten neutral density filters were superimposed between the eye (dark-adapted for at least 25 min) and the stimulus. Using the method of limits procedure, the filter density was found at which the stimulus was “just foveally visible” and “just foveally invisible.” The second method was used as a check on the accuracy of the first and also to determine the approximate suprathreshold level of each color. Availability of neutral density filters in only 0.1 $\log_{10}$ steps made it impossible to match the red to the other three colors.

To help mask auditory cues generated by the electronic sequencing equipment, the subject wore padded earphones over which white noise was inserted at a comfortable volume from a Grason-Stadler Model 455C noise generator with a low pass frequency of 25 kHz.

Procedure

Each subject was given either 6 or 7 days of training, depending upon how long it took his mean RT to reach asymptotic levels; each day two sessions of 300-RT trials each were administered. All testing occurred at approximately the same hour of the day (±20 min). By the end of training, the standard deviation (SD) value for a given θ position after at least 90 trials was about 20 msec. All training was conducted using only white stimuli imaged across the $\varphi = 90°–270°$ (horizontal) meridian. Each subject was told when his training was completed and when the experimental portion of the investigation was to begin; however, no detailed feedback regarding RT performance was ever provided during the study.

The experimental part of the study consisted of two sessions per day per subject; each session included 475 trials of a single color. A different meridian was presented during each session. Each subject underwent 20 sessions for a total of 9500 RT trials for the entire experiment. A total of 32,898 RTs were obtained for the blue, yellow, and green test conditions and another 21,519 RTs for the red and white test conditions.

In order to help insure temporal uncertainty regarding when a stimulus was going to appear, the intertrial interval was varied randomly in five steps. The percentages of occurrences within a block of 120 trials are shown in parentheses: 1.8 sec (30.2); 2.2 sec (26.5); 2.4 sec (24.5); 2.8 sec (13.2); and 3.2 sec (5.6). The mean intertrial interval was 2.19 sec for a total of 26.5 trials/min.

The initial phase of dark-adaptation took place under the ambient light conditions of the lab by having the subject wear red goggles (Kodak filter no. 29) while preparing to enter the High Luminance Vision Laboratory clean room (ref. 32) (this time period commonly ranging from 5 to 10 min). The subject was then accurately positioned on a padded gurney beneath the fixation cross with his head in a padded head rest. The final stage of dark-adaptation occurred when the goggles were removed after all ambient lights had been extinguished. He remained in total darkness for at least another 10 min (usually 15 min) prior to testing.

Both the beginning and end of RT testing was signalled by an auditory tone. The brightness of the fixation cross was progressively reduced during initial dark-adaptation. The variac output to the fixation-cross projector lamp was recorded after each test session. The brightness of this cross was set at a relatively consistent level within subjects from day to day.

Test Subjects

Four male and three female paid volunteers participated in the study. The age, uncorrected acuity, dominant eye, handedness, and number of training trials for each subject are given in table 2. All subjects possessed normal trichromatic color vision as determined by the American Optical and Ishihara pseudoisochromatic color plates.

TABLE 2.– SUBJECT INFORMATION

Initial	Sex	Age	Uncorrected acuity		Dominant eye	Handed-ness	Number of trials[a]	
			Far	Near			Training	Exp.
C.K.	M	25	:17	:17	R	R	3600	9500
R.I.	M	22	:17	:17	R	R	4200	9500
G.L.	M	27	:17	:17	R	R	3600	9500
T.M.	M	18	:17	:17	L	R	3600	9500
N.C.	F	34	:18	:18	R	R	3600	9500
K.D.	F	18	:17	:17	R	R	3600	9500
N.S.	F	23	:18	:17	L	R	4200	9500
Mean 24						Total	31,200	76,000

[a]The number of experimental trials indicated represents the total number of stimulus presentations and not the number of responses upon which these RT data are based.

RESULTS

Response Time Data

The mean RT, SD, N, and number of NRs for each test condition are given in appendix A. The means presented here do not include "early responses" (less than 75 msec) or extremely "long responses" (greater than 1800 msec). If subject failed to respond within 1800 msec, NR was automatically recorded for that trial.

The mean RT data have been plotted in figures 2–6 to illustrate the overall trends found. In each figure the θ positions are plotted on the abscissa, and mean RT (msec) on the ordinate. The curves have been fit by eye; the number near each curve gives the number of RTs upon which that set of data is based. Each meridian is labeled by its angular designation as well as by the following letter designations: T = top, UR = upper right, R = right, B = bottom, LL = lower left, L = left, and UL = upper left with respect to the fovea. The small vertical line drawn through several of the curves indicates the outer limit of the binocular visual field for these subjects. In two cases (blue, green), the mean RT at the fovea was notably different from what would be expected on the basis of curvilinear extrapolation from the adjacent data points at the $10° \leqslant \theta \leqslant 10°$ portion of the curve.

In order to make these mean RT data more useful to persons involved with the design and layout of warning indicators, actuators, etc. on instrument panels, the data have been replotted in

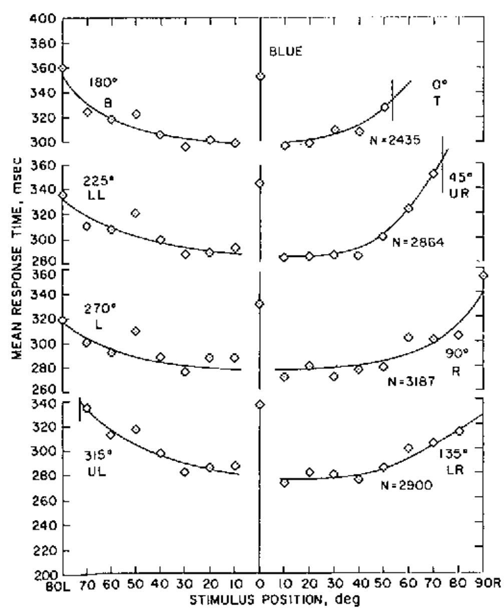

Figure 2.– Mean RT results for blue.

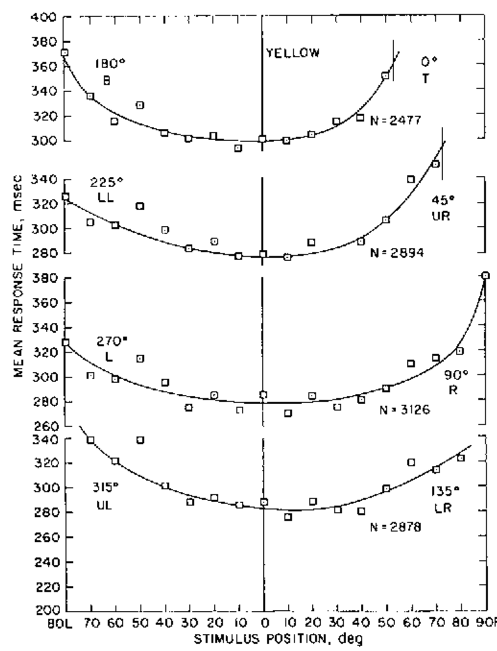

Figure 3.– Mean RT results for yellow.

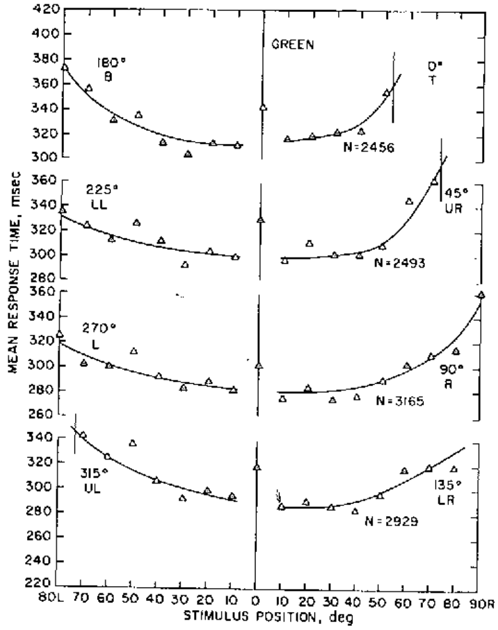

Figure 4.— Mean RT results for green.

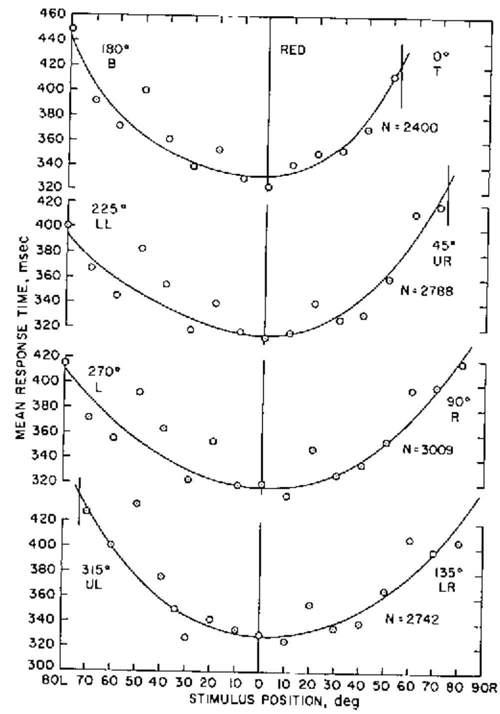

Figure 5.— Mean RT results for red.

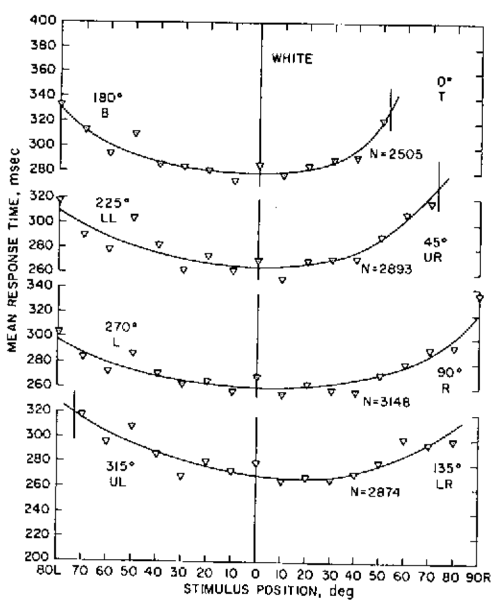

Figure 6.— Mean RT results for white.

figures 7–11 as iso-RT zones within the full visual field. In each figure the heavy solid line surrounding the plots indicates the outer limit of the *binocular* field of view according to reference 25. Perimetry of our subjects' monocular and binocular field of view limits indicated that their visual fields were within ±2° of this boundary. The dashed contour represents the limits of the monocular left and right eyes. The manner in which the mean RT data in figures 2–6 were replotted resulted in the fastest RT contours progressing into the fovea for several meridians. This indicates that the foveal mean RT was even faster than the msec value associated with the inner-most contour. From figures 7–11 it is evident that there are right- and left-hand "lobes" of equal RT whose centers lie 10°-15° away from the fovea (for the minimum RT shown here). This finding is discussed later.

In order to illustrate the manner in which the binocular visual field is represented by progressively longer iso-RT zones, the areas within each iso-RT zone shown in figures 7–11 were measured and converted into percentages of the binocular visual field area. These percentages are given in appendix B and are plotted in figure 12. The slopes for the blue, yellow, green and white curves are

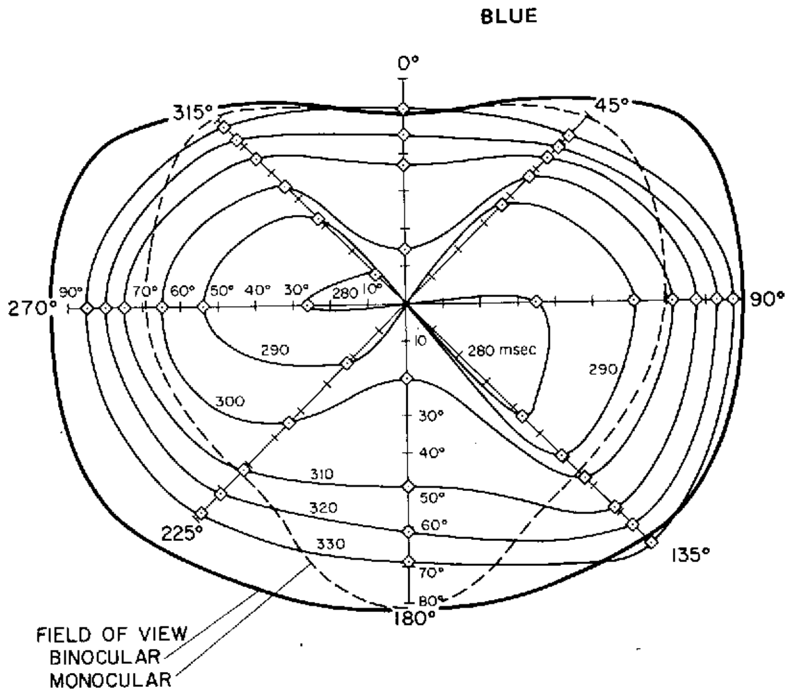

Figure 7.– Retinal iso-RT zones for blue.

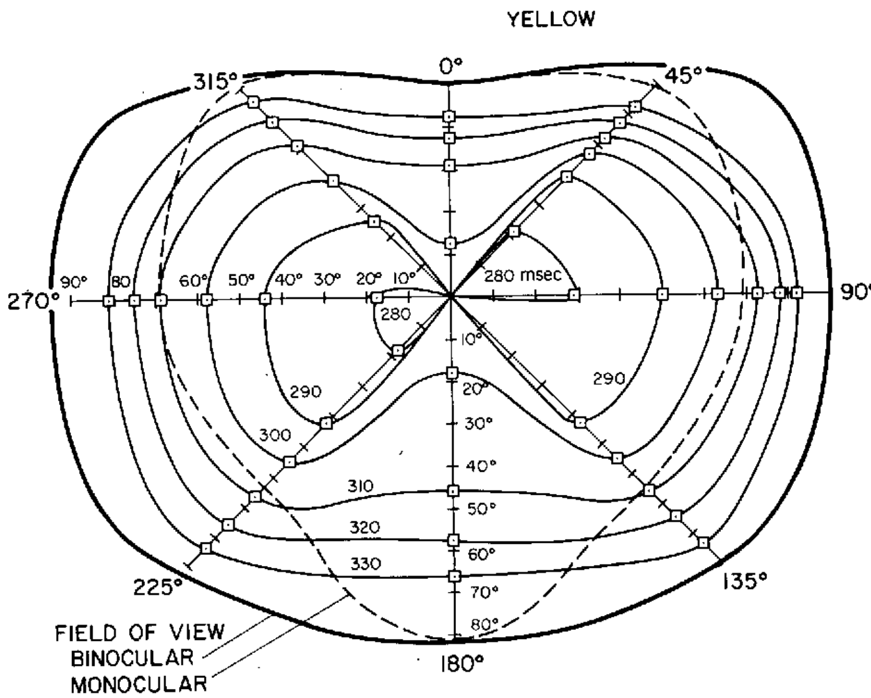

Figure 8.– Retinal iso-RT zones for yellow.

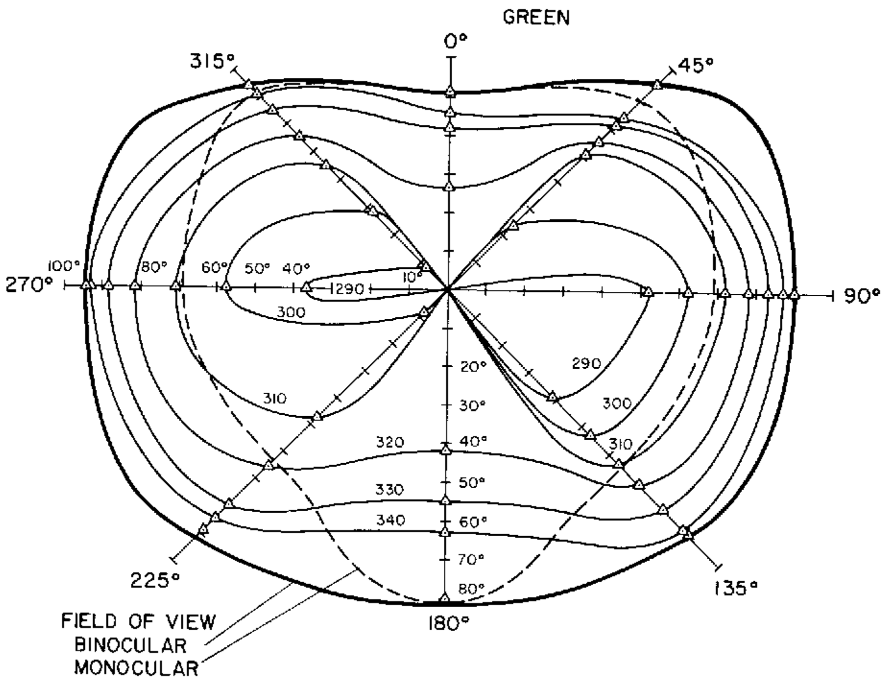

Figure 9.– Retinal iso-RT zones for green.

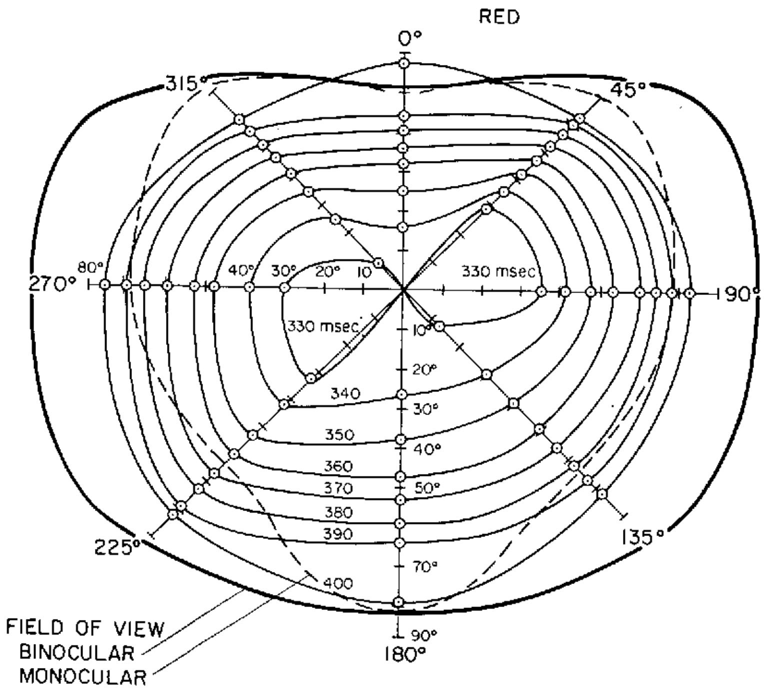

Figure 10.– Retinal iso-RT zones for red.

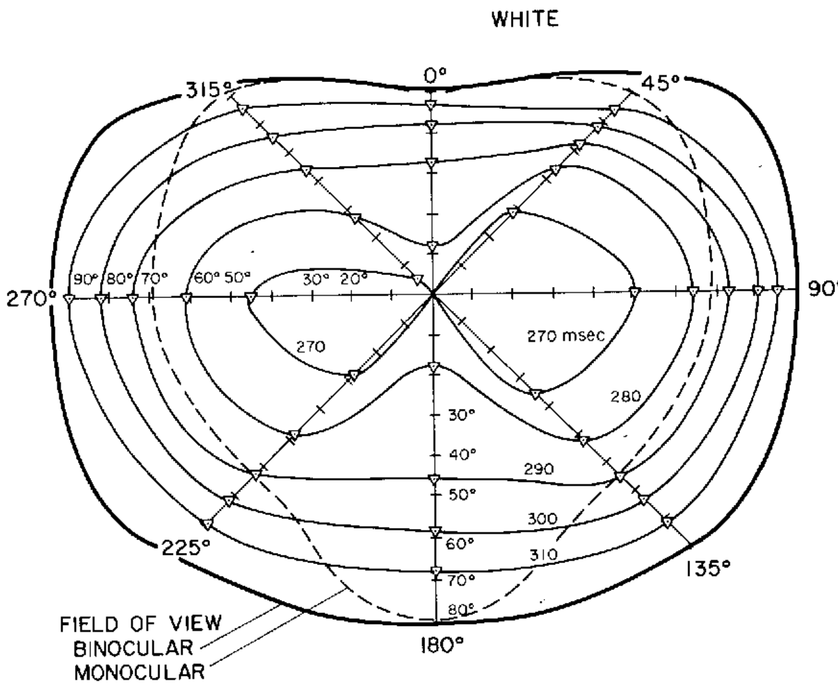

Figure 11.– Retinal iso-RT zones for white.

nearly the same (approx. +1.4). The slope for the red condition is not as steep (approx. +1.1) and is displaced toward the longer end of the RT scale. It is tempting to relate these findings to the fact that the luminances of the four above stimuli (blue, yellow, green, and white) were close to each other while the luminance of the red condition was about 1.6 $\log_{10}$ units dimmer.

Table 3 presents the results of an analysis of variance of the mean RT data (ref. 26). Both the stimulus position and meridian main effects were significant, as were four of the six two-way interactions and one of the three-way interactions.

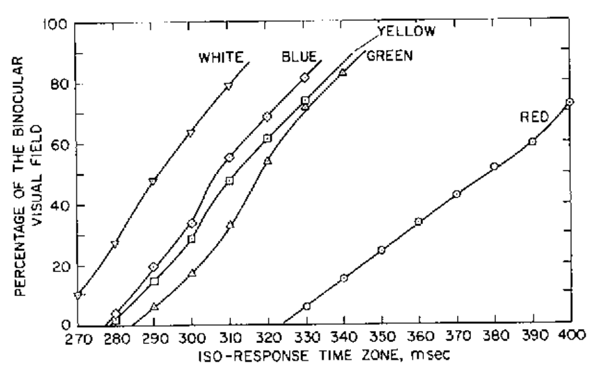

Figure 12.– Percentage of the binocular visual field represented by the iso-RT zones presented in figures 7–11 for each color.

These RT data were also fit by the linear least squares technique as follows: the equation's coefficients were determined for the $10° \leqslant \theta \leqslant 50°$ data along each meridian for each color. The coefficients for a second equation were determined for the $60° \leqslant \theta \leqslant$ visual field limit along each meridian for each color. These best-fit regression equation coefficients are presented in tables 4 and 5 in the standard form: $Y = A + BX$ where Y = mean RT (msec), A = ordinate intercept value (msec), B = slope, and $X = \theta$ value.

Considering only the slopes of the $10° \leqslant \theta \leqslant 50°$ segment, it is possible to say that the steepest slopes tend to occur in the upper half of the visual field and the flattest slopes in the lower

TABLE 3.– ANALYSIS OF VARIANCE SUMMARY FOR YELLOW, GREEN, AND BLUE HUES AND FIVE[a] SUBJECTS

Source of variance	df	SS	MS	F
Stimulus position (L)	12	0.18029	0.15024	17.33[b]
Meridian (M)	3	.90159	.30053	21.72[b]
Hue (H)	2	.17157	.08578	2.96
Sex (S)	1	.25213	.25213	.39
Subjects[c]	4	.25665	.64164	
(L) X (M)	36	.31338	.00870	3.60[b]
(L) X (H)	24	.53007	.02208	10.34[b]
(L) X (S)	12	.22373	.01864	2.15[d]
(M) X (H)	6	.14152	.02358	.77
(M) X (S)	3	.01040	.00346	.25
(H) X (S)	2	.94687	.47343	16.35[e]
Subject X (L)[c]	48	.41599	.00866	
Subject X (M)[c]	12	.16600	.01383	
Subject X (H)[c]	8	.23158	.02894	
(L) X (M) X (H)	72	.06479	.00089	0.86
(L) X (M) X (S)	36	.03131	.00086	0.35
(L) X (H) X (S)	24	.19286	.00803	3.76[b]
(M) X (H) X (S)	6	.22446	.03741	1.23
Subject X (L) X (M)[c]	144	.34811	.00241	
Subject X (L) X (H)[c]	96	.20497	.00213	
Subject X (M) X (H)[c]	24	.72624	.03026	
(L) X (M) X (H) X (S)	72	.07631	.00105	1.01
Subject X (L) X (M) X (H)[c]	288	.30121	.00104	
Mean	1	87.39690	87.39690	

[a]Due to missing data for two of the seven subjects and an ANOVA requirement for complete cells, only five subjects' data were included in this analysis of variance.

[b]$p < 0.001$

[c]The sex main effect was nested within the subject variable to be used as an error term. Therefore, there is no subject main effect available.

[d]$p < 0.05$

[e]$p < 0.005$

right quadrant of the visual field. The relatively large variability of the mean RT data presented in figures 2–6 at some of the θ positions tested suggests that caution be used in interpreting the goodness of the regression equations.

Once a subject is trained the assumption is often made that mean RT will remain relatively constant over the course of the investigation. Although this might be true for shorter-length studies (say from one to several days), it may not be true for RT investigations lasting as long as the present study. Therefore, an analysis was performed on the mean RT data for only the $\theta = 0°$ stimulus position over the entire study. This position was chosen since it was common to every meridian and was, therefore, sampled every test day. In addition to the findings presented in table 6 which give the minimum, mean and maximum RT by color averaged across subjects, the following observations were made: (1) no particular trends in RT were found over the course of the investigation, and

TABLE 4.– COEFFICIENTS FOR LINEAR LEAST-SQUARES FIT

EQUATIONS FOR MEAN RT DATA

($10° \leqslant \theta \leqslant 50°$ segment)

Meridian		Color				
		Blue	Yellow	Green	Red	White
0°	A[a]	285.5	283.2	304.2	319.4	264.8
	B[a]	0.73	1.16	0.80	1.62	0.96
45°	A	278.1	270.2	299.3	312.4	251
	B	0.37	0.60	0.17	0.80	0.70
90°	A	272.8	269.6	274.2	312.4	253.6
	B	0.14	0.36	0.22	0.78	0.26
135°	A	273.8	274.6	284.3	284.3	260.4
	B	0.18	0.36	0.13	0.13	0.34
180°	A	288.7	285.4	301.7	313.2	263.6
	B	0.53	0.70	0.49	1.48	0.78
225°	A	277.1	265.8	288.6	298.6	249.2
	B	0.67	0.92	0.62	1.48	0.92
270°	A	277.2	260.7	273.1	303.6	248.6
	B	0.42	0.95	0.61	1.56	0.66
315°	A	279.6	266.6	279.1	279.7	260.1
	B	0.52	1.16	0.87	0.87	0.77

[a]The A and B values refer to the ordinate intercept and slope values of the least squares best fit for the conditions noted.

(2) for any given color the mean SD was 1.3-3.6 times the RT range, which indicates the reliability of these foveal RT data over the (protracted) course of this investigation.

No-Response Data

The percentage of total trials presented for which NR was recorded was determined within each of the following three retinal regions: (1) visual field limit $\leqslant \theta \leqslant 40°$; (2) $30° \leqslant \theta \leqslant 30°$; and (3) $40° \leqslant \theta \leqslant$ visual field limit on the opposite side. Considering only the NR data for blue, yellow, and green, the following results were found for all three colors: the lowest percentage of NRs occurred within the $30° \leqslant \theta \leqslant 30°$ region (1.4 percent), while the highest percentage of NRs occurred within the $40° \leqslant \theta \leqslant 80°$ region *below* the fovea (7 percent). The $40° \leqslant \theta \leqslant 50°$ region

TABLE 5.– COEFFICIENTS FOR LINEAR LEAST-SQUARES FIT EQUATIONS FOR MEAN RT DATA

($60^\circ \leqslant \theta \leqslant$ limit of visual field)

Meridian		Color				
		Blue	Yellow	Green	Red	White
0°[a]	A	---	---	---	---	---
	B	---	---	---	---	---
45°	A	156.0	267.0	251.0	378.0	255.0
	B	2.80	1.20	1.60	0.60	0.90
90°	A	202.5	170.0	190.0	327.3	172.0
	B	1.52	2.15	1.76	1.10	1.71
135°	A	267.5	308.5	311.3	311.3	301.8
	B	0.55	0.15	0.10	0.10	−0.05
180°	A	190.8	184.0	207.3	138.0	174.0
	B	2.05	2.20	2.10	3.80	2.00
225°	A	216.2	230.8	240.0	175.0	159.2
	B	1.45	1.15	1.20	2.80	1.95
270°	A	209.2	204.0	221.5	174.5	178.5
	B	1.35	1.50	1.25	2.95	1.55
315°	A	174.0	133.8	86.8	86.8	164.0
	B	2.30	3.05	3.85	3.85	2.20

[a]Insufficient data upon which to make a calculation.

TABLE 6.– SUMMARY OF RT DATA FOR $\theta = 0^\circ$ STIMULUS POSITION FOR EACH SUBJECT AND MERIDIANS[a]

	Stimulus color				
	Blue	Yellow	Green	Red	White
Min. RT	331	279	301	313	269
Max. RT	353	301	343	330	286
Range	22	22	42	17	17
Mean RT	341	288	323	322	276
Mean S.D.	76.2	43	56.5	52.3	39.2
S.D./Range[b]	3.57	1.96	1.34	3.07	2.30

[a]All values in msec except as noted.
[b]Dimensionless value.

above the fovea produced 6 percent NRs. Considering these same three colors imaged only across the horizontal meridian, the lowest percentage of NRs occurred within the 40° left $\leqslant \theta \leqslant$ 80° left region (1.1 percent). The 40° right $\leqslant \theta \leqslant$ 90° right region produced a slightly higher percentage of NRs (1.9 percent), while the 30° left $\leqslant \theta \leqslant$ 30° right region produced the highest percentage of NRs (2.8 percent). These findings are in general agreement with those found in a previous investigation in this laboratory (ref. 2). The percentage of NRs that occurred across each of the diagonal meridians showed no particular order by color or stimulus position. The mean percentage of NRs found for the 30° $\leqslant \theta \leqslant$ 30° region across all meridians and three colors was 1.9. The percentage of NRs across all meridians by color were: yellow (2.9), blue (2.4), and green (2.3). The red condition produced an average of 4.4 percent of NRs and the white, 1.4 percent across all meridians.

DISCUSSION

This discussion will be confined to two major subjects, a comparison of the present data to those obtained by other investigators and a discussion of how these data may be applied to various design areas.

Comparison with Other Data

Response time to colored stimuli– As reviewed earlier, many investigators have quantified simple RT to the onset of colored stimuli presented to the *fovea*. The results presented here are compared with similar RT data of others in table 7 for studies in which more than one color was tested. Selected experimental parameters used in these investigations are also cited where they are known to play an influential role in determining simple RT. It is apparent that differences in many of these parameters – both within and between subjects – make it difficult to compare one RT value with another. Nevertheless, the present data do compare well with those reported earlier from this laboratory (ref. 2), taking into account stimulus luminance differences. Relatively good agreement is also found between the present data and those of references 5 and 9 taking into account differences in stimulus luminance, dominant wavelength, and number of stimuli presented. If the present mean RT data are plotted at their proper log ml and wavelength location in figure 4 of reference 9, then the agreement is almost perfect for the yellow and red conditions. The present mean RT for green was about 33 msec longer than that reported in reference 9, and the blue was about 65 msec longer. These differences may be accounted for by the fact that the reference cited above used a somewhat larger foveal stimulus (which would be expected to reduce mean RT according to reference 27) and also by the fact that a relatively large photopic (20 ml) background was used which would be expected to reduce the effective contrast of the lowest luminance stimulus, thereby lengthening RT. Nevertheless, no data are available with which to determine the size of the influence of these combined factors. Regarding the lowest luminance condition Pollack states, "...rods may be said to be playing a dominant part in the reaction times obtained at the lowest luminance level. However, cones are also playing a role. At this lowest luminance level, the subjects reported seeing color. Thus, the functions at the lowest luminance level, represented by the branches of the reaction time curves (see fig. 2), probably represent the activity of both rods and cones" (ref. 9). That this may be true on purely neurological grounds is indicated by the fact that the RT stimulus subtended a 2.1° arc diam which, assuming even small saccadic and drift movements of the eye, would cause the stimulus' image to fall upon retinal regions known to possess rods (refs. 16-18).

TABLE 7.– REVIEW OF INVESTIGATIONS OF FOVEAL RT

Parameters	Reference					
	1	2	4	5	9[a]	This study
Stimulus color						
Red						
Kodak filter no.	70	29	---	72	---	29
Dom. wavelength (nm)	650+	631.6	650–700	605	657	631.6
Stim. luminance (ml)	0.013	0.027	*b*	0.063	0.039	0.027
Mean RT (msec)	258	370	176.2	237.5	516[c]	322[d]
S. D. (msec)	21.3	57.4	9.85[e]	---	---	52.3
Stim. luminance (ml)	0.129	---	---	0.0063	---	---
Mean RT (msec)	235.3	---	---	315	---	---
S. D. (msec)	26	---	---	---	---	---
Blue						
Kodak filter no.	49*b*	47	---	75	---	47
Dom. wavelength (nm)	495	463.7	360–510	485	415	463.7
Stim. luminance (ml)	0.043	0.027	*b*	0.063	0.039	0.078
Mean RT (msec)	247.6	314.3	171.5	230	363[c]	341[d]
S.D. (msec)	29	43.4	9.07[e]	---	---	76.3
Stim. luminance (ml)	0.43	---	---	---	---	---
Mean RT (msec)	226.6	---	---	---	---	---
S.D. (msec)	22	---	---	---	---	---
Green						
Kodak filter no.	---	60	---	74	---	60
Dom. wavelength (nm)	---	526	510–560	530	530	526
Stim. luminance (ml)	---	0.033	*b*	0.063	0.039	0.050
Mean RT (msec)	---	298.1	172.8	245	369[c]	323[d]
S.D. (msec)	---	50.5	9.2[e]	---	---	56.5
Yellow						
Kodak filter no.	---	16	---	73	---	16
Dom. wavelength (nm)	---	582.7	500–700	575	589	582.7
Stim. luminance (ml)	---	0.070	*b*	0.063	0.039	0.078
Mean RT (msec)	---	272.1	172.3	240	419[c]	288.5[d]
S.D. (msec)	---	45.6	8.35[e]	---	---	43
White						
Stim. luminance (ml)	---	0.107	---	0.063	---	0.072
Mean RT (msec)	---	282.2	---	247.5	---	276.3[d]
S.D. (msec)	---	38.7	---	---	---	39.3

TABLE 7.– REVIEW OF INVESTIGATIONS OF FOVEAL RT – Concluded.

Selected stimulus characteristics	Reference					
	1	2	4	5	9[a]	This study
Stimulus size	21′	45′	4° 10′	---	2° 6′	45′
Shape	round	round	round	?	round	round
On duration	---	50 msec	= RT	1 sec	740 msec	50 msec
Source (type)	glowmod.	fluor.	tungsten	fluor.	tungsten	fluor.
Background characteristics						
Luminance	?	dark	illum.	dark	20 ml	dark
Size	?	full FOV[f]	?	?	10° 30′	full FOV
Miscellaneous details						
Viewing eye	OD	OU	O	monoc.	OD	OU
Prior dark-adaptation	30 min	10 min	0[a]	30 min	10 min	15 min
Artificial pupil	?	none	none	2.5 mm	3 mm	none
Response type	release	press	release	press	release	press
Digit used	?	thumb	forefinger	index	?	thumb
Inter-stim. interval (sec)	?	1.8-3.2	?	?	minimum = 25	1.8-3.2
Number of subjects	3	2	2	2	2	7
Foreperiod duration (sec)	1.7-3.7	none	2-4	1-4	$\bar{X}$= 2	none
Foreperiod initiated by	subject	---	subject	---	---	---
Prior training	yes	yes	yes	?	yes	yes

[a]All testing was conducted in a "lighted area."
[b]No value cited in original text.
[c]Median RT.
[d]Value based upon mean RT at $\theta = 0°$ averaged across all meridians.
[e]Original text cites this value as a mean variation.
[f]Field of view.

Detection of stimulus color– Each subject was asked if he perceived the hue of each stimulus condition, after he had been in darkness for about 30 min. Correct hue names were given for the $\theta = 0°$ position in the great majority of cases. Yellow was sometimes called white and vice versa, however, It is probably because of its extremely low luminance that the red stimulus elicited the largest number of incorrect hue-naming responses. In some instances red was perceived as pink or a grey-white. Almost all subjects said they felt they could perceive the hue of the $\theta = 10°$ stimulus positions, but they were not nearly as confident of it as they were for the foveal stimulus. Stimuli imaged between 10° and about 50° arc from the fovea elicited a low proportion of correct hue-naming responses, regardless of meridian. Beyond about 50° arc the hue-naming performance of all subjects was at chance level.

Binocular response time compensation for the blind spot– The present RT findings may also be compared to those reported by Payne (ref. 28). Payne quantified simple RT to white stimuli imaged across four meridians, each of which passed through or near the blind spot out to 30° arc on both sides of the fovea. It was found that minimum RT occurred to stimuli imaged on the *light*-adapted retinal region of one eye that corresponded to the region of the blind spot in the other eye. This is particularly interesting since the minimum RT lobes (cf. figs. 7-11) reported here may represent this same phenomenon in the *dark*-adapted eye. Our stimuli were bright enough to elicit a foveally mediated RT response, yet had our subjects been light-adapted an adaptation level could conceivably have been reached where the stimulus' luminance would not have elicited a response. This kind of possibility must be seriously considered in many applied situations such as those discussed below.

Color sensitive zones and response time– Simple visual RT to white stimuli imaged across the retina is highly correlated with the light threshold distribution across the same retinal region (ref. 29). It is not difficult to accept the possibility that the same is true for colored stimuli. The primary difficulty arises from the fact that there is no definitive data available on where the various color-sensitive cones lie over the retina's surface.

It is possible to say that the low-stimulus luminances tested here were on the lower end of the luminance continuum, which would be expected to yield smaller iso-RT zones than otherwise would have been produced had higher luminances been used. Color-threshold sensitivity data (refs. 19,20,22) have shown the relatively large variability of the boundary of each color-sensitive area both within and between subjects. The present RT data may well reflect these color-responsive zones in addition to a proportion of the RT due to neural transmission time and the final motor response.

In a previous report from this laboratory (ref. 24), white light RT data were related to the design of an instrument panel and aircraft window outline. The present RT data for colored stimuli may be applied in the same manner.

Application of Data to Selected Operational Environments

It should be remembered that these RT data were obtained under almost ideal viewing conditions. The subject was dark-adapted and relaxed, looking steadily in one direction, and was expecting the stimulus to occur at least every 3.2 seconds. These laboratory conditions may well cause some caution in applying these data to situations in which the subject is light-adapted and (possibly) tired, continually fixating new locations, and has no idea when or where a warning light may appear. Nevertheless, these data do indicate the optimal RT that may be expected within the full visual field for these test conditions. Further investigation is needed to determine the degree to which these iso-RT regions will change with changes in other testing conditions.

Aircraft instrument panel redesign– Despite the factors just mentioned that might limit these data in many operational environments, some comment should be made as to how these data may be used in design situations. Let us begin with an aircraft instrument panel redesign problem where four red fire-warning lights must be added to an existing array of instruments, controls, and other indicators. Figure 13 is a photograph of a fixed-base landing simulator with CRT forward window display. The iso-RT data for red stimuli (from fig. 10) have been superimposed over this photograph and centered upon the flight director. The same angular scale has been used for both the instrument panel and the superimposed RT data. It is clear that the four red fire-warning lights cannot be located at the point of fixation but could be inserted along the $\varphi = 90°–270°$ (horizontal) meridian between the air speed indicator and the clock (just left of the flight director), and/or between the radio altimeter and IVSI (just right of the flight director).

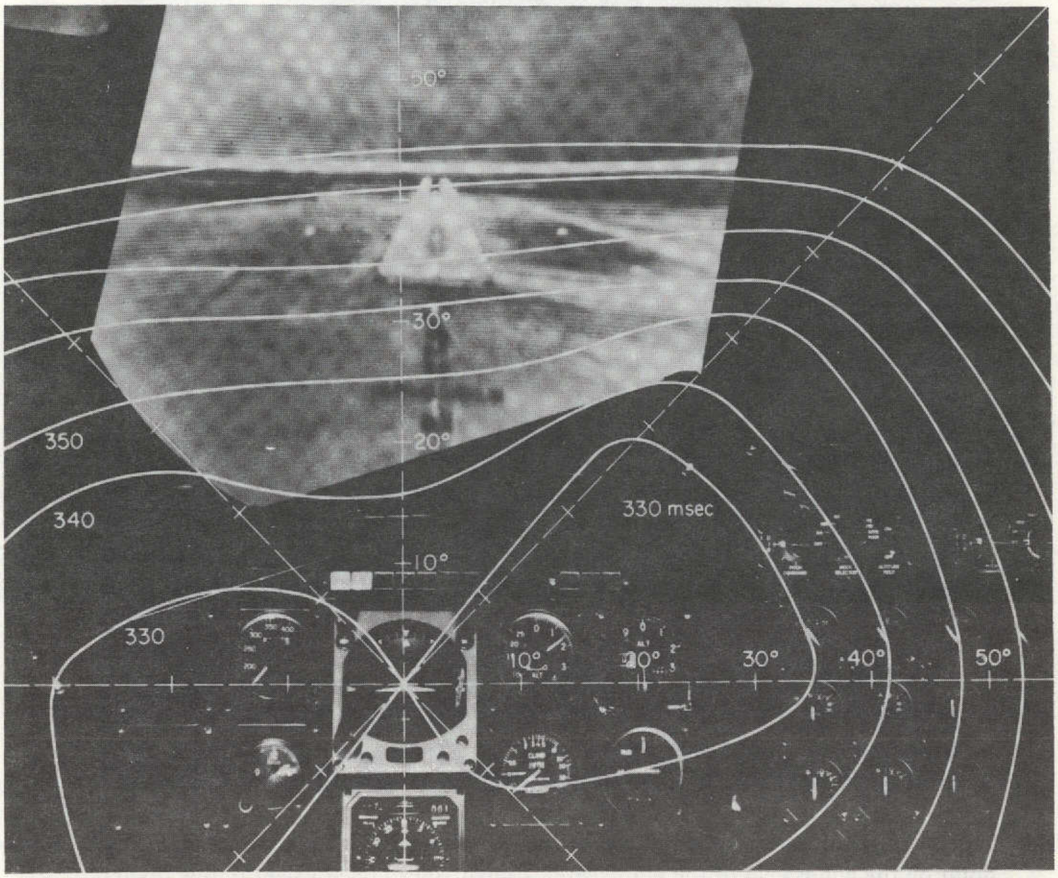

Figure 13.– Superposition of iso-RT zones for red upon simulator cockpit instrument panel and runway scene.

Because of the importance of grouping the flight instruments so that they require minimal eye scan distance, it is necessary to prioritize all of the panel instruments, visual warning lights, manual controls, and other information sources so that they may be optimally positioned within the pilot's field of view. By "optimal position" is meant that particular location within the field of view that yields the highest probability of visual detection and also fastest manual response without having to refixate the instrument in question.

Figure 14 has been prepared to illustrate how the present mean RT data may be applied in a design situation involving an entire cockpit. A typical commercial jet aircraft cockpit is shown with the center of the iso-RT plot for white stimuli located at the intersection point on the pilot's windshield of his level, straight-ahead line of sight. It is assumed that the aircraft is in straight and level flight and that the captain's eyes are also at the correct (reference) position. Various meridian lines are somewhat curved because the hemispheric arc that this iso-RT plot represents is being viewed from a point several feet to the right and above the pilot's eye position. This vantage point tends to distort (slightly) some of the RT contours as well. Nevertheless, it should be clear how a projection of the iso-RT plots provided in this report upon a work station can aid in positioning luminous warning lights and other visual indicators so as to yield the most rapid manual response.

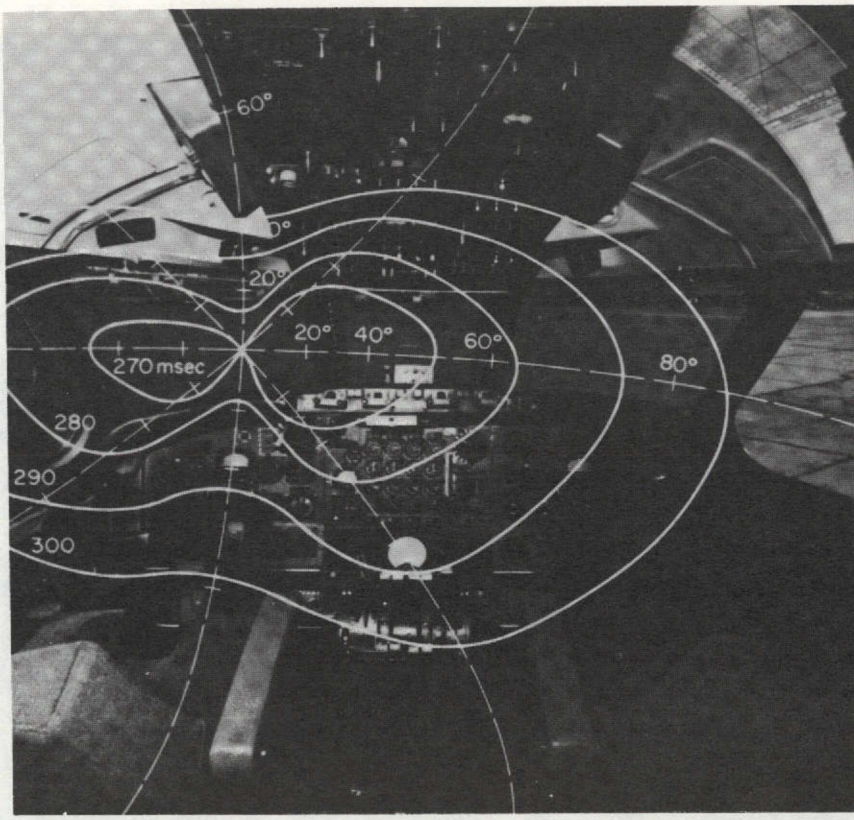

Figure 14.– Superposition of iso-RT zones for white upon Convair 990 jet cockpit (centered at the intersection point on the windshield of the pilot's level, straight-ahead line of sight during flight).

The present data have shown the approximate amount of button-pressing RT that can be saved by moving a self-luminous indicator a matter of even 5° arc from its former position. Savings of 10-20 msec may seem insignificant until these short durations are translated into distance traveled at typical jet aircraft landing (or takeoff) speeds. For instance, at 140 knots, an aircraft will travel 1.44 m (4.73 ft) in 20 msec. When distance traveled is calculated for a typical foveal mean RT (from the present investigation), an aircraft will travel 21.62 m (70.94 ft) in 300 msec, at 140 knots.

Comparison of recommended indicator luminance with present stimulus luminance– Comment should also be made here regarding the stimulus luminances used in the present investigation. The luminances of the blue, yellow, and green stimuli were from 2.3 to 2.5 $\log_{10}$ units below the recommended warning, caution, and advisory lighted-indicator luminance for nighttime viewing conditions (ref. 30). If the present colored stimuli were increased in luminance to the recommended 5.139×10^{-3} cd/cm^2 (15 ft-L), mean RT could be as much as 43 msec faster than is shown for the fovea in figure 6. This estimated saving in RT is based upon the results of an earlier investigation from this laboratory in which five subjects were presented a 50-msec duration white stimulus imaged upon the fovea at a luminance of 7.605×10^{-3} cd/cm^2 (22.2 ft-L). Mean foveal RT for 954 trials was found to be 227.3 msec. This value increased to 236.5 msec when the luminance was reduced to 8.907×10^{-4} (2.6 ft-L). An estimate of foveal RT for stimuli possessing a luminance of 5.139×10^{-3} cd/cm^2 (15 ft-L) may be calculated by interpolation between these two values, yielding 233.1 msec. Subtracting this value from the grand mean foveal RT for white from appendix A (viz. 276.2 msec) yields the estimated 43 msec referred to above. Further work should be conducted, however, to determine for the other stimulus colors the precise influence of using a stimulus luminance that corresponds to the recommended luminance for warning, caution, and advisory lighted indicators.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California 94035, December 6, 1974

APPENDIX A

RESULTS FOR EACH STIMULUS POSITION, MERIDIAN, AND COLOR ACROSS SUBJECTS

Stimulus meridian		Stimulus position, deg																			Stimulus meridian
		80	70	60	50	40	30	20	10	0	10	20	30	40	50	60	70	80	90		
(a) Blue																					
180°	$\bar{X}$	360	324	319	322	306	296	301	298	353	296	297	309	308	327						
	SD	68	59	60	47	45	38	43	40	71	40	38	48	44	45						0°
B	N	149	183	187	184	185	157	185	158	167	186	159	185	185	165					ΣN = 2435	
	NR	28	4	2	5	4	1	1	1	15	2	2	2	4	19						T
225°	$\bar{X}$	336	310	307	320	299	287	288	292	344	284	285	286	286	302	324	352				
	SD	65	53	53	59	52	38	40	37	96	34	39	38	41	38	51	66				45°
LL	N	183	188	191	193	187	161	186	162	168	188	164	190	187	186	187	143			ΣN = 2864	
	NR	4	5	1	0	0	1	2	0	17	0	3	1	0	2	4	0				UR
270°	$\bar{X}$	319	300	292	309	288	276	288	288	331	272	281	273	279	280	304	303	305	354		
	SD	55	44	52	44	38	41	43	42	75	32	42	39	35	33	46	42	38	58		90°
L	N	184	192	190	184	182	164	190	160	175	183	158	187	192	192	185	157	160	152	ΣN = 3187	
	NR	1	1	0	1	3	1	1	2	14	2	2	2	2	0	2	0	0	0		R
315°	$\bar{X}$		335	312	316	297	282	285	286	336	273	282	280	276	285	301	305	312			
	SD		58	39	42	41	35	39	36	63	28	37	36	36	32	40	49	46			135°
UL	N		174	190	188	187	159	187	165	173	183	164	190	190	188	190	160	158		ΣN = 2846	
	NR		11	2	3	0	4	4	1	11	1	1	4	1	2	0	0	0			LR
(b) Yellow																					
180°	$\bar{X}$	361	336	317	328	306	300	304	294	301	300	305	315	319	351						
	SD	58	62	52	47	42	40	42	45	45	44	42	51	43	51						0°
B	N	144	184	188	190	186	160	189	161	189	189	161	192	189	155					ΣN = 2477	
	NR	38	6	4	0	6	1	2	3	0	0	0	1	2	27						T
225°	$\bar{X}$	326	305	303	318	299	284	289	277	279	276	288	283	288	306	339	351				
	SD	46	45	40	44	40	31	34	33	38	33	32	34	30	32	46	44				45°
LL	N	190	187	190	183	191	165	191	165	189	189	160	191	191	188	187	137			ΣN = 2894	
	NR	0	1	1	4	1	2	0	2	2	0	2	1	0	3	1	0				UR
270°	$\bar{X}$	328	301	298	315	296	277	285	273	286	270	285	276	281	290	310	315	320	380		
	SD	51	50	41	40	39	40	44	45	44	34	41	39	42	41	47	36	48	61		90°
L	N	180	187	188	185	182	151	187	159	187	178	156	186	184	186	186	152	158	154	ΣN = 3146	
	NR	9	4	6	8	10	10	7	6	5	11	6	8	10	6	6	0	0	0		R
315°	$\bar{X}$		339	321	338	303	289	291	286	288	277	289	281	281	299	320	314	323			
	SD		54	51	50	43	39	39	41	45	37	37	33	35	49	45	50	52			135°
UL	N		182	181	180	178	158	188	159	186	184	162	185	185	185	183	164	164		ΣN = 2824	
	NR		7	8	5	5	4	4	5	6	3	2	5	5	3	4	0	0			LR
(c) Green																					
180°	$\bar{X}$	374	357	332	336	315	305	314	312	343	318	320	323	324	356						
	SD	54	55	49	49	43	37	41	48	54	47	49	54	57	59						0°
B	N	120	168	194	181	189	163	190	163	180	187	162	188	188	183					ΣN = 2456	
	NR	61	19	0	3	2	1	3	1	9	1	0	5	2	9						T
225°	$\bar{X}$	336	324	312	327	312	293	304	300	330	297	311	302	302	310	347	363				
	SD	63	66	61	61	55	49	54	55	73	55	59	54	52	63	63	83				45°
LL	N	167	183	189	184	187	160	191	161	175	188	162	183	184	180	179	120			ΣN = 2793	
	NR	19	4	1	2	0	2	0	1	12	3	1	5	4	3	10	0				UR
270°	$\bar{X}$	325	302	300	311	292	283	289	282	301	276	284	276	278	290	303	310	315	360		
	SD	58	45	41	51	40	34	39	38	49	37	39	37	36	47	36	38	41	57		90°
L	N	185	186	180	187	190	160	183	160	186	190	159	181	183	186	184	158	159	148	ΣN = 3165	
	NR	2	2	3	2	3	3	3	3	8	2	2	2	3	2	1	0	0	0		R
315°	$\bar{X}$		342	325	336	306	292	299	296	318	286	290	286	283	296	317	319	319			
	SD		53	50	50	49	38	41	34	50	36	37	35	35	35	43	43	39			135°
UL	N		188	187	191	194	162	189	162	186	188	163	192	190	191	189	160	154		ΣN = 2886	
	NR		3	4	2	0	2	0	2	1	2	1	1	0	0	1	0	0			LR
(d) Red																					
180°	$\bar{X}$	448	392	372	401	362	340	354	331	325	344	353	355	373	415						
	SD	73	62	62	63	56	50	56	46	56	60	51	58	55	80						0°
B	N	192	170	182	188	184	166	195	161	190	186	160	192	186	165					ΣN = 2517	
	NR	79	17	5	4	2	0	2	2	3	2	0	1	5	21						T
225°	$\bar{X}$	401	367	345	383	356	319	340	317	313	318	341	328	333	362	414	420				
	SD	59	57	51	64	49	43	48	44	48	46	49	46	50	61	76	69				45°
LL	N	177	187	191	190	193	163	192	163	191	193	163	192	192	182	141	73			ΣN = 2783	
	NR	7	4	0	2	1	1	1	1	1	1	2	0	0	5	44	0				UR
270°	$\bar{X}$	415	372	356	392	364	323	354	319	320	310	349	328	337	355	396	399	418			
	SD	59	55	54	53	56	45	56	41	54	42	41	44	49	46	46	50	64			90°
L	N	173	185	188	170	187	166	185	162	190	186	158	191	187	187	181	163	150		ΣN = 3009	
	NR	7	1	2	10	2	1	4	2	1	1	1	0	1	0	10	0	0			R
315°	$\bar{X}$		427	401	434	376	327	342	334	330	325	355	336	340	367	408	399	406			
	SD		67	56	53	54	56	64	46	51	44	44	40	45	49	47	55	47			135°
UL	N		151	184	146	188	166	183	165	187	192	164	188	194	191	155	158	130		ΣN = 2742	
	NR		37	5	42	4	1	4	1	4	0	0	0	1	3	33	0	0			LR
(e) White																					
180°	$\bar{X}$	334	314	294	310	286	284	282	273	286	278	285	290	293	322						
	SD	44	47	39	40	36	35	36	34	37	33	40	37	42	50						0°
B	N	134	192	188	191	187	166	191	160	189	190	166	188	184	179					ΣN = 2505	
	NR	26	1	2	1	4	1	1	3	2	1	1	1	5	12						T
225°	$\bar{X}$	318	290	279	304	282	262	274	262	270	256	270	272	272	290	309	318				
	SD	53	40	38	40	41	38	39	31	36	36	28	38	34	39	44	44				45°
LL	N	186	187	188	185	185	163	190	160	187	191	159	193	190	188	189	152			ΣN = 2893	
	NR	2	3	1	4	0	0	0	0	2	2	3	0	1	1	1	0				UR
270°	$\bar{X}$	304	284	273	287	271	262	265	257	269	255	264	259	258	271	280	291	294	336		
	SD	40	37	37	34	35	30	37	30	37	28	25	33	37	39	39	31	37	47		90°
L	N	182	185	181	185	185	158	186	160	182	185	159	182	185	184	182	151	160	156	ΣN = 3148	
	NR	2	0	4	1	1	2	1	3	2	1	2	3	2	5	4	0	0	0		R
315°	$\bar{X}$		318	296	309	285	269	280	273	280	265	269	267	271	281	300	296	299			
	SD		53	42	40	40	32	40	32	47	35	32	30	37	40	43	42	32			135°
UL	N		186	187	183	182	159	185	162	186	189	158	184	191	186	186	159	157		ΣN = 2840	
	NR		6	3	3	4	1	2	2	1	1	4	2	3	0	1	0	0			LR

APPENDIX B

PERCENTAGE OF THE FULL BINOCULAR VISUAL FIELD REPRESENTED BY EACH ISO-RESPONSE TIME ZONE

Iso-RT zone (msec)	Color				
	Blue	Yellow	Green	Red	White
270					11.04
280	4.34	1.76			26.38
290	20.59	15.52	5.50		50.91
300	38.09	30.12	14.95		69.43
310	59.01	49.74	32.91		87.36
320	74.76	64.98	56.23		
330	88.80	78.05	74.79	5.61	
340			88.66	16.04	
350				26.94	
360				37.00	
370				46.59	
380				56.08	

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