ARPA ORDER NO. 189-1

MEMORANDUM
RM-5303-ARPA
NOVEMBER 1967

COLOR DISCRIMINATION IN STATIC DISPLAYS

J. J. Sheppard, Jr., H. L. Moshin, R. H. Stratton
D. Dugas and A. Madansky

PREPARED FOR:
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PREFACE

This work was initiated as part of an ARPA Project. The present Memorandum reports on an experimental investigation of human capabilities for color discrimination with simulated displays, and is concerned with stationary targets on a constant background. Further work is required to investigate the effects of moving targets and variable backgrounds. The present results should be applicable to other similar display situations in which color is used as an additional dimension.

Other reports describing various component parts of the ARPA program are: a review of human color vision (RM-4106-ARPA), a discussion of subjective color phenomena (RM-4770-ARPA), reviews and investigations of the neurophysiological mechanisms of vision (RM-4870-ARPA, RM-4877-ARPA, RM-4912-ARPA), and a color-film calibration procedure for use in the design of simulated displays (PM-5015-ARPA).

One of the authors, A. Madansky is President of the Market Planning Corporation, Rockefeller Center, New York, and consultant to The RAND Corporation.

SUMMARY

An experimental test of the color discrimination ability of a group of untrained observers in a simulated display situation is described and the results are analyzed. The questions posed for this investigation were: (1) Is it meaningful to use the MacAdam results, scaled by an appropriate factor, to calculate color discrimination vectors for multi-image displays? and (2) If so, what is the magnitude of the scaling factor?

The experimental apparatus used was a static display system with widely separated, self-luminous 1/3-deg target spots in a dark 17-deg field. Just-noticeable-differences (JNDs) in saturation at constant brightness were determined for 39 subjects for each of six hue series about the 3200°K tungsten achromatic point. After correction for individual guessing probabilities, the 39-subject mean JND data were graphically smoothed by fitting with an ellipse in the CIE 1931 (x,y) chromaticity diagram. This experimental ellipse was then compared with the appropriate MacAdam empirical ellipse derived from 2-deg bipartite-field data. The results indicate that the answer to the first question above is affirmative. As for the second question, the scaling procedure obtained requires that the major axis of the MacAdam ellipse be multiplied by a factor of 4.5, accompanied by an increase of 15 deg in the eccentricity of the ellipse, both modifications being performed in the CIE 1960 Uniform Chromaticity Scale diagram.

A combined graphical/analytical procedure employing the MacAdam ellipses is presented for use in the preliminary design of display systems for which the target spots are chromaticity encoded in the low-saturation region surrounding the achromatic point.

The present results indicate that human chromaticity discrimination ability is only moderately degraded for widely separated 1/3-deg target spots in a dark field subtending 17 deg. Evidence of tritanopic effects was found with the 1/3-deg targets, but these effects were moderate and are approximately accounted for in the proposed scaling procedure.

The present results should be applicable to other similar display situations in which color is used as a means of encoding additional information.

ACKNOWLEDGMENTS

The authors wish to express their sincere appreciation to Carl Gazley, Jr. of The RAND Corporation for his many helpful discussions and useful suggestions during the course of this investigation, and to Carolyn Huber, Jeannine Lamar, and Gary Traeger for assistance with the data reduction and illustrations. We are obviously indebted to the many RAND staff members who volunteered to serve as subjects, and we are grateful for their cooperative participation.

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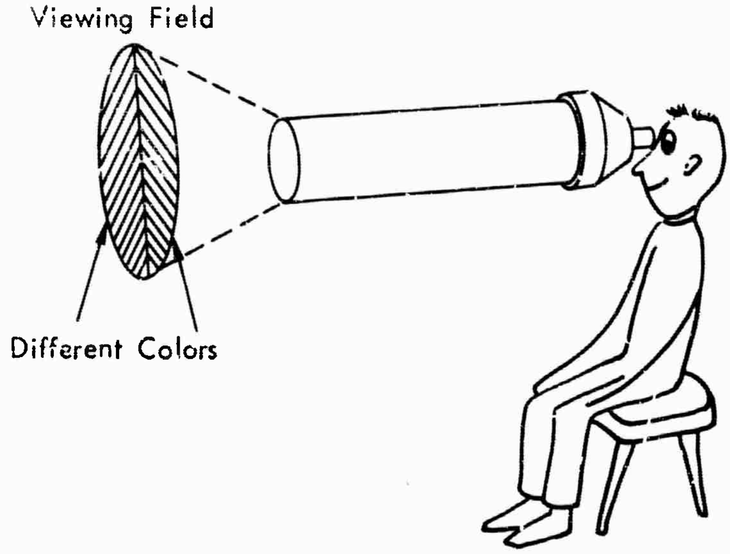
I. INTRODUCTION

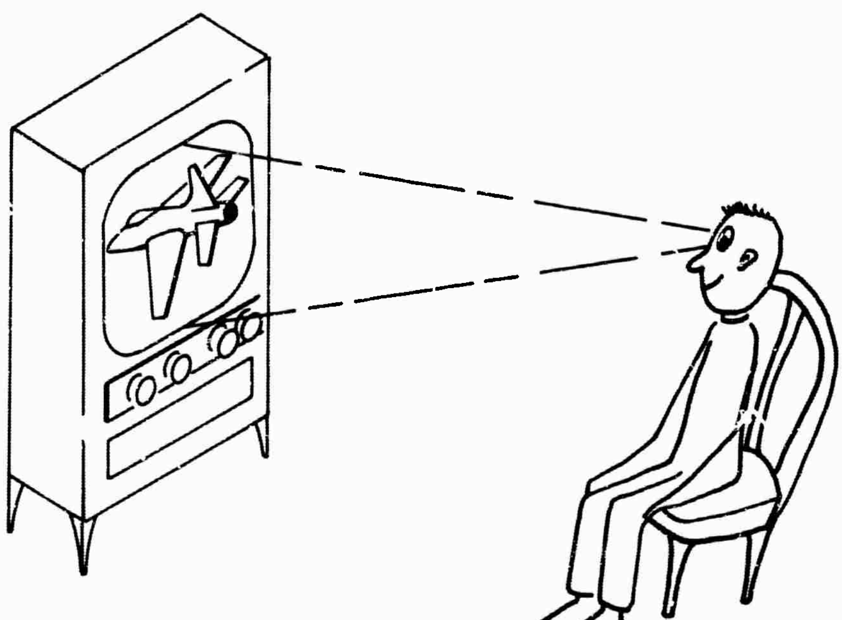
Color coding is used as a discriminant in many applications, although the full capability of the human observer for color discrimination is seldom utilized. The increasing use of remote sensing devices emphasizes the need for improved display systems allowing information from multiple sources to be conveyed in a usable form to the observer. Color encoding provides a means of adding information channels to conventional black-and-white displays. However, the use of this technique requires that the display designer know the color discrimination characteristics of those who will observe the display.

In the present study, 39 selected observers were tested for their saturation thresholds on a simulated operational display. The testing conditions may be classified with those of the "practical group" of investigations cited in the literature, wherein the subject performs color discrimination tasks under conditions identical with or similar to those of a practical task of interest. Another approach, which we shall refer to as the "laboratory group," consists of tests wherein the subject (observer) compares adjacent regions of a visual field monocularly viewed through an artificial pupil (see Fig. 1). The laboratory group tests allow substantially better experimental control, and the data generally reflect the inherent characteristics of the human visual system. Thus determined, the color discrimination capabilities of subjects are uniformly superior to those found with the practical-group tests.

Unfortunately, laboratory-group data generally cannot be applied with confidence to a practical situation <u>without actual tests under the specific conditions of interest</u>. This fact provides the impetus for many of the practical-group tests, in which a limited number of specific data are obtained to guide the application of the more extensive laboratory-group data to the practical situation. This procedure is dictated by the fact that there is no satisfactory theory to permit the direct transformation of color discrimination results from one viewing situation to a substantially different one. A more precise definition of the meaning of human color-discrimination capability will clarify this point.



"Laboratory Group" Investigations



"Practical Group" Investigations

Fig. 1 — Illustrative classification of color discrimination investigations into two groups

COLOR DISCRIMINATION

The unqualified term color discrimination refers to a visual discrimination based on any combination of the three psychological attributes of a color percept, viz., its hue, saturation, and brightness. Considered as dimensions of color-perception space, these attributes comprise a coordinate system such as the cylindrical-polar system shown in Fig. 2. In such a system the angle θ_p specifies the hue (H), the radial distance r_p specifies the saturation (S), and the vertical location z_p specifies the brightness (B) of a color percept $P(\theta,r,z)$. In this space, the percept P is represented by the three-vector (H,S,B).

If two visual stimuli evoke, under given viewing conditions, two similar color percepts P and Q which can just be distinguished by the observer, then the directed line segment (i.e., vector) $\overline{PQ}$ is defined as the just noticeable difference (JND) in the direction of $\overline{PQ}$ from either point P or point Q. The totality of the JNDs about a given point define a closed "discrimination surface" surrounding the point.

The color-percept space of Fig. 2 is purely psychological. This psychological space may be related to a psychophysical color-stimulus space, such as the standard CIE system, in which the coordinates of the point representing a color-stimulus constitute the vector

$$(X,Y,Z) = f(E_\lambda;\bar{x},\bar{y},\bar{z}) \qquad (1)$$

The stimulus vector is completely determined as a function of the spectral energy distribution E_λ of the radiation constituting the stimulus, and the defined color-mixture properties $(\bar{x},\bar{y},\bar{z})$ of the CIE Standard Observer.

If the relationship between the two spaces were unique, the standard CIE system could be used directly to express the JNDs determined in color-percept space. However, the relationship is not unique. The three-vector (H,S,B) representing a color-percept may be operationally defined as

$$(H,S,B) = g(E_\lambda,\bar{r},\bar{g},\bar{b},\Omega,\Sigma) \qquad (2)$$

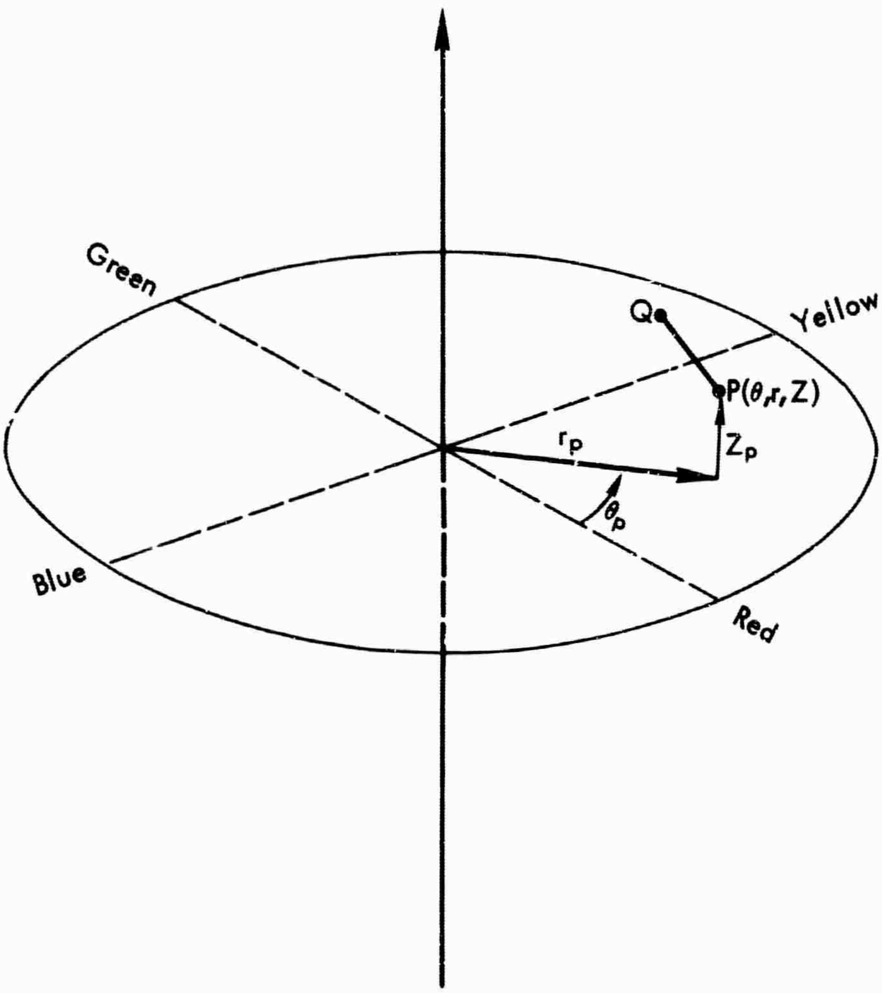


Fig. 2—Color perception space with coordinates θ (hue), r (saturation), and Z (brightness)

where $(\bar{r},\bar{g},\bar{b})$ are the color-mixture properties of the actual observer, Ω represents the psychophysiological history and present state of the actual observer, and Σ represents the conditions of the actual viewing situation. Hence, only by holding the experimental parameters $(\bar{r},\bar{g},\bar{b},\Omega,\Sigma)$ fixed can the percept vector (H,S,B) be meaningfully represented by the stimulus vector (X,Y,Z). Further, since the functional form of Eq. (2) is not known, the experimental results for a given set of parametric values cannot in principle be adjusted to apply to conditions represented by a new set of parametric values. The experiment must be performed again under the new conditions.

Investigators of human color perception have sought to minimize or control the effects of parametric variations on their results, by developing standard procedures for experimentation and reporting. The parametric set $(\bar{r},\bar{g},\bar{b},\Omega,\Sigma)$ may be regrouped into two subsets, the situation parameters (Σ) which can be objectively specified and controlled, and the observer parameters $(\bar{r},\bar{g},\bar{b},\Omega)$ which can be measured (at least partly) and reported, if not controlled. In one situation subset (Σ) widely used for laboratory-group investigations, the observer's head is clamped in a rigid apparatus that presents a monocular bipartite visual field. In such a situation, (Σ) can be reproduced from session to session during an experiment and can be duplicated in another laboratory. However, this (Σ) is not representative of the (Σ) under more common viewing conditions (e.g., watching TV from an easy chair).

There are two widely used standard procedures for handling the observer subset $(\bar{r},\bar{g},\bar{b},\Omega)$. The first makes use of very few observers (typically, the investigator alone) and provides detailed measures of characteristics of their visual systems. This procedure allows us to determine what might be called the "actual visual system" of the observer(s). The second procedure makes use of many observers and treats the data statistically to determine the "probable visual system" of a typical observer. The first procedure is most applicable to the laboratory-group investigations and is used primarily by psychophysicists. The second has a general application and is used primarily by psychologists. This latter is the better choice for practical-group investigations.

One of the best known and most widely used sets of laboratory-group color discrimination data is that of MacAdam[1] and Brown--MacAdam;[2] the data are obtained principally from a single observer. These data invite wide use for two reasons: (1) the single observer used has been shown[3] to be "typical" of the general color-normal population; and (2) the data have been fitted[4] by analytical expressions that permit rapid calculations of JNDs in any region of (X,Y,Z) color space. Hence, if these laboratory-group data can be applied to a practical-group situation of design interest by the use of an experimentally determined scaling factor, considerable effort can be saved in experimentation and in design calculations.

The present investigation assumes that such a procedure may be followed for conventional display situations. This assumption appears to be justified by earlier investigations reported in the literature, and receives additional confirmation from the present investigation -- a point that we shall subsequently discuss in detail.

Hence, the purpose of our investigation was to determine the scaling factor for the MacAdam analytical expressions for calculating JNDs in the colors of stationary, separated targets on a typical display under simulated operational conditions.

II. APPARATUS

DISPLAY SYSTEM

The experimental configuration is shown schematically in Fig. 3. Rear projection was used to allow images to be viewed directly without the use of mirrors or prisms, and to simulate more closely actual display hardware. The display format selected was 12 by 15 in., a comfortable and realistic size for an observer seated approximately 40 in. from the display. A rear-projection material was chosen to give diffuse light transmission. This material has a transmissivity of approximately 50 percent, and is spectrally nonselective throughout the wavelength range of 0.38 to 0.76 microns. The rear-projection format was centered in a wooden enclosure painted flat black to eliminate a surround. The opening at the viewing end of the enclosure is 26 in. wide by 20 in. high and the rear-projection format is recessed to a depth of 8 in. The light path between projector and viewing box was covered to reduce stray light from the projection system.

A 3¼-by-4-in. lantern-slide projector, fitted with a 500-watt, 3200°K tungsten lamp, was used to project test slides on the rear-projection format. The lamp was changed every 10 hours of operation to prevent the reduction of color temperature by lamp aging. Line voltage to the projector was checked periodically and was found to stay within the range of 117--120 volts ac. The color temperature of a tungsten lamp operated at 120 volts varies approximately 10°K per volt.

The test slides, which are discussed fully in the next section, each contained four small images arranged in a rectangular configuration. The uniformity of illumination in the four corresponding regions of the screen was checked with a Weston Illumination Meter, Model 756, fitted with a Viscor filter with a spectral sensitivity comparable to that of the eye. The illumination in each of the four regions, measured on the side toward the observer with two clear pieces of slide glass in the carrier, was 170 ± 3 foot-candles. All test slides were enclosed in two such pieces of glass. The ambient illumination in the room where the observer was seated was 2 foot-candles.

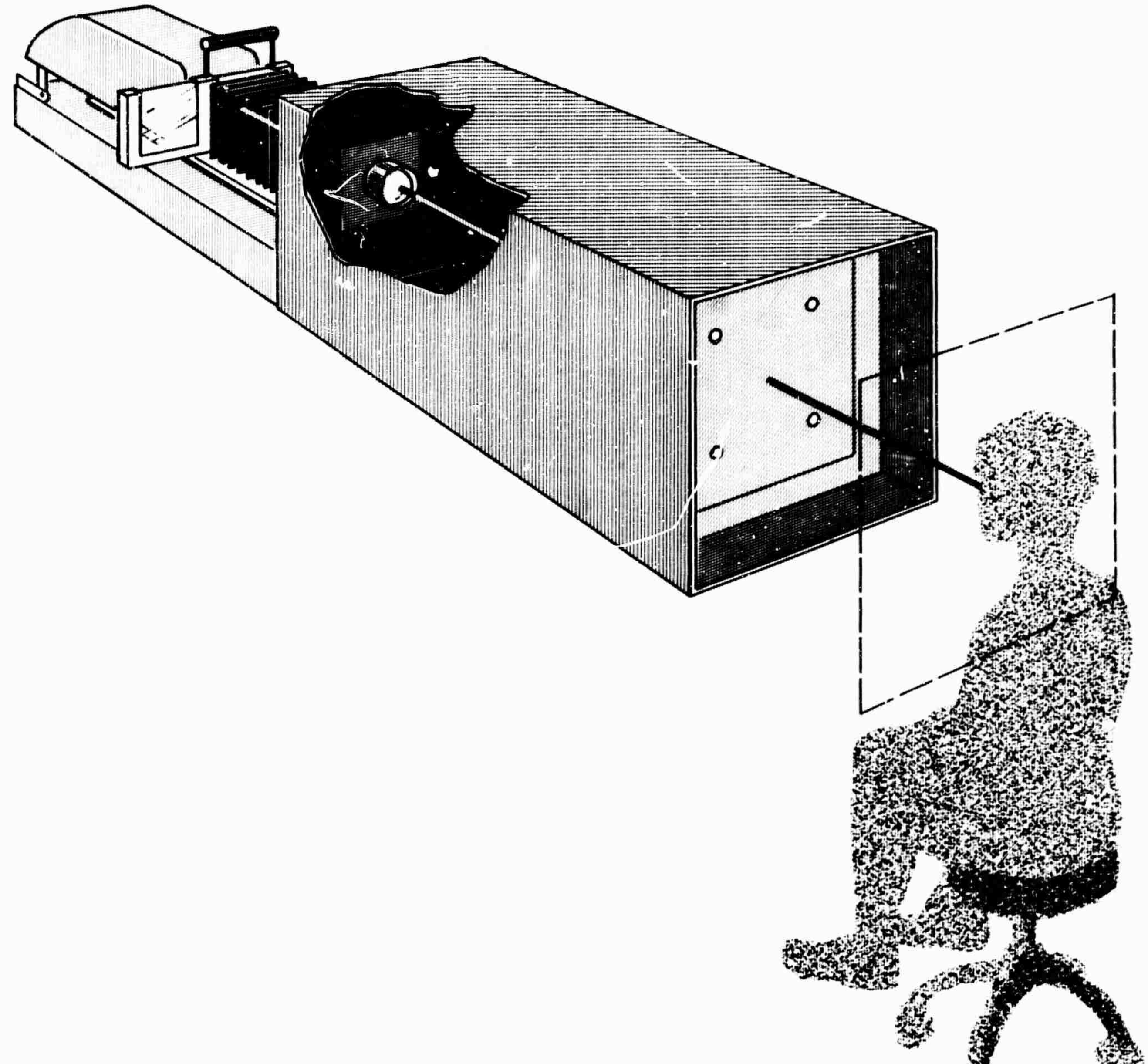


Fig. 3—Schematic of display system

As indicated schematically in Fig. 3, the subject was positioned centrally without restricting his freedom of normal tonus by means of a string-and-tape alignment device. These seating and viewing conditions were chosen to simulate those of conventional display systems.

TEST SLIDES

The layout and dimensions of the image format as seen by the observer are shown in Fig. 4. Each test spot subtended approximately 20 min of arc at the observer. The chromaticity and luminosity of each of the four 1/4-inch diameter images projected by each test slide were controlled by means of Wratten color-compensating (CC) and neutral density (ND) filters.

The test slides were of two types, dummy and hued. Dummy slides had identical neutral-density filters in each of the four test-spot locations. Hence the image format presented four test spots of equal luminosity and zero saturation referred to the chromaticity of the projection-light source as the achromatic point. The chromaticity coordinates of the achromatic point are ($x = 0.4167$, $y = 0.3967$) as computed from the spectral-energy distribution curve furnished by the manufacturer of the projection lamp. The location of the achromatic point (herein called "neutral") on the standard CIE Chromaticity Diagram is shown in Fig. 5.

On hued slides, one of the four test spots was given a nonzero saturation with one of the six series of (CC) filters: red, yellow, green, cyan, blue, and magenta. The location and dominant wavelength of each of these six CC series are shown on the chromaticity diagram in Fig. 5. The three remaining test spots on a hued slide were given zero saturation with neutral filters, and had luminosities approximately equal to that of the hued spot. Hence, with the hued slides the image format presented four test spots of approximately equal luminosity, one of which had nonzero saturation with one of the six hues, and three of which had zero saturation.

To construct the test slides, a piece of brass shimstock was cut to fit a standard 3¼-by-4-in. lantern-slide glass binder. The shimstock was then drilled with four holes whose size and location rendered

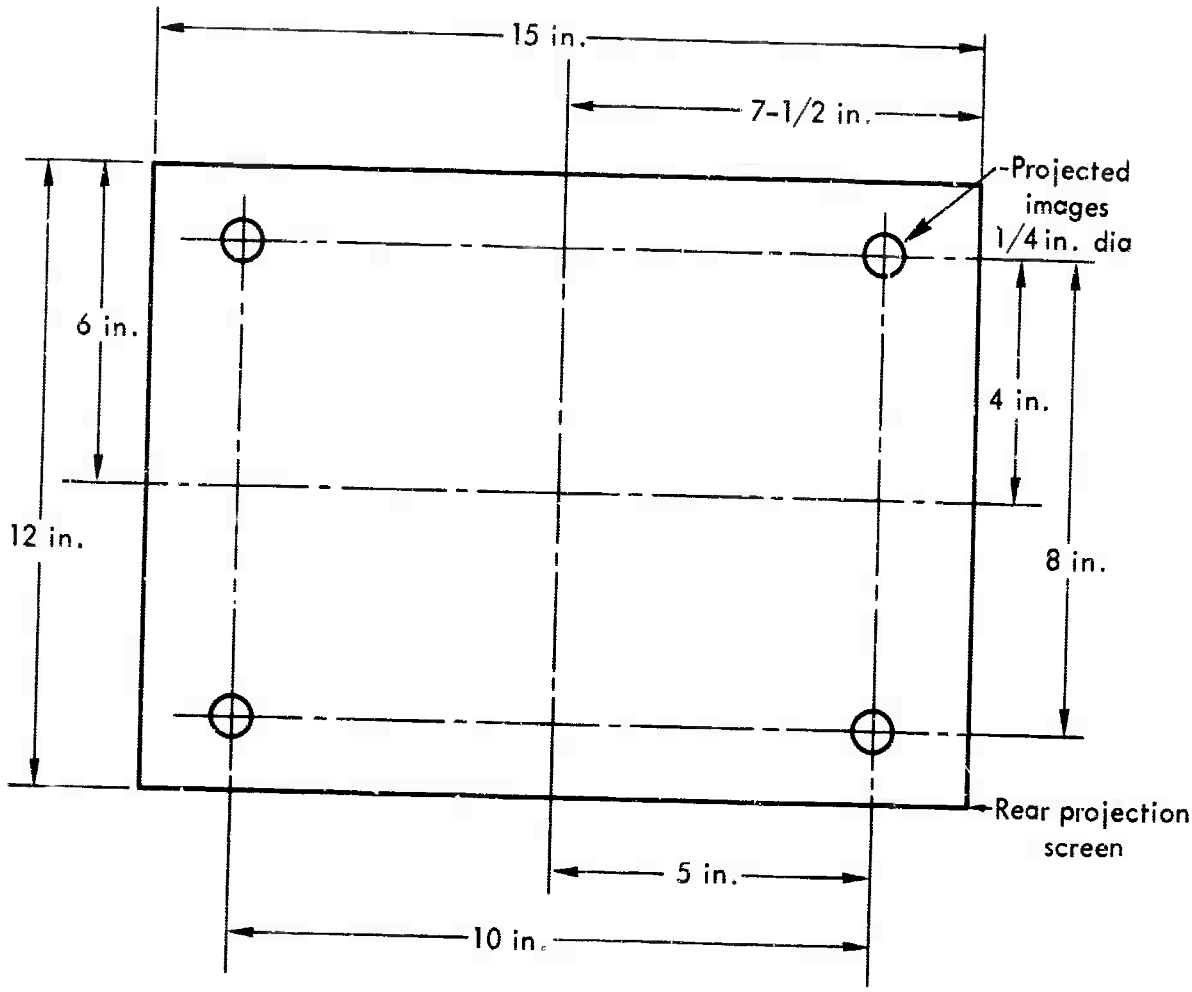


Fig. 4—Image format as seen by the observer

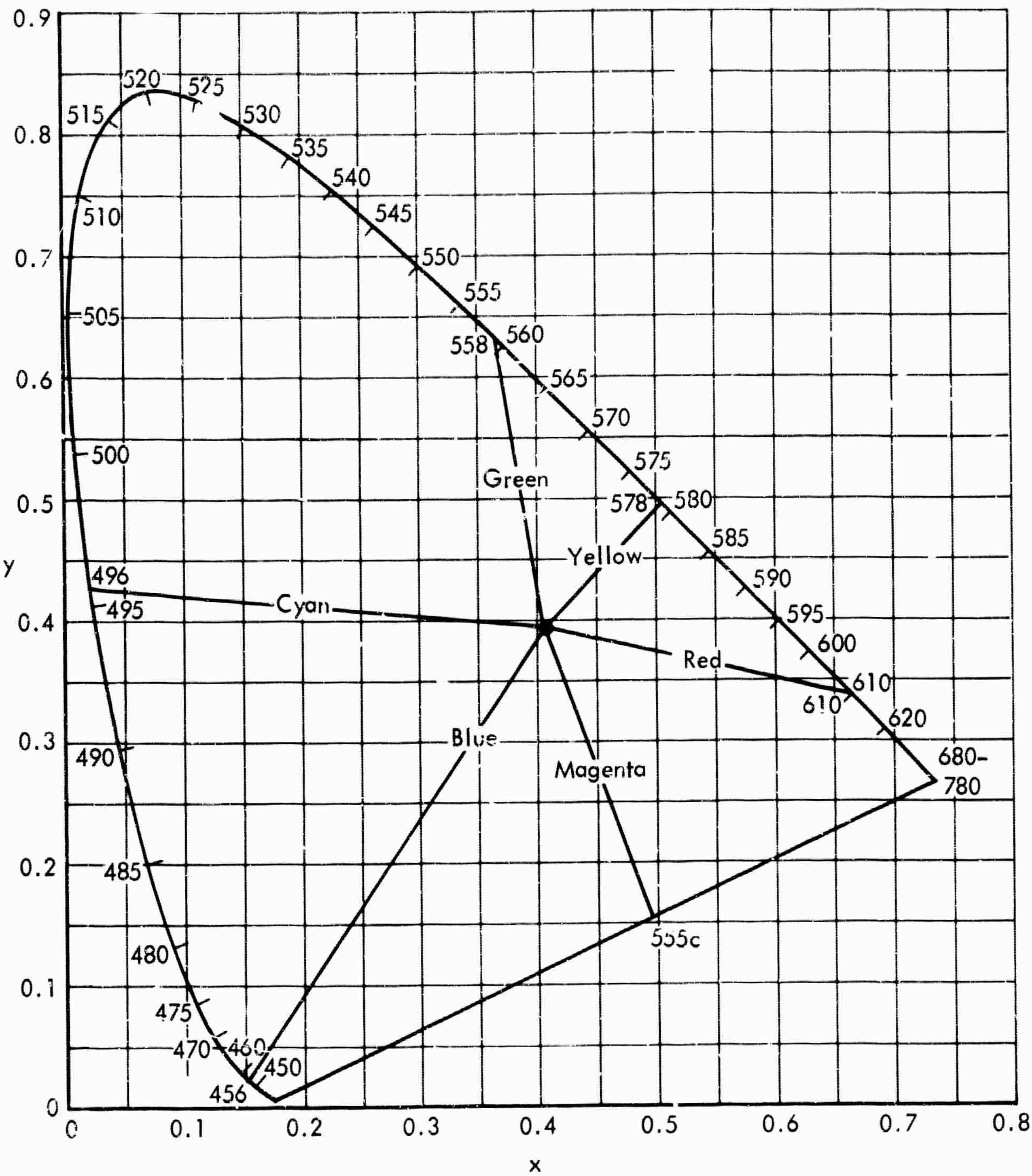


Fig. 5—Location of six test hue series on CIE chromaticity diagram

a projected image size and position as shown in Fig. 4. Small pieces of CC and ND gelatin filters were then cemented to the shimstock, covering the holes completely; care was taken to ensure that cement was kept clear of the holes. The shimstock was then sandwiched between two pieces of slide glass and the slide binder was assembled.

The Wratten CC filters are available in nominal saturations of 0.025, 0.050, 0.100, 0.200, and 0.300 for the red, yellow, cyan, and magenta hues, and in nominal saturations of 0.050, 0.100, 0.200, and 0.300 for the green and blue hues. Combinations were used to produce the smallest possible saturation steps in each hue series. The luminous transmittance to a 3200°K tungsten source of the CC filter combination used on the hued spot of each hued test slide was matched as closely as possible on the three nonhued spots by means of available Wratten ND filter combinations.

The filter combinations used, the chromaticities, and the luminous transmittances of all test slides are listed in Table 1. The percentage difference in luminous transmittance between the hued spot and the three neutral spots is given in the last column for each test slide. Also listed for each hued test spot is the actual length of the saturation vector measured from the achromatic point on the CIE diagram. The locations of these hued spots are shown on an enlarged portion of the CIE chromaticity diagram in Fig. 6.

Chromaticity data were computed for the CC filters from published transmission curves. Several of the filters were selected at random and subjected to actual spectrophotometric examination, and were found to be in excellent agreement with published transmission data. A computer program was written to facilitate reduction of the spectrophotometric data to chromaticity data.

Since the fabrication procedure for the test slides was restricted to available Wratten gelatin filters, the luminosity could not be held constant among the 62 test slides, although the control on each slide was generally satisfactory. Hence the range of slide spot luminances as seen by the observers was 105 to 160 foot-lamberts, i.e., 113 to 173 millilamberts. The resulting luminance range at the observer's eye was 13

Table 1

TEST-SLIDE DATA

Group No.	Slide No.	Hue	Vector Length	Chromaticity (x)	Chromaticity (y)	Colored Images Filters Used	Colored Images Luminosity	Neutral Images Filters Used	Neutral Images Luminosity	Difference in Luminous Transmittance of Colored and Neutral Images (%)
	1	Cyan	.0028	.4139	.3973	.025 C	.9123	.05 ND	.9160	0.40
	2	Magenta	.0041	.4187	.3931	.025 M	.8980	.05 NO	.9160	1.97
I	3	Neutral	0	.4167	.3967	--	--	.05 NO	.9160	--
	4	Red	.0043	.4209	.3957	.025 R	.8963	.05 ND	.9160	2.15
	5	Yellow	.0046	.4198	.4001	.025 Y	.9285	.05 NO	.9160	1.37
	6	Red	.0086	.4251	.3947	.05 R	.8428	2(.05)ND	.8390	.45
	7	Cyan	.0057	.4111	.3978	.05 C	.8753	.05 ND	.9160	4.45
II	8	Yellow	.0092	.4229	.4035	.05 Y	.9073	.05 ND	.9160	1.06
	9	Neutral	0	.4167	.3967	--	--	.05 ND	.9160	--
	10	Blue	.0059	.4132	.3919	.05 B	.8260	2(.05)NO	.8390	1.55
	11	Magenta	.0082	.4206	.3895	.05 M	.8460	2(.05)NO	.8390	.84
	12	Green	.0067	.4147	.4031	.05 G	.8688	.05 NO	.9160	5.15
	13	Yellow	.0127	.4251	.4063	.05 Y + .025 Y	.8437	2(.05)NO	.8390	.56
	14	Cyan	.0093	.4075	.3980	.05 C + .025 C	.8140	2(.05)ND	.8390	2.98
III	15	Red	.0130	.4295	.3941	.05 R + .025 R	.7838	.10 ND	.7950	1.41
	16	Neutral	0	.4167	.3967	--	--	2(.05)ND	.8390	--
	17	Magenta	.0125	.4221	.3855	.05 M + .025 M	.7867	.10 ND	.7950	1.04
	18	Cyan	.0129	.4039	.3982	.10 C	.8408	2(.05)ND	.8390	.22
	19	Blue	.0142	.4080	.3855	.10 B	.7506	.10 ND + .05 NO	.7282	3.08
	20	Neutral	0	.4167	.3967	--	--	2(.05)NO	.8390	--
IV	21	Green	.0129	.4154	.4095	.10 G	.8439	2(.05)ND	.8390	.58
	22	Red	.0174	.4338	.3935	.10 R	.7815	.10 NO	.7950	1.70
	23	Yellow	.0162	.4272	.4090	.10 Y	.9057	.05 ND	.9160	1.12
	24	Magenta	.0168	.4236	.3814	.10 M	.7865	.10 ND	.7950	1.07
	25	Cyan	.0155	.4013	.3986	.10 C + .025 C	.7819	.10 ND	.7950	1.65
	26	Yellow	.0203	.4302	.4119	.10 Y + .025 Y	.8423	2(.05)ND	.8390	.39
V	27	Neutral	0	.4167	.3967	--	--	.10 ND	.7950	--
	28	Red	.0220	.4383	.3923	.10 R + .025 R	.7267	.10 ND + .05 NO	.7282	.21
	29	Magenta	.0209	.4257	.3779	.10 M + .025 M	.7314	.10 ND + .05 NO	.7282	.44
	30	Blue	.0204	.4045	.3803	.10 B + .05 B	.6207	.20 ND	.6300	1.48
	31	Red	.0267	.4428	.3911	.10 R + .05 R	.6612	.10 ND + 2(.05)NO	.6670	.87
	32	Magenta	.0250	.4278	.3743	.10 M + .05 M	.6678	.10 ND + 2(.05)ND	.6670	.12
VI	33	Cyan	.0181	.3987	.3990	.10 C + .05 C	.7372	.10 ND + .05 NO	.7282	1.24
	34	Neutral	0	.4167	.3967	--	--	.10 ND	.7950	-
	35	Green	.0193	.4135	.4157	.10 G + .05 G	.7343	.10 ND + .05 ND	.7282	.84
	36	Yellow	.0244	.4331	.4147	.10 Y + .05 Y	.8225	2(.05)ND	.8390	1.97
	37	Cyan	.0224	.3944	.3985	.10 C + .05 C + .025 C	.6856	.10 ND + .05 NO	.7282	5.66
	38	Yellow	.0274	.4347	.4174	.10 Y + .05 Y + .025 Y	.7649	2(.05)ND	.8390	8.85
VII	39	Neutral	0	.4167	.3967	--	--	.10 ND + .05 ND	.7282	--
	40	Magenta	.0288	.4281	.3702	.10 M + .05 M + .025 M	.6210	.10 ND + 2(.05)NO	.6670	6.90
	41	Red	.0306	.446[illegible]	.3898	.10 R + .05 R + .025 R	.6149	.10 ND + 2(.05)NO	.6670	7.81
	42	Red	.0346	.4503	.3884	.20 R	.6727	.10 ND + 2(.05)ND	.6670	.85
	4[illegible]	Blue	.0307	.3988	.3717	.20 B	.6159	.20 ND	.6300	2.24
VIII	[illegible]	Neutral	0	.4167	.3967	--	--	.10 ND	.7950	--
		Cyan	.0267	.3900	.3980	.20 C	.7703	.10 ND	.7950	3.11
		Magenta	.0327	.4283	.3661	.20 M	.6834	.15 ND + 2(.05)ND	.6670	2.46
		Yellow	.0305	.4363	.4201	.20 Y	.9002	.05 ND	.9160	1.73
	4[illegible]	Green	.0281	.4103	.4241	.20 G	.7677	.10 ND	.7950	3.44

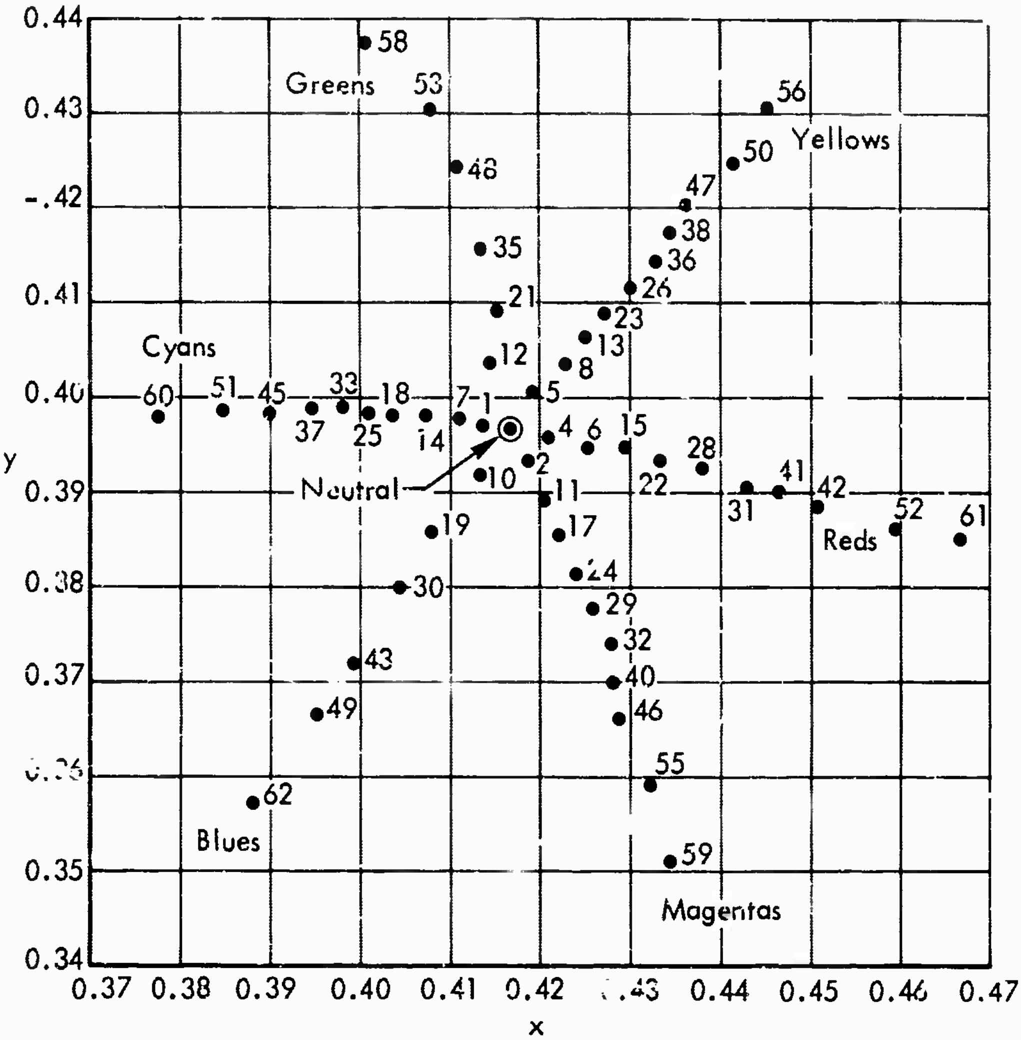


Fig.6—Enlarged portion of chromaticity diagram showing coordinates of test slides

to 19 mL. These values were calculated by multiplying the screen illuminance of 170 foot-candles by the individual spot luminous transmittances listed in Table 1. The rear-projection screen is essentially a perfect diffuser at near normal view. The range in slide transmittance was 0.62 to 0.93. Luminosity effects on the subject test data are considered in Section V.

III. PROCEDURE

SUBJECTS

Most of the subjects were selected from a group of volunteers from the professional staff at RAND. In addition, some children were included in the test to extend the age group of test subjects to a range of 10--45 years. Four of the subjects were involved in other phases of the color discrimination study, and thus had a professional interest in the results. The remainder of the subjects had only a general interest in color and color vision, and were not experienced test subjects. A total of 39 subjects completed the test series.

Several standard clinical tests were given to prospective subjects in order to select a group that was fairly uniform with regard to binocular perception:

1. Ishihara Pseudo-Isochromatic Test. Each subject was given the Ishihara test under the conditions of low illumination to be used in the final experimental environment. If four or more of the 12 test plates were missed, the person was eliminated as a test subject.
2. Howard Vocational Test Chart. Visual acuity for near vision was tested both binocularly and monocularly using the Howard Vocational Test Chart. The chart was viewed at a distance of 32 inches under the same illumination as that to be used in the test environment. Only subjects with a (corrected) acuity of 20/30 or better in each eye were selected.
3. Vectoluminator (Polaroid 3-D) and Cheiroscope. These were used to test near vision for fusion, suppression, and simultaneous binocular perception. Subjects who did not pass were eliminated from further testing.

After finishing the color discrimination experiment, each subject was given a written questionnaire concerning his subjective impressions about the test, his methods of deciding upon responses, and his personal interest in color or vision, all of which might have affected his performance on the test. The questionnaire was scored to provide several indices which were subsequently correlated to the subject's color-discrimination performance. The questionnaire and scoring procedure are reproduced in Appendix I.

PRE-TEST INSTRUCTIONS

The subject was seated before the display apparatus and instructed to assume a comfortable position. No restrictions on body movement were mentioned except that the subject was to remain seated and was not to lean forward. The subject was instructed to inform the experimenter if at any time during the test he became uncomfortable.

The experimenter explained that he would project on the screen a series of slides on which four spots of lights arranged in a rectangular format would appear. One of the spots might appear different in color from the others. If so, the subject was to call out the position of the one different spot -- whether upper right, upper left, lower right, or lower left -- and the next slide would be shown. If no difference could be detected, the subject was to respond by saying "no difference," and the test would proceed. If no response was made within 10 seconds, the experimenter would assume that no difference could be detected and would proceed to the next slide. Several sample slides in which there were obvious color differences were then displayed to the subject to ensure that he understood the procedure.

It was emphasized to the subject that he was not required to recognize or name a particular color, but merely to detect a color difference between one spot and the other three. He was told that each slide would appear for only 10 seconds, and that he should call out his first impression without repeated study of the images. He was asked not to guess, but to indicate any difference that he perceived, no matter how slight. The experimenter made no comment on the correctness of the responses.

In response to recent pleas[5] for more complete reporting on pre-test instructions to the subjects, the instructions used in the present investigation are reproduced in full in Appendix II.

TEST METHOD

The ability of the 39 subjects to discriminate saturation differences was measured by the method of constant stimulus difference. This method has been recommended by Siegel[6] as the best psychophysical procedure for color discrimination investigations. The method of constant stimulus difference requires the use of a random series of fixed stimuli. Each observation leads to a judgment and each judgment is completely independent of the others. The observer is given no clue about the hue of the next stimulus presentation. Hence there is less chance for errors of anticipation and habituation to distort the observer's response criteria.

An additional requirement of the method of constant stimulus difference is that a minimum range of correct response frequencies from 15 percent to 85 percent be included in the series. The inclusion of these end points serves to anchor the observer's judgments and reinforce his criteria.[6] The JND in saturation is arbitrarily defined as the saturation difference for the 50-percent point on a plot of frequency of correct response versus saturation difference.

The presentation sequences of the test-slides are shown in Fig. 7, which is a reproduction of the data sheet used in the investigation. Four sequences (A,B,C,D) were used for each subject. The first half of each sequence (A1,B1,C1,D1) began with slide number 1 and proceeded in ascending order until a saturation group was reached for which the subject responded correctly to all hued slides. The sequence was then reversed and the slides were presented in descending order, terminating with slide number 1 for the second half of each sequence (A2,B2,C2,D2). Although ten saturation groups totaling 62 slides were available, it was generally necessary to use only the first eight groups, totaling 48 slides. Hence each subject made a total of at least 384 decisions. The entire test generally took about one hour for each subject. It was found that this was best broken into two half-hour sessions to avoid subject fatigue or boredom.

As can be seen in Fig. 7, the hue sequence and location of the dummy in each saturation group were randomized. The locations of the

Slide no.	Filter group	KEY	A1	A2	KEY	B1	B2	KEY	C1	C2	KEY	D1	D2	Score
		POSITION OF SLIDE IN PROJECTOR												
I. 1	.025 C	UR			LL			LR			UL			
2	M	LR			UL			UR			LL			
3	dummy	--			--			--			--			-
4	R	LL			UR			UL			LR			
5	Y	UL			LR			LL			UR			
II. 6	.050 R	LL			UR			UL			LR			
7	C	LR			UL			UR			LL			
8	Y	UL			LR			LL			UR			
9	dummy	--			--			--			--			
10	B	UR			LL			LR			UL			
11	M	UL			LR			LL			UR			
12	G	UR			LL			LR			UL			
III. 13	.075 Y	LL			UR			UL			LR			
14	C	UR			LL			LR			UL			
15	R	LR			UL			UR			LL			
16	dummy	--			--			--			--			-
17	M	UR			LL			LR			UL			
IV. 18	.100 C	UR			LL			LR			UL			
19	B	LR			UL			UR			LL			
20	dummy	--			--			--			--			-
21	G	LL			UR			UL			LR			
22	R	UL			LR			LL			UR			
23	Y	LL			UR			UL			LR			
24	M	LR			UL			UR			LL			
V. 25	.125 C	UL			LR			LL			UR			
26	Y	LR			UL			UR			LL			
27	dummy	--			--			--			--			-
28	R	LL			UR			UL			LR			
29	M	UR			LL			LR			UL			
VI. 30	.150 B	UR			LL			LR			UL			
31	R	UR			LL			LR			UL			
32	M	LR			UL			UR			LL			
33	C	LL			UR			UL			LR			
34	dummy	--			--			--			--			-
35	G	UL			LR			LL			UR			
36	Y	LR			UL			UR			LL			
VII. 37	.175 C	UL			LR			LL			UR			
38	Y	LL			UR			UL			LR			
39	dummy	--			--			--			--			-
40	M	LL			UR			UL			LR			
41	R	UL			LR			LL			UR			
VIII. 42	.200 R	LR			UL			UR			LL			
43	B	LL			UR			UL			LR			
44	dummy	--			--			--			--			
45	C	UR			LL			LR			UL			
46	M	UL			LR			LL			UR			
47	Y	UL			LR			LL			UR			
48	G	LL			UR			UL			LR			
IX. 49	.250 B	UL			LR			LL			UR			
50	Y	UR			LL			LR			UL			
51	C	LL			UR			UL			LR			
52	R	LR			UL			UR			LL			
53	G	LR			UL			UR			LL			
54	dummy	--			--			--			-			-
55	M	LL			UR			UL			LR			
X. 56	.300 Y	UR			LL			LR			UL			
57	dummy	--			--			--			--			
58	G	LR			UL			UR			LL			
59	M	UL			LR			LL			UR			
60	C	LL			UR			UL			LR			
61	R	UR			LL			LR			UL			
62	B	UL			LR			LL			UR			

SUBJECT'S NAME______________________

SEX______ AGE______ RACE__________

BINOCULAR VISION_____ LIGHT SENSITIVE_____

GENERAL HEALTH______________________

EYE HEALTH: R_______________________

L_______________________

EYE PATHOLOGY: CAT.____, GLAUCOMA_____, _____

Rx: 1. NONE__________ PDis__________mm

2. SV const.___,far_____,near___,tinted__

3. Bifocal_______, tinted__________

4. Contact lenses_______, hrs/day____tint___

5. Sunglasses______; plano_____, Rx______

6. no. years subject worn Rx (_) ________

TESTS:

VA thru(no)Rx: OU-PR_______, illum.____fc

OU-PP(32, 36, 42)__________, illum.____fc

____

2. COLOR:

a) AC Pseudo-Isochromatic Plates (26)______

b) AC H-R-R Pseudo " " " " (24)______

c) AC Holmgren Wool Test (40 skeins)______

d) Farnsworth-Munsell 100 Hue Test (85 color chips)______

e) Farnsworth D-15 Test (16 " ")______

f) Color Aptitude Test (98) " ")______

g) Eldridge Lantern Test( )______

h) Anomaloscope (Nagel) ( )______

____

Illum. ( )______fc, ( )______fc

3. EYE-HAND DOMINANCY:

a) Eye (R/G, pen)________________

b) Hand________________

4. COLOR IDENTIFICATION:

a) Slide_____: dom. λ_{AC}, R (610/604)______

B (479/458)______

G (555/553)______

Y (582/572)______

M (535c/541c)______

C (500/489)______

b) Slide_____: ______________________

5. COLOR FATIGUE:

____

6. VISUAL FATIGUE:

____

Fig. 7 — Data sheet for JND tests

hued spots were changed in each of the four sequences so that a given test spot appeared in all four possible locations in a complete test series.

The sequences used effectively satisfied the condition of random presentation of saturation-differences for each hue required by the method of constant stimulus difference. This resulted from three factors: (1) the subjects were unaware of the ascending/descending order in saturation differences, (2) the six different hues, each with a different JND, were handled simultaneously, and (3) the frequent inclusion of the dummy slides reinforced the subject's awareness of low-saturation slides. The joint result of these factors was an effectively random presentation so far as the subject was concerned.

The validity of this procedure is confirmed by an analysis of the responses to the dummy slides. If a subject is aware of an ascending order of saturation differences, he will readily identify the dummy slides as such in the high-saturation groups. Calling a hued response to a dummy slide a "guess," one would thus expect a substantial decrease in the number of guesses for the high-saturation groups. The data did not indicate that this occurred. Table 2 presents the number of guesses on the dummy slides by saturation group and by response location for each of the 39 subjects. With few exceptions (notably Subjects 9, 12, 13, 32) there is no significant decrease in guessing rate with increasing saturation. This conclusion was verified statistically by applying a T^2 test. Hence, despite a wide intersubject variation in tendency to guess, the guessing rate of each subject was sensibly constant over saturation groups. This result verifies the effectiveness of the procedure as a method of constant stimulus difference, and furthermore provides a means of correcting each subject's performance for the effects of guessing. The latter is discussed in the following section on Results.

Table 2

GUESSES: HUED RESPONSES TO DUMMY SLIDES

Subject	Guesses by Saturation Group									Guesses by Location			
	I	II	III	IV	V	VI	VII	VIII	Total	UL	UR	LR	LL
1	4	5	2	3	2	2	2	3	23	3	7	1	12
2	3	4	5	2	3	3	0	1	21	4	10	5	2
3	4	3	5	3	3	3	4	3	28	14	5	6	3
4	6	5	8	7	6	7	8	3	50	12	16	11	11
5	4	1	3	3	0	2	1	1	15	2	2	4	7
6	3	2	2	0	1	2	1	0	11	1	1	1	8
7	3	5	2	7	3	3	7	7	37	3	6	8	20
8	1	1	2	1	1	2	0	1	9	4	3	0	2
9	4	1	3	1	0	0	1	0	10	1	1	6	2
10	3	4	5	4	1	2	3	1	23	9	2	9	3
11	4	1	6	3	4	2	4	1	25	7	7	9	2
12	5	4	2	1	1	1	1	0	15	4	3	2	6
13	4	3	6	3	3	2	1	0	22	2	4	11	5
14	3	6	5	5	3	7	2	4	35	8	9	7	11
15	1	1	2	0	0	1	2	1	8	6	1	1	0
16	6	6	6	6	5	6	4	6	45	4	19	6	16
17	6	8	5	6	4	5	4	5	43	11	5	12	15
18	0	0	2	0	1	1	0	1	5	2	0	2	1
19	1	1	0	0	1	2	3	1	9	4	1	3	1
20	4	2	4	4	3	1	1	2	21	15	1	4	1
21	1	4	2	2	5	2	0	1	17	4	4	6	3
22	1	1	0	0	0	0	0	0	2	2	0	0	0
23	5	6	6	5	3	6	7	6	44	14	3	14	13
24	3	4	3	3	4	1	1	2	21	4	3	7	7
25	2	0	3	5	4	2	1	4	21	8	5	0	8
26	0	0	0	1	0	1	0	0	2	2	0	0	0
27	6	6	7	5	7	7	5	5	48	9	19	5	15
28	5	7	5	3	4	2	2	3	31	6	8	11	6
29	1	2	2	1	1	0	0	0	7	0	1	2	4
30	0	1	1	1	0	0	1	0	4	1	0	2	1
31	5	4	5	8	4	5	2	3	36	21	2	2	11
32	5	5	4	2	2	0	0	0	18	3	5	6	4
33	3	6	4	5	4	4	2	3	31	21	3	1	6
34	3	4	4	1	3	1	4	2	22	8	2	1	11
35	1	0	4	0	0	0	0	2	7	2	2	0	3
36	1	1	0	1	3	1	1	1	9	1	0	0	8
37	2	4	1	2	2	4	2	3	20	4	10	3	3
38	6	4	6	7	6	8	7	7	51	20	17	10	4
39	1	0	0	0	0	0	0	0	1	0	1	0	0
Totals:	120	122	132	111	97	98	84	83	847	246	188	178	235

IV. RESULTS

PRESENTATION OF DATA

The number of correct responses to the hued test slides is presented in Table 3 for each of the 39 subjects. As noted in the section on Procedure, each hued slide was presented a total of 8 times to each subject. Hence an entry of "8" in Table 3 indicate a correct-response frequency of unity.

Means and standard deviations of the correct-response frequencies for the 39-subject data are plotted in Figs. 8a--8f as a function of saturation vector length for the six hues red, yellow, green, cyan, blue, and magenta. The smooth curves faired through the mean data in each plot are typical of psychophysical frequency curves.

The standard deviations plotted in Fig. 8 are measures of the intersubject variability in saturation-discrimination ability, and are not indicative of experimental scatter. For example, from Fig. 8a the CIE vector length for JND toward the red is 0.0064 for the mean data. However, a curve faired through the mean $+\sigma$ points would give a JND of 0.0048, whereas one through the mean $-\sigma$ points would give 0.0084. This $\pm$ 30 percent variation in discrimination ability for a given hue indicates that for an operational display system, some selection procedure might be used to obtain a group of observers of reasonably uniform ability.

Correction for Guessing

The influence of one intersubject variable on the test results may be reduced by applying a correction procedure. This variable is the subject's tendency to guess the location of a hued spot when no differences are apparent to him among the four test spots. Since no penalty is assessed for incorrect responses, it is reasonable to assume that a subject who guesses frequently will be assigned an artificially high discrimination ability in the data leading to Fig. 8.

The effect of guessing may be removed from each subject's data by the following procedure. It was assumed for the high-saturation groups,

Table 3

NUMBER OF CORRECT RESPONSES TO HUED SLIDES

	Group I				Group II						Group III				Group IV					
Subject	R	Y	C	M	R	B	G	Y	C	M	R	Y	C	M	R	B	G	Y	C	M
1	2	0	1	3	7	4	4	0	3	8	8	5	4	8	8	7	8	4	7	8
2	5	2	1	5	8	4	5	2	6	8	8	5	5	8	8	7	8	8	8	8
3	4	0	2	5	7	3	4	2	1	8	8	3	1	8	8	7	8	4	7	8
4	4	2	1	6	5	4	4	2	1	8	8	5	3	8	8	7	6	6	5	8
5	1	0	0	1	5	4	1	0	0	7	7	2	4	8	8	5	7	3	5	8
6	3	1	1	4	7	2	3	1	0	7	8	3	1	8	8	7	8	7	6	8
7	1	2	2	2	5	1	5	2	2	6	8	2	2	8	8	6	7	3	4	8
8	0	1	0	3	6	1	4	1	0	8	8	0	4	8	8	8	8	4	7	8
9	2	2	4	3	5	3	5	3	3	8	8	4	5	8	8	8	8	8	4	8
10	2	3	1	5	8	4	6	3	5	8	8	7	7	8	8	7	6	7	8	8
11	2	2	0	4	5	2	4	3	4	7	7	4	1	6	8	3	7	6	3	8
12	0	0	0	2	3	2	1	1	3	6	3	4	1	5	3	6	5	5	4	7
13	3	0	1	2	3	0	1	2	4	5	7	1	4	8	8	7	4	5	5	8
14	3	3	3	5	6	4	3	1	2	8	8	6	1	8	8	6	6	6	5	8
15	3	0	0	3	7	1	2	1	5	7	8	0	3	8	8	8	8	4	7	8
16	6	3	3	6	6	1	3	4	4	7	8	3	7	8	8	1	8	4	8	8
17	3	1	0	5	7	8	2	4	3	8	8	6	2	8	8	8	8	8	6	8
18	3	0	0	2	6	2	3	1	3	7	8	7	4	8	8	8	6	7	6	8
19	3	0	0	3	7	1	4	2	0	8	8	5	2	8	8	7	8	7	5	8
20	2	0	2	3	7	3	3	1	1	8	8	1	5	8	8	8	7	5	7	8
21	3	3	1	3	6	0	5	3	4	7	7	4	5	7	8	1	6	6	6	8
22	1	0	0	1	5	1	1	0	0	5	6	1	1	7	7	3	2	3	2	8
23	2	3	1	4	4	2	3	3	3	8	8	8	1	8	8	7	8	8	5	8
24	2	0	3	1	7	0	3	1	0	6	7	3	2	8	8	6	7	6	5	8
25	4	2	1	3	6	3	4	0	2	5	7	2	1	8	8	8	5	5	5	8
26	0	0	1	0	2	1	3	0	2	4	[illegible]	0	2	6	6	2	3	1	2	8
27	1	0	1	1	6	5	4	2	4	8	7	4	3	8	8	5	7	5	6	8
28	4	1	4	5	5	3	2	1	2	6	8	3	1	8	7	7	3	5	1	8
29	0	0	1	1	3	1	1	0	0	6	5	3	0	7	7	1	5	3	2	7
30	1	1	1	4	7	0	1	2	1	4	6	1	1	7	7	5	4	1	4	8
31	2	0	0	6	7	3	1	4	3	8	8	4	2	8	8	6	6	2	6	8
32	1	0	2	3	8	2	4	2	2	8	8	2	5	8	8	8	8	4	8	8
33	3	3	4	4	8	4	3	4	5	8	7	4	5	8	8	8	7	6	8	8
34	1	2	1	2	3	2	1	1	1	7	7	3	2	8	8	5	6	3	5	8
35	1	0	1	0	3	0	0	1	0	2	3	0	0	5	4	5	2	4	1	8
36	1	1	0	1	6	3	2	1	1	8	7	1	0	8	8	4	7	3	2	8
37	1	2	3	4	7	4	5	4	4	8	8	3	2	8	8	7	8	8	7	8
38	3	3	2	4	7	2	3	4	3	8	8	5	3	8	8	7	7	8	4	8
39	1	0	0	0	5	0	3	1	1	8	8	2	1	7	7	3	6	3	3	8

	Group V				Group VI						Group VII				Group VIII						Group IX					
Subject	R	Y	C	M	R	B	G	Y	C	M	R	Y	C	M	R	B	G	Y	C	M	R	B	G	Y	C	M
1	8	6	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
2	8	8	8	8	8	8	8	6	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
3	8	6	6	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
4	8	7	1	8	8	8	8	6	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
5	8	5	6	8	8	8	8	7	7	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
6	8	8	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
7	8	6	6	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	7	8	-	-	-	-	-	-
8	8	5	5	8	8	8	8	8	8	8	8	7	8	8	8	8	8	8	6	8	-	-	-	-	-	-
9	8	8	8	8	8	8	8	3	7	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
10	7	6	8	8	8	8	8	7	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
11	8	7	7	8	8	8	8	7	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
12	6	4	4	8	8	8	5	6	6	8	8	8	5	8	8	8	7	7	7	8	8	8	8	8	6	8
13	7	0	5	8	8	6	8	7	5	8	8	7	7	8	8	7	8	8	8	8	-	-	-	-	-	-
14	8	7	7	8	8	8	7	8	5	8	8	8	5	8	8	8	8	8	6	8	8	8	8	8	7	8
15	8	5	6	8	8	7	8	8	7	8	8	7	8	8	8	8	8	8	8	8	-	-	-	-	-	-
16	8	4	8	8	8	6	8	4	8	8	8	5	8	8	8	7	8	8	8	8	-	-	-	-	-	-
17	8	7	7	8	8	8	8	7	7	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
18	8	7	7	8	8	8	8	8	7	8	8	8	7	8	8	8	8	8	8	8	-	-	-	-	-	-
19	8	6	5	8	8	8	8	8	6	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
20	8	5	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-	-	-	-	-	-	-
21	8	3	7	8	8	2	8	7	7	8	8	6	8	8	8	4	8	8	8	8	8	8	8	8	8	8
22	7	3	2	8	8	5	8	6	4	8	8	8	4	8	8	8	8	8	6	8	-	-	-	-	-	-
23	8	8	5	8	6	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
24	8	4	4	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
25	8	4	4	8	8	8	8	8	6	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
26	7	1	3	8	8	2	6	4	4	8	8	8	7	8	8	5	7	5	8	8	8	8	8	8	8	8
27	8	7	7	8	8	8	8	8	5	8	8	8	8	8	8	7	8	8	8	8	-	-	-	-	-	-
28	8	4	5	8	8	6	8	8	5	8	8	8	6	8	8	7	8	8	6	8	-	-	-	-	-	-
29	8	6	1	8	8	5	8	8	2	8	8	8	6	8	8	7	8	8	5	8	-	-	-	-	8	-
30	8	1	0	8	8	6	6	6	5	8	8	7	5	8	8	8	8	8	6	8	-	-	-	-	-	-
31	8	4	3	8	8	8	8	7	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
32	8	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
33	8	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
34	8	6	5	8	8	7	7	7	6	8	8	8	7	8	8	8	8	8	8	8	-	-	-	-	-	-
35	7	6	0	8	8	7	6	8	4	8	8	7	5	8	8	6	8	7	8	8	8	8	8	8	8	8
36	8	6	2	8	8	8	6	4	8	8	8	6	6	8	8	8	8	8	8	8	-	-	-	-	-	-
37	8	7	4	8	8	8	8	8	6	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
38	8	8	4	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	-	-	-	-	-	-
39	8	4	2	8	8	8	8	4	7	8	8	8	7	8	8	8	8	8	7	8	-	-	-	-	-	-

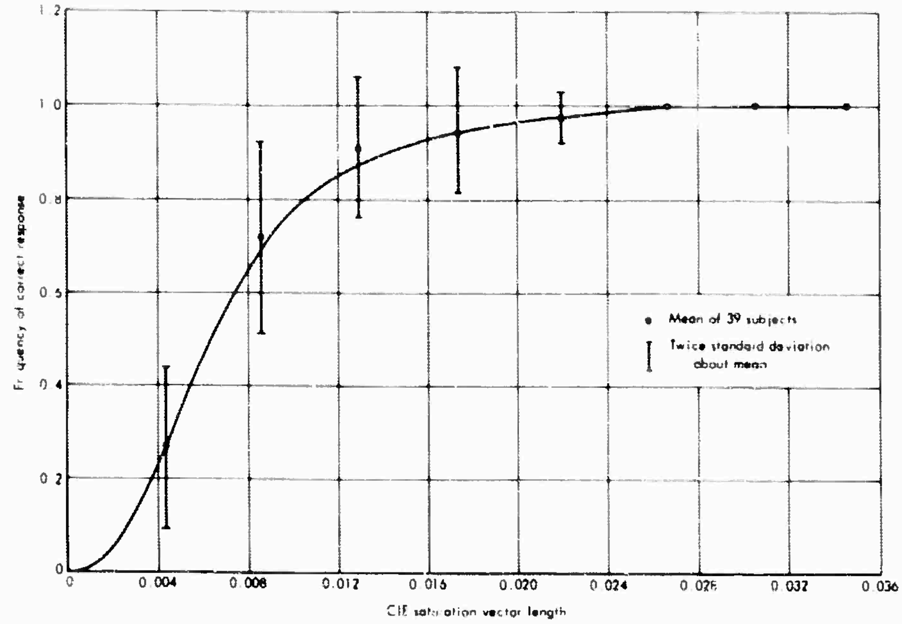


Fig. 8A — Experimental results for red (uncorrected data)

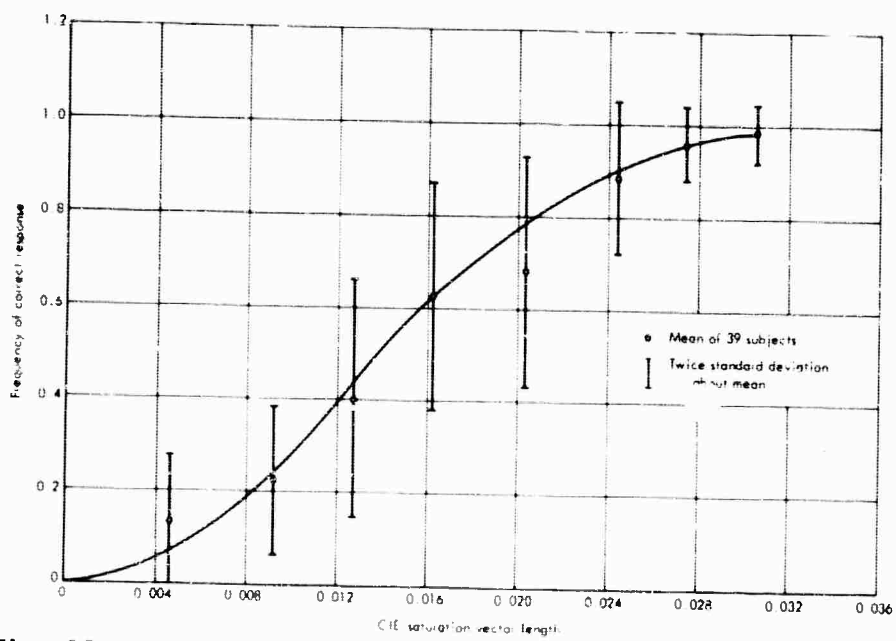


Fig. 8B — Experimental results for yellow (uncorrected data)

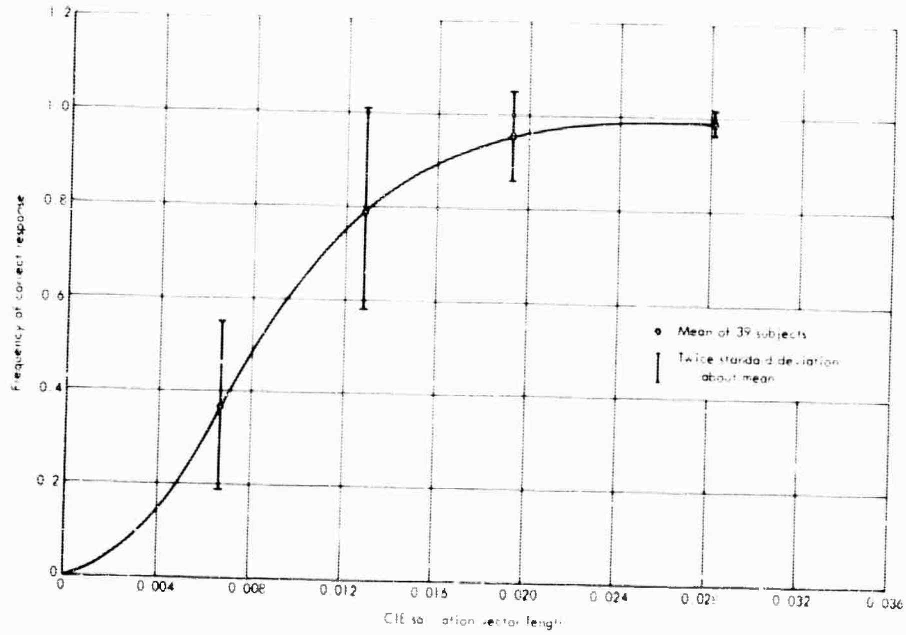


Fig. 8C — Experimental results for green (uncorrected data)

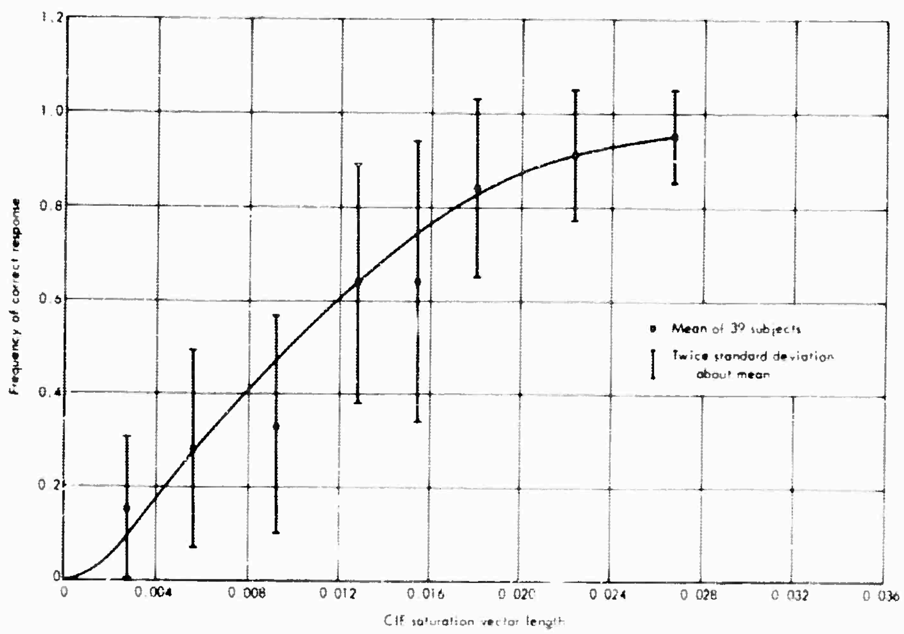


Fig. 8D — Experimental results for cyan (uncorrected data)

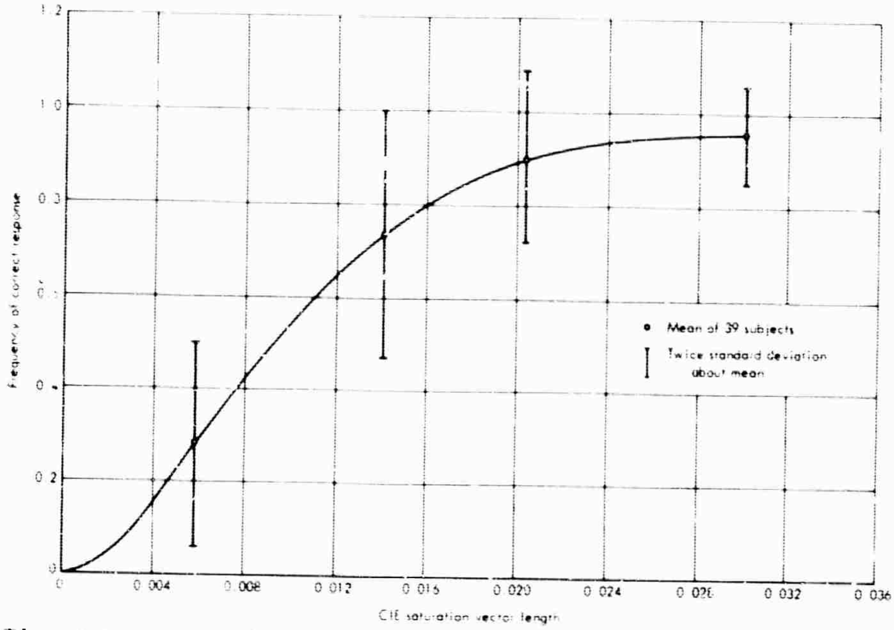


Fig. 8E — Experimental results for blue (uncorrected data)

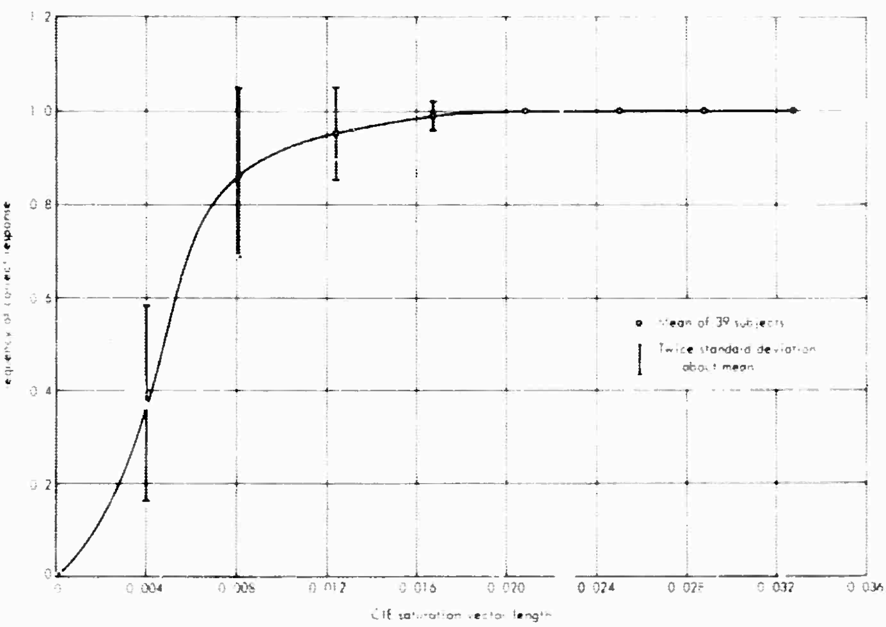


Fig. 8F — Experimental results for magenta (uncorrected data) where a subject always responded correctly to a hued slide, that the saturation difference was obvious to him and no guessing was involved. Hence no correction for guessing was applied to a subject's data for each hue at and above the saturation vector length for which a sustained correct-response frequency of unity was attained.

Next, it was assumed that the probability P_g that a subject would guess given that no spot appeared obviously different to him may be expressed by

$$P_g = \frac{\text{total hued responses to dummy slides}}{64} \qquad (3)$$

The quantity P_g was calculated for each subject using the dummy-slide data for saturation Groups I--VIII (64 dummy-slide presentations). Finally, it was assumed that the saturation vectors for Group I were far enough below the JNDs for each hue so that no spot in Group I slides appeared obviously different to the subject. Reference to Table 3 shows this to be a sound assumption, with the possible exception of magenta.

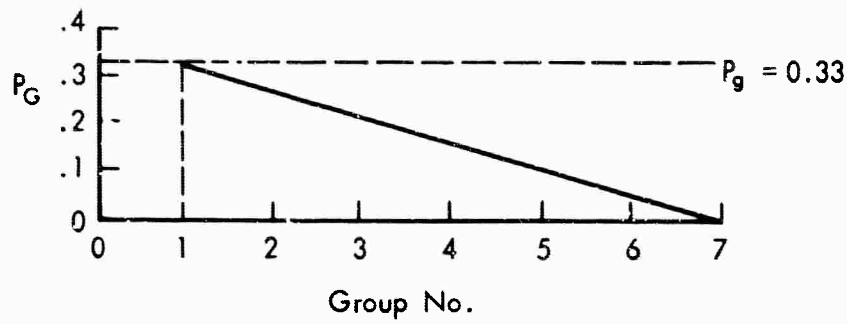
Now if P_G is the probability that a subject will guess when looking at a hued slide, 1/4 P_G is the probability of a correct guess. Hence, if P_c is his probability of a correct response, the probability P_D of a saturation discrimination is given by

$$P_D = P_c - \frac{1}{4} P_G \qquad (4)$$

where P_c is the frequency of correct response given by the uncorrected data of Table 3. Under the preceding assumptions, $P_G = P_g$ for Group I saturations and $P_G = 0$ at the first saturation group where sustained unity performance is attained for that hue. Linear interpolation yields P_G for intervening groups under the assumption that the number of non-obvious presentations decreases with increasing saturation. Each hue is treated separately for each subject.

As an example of the procedure, consider the following:

Subject #2
Hue: Yellow
No. of Dummy Guesses: 21 (Table 2)
Group at which $P_c = 1$: 7 (Table 3)



Use of Eq. (4) and Table 3 yields:

Group	P_c	P_G	P_D
I	0.25	0.33	0.17
II	0.25	.28	.18
III	0.625	.22	.57
IV	1.00	.16	.96
V	1.00	.11	.97
VI	0.75	.06	.74
VII	1.00	.00	1.00
VIII	1.00	.00	1.00

The data for all 39 subjects were corrected in this fashion to remove the effects of guessing.

Correlation Coefficients

The assumptions of the correction procedure for guessing, outlined above, receive additional corroboration from the post-test questionnaire analysis, the results of which are summarized in Table 4. The details of the scoring procedure used to obtain the tabulated values of the nine indices for the 32 subjects who completed the questionnaire are given in Appendix I. Also listed in Table 4 are the number of guesses (i.e., hued responses to dummy slides) and for each hue the saturation group at which incorrect responses to hued slides began. The latter may be

Table 4

SUMMARY OF POST-TEST QUESTIONNAIRE ANALYSIS

Subject	Vitae				Post-Test Questionnaire Indices									Saturation Group at which Errors Began							Dummy Guesses
	Age	Sex	Race	Eye Correction	Sys.	Adap.	Pig.	Crit.	Guess	Att.	Color	Fat.	Test	R	C	Y	B	M	G	Over-all	64 Max.
1	44	F	C	None	2	1	1	6	2	6	9	2	2	2	4	5	4	1	2	5	23
2	42	M	C	None	1	2	5	8	1	5	5	3	0	1	3	6	4	1	2	6	21
3	31	M	C	None	--	--	--	--	--	--	--	--	--	2	5	5	4	1	2	5	28
4	32	F	C	None	2	2	1	6	3	6	5	3	3	2	5	7	4	1	4	7	50
5	31	M	C	Single	0	2	4	5	2	6	6	2	0	3	6	6	4	2	4	6	15
6	34	M	C	None	0	0	3	3	4	3	3	1	1	2	5	4	4	2	2	5	11
7	46	M	C	Bifocal	2	2	4	6	1	7	5	2	1	2	8	5	4	2	4	8	37
8	35	M	M	None	1	1	5	5	1	5	3	3	0	2	5	7	2	1	2	7	9
9	40	M	C	None	0	0	1	7	1	10	8	0	4	2	6	3	2	1	2	6	10
10	44	M	C	Single	1	0	4	6	2	9	5	2	7	5	3	6	4	1	4	6	23
11	37	F	C	None	4	3	0	3	2	4	9	1	3	3	5	6	4	2	4	6	25
12	14	M	C	None	--	--	--	--	--	--	--	--	--	5	10	8	4	4	8	10	15
13	9	M	C	Single	--	--	--	--	--	--	--	--	--	5	7	7	8	2	4	8	22
14	29	M	N	None	--	--	--	--	--	--	--	--	--	2	9	5	4	1	6	9	35
15	32	M	C	Single	1	2	4	5	2	3	4	1	2	2	6	7	6	2	2	7	8
16	36	M	C	Blind[a]	1	1	4	2	5	6	8	2	3	2	3	7	8	2	2	8	45
17	16	M	C	None	1	0	1	4	2	4	4	1	0	2	6	5	1	1	2	6	43
18	29	M	C	Single	0	2	3	4	4	5	7	5	3	2	7	5	2	2	4	7	5
19	33	M	C	Single	0	1	4	3	2	3	3	4	[illegible]	2	6	5	4	1	2	6	10
20	30	F	C	Contact	0	2	2	2	5	8	5	1	5	2	4	5	2	1	4	[illegible]	21
21	41	M	C	Single	2	0	2	4	3	5	8	0	4	3	6	7	8	3	4	8	17
22	36	M	C	None	3	1	2	6	2	6	5	1	4	5	8	6	6	3	4	8	2
23	45	M	C	Single	1	0	4	3	6	9	7	1	3	2	5	2	4	1	2	5	44
24	20	M	C	None	0	0	3	9	1	8	6	2	2	3	5	5	4	2	4	5	21
25	31	M	C	Single	1	2	2	2	4	5	5	4	1	3	6	5	2	2	4	6	16
26	35	M	C	Single	2	1	2	9	1	5	6	3	7	5	7	8	8	3	8	8	2
27	23	M	C	Single	1	2	2	7	3	5	5	1	0	3	6	5	8	1	4	8	48
28	9	M	C	None	--	--	--	--	--	--	--	--	--	4	8	5	8	2	4	8	31
29	25	F	C	Single	1	2	3	5	2	7	7	0	0	4	8	5	8	4	4	8	7
30	22	F	N	None	1	2	5	7	1	2	4	1	0	4	8	7	6	3	6	8	4
31	12	M	C	Single	1	1	3	7	3	3	4	5	3	2	5	6	4	1	4	6	35
32	26	F	C	None	0	3	2	6	3	6	6	4	2	1	3	4	2	1	2	4	18
33	25	M	C	Single	--	--	--	--	--	--	--	--	--	3	5	5	2	1	4	5	31
34	23	F	C	None	3	1	2	6	2	4	6	4	2	3	7	6	6	2	6	6	22
35	26	M	C	None	0	0	3	9	0	7	4	2	1	5	7	8	8	3	6	8	7
36	20	F	C	None	--	--	--	--	--	--	--	--	--	3	7	7	4	1	6	7	9
37	27	M	C	Single	0	1	3	5	2	6	7	3	0	2	6	5	4	1	2	6	20
38	30	F	M	Contact	0	0	5	4	2	7	4	0	2	2	5	3	4	1	4	5	51
39	37	M	C	Single	3	[illegible]	4	4	3	7	6	3	1	4	7	6	4	3	4	7	1
				Totals 32 Subjects	38	38	93	166	81	183	179	67	70								
Correlation Coefficients[b]				Scores vs. Y Group	0.28	0.17	0.052	0.35	-0.34	-0.41	-0.11	0.19	0.084								
				Scores vs. C Group				0.20	-0.30												
				Scores vs. Over-all Group	0.37	0.088	0.10	0.30	-0.24	-0.19	0.0	-0.15	-0.011								
				Scores vs. Number of Guesses				-0.18	0.32												

[a]Legally blind; color vision normal.

[b]Correlation between questionnaire indices and the test results as noted.

regarded as an inverse index of subject performance in the saturation discrimination task: The better a subject's performance, the lower the saturation group number at which a correct-response frequency of unity is attained.

The post-test questionnaire provides two indices of a subject's tendency to guess. The Guessing Index was designed as a direct measure of this tendency. The Criteria Index was designed to measure the severity of a subject's criteria for a hued response and is thus an inverse index of the guessing tendency. Correlation coefficients between the Criteria and Guessing Indices and subject performance measures are given in Table 4. Also shown are the correlations between the two indices and the number of dummy-slide guesses. All these correlations support the assumptions that guessing enhances performance and that the number of dummy guesses provides a probability measure of guessing rate.

Table 4 also presents correlation coefficients between the seven remaining questionnaire indices and subject performance measures. Of the seven, only two appear to have significant correlations: the Systemic Index and the Attitude Index. The former is a measure of possible general physiological influence (principally whether the subject is a smoker or is undergoing chemotherapy) and the correlations indicate possible performance degradation. The Attitude Index was designed to provide a direct measure of a subject's favorable attitude toward test participation, and the correlations indicate that the more favorably disposed subjects tend to perform better.

The distribution of the correlation coefficients by age-group and sex is given in Table 5. No significant variation occurs for these subgroups, and the comments of the preceding two paragraphs apply to the subgroup coefficients as well. Table 5 does indicate a possible significance for the Adaptive Index not apparent from Table 4; namely, that there is some performance degradation for those subjects who do not easily tolerate wide variations in illumination levels.

While no quantitative significance is attributed to the individual correlation coefficients listed in Tables 4 and 5, the pattern for the particular indices discussed above supports the data-handling procedures

Table 5

CORRELATION COEFFICIENTS BY AGE AND SEX

Mode of Comparison	Sys.	Adap.	Pig.	Crit.	Guess	Att.	Color	Fat.	Test
Scores Versus Over-all Group:									
Female (9)	.47	.069	.26	.32	-.46	-.43	-.14	-.34	-.57
Male (23)	.55	.31	-.11	.18	-.20	-.086	.13	-.090	.14
32 and under (17)	.41	.11	.13	.28	-.29	-.32	-.089	-.25	-.45
33 and over (15)	.35	.20	0.77	.17	-.23	-.057	0	.05	.19
All subjects (32)	.37	.088	.10	.30	-.24	-.19	0	-.15	-.011
Scores Versus Number of Guesses:									
Female (9)	--	--	--	-.20	.19	--	--	--	--
Male (23)	--	--	--	-.14	.38	--	--	--	--
32 and under (17)	--	--	--	-.035	.17	--	--	--	--
33 and over (15)	--	--	--	-.38	.51	--	--	--	--
All subjects (32)	--	--	--	-.18	.32	--	--	--	--

used herein and indicates the fruitfulness of devising suitable screening procedures for selecting observers in operational systems.

Summary of Results

Means and standard deviations of the discrimination probabilities P_D for the 39-subject data after correction for guessing are plotted in Figs. 9a--9f as a function of saturation vector length for the six hues red, yellow, green, cyan, blue, and magenta. The curves in Fig. 9 are smooth fits to the means. These curves are presented in a summary plot in Fig. 10 for intercomparison. The length of the group-mean JND saturation vector for each of the six hues may be read directly from Fig. 10 at $P_D = 0.50$.

The JND results presented in Figs. 9 and 10 may be summarized in the following table:

SUMMARY OF JND RESULTS FOR A STATIC DISPLAY

Hue	Mean JND	JND - σ	JND + σ
Magenta	0.0050	0.0044	0.0066
Red	.0069	.0056	.0088
Green	.0089	.0069	.0116
Blue	.0100	.0075	.0135
Cyan	.0105	.0088	.0148
Yellow	.0153	.0130	.0190

The entries in the above table are CIE vector lengths measured from the achromatic point ($x = 0.4167$, $y = 0.3967$) in the direction of the dominant wavelength of the appropriate hue. This format is more convenient for design calculations than a percent-saturation mode of expression.

It is evident from Fig. 9 that the determination of JNDs for the six hues is not uniformly precise. This is a direct consequence of restricting the test slide fabrication to the available Wratten CC filter series, as discussed in Section II. As a result, only the yellow, cyan, and possibly the red series have a sufficient number of properly spaced stimuli to provide high precision in the JND determinations. The green

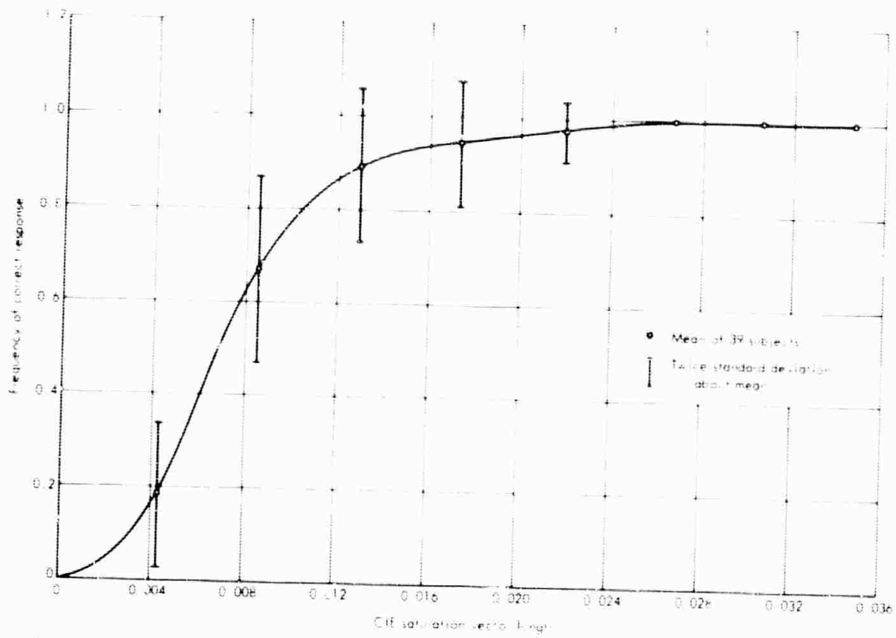


Fig. 9A — Experimental results for red (corrected for guessing)

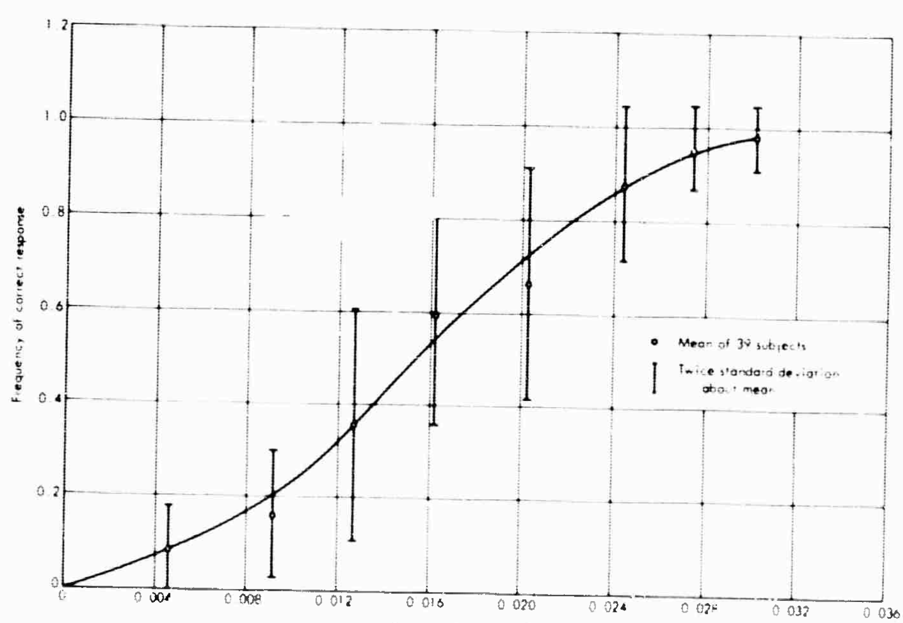


Fig. 9B — Experimental results for yellow (corrected for guessing)

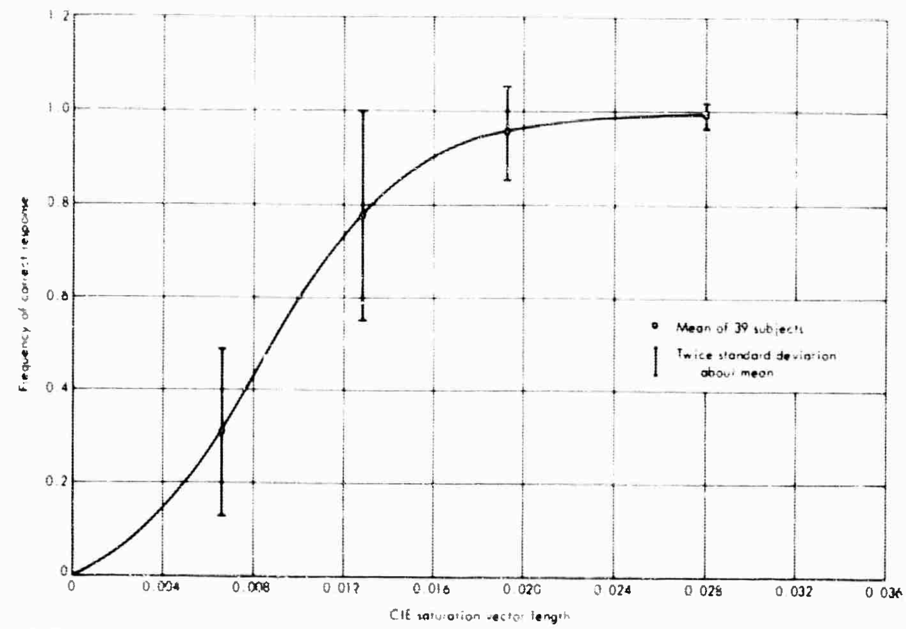


Fig. 9C — Experimental results for green (corrected for guessing)

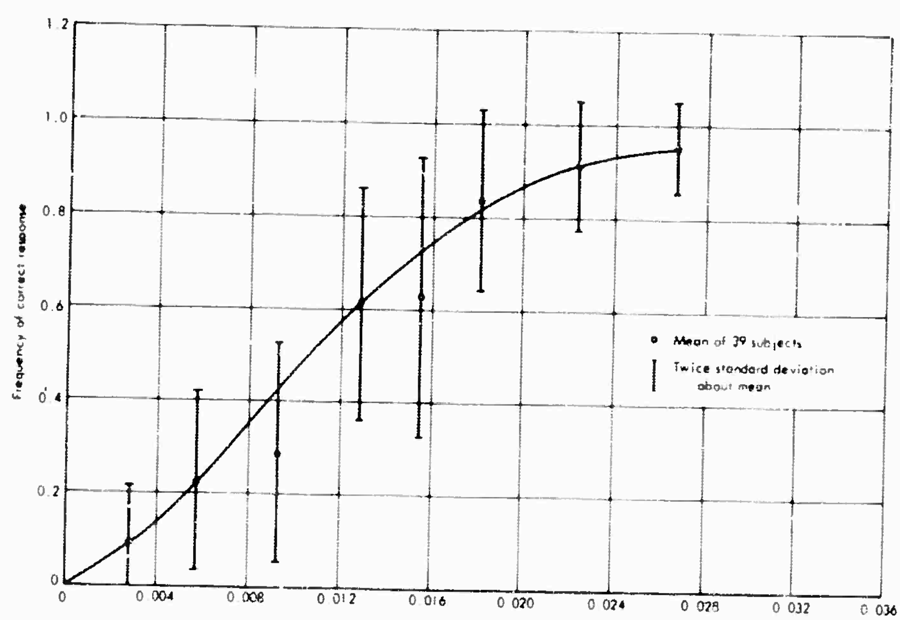


Fig. 9D — Experimental results for cyan (corrected for guessing)

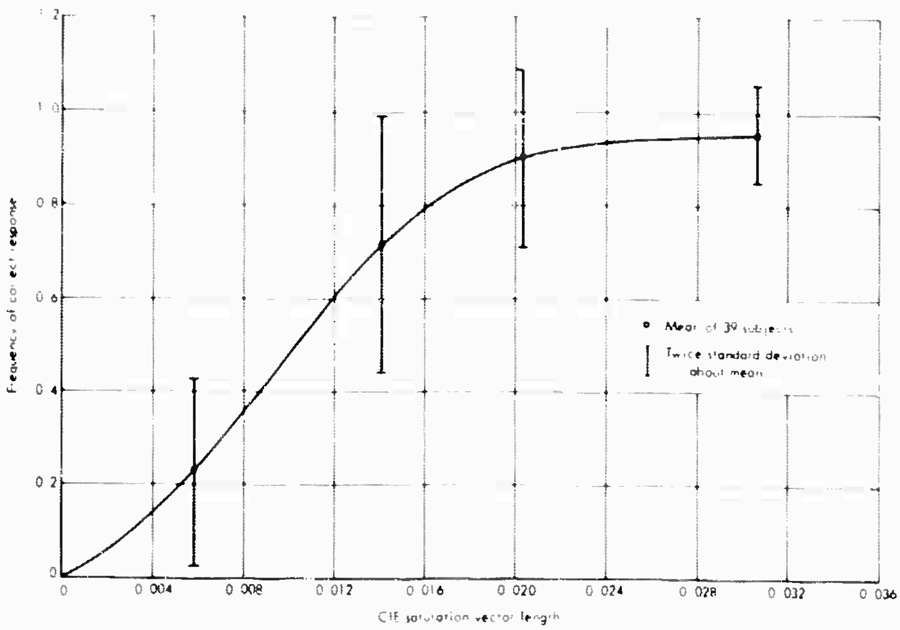


Fig. 9E — Experimental results for blue (corrected for guessing)

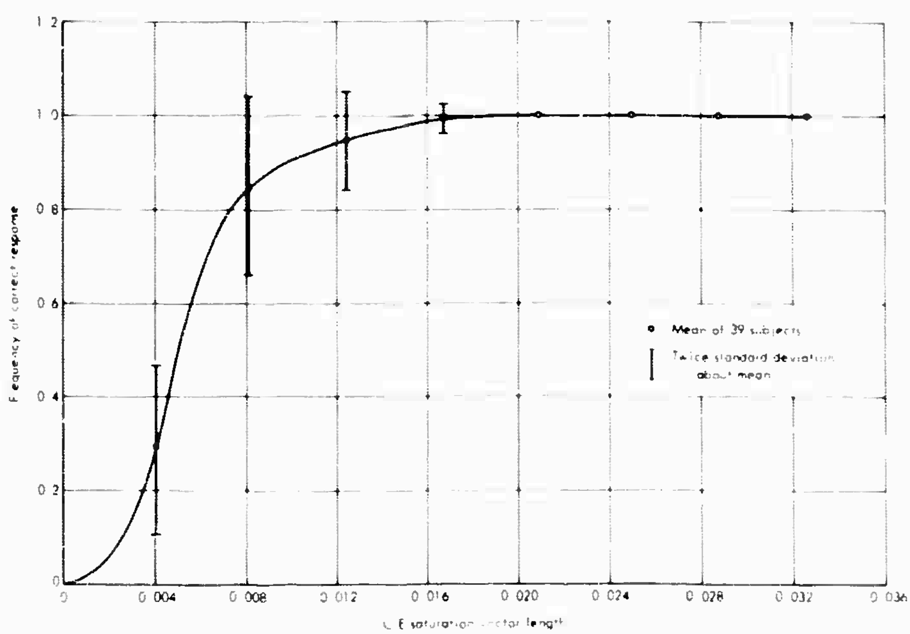


Fig. 9F — Experimental results for magenta (corrected for guessing)

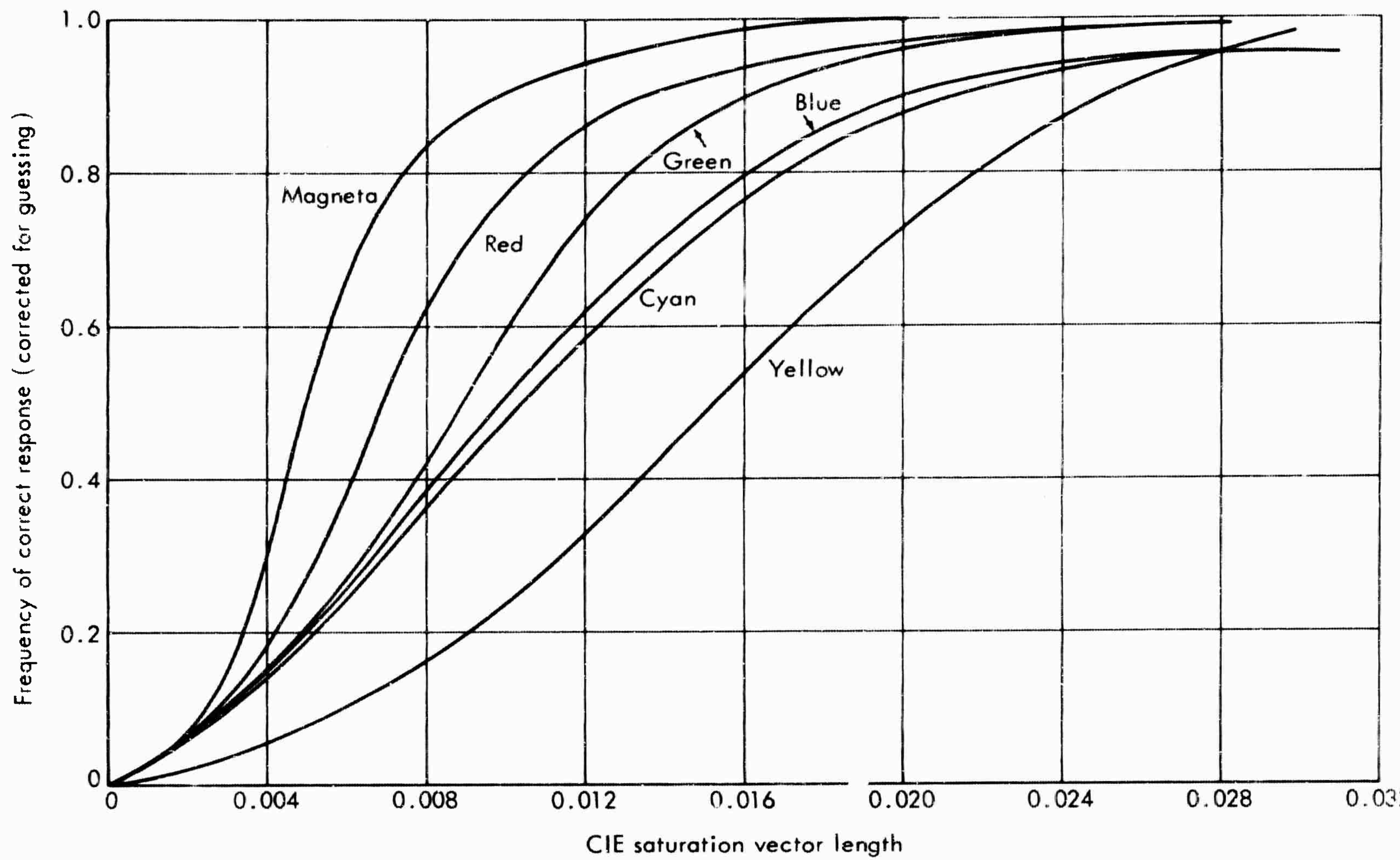


Fig. 10—Mean frequency curves for six hues

and blue series suffer from a lack of sufficient stimuli, though the stimuli used are properly spaced. Saturation discrimination is very sensitive for the magenta used, and this series suffers from a lack of sufficient short-vector-length stimuli.

The expense of fabricating special filters to correct the foregoing deficiencies was judged to be unwarranted for two reasons. First, an increased sophistication of stimulus spacing would be rather pointless unless accompanied by a more precise control of stimulus brightness and the subject's state of adaptation. Second, the data obtained with available filters are regarded as adequate to answer the experimental questions posed by this investigation, to wit: Can the MacAdam results be scaled to predict JNDs for the static display format; and if so, what are the appropriate scaling factors? The adequacy of the present results for design purposes is discussed in Section V.

FACTORS AFFECTING RESULTS

Brightness Variations

Two possible effects of brightness variation on the test results must be considered. First, the brightness of the test spots decreased with increasing saturation group, as shown in Table 1, causing a variation in luminance at the observer's eye from about 13 to 19 mL for slides 1 through 48. Saturation JND has been shown to vary inversely with brightness level below about 1 mL,[7,8] but remains constant over the brightness range of 1 to 11 mL.[7] The latter range of data does not quite extend to the present case, but we note that the brightness JND behaves similarly to the saturation JND at low brightness levels, then remains constant from 1 to 100 mL.[9] This indicates that the saturation JND might also be constant at the higher brightness levels; on this basis, the brightness variation among the test slides would have had a negligible effect on the saturation JND results.

The second possible effect could be due to the brightness difference between the neutral spots and the colored spot on each individual test slide. The limitations of available materials precluded a precise luminosity match, and hence the colored spots always exhibited a brightness difference as well as a saturation difference when compared with the neutral spots. The percentage differences in luminosity are shown in the last column of Table I. Except for Group VII, where an error was made during fabrication, the luminosity differences are typically about 1 percent. Of the 40 hued slides, 26 have colored spots of lower luminosity than the neutrals, and 14 have colored spots of higher luminosity than the neutrals.

Walraven[8] has shown that the brightness JND is about 1 percent for a single test spot against an adjacent comparison field, with spot size and brightness level comparable to the conditions used in the present investigation. If the brightness discrimination mechanism were equally sensitive in the more complex display format used here, the luminosity differences noted above would have the effect of lowering the apparent saturation JND by increasing the discrimination probability P_D for the colored spots whose luminosity differs by 1 percent or more from their neutral reference spots. However, the data of Fig. 9 fail to exhibit such a correlation. The yellow series, Fig. 9b, and the cyan series, Fig. 9d, with their large JNDs, afford a good test of any significant intrusion of the brightness discrimination mechanism into the data. Examination of the first six data points (which determine the JNDs) in each of these two series for deviations from the smooth curves fails to support the possible brightness effect described above; some of the data points that should be "high" <u>are</u> "high," some are "low," and some are "unaffected."

Hence we conclude that the luminosity differences in the test slides were not large enough to significantly affect the saturation JND determinations. This result agrees with the implications of previous work,[2,8] where JNDs for combined brightness-saturation differences were plotted as regular ellipsoids about the comparison point. By analogy, the larger saturation JNDs for the more complex viewing conditions of the present investigation would be accompanied by larger brightness JNDs, and hence the brightness differences present in the test slides were subliminal.

It is important to note that this conclusion has design significance for display systems comparable to the one used in the present investigation, since it indicates that holding the brightnesses of multiple spots constant to within about 1 percent will not affect the interspot saturation JNDs in an operational system. This constitutes a substantial relaxation in brightness tolerance over that resulting from a direct application of the bipartite-field data.

Evidence of Learning

Since a complete test series for each subject consisted essentially of 8 replicated runs, a significant learning effect would be manifested by better performance on the eighth trial than on the first. The data do not exhibit any such correlation; hence it is concluded that there is no evidence for a learning effect in the present results.

Location of Achromatic Point

Sproson[10] has investigated subjective "white" under various conditions of daylight and tungsten illumination. He found that acceptable whites for most conditions lie within an ellipse on the CIE chromaticity diagram enclosing the blackbody curve from about 3000 to 4000°K. The reference achromatic (or "white") spot at 3200°K chosen for the present investigation lies well within this subjective "white" area.

Viewing Time

Siegel[11] has tested color discrimination ability as a function of viewing time using a bipartite field and trained observers. He found that performance improved with increased viewing time, but leveled off for viewing times of about 5 seconds. However, the standard deviation decreased with increased viewing time only up to about 1 second, and then began to increase again. Siegel concluded that an optimum viewing time for bipartite fields is about 0.2 sec, since performance did not change significantly for longer exposures.

Since in the present investigation the subjects were required to compare four separated spots, a longer viewing time would be required for optimum results. As discussed in Section III, a new slide was presented as soon as the subject made a respons or after 10 seconds viewing time if no response was made by then. Most responses were made in substantially less than the 10 sec allowed, and about 5 sec viewing time would appear to be adequate for the complexity of the display system used in the present tests. Differences not detected within this viewing time can be considered subliminal.

Spot Size

The effect of spot size on saturation JND for adjacent fields has been investigated by Walraven,[8] who found a small-field tritanopia effect for spot sizes less than about 1/3 to 1/2 deg of arc. Hence discrimination ability in the yellow-blue direction becomes progressively worse with decreasing diameter than that in the red-green direction. This indicates that test spots subtending less than 1/3 deg should not be used in display systems. On the other hand, an operational display system must be capable of handling a fairly large number of target spots without overlap within a total viewing field of about 20 deg, and hence the target spots cannot be substantially larger than 1/3 deg each. The present investigation used 1/3-deg spots, and the results should be applicable for target spots up to 1/2 deg. Although larger spots do not seem applicable to display systems comparable to ours, their corresponding saturation JNDs would probably differ from those reported herein. The tritanopic effect is discussed further in Section V.

Adaptation

The subjects were adequately dark-adapted before the tests to an ambient illumination of 2 foot-candles, the chromaticity of which was essentially that of the test achromatic point. The test screen surround was at ambient illumination. The controlling influence on any chromatic adaptation of the subjects during the test series was thus the test spots themselves. This is the most favorable adaptive condition for detecting chromaticity differences. An adaptive surround with a luminance comparable to that of the test spots could have a substantial effect on the JND in chromaticity, and caution should be used in applying the present results for a dark surround to such viewing situations.

V. DISCUSSION

COMPARISON WITH PREVIOUS INVESTIGATIONS

We know of no previous work that is directly comparable to the present investigation. However, there are three groups of published results that may be related to the RAND studies. The similarities and differences of these investigations will now be discussed in some detail.

The first group of related data is typified by the investigations of MacAdam[1] and Walraven[8] previously cited. Both used monocular viewing with an artificial pupil and the method of adjustment with adjacent comparison fields. One would expect that these test conditions would result in smaller JNDs than those found with the more complex viewing conditions of the RAND studies. Furthermore, MacAdam's target size of 2 deg would be expected to yield smaller JNDs than Walraven's smaller (23') target. Since the latter is comparable to the 20' targets used in our investigation, the principal distinction of Walraven's tests is their use of the more sensitive viewing conditions.

The results of Halsey and Chapanis,[12] which are typical of the second group of data, are from tests that involved color matching by comparison of an 18' central target of one hue with 170 other hues distributed over the CIE chromaticity diagram, each presented as an 18' target arrayed in a surround within a total viewing field of 35 deg. Binocular viewing with a natural pupil was employed. Confusion contours were drawn on the CIE chromaticity diagram for 58 of the targets, and various levels of confusion from 2.5 percent to 80 percent were determined. Subtracting the Halsey-Chapanis confusion levels from 100 percent yields frequency-of-correct-response measures for comparison with the present results. The more complex display system used by Halsey and Chapanis would be expected to yield larger JNDs than the RAND studies.

The third group of data related to the present investigation comes from tests involving the color naming of signal lights. Such tests have been performed by Holmes,[13,14] Hill,[15] McNicholas,[16] and Halsey.[17]

Typically, in this type of test a simulated signal light is flashed in a darkened room and the observer is required to name its hue from a list of possible hues plus white. Thus, although many of the test conditions differ from those of the RAND tests, the contour on the CIE chromaticity diagram that encloses the signals called "white" may be considered essentially the area where observers could not detect any of the given hues. Regarded as tests for saturation discrimination, the results would be expected to give the largest JNDs of all the investigations considered.

A summary of the test parameters for four of the above experiments selected as most relevant to the present investigation is shown in Table 6 along with the RAND test parameters for comparison. The listing in Table 6 is in order of expected decreasing sensitivity.

The results of the five investigations listed in Table 6 are plotted as frequency-of-correct-response versus CIE vector length in Fig. 11. MacAdam and Walraven published only their resultant JNDs (defined differently); hence their frequency curves cannot be drawn and these data appear as points in Fig. 11.

The Halsey and Chapanis curves in Fig. 11 were obtained from a transformation of their confusion-contour plots by drawing vectors in the directions of the dominant wavelengths of the RAND filters and reading the points of intersection of these vectors with the various confusion contours. This method is admittedly crude, both because their original data did not allow contours of equal accuracy to be determined in all directions on the CIE diagram, and also because their published figure is small. Hence, not too much credence can be placed in the exact shape of the Halsey and Chapanis curves presented in Fig. 11. However, taken as a group, the Halsey and Chapanis curves are similar to the RAND curves and yield larger JND values, as would be expected, considering the greater difficulty of the Halsey and Chapanis experiment.

The Holmes curves in Fig. 11 were obtained from his 90-and 50-percent contours for the recognition of white, treated as the 10- and 50-percent contours, respectively, for the recognition of a hue. The CIE

Table 6

COMPARISON OF TEST PARAMETERS FOR SEVERAL INVESTIGATORS

Viewing Condition	Investigator	Ref. and Fig.	Size (min of arc)	Target Luminance (millilamberts)	Duration	Comparison Object or Field	Background Brightness	Number of Observers	Psychophysical Method
Monocular, artificial pupil	MacAdam	Ref. 1, Fig. 36	120	15	Unlimited	Split field $x = .385$ $y = .393$	7.5 mL	1	Measured standard deviation with method of adjustment
	Walraven	Ref. 8, Fig. 38	23	~ 6 (500 trolands)	Unlimited	White field $2848^{\circ}K$ $x = .447$ $y = .407$	Same as comparison field	1	Method of adjustment using adjacent fields
Binocular, natural pupil	--	RAND (present results)	20	13--19	10 sec	3 separate spots at $3200^{\circ}K$ $x = .417$ $y = .397$	.024 mL	39	Measure of JND in chromaticity by method of constant stimulus difference
	Halsey and Chapanis	Ref. 12, Fig. 3, std. No. 85	18	2.7	Unlimited	170 color standards	.014 mL	20	Color matching with reference spots at varying distances from target spot
	Holmes	Ref. 13, Fig. 11	40	$\sim 10^{-4}$ (3400 n mi-cd)	1-sec flash at 2-sec intervals	None	Unlighted room	4	Color naming from choice of 6 names, contours for white used

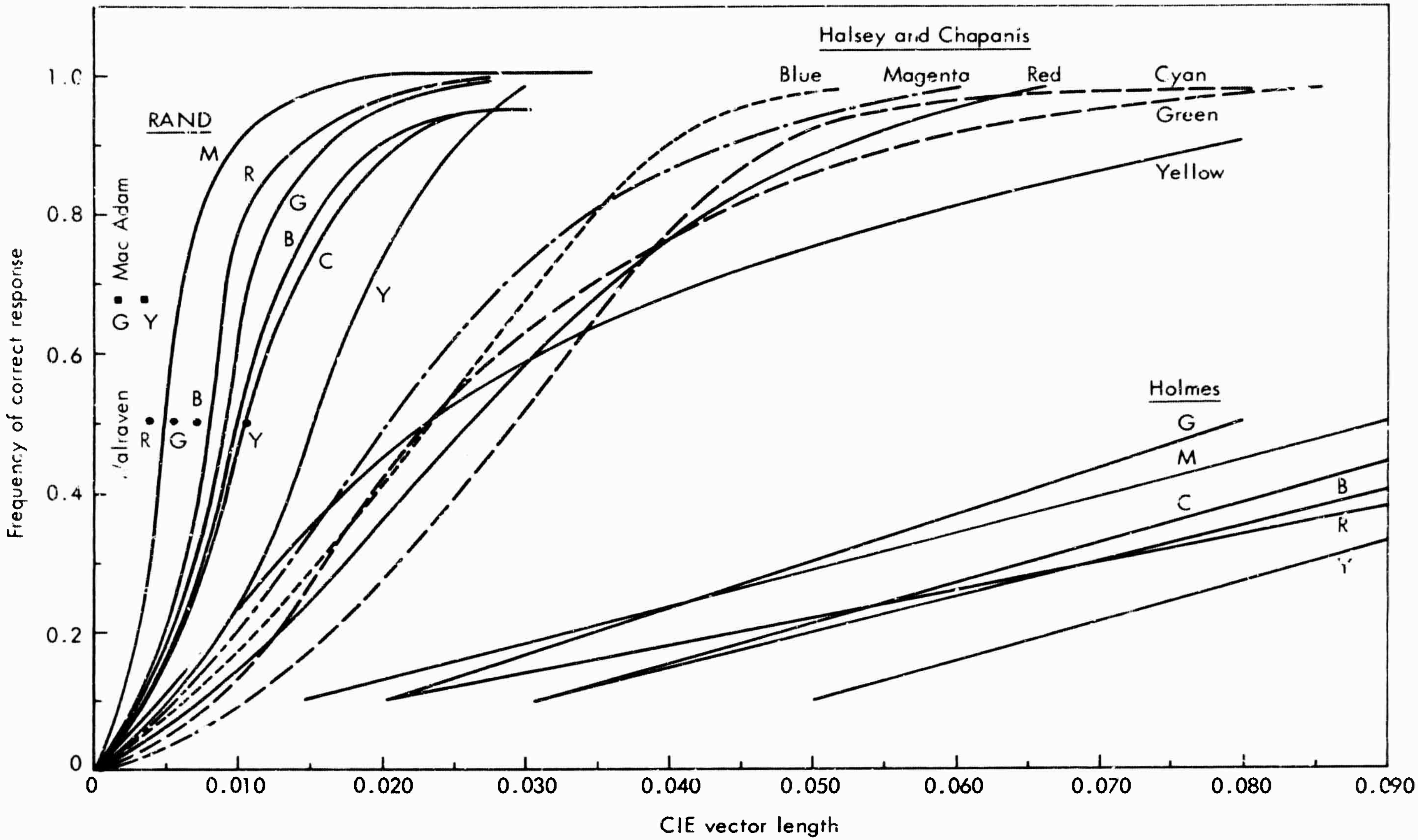


Fig. 11—Comparison of color discrimination data (see Table 6 for sources)

vector lengths in the directions of the six RAND dominant wavelengths were determined in the same manner as those for the Halsey and Chapanis curves. The Holmes discrimination experiment was the most difficult of those considered in Table 6, requiring the positive recognition of a hue (rather than a difference between two hues) at very low luminance levels. However, again taken as a group, the Holmes curves in Fig. 11 are similar to both the RAND curves and the Halsey and Chapanis curves, and yield the largest JND values, as would be expected.

Discrimination "ellipses" for the data represented in Fig. 11 are shown on an enlarged portion of the CIE diagram in Fig. 12. Only a portion of the Holmes 50-percent naming-of-white contour is shown, as the entire contour is comparable to the size of the page. Also included in Fig. 12 are Halsey and Chapanis's 50-percent confusion contour for their standard number 95 and the two nearest MacAdam experimental ellipses.

It is apparent from Fig. 12 that the discrimination task with a display system such as the one used in the present investigation yields an "ellipse" that, although quite asymmetric, has the same general shape and orientation as those of MacAdam and Walraven. By contrast, the more difficult tasks employed by Halsey and Chapanis and by Holmes yield "ellipses" that are markedly different in shape and orientation. The asymmetries in the latter can be explained qualitatively in terms of the MacAdam results, and the procedure will be applied quantitatively to explain the asymmetry in the RAND "ellipse" in the following subsection. The Halsey-Chapanis and Holmes "ellipses" will be excluded from further comparisons with the RAND "ellipse."

EMPIRICAL REPRESENTATION OF RESULTS

The experimental discrimination ellipses of MacAdam, Walraven, and RAND are shown, with their achromatic points, on an enlarged portion of the CIE diagram in Fig. 13. The relative locations on the full CIE chromaticity diagram are indicated in Fig. 14 for general orientation.

In Fig. 13, smooth ellipses have been faired through both the RAND and the Walraven data, without regard for the location of the central reference points. It must be recalled that MacAdam's original data[1]

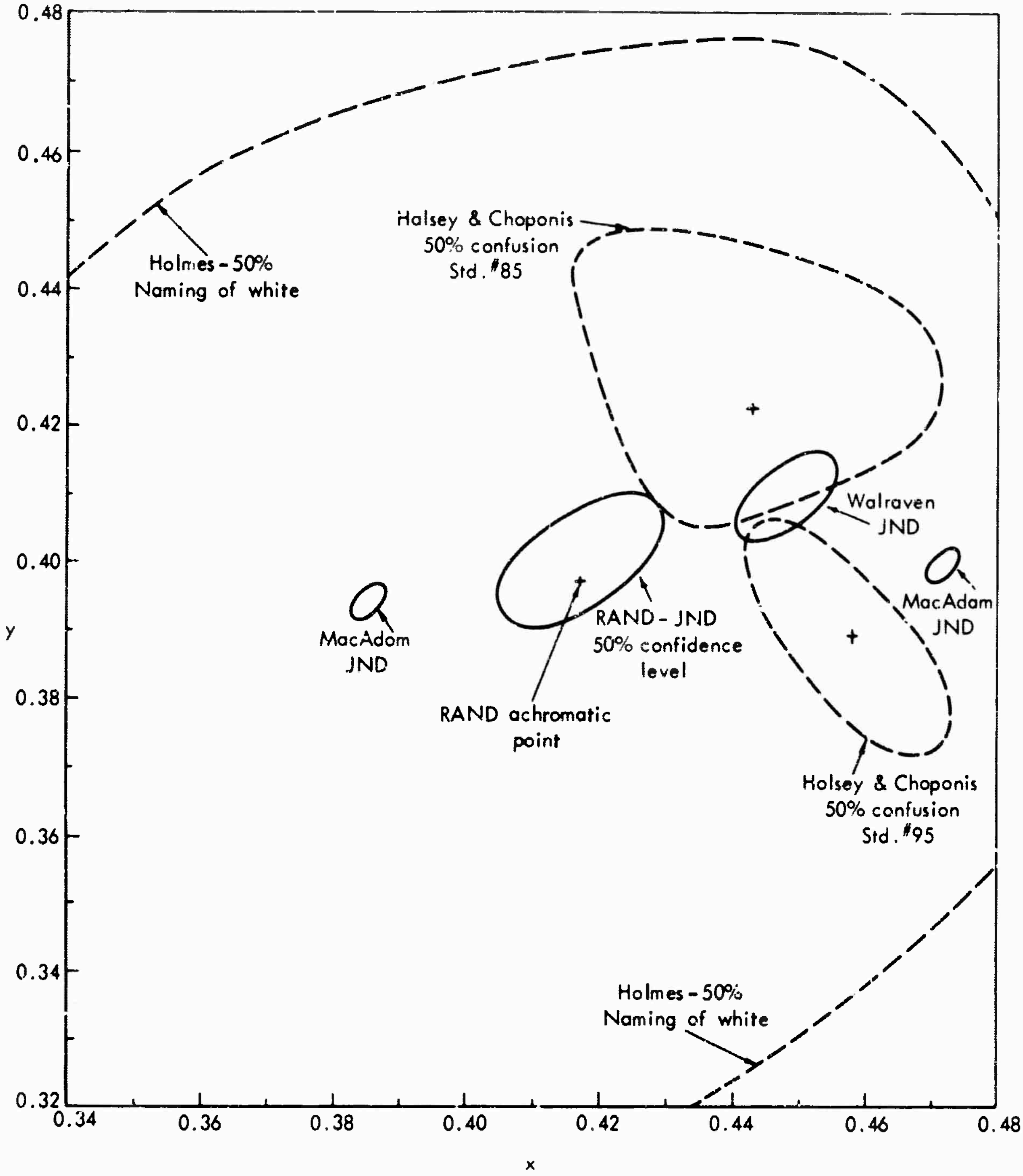


Fig. 12—Comparison of RAND discrimination ellipse with those from other investigations (CIE coordinates)

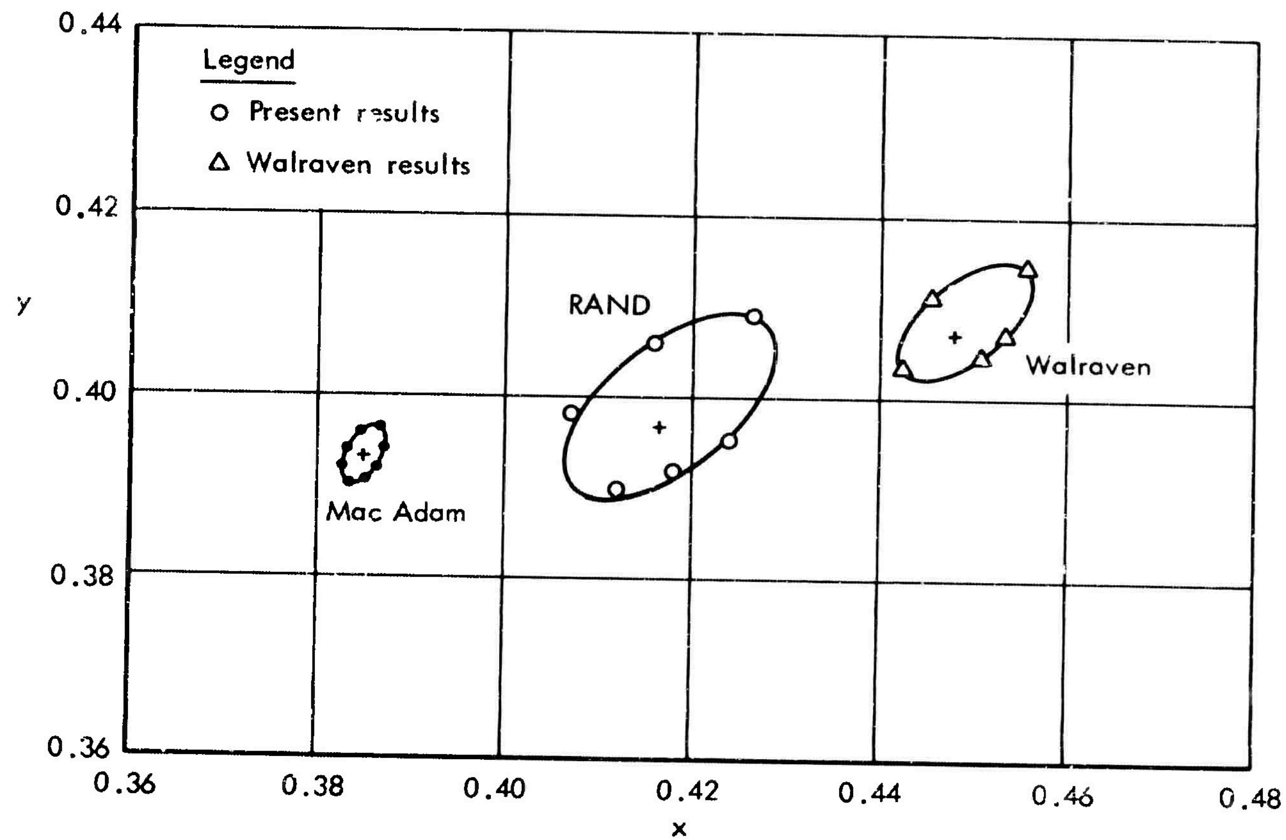


Fig.13—Comparison of experimental discrimination ellipses (CIE coordinates)

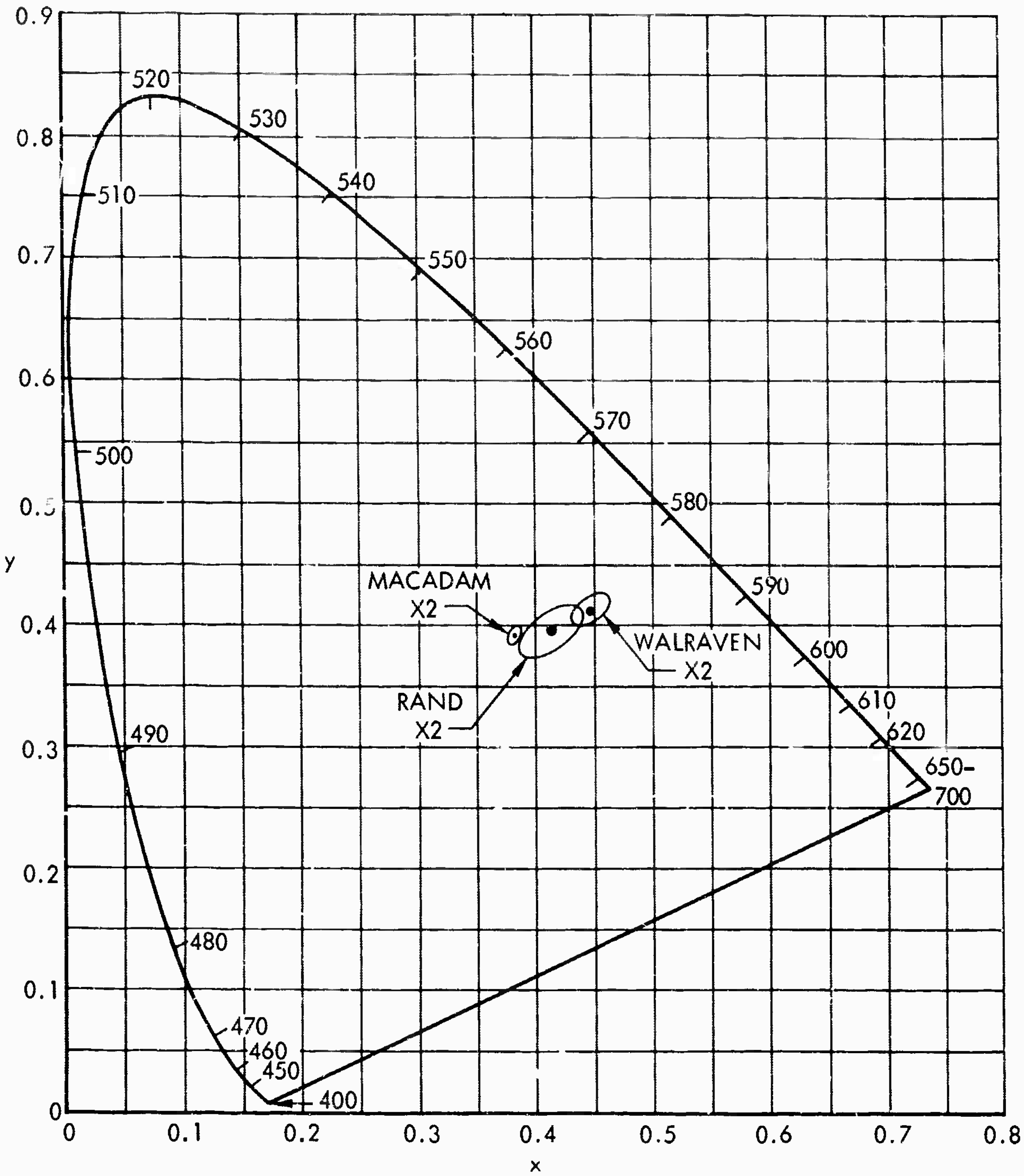


Fig. 14—Location of the three experimental ellipses of Fig. 13 on CIE chromaticity diagram

did not define precise ellipses, although they were symmetrical about the reference points by virtue of his data-reduction procedure. However, his data were sufficiently well fitted by symmetrical ellipses to allow them to be treated as such for practical purposes. Similarly, the present data are justifiably smoothed by fitting with an ellipse.

Figure 13 clearly indicates the asymmetry about the reference point of both the RAND and the Walraven ellipses. This asymmetry of the RAND ellipse was anticipated, and the resultant form indicated in Fig. 13 is quite consistent with that expected from the variation in size and orientation of the MacAdam ellipses in different regions of the CIE diagram shown in Fig. 15. As one moves in different directions on Fig. 15 from the RAND achromatic point, the JND vector length changes more rapidly in the yellow, green, cyan, and blue directions than in the red and magenta directions, resulting in the type of asymmetry shown on the RAND ellipse in Fig. 13. This asymmetry is further enhanced by the tritanopic tendencies encountered with small targets, and hence may be even greater in the RAND and the Walraven results for 1/3-deg targets than the MacAdam results of Fig. 15, which are for 2-deg targets, would indicate.

Although the asymmetry of the RAND experimental ellipse is thus qualitatively explained, a direct quantitative comparison of the RAND and MacAdam ellipses in Fig. 13 is not possible, since they have different achromatic (or reference) points. This problem may be obviated by the use of an empirical procedure devised by MacAdam[18,19] to interpolate among the 25 experimental ellipses shown in Fig. 15. In the linear coordinates of Fig. 15, the locus (x,y) of each ellipse (actual size) relative to its center (x_o, y_o) may be represented by

$$g_{11}(\Delta x)^2 + 2g_{12}\Delta x\Delta y + g_{22}(\Delta y)^2 = 1 \qquad (5)$$

where

$$\Delta x = x - x_o$$

$$\Delta y = y - y_o$$

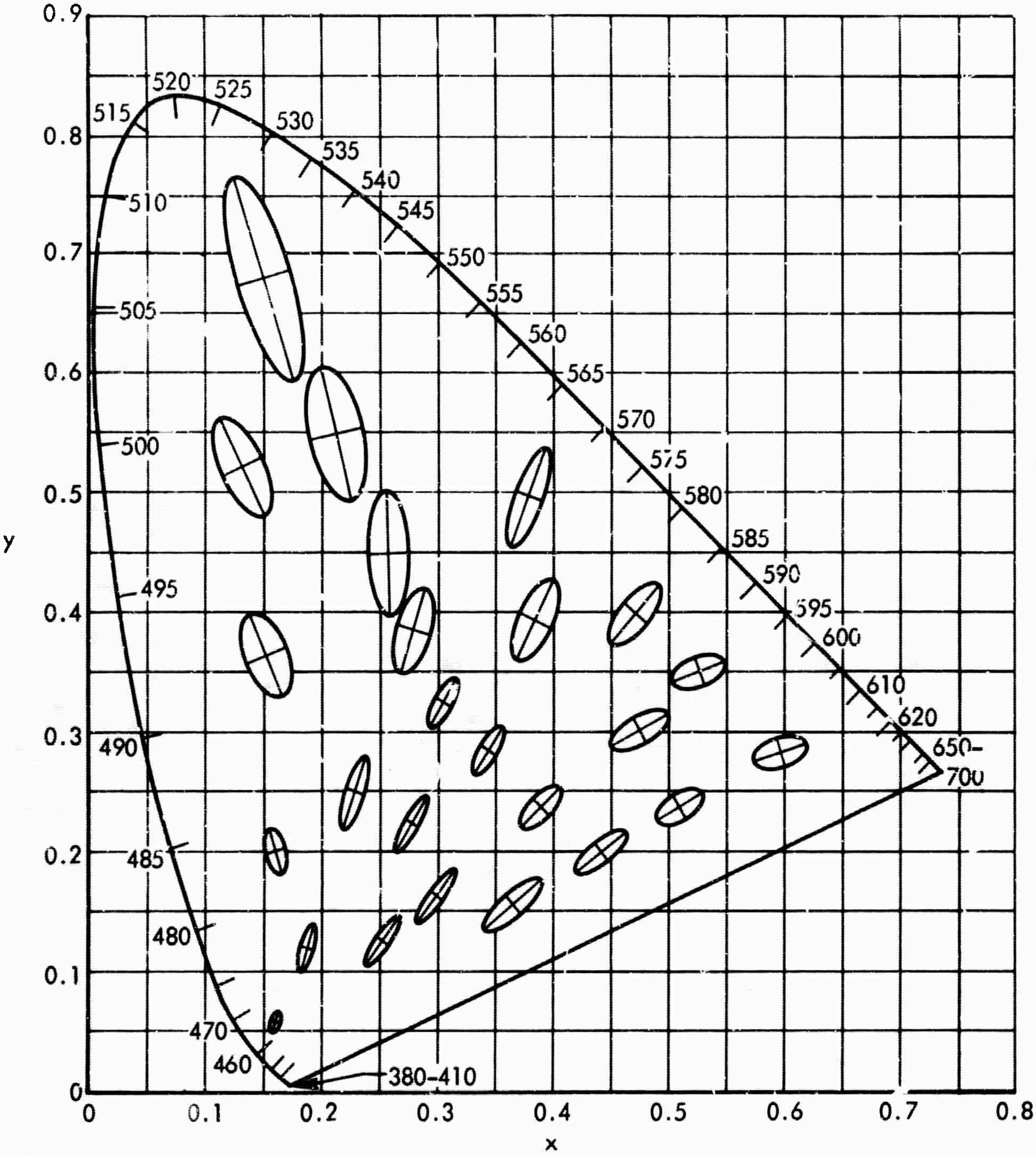


Fig. 15—The Mac Adam experimental ellipses (X 10)
(from Ref. 1)

The color-metric coefficients (g_{11}, g_{12}, g_{22}) are functions of location on the CIE diagram, and may be determined empirically by fairing smooth curves through their values for the 25 ellipses of Fig. 15. The results thus obtained by MacAdam[18] are shown in Figs. 16, 17, and 18.

To construct a MacAdam ellipse about any point (x_o,y_o) on the CIE diagram, we first determine the values of g_{11}, g_{12}, and g_{22} for the point (x_o,y_o) from Figs. 16, 17, and 18. The orientation of the ellipse's major axis is then given by

$$\tan 2\theta = \frac{2g_{12}}{g_{11} - g_{22}} \tag{6}$$

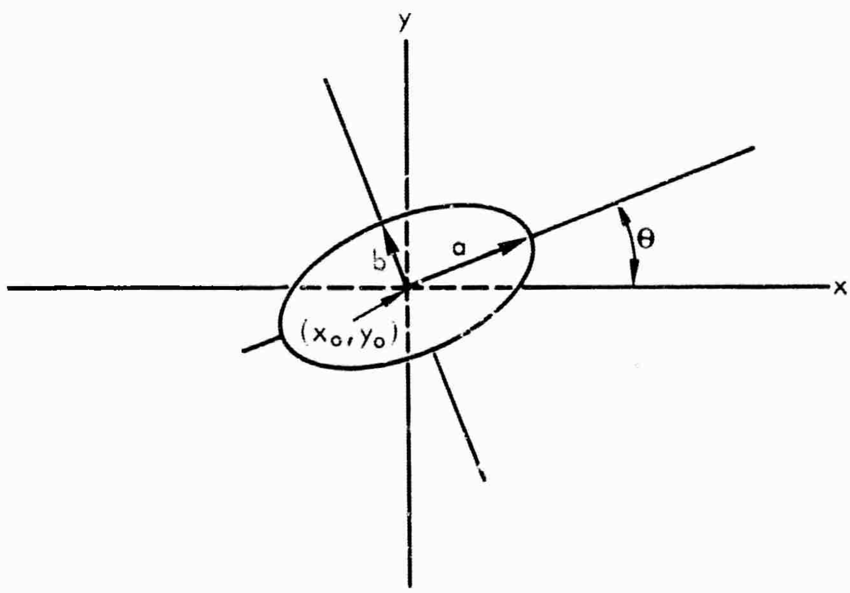
the vector length of the semi-major axis is given by

$$a = (g_{22} + g_{12} \cot \theta)^{-1/2} \tag{7}$$

and the vector length of the semi-minor axis by

$$b = (g_{11} - g_{12} \cot \theta)^{-1/2} \tag{8}$$

where θ is measured counterclockwise from the positive x-direction. The construction procedure is illustrated in the following sketch:



Construction of MacAdam ellipse

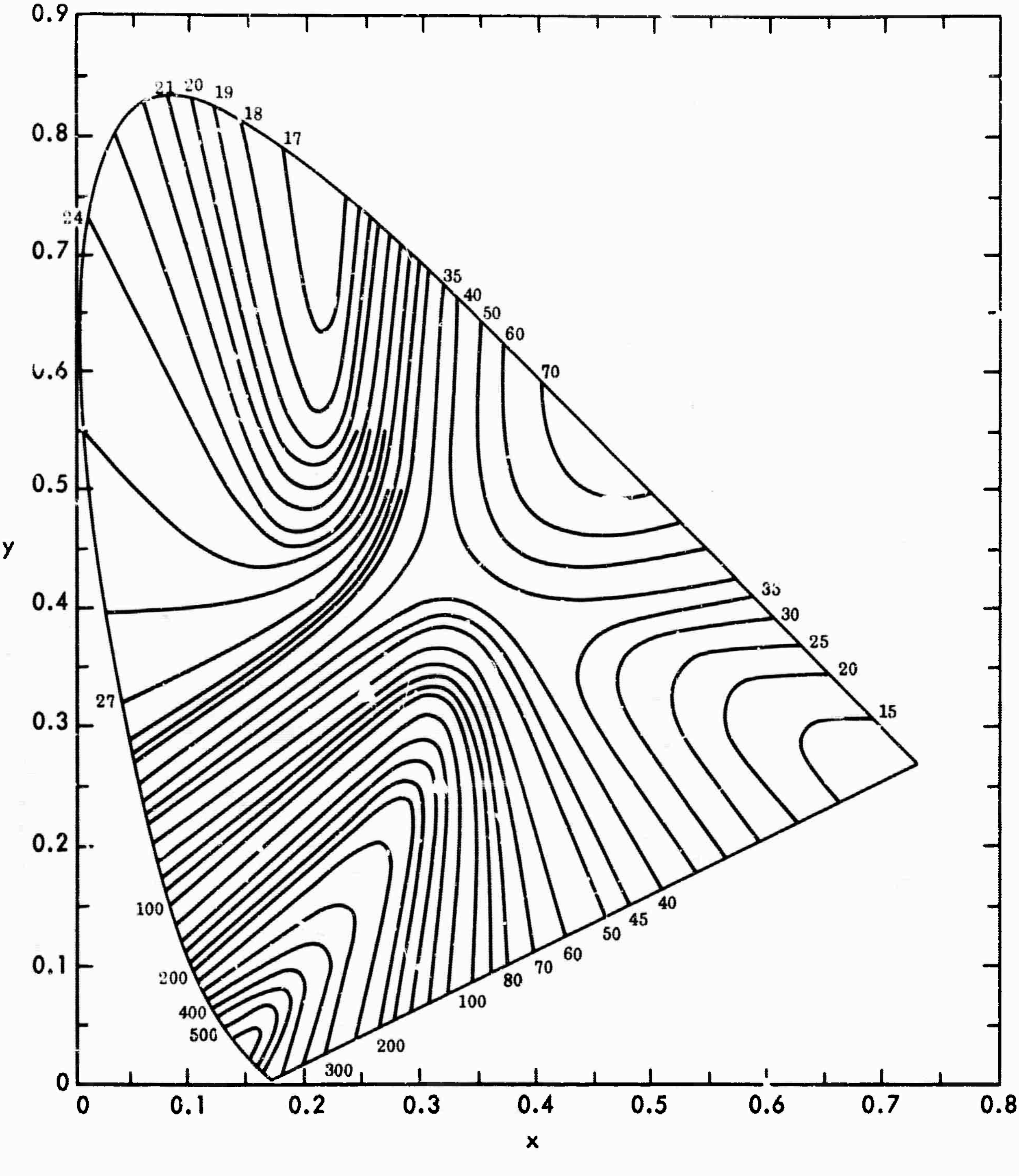


Fig. 16—MacAdam's empirical curves for the color metric coefficient g_{11} (to be multiplied by 10^4)

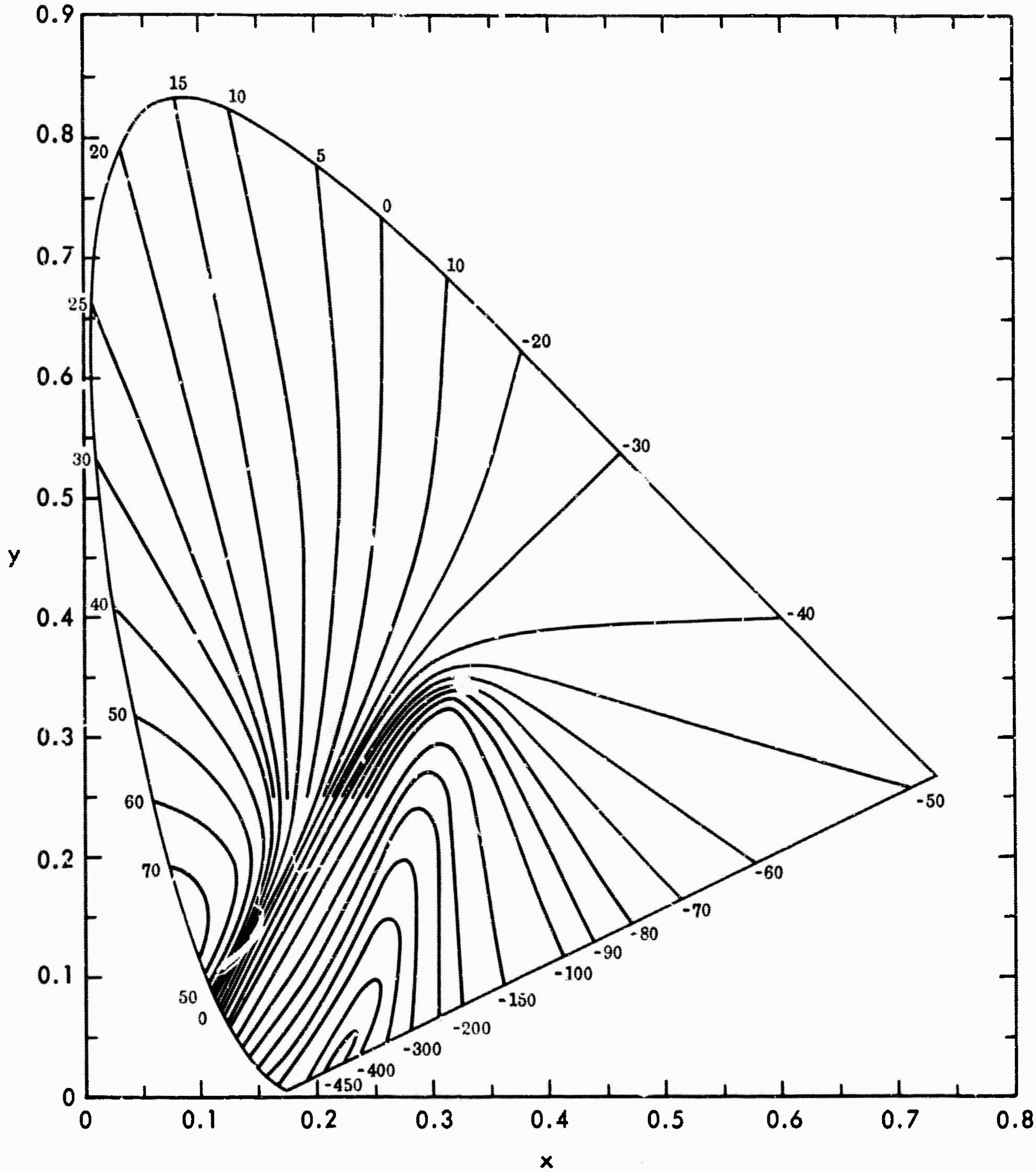


Fig. 17—MacAdam's empirical curves for the color metric coefficient $2g_{12}$ (to be multiplied by 10^4)

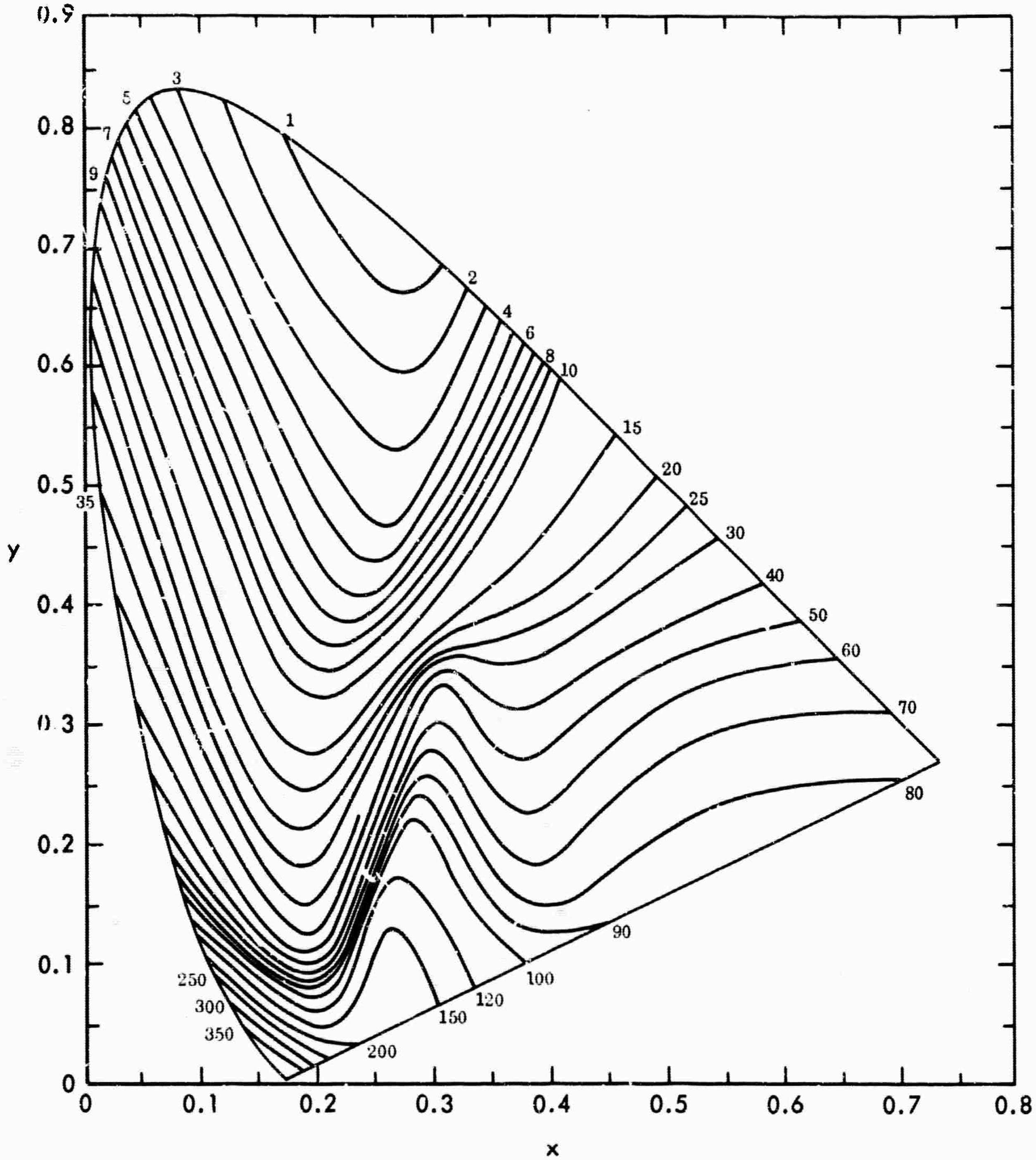


Fig. 18—MacAdam's empirical curves for the color metric coefficient g_{22} (to be multiplied by 10^4)

The eccentricity of an ellipse may be expressed either as a numeric ϵ or as an angle ϕ, the two quantities being related by

$$\epsilon = \left[1 - \left(\frac{b}{a}\right)^2\right]^{1/2} = \sin\phi \qquad (9)$$

Hence $\phi = \cos^{-1}(b/a)$, a 0-deg ellipse is a circle, and a 90-deg ellipse is a line.

The empirical MacAdam ellipse thus determined for the RAND achromatic point ($x = 0.417$, $y = 0.397$) is shown for direct comparison with the RAND experimental ellipse in Fig. 19 on an enlarged portion of the CIE diagram. It should be noted that the RAND experimental ellipse in Fig. 19 is the ellipse faired through the original data points in Fig. 13, whereas the points indicated in Fig. 19 are taken directly from this faired ellipse. The smoothed data of Fig. 19 will be used for the determination of an empirical representation of the present results in terms of the MacAdam procedure. Such smoothing appears justified in view of the uncertainties in the present data as well as the possible 30-percent uncertainty in the coefficients g_{ij} and the 15-percent uncertainties in the original MacAdam data.[18]

It should be further noted that the MacAdam empirical ellipse in Fig. 19 is symmetric about the achromatic point by virtue of Eq. (5), that the ellipse orientation is determined by Eq. (6), and that it is a 60-deg ellipse by virtue of the ratio (b/a) given by Eqs. (7) and (8). On the other hand, the symmetry, orientation, and eccentricity of the RAND experimental ellipse in Fig. 19 are the result of a graphical fit to the RAND experimental data in Fig. 13, using an ellipse template and ignoring the achromatic point. Hence the RAND ellipse in Fig. 19 is quite asymmetric with respect to the achromatic point, its orientation differs slightly from that of the MacAdam ellipse, and it is also a 60-deg ellipse by virtue of graphical best-fit.

Hence, to interpret Fig. 19 it is necessary to keep the sources of the two ellipses clearly in mind. The MacAdam ellipse represents the loci of CIE vector lengths for one JND from the achromatic point in any direction, where the JND is defined as the standard deviation

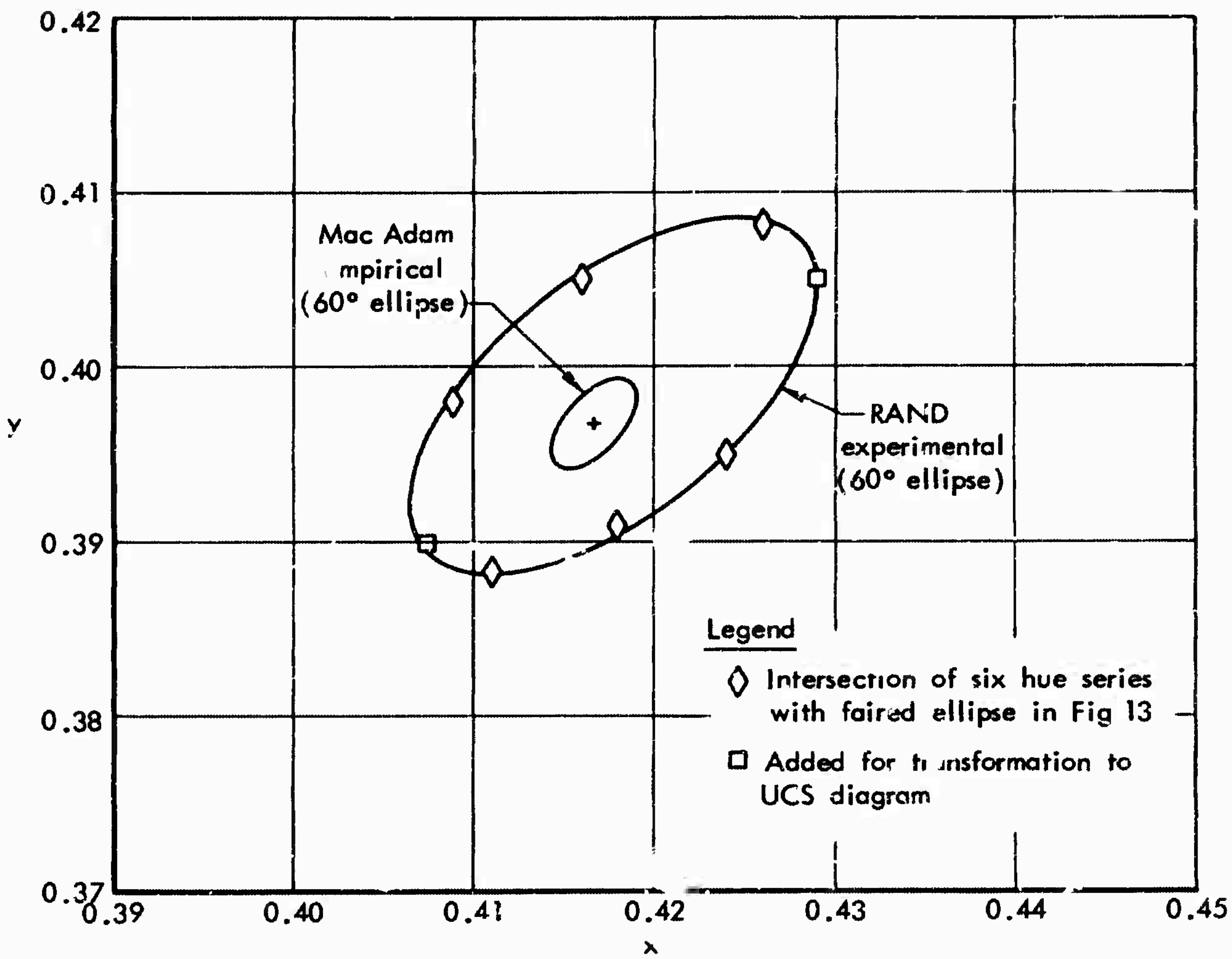


Fig. 19—Comparison of RAND experimental ellipse and Mac Adam empirical ellipse in CIE coordinates

in color matching under the conditions of MacAdam's experiment. The RAND "ellipse" represents the loci of CIE vector lengths for one JND from the achromatic point in any direction, where the JND is defined as the 50 percent frequency-of-correct-response under the conditions of the RAND experiment. Thus both ellipses in Fig. 19 are the loci of unit JNDs. A scaling factor must be determined between these two unit loci if we are to use the MacAdam empirical procedure to represent the RAND results.

The existence of such a scaling factor presumes that the unit JND in chromaticity for a display system of the type investigated herein is some "multiple" of the MacAdam unit JND in chromaticity. It is readily apparent that no simple scaling procedure exists between the two ellipses in the (x,y) coordinates of Fig. 19, due to the asymmetry of the RAND ellipse. As noted previously, this asymmetry results primarily from the fact that equal vector lengths do not represent equal perceptual changes in different regions of the (x,y) chromaticity diagrams. Hence the scaling procedure must be performed in a uniform discrimination space. By definition, the latter is a space in which perceptually equal distances in any direction from a point are represented by equal vector lengths, i.e., a unit JND locus would be a circle. Transformation of the coordinates (x,y) of the CIE chromaticity diagram into such a space yields a uniform chromaticity scale.

Although there is no completely satisfactory transformation, we shall use the one adopted by the CIE, known as the 1960 CIE-UCS diagram,[20] based on the MacAdam data of Fig. 15. The coordinates (u,v) of the 1960 CIE-UCS diagram are given in terms of the coordinates (x,y) of the CIE chromaticity diagram by the relations

$$u = \frac{4x}{-2x + 12y + 3} \tag{10}$$

$$v = \frac{6y}{-2x + 12y + 3} \tag{11}$$

The RAND experimental and MacAdam empirical ellipses of Fig. 19 are shown on an enlarged portion of the UCS diagram in Fig. 20. Again,

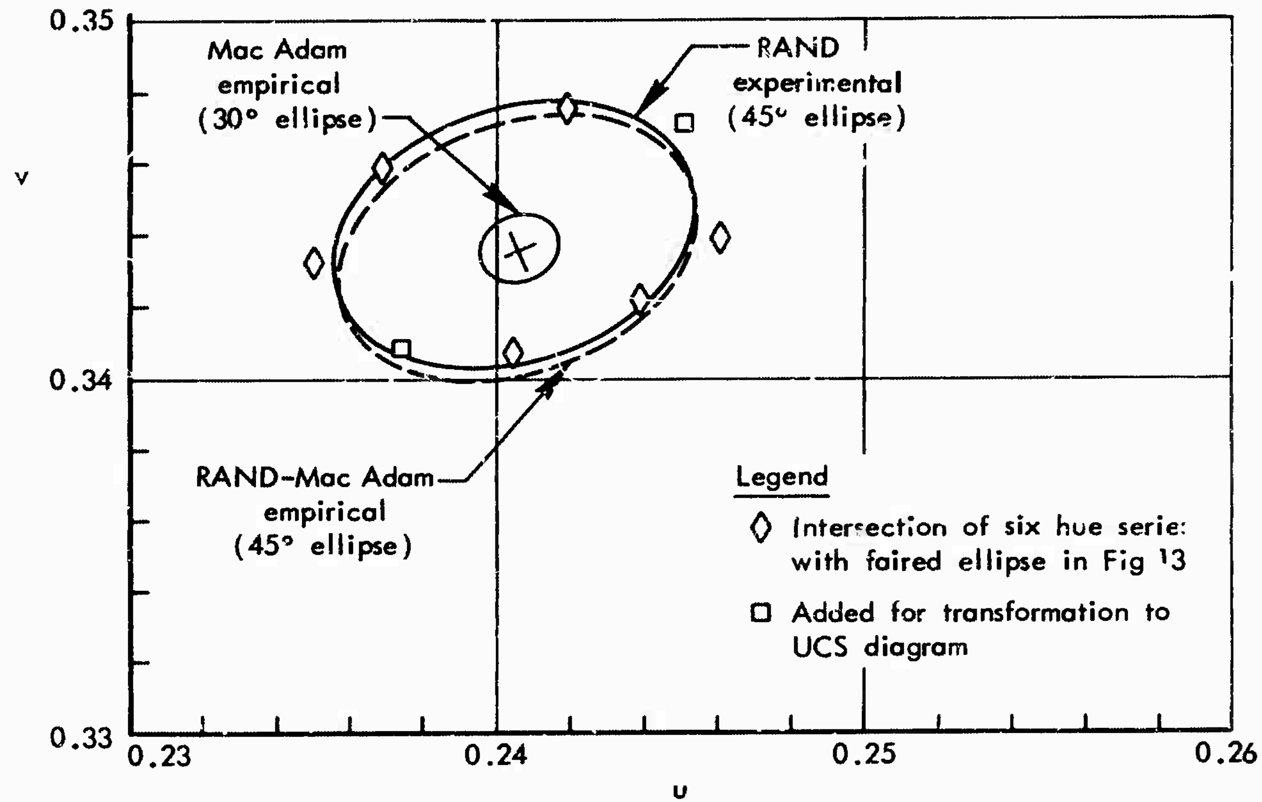


Fig. 20—Comparison of RAND experimental ellipse and Mac Adam empirical ellipse in UCS coordinates

smooth ellipses are faired through the transformed points. One notes immediately that the 1960 CIE-UCS transformation does not produce a completely uniform chromaticity diagram, but does reduce the eccentricity of the ellipses. The MacAdam ellipse is reduced from 60-deg eccentricity in the (x,y) coordinates of Fig. 19 to 30-deg eccentricity in the (u,v) coordinates of Fig. 20. The RAND ellipse is similarly reduced from 60- to 45-deg eccentricity. Furthermore, the asymmetry of the RAND ellipse in the (x,y) coordinates of Fig. 19 is substantially reduced by transformation to the (u,v) coordinates of Fig. 20.

The residual asymmetry and greater eccentricity of the RAND ellipse in Fig. 20 is evidence of a tritanopic influence in the RAND data for 1/3-deg targets; this influence is not accounted for by the UCS transformation, the latter being based on 2-deg data. As noted by Judd and Wyszecki,[20] to obtain a uniform chromaticity scale diagram better suited to small targets, one would have to further condense the violet-green-yellow portion of the 1960 UCS diagram. Such a condensation would have the effect of reducing the minor-axis asymmetry and the eccentricity of the RAND ellipse in Fig. 20. In the absence of such a transformation, the MacAdam ellipse may be scaled to a reasonable fit of the RAND ellipse in Fig. 20 only by a change in the eccentricity of the former.

An examination of Fig. 20 shows that the ratio of the RAND major axis to the MacAdam major axis is about 4.5, whereas the ratio of the RAND minor axis to the MacAdam minor axis is about 3.9. This is approximately the scaling ratio for a change from a 30- to a 45-deg ellipse ($\cos 45^\circ/\cos 30^\circ = 0.82$; $3.9/4.5 = 0.87$). Hence a scaling factor of 4.5 plus an increase in eccentricity of 15 deg applied to the MacAdam empirical procedure should yield an adequate representation of the RAND experimental results. A MacAdam ellipse thus scaled will be termed a RAND-MacAdam ellipse, and is shown as the dashed ellipse in the UCS diagram of Fig. 20 for comparison with the RAND data

Since an ellipse in the (x,y) diagram is required for design purposes in order to specify the differences in chromaticity coordinates, the comparison will also be made in the chromaticity diagram. The RAND-MacAdam empirical ellipse in Fig. 20 is converted to (x,y) coordinates by means of the inverse transformation

$$x = \frac{3u}{2u - 8v + 4} \qquad (12)$$

$$y = \frac{v}{u - 4v + 2} \qquad (13)$$

The resulting ellipse is compared with the RAND data in Fig. 21. The fit is satisfactory, and it is therefore concluded that the RAND results may be represented by the appropriately modified MacAdam procedure.

It is to be emphasized that the scaling procedure must be applied to the MacAdam ellipse in the CIE-UCS diagram, and the resulting RAND-MacAdam ellipse then transformed to the CIE chromaticity diagram. The latter, as in Fig. 21, then gives the loci of CIE vector lengths representing unit JND steps in any direction from the reference point for a display system of the type investigated herein.

EXTRAPOLATION OF RESULTS

The direct experimental result of the present investigation is that a suitable scaling procedure can be used with the MacAdam empirical procedure to predict the chromaticity JND from the 3200°K chromatic point (equivalent to saturation JND) for a static display system of the type tested.

Although it might retain the same format as the present static system, an operational display system will most probably contain two additional parameters: (1) the several test spots will be in relative motion; and (2) increases in saturation of individual spots beyond one JND will be used to encode additional information into the display. The effect of motion of the test spot must be investigated separately.[21] A procedure for determining additional JND steps in chromaticity may be obtained by extrapolation of the present results.

The following procedure may be used to determine the next JND step in a given direction from a particular point (x,y) on the RAND-MacAdam ellipse of Fig. 21:

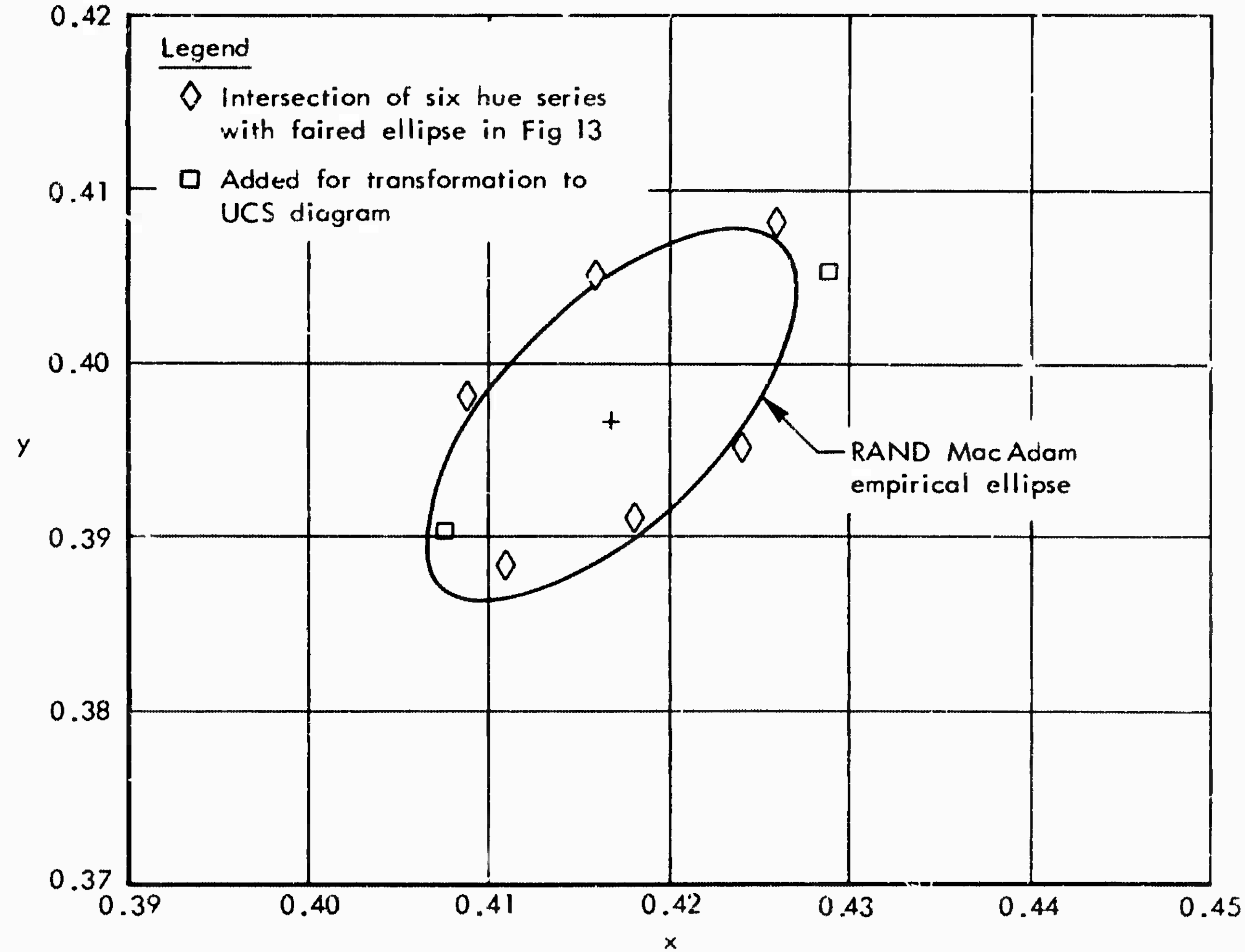


Fig.21—Comparison of RAND-Mac Adam empirical ellipse with data from Fig. 19

(1) Calculate the MacAdam ellipse about the point (x,y) using Figs. 16, 17, and 18 and Eqs. (6), (7), and (8).

(2) Transform the MacAdam ellipse to (u,v) coordinates using Eqs. (10) and (11).

(3) On the UCS (u,v) diagram multiply the major axis of the MacAdam ellipse by 4.5 and increase its eccentricity by 15 deg to obtain the RAND-MacAdam ellipse.

(4) Transform the RAND-MacAdam ellipse back to the CIE (x,y) diagram using Eqs. (12) and (13).

The above procedure may then be repeated for the next JND step in chromaticity, in order to cover the low-saturation region about the achromatic point.

Several arguments may be advanced to justify the preceding extrapolation. First, the RAND JND ellipse is the mean for the 39-subject data, which exhibit rather large individual differences among the subjects. For design calculations, a mean result "typical" of the general color-normal population is needed. The MacAdam procedure, based on his one-subject data, has been shown[3] to be "typical" in this sense. The RAND 39-subject mean serves to determine the typical scaling factors for use with the MacAdam procedure.

Second, although Halsey and Chapanis[12] also found large individual variations in discrimination ability among their 20 subjects, the relative sizes of the confusion contours for any given subject were quite consistent. Thus a subject who produced large contours in one area of the CIE chromaticity diagram also produced large contours in all other areas of the diagram. Furthermore, the contours produced by the different subjects for the same reference point varied only in size, and not in shape or orientation. Halsey-Chapanis mean 10-percent contours gave scaling factors of about 30 when compared with MacAdam ellipses. The Halsey-Chapanis results indicate the existence of a scaling factor that is approximately constant throughout the CIE diagram even for their complex display system. This provides a justification for using the RAND scaling procedure over a substantially larger region of the CIE diagram than that for which the factor was experimentally determined.

Finally, the asymmetry of the RAND experimental ellipse is adequately determined by the limited number of hue-series used, so that comparison with the MacAdam procedure in the UCS diagram is meaningful. This is clearly shown by Fig. 22, which is a plot of experimental saturation thresholds as a function of dominant wavelength. The RAND hue-series are properly spaced for the determination of the asymmetries.

It is the residual asymmetry on the minor axis of the RAND ellipse in Fig. 20 that requires an increase in eccentricity of the MacAdam ellipse in the scaling procedure. This results in a compromise fit of the RAND data by a symmetric ellipse. As previously noted, it seems most probable that the residual asymmetry of the RAND ellipse in the 1960 CIE-UCS diagram is a defect in the transformation itself and that in fact the transformation is not the most appropriate for small targets in a dark surround, as used herein. For such cases the yellow-green-violet half of the ellipse should be condensed more in the UCS diagram than the transformation affords. It should be possible to develop a new UCS diagram with these properties and thus to handle the JND specifications for display systems similar to that investigated herein by means of a uniform scaling factor. In such a development it might be more appropriate to use the procedure of Stiles,[22] which, though more complex than that of MacAdam, is perhaps better suited to chromaticity spacing calculations for small targets on a dark surround.[20] However, such a consideration is beyond the scope of the present investigation, which was to determine the scaling procedure to be used with the MacAdam ellipse.

The importance of the preceding arguments for justifying the extrapolation of the present results can scarcely be overemphasized. The experimental determination of the single RAND ellipse required a lengthy and complex investigation. Yet the task was relatively easy compared to that of MacAdam, in which each ellipse was the result of a very large number of observations under invariant conditions for a single observer. These latter conditions are strictly necessary for the empirical determination of a uniform calculation procedure embracing the entire CIE diagram. Application of the MacAdam results to the RAND scaling procedure, determined for the most important region (i.e., about the achromatic

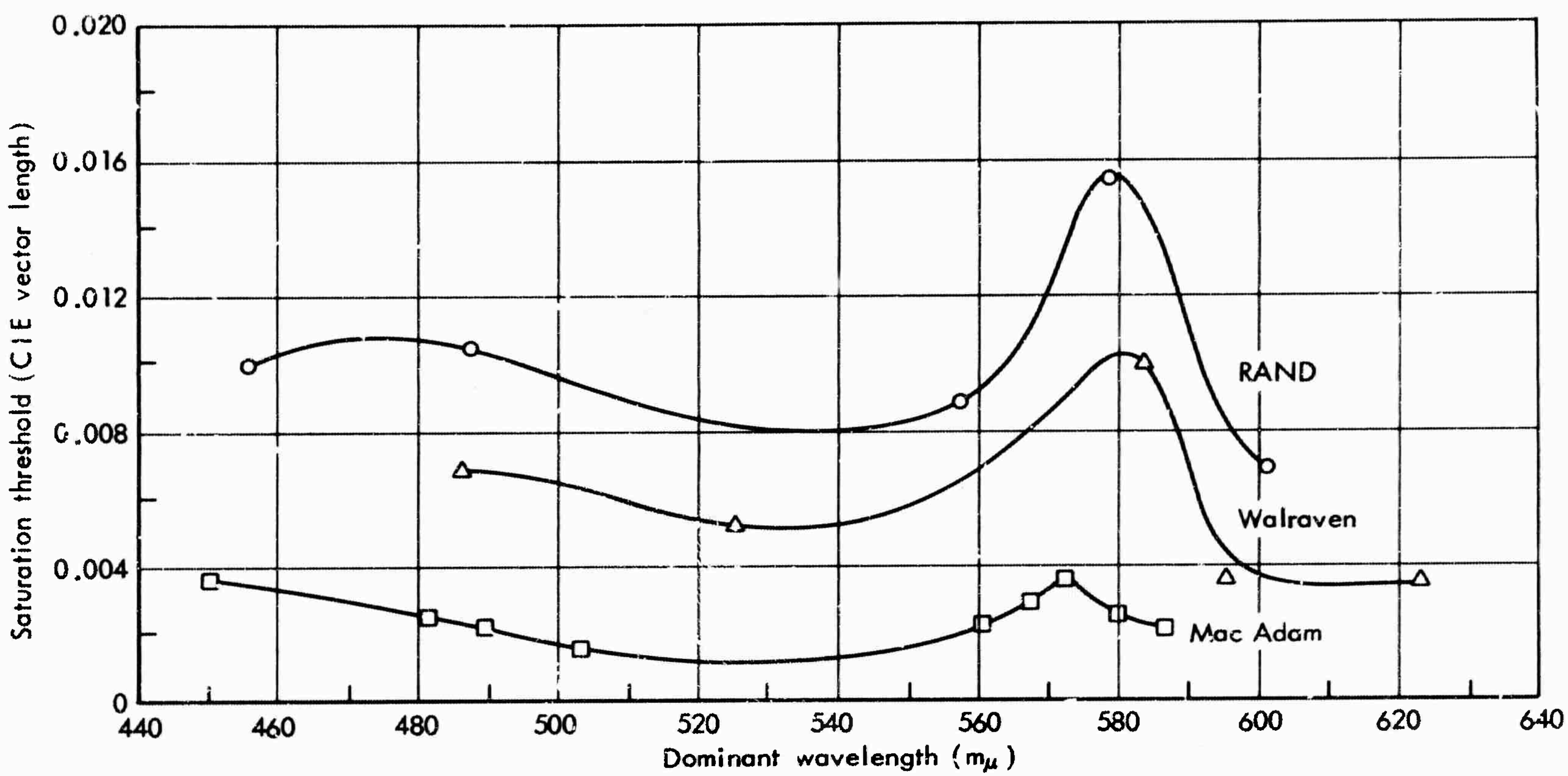


Fig. 22—Variation of saturation thresholds with dominant wavelength

point), can be expected to yield results of reasonably uniform validity for the region near the achromatic point. This would likely include the region of interest for encoding display systems of the type investigated, which involve low saturations. Attempts to determine separate scaling factors for different areas of this region are not indicated, and the present results should be adequate to guide design calculations for such display systems. Further effort would be more appropriately directed toward the development of a UCS calculation procedure more suitable for such display systems.

DISPLAY SYSTEM DESIGN

The use of variable color to encode additional information about the object represented by a target spot in a display system requires a design relationship between changes in the information input level and the corresponding chromaticity change in the target spot. Assuming that the chromaticity of an individual target spot is intended to facilitate its selection or rejection by the observer, an appropriate design relationship might be developed in terms of a mosaic of chromaticities about the achromatic point. The latter would represent the "white" target spots, i.e., those for which the input levels of chromaticity information were insignificant. The grid points of the mosaic would represent integral multiples of the JND in chromaticity from the achromatic point and from adjacent grid points. These discrete steps would then correspond to various levels of significance of the chromaticity information inputs. Such a system may be preferable to one employing continuously variable chromaticity for several reasons. First, a continuous subthreshold variation of chromaticity, being undetected, could represent a needless complexity in the system. Second, the variation in a given information input level will likely have to exceed some predetermined threshold to attain significance. And finally, since the assumed purpose of variable color encoding is to aid the observer's selection of a few spots out of several, step chromaticity changes will likely enhance his detection ability.

Unit JND chromaticity steps for such a discrete system may be determined from the RAND-MacAdam ellipses by means of the combined analytical/graphical procedure presented above.

If several distinct hues are desired for use in a display system their choice may be guided by the requirements that each hue have a simple color-name acceptable to most people and that no two hues are likely to be confused by an observer.

The results of Halsey and Chapanis[12] indicate that at least six hues that satisfy these requirements may be chosen, and a six-hue display system based on their recommendations would employ chromaticity changes from the white point toward the following dominant wavelengths: 450 mμ (violet), 485 mμ (blue), 545 mμ (green), 580 mμ (yellow), 620 mμ (red), and 560c mμ (purple). The color-names given in parentheses are rather arbitrary in some instances, and could be replaced by code words if desired. A comparison of the above dominant wavelengths with those indicated in Fig. 5 shows that the six hues used in the present investigation form an acceptable set.

Finally, the present results indicate that human chromaticity discrimination ability is only moderately degraded for widely separated 1/3-deg target spots in an overall field subtending 17 deg. Although motion of the target spots might be expected to further degrade discrimination ability, the probable closer spacing resulting within the same 17-deg field might be expected to enhance discrimination ability, and the effects might essentially cancel each other. Dynamic studies using a format similar to that investigated herein are required to resolve this question. In any event, the 1/3-deg target spot size appears appropriate for this type of display system.

The preceding remarks should be applicable to other similar display situations in which color is used as a means of encoding additional information.

VI. CONCLUSIONS

The questions posed for the present investigation were: (1) Is it meaningful to use the MacAdam results, scaled by an appropriate factor, to calculate color discrimination vectors for multi-image displays? (2) And if so, what is the magnitude of the scaling factor?

The direct experimental result of the present investigation is that suitable scaling factors can be used with the MacAdam empirical procedure to predict the constant-brightness chromaticity JND from the 3200°K chromatic point (equivalent to saturation JND) for a static display system of the type tested. The multiplicative factor required is moderate, being about 4.5 in the CIE 1960 Uniform Chromaticity Scale diagram, accompanied by a 15-deg increase in eccentricity.

Analysis of the present results and their comparison with related previous investigations thus indicate that the answer to the first question above is affirmative. As for the second question, a quantitative scaling procedure based on an extrapolation of the present experimental results is presented for use in the low-saturation region surrounding the achromatic point. This would likely include the region of interest for encoding display systems of the type investigated, which involve small self-luminous targets on a dark surround.

The present results indicate that human chromaticity discrimination ability is only moderately degraded for widely separated 1/3-deg target spots in an overall field subtending 17 deg. Evidence of tritanopic effects is found with the 1/3-deg targets, so that the degradation in discrimination ability is greater along the yellow-blue axis than in other directions. This tritanopic influence is moderate with the 1/3-deg targets tested, and is approximately accounted for in the proposed scaling procedure.

The saturation JNDs for individual subjects fall in a band of about ± 30 percent around the 39-subject mean. This intersubject variation is consistent with previous investigations of this type, and indicates that for an operational display system some selection procedure might be used to obtain a group of observers of reasonably uniform ability.

The potential usefulness of such screening procedures is further indicated by the correlations between a post-test questionnaire and test performance.

The present results also indicate that luminosity differences of about one percent among the separated 1/3-deg targets are probably subliminal. This implies that holding the brightnesses of multiple spots constant to within about one percent should not affect the interspot saturation JNDs in an operational system similar to that investigated herein. This could constitute a substantial relaxation in brightness tolerance over that resulting from a direct application of bipartite-field data which yield a brightness JND of about one percent.

The present experimental results and approximate scaling procedures should be adequate to guide preliminary design calculations for display systems similar to the one tested. The analytical/graphical scaling procedure presented may be converted into a purely analytical procedure for computer programming. However, further analytical effort would be more appropriately directed toward the development of a UCS diagram better suited to color discrimination of small targets on a dark surround. With such a diagram, the present experimental results should determine a single multiplicative scaling factor without changes in eccentricity.

The effect of target-spot motion requires separate investigation.

Appendix I

STATIC COLOR - JND - POST-TEST QUESTIONNAIRE

Date: ______________________ Subject: ____________________

READ INSTRUCTIONS BEFORE STARTING

INSTRUCTIONS

Recently you participated as a subject in a series of color-discrimination tests. In all such psychophysical tests, intersubject variability is an important parameter which is essentially beyond the control of the investigator. However, failure to properly account for such variability can sometimes obviate the usefulness of the test data. The following questionnaire seeks information for known correlates in intersubject variability. We would appreciate your continued cooperation by completing this questionnaire.

Please answer the questions in order; do not read through the questionnaire before starting.

1. What criteria did you use to determine which, if any, light spot was different? ______________________________

____

____

____

____

2. Did you use a regular sequence of comparing the four spots in a test presentation? (1) ___ Yes; (2) ___ No. If yes, number in sequence (i.e., 1-2-3---) on the diagram the search pattern you used:

UL	UR
LL	LR

(3) ___ Yes, but don't remember.

3. Have you had previous experience with psychophysical tests? (1) ___ No; (2) ___ Yes. If yes, as (3) ___ subject; (4) ___ investigator.

4. Do you smoke? (1) ___ No; (2) ___ Moderately $<$ 20/day; (3) ___ Heavily $>$ 20/day; (4) ___ Pipe; (5) ___ Cigars.

5. Did you notice differences in the light spots during the tests which you rejected as not being color differences? (1) ___ Frequently; (2) ___ Occasionally; (3) ___ Rarely; (4) ___ Never; (5) ___ Don't Remember.

6. Your general professional area may be classified as: (1) ___ Physics; (2) ___ Biology; (3) ___ Psychology; (4) ___ Medicine; (5) ___ None of these.

7. Did one half of the field generally seem brighter than the other? (1) ___ Left Spots; (2) ___ Right Spots; (3) ___ About Same; (4) ___ Don't Remember.

8. How would you describe your posture during the test sessions? (1) ___ Straight; (2) ___ Relaxed; (3) ___ Don't Remember.

9. Were you physically comfortable during the test sessions? (1) ___ Yes; (2) ___ No.

10. Are you familiar with the general subject of color? (1) ___ Professionally; (2) ___ Artistically; (3) ___ Neither.

11. What color is your hair? ______________

12. Did you notice any variation in the size of the light spots during the test sequences? (1) ___ Yes; (2) ___ No. If yes, did it annoy you? (3) ___ Yes; (4) ___ No. Did it make your task more difficult? (5) ___ Yes; (6) ___ No.

13. Did you feel that your position relative to the test screen was: (1) ___ Too Close; (2) ___ About Right; (3) ___ Too Far; (4) ___ Don't Remember.

14. How would you describe the general room illumination during the tests? (1) ___ High; (2) ___ Moderate; (3) ___ Subdued; (4) ___ Low.

15. Do you have favorite colors? (1) ___ No; (2) ___ Yes, viz: ______________________.

16. Are there some colors you distinctly dislike? (1) ___ No; (2) ___ Yes, viz: ____.

17. Did you understand the purpose of the tests in which you participated? (1) ___ In Detail; (2) ___ In General; (3) ___ Vaguely, or not at all.

18. What motivated your willingness to participate in the tests? (1) ___ Professional Interest; (2) ___ General Interest; (3) ___ Just Cooperative.

19. Did you consciously move your head while comparing the four spots in a test presentation? (1) ___ Yes; (2) ___ No; (3) ___ Don't Remember.

20. What color did the background (test screen) appear to you?

______________________________.

21. When in doubt did you choose the spot which seemed the most different? (1) ___ Always; (2) ___ Usually; (3) ___ Rarely; (4) ___ Never.

22. After participating in these tests would you say that your interest in color and vision has: (1) ___ Increased: (2) ___ Remained Unchanged; (3) ___ Decreased.

23. What color are your eyes? ________________.

24. Have you ever served as a radar observer? (1) ___ Yes; (2) ___ No.

25. Are you more than casually familiar with the aspects of human color vision? (1) ___ Yes; (2) ___ No.

26. How would you rate your competence in photography?

Black and White

(1) ___ Professional; (2) ___ Advanced Amateur; (3) ___ Layman.

Color

(4) ___ Professional; (5) ___ Advanced Amateur; (3) ___ Layman.

27. Did you become tired or uncomfortable during a test session? (1) ___ Yes; (2) ___ No.

28. Was the brightness level of the test spots generally: (1) ___ Glaring; (2) ___ Bright; (3) ___ Comfortable; (4) ___ Dim.

29. Were you consciously aware of a specific hue when reporting a positive choice of one of the four light spots? (1) ___ Usually; (2) ___ Occasionally; (3) ___ Never; (4) ___ Don't Remember.

30. Have you actively participated professionally in experimental investigations? (1) ___ Frequently; (2) ___ Occasionally; (3) ___ Rarely; (4) ___ Never.

31. How would you judge your complexion? (1) ___ Fair; (2) ___ Medium; (3) ___ Dark.

32. Are the results of the tests of professional interest to you? (1) ___ No; (2) ___ Yes.

33. Do you, or have you, painted as a hobby? (1) ___ Yes; (2) ___ No.

34. Toward the end of the test did you find your task:
(1) ___ Easier; (2) ___ More Difficult; (3) ___ About the Same.

35. Are you on a special diet? (1) ___Weight Control;
(2) ___ Other Reasons; (3) ___ No.

36. Do you normally wear sunglasses when outside during the day?
(1) ___ Yes; (2) ___ No.

37. Did you know what colors to expect during the tests from prior knowledge of the test slides? (1) ___ Yes; (2) ___ No.

38. Did you think the light spots were: (1) ___ Too Small;
(2) ___ Too Large; (3) ___ About Right.

39 Are you willing to participate as a subject in additional tests? (1) ___ Of the Same Type; (2) ___ Of Different Types;
(3) ___ No.

40. Are you under continued medication of any kind? (1) ___ Yes;
(2) ___ No.

41. During the test sequences did the light spots ever blur or appear double? (1) ___ Yes; (2) ___ No.

42. Do your extra-RAND activities require close eye-work?
(1) ___ Yes; (2) ___ No. If yes, state nature of activity ______
____

Static Color - JND - Post-Test Questionnaire

Scoring Instructions

The questionnaire is designed to provide information on intersubject variability which can be useful in two ways: (1) aid in explaining large sample deviations in JND test results; (2) increase confidence limits in JND test results by applying corrections where appropriate.

The information for each S is encoded into nine indices. The intended measure of, and the scoring method for, each index is given below.

The significance of the several indices may be checked a posteriori by standard statistical methods of hypothesis testing.

I. Clinical Indices: Measure of three factors (Systemic, Adaptive, Pigment) of S which might be expected to correlate with anomalous deviations in JND results.

Systemic:	(5) Max		
#4:	(1) = 0	(3) = 2	(5) = 1
	(2) = 1	(4) = 1	
#35:	(1) = 1	(2) = 1	(3) = 0
#40:	(1) = 2	(2) = 0	
Adaptive:	(5) Max		
#14:	(1) = 2	(3) = 0	
	(2) = 1	(4) = 0	
#28:	(1) = 2	(3) = 0	
	(2) = 1	(4) = 0	
#36:	(1) = 1	(2) = 0	
Pigment:	(8) Max		
#11:	blonde = 0	red, brown = 1	
	black = 2		
#23:	blue = 0	hazel, green = 1	
	brown = 2		
#31:	(1) = 0	(2) = 1	(3) = 2
Race:	C = 0	M = 1	N = 2

II. Judgment Indices: Measure of the severity of S requirements for a positive spot choice. Judgment Indices is measured directly by the Criteria Inde and inversely by the Guessing Index.

Criteria: (10 Max) Guessing: (7 Max)

Question	Response	C - Score	G - Score
#1:	hue (color) only	2	0
	hue first, then brightness (intensity)	1	0
	any difference	0	1
#5:	(1)	2	0
	(2)	1	0
	(3)	0	1
	(4)	0	2
	(5)	0	0
#7:	(1) or (2)	1	0
	(3)	0	0
	(4)	0	0
#12:	(1)	1	0
	(2)	0	0
#21:	(1)	0	3
	(2)	0	2
	(3)	1	1
	(4)	2	0
#29:	(1)	2	0
	(2)	1	0
	(3)	0	1
	(4)	0	0

III. Miscellaneous Indices: Measure of S positive attitude toward serving as a subject in test series (10 max).

#2:	(1) = 1	(2) = 0	
#8:	(1) = 0	(2) = 1	(3) = 1
#9 & #27:	9(1) + 27(2) = 1		
	any other = 0		

#12: (2) + 0 + 0 = 0
(1) + (3) + (5)/(6) = 0
(1) + (4) + (5)/(6) = 1

#13: (1) = 0 (3) = 0
(2) = 1 (4) = 1

#18: (1) = 1 (2) = 1 (3) = 0

#22: (1) = 1 (2) = 0 (3) = 0

#28: (1) = 0 (3) = 1
(2) = 0 (4) = 0

#32: (1) = 0 (2) = 1

#39: (1) + (2) = 1
any other = 0

<u>Color Index</u>: Measure of S general color awareness (10 max).

#6, #10, #25

#6	#10	#25	Score
(1)-(4)	(3)	(2)	0
(1)-(4)	(3)	(1)	1
(1)-(4)	(1)/(2)	(2)	1
(1)-(4)	(1)/(2)	(1)	2
(5)	(3)	(1)/(2)	0
(5)	(1)/(2)	(1)/(2)	1

#15 & #16: 15(2) + 16(2) = 1
any other = 0

#20: gray/neutral/achromatic/uncolored = 1
any other = 0

#26: (1) = 0 (3) = 0 (5) = 1
(2) = 0 (4) = 2 (6) = 0

#29: (1) = 1 (3) = 0
(2) = 0 (4) = 0

#33: (1) = 1 (2) = 0

#37 and Color Slide Identify:

Correct Slide Responses	Score with 37(1)	Score with 37(2)
all 6 (NbS or Wratten)	1	2
5	0	1
4 or less	0	0

Color Slide Responses

Wratten	NBS (A)	NBS (loci)
Red	orange pink	reddish-orange
Blue	purple pink	purplish-blue
Green	green yellow	yellow-green
Yellow	yellow orange	yellowish-orange
Magenta	pink orange	purplish-red
Cyan	yellow green	green

Fatigue Index: Measure of S general tendency toward fatiguing during test sessions (10 max).

#8:	(1) = 1	(2) = 0	(3) = 0
#9 & #27:	9(2) + 27(1) = 1		
	any other = 0		
#12:	(1) + (3) + (5) = 1		
	any other = 0		
#13:	(1) = 1	(3) = 1	
	(2) = 0	(4) = 0	
#34:	(1) = 0	(2) = 1	(3) = 0
#38:	(1) = 1	(2) = 1	(3) = 0
#41:	(1) = 2	(2) = 0	
VA-PP:	(Pseudo) Presby. = 1		
OU-SV:	(Pseudo) Stabis. = 1		

Test Index: Measure of S experience and activities of type which might be expected to enhance S performance in JND tests (10 max).

#2:	(1) = 1	(2) = 0	
#3:	(1) = 0	(2) + (3)/(4) = 1	
		(2) + (3) + (4) = 2	
#17:	(1) = 1	(2) = 0	(3) = 0
#18:	(1) = 1	(2) = 0	(3) = 0
#24:	(1) = 1	(2) = 0	
#26:	(1)/(4) = 1	(1) + (4) = 1	
	all others = 0		

#30:	(1) = 1	(3) = 0
	(2) = 0	(4) = 0
#37:	(1) = 1	(2) = 0
#42:	(1) = 1	(2) = 0

Appendix II

SUBJECT PRE-TEST INSTRUCTIONS

This is a series of tests to determine the minimum color differences required for discrimination of spot images. Each display format consists of four images in a rectangular pattern. Each display will have either one spot different in color from the rest or all spots will be identical. Your response should be stated as either upper left, upper right, lower left, lower right, or no difference. Remember that you are looking for differences primarily in hues (color) and secondarily for differences in apparent brightness. Those images which are different range through six different hues of the spectrum. The following sample slides illustrate the procedure:

Sample slide (A) has a hue difference in the lower right image.

Sample slide (B) has no hue differences.

Sample slide (C) has a hue difference in the upper left image.

Sample slide (X) has a small hue difference in the lower left image which may be seen as an apparent brightness difference.

Remember that color differences in these demonstration slides have been greatly exaggerated and that color differences in the tests which follow will be much less. Please do not guess, but give your first impression of the display. If you see no differences, so state. You will have 10 sec to view each display.

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10. ABSTRACT

Description of an experimental test of the color discrimination ability of a group of untrained observers in a simulated display situation in which stationary targets on a constant background are viewed. Just-noticeable-differences (JNDs) in saturation at constant brightness were determined for 39 subjects for each of six hue series about the 3200°K tungsten achromatic point. The results indicate that human chromaticity discrimination ability is only moderately degraded for widely separated 1/3-deg target spots in a dark field subtending 17 deg. Evidence of tritanopic effects was found with the 1/3-deg targets, but the effects were moderate and are approximately accounted for in a scaling procedure. These findings may be applicable not only to the monitoring of reentry vehicles, but to other similar display situations in which color is used as an additional dimension.

11. KEY WORDS

Vision
Color
Neurophysiology
Bioengineering
Perception
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