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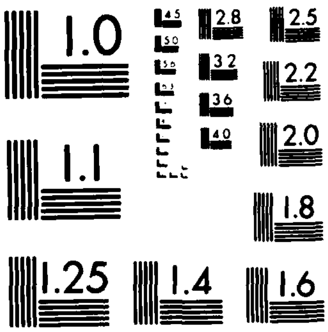

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THE PERCEPTION OF SATURATION AND HUE ON COLOUR CATHODE RAY TUBES

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13 July 1984

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As a result of the use of colour cathode ray tubes in military aircraft, an experiment is reported which considered the perception of hue at representative luminance levels. This experiment was conducted to test the theoretical lines of constant perceived hue in 1976 Uniform-Chromaticity-Space. A unique, computer-controlled tri-stimulus colorimeter was used to present two degree stimuli for hue match at luminance levels ranging from 250 to 2000 cd/m^2.

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PREFACE

The authors of this report would like to acknowledge the patient and kind assistance of Mr. Christopher P. Gibson of the Human Factors Group, Flight Systems Department, Royal Aircraft Establishment, without whose knowledge of the trichromator hardware this research would not have been possible.

Grateful thanks are extended to the following eight subjects who contributed enormous amounts of their time to the data collection effort: S. Browne, D. Delandro, J. Featherstone, J. Finch, C. P. Gibson, F. A. Greene, C. Wilson and J. Woods.

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1. INTRODUCTION

With the technological advent of high-brightness, high-resolution colour cathode ray tubes (CRTs), an obvious application for these devices is in military cockpits. In Great Britain the EH-101, Westland and Augusta helicopter, will use colour CRT technology. The future European Fighter Aircraft, a multi-nation development, will also have colour CRTs in the cockpit. In the United States the Air Force is placing this technology in the two-seat version of the F-15. In addition, plans include that these displays be used in the offensive station of the B-1B. Shadow mask colour CRTs have already been introduced into several civil aircraft cockpits, most notably, the Boeing 757 and 767.

The use of these displays is to aid in the presentation of many types of information to the system operator. It is hoped that by adding colour as another coding dimension to information portrayal, operator performance will be improved. The literature contains many studies investigating very specific applications of colour to display formats (1). However, the application of this technology is presenting some new problems for designers of these displays. Examples of such information displays require not only coloured symbols and alphanumerics to be viewed on a dark background but also superimposed over other different coloured backgrounds.

Unfortunately for the designers of colour CRTs, the only specifications and guidelines widely accepted deal solely with surface colours (2). Experts in the field of visual colour perception have recognized the failings of applying specifications for surface (reflective) colours to self-luminous (emitting) displays. It was recently noted that for the viewing of coloured alphanumerics on a dark CRT screen, an alternative to the Commission Internationale de l'Eclairage (CIE) specifications must be found (3). The CIE standards were only intended to guide the industries concerned with commercial interests such as paints, dyes and textile materials.

Over the past several years, researchers within Great Britain have been developing various models of human colour perception. These models are being constructed in order to enable predictions to be made about the perception of colour on self-luminous displays under varying viewing conditions (4,5,6) But to date, these models are purely theoretical. In order to validate, refine and extend these models to include a multitude of viewing condition parameters, a large volume of empirical data is needed. It is hoped that once these models are thoroughly developed, they can be used as a first step in making practical guidelines available for the designers of colour CRTs and for human factors engineers who must specify the use of colours for these devices.

The research reported in this paper is one of the first studies performed to gather part of the empirical data needed to validate the basic perceptual model. This study was designed to test the theoretical predictions of constant perceived hue and saturation as a function of luminance level. From these new data, answers can begin to be given to questions such as: 1) which colours should be used on a CRT to assure maximum discrimination, 2) what saturation level of colours should be chosen, 3) what effect do displays with phosphors possessing increasing luminance capabilities have on visual perception.

2. BACKGROUND

In 1931 the Commission Internationale de L'Eclairage (CIE) first published the data which have become known as the 1931 Standard Colorimetric Observer. The colour-matching properties of the 1931 Standard Observer are defined by colour-matching functions in the range of wavelengths visible to the human eye - 380 to 780 nanometers (nm). A corresponding 1931 CIE chromaticity diagram (figure 1) was created from a transformation of the colour-matching functions for the Standard Colorimetric Observer. Within this diagram, a line of dominant wavelength correlates approximately with hue, and is portrayed by a straight line drawn from the achromatic point (white point) to a point on the spectrum locus (figure 2). Colorimetric or excitation purity, which correlates with saturation, is portrayed as shown in figure 2. A chromaticity diagram is a two-dimensional representation of a three-dimensional space; the third dimension being luminance. Therefore, a chromaticity diagram is showing a slice taken at a given luminance plane; i.e., iso-luminance.

However, the 1931 CIE chromaticity diagram does not represent a perceptually uniform colour space; i.e., it does not portray the distance between pairs of points as being proportional to the perceptual size of the colour distance between the two points.

The most recent attempt to construct a perceptually uniform colour space is the 1976 Uniform-Chromaticity-Scale (UCS) diagram. The UCS colour space is a transform of the original

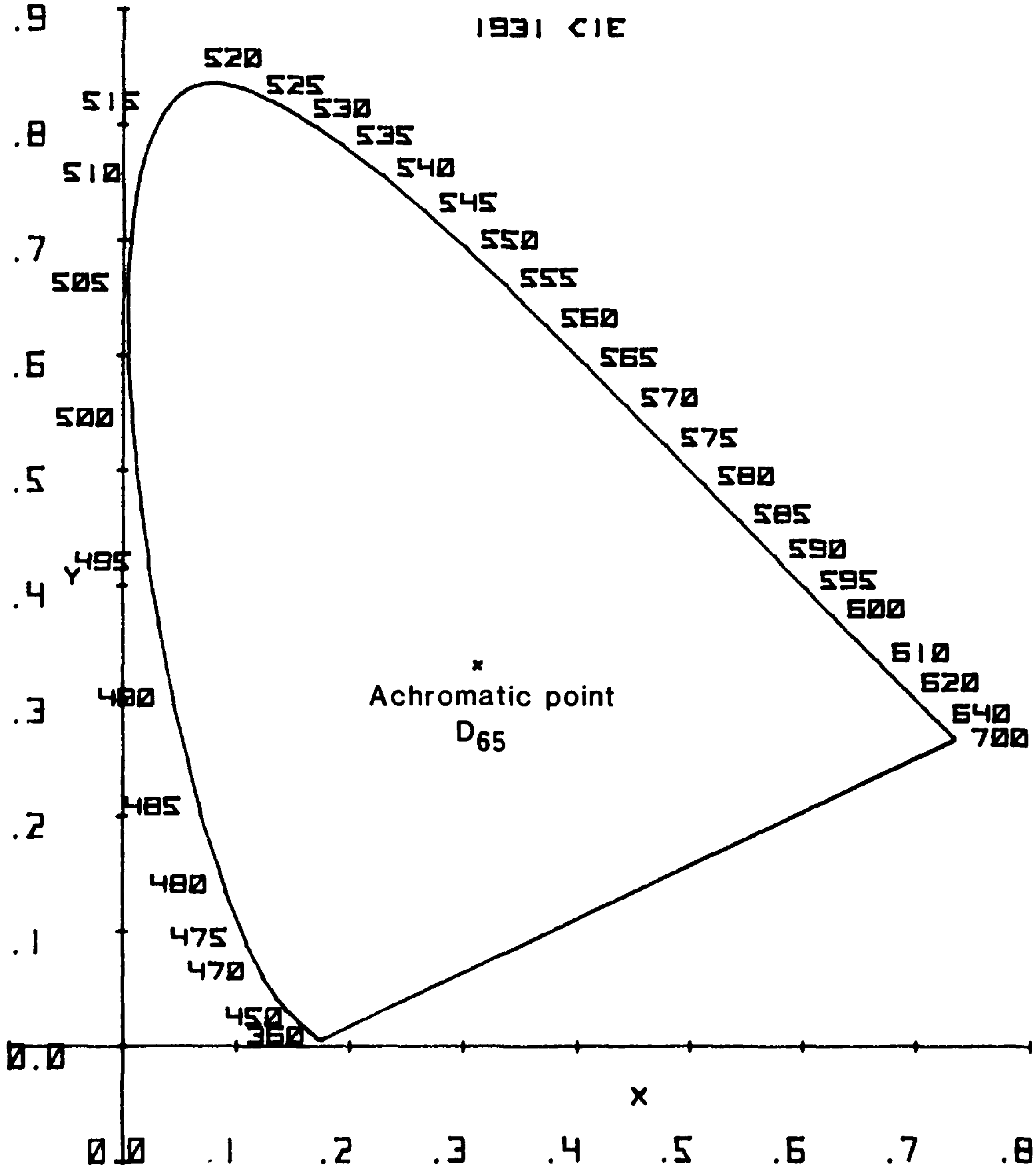

FIG 1 1931 CIE CHROMATICITY DIAGRAM

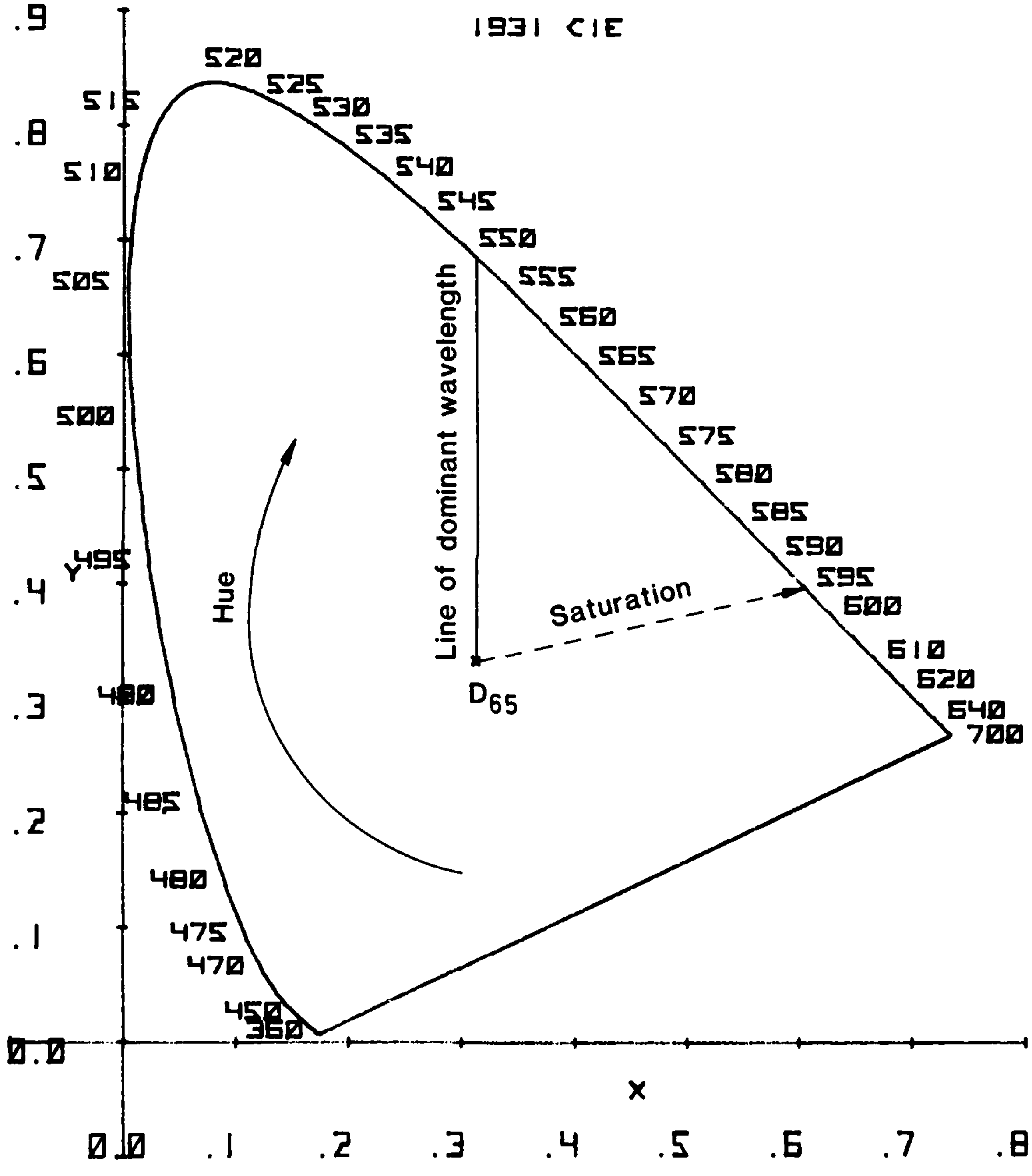
1931 CIE
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
Y
520
525
530
535
540
545
550
555
560
565
570
575
580
585
590
595
600
610
620
640
700
515
510
505
500
495
490
485
480
475
470
450
360
Hue
Line of dominant wavelength
Saturation
D_{65}
X
0.0
.1
.2
.3
.4
.5
.6
.7
.8

FIG 2

1931 CIE diagram. If it is accepted in theory that the 1976 UCS diagram does accurately represent a "uniform" colour space, then several assumptions follow:

Lines of constant perceived hue: From figure 3 it can be seen that lines of constant hue are shown as straignt lines drawn from the white point. All points on the radial line represent stimuli of the same hue. Figure 4 shows theoretical lines of constant perceived hue within the 1976 UCS diagram.

Lines of constant perceived saturation: Again from figure 3, lines of constant saturation are portrayed as circles centered at the white point. Points on the circle represent stimuli of constant saturation, with lines of higher level saturation represented as circles of increasing radius. Figure 5 shows theoretical lines of constant perceived saturation within the 1976 UCS diagram.

It must be remembered that the 1976 UCS diagram is a surface of a single, constant luminance. Figure 6 shows the third dimension of luminance.

Previous Research: Loci of constant hue have been a subject of previous research, both theoretically and empirically derived. MacAdam, 1950 (7) plotted, in 1931 colour space, loci of constant hue as a function of various surround colours. In 1951, MacAdam (8) plotted, again in 1931 CIE space, loci of constant hue and saturation. But his research was performed with an adapting surround field and at relatively low luminance levels. When

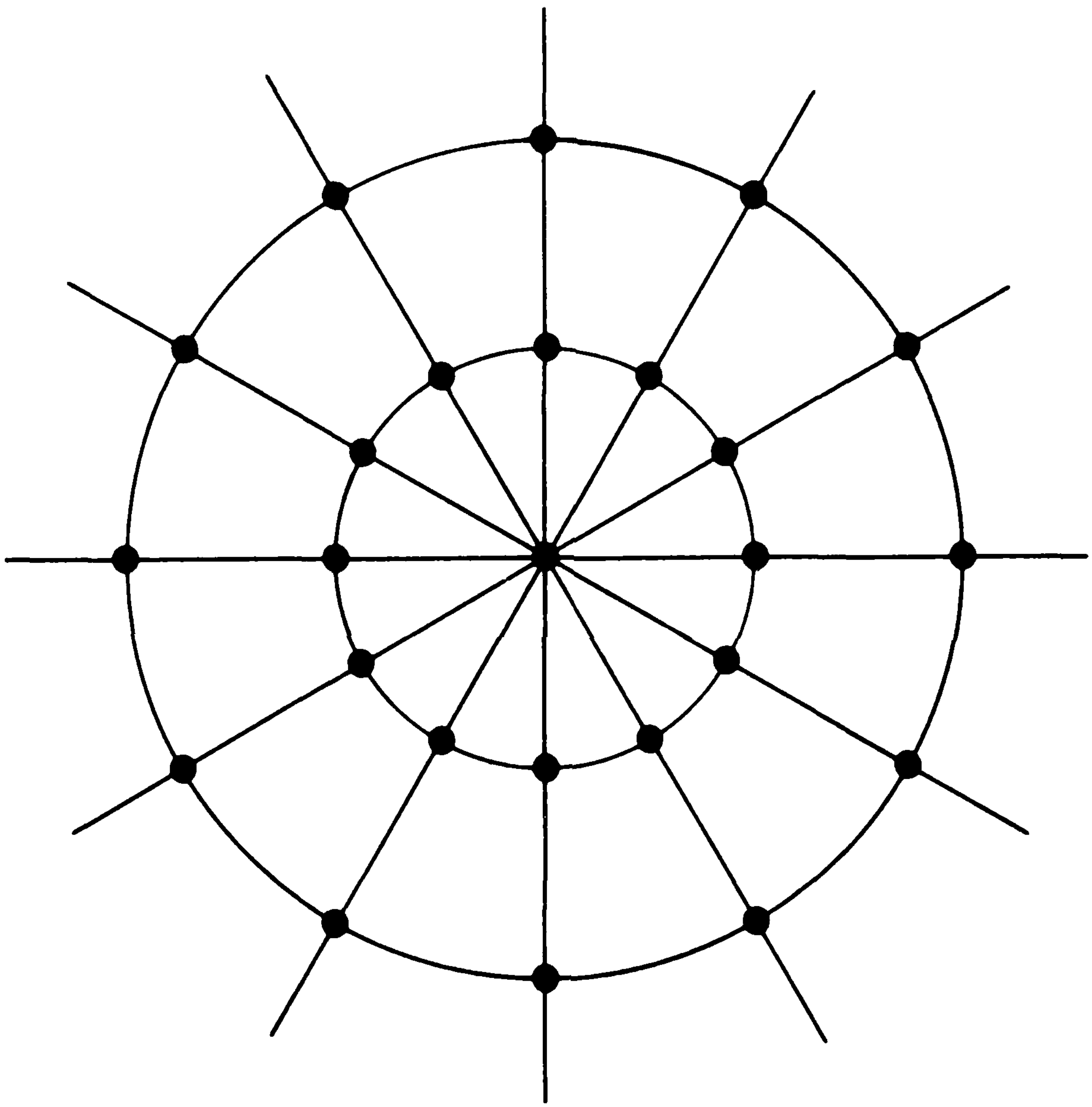

FIG 3 LOCI OF CONSTANT HUE AND CONSTANT SATURATION ON A SURFACE OF CONSTANT LIGHTNESS
(From Wyszecki and Stiles 1982)

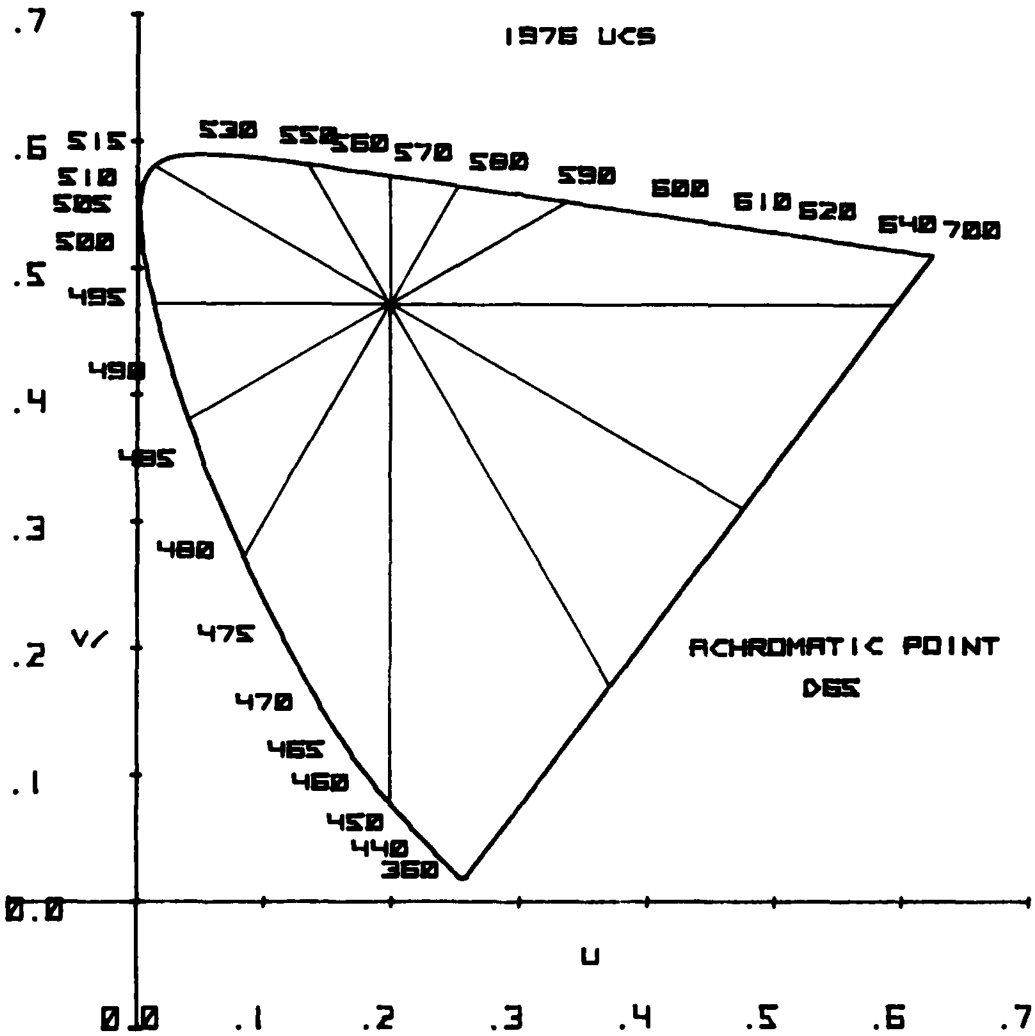

FIG 4 THEORETICAL LINES OF CONSTANT PERCEIVED HUE IN 1976 UCS DIAGRAM

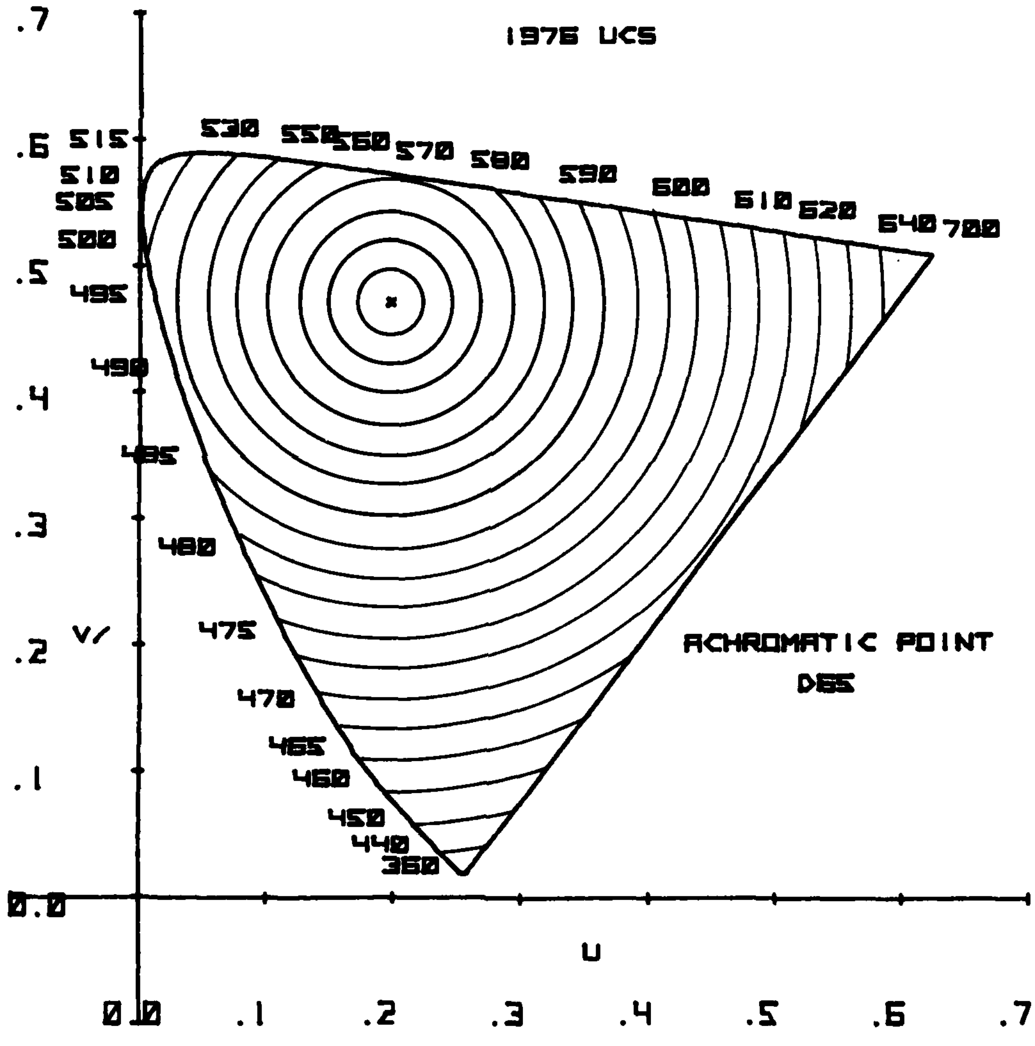

FIG 5 THEORETICAL LINES OF CONSTANT PERCEIVED SATURATION IN 1976 UCS DIAGRAM

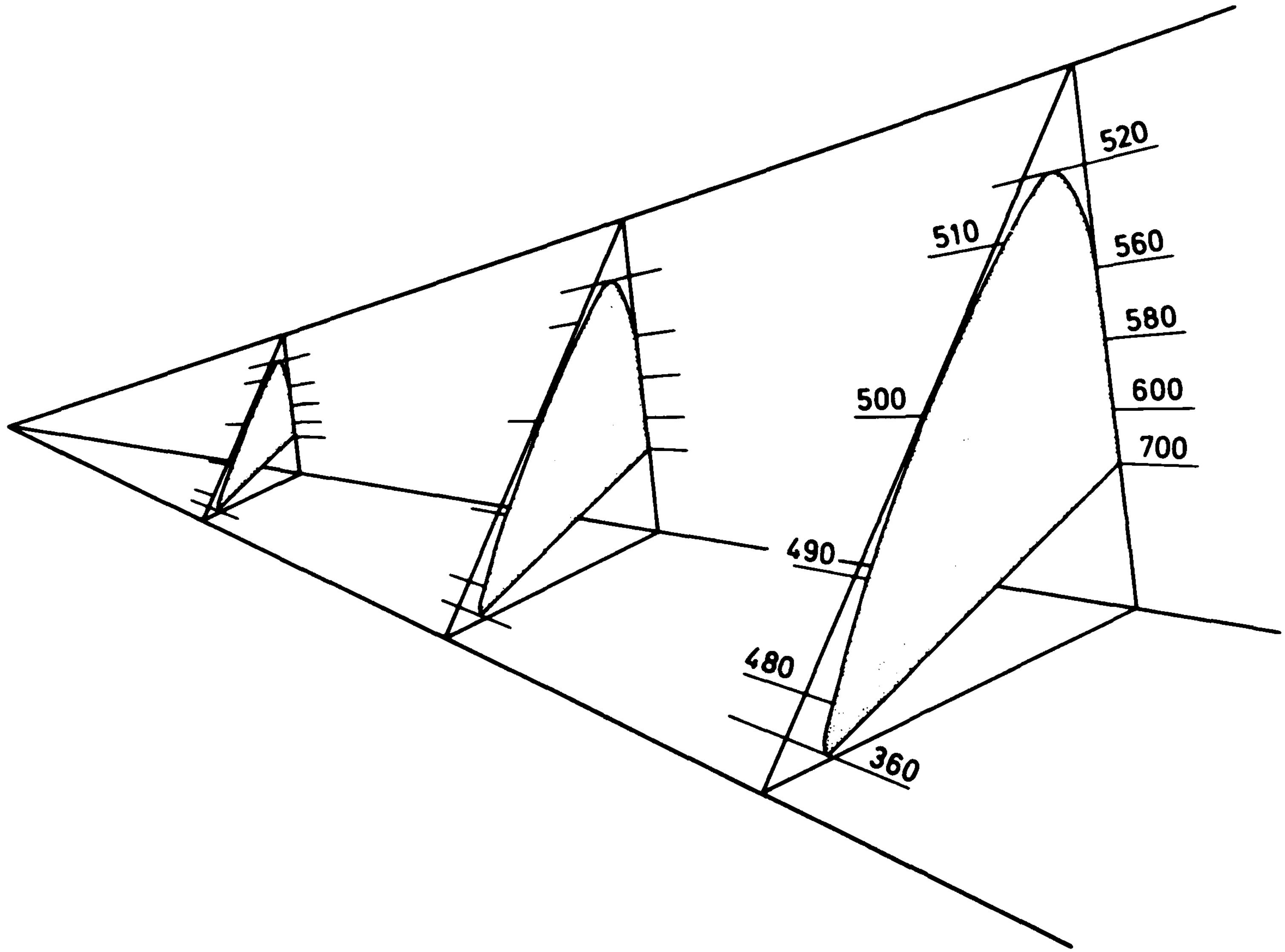

FIG 6 1931 CIE COLOUR SPACE – LUMINANCE: THE THIRD DIMENSION viewing a colour CRT display, the viewing condition arises that the symbology is viewed on a dark background, therefore, MacAdam's results would not be applicable to present viewing circumstances. Also, MacAdam's data are plotted in the 1931 CIE diagram, which was never intended to be representative of a perceptually uniform colour space.

From a purely theoretical base, Wyszecki and Stiles, 1967 (9), derived a series of geodesic lines and circles all based on Stiles' line element. This different approach to constructing a uniform colour space gets its basis from the theory and assumptions of the operation and function of the visual process. Figure 7 shows a plot of these geodesic lines. It should be noted that these lines very closely resemble lines of constant hue and constant saturation.

Robertson, 1969 (10), used three experimental methods to determine lines of constant hue. However, his stimuli were viewed against an adapting surround field, which is again not representative of anticipated colour CRT viewing conditions. Also, his data are plotted in the 1960 Uniform Chromaticity Space, the predecessor to the 1976 UCS diagram.

Bartleson, 1979 (11), plotted contours of constant colour appearances in the 1976 UCS diagram. However, Bartleson was examining the change in colour appearance as a function of different chromatic adaptations. In addition, his stimuli were presented as surface colours.

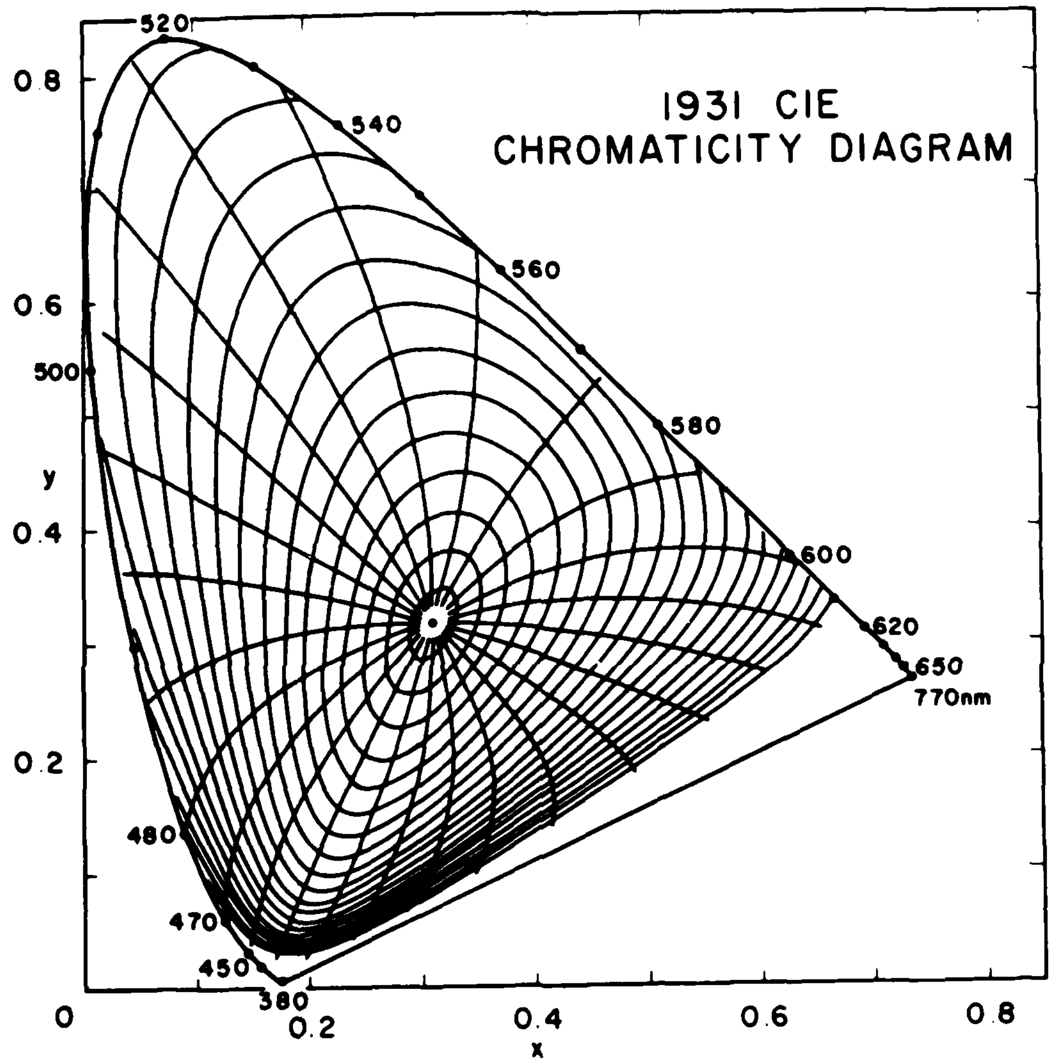

FIG 7 NETWORK OF GEODESIC LINES AND CIRCLES, DERIVED FROM STILES' LINE ELEMENT, RESEMBLING LINES OF CONSTANT HUE AND SATURATION
(From Wyszecki and Stiles 1982)

Uchikawa et al, 1982 (12), empirically derived a set of equally saturated stimuli using a modified step-by-step brightness matching method. They plotted these equally saturated colours produced in their experiment in the 1976 UCS diagram. However, their stimuli were determined at equal brightness, not equal luminance, which they offer as an explanation for why their data did not plot as a circle within 1976 colour space.

It can be seen from the above outline of past research that data on lines of constant hue and constant saturation have not been produced previously for aperature colours viewed against a dark surround and dealt with in 1976 UCS space. In addition, the luminance levels examined in the previous research are, for the most part, much lower than the luminance levels capable of being produced on state-of-the-art shadow mask CRTs. The research described herein addresses these experimental conditions.

3. APPARATUS:

In the proposal for this reseach, the experimental hardware was to be an actual high-resolution, high-brightness colour CRT, driven by a digital image processing computer. However, it was very quickly determined that the precision of the computer software used to drive the CRT guns to produce a colour stimulus of an exact chromaticity was not sufficient for this basic research.

Therefore, the research was transferred to an existing, unique, computer-controlled tri-stimulus colorimeter. This hardware, henceforth referred to as the trichromator, is shown diagrammatically in figure 8. Briefly, the trichromator consists of the following: three, 1-kilowatt xenon arc lamps as light sources; three tunable monochromators, accurate to 0.1 nm; pairs of neutral density (ND) wedges to control the luminance output reaching the subject's eye; and associated optical lenses and beam splitters shown in the diagram. A more complete description of the trichromator is found in reference 13.

The operation of the trichromator hardware was completely automated and was controlled by a DEC PDP 11/05 computer. The computer controlled the precise positioning of the diffraction grating of each of the three monochromators which determined the wavelength output. Positioning of one of the neutral density wedges, by driving the stepper motors connected to the ND wedge, was also automated. (For this experiment the second ND wedge remained static.) This movement of the ND wedge controlled the

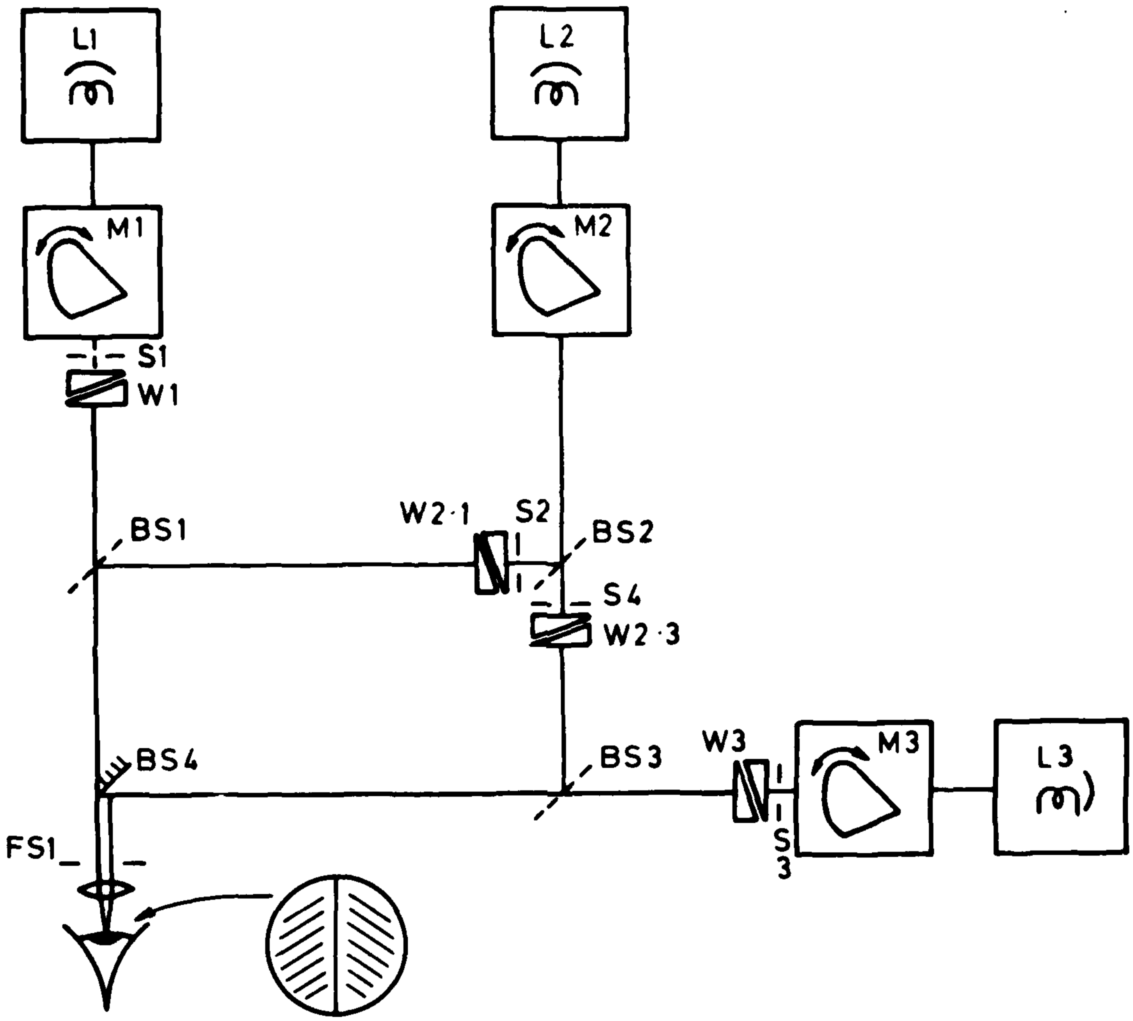

FIG 8 OPTICAL REPRESENTATION OF THE TRICHROMATOR HARDWARE

luminance produced by each arm of the trichromator.

The subjects were presented with a bi-partite field, in Maxwellian-view, in which a field stop was placed to form two, 2 degree circular fields, separated by 2 degrees. The field viewed on the right by the subject is referred to as the TEST FIELD. The field on the left is referred to as the VARIABLE FIELD.

Figure 9 shows how the trichromator operates in chromaticity space. For this experiment the monochromator in arms 2 and 4 were always set at 650 nm. The output from arm 1 and arm 2 were mixed to form the chromaticity required for the test (or comparison) field. Similarly, output from arms 3 and 4 were combined to produce the chromaticity of the variable field. The following equations derived by Hunt (14) were used to calculate the required monochromator settings for arms 1 and 3 and luminance requirements for all four arms.

Given that:

$$X3 = (((X1/Y1) \times L1) + ((X2/Y2) \times L2))/((L1/Y1) + (L2/Y2))$$

$$Y3 = ((L1+L2)/((L1/Y1) + (L2/Y2)))$$

and that $L1 + L2 = L3$

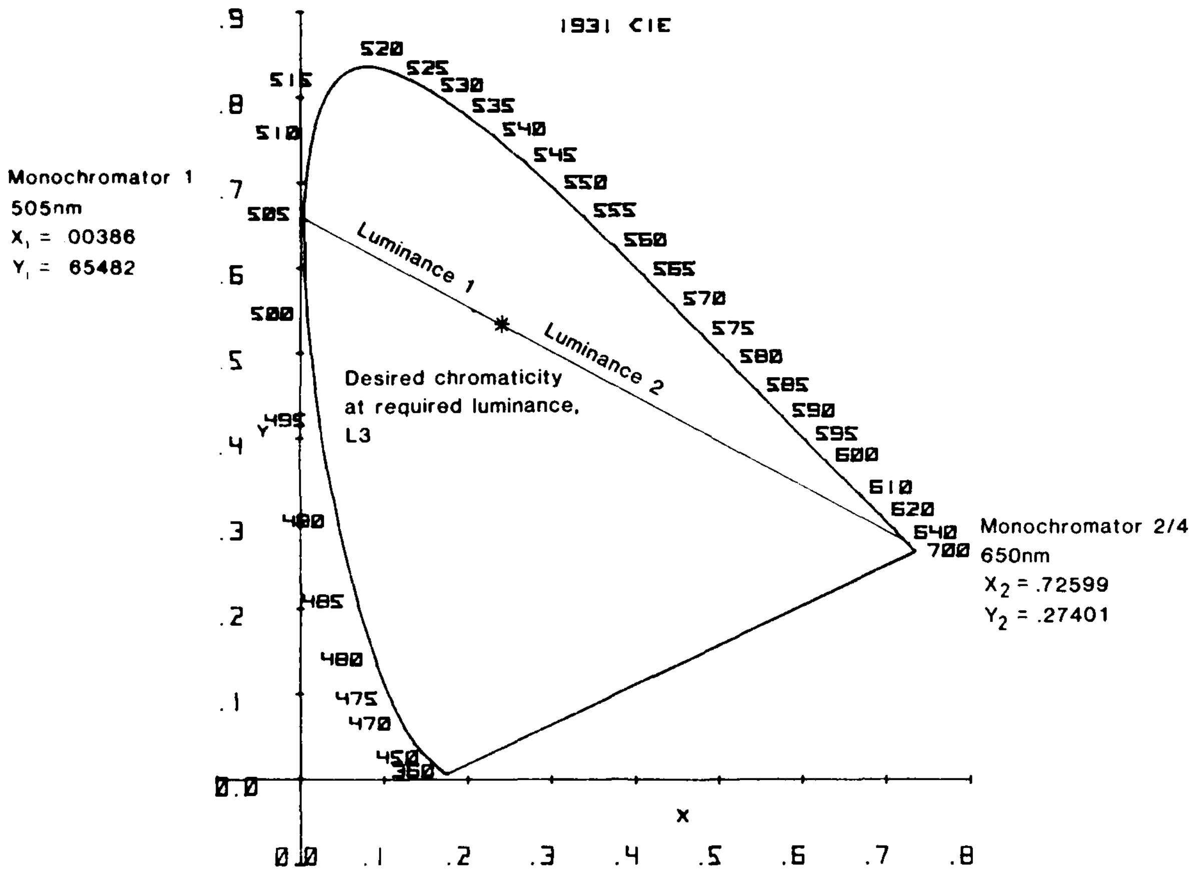

FIG 9 LIGHT AT WAVELENGTH 505nm AT LUMINANCE 1 IS COMBINED WITH LIGHT AT WAVELENGTH 650nm AT LUMINANCE 2 TO PRODUCE DESIRED CHROMATICITY OF LUMINANCE L3 - SHOWN BY '*'

where (X1, Y1), (X2, Y2), (X3, Y3) are pairs of 1931 CIE chromaticity coordinates for Monochromator 1 wavelength setting, Monochromator 2 wavelength setting and desired point inside chromaticity space, respectively. Also, L1 = Luminance from arm 1, L2 = Luminance from arm 2 and L3 = Luminance of resultant point of desired chromaticity.

It follows that:

$$L1 = ((-d/(c-d)) \times L3) \text{ and } L2 = ((c/(c-d)) \times L3)$$

$$\text{where } c = ((Y3-Y1)/Y1) \text{ and } d = ((Y3-Y2)/Y2)$$

All four arms of the trichromator were continuously calibrated in luminance for the wavelength range required during each experimental session. The luminance calibration data were stored at 1 nm intervals over the full range of the ND wedge. Therefore, interpolation of wavelength settings to 0.1 nm accuracy was possible, as well as the interpolation of corresponding wedge position needed to achieve a certain luminance. In this way, constant controlled luminance in both fields was ensured.

The calculations using the above equations were all done with coordinate pairs within the 1931 CIE chromaticity space. Subsequently, a transform was performed on the final resultant calculations to change them into 1976 UCS coordinates.

4. METHOD AND PROCEDURE

4.1 Subjects: Five females and three males, ranging in age from 20 to 33, tested as colour-normal with the Ishihara Colour Plates, served as subjects for the experimental sessions. All eight subjects were used in the determination of three of the five lines of constant perceived hue: 470, 520 and 640 nm. Due to unavoidable loss of subjects, six of the eight were used to determine the line of constant hue for magenta, and five of the eight for 570 nm.

4.2 Procedure: Five areas of the chromaticity diagram were chosen for the empirical determination of lines of constant perceived hue. Figure 10 shows the five theoretical lines, whose dominant wavelengths were: 470 nm (blue), 520 nm (green), 640 nm (red), 570 nm (yellowish-green) and magenta (u' = .42553, v' = .24468). A shadow-mask colour CRT, being a three gun system, is capable of producing stimuli that are red, green, blue and their complementary colours of cyan, magenta and yellow; thus, the rationale for the hue areas of the chromaticity diagram chosen for experimental investigation. However, in the interest of the time remaining on the grant, only five of the six hues were examined, with cyan being the hue omitted.

4.3 Method: Subjects viewed, in Maxwellian-view, two, 2 degree circular stimulus fields. These fields were viewed against a dark background, i.e., there was no adapting surround field present. Subjects were attached to a dental bite bar during each experimental run to ensure continuity of head

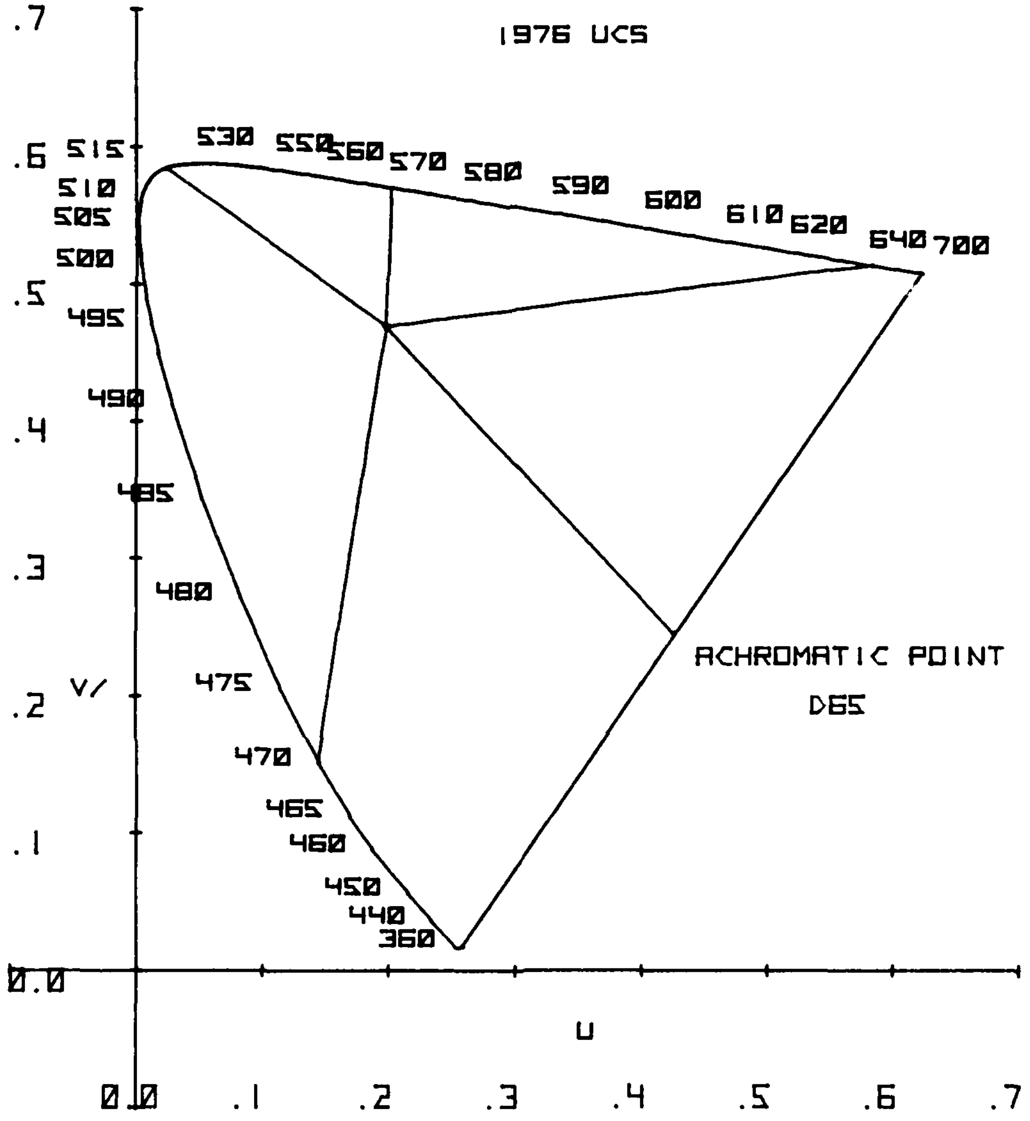

FIG 10 THEORETICAL LINES OF CONSTANT HUE EXAMINED EXPERIMENTALLY

alignment. Due to the nature of the trichromator and the mixing of light from different sources to form the resultant stimuli, it was found that head and eye alignment were critical. Considerable time was spent before each trial assuring proper alignment.

The test, or comparison, stimulus was the field viewed on the right. The variable, or changing, field was the one on the left. The test field for the first trial of each experimental session was predetermined and remained fixed at a constant chromaticity and luminance level. The variable field was always of a fixed saturation level which was slightly higher than that of the test field. However, the luminance level of the test and variable fields were always identical.

Figure 11 shows the five theoretical lines of constant hue in the 1976 UCS diagram. The distance in chromaticity space over which the variable field traversed is indicated by the lines shown at right angles to the predicted line of constant perceived hue. The first field, the test stimulus, is indicated in the figure by the "x". The test field was always 10 just-noticeable-differences (JNDs)(10 x 0.004u') (15) away from the achromatic point of illuminant D65 (u' = .1978, v' = .4683). D65 was chosen for the illuminant point in the calculations because of its proximity to daylight conditions experienced in the cockpit of a modern canopy fighter aircraft. However, it must be noted that the subjects never actually saw an achromatic stimulus during the experiment. The experimental trials began

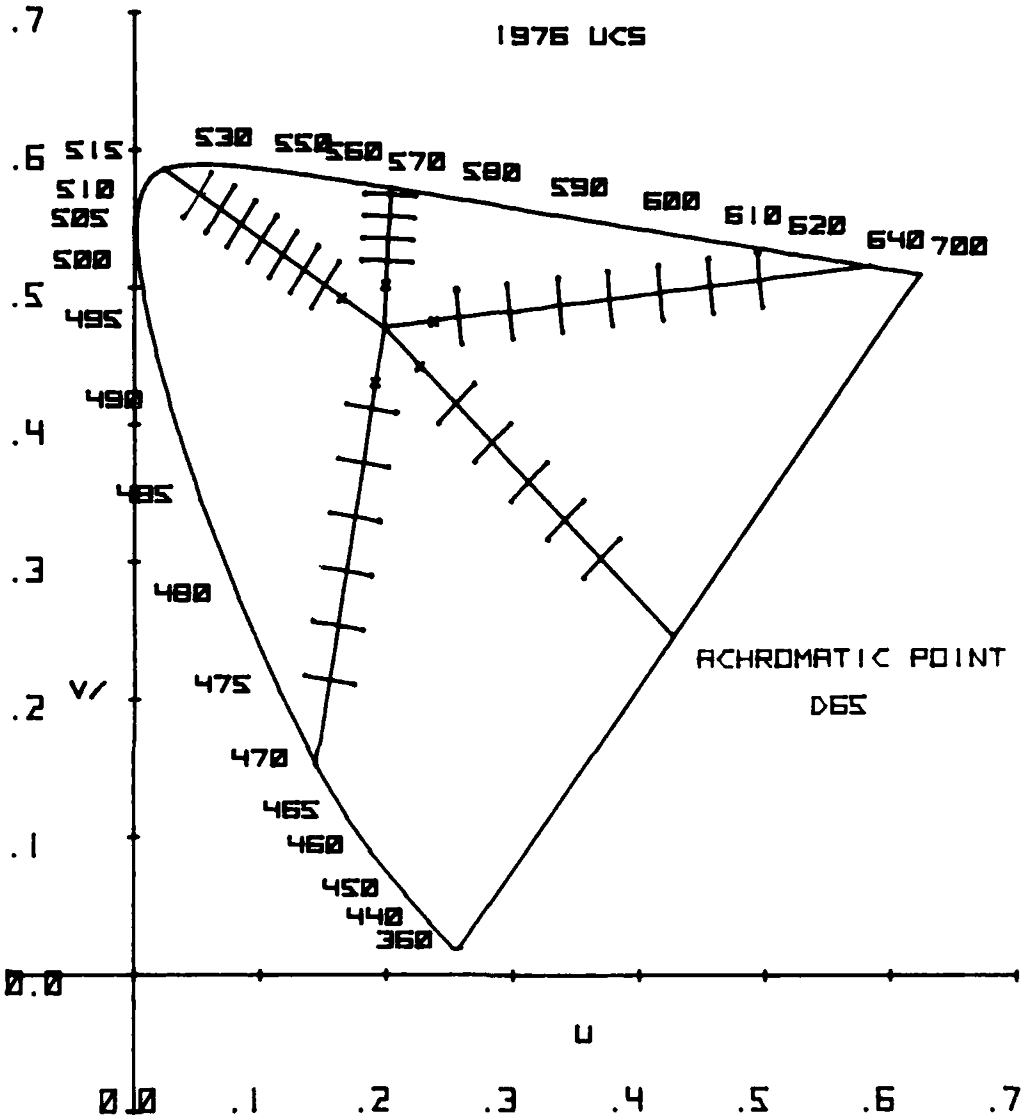

FIG 11 AREAS OF CHROMATICITY DIAGRAM FOR TEST FIELD (x) AND VARIABLE FIELDS

with the test field at 10 JNDs from D65 and proceeded with successive variable fields increasing in saturation out along the line toward the spectrum locus.

The subjects used the method-of-limits procedure to determine the threshold for a match between the test (comparison) field and the variable field. Instructions to the subject were to press a response button when they felt that the difference in dominant wavelength between the two fields was at a minimum. Further instructions included not to press the response button if they felt that they had missed the match.

The subjects made 10 matches in hue at each saturation level between the test and variable field. Five matches were made with the variable field beginning at one end of the line parallel to the predicted line; and alternated with five matches made from the opposite direction. The variable field traveled in a line perpendicular to the predicted line of constant hue. The extent of the chromaticity diagram covered by each variable field was plus and minus 5 JNDs (5 x 0.004u') on either side of the predicted match point (the point lying on the theoretical straight line). The movement along the line shown in figure 11 comprising the variable field was in 1/4 JND steps, for a total of 41 steps for the completion of each variable field from one end to the other. The computer logged monochromator and wedge position for each match point. From this information 1976 u',v' chromaticity coordinates for the subjects' matches were calculated.

After 10 matches were made by each subject, the next "test" field was calculated in real time as being the mean of the 10 matches. This new test field was then presented in the right hand field, and the next variable field was judged against the new comparison field. This experimental procedure continued in the same manner until all the variable fields had been exhausted. The same method was used for each luminance level condition.

It is important to note that shutters in the trichromator system were opened at the beginning of each experimental trial and were not closed until 10 matches were completed. The shutters remained closed while the computer calculated monochromator position and wedge positions for the next comparison field. Each match took approximately 30 seconds to make, with an experimental session lasting between 15 to 30 minutes.

4.4 Design: A latin square design was chosen to minimize any order effects of luminance level. All five areas of the chromaticity diagram were investigated at four luminance levels: 250, 500, 1000, and 2000 cd/m^2.

Four preliminary practice sessions with six variable field comparisons at one luminance level were completed by all subjects. This pratice familiarized the subjects with the difficult ask of detecting very small colour differences.

As can be seen from figure 11, the number of saturation levels for each line of dominant wavelength was not the same.

This is due partly to the fact that, for example, in the yellow part of the UCS diagram (570-580 nm), the distance between the achromatic point and the spectrum locus is very small compared with other areas of the diagram. Also, it can be noted that with two exceptions, the saturation levels fall short of the spectrum locus. The reason for this is that the calculations for the variable field would either have put the stimuli outside of the spectrum locus, or would have required an exceedingly small luminance output from one of the arms. An effort was made to keep the distance between saturation levels as constant as possible for all lines. However, this was not stricly achieved because of the excessive length of experimental trials that would have been required for some areas of the chromaticity diagram. Therefore, it was important to try to maintain an approximately equal number of saturation levels between lines of dominant wavelength.

5. RESULTS

A global summary of the results of the above described experiment are shown in figure 12. The five lines of theoretical constant perceived hue are portrayed in the 1976 UCS diagram, together with their empirically derived lines of constant hue. In order to construct the data within the diagram, the two extremes of subjects' mean deviation from the predicted line were obtained. This range is diagramatically illustrated by the pair of lines drawn in conjunction with each individual hue line investigated.

It is very important to note that the "corridors" of constant hue, represented by the range of delta distances, are plotted at five times the delta deviation actually obtained in the experiment. This magnification of deviation is performed strictly to enhance the readability of the figure. Under no circumstances should any u', v' chromaticity coordinates be read off this figure and interpreted to be representative of the actual results of this experiment.

This summary figure is provided only to give the reader a quick overview of the size differential for the ranges of deviations between lines and a flavor for the trends of the general shapes of the lines of constant perceived hue derived under the experimental conditions studied.

The balance of this section is dedicated to a detailed

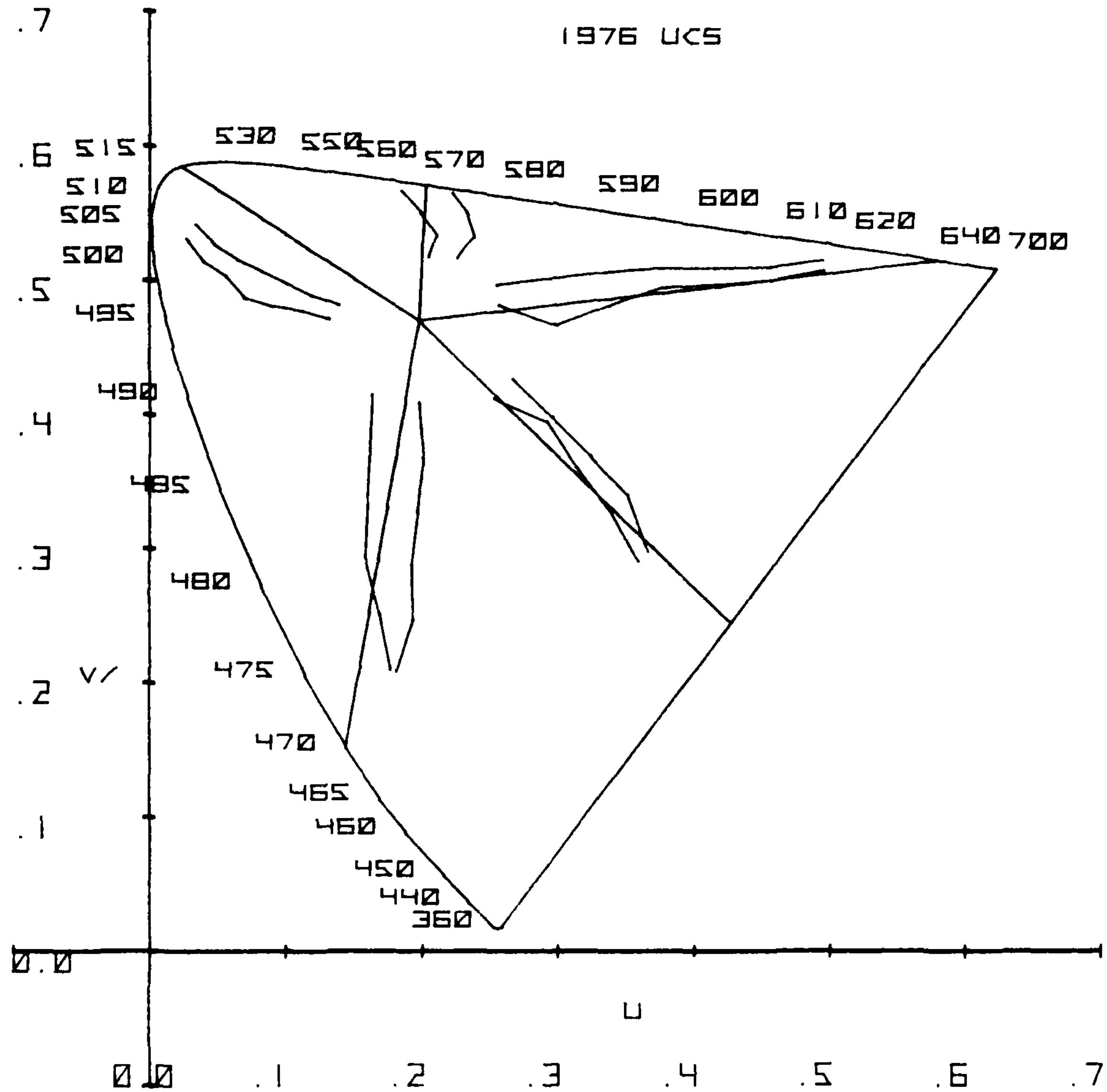

FIG 12 FROM EXPERIMENTAL RESULTS – RANGE OF DELTA DISTANCES FROM PREDICTED LINE OF CONSTANT PERCEIVED HUE. <u>NOTE</u>: DELTAS ARE MULTIPLIED BY A FACTOR OF 5 FOR CLARITY OF PRESENTATION

presentation and discussion of the statistical analysis results obtained. For all data analyses subjects' individual and mean u',v' pairs for match points were converted into a single measure of "delta distance." This delta reflects the amount and the direction of deviation of the subjects' match point from the predicted line of constant perceived hue. In order to achieve this, an equation for each line of constant hue was calculated. Subjects' u',v' pairs were entered into the equation and deltas from this line were computed with direction being accounted for by a signed delta. All delta measures are standardized so that the resultant units are of the same metric. In this manner, delta distances can be directly compared in all parts of the chromaticity diagram.

Because the saturation levels between hue lines were not a constant number and not representative of identical steps in saturation from the achromatic point, data from each hue line were analyzed individually. A separate four-way analysis of variance (ANOVA) with replications was performed on the delta distances pertaining to each line of constant perceived hue.

For all data, factors investigated included: subjects (S), replications (R), saturation level (I for Intensity), luminance (L), and direction (D). The ten replications were split into five pairs, of which the first replicate pair was dropped from the analyses. It was found that a large proportion of the total missed responses occurred during the first two replications. It was theorized that the subjects were watching the movement of the first variable field completely through from one end to the other to ascertain the amount of hue change involved in each step. It was felt that if the subject responded at all during the first two trials, it would have been late - after the match had already passed. Data for all missed responses during subsequent replications were estimated through the least squares method.

Analysis of where the subject made his/her response as a function of the direction in which the variable field started moving, i.e., from which end of the variable field the trichromator started stepping, may provide some insight into the strategy adopted by the subject.

For purposes of convenience and clarity of presentation of data in figures and tables, delta distances are multiplied by a factor of 10. In the reporting of delta distances, a positively signed delta is indicative of a clockwise movement within the chromaticity diagram relative to the theoretical line of constant perceived hue. The presentation of the data are organized by individual hue lines.

5.1 470 nm (Blue):

The analysis for 470 nm is split into two parts: one for luminance levels 1, 2, and 3 (corresponding to 250, 500 and 1000 cd/m^2, respectively) and one for luminance 4 (2000 cd/m^2). The reason for this second analysis is that during the experimental trials, several subjects reported that the area of chromaticity space covered by plus and minus five JNDs either side of the predicted hue line was not sufficient to include their perceived match point. Therefore, for luminance level 4 only, the area within the chromaticity diagram tracked by the variable fields was doubled, i.e., plus and minus 10 JNDs either side of the theoretical match point. Because of this doubling of track size, saturation levels had to be altered to accommodate six saturations within the chromaticity space. Thus some of the saturation levels investigated at luminance 4 were different and, therefore, not comparable with the saturations studied at luminance levels 1 through 3.

5.1.1 Luminance levels 1, 2, and 3: The resultant empirical line of constant perceived hue for 470 nm is plotted in figure 13. The experimentally-obtained line lies across the theoretical line for 470 nm - starting on the green side of it at the lower saturation levels and crossing over to the blue side at increased saturation levels. The shape of this empirically derived line is the same regardless of luminance level, therefore, figure 13 shows a plot of the mean for the three luminance levels tested.

The analysis of variance table for these data is summarized in Table 5.1. For the sake of clarity, the label "I" is used throughout the report in the tables to signify "saturation level," so as not to be confused with "S" for subjects. From the ANOVA table it can be seen that the only significant source of variation is saturation level. This significance is clearly illustrated in figure 14 - a plot of delta distance as a function

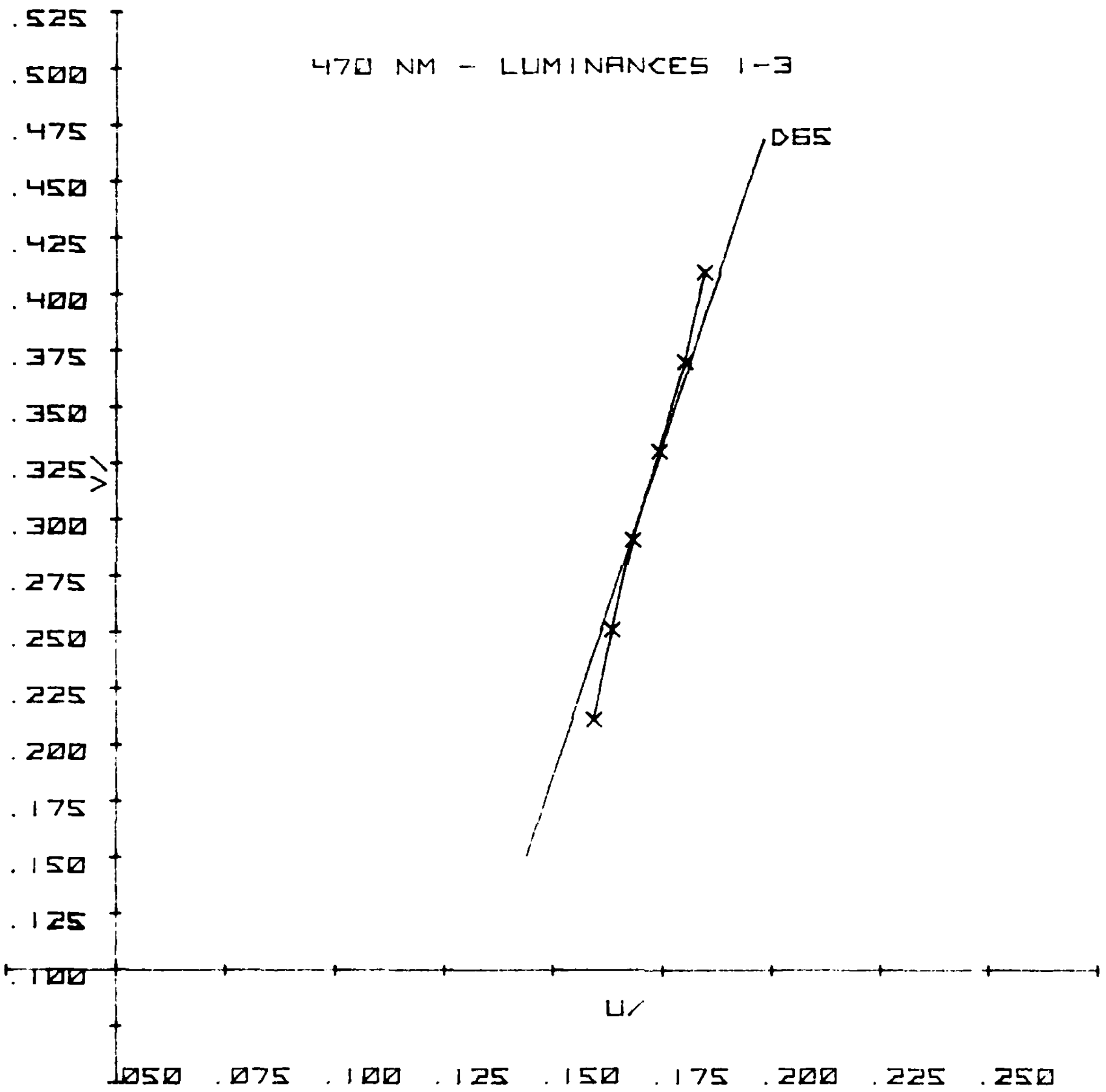

FIG 13 470nm EMPIRICALLY DERIVED LINE OF CONSTANT HUE (MEANED OVER LUMINANCES 1-3)

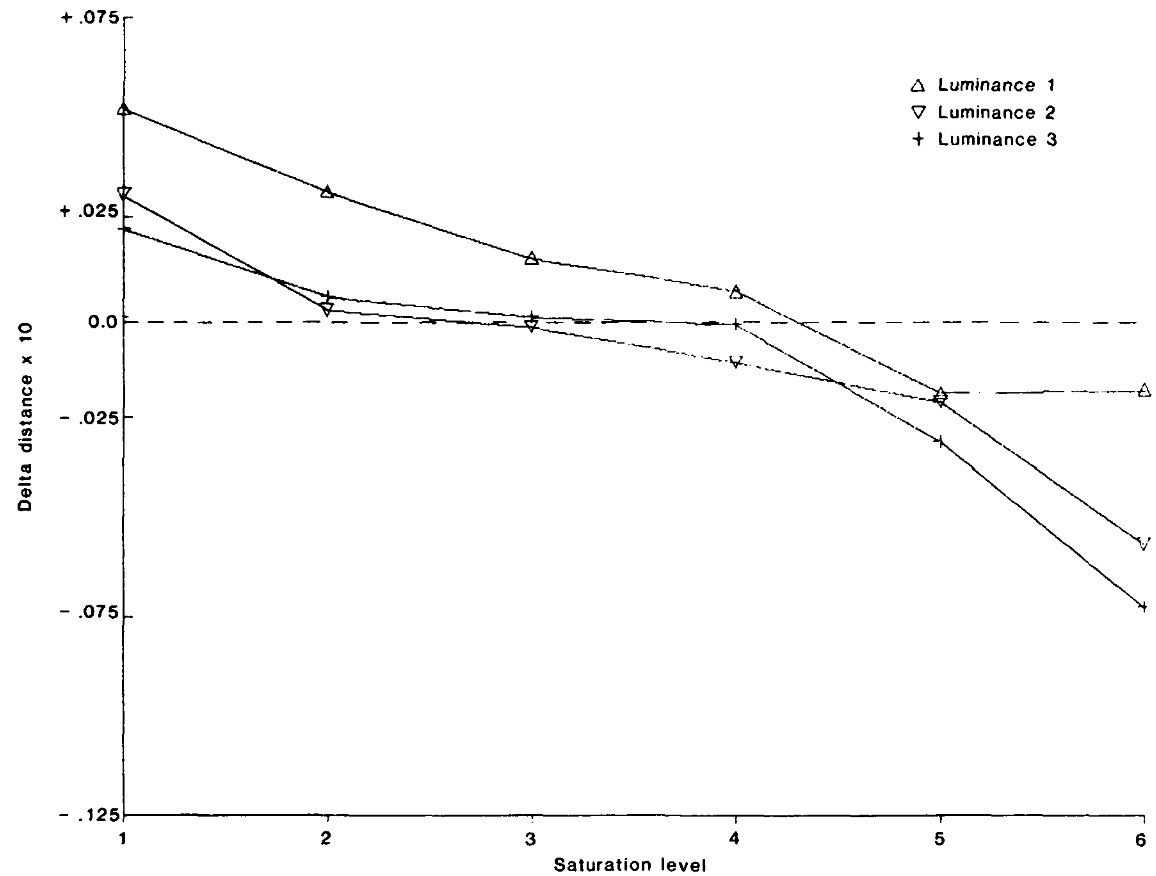

FIG 14 470nm DELTA x SATURATION LEVEL FOR L1, L2 AND L3 (L x I) of the six saturation levels for the three luminance level conditions. This plot of delta deviation from the predicted line across the saturation levels is not zero - i.e., it is not a flat line. Table 5.2 gives the subjects' mean delta distances at each saturation level for luminances 1, 2, and 3. Again it must be noted that all delta distances are normalized and multiplied by a factor of 10. Also, for this case, a positive delta is indicative of the point lying above (to the green side of) the theoretical line. In the same manner, a negative delta is for a point which lies below (to the blue side of) the predicted line. Table 5.3 converts those delta distances into u', v' coordinates for the mean hue match point for the three luminance levels.

Source	SS	df	MS	Error	F	Prob
Subjects (S)	0.4062	7	0.58E-01			
Replications (R)	0.1332	7	0.19E-01	RS	0.534	0.8045
RS	1.7456	49	0.36E-01			
Saturation (I)	0.8294	5	0.1659	IS	11.421	0.000 ***
IS	0.5083	35	0.145E-01			
Luminance (L)	0.1341	2	0.67E-01	LS	0.65	0.5345
LS	1.4449	14	0.103			
RI	0.1271	35	0.36E-02	RIS	1.086	0.3486
RIS	0.819	245	0.33E-02			
RL	0.61E-01	14	0.43E-02	RLS	0.876	0.586
RLS	0.4815	98	0.49E-02			
IL	0.565E-01	10	0.565E-02	ILS	0.547	0.8507
ILS	0.7231	70	0.103E-01			
RIL	0.2229	70	0.32E-02	RILS	1.154	0.1996
RILS	1.1977	434	0.276E-02			
TOTAL	8.8899	1095				

Table 5.1 - ANOVA 470 nm

	SAT 1	SAT 2	SAT 3	SAT 4	SAT 5	SAT 6
Lum 1	0.523E-01	0.313E-01	0.146E-01	0.630E-02	-.193E-01	-.184E-01
Lum 2	0.308E-01	0.151E-02	-.279E-02	-.117E-01	-.214E-01	-.568E-01
Lum 3	0.224E-01	0.491E-02	-.208E-03	-.196E-02	-.314E-01	-.725E-01
MEAN	0.351E-01	0.126E-01	0.388E-02	-.244E-02	-.240E-01	-.493E-01

TABLE 5.2 470nm Delta Distance - Saturation X Luminance

	Luminance 1		Luminance 2		Luminance 3		Mean	
	u'	v'	u'	v'	u'	v'	u'	v'
Sat 1	.1826	.4100	.1847	.4096	.1856	.4095	.1843	.4097
Sat 2	.1780	.3700	.1809	.3697	.1806	.3698	.1799	.3699
Sat 3	.1730	.3305	.1747	.3302	.1745	.3302	.1741	.3303
Sat 4	.1671	.2909	.1689	.2906	.1680	.2908	.1680	.2908
Sat 5	.1630	.2511	.1632	.2510	.1642	.2508	.1635	.2510
Sat 6	.1562	.2116	.1600	.2110	.1616	.2107	.1593	.2111

Table 5.3: Chromaticity coordinates for hue match: 470 nm, Lum 1-3

5.1.2 Luminance level 4: Figure 15 is a plot of the empirically-derived line of constant perceived hue obtained for the highest luminance level examined - 2000 cd/m^2. By comparing figures 13 and 15 one can readily observe that the shape of the curve for luminance 4 is different from that obtained for the three lower luminance level conditions. Instead of the empirically-derived line of constant hue lying across the predicted line as reported above, at the higher luminance level

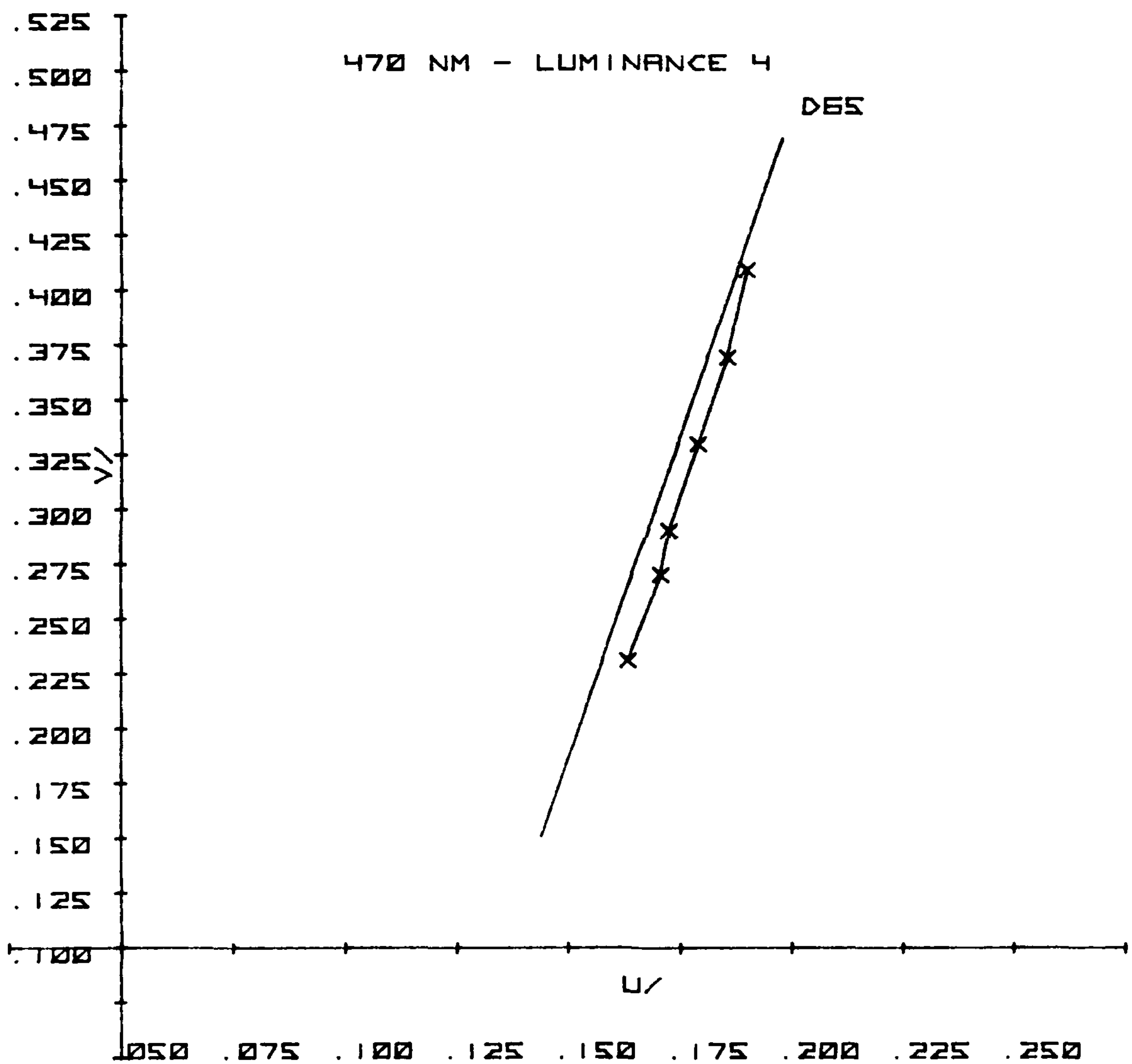

FIG 15 470nm EMPIRICALLY DERIVED LINE OF CONSTANT HUE - LUMINANCE 4 it lies to the blue side of it, regardless of saturation level. Figure 16 plots the delta distance from the theoretical line of constant hue across the six saturation levels. The analysis of variance performed on the deltas for this luminance level showed that none of the factors were significant.

Table 5.4 is the mean delta distances for all subjects at each of the six saturation levels. The same sign rules, as discussed above, apply. Accompanying table 5.5 is the resultant chromaticity coordinates for the hue match point meaned over subjects, direction and replications.

	Sat 1	Sat 2	Sat 3	Sat 4	Sat 5	Sat 6
L4	-.198E-01	-.440E-01	-.448E-01	-.461E-01	-.633E-01	-.566E-01

TABLE 5.4 470 nm Delta distance - Luminance 4 X Saturation

	Sat 1		Sat 2		Sat 3		Sat 4		Sat 5		Sat 6	
	u'	v'	u'	v'	u'	v'	u'	v'	u'	v'	u'	v'
Lum4	.190	.409	.185	.369	.179	.330	.172	.290	.171	.270	.163	.231

Table 5.5 Chromatacity coordinates for hue match: 470 nm, Lum 4

5.2 520 nm (Green):

Figure 17 shows the line of constant perceived hue for 520 nm, meaned over all luminance levels. One can see that the experimentally-produced line lies considerably to the blue side of the predicted line. A study of the ANOVA in Table 5.6 reveals

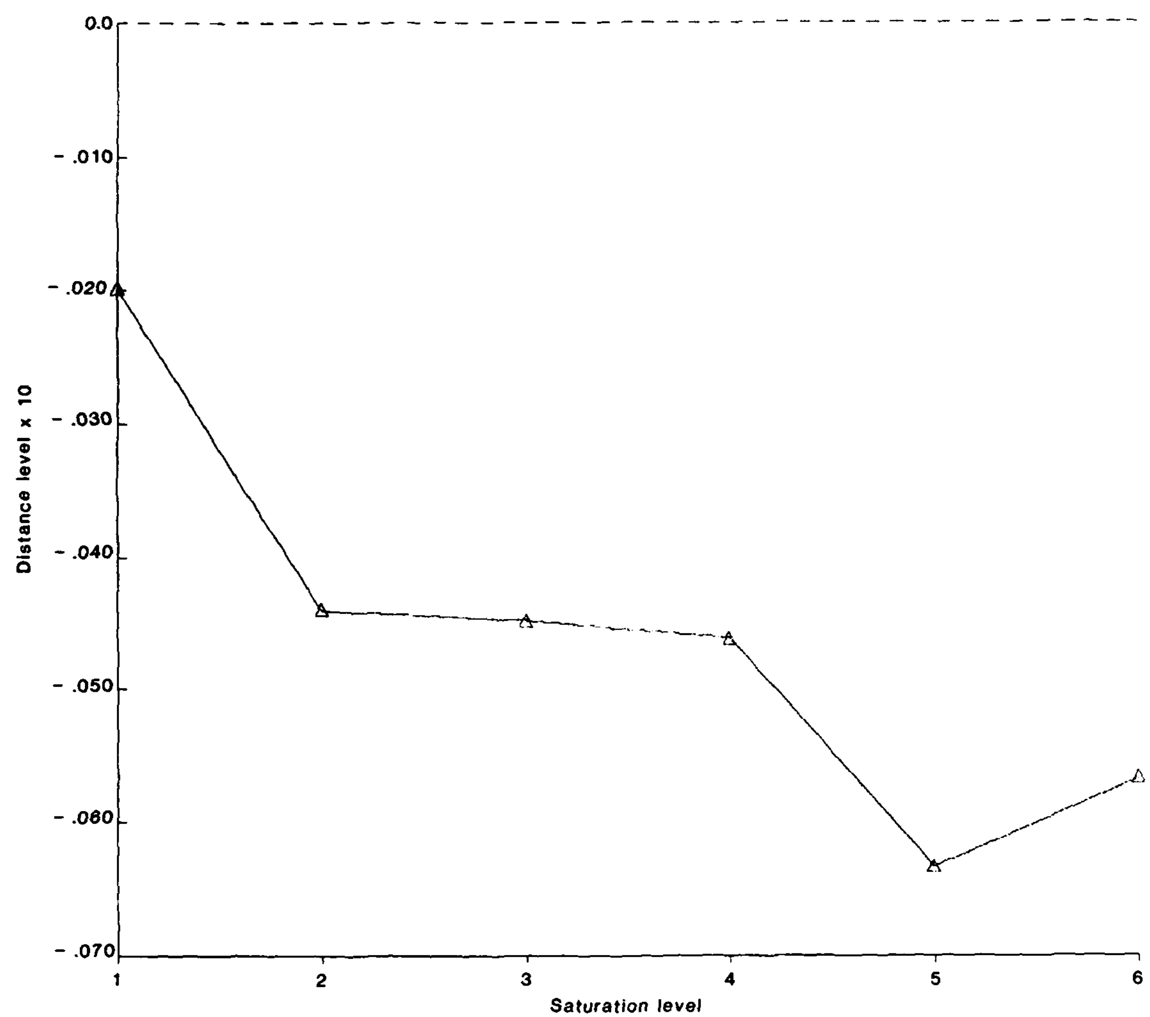

FIG 16 470nm LUMINANCE 4 DATA (L x 1)

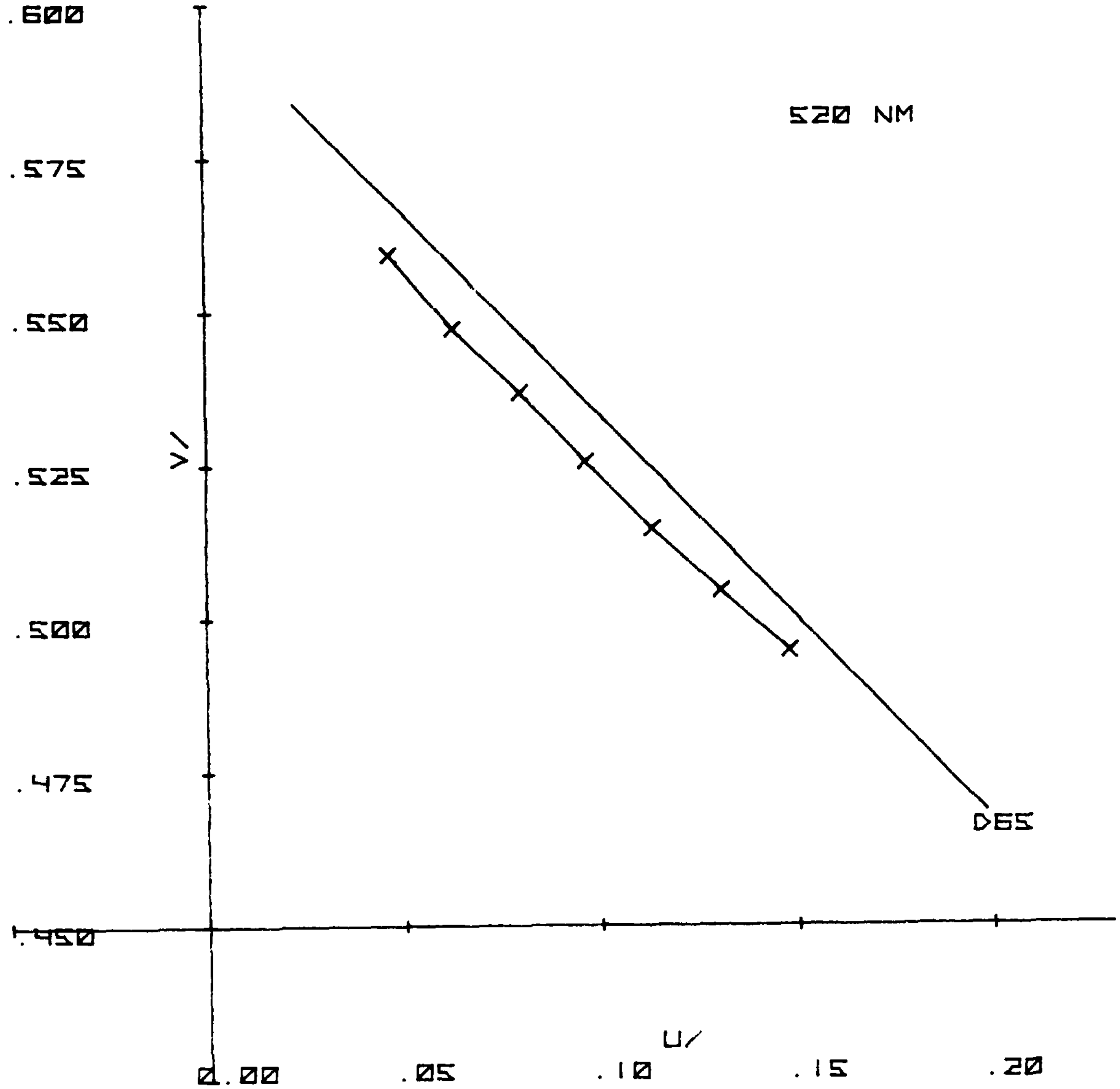

FIG 17 520nm EMPIRICALLY DERIVED LINE OF CONSTANT HUE (ALL LUMINANCES) a significant main effect of saturation, along with a direction x saturation x luminance interaction effect. The main effect of saturation is best illustrated in figure 18, a plot of delta distance as a function of the saturation levels. As was the case for 470 nm, this plot is not flat.

Figures 19-22 show the plots for the significant interaction of direction x saturation x luminance level. Examining these four plots closely reveals the following:

(1) the degree of uncertainty surrounding the hue match, exemplified by the absolute value of the separation between the pairs of points on the two curves, is reasonably small at all luminance levels except for luminance 3. One notable exception is luminance 4, saturation level 3. At luminance level 3 (1000 cd/m^2) the separation between the two points is more pronouonced, thus indicating subjects found a larger area of uncertainty around the match point at all saturation levels for that luminance level.

(2) if the subjects responded as would be expected using the method of limits to determine match point, the response pattern would classically be one of stopping short of the match, irrespective of direction of approach to the match. If this were happening, one would expect to see the plot for directions 1 and 2 to be parallel lines, with, for this hue line, direction 2 being above direction 1. However, at luminance 2 and 3, although the lines are essentially parallel to one another, the orientation of lines for directions 1 and 2 with respect to each

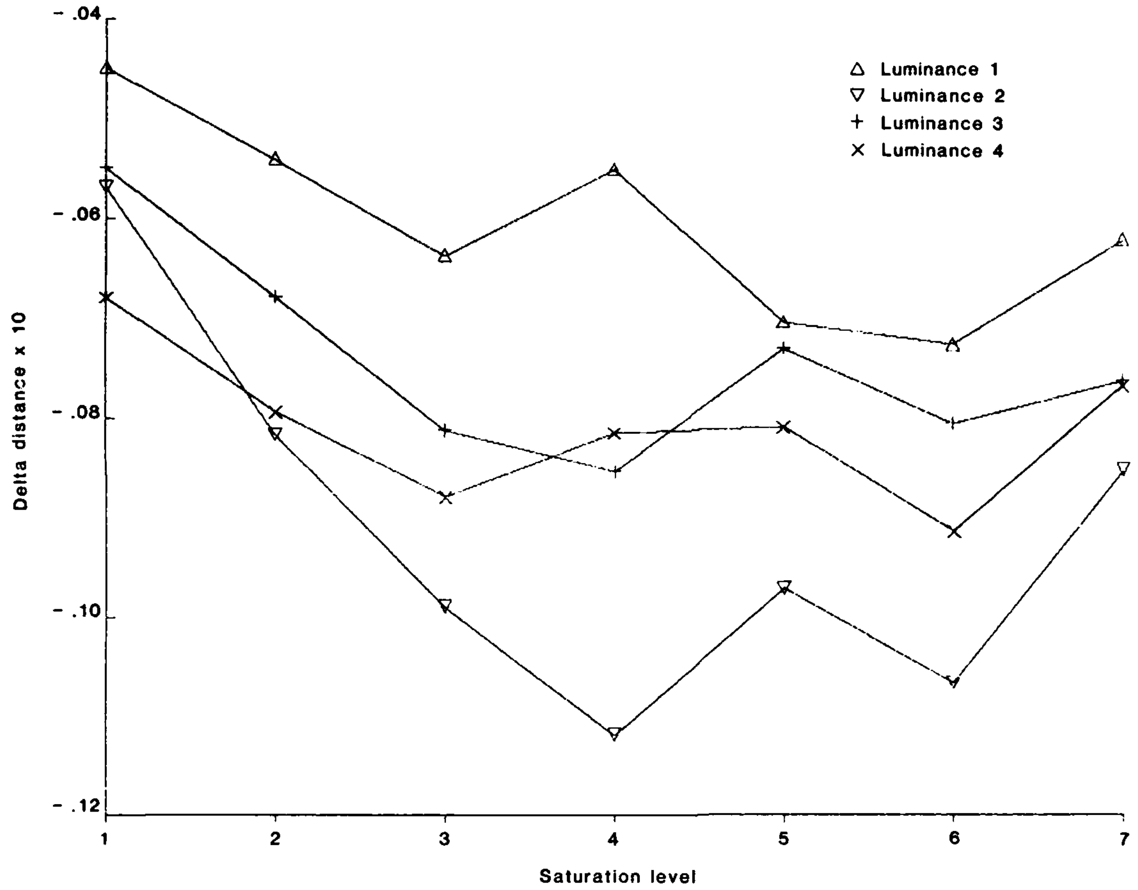

FIG 18 520nm LUMINANCE x SATURATION (L x I)

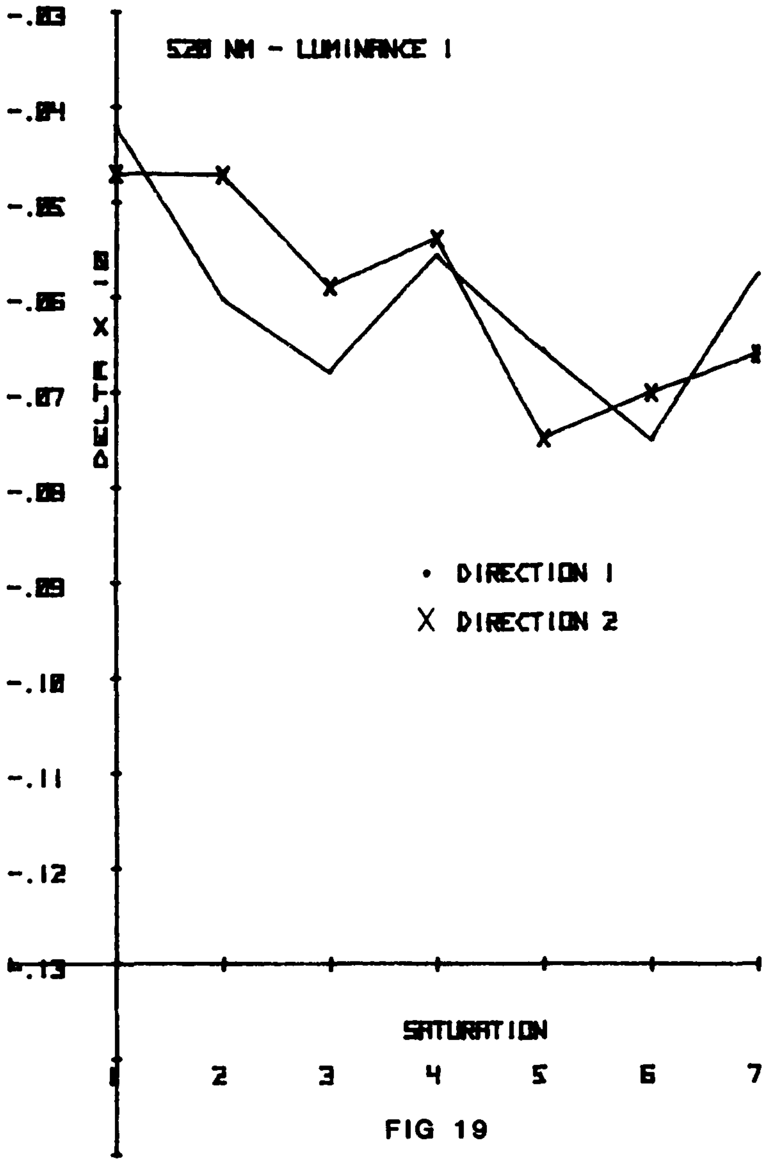

FIG 19

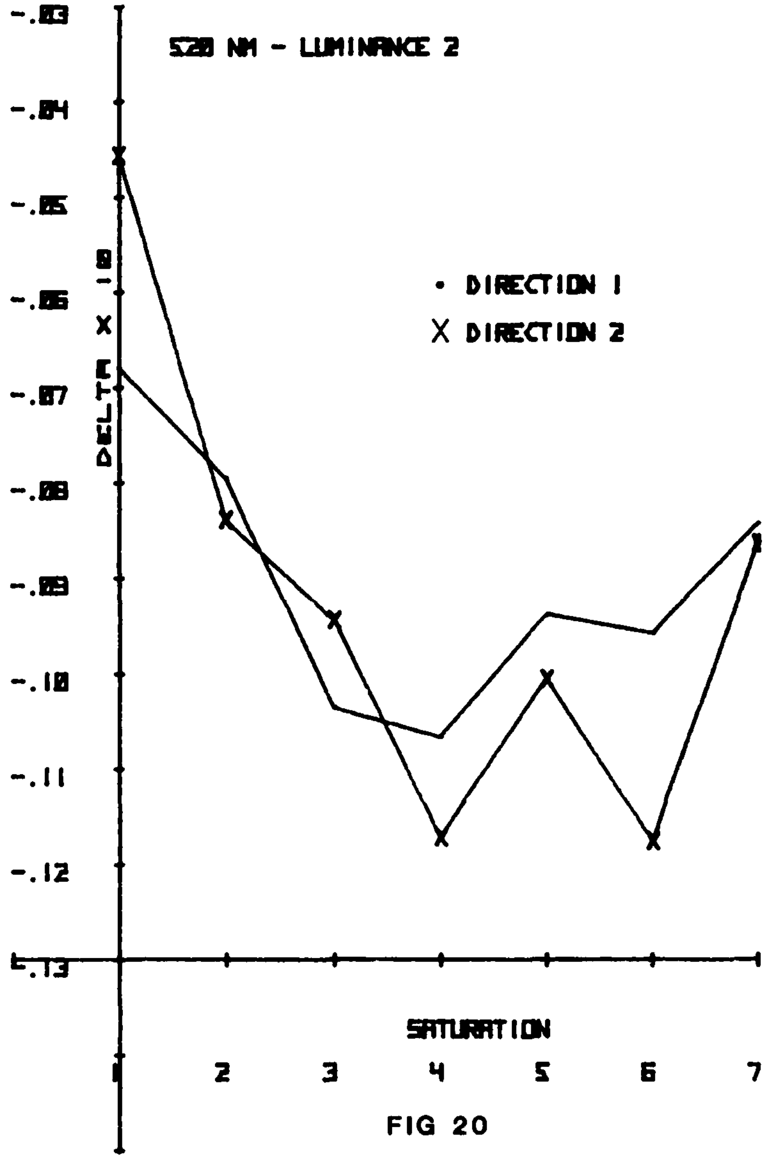

FIG 20

520nm DIRECTION x SATURATION x LUMINANCE INTERACTION - LUMS 1 AND 2

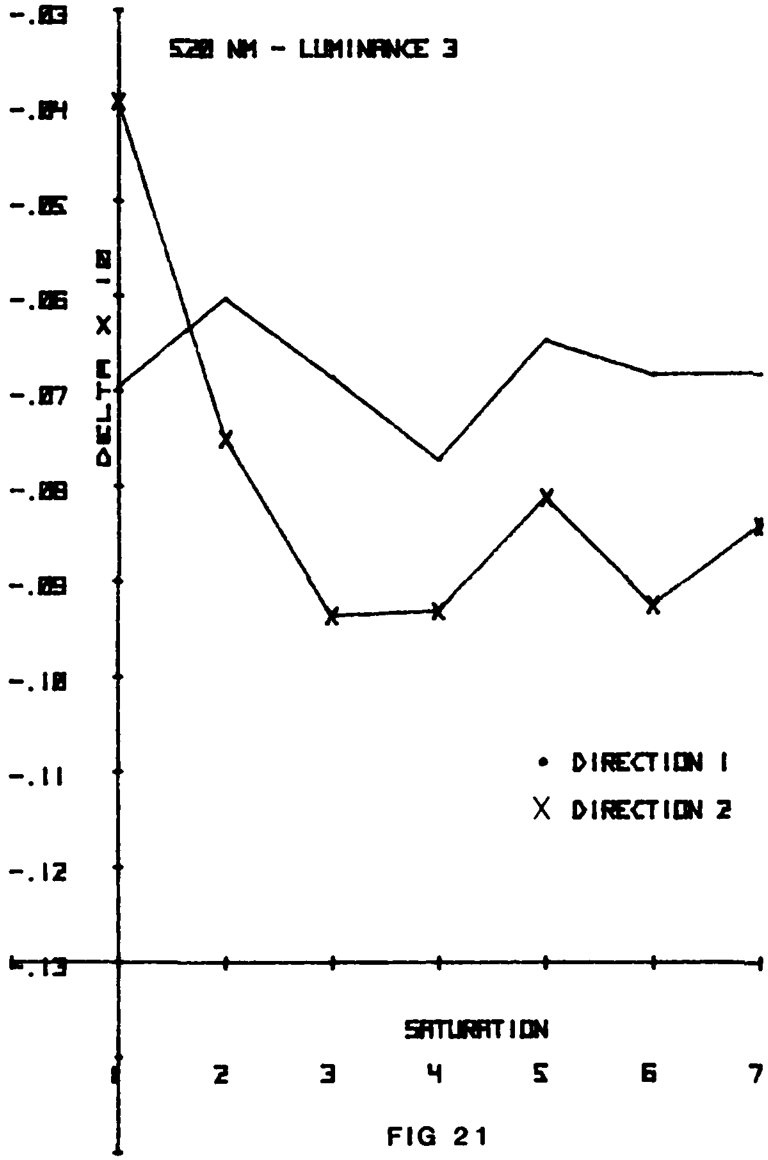

FIG 21

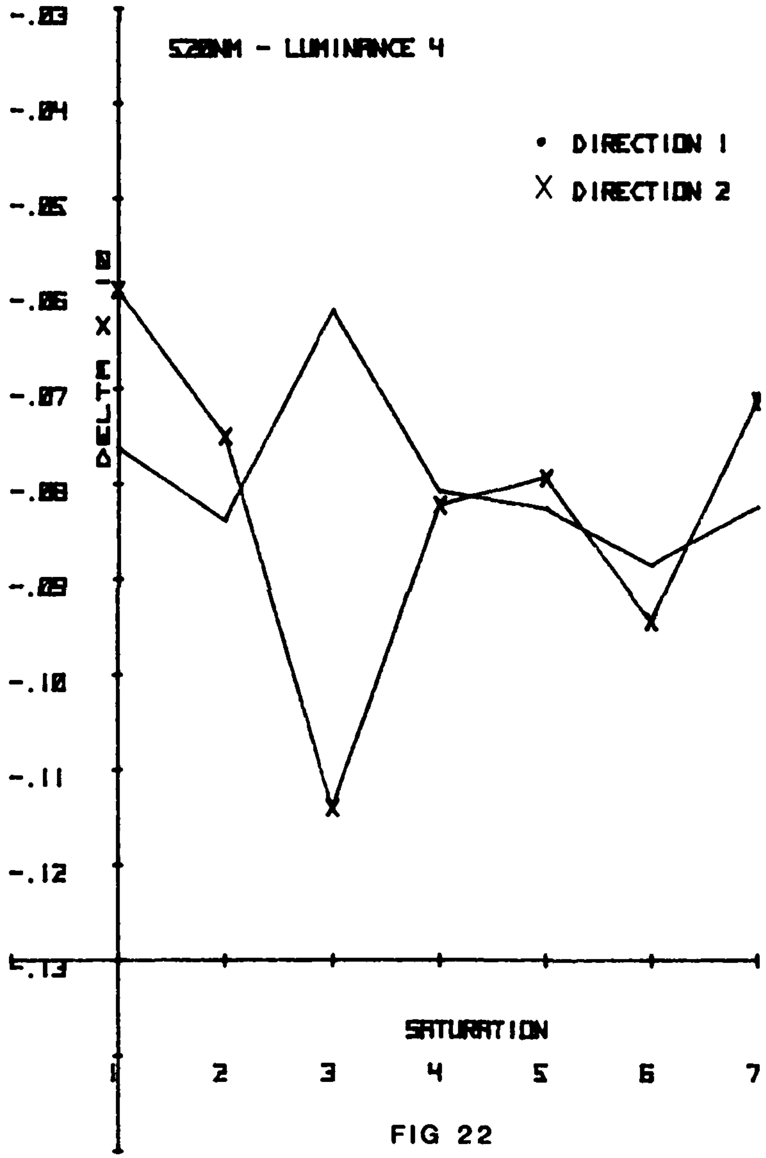

FIG 22

520nm DIRECTION x SATURATION x LUMINANCE INTERACTION - LUMS 3 AND 4

other is the opposite of that expected. So indeed, for these two luminances, subjects are going past the match point from both directions instead of stopping short of it. For luminances 1 and 4 the effect of direction is mixed, with several crossovers between the two lines. One comment is that crossovers for directions seem to be occurring for all luminance levels at both the lowest (saturation 1) and highest (saturation 7) saturation levels. This would tend to suggest that subjects have let the match point pass by before responding at those two saturations.

Since the saturation levels used for this hue line formed a series of equal steps along an ordered scale, i.e., the variable fields were equal steps of increasing saturation out from the achromatic point, the saturation variation was subdivided into linear, quadratic, cubic and "other" trend components. The ANOVA depicts the result of this test for trend on the two significant interactions. For the saturation level factor, the quadratic component is significant, thus implying that a quadratic polynomial would best describe the form of the curve of delta distance against saturation level. The quadratic component of the data plots in figure 18 is clearly evident. For the higher order interaction, DIL, the shape of the curve cannot be adequately fit with either a linear, quadratic or cubic polynomial. A higher degree polymonial is required to describe the equation for the line depicting the interaction.

Source	SS	df	MS	Error	F	Prob
S	1.769	7	0.253			
D	0.698E-02	1	0.698E-02	DS	0.131	NS
DS	0.374	7	0.535E-01			
R	0.118E-02	3	0.392E-03	RS	0.196	0.898
RS	0.42E-01	21	0.20E-02			
I	0.176	6	0.293E-01	IS	5.457	0.0003***
IS	0.226	42	0.537E-02			
I(L)	0.728E-01	1	0.728E-01	IS(L)	4.896	NS
IS(L)	0.104	7	0.148E-01			
I(Q)	0.857E-01	1	0.857E-01	IS(Q)	16.401	**
IS(Q)	0.366E-01	7	0.523E-02			
I(C)	0.869E-03	1	0.869E-03	IS(C)	0.191	NS
IS(C)	0.319E-01	7	0.455E-02			
I(O)	0.166E-01	3	0.553E-02	IS(O)	2.182	0.1192
IS(O)	0.532E-01	21	0.253E-02			
L	0.2225	3	0.742E-01	LS	2.1	0.1296
LS	0.7417	21	0.353E-01			
DR	0.461E-02	3	0.154E-02	DRS	1.206	0.3305
DRS	0.267E-01	21	0.127E-02			
DI	0.392E-01	6	0.654E-02	DIS	2.133	0.0692
DIS	0.128771	42	0.307E-02			
DL	0.100E-01	3	0.333E-02	DLS	0.584	0.6314
DLS	0.1198	21	0.571E-02			
RI	0.4687E-01	18	0.260E-02	RIS	1.435	0.1263
RIS	0.2286	126	0.181E-02			
RL	0.1447E-01	9	0.161E-02	RLS	0.823	0.5971
RLS	0.1230	63	0.195E-02			
IL	0.570E-01	18	0.317E-02	ILS	1.412	0.137
ILS	0.2828	126	0.224E-02			
DRI	0.4115E-01	18	0.229E-02	DRIS	1.651	0.0571
DRIS	0.1744	126	0.138E-02			
DRL	0.159E-01	9	0.177E-02	DRLS	1.367	0.222
DRLS	0.815E-01	63	0.129E-02			
DIL	0.7244E-01	18	0.402E-02	DILS	1.911	0.0204*
DILS	0.2654	126	0.211E-02			
DIL(L)	0.908E-02	3	0.303E-02	DILS(L)	0.775	0.52
DILS(L)	0.82E-01	21	0.391E-02			
DIL(Q)	0.156E-01	3	0.519E-02	DILS(Q)	2.756	0.067
DILS(Q)	0.395E-01	21	0.188E-02			
DIL(C)	0.103E-01	3	0.343E-02	DILS(C)	2.094	0.1304
DILS(C)	0.344E-01	21	0.164E-02			
DIL(O)	0.375E-01	9	0.416E-02	DILS(O)	2.398	0.021*
DILS(O)	0.1094	63	0.174E-02			
RIL	0.122	54	0.226E-02	RILS	1.274	0.104
RILS	0.6690	377	0.177E-02			
DRIL	0.729E-01	54	0.135E-02	DRILS	1.098	0.3059
DRILS	0.4142	337	0.123E-02			
TOTAL	6.5708	1749				

Table 5.6 - ANOVA 520 nm

Table 5.7 contains the delta distances at the seven saturation levels studied for all four luminance levels. Deltas in this table have been meaned over direction, subjects and replications. Also included in the table is the overall mean deviation across all luminance levels. In the interpretation of the signed deltas, all deltas carry a negative sign, indicative of the fact that all the lines fall to the blue side of the predicted line for all saturation levels.

	Sat 1	Sat 2	Sat 3	Sat 4	Sat 5	Sat 6	Sat 7
Lum 1	-.0448	-.054	-.0637	-.0551	-.0705	-.0728	-.0622
Lum 2	-.0568	-.0816	-.0989	-.1119	-.0971	-.1066	-.0853
Lum 3	-.0549	-.0679	-.0813	-.0854	-.0732	-.0806	-.0764
Lum 4	-.0679	-.0794	-.0879	-.0815	-.0810	-.0915	-.0769
Mean	-.0561	-.0707	-.0829	-.0835	-.0805	-.0879	-.0752

Table 5.7 520 nm Delta distance - Saturation X Luminance

Table 5.8 gives the u', v' coordinates for each of the mean hue match points at the seven saturation levels. This table is the conversion of mean deltas into chromaticity coordinates. The points for each of the four luminance levels, as well as the mean for all luminances, are given in the table.

	LUM 1		LUM 2		LUM 3		LUM 4		Mean	
	u'	v'	u'	v'	u'	v'	u'	v'	u'	v'
Sat 1	.1486	.4954	.1479	.4944	.1480	.4946	.1473	.4935	.1480	.494
Sat 2	.1314	.5057	.1299	.5034	.1306	.5045	.1300	.5036	.1305	.504
Sat 3	.1141	.5159	.1122	.5129	.1132	.5144	.1129	.5139	.1131	.514
Sat 4	.0979	.5276	.0948	.5229	.0963	.5251	.0965	.5254	.0964	.525
Sat 5	.0804	.5374	.0789	.5351	.0803	.5371	.0798	.5365	.0799	.536
Sat 6	.0636	.5482	.0617	.5454	.0632	.5475	.0626	.5466	.0628	.546
Sat 7	.0475	.5601	.0462	.5582	.0467	.5589	.0467	.5589	.0468	.559

Table 5.8 Chromaticity coordinates for hue match: 520 nm

5.3 570 nm (Yellow):

Out of all of the lines of constant hue investigated, 570 nm is the only one where the luminance level factor is significant. This effect of luminance on the resultant experimentally-derived lines of constant perceived hue is evident in figure 23. Although an analysis of trends was not carried out on these data, a description of the general shape of the curve emerging appears to be one of being quadratic, moving with luminance. For all luminances, the curve goes to the red side of the predicted line for the first two saturation levels. By the third saturation level, for all three of the lower luminances, th curve is still on the red side. However, at that point for the highest luminance level (2000 cd/m^2) the mean match point is just crossing over the theoretical line toward the green side. At the most saturated level, which can be seen from figure 11 to be very

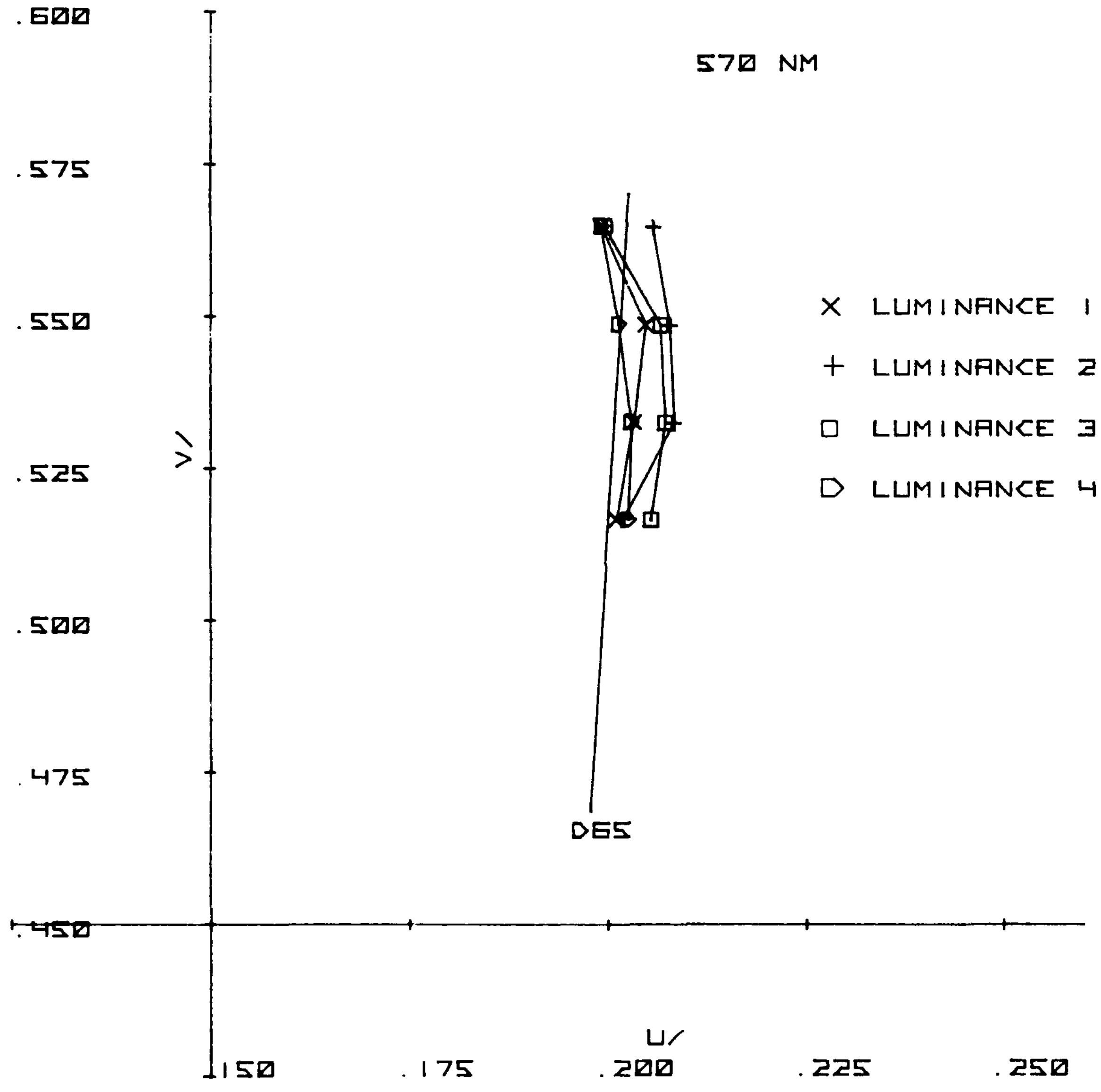

FIG 23 570nm EMPIRICALLY DERIVED LINES OF CONSTANT HUE FOR ALL 4 LUMINANCE LEVELS close to the spectrum locus, three of the four luminances take a dramatic swing across the predicted line toward the green side. Luminance 2 is the only condition where the mean hue match point remains on the red side of the predicted line.

The ANOVA (see table 5.9) shows the significant main effect of saturation and two interaction effects: saturation by luminance and replications by saturation. Figure 24 plots delta deviation over saturation levels as a function of luminance level. The main effect of saturation level is distinctly illustrated from this figure - the delta distances change substantially across saturation levels.

From a study of the saturation x luminance effect, shown in figure 24, several observations can be made: the largest amount of deviation from the theoretical line across saturations is for luminance 2, followed by luminance 3, then luminance 1 and finally luminance 4. The shape of the resultant curve of delta over saturation level for luminance 4 is more gentle than for the other three luminance levels.

Figure 25 is the plot of the saturation by replication effect. At the first replicate pair, the amount of deviation from the predicted line for all saturations is fairly consistent. But by the second replicate pair, the spread of delta distances becomes more evident and that trend continues for the rest of the replications. A possible explanation for this interaction effect is that of chromatic induction or adaptation occurring. Because the shutters were kept open during all 10 replications for hue

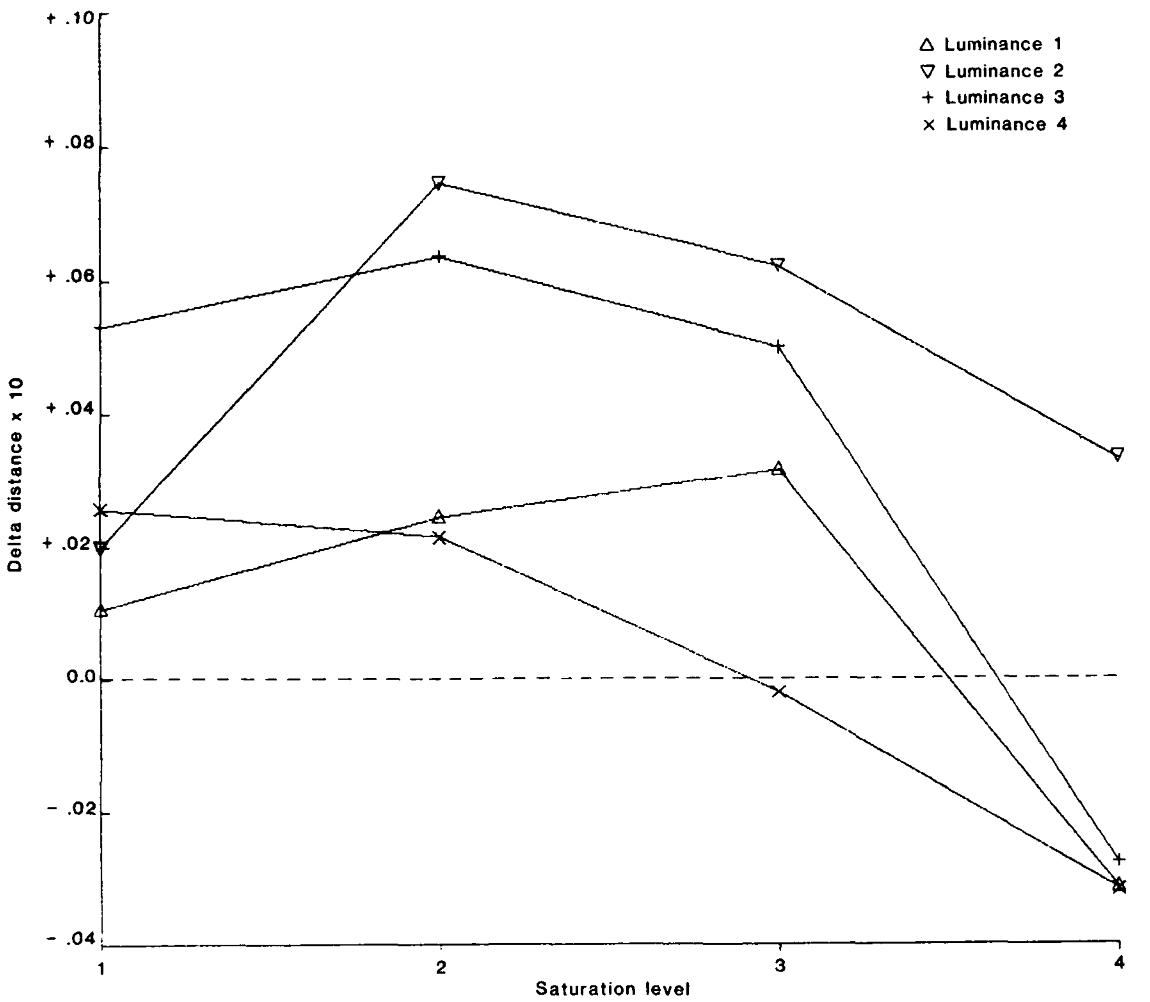

FIG 24 570nm LUMINANCE x SATURATION (L x I)

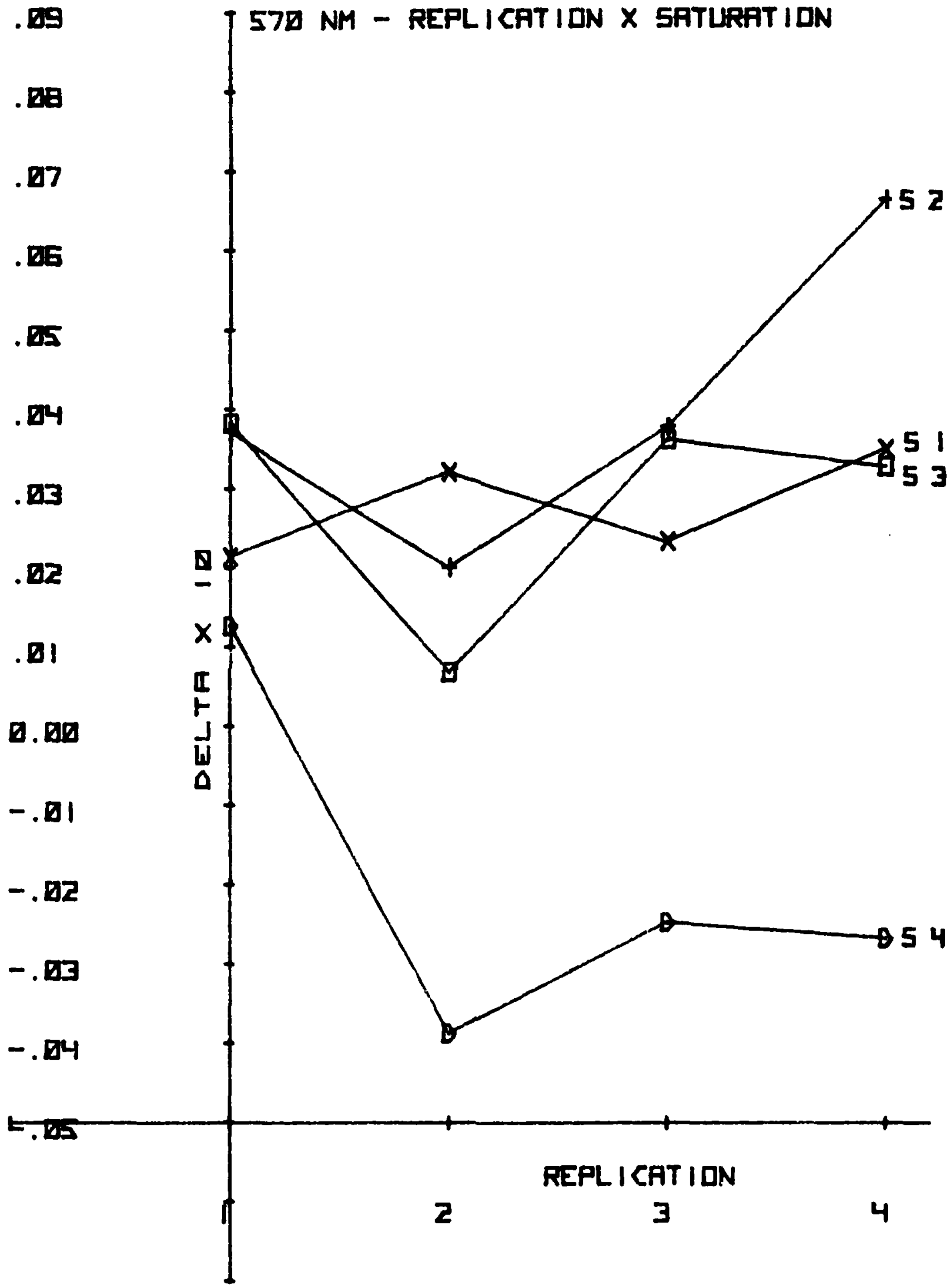

FIG 25 570nm REPLICATIONS x SATURATION INTERACTION match, the subjects probably experienced chromatic induction very early in the trials. Thus, the spread of responses for the first replications would be small, but would become much larger through succeeding trials. This larger spread of responses can be seen in figure 25 and is indicative of the greater amount of uncertainty surrounding the match point in these later trials.

Source	SS	df	MS	Error	F	Prob
S	0.334E-01	4	0.834E-02			
D	0.844E-01	1	0.844E-01	DS	1.059	
DS	0.3189	4	0.797E-01			
R	0.875E-02	3	0.292E-02	RS	0.656	.594
RS	0.533E-01	12	0.444E-02			
I	0.33537	3	0.111789	IS	20.452	.0001***
IS	0.656E-01	12	0.547E-02			
L	0.2105	3	0.702E-01	LS	1.376	.296
LS	0.6118	12	0.510E-01			
DR	0.659E-02	3	0.219E-02	DRS	0.445	.725
DRS	0.592E-01	12	0.494E-02			
DI	0.374E-01	3	0.125E-01	DIS	2.252	.133
DIS	0.665E-01	12	0.554E-02			
DL	0.261E-01	3	0.871E-02	DLS	0.523	.674
DLS	0.20009	12	0.167E-01			
RI	0.596E-01	9	0.662E-02	RIS	2.477	.026*
RIS	0.962E-01	36	0.267E-02			
RL	0.215E-01	9	0.238E-02	RLS	0.697	.707
RLS	0.1231	36	0.342E-02			
IL	0.13068	9	0.145E-01	ILS	2.245	.041*
ILS	0.23286	36	0.647E-02			
DRI	0.388E-01	9	0.431E-02	DRIS	1.352	.246
DRIS	0.1147	36	0.319E-02			
DRL	0.538E-01	9	0.598E-02	DRLS	2.044	.0623
DRLS	0.10527	36	0.292E-02			
DIL	0.368E-01	9	0.409E-02	DILS	1.279	.281
DILS	0.11511	36	0.320E-02			
RIL	0.819E-01	27	0.303E-02	RILS	1.097	.357
RILS	0.2988	108	0.277E-02			
DRIL	0.772E-01	27	0.286E-02	DRILS	1.124	.332
DRILS	0.2288	90	0.254E-02			
TOTAL	3.9328	621				

TABLE 5.9 ANOVA for 570 nm

Table 5.10 contains delta distances for the four luminance levels and the mean of the four luminances, which have been meaned over the factors of direction, replication, and saturation. Table 5.11 takes those same delta distances and tables the corresponding u', v' chromaticity coordinates.

	SATURATION 1	SATURATION 2	SATURATION 3	SATURATION 4
Luminance 1	.1067E-01	.2438E-01	.3143E-01	-.3135E-01
Luminance 2	.1980E-01	.7443E-01	.6196E-01	.3299E-01
Luminance 3	.5320E-01	.6352E-01	.4973E-01	-.3177E-01
Luminance 4	.2566E-01	.2138E-01	-.1968E-01	-.3177E-01
Mean	.2733E-01	.4593E-01	.3529E-01	-.1444E-01

Table 5.10 570 nm - Delta distances Saturation x Luminance

	SAT 1		SAT 2		SAT 3		SAT 4	
	u'	v'	u'	v'	u'	v'	u'	v'
LUM 1	.2011	.5162	.2033	.5321	.2047	.5481	.1992	.5643
LUM 2	.2020	.5162	.2083	.5319	.2078	.5479	.2056	.5640
LUM 3	.2054	.5160	.2072	.5319	.2065	.5480	.1996	.5643
LUM 4	.2026	.5161	.2029	.5321	.2014	.5482	.1992	.5643
MEAN	.2028	.5161	.2054	.5320	.2051	.5480	.2009	.5643

TABLE 5.11 Chromaticity coordinates for hue match: 570 nm

5.4 640 nm (Red):

For this hue line, there are no significant factors of either saturation level or luminance. All that the ANOVA (see Table 5.12) reveals for significance are two interactions of direction by saturation by luminance and direction by replication by luminance.

Figure 26 shows the line of constant perceived hue for 640 nm produced by this experiment. As one can see, it is essentially a straight line across saturation levels, which parallels the predicted line, but falls slightly to the yellow side of it.

Figure 27 is the plot of delta distance across saturation levels for the four luminances. The results of the ANOVA show that all four lines are more or less the same and that they are flat. Of course, of note, is luminance level 3 at saturation level 2, where the line makes a dramatic shift across the predicted line towards the red side. Figure 28 shows a plot of each of the resultant lines for the four luminance levels. This figure illustrates the dip the line for luminance 3 takes at the lower saturation levels. Also of note is that the empirically derived line for luminance 3 is always closer to the predicted line than the other luminance levels. However, the statistics do not pick up any effect of luminance. Figure 28 also portrays the similarity of the shapes of the lines for luminances 1, 2 and 4.

Source	SS	df	MS	Error	F	Prob
S	0.9842	7	0.1406			
D	0.447E-01	1	0.447E-01	DS	0.797	NS
DS	0.3925	7	0.561E-01			
R	0.583E-03	3	0.194E-03	RS	0.177	.911
RS	0.231E-01	21	0.110E-02			
I	0.509E-01	6	0.849E-02	IS	0.752	.6112
IS	0.4741	42	0.113E-01			
L	0.2258	3	0.753E-01	LS	1.301	.299
LS	1.2146	21	0.578E-01			
DR	0.335E-02	3	0.111E-02	DRS	0.423	.738
DRS	0.554E-01	21	0.264E-02			

Table 5.12 ANOVA for 640 nm

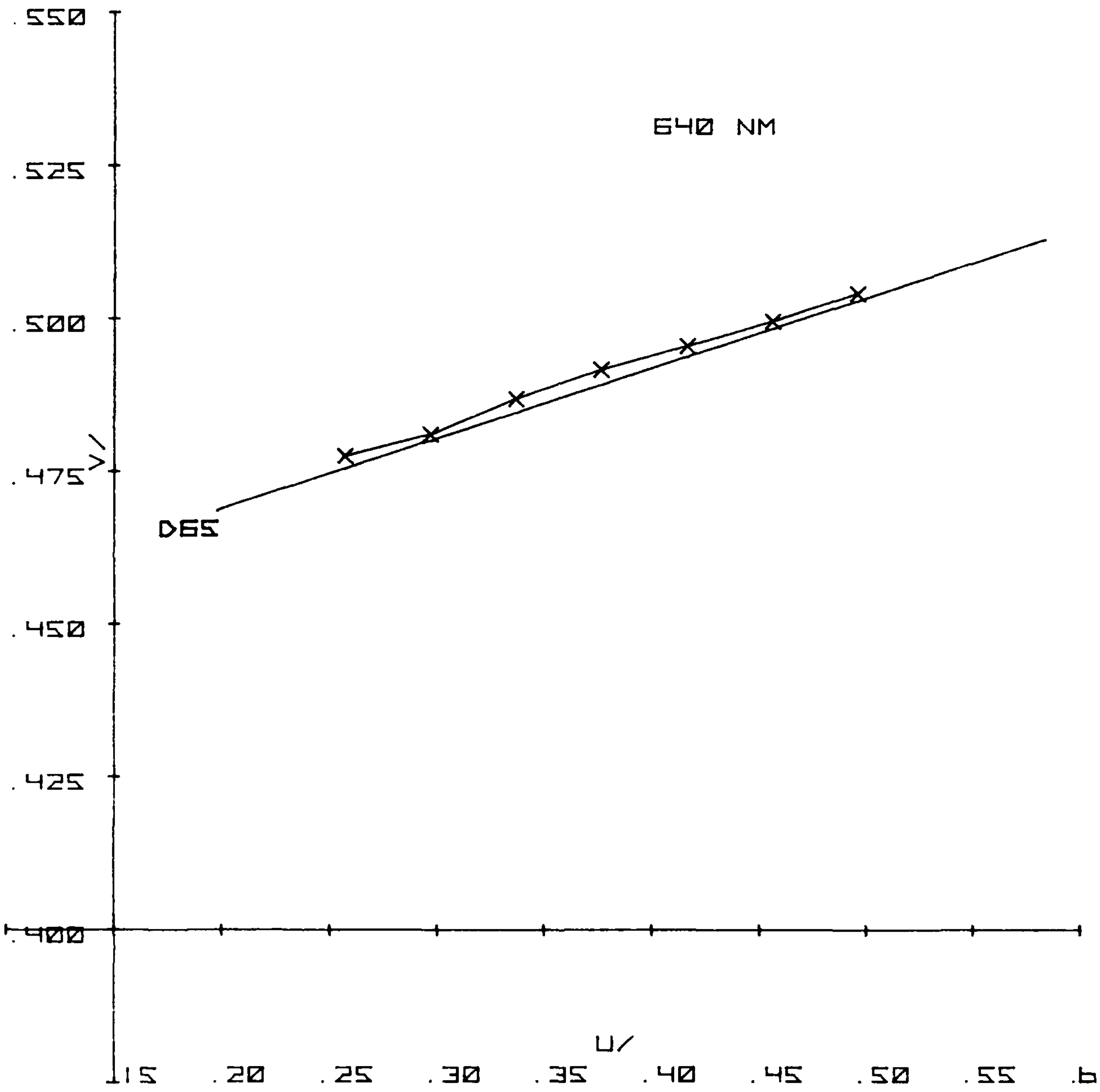

FIG 26 640nm EMPIRICALLY DERIVED LINE OF CONSTANT HUE

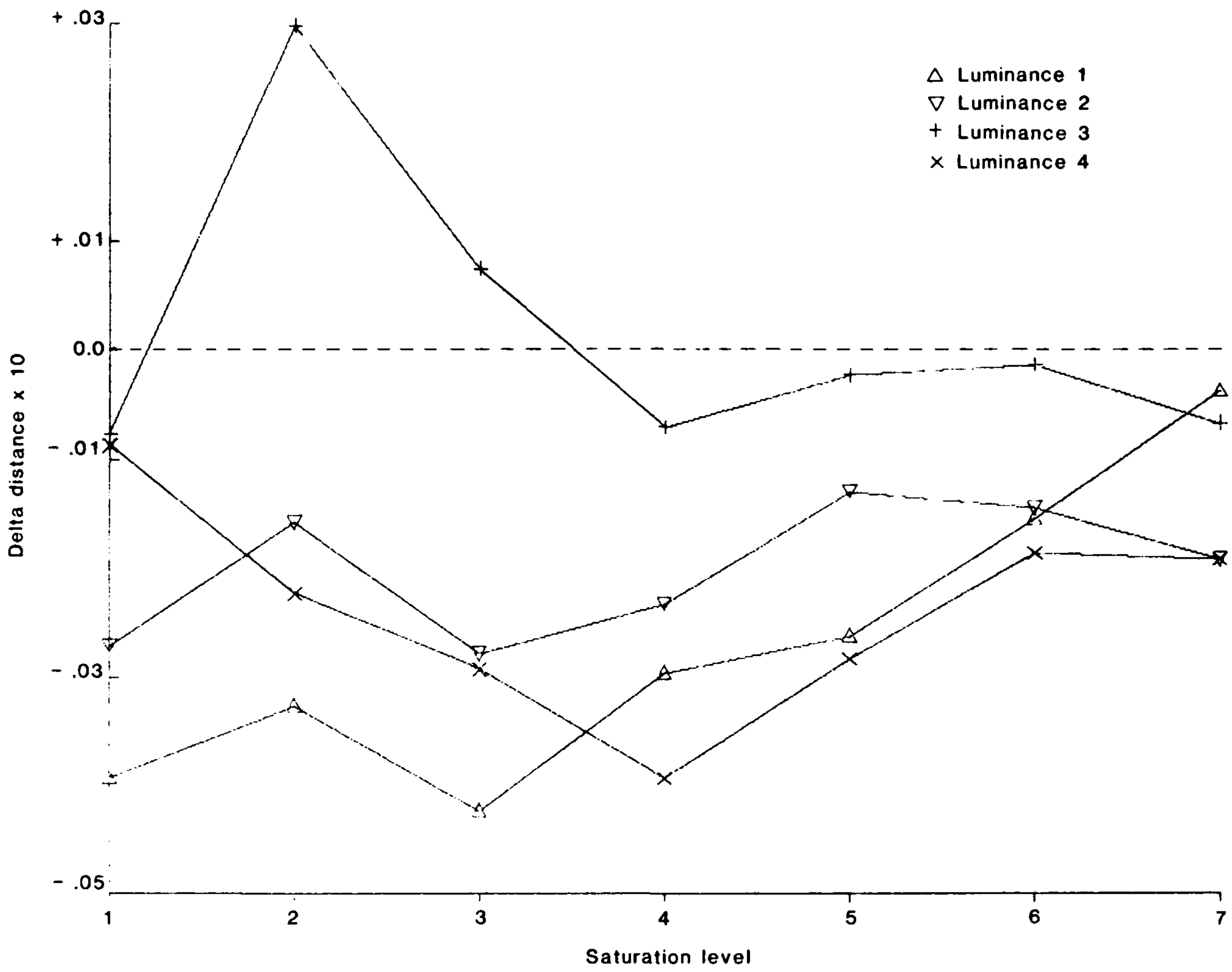

FIG 27 640nm LUMINANCE x SATURATION LEVEL (LxI)

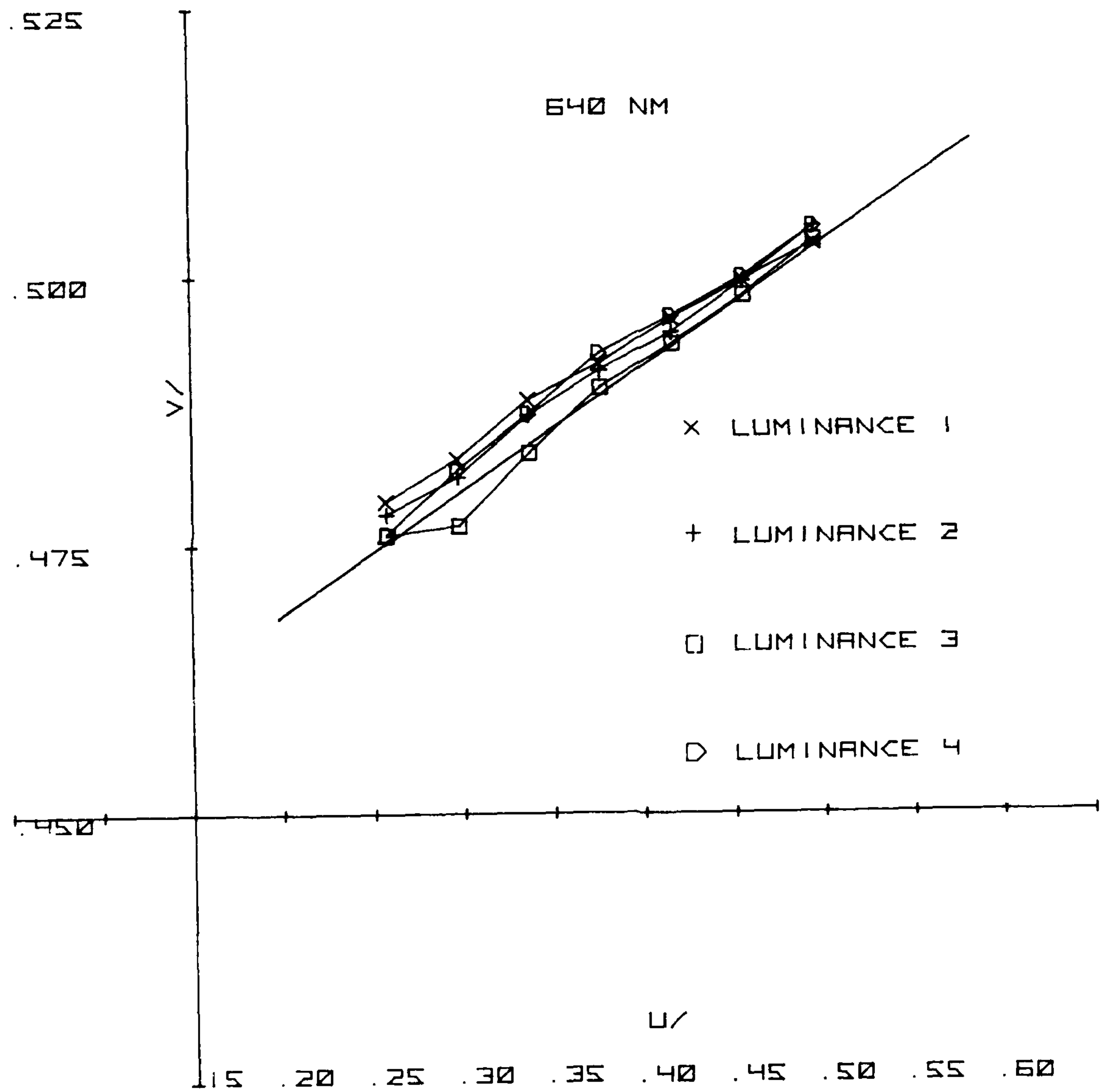

FIG 28 640nm LINES OF CONSTANT HUE - LUMINANCES 1-4

Source	SS	df	MS	Error	F	Prob
DI	0.522E-01	6	0.871E-02	DIS	0.491	.811
DIS	0.7436	42	0.177E-01			
DL	0.262E-01	3	0.874E-02	DLS	0.956	.43
DLS	0.19199	21	0.914E-02			
RI	0.508E-01	18	0.282E-02	RIS	0.987	.479
RIS	0.3600	126	0.286E-02			
RL	0.324E-01	9	0.360E-02	RLS	0.971	.473
RLS	0.2338	63	0.371E-02			
IL	0.1394	18	0.774E-02	ILS	1.264	.223
ILS	0.7717	126	0.613E-02			
DRI	0.434E-01	18	0.241E-02	DRIS	1.105	.355
DRIS	0.2752	126	0.218E-02			
DRL	0.470E-01	9	0.522E-02	DRLS	2.178	.035*
DRLS	0.1511	63	0.239E-02			
DIL	0.1279	18	0.711E-02	DILS	1.787	.034*
DILS	0.5012	126	0.398E-02			
DIL(L)	0.652E-01	3	0.217E-01	DILS(L)	5.666	.005**
DILS(L)	0.805E-01	21	0.383E-02			
DIL(Q)	0.869E-02	3	0.290E-02	DILS(Q)	0.727	.547
DILS(Q)	0.838E-01	21	0.399E-02			
DIL(C)	0.199E-01	3	0.665E-02	DILS(C)	1.516	.238
DILS(C)	0.921E-01	21	0.438E-02			
DIL(O)	0.342E-01	9	0.379E-02	DILS(O)	0.976	.468
DILS(O)	0.2449	63	0.389E-02			
RIL	0.1715	54	0.318E-02	RILS	1.266	.11
RILS	0.9359	373	0.251E-02			
DRIL	0.825E-01	54	0.153E-02	DRILS	0.826	.802
DRILS	0.6125	331	0.185E-02			
TOTAL	9.0199	1739				

TABLE 5.12 ANOVA for 640 nm (cont'd)

As was the case at 520 nm, there is a significant interaction of direction x saturation x luminance. Figures 29-32 are the plots for delta distance over saturation level, one for each luminance level. Several observations/conclusions can be made from studying these plots:

(1) looking at the plots of the directions with relationship to each other for luminances 1, 2 and 3, the plot for direction 1 is above that of direction 2 with very few exceptions.

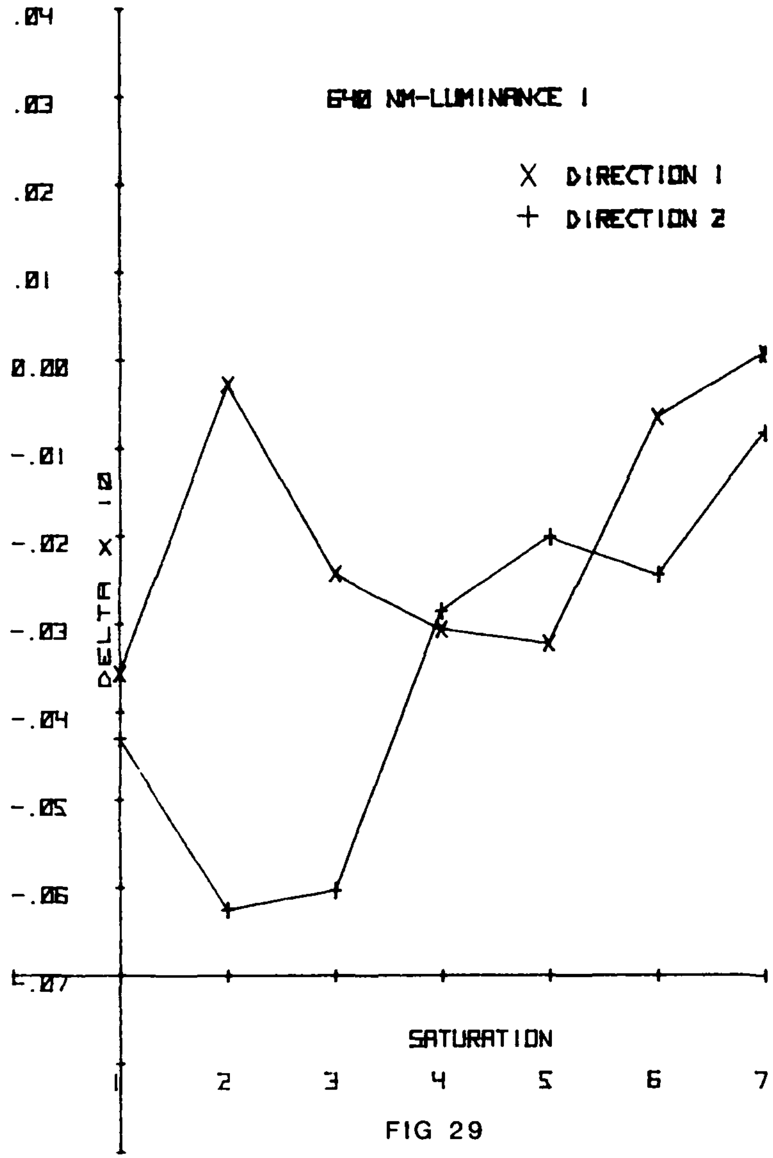

FIG 29

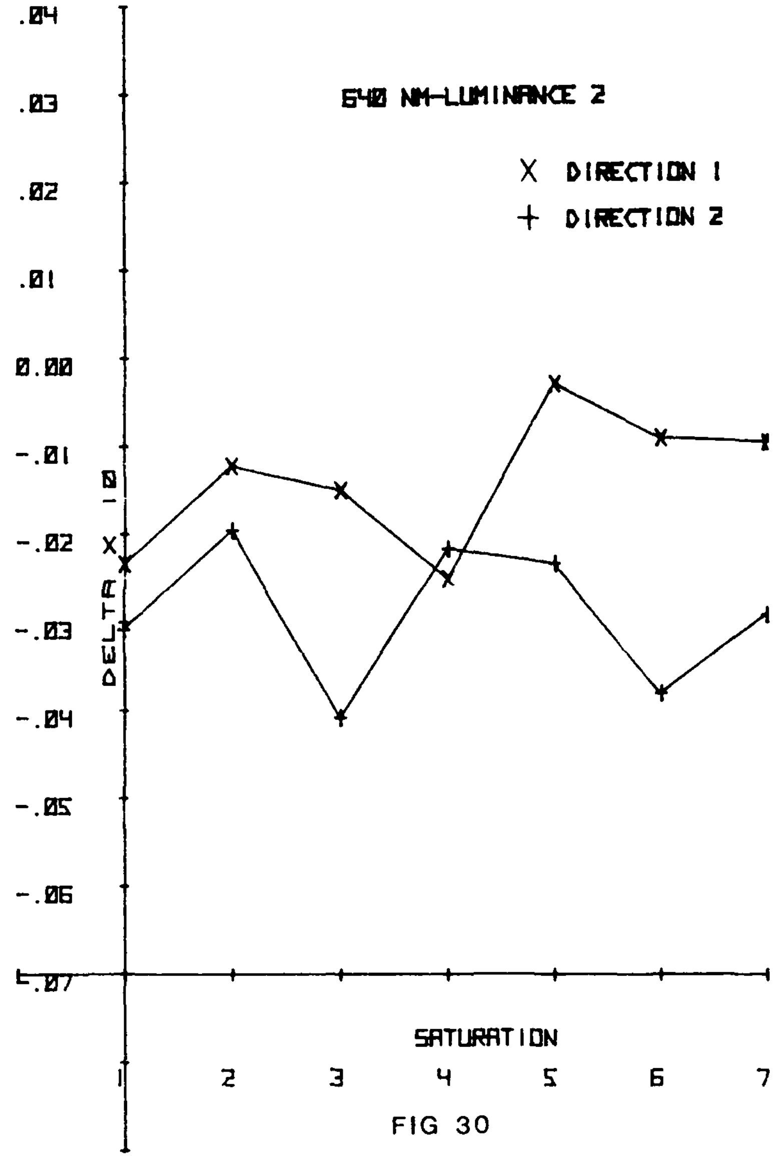

FIG 30

640nm DIRECTION x SATURATION x LUMINANCE INTERACTION - LUMS 1 AND 2

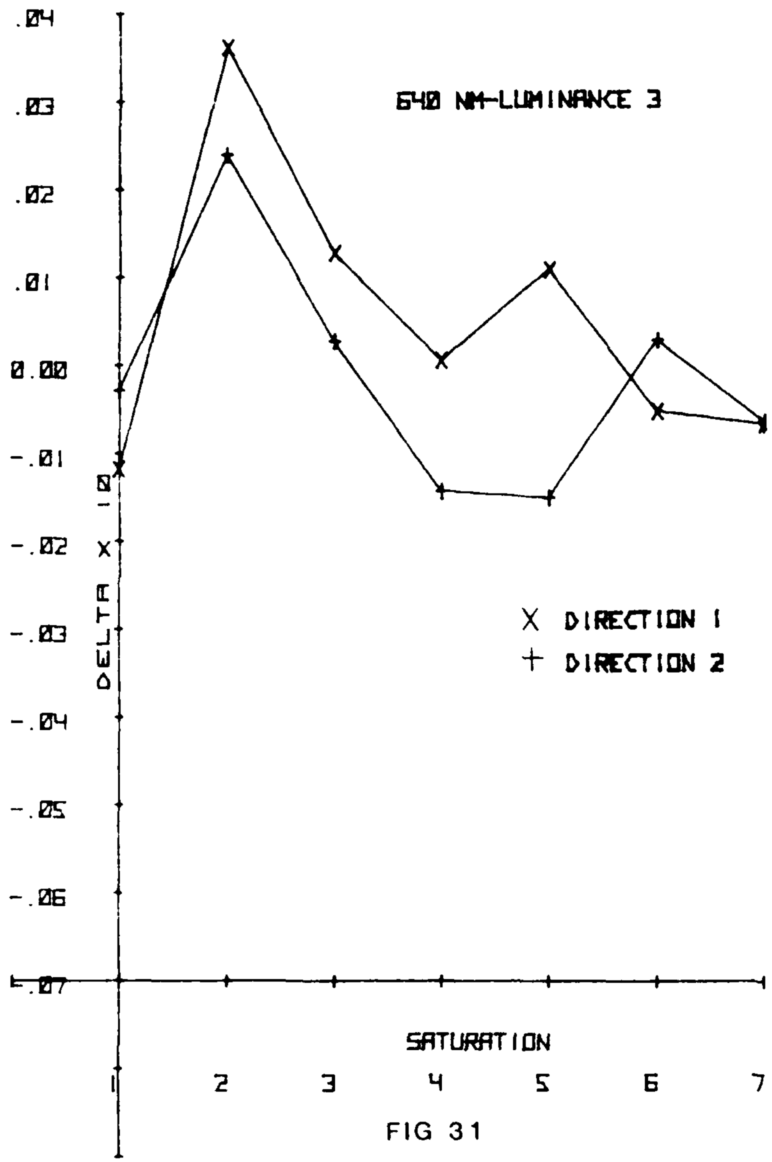

FIG 31

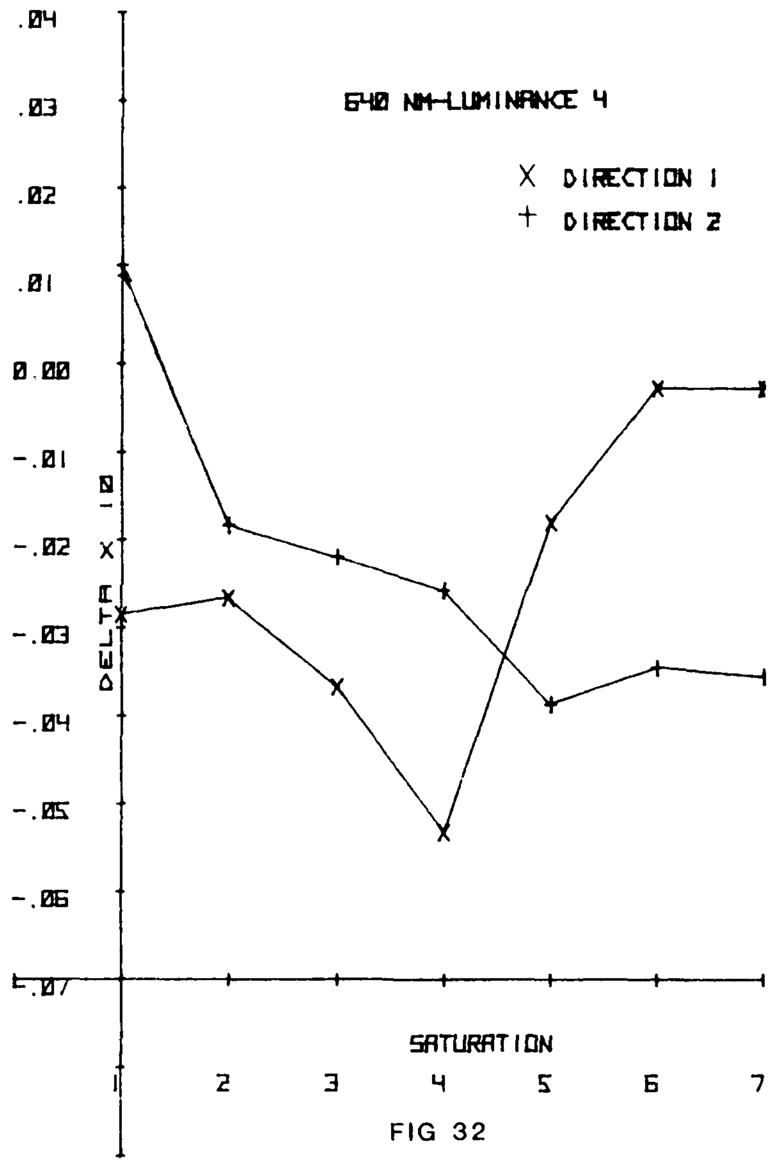

FIG 32

640nm DIRECTION x SATURATION x LUMINANCE INTERACTION - LUMS 3 AND 4

For this hue line, that indicates that at the three lower luminances, subjects were consistently going past the match poin regardless of direction of approach. Luminance 4, however, show that subjects were stopping short of the hue match from both directions, until the last three saturation levels, where their response pattern crossed over. Therefore, it is found that for saturations 5, 6 and 7, subjects were going past the match point from both directions.

(2) Examining the absolute value of the difference between the points on the two curves gives insight into the amou of uncertainty surrounding the hue match point that the subjects experienced. At luminance 1, the lower saturation levels 2 and 3 show the two single largest differences between the two curves. Here the subjects were responding with the greatest amount of uncertainty. At luminance 2, subjects experienced greater uncertainty at the higher saturation levels, 5-7. Subjects' matc points are very close together coming from either direction at luminance 3. Luminance 4 shows that subjects are consistently more uncertain across all saturation levels. An analysis of trend indicates that this three-way interaction effect can best be represented by a linear fit to the data.

(3) It is interesting to notice that for luminance 3, which shows the dramatic dip in the curve toward the red side (as described above), this breakout of the data shows that the direction effect is accordant at these points. The difference in hue between the points on the two direction curves at

saturations 2 and 3 are very small. Both these curves demonstrate that despite direction of approach, subjects only signify a hue match when the variable field appears more red (compared to the match at other saturation levels).

Figures 33-36 are plots of the direction x replication x luminance effect. At luminance 1, the lines for the two directions are parallel to one another and as mentioned above, reveal that subjects let the match point pass in both instances before pressing the response button. The band of uncertainty surrounding the match across replications for all subjects at all saturations is consistently large. With luminance level 2, subjects' uncertainty drops markedly after the first replicate pair. Again, the pattern of direction is uniformly parallel with subjects going past the match point before making a response. For luminance 3, with the exception of the second replicate pair (responses 5 and 6), the responses are very close together. At luminance 4 it is observed that the subjects are very confident as to their match point across all replications, with the two curves for the two directions lying one on top of the other. Also, the pattern of responses for luminance 4 shows that subjects are stopping short of the match at nearly all replications.

It, therefore, seems that all subjects at all saturation levels are relatively unsure as to their match at the lowest luminance level - 250 cd/m^2. Uncertainty decreases as a function of increasing luminance with luminance 4 showing the most uniformity of responses.

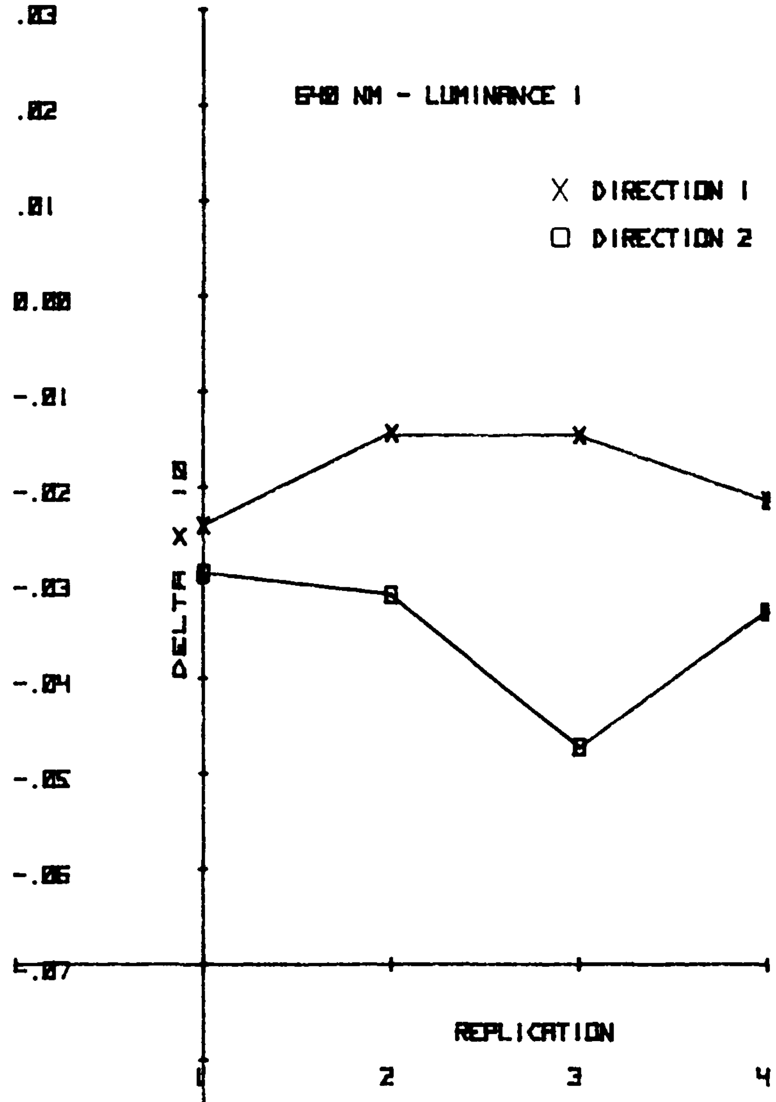

FIG 33

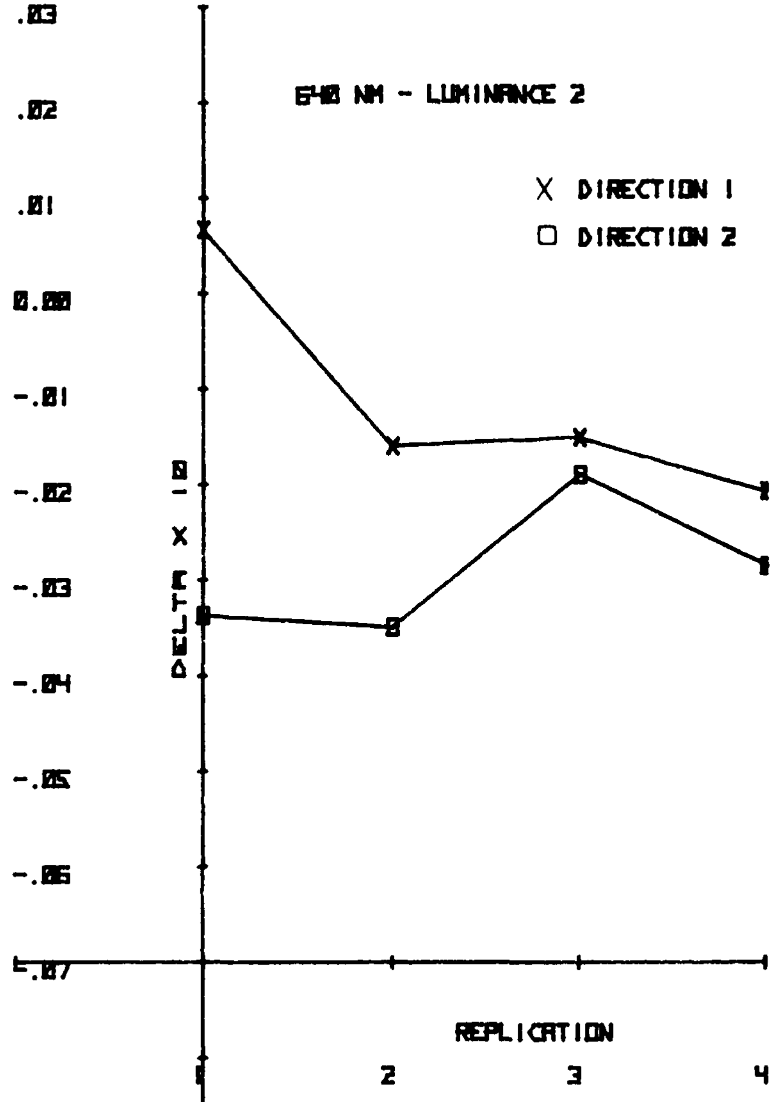

FIG 34

640nm DIRECTION x REPLICATION x LUMINANCE INTERACTION - LUMS 1 AND 2

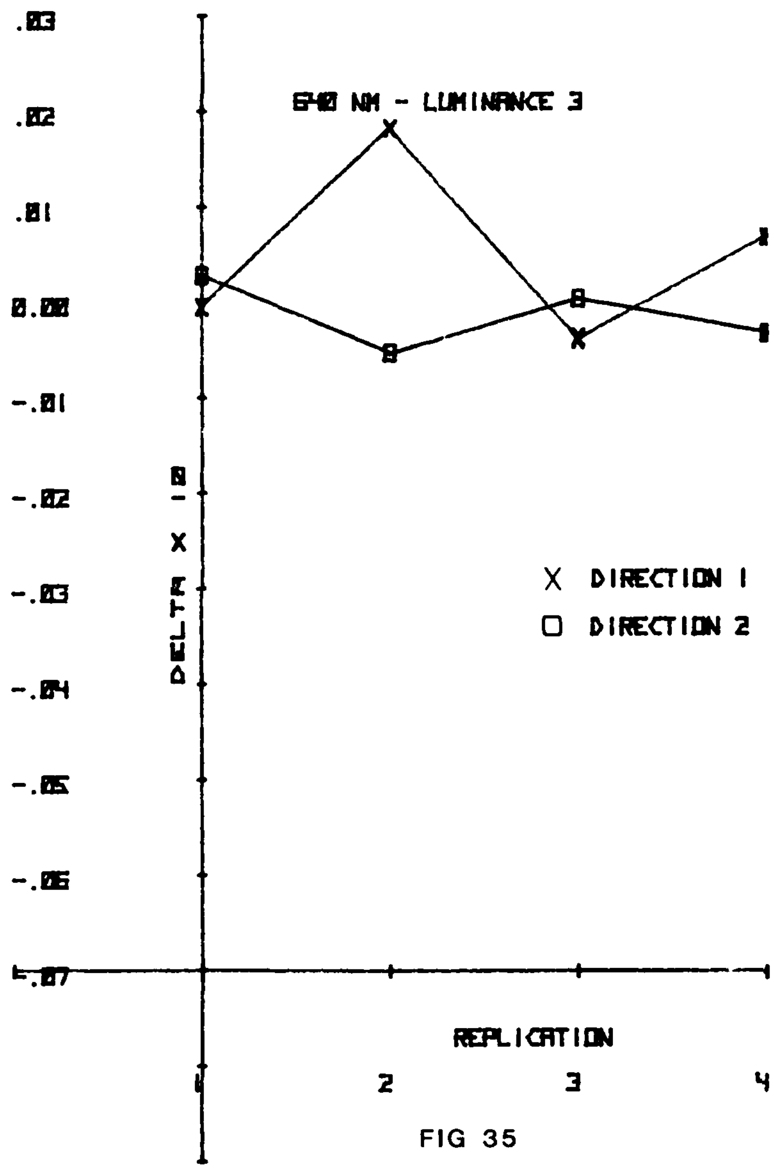

FIG 35

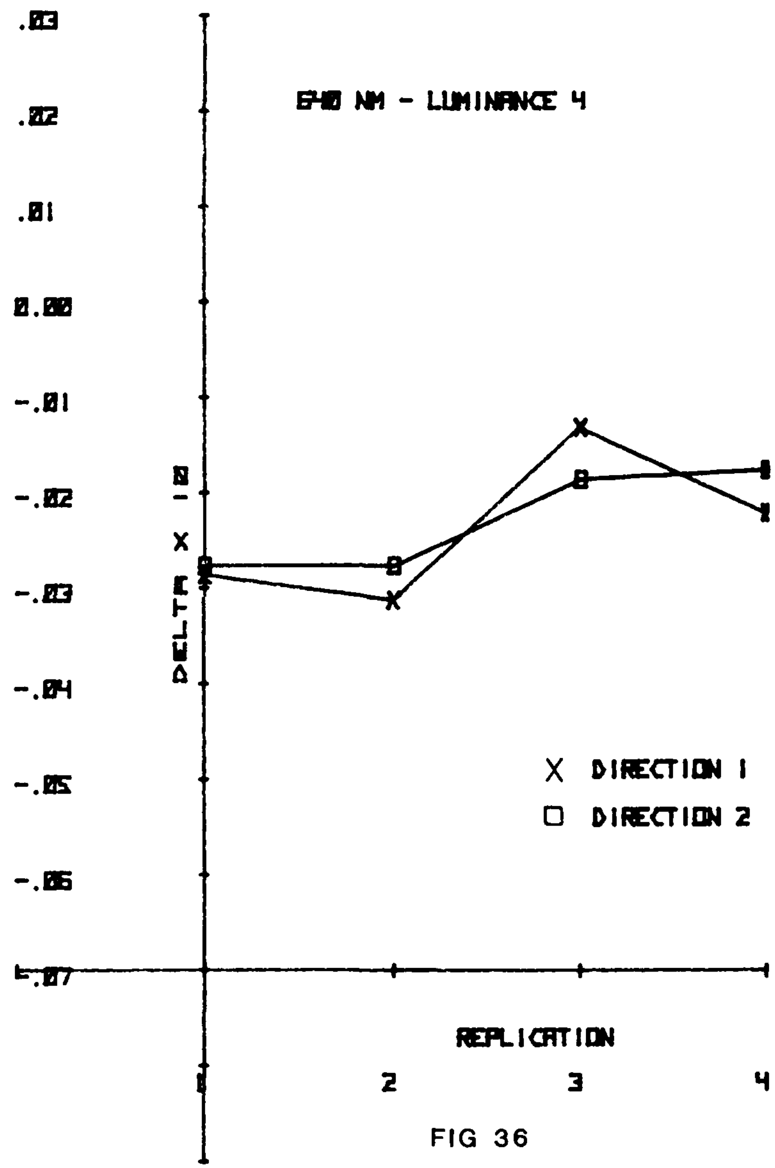

FIG 36

640nm DIRECTION x REPLICATION x LUMINANCE INTERACTION - LUMS 3 AND 4

Table 5.13 tabulates the delta distance from hue match point across saturation levels for all four individual luminance levels as well as the mean of the luminances. As in earlier sections, 5.14 tabulates those same delta distances as u', v' chromaticity coordinates.

	Lum 1	Lum 2	Lum 3	Lum 4	Mean
Sat 1	-.393E-01	-.271E-01	-.764E-02	-.864E-02	-.207E-01
Sat 2	-.326E-01	-.159E-01	+.298E-01	-.223E-01	-.013E-01
Sat 3	-.423E-01	-.279E-01	+.748E-02	-.292E-01	-.230E-01
Sat 4	-.296E-01	-.233E-01	-.717E-02	-.393E-01	-.248E-01
Sat 5	-.262E-01	-.130E-01	-.233E-02	-.283E-01	-.175E-01
Sat 6	-.155E-01	-.145E-01	-.139E-02	-.186E-01	-.125E-01
Sat 7	-.377E-02	-.193E-01	-.678E-02	-.191E-01	-.122E-01

Table 5.13 640 nm delta distance - Saturation X Luminance

	Luminance 1		Luminance 2		Luminance 3		Luminance 4		Mean	
SAT 1	.2570	.4790	.2571	.4778	.2573	.4759	.2573	.4760	.2572	.4772
SAT 2	.2968	.4829	.2970	.4813	.2975	.4767	.2969	.4819	.2970	.4807
SAT 3	.3364	.4885	.3366	.4870	.3370	.4835	.3365	.4872	.3366	.4866
SAT 4	.3763	.4918	.3764	.4911	.3765	.4895	.3766	.4888	.3763	.4913
SAT 5	.4161	.4960	.4162	.4947	.4163	.4936	.4164	.4934	.4162	.4951
SAT 6	.4559	.4995	.4559	.4994	.4561	.4981	.4559	.4998	.4559	.4992
SAT 7	.4958	.5029	.4956	.5044	.4958	.5032	.4956	.5044	.4957	.5037

Table 5.14 Chromaticity coordinates for hue match: 640 nm

5.5 Magenta:

As with the hue lines for 470, 520 and 570 nm, the main effect of saturation level is a significant factor in the analysis for magenta. Figure 37 illustrates an enlarged view of the line of constant perceived hue derived from the experimental data. The hue line starts on the red side of the theoretical line but crosses over to the blue side at the higher saturation levels. There is no effect of varying luminance level and this fact is evident in figure 38. Figure 38 is the plot of delta distance against saturation level for the four luminances. The shape of the curve is not substantially different between luminance levels.

The ANOVA table for this hue line in contained in table 5.15. Keeping the same format for data presentation of the other hue lines, tables 5.16 and 5.17 are the delta distances across saturation levels for all luminances, as well as the mean of all luminances; and those delta distances translated into u', v' chromaticity coordinates, respectively. Delta distances are meaned over the factors of direction, replications and subjects.

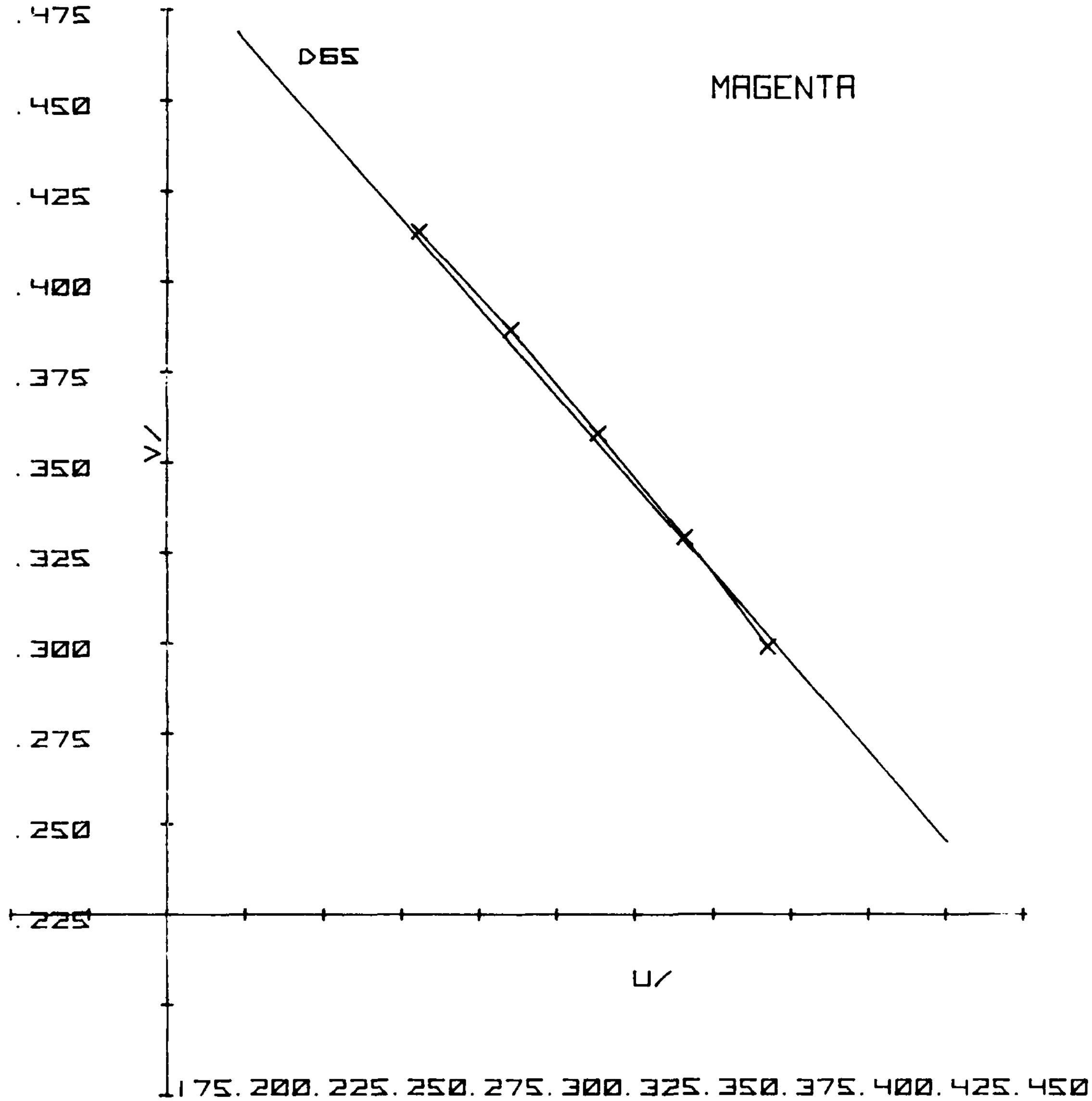

FIG 37 MAGENTA EMPIRICALLY DERIVED LINE OF CONSTANT HUE

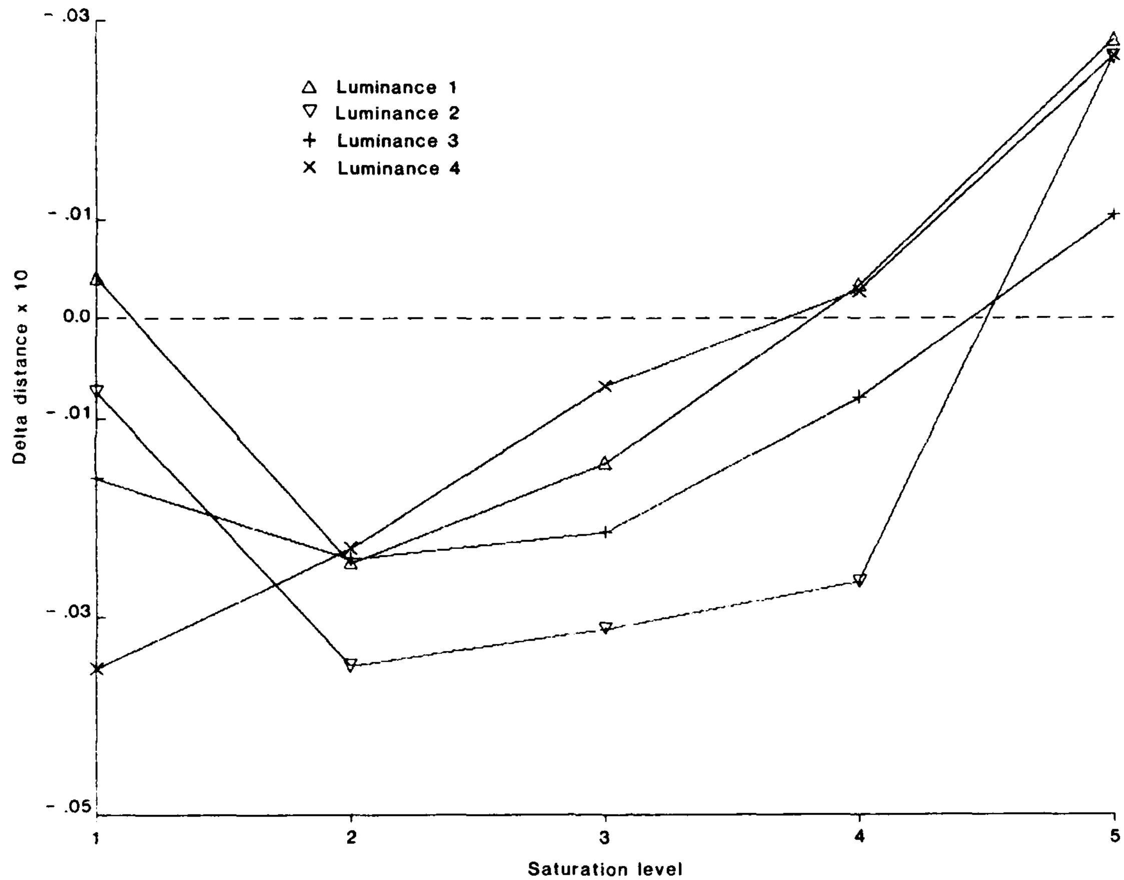

FIG 38 MAGENTA LUMINANCE x SATURATION (L x I)

Source	SS	df	MS	Error	F	Prob
S	0.21175	5	0.423E-01			
D	0.20925	1	0.20925	DS	0.897	NS
DS	1.1665	5	0.2333			
R	0.254E-02	3	0.847E-03	RS	0.331	.803
RS	0.384E-01	15	0.256E-02			
I	0.27494	4	0.687E-01	IS	4.344	.0107*
IS	0.31643	20	0.158E-01			
I(L)	0.16268	1	0.16268	IS(L)	8.086	.01*
IS(L)	0.1006	5	0.201E-01			
I(Q)	0.1091	1	0.1091	IS(Q)	3.037	NS
IS(Q)	0.17962	5	0.359E-01			
I(C)	0.178E-03	1	0.178E-03	IS(C)	0.035	NS
IS(C)	0.254E-01	5	0.508E-02			
I(O)	0.298E-02	1	0.298E-02	IS(O)	1.376	NS
IS(00	0.108E-01	5	0.217E-02			
L	0.271E-01	3	0.902E-02	LS	1.272	.318
LS	0.10633	15	0.709E-02			
DR	0.229E-01	3	0.763E-02	DRS	2.204	.129
DRS	0.520E-01	15	0.346E-02			
DI	0.867E-01	4	0.217E-01	DIS	2.234	.1012
DIS	0.19411	20	0.971E-02			
DL	0.222E-02	3	0.739E-03	DLS	0.100	.959
DLS	0.11071	15	0.738E-02			
RI	0.331E-01	12	0.276E-02	RIS	1.216	.294
RIS	0.1363	60	0.227E-02			
RL	0.726E-02	9	0.807E-03	RLS	0.341	.956
RLS	0.10657	45	0.237E-02			
IL	0.705E-01	12	0.587E-02	ILS	0.978	.479
ILS	0.36005	60	0.600E-02			
DRI	0.351E-01	12	0.292E-02	DRIS	1.146	.342
DRIS	0.15316	60	0.255E-02			
DRL	0.228E-01	9	0.253E-02	DRLS	1.037	.427
DRLS	0.10993	45	0.244E-02			
DIL	0.247E-01	12	0.206E-02	DILS	0.708	.737
DILS	0.17413	60	0.290E-02			
RIL	0.856E-01	36	0.238E-02	RILS	1.121	.308
RILS	0.38184	180	0.212E-02			
DRIL	0.530E-01	36	0.147E-02	DRILS	1.202	0.22
DRILS	0.19118	156	0.122E-02			
TOTAL	4.76708	935				

Table 5.15 ANOVA for Magenta

Sat 1	0.4293E-02	-.72649E-02	-.06021E-01	-.35117E-01	-.13528E-01
Sat 2	-.2458E-01	-.3493E-01	-.24216E-01	-.23089E-01	-.26704E-01
Sat 3	-.1457E-01	-.31233E-01	-.2154E-01	-.6866E-02	-.1855E-01
Sat 4	0.3339E-02	-.2648E-01	-.7948E-02	0.2787E-02	-.70745E-02
Sat 5	0.279E-01	0.26137E-01	0.10317E-01	0.26362E-01	0.22683E-01

Table 5.16 Delta distances - Saturation x Luminance: Magenta

Sat 1	.2546	.4119	.2554	.4128	.2560	.4134	.2573	.4147	.2558	.4132
Sat 2	.2851	.3860	.2859	.3867	.2851	.3859	.2850	.3859	.2853	.3861
Sat 3	.3129	.3572	.3141	.3584	.3135	.3577	.3124	.3567	.3133	.3575
Sat 4	.3403	.3279	.3424	.3301	.3411	.3287	.3403	.3280	.3410	.3287
Sat 5	.3671	.2982	.3672	.2983	.3683	.2994	.3672	.2983	.3675	.2985

Table 5.17 Chromaticity coordinates for hue match: Magenta

6. DISCUSSION

The hypothesis under test for this experiment was that lines of constant hue can be represented in the 1976 UCS chromaticity space as straight lines eminating from the achromatic point out to a point on the spectrum locus. The concern with this empirical test of the representation of iso-hue lines is for the practical, real-life application of colour CRTs in a cockpit environment. The most salient issue is whether, with increasing saturation and/or luminance, substantial deviations from the predicted lines occur. If deviations are found to exist, then an argument can be supported for the necessity for complex control functions within colour displays. These control functions, in the form of large amounts of empirical data in computer look-up tables, are to ensure that each displayed colour is systematically adjusted in both chromaticity and luminance to maintain a visual perception of iso-hue under varying viewing conditions. However, the amount of empirical data required to construct these look-up tables for the control algorithms over the range of all possible viewing conditions anticipated in a multi-role aircraft is staggering and cost prohibitive.

A review of section 5, Results, indicates that there are indeed deviations from the lines of constant perceived hue predicted within 1976 UCS space. Thus, it can be concluded that the 1976 UCS space, for the areas tested in this experiment, is not representative of a perceptually uniform colour space. Looking at summary figure 12, it may be concluded that the deviations found in this experiment were rather large. However, it must be remembered that figure 12 portrays differences observed at five times their actual value.

Overall, with the exception of yellow (570 nm), it was found that the threshold for a hue match is the same at all luminance levels tested (250-2000 cd/m^2). Every hue line examined, except for red, shows that the threshold for a hue match under an iso-luminance condition, expressed as delta distance from predicted iso-hue line, varies with saturation level.

Returning to the discussion of JNDs within chromaticity space, it was indicated that 0.004u' has been taken to be equivalent to 1 JND for chromaticity within 1976 UCS space. Given that this figure is correct, reviewing the delta distances from theoretical lines of constant hue (Tables 5.2, 5.4, 5.7, 5.10, 5.13 and 5.16) shows that the empirically-derived lines of constant perceived hue for blue (470 nm), yellow (570 nm), red (640 nm) and magenta do not exceed 2 JNDs (2 x 0.004u') from the predicted iso-hue lines. The deviation for green (520 nm) is 3 JNDs (3 x 0.004u') from predicted values. If one can assume that 3 JNDs is correct, then the results show that variations in saturation and luminance have little effect on hue perception. However, the adequacy of using 0.004u' as a metric equivalent to 1 JND is questionable. A recent, unpublished research finding in Great Britain estimates 0.001u' is more accurate at predicting perception around the achromatic point. This smaller u' value for 1 JND results in deviations as great as 12 JNDs for these reported data. But it is not yet verified how the value of u' for 1 JND varies as a function of increasing saturation level. It is fairly safe to assume that values as low as 0.001u' to represent 1 JND in 1976 chromaticity space cannot be applied over the saturation range used in this investigation.

It is not possible to predict extrapolations to the empirically-derived lines of constant perceived hue at either ends. Insufficient data are available to accurately estimate how the hue lines converge toward the achromatic point. For this experiment, it must be remembered that subjects never actually saw D65 or any white point. D65 was only used to facilitate computations for the trichromator. However, it is likely that a smooth convergence occurs and highly improbable that any spontaneous shift in hue will occur at a specific saturation level relative to the achromatic point. Current data for surface colours indicate these gradual trends. But the above data, for emissive stimuli, illustrate departures from published surface colour plots, particularly in the green and yellow regions of the chromaticity diagram. The slope of the green hue line (520 nm) shows an increased bias toward blue at medium saturations. Yellow (570 nm) shows an increased bias toward red at all but the highest saturation level studied. Both of these observed slopes are contrary in sign (direction from predicted hue line) to those observed for surface colours. Due to the nature of the trichromator and the wedges to control the luminance levels achieved from each arm, it was not possible to examine any points closer to the spectrum locus than those shown in figure 11

Getting any closer to the spectrum locus would have required extremely small luminance amounts from one of the two arm combining to make either the variable or test field. It was felt that the very small luminance requirements could not be reliably produced by the system.

The overall shift of the green line toward blue needs some additional comment. Although the absolute value of the shift is relatively small, it occurs in a portion of the chromaticity diagram where chromatic spacing is critical if colour naming confusions on a shadow mask cathode ray tube are to be avoided. When the colour-rendering envelope of a typical shadow mask CRT is superimposed on the 1976 chromaticity diagram, only a very small portion of the envelope is available for allocation to the colour "green". This occurs because there is limited chromatic distances available between the hues of blue and cyan, and between cyan and green (16). It has been suggested that the [illegible] be positioned between 530 and 555 nm in order to [illegible] does not occur with cyan. Again, it must be [illegible] dominant wavelength investigated in this [illegible] "green" was 520 nm. In the case for very [illegible] the apparent shift of green toward [illegible] only marginally the probability [illegible] when recalling the slight [illegible] medium saturation [illegible] ambient illumination on the saturated [illegible] the distances between adjacent colours [illegible]

7 CONCLUSIONS

The results obtained during this experiment indicate that comparatively small deviations in predicted lines of constant perceived hue are found with increasing saturation level and over a wide range of increasing luminances. However, since very little experimental data and guidelines exist for emitting displays, the findings are of significant use. Recently, there have been arguments and debates over whether the 1976 UCS space is adequate to use when predicting colour display performance. These debates stem from the review of studies of surface colours which have proven the non-linearities of this newest attempt by the CIE to devise a perceptually uniform colour space. The present experiment does indicate that it is acceptable to use the 1976 chromaticity space to calculate hue perception under conditions of constant luminance.

In answer to the question of whether display system designers of the future should incorporate complicated control function algorithms to automatically compensate for changes in saturation level due to ambient illumination changes to guarantee the chromaticity and luminance remains the same, appears to be [illegible]. It also seems that a rather large variations in display [illegible]nance can be experienced without seriously affecting the hue [illegible]n on that display.

A recommendation to be made would be that, although the trichromator is a very powerful experimental tool, more data need be collected using a state-of-the-art colour shadow mask display in ambient conditions as near as can be estimated for its application.

8.

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