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Colour Discrimination as a Function of Observer Adaptation

by

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Abstract

A piece of apparatus was built to measure the size of just noticeable colour differences as a function of observer adaptation.

The colorimeter used was of the Burnham type with 1·6 degree test and matching fields and a 15 degree adaptation field. Nine different types of adaptation were used: dark adaptation, five types of Plankian adaptations of different colour temperature and three coloured adaptations. Very little difference was found between the sets of results for the five white light adaptations, a slight increase in the size of the just noticeable colour difference with decreasing colour temperature being observed.

To enable the data to be correctly represented in the u,v chromaticity diagram, which is only defined as uniform for daylight adaptation, the apparatus was modified to enable colour appearance shifts to be measured using a binocular matching technique. An appearance shift matrix was computed from the experimental results that could be applied to the sets of discrimination data obtained with adaptations other than daylight to give the relative appearance of the data in daylight adaptation. This enabled the data to be plotted in the u,v chromaticity diagram and the results considered in terms of absolute uniformity. The results for the white light adaptations showed that the data could be directly represented in this way since the discrimination data were invariant to the appearance transformation for any particular sampling point. This was also

true for the results taken using dark adaptation but not true for the results observed using coloured adaptations.

The implications of the results with respect to colour differences between points measured under various illuminants and represented in the u,v chromaticity diagram are considered. The possible location of the observed visual effects has been considered with respect to the physiological processes in the eye.

Contents

Chapter 1

The Measurement of Colour Discrimination

1.1 Introduction

If an observer is presented with two patches of monochromatic light, either separated by a sharp dividing line or by a finite distance, their wavelength difference must have a finite value before the difference in their colour can be detected. In general when the wavelength of one patch is changed the brightness will also change. By adjusting to keep the brightness equal in both patches a just noticeable hue step is observed. Alternatively both patches may be kept at the same wavelength and a just noticeable brightness step observed by moving a variable neutral filter over one patch. By adding white light to one patch a just noticeable saturation step can be observed. It might be thought that the receptors in the eye should be able to detect an infinitely small colour change, but this is not so. The wavelength difference that can be detected depends on several factors. The first requirement is that the response of the retinal receptors must vary as the wavelength is changed. If the response changes rapidly, then a small wavelength difference is detectable provided the distinctive characteristic of the responses to the two wavelengths is retained during transmission of the signals from the receptors to the brain. There are, however, effects such as random fluctuations of receptor sensitivity, neural interactions, the efficiency of the signal transmission in the nerve, fluctuations of brain cell sensitivity and the spontaneous discharge of nerve impulses and other sources of 'noise' in the neurons and nerve fibres, which tend to reduce the discriminating power of the receptor system by blurring the response of the receptors in the retina. Another factor affecting the discrimination step size is the continuous movement of the eye itself causing different receptors to be brought into line with a particular ray of light. It is unlikely that all receptors have a similar response characteristic and so different receptors will give different signal outputs for the same stimulus.

1.2 Methods of Recording Discrimination Data

At least three techniques are available for recording discrimination data in the laboratory.(Birch and Wright, 1961).

(a) Measurement of the just noticeable difference between two stimuli by direct observation.

(b) The matching of two stimuli under given experimental conditions and a statistical analysis of the spread in the results.

(c) The forced choice technique. For a number of different settings of the stimuli the observer is required to state which is the louder, brighter, etc.

Method (a) was used by Wright(1941, 1943) who reported the first extensive set of data dealing with the perceptibility of chromaticity differences along the spectrum locus and along thirty-four lines produced by the additive mixture of pairs of lights. The field size used was 2 degrees square, divided in half horizontally. It was kept at a constant luminance of 75 Trolands, this figure being set by the amount of light available in the blue end of the spectrum. A dark surround was used. The observer first matched the comparison field to the test half of the field, this half of the field having been set to the required colour. The amount of one of the lights in the comparison field was then changed by an amount judged to be just noticeable, the brightness of the test field being simultaneously adjusted to keep the overall brightness constant. The readings were recorded and then a second observation was taken by adjusting the amount of light in the comparison field to give a just noticeable step in the opposite sense. The readings were noted and repeated twice. The observations were repeated for various mixtures of the two lights and for different pairs of lights. The results were recorded as a series of short lines, each representing a just noticeable chromaticity interval, drawn on the 1931 CIE(x,y) chromaticity diagram as shown in Figure 1.1. The lines are shown drawn three times their correct size. All thirty-five lines were recorded by Wright and a further three observers repeated six of the lines. This method of recording the just noticeable difference depends on the decision made by the observer as to what he calls 'just noticeable' and this varies from observer to observer. The observations from the other observers were normalized by multiplying by a factor to give similar lengths in the blue region of the chromaticity chart. It is evident from Figure 1.1 that the 1931 CIE(x,y) chromaticity diagram is far from uniform; the green region is spread out too much and the blue region is greatly compressed. The ratio of the smallest step in the blue corner to the largest step in the green-yellow region is about 1:20. This non-uniform spacing of the colours in the chromaticity chart was anticipated by Judd(1935) from data on purity discrimination.

Method (b) was used by MacAdam(1942) who reported the second extensive set of data dealing with small chromaticity differences.

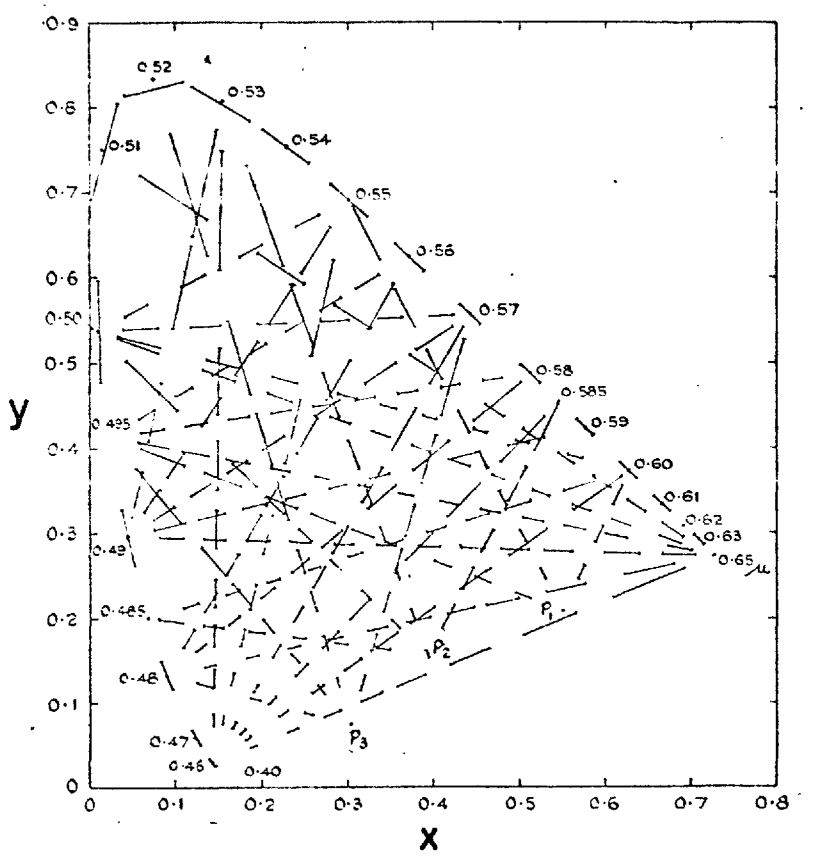
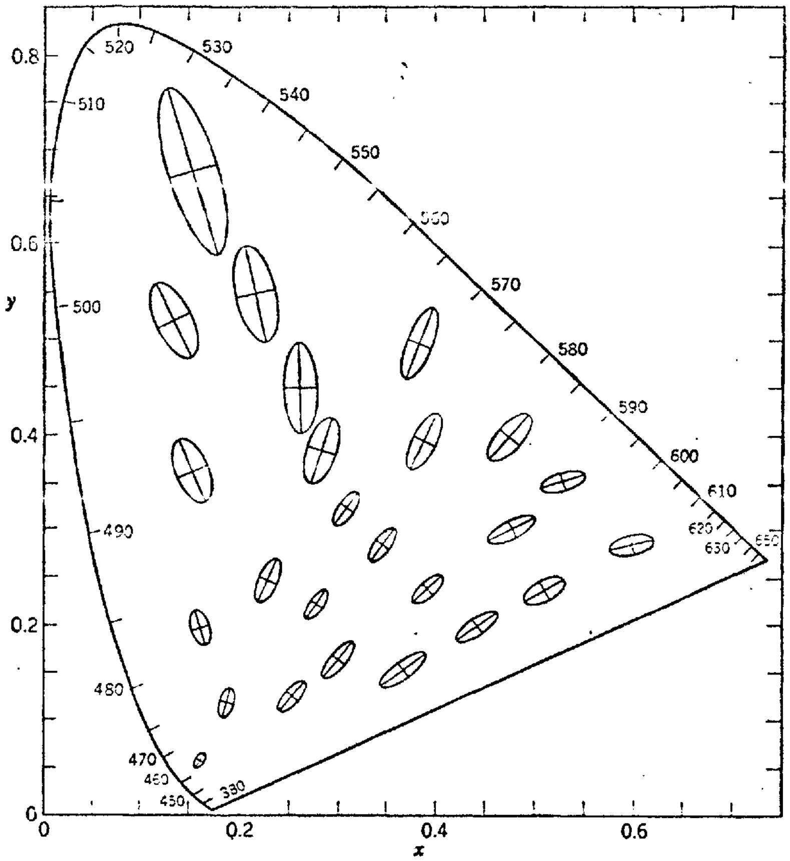


Fig 1.1

(From Wright 1941)

MacAdam's colour difference criterion was the standard deviation of the results of a series of colour matches of a filter. The instrument that he used had a 2 degree circular field divided vertically and surrounded by a 42 degree circular adapting field. The luminance of the field was 15mL and the surround was of daylight quality (S_c) with luminance 7·5mL. Up to eight pairs of filters were obtained, each of which could be used to synthesise the same chromaticity. Fifty colour matches were made for each pair and the standard deviation of the readings determined. This deviation was represented in the 1931 CIE x,y diagram by two opposite radii from the centre point, representing the synthesised chromaticity, towards the pair of points representing the chromaticities of the two filters used in the synthesise. Each pair of filters gave another diameter of an ellipse. Figure 1.2 shows the results for twenty-five filter sets. The ellipses are shown ten times their correct size. The results show the same overall effects as those of Wright(1941, 1943) with the longer radii of the ellipses pointing towards the blue region. The longest radii are in the green-yellow region. The ratio of the longest radius to the shortest radius is 27:1. This method of recording discrimination data is basically sounder than the first method used by Wright because it relies on a statistical quantity and not on an observer's opinion as to what is just noticeable. However, many more readings must be taken and hence observer fatigue becomes an important factor controlling the consistency of the readings.

Stiles(1946), using the results from experiments on the noticeability of the colour change produced by flashing a patch of light subtending one degree on to a field subtending 10 degrees,



Nutting's data on perceptibility of chromaticity differences shown on the (x,y)-chromaticity diagram (after MacAdam, 1942). The elliptical loci correspond to chromaticities separated from the central point by 10 times the standard deviation of settings for chromaticity match.

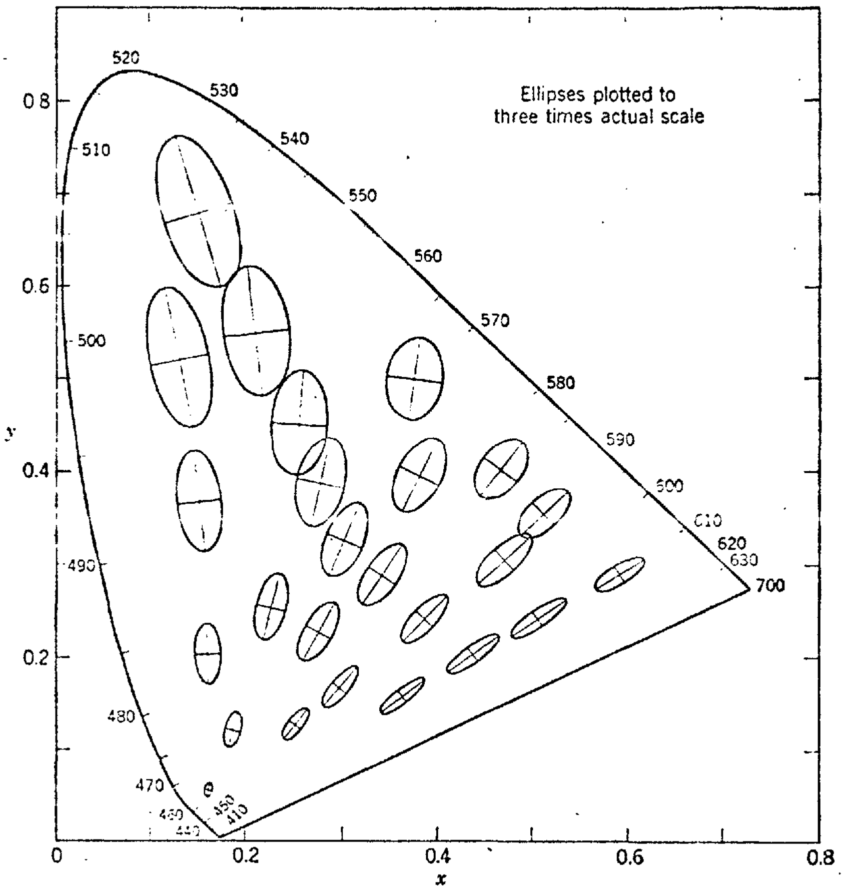
Fig 1.2

(From MacAdam 1942)

centrally fixated by the observer, modified the Helmholtz line element theory.(Helmholtz, 1896). (The line element, a geometrical term, is a measure of the distance between two points that represent two colours that are just perceptibly different.) The criterion used was to adjust the intensity of the flashed patch until it was only seen 50% of the time by the observer. Stiles then applied his theory to the twenty-five colour centres of the MacAdam ellipses to produce the results shown in Figure 1.3, that are free from the local irregularities found by MacAdam. Stiles' data corroborates the main trends of MacAdam's results.

Brown later extended MacAdam's work to take in twelve observers, (Brown, 1957). The instrument used had a binocular field of view. The field subtended 10 degrees and was divided vertically. The average field luminance was 4·9ftL. The surround was white with a luminance of 3·0ftL. The results for the twelve observers were in general agreement with previous work although some results had to be weighted. This was due either to the lack of experience of some of the observers or possibly to tiredness in the observing sessions giving abnormally large ellipses.

In a recent study Wyszecki and Fielder(1971) determined the colour matching ellipses for three observers. A colorimeter with a binocularly viewed bipartite field was used. Each half of the field subtended 3 degrees. The luminance of each half was 12cd m^{-2}; the white surround, which subtended 40 degrees, was maintained at 6cd m^{-2}. The computed colour matching ellipses correlated well with the Brown(1957) ellipses but showed significant deviations from the MacAdam(1942) ellipses.



Perceptibility of chromaticity differences derived from the three-components theory and shown on the (x,y)-chromaticity diagram

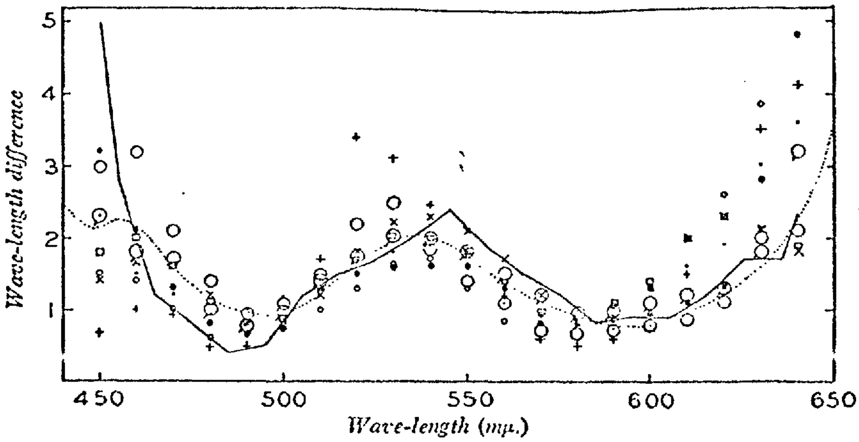
Fig 1.3

(From Stiles 1946)

1.3 Early Discrimination Investigations

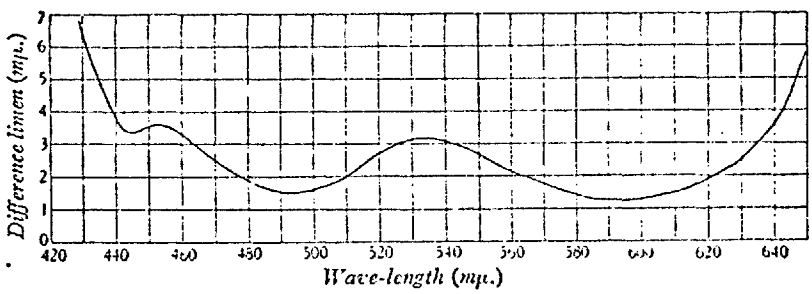
Most early workers were concerned only with hue discrimination. Konig and Dieterici(1903) performed hue matches fifty times at intervals throughout the spectrum. Steindler(1906) measured the minimum change of wavelength perceptible as a difference of hue between two juxtaposed fields using twelve observers. However her apparatus seems to have given a low intensity field of view and the observers did not equate the luminance of both halves of the field as the wavelength was changed. Jones(1917) obtained results, using his own eye, in good agreement with those of Steindler. Laurens and Hamilton(1923) obtained results for ten observers. The apparatus gave only low intensity stimuli and they employed a forced choice technique of observation. Tyndall(1933) obtained results in good agreement with earlier work. Judd(1932) has analysed some of the earlier experimental data on hue discrimination and reproduced them on one diagram as shown in Figure 1.4. He also developed a theoretical curve to approximately fit the points. Wright and Pitt(1934) obtained hue discrimination curves for five observers. Their curve is different from that of earlier workers in that it shows no secondary minimum at the red end of the spectrum. This curve is shown in Figure 1.5.

Work on saturation discrimination has been performed by Martin, Warburton and Morgan(1933). The number of just perceptible steps between white and the various spectral colours was recorded for two observers. It can be seen in Figure 1.6 that a very pronounced minimum occurs in the yellow-green region of the spectrum; the number of steps increases rapidly on either side to approximately the same number in the red and blue ends of the spectrum. This



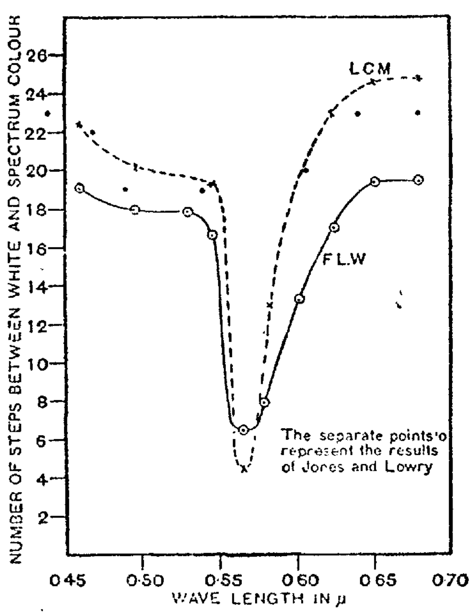
Experimental results from various observers as given by Judd. Continuous line represents Judd's theoretical curve; dotted line represents curve shown in figure 3. • Koenig[1]; ∘ Dieterici; ⊙ Koenig[2]; + Exner; □ Steindler; ◯ Tyndall; ◯ Uhthoff; × Jones; — from empirical law.

Fig 1.4 (from Wright & Pitt 1934)



Mean hue-discrimination curve for five normal observers.

Fig 1.5(from Wright & Pitt 1934)



Number of just perceptible steps between white and the spectral colours, using a 2° field. Colour temperature of white, 4,800° K.

Fig 1.6 (from Wright 1946)

work was later corroborated by Nelson(1937) and by Pitt and Wright(1943).

1.4 The Effects of Field Luminance

The extensive work done by both Wright and MacAdam involved measuring the sensitivity of the eye to changes of colour measured at constant luminance. Brown and MacAdam(1949) investigated colour discrimination for the more general case of combined chromaticity and luminance differences by analysis of the errors of visual trichromatic colour matching. Their instrument had a 2 degree field, observed monocularly with the natural pupil, and a dark surround. Using formulae devised by Silberstein(1946) the coefficients and axes of ellipsoids in colour space were found. Most of the results were nearly symmetrical above and below the constant luminance chromaticity cross section. The ellipses corresponding to the latter agree with those of the previous workers. Thirty-nine colour centres were investigated. The influence of changing the level of luminance was studied for three of these colours. It was found that the ratio between the standard deviation of each primary and its amount appeared to be a function of only the luminance contributed by that primary to the mixture.

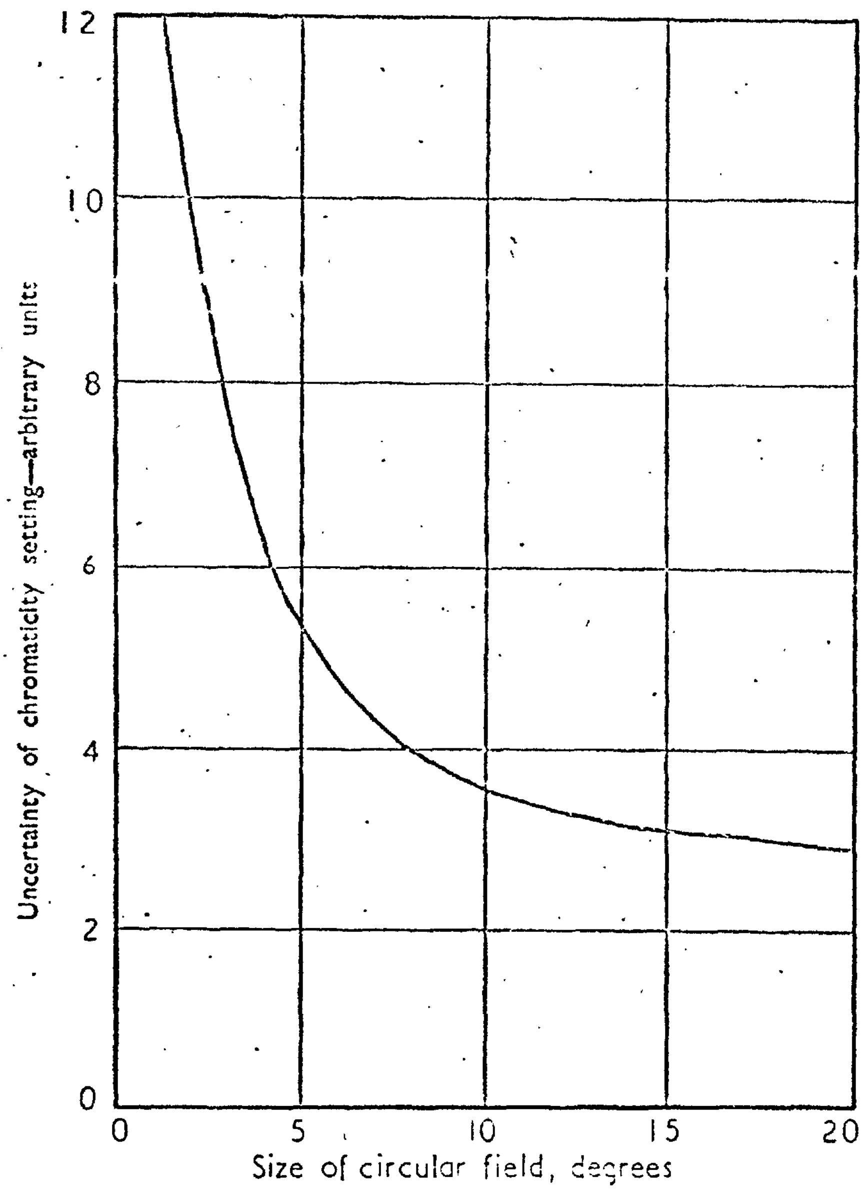
Brown(1951) obtained colour matches for several colours within the luminance range 0·03 - 10·0ftL using an instrument with a 2 degree field and a dark surround. Colour discrimination ellipses were obtained for two observers. These showed that the sensitivity of colour difference remains constant until the field luminance goes below 1·0ftL when discrimination decreases rapidly.

Burnham(1952), using a colorimeter to match Munsell chip test samples subtending visual angles of 2 degrees and 12 degrees at test field luminance levels of 0·84 and 6·30ftL, observed that a given area of colour appeared brighter and more saturated at a higher luminance level.

1.5 The Effect of Field Size and Retinal Illumination

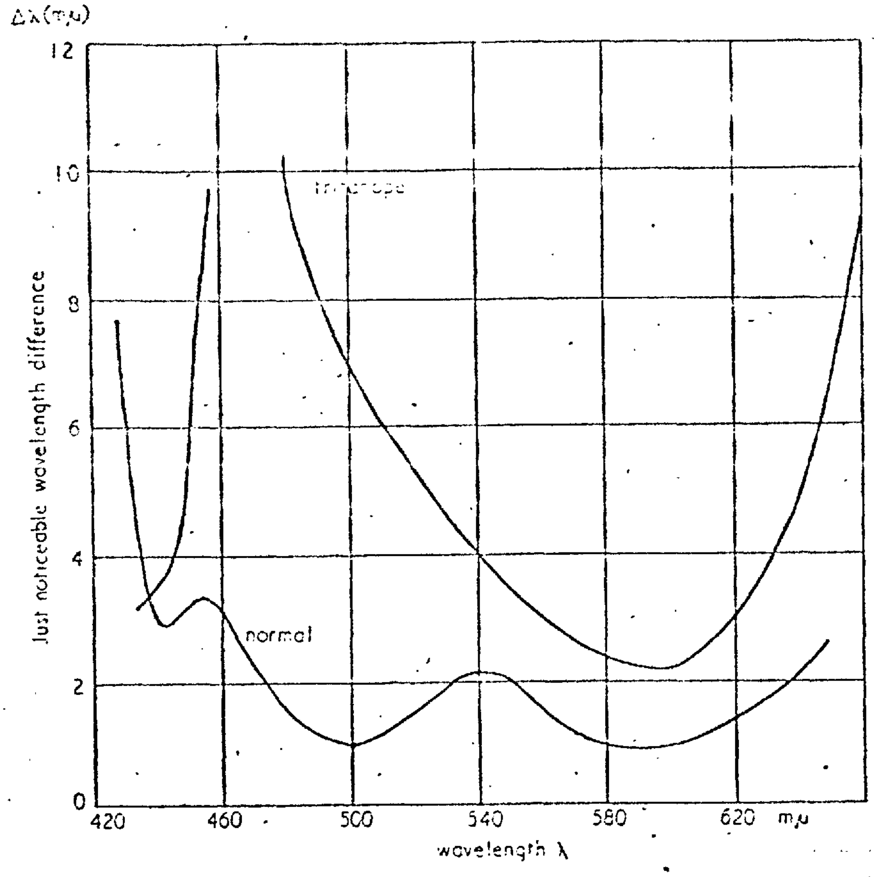
A 2 degree field size has been used extensively in colorimetric work because it corresponds fairly closely to the rod-free area in the central part of the retina. This avoids complicating effects due to the interaction of rod and cone responses and to the Purkinje Shift phenomenom (the change in spectral sensitivity of the eye associated with the transition from cone to rod vision). The area of the retina stimulated is still by no means homogeneous or uniform in structure, since the retinal cones become more widely spaced near the edge of the fovea.

Measurement of hue discrimination is a function of both the field size and the viewing conditions used. Generally, enlarging the field size and increasing the illumination level allows smaller hue changes to be detected. Judd(1963) determined the relation between colour discrimination and field size from the statistical uncertainty of colour matching, Figure 1.7. Willmer and Wright(1945) recorded a hue discrimination curve using a field size of 20 minutes. This is shown in Figure 1.8. Observations were made at several brightness levels, the average retinal illumination being 100 Trolands. No evidence was found of changes in colour or brightness matching with change in intensity level. Maximum discrimination was found to be in the yellow and orange parts of the spectrum although the discrimination step size was five times that obtained by using a 2 degree field. In the blue-green region of the spectrum the



Effect of field size on colour discrimination, as evaluated from the uncertainty of colour matching.

Fig 1.7 (from Birch & Wright 1961)



Wavelength discrimination in defective colour vision. Tritanope.

Fig 1.8 (from Birch & Wright 1961)

step size became so large that discrimination almost ceased to be possible. The discrimination curve obtained was similar to that obtained by a tritanope. Thus it would appear that colour matching with small fields subtending 20 minutes or less can be performed with only two stimuli; an effect known as small field tritanopia. The effect reported by Willmer and Wright confirms Konig's observations of 1894.

Thomson and Trezona(1951) recorded hue discrimination data for foveal viewing with luminance levels near threshold and up to 4 log units times the threshold. They found that with reduction in luminance, discrimination deteriorates in the same proportion for all wavelengths between 490 and 620nm. In the blue and violet region of the spectrum however, there was very little loss in discrimination. Brown(1952) determined colour discrimination ellipsoids for four colours (red, green, blue, white). The average field luminance was 6·6ftL and the average surround luminance was 5·0ftL. He used both a field subtending 2 degrees and a field subtending 12 degrees. The effects of chromatic adaptation will be referred to in a later section. Overall he found that a large field size allowed better discrimination than a small field covering only the fovea but the increase in field size has little effect on the relative discriminating ability for different hues. Bedford and Wyszecki(1958) reported results using fields of only 1·5 minutes (at 300, 900 and 2000 Trolands), 12 minutes (at 25, 100 and 500 Trolands) and one degree (at 100 Trolands). The one degree field was bipartite but the other two fields were separated; the 1·5 minute field by 40 minutes and the 12 minute field by 24 minutes. Xenon lamps were used to give high intensity blue light.

The two observers were told to scan the field of view rather than fixate it. The results for the one degree field agreed with those of previous workers. The results for the smaller fields showed a general decrease in discrimination compared with the 2 degree curve but little relative change in its shape although discrimination became very poor at both ends of the spectrum. These observations were confirmed by McCree(1960,a) for field sizes ranging from 15 minutes to 75 minutes. There was also evidence that, whereas discrimination improved with increasing field luminance, an optimum level could be found beyond which discrimination again deteriorated.

MacAdam(1959), in an investigation of colour graininess in film emulsion, determined colour discrimination ellipses for eleven chromaticities using fields of 4·4 degrees and 3 minutes at a luminance level of 3 to 26ftL. The 3 minute fields were separated by 6 minutes. A bright surround (30ftL) was used. The results for the 3 minute field have been summarised in the form of a plane uniform chromaticity diagram in which the standard CIE coordinate system is made curvilinear. This means that constant luminance discrimination ellipses for a 3 minute field are represented by circles.

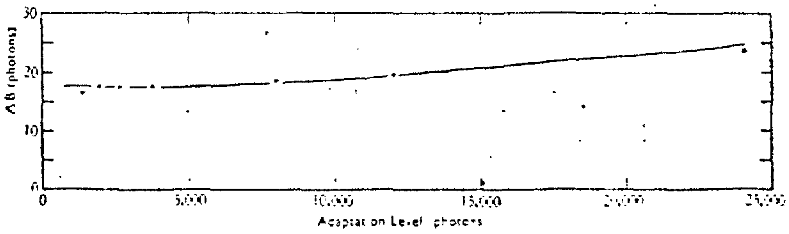
1.6 The Effect of Retinal Position and Fixation

In recent years many experiments have been performed to establish the colour matching properties of the extra-foveal and peripheral retina. The experiments are made particularly difficult by the rapid local adaptation that occurs - Troxler's Effect. Test patches viewed extra-foveally fade and may eventually disappear as a result of a few seconds' fixation. Moreland and Cruz(1959) compared stimuli viewed foveally and extra-foveally and reported a desaturation of colours seen in peripheral vision. This would mean a loss of hue discrimination. Weale(1953) made determinations of the wavelength discrimination curves at high and low levels of illumination for eccentricities of 10, 15, 45 and 75 degrees. For low eccentricities the greater loss of discrimination occured in the blue-green region of the spectrum but at high eccentricities (greater than 45 degrees) discrimination became very poor in the red-yellow-green half of the spectrum while remaining relatively good in the blue-green region. McCree(1960,b) has shown that a major failure of colour discrimination can occur with only voluntary fixation. With a field subtending one degree 20 minutes he was able to cause all colour discrimination to vanish at retinal illumination levels lower than 60 Trolands provided that an accurate luminance match was made. At higher illumination levels it was only possible to distinguish two wavelengths if one half of the field included some element of redness and the other half did not. There was a big variation in susceptibility to fixation effects between observers but more than half found that their discrimination was affected by voluntary fixation.

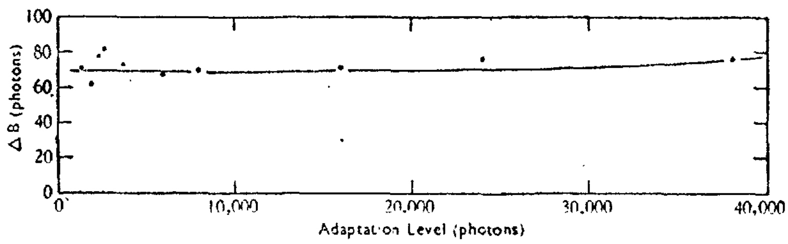
1.7 The Effects of Adaptation

Very little work has been done on colour discrimination with the eye adapted to lights of various colour temperatures or chromaticities. It is this effect that is to be reported on in this thesis.

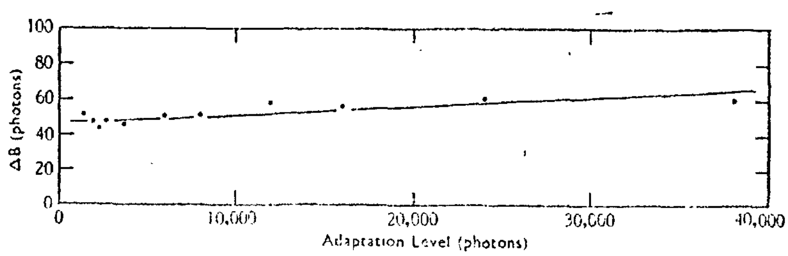
Wright(1934) investigated brightness discrimination using a red, yellow, green and blue test colour of average brightness 500 Trol. The test field subtended 2 degrees at the eye and was only viewed momentarily when the adapting field was taken away. The adapting field was provided by a separate optical system so that its level could be adjusted independently of the test field level. White light was used of approximately 2800°K colour temperature. In all experiments, which were preceded by a period of dark adaptation, the lowest adaptation brightness was higher than the brightness of the test radiation. It can be seen in Figure 1.9 that the size of the brightness discrimination step is effectively independent of the adaptation level of the eye. Further experiments by Wright(1936) studied the change in wavelength discrimination produced by adapting the eye to various colours and intensities of adaptation stimulus. The adapting field, which subtended 5 degrees, was viewed for three minutes and then the test field, which subtended 2 degrees, viewed for about one second. In between these observations light adaptation was continued. White, red and green adaptation was used. The results for white light adaptation are shown in Figure 1.10. In the first two diagrams the same intensity range was used for two different intensities of the yellow test field. The other two diagrams show results for a green (530nm) and a blue-green (494nm) test colour. The maximum range of intensity is limited by the brightness of the test field which approaches the threshold of visibility after the eye has been light adapted. The step size obtained before light adaptation is indicated in each diagram by an arrow. The results for the yellow (580nm) test field show an increase in sensitivity as the adaptation level is increased, a wavelength discrimination step of 0·04nm being detectable. There is a subsequent reduction in sensitivity which is to be expected as the apparent brightness of the test colour falls. Figure 1.11



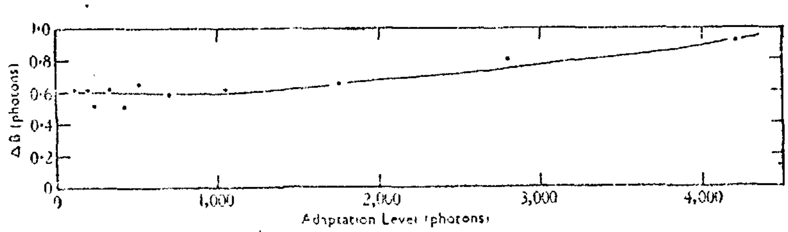
Effect of adaptation on brightness discrimination. Test colour of wavelength 0·65μ and brightness 250 photons. Initial value of ΔB before light adaptation = 15 photons.



Effect of adaptation on brightness discrimination. Test colour of wavelength 0·5825μ and brightness 1,080 photons. Initial value of ΔB before light adaptation = 68 photons.

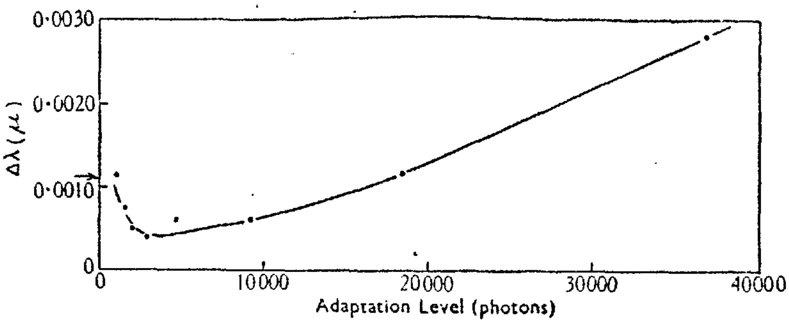


Effect of adaptation on brightness discrimination. Test colour of wavelength 0·53μ and brightness 550 photons. Initial value of ΔB before light adaptation = 52 photons.

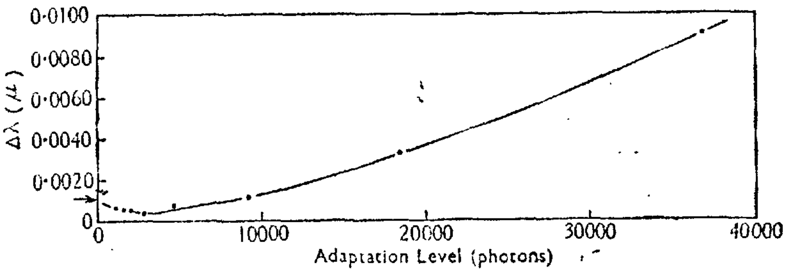


Effect of adaptation on brightness discrimination. Test colour of wavelength 0·46μ and brightness 6 photons. Initial value of ΔB before light adaptation = 0·70 photons.

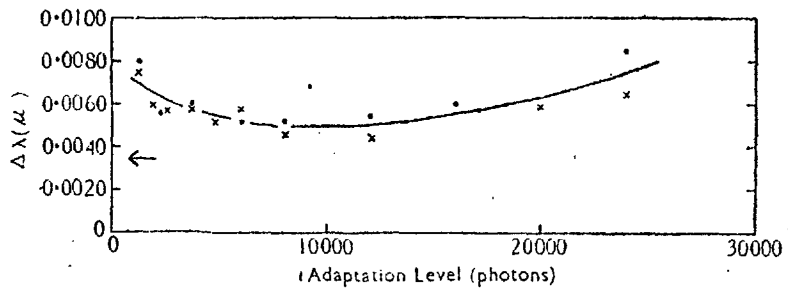
Fig 1.9 (from Wright 1946)



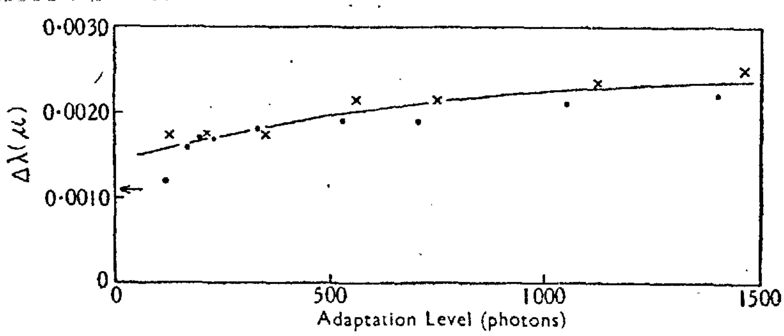
Effect of white adaptation on hue discrimination. Test colour of wavelength 0·58μ and brightness 900 photons. Initial value of $\Delta\lambda$ shown by small arrow.



Effect of white adaptation on hue discrimination. Test colour of wavelength 0·58μ and brightness 500 photons. Initial value of $\Delta\lambda$ shown by small arrow.

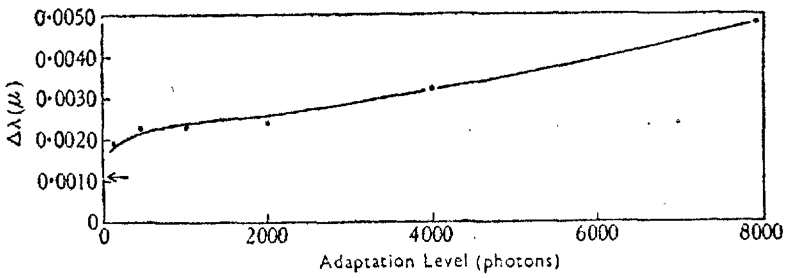


Effect of white adaptation on hue discrimination. Test colour of wavelength 0·53μ and brightness 550 photons. Initial value of $\Delta\lambda$ shown by small arrow.

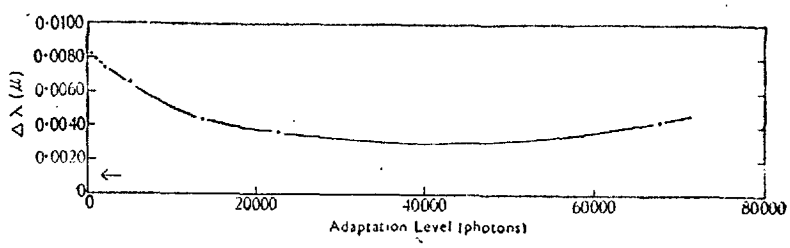


Effect of white adaptation on hue discrimination. Test colour of wavelength 0·494μ and brightness 75 photons. Initial value of $\Delta\lambda$ shown by small arrow.

Fig 1.10 (from Wright 1936)

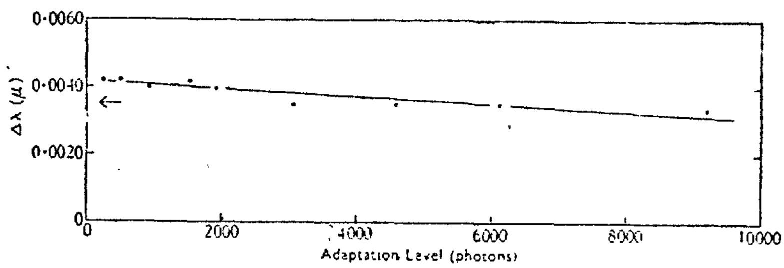


Effect of green adaptation on hue discrimination using a yellow test colour. Wavelength of test colour 0·58μ, brightness 500 photons. Initial value of $\Delta\lambda$ shown by small arrow.

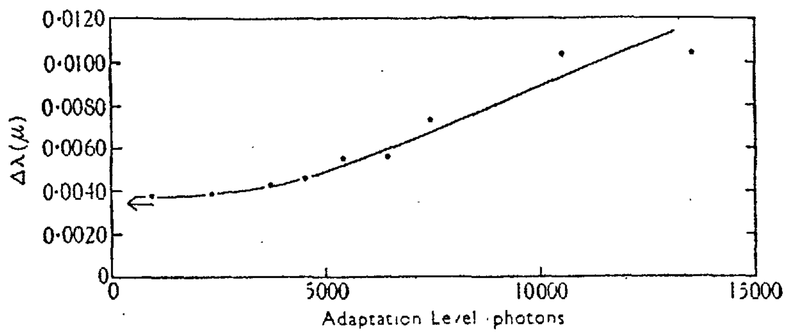


Effect of red adaptation on hue discrimination using a yellow test colour. Wavelength of test colour, 0·58μ, brightness 1,080 photons. Initial value of $\Delta\lambda$ shown by small arrow.

Fig 1.11 (from Wright 1936)



Effect of green adaptation on hue discrimination using a green test colour. Wavelength of test colour, 0·53μ, brightness 550 photons. Initial value of $\Delta\lambda$ shown by small arrow.



Effect of red adaptation on hue discrimination using a green test colour. Wavelength of test colour, 0·53μ, brightness 550 photons. Initial value of $\Delta\lambda$ shown by small arrow.

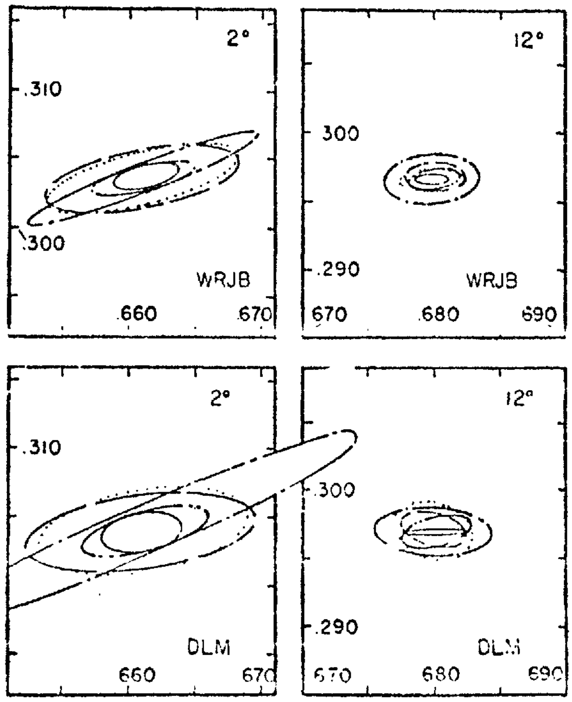
Fig 1.12 (from Wright 1936)

shows the different results for green and red adaptation on a yellow test colour. An increase in discrimination step size compared with the pre-adaptation value is observed. This can be expected on the grounds that coloured adaptation has upset the balance between the red and green responses normally expected for a yellow stimulus. It might further be expected that as the adaptation level increases the size of the discrimination step should increase. This is shown to be true for green adaptation but not for red. Figure 1.12 shows the effect of red and green adaptation on a green test stimulus. The main effect to be expected is for the green adaptation to decrease the green response relative to the red.

Davidson(1951) showed that the visual sensitivity to surface colour differences could be well represented by MacAdam ellipses provided that they were taken to represent differences somewhat larger than just perceptible. His observers were four professional colorists who arranged a red, a green and a blue series of wool dyeings in order, viewing them against a grey background.

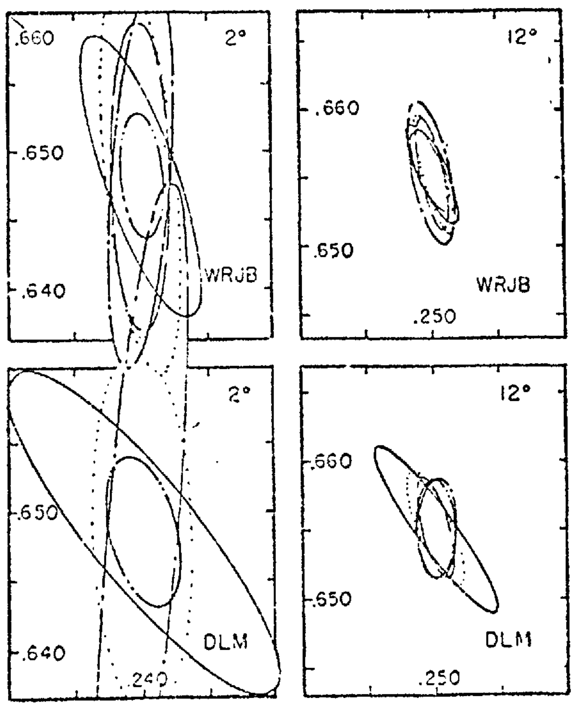
Brown(1952) in his investigation into the effect of field size and chromatic surrounds on colour discrimination used red, green, blue and white test colours with red, green, blue, white or dark surrounds. Two field sizes were used; subtending 2 degrees and 12 degrees. Using the standard deviation of a set of colour matches to compute discrimination ellipses he found that, for the small field, discrimination was reduced by having a chromatic surround field. The influence of the surround on the large field was somewhat less although discrimination was always better than for the small field. Discrimination was more sensitive when the surround and the matching field had the same chromaticity, it being most sensitive for the red field with the red surround. This is shown in Figure 1.13. The dark surround gave an ellipse of the same shape and orientation as the red but it was somewhat larger. The green and white surrounds gave further increases in ellipse size. With the blue surround the ellipse for the 2 degree field was elongated and rotated so that its major axis pointed in the direction of the blue primary. The ellipse for the 12 degree field showed enlargement but little elongation or rotation. Figure 1.14 shows results for the green matching field. The best discrimination was obtained with a dark surround. With the small field and a blue surround elongation and rotation of the ellipses to the blue primary were again observed. The red surround caused orientation in the direction of the red primary. The green and white surrounds produced larger ellipses but no reorientation. Only the red surround had any effect on the ellipses for the 12 degree green field. The colour of the surround had little effect on the discrimination using the blue matching field as shown in Figure 1.15. With the 2 degree field discrimination was marginally better with the dark surround. The ellipse for the red surround was rotated slightly towards the red primary. The results for the 12 degree field show the same trends to a smaller extent although the ellipses are smaller than for the 2 degree field. Using a white field with the coloured surrounds gave ellipses which were distinctly orientated towards the chromaticity of the surround as shown in Figure 1.16. These effects were more pronounced for the small field than for the large field.

Coates, Day and Rigg(1970) conducted some experiments to investigate the effects of viewing conditions on the visual



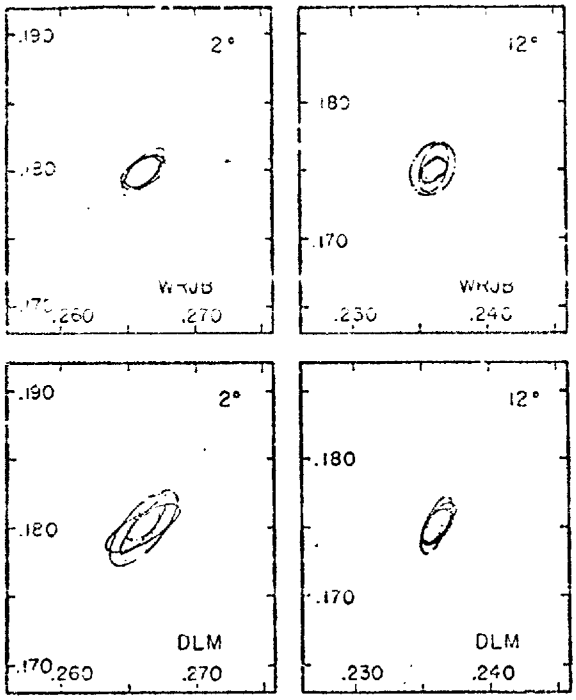
Constant-luminance cross sections of discrimination ellipsoids for a red matching field with —— red surround, —— ——green surround, ——·—— blue surround, ... white surround, and ——··—— dark surround.

Fig 1.13 (from Brown 1952)



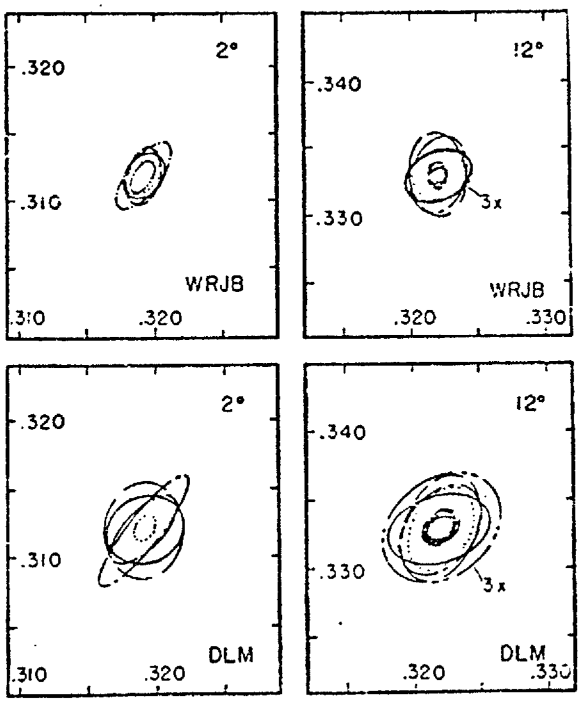
Constant-luminance cross sections of discrimination ellipsoids for a green matching field with —— red surround, —— —— green surround, ——·—— blue surround, ... white surround, and ——··—— dark surround.

Fig 1.14 (from Brown 1952)



Constant-luminance cross sections of discrimination ellipsoids for a blue matching field with —— red surround, —— —— green surround, ——·—— blue surround, ... white surround, and ——··—— dark surround.

Fig 1.15 (from Brown 1952)



Constant-luminance cross sections of discrimination ellipsoids for a white matching field with —— red surround, —— —— green surround, ——·—— blue surround, ······ white surround, and ——··—— dark surround.

Fig 1.16 (from Brown 1952)

assessment of colour differences. Twenty-six observers were asked to rank a set of painted samples in order of increasing colour difference relative to a standard. The samples were 2cm square and they were viewed on a background 30cm square. Grey, green and white samples and backgrounds were used. The results showed that the colour of the surround appears to have little effect on the discrimination. This is probably due to the fact that all the colours used were fairly neutral.

1.8 Conclusion

Thus it is seen that there are many factors affecting the size of the colour difference that is considered just discriminable. The research reported in this thesis was designed to investigate the effects of different illuminating conditions on colour discrimination and to take into account the changes in appearance that occur when these illuminating conditions are altered.

Chapter 2

The Scope of the Work and the Apparatus Used

2.1 General Aims

The aim of the first half of the experimental work was to obtain a set of discrimination data embracing as much colour space as possible and using five different near Plankian adaptations. Further sets of data were to be obtained for three coloured adaptations and dark adaptation. Monocular viewing conditions with the natural pupil were to be used. Various methods of recording discrimination data have already been outlined in the previous chapter and method (a), 'the measurement of the just noticeable difference between two stimuli by direct observation', was used in this study. Thus an instrument was required which had a field of view containing two equally sized test fields surrounded by a fairly large adaptation field. A further requirement was that each field should be of variable colour quality, and that the luminance of one of the fields should either be constant or that there should be some means of keeping it constant as the colour of the field was changed.

2.2 The Apparatus

The apparatus used was a colorimeter constructed by Hunt to investigate colour appearance changes under various illuminating conditions. The main reason for choosing this instrument, apart from it being readily available for use, was that it is capable of giving a surround adaptation field of a very high level of luminance with an equally bright test field. This high luminance enabled a large gamut of colour saturation to be observed.(Hunt,1965).

Some additional parts were necessary and these were constructed by the author. The Hunt instrument consisted of two distinct parts; a test field composed of a variable mixture of red, green and blue lights, and a surround adaptation field of fixed chromaticity. To this was added a further comparison field which was also composed of a variable mixture of red, green and blue lights.

2.3 The Standard Field

The standard test field was provided by a colorimeter of the Burnham type outlined in Figure 2.1.(Burnham, 1952). Like most colorimeters, it operates by the principle of the additive mixture of coloured lights and is unique only in the method by which the lights are mixed together. An illuminated frame containing the filter primaries is moved over one end of an optical integrating bar to introduce the desired proportions of the primaries into the integrating system, and the integrated light is then viewed as a uniform colour at the other end of the bar.

Figure 2.2 shows an expanded view of the complete optical system. The light source S_1 was a 150 Watt Truflector type lamp. This type of lamp had the advantage of having a reflector in the envelope to give greater forward transmission of light and also a very small coiled coil filament. It was set to run at 90% of its rated voltage in order to give a filament colour temperature approximately corresponding to that of Standard Illuminant S_A (2856^oK). The beam from this source, after passing through a piece of heat absorbing glass G_1, that consisted of a small piece of glass cut into several strips, was rendered parallel by the lens L_1. An image of the whole of the lamp filament was then re-focussed by the lens L_1' on to the end of a small integrating bar I_1.

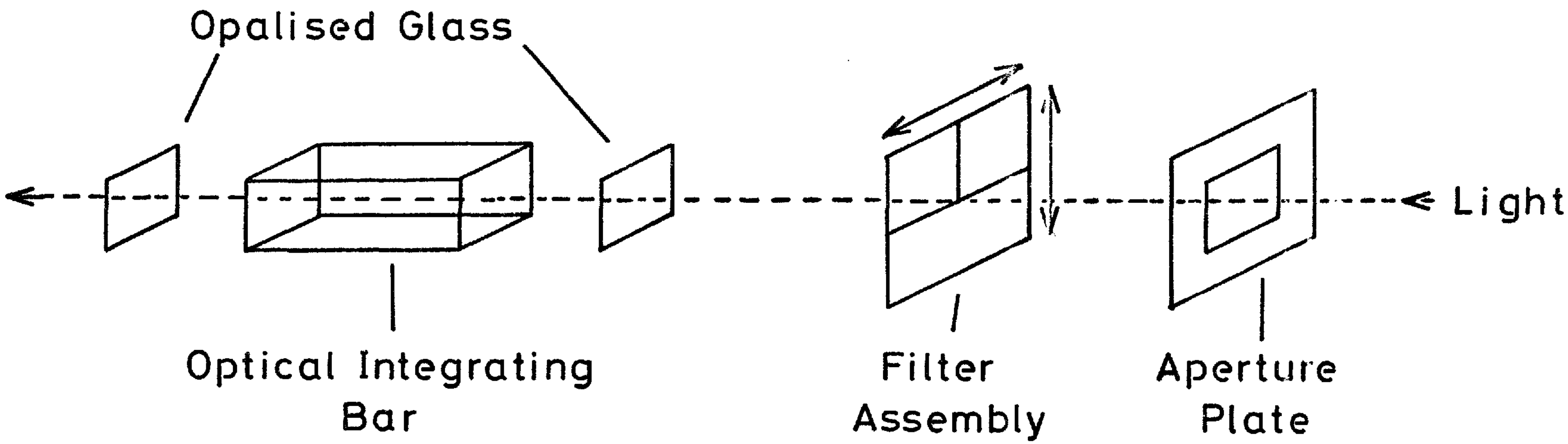


Fig 2.1 The Principle of the Burnham Colorimeter

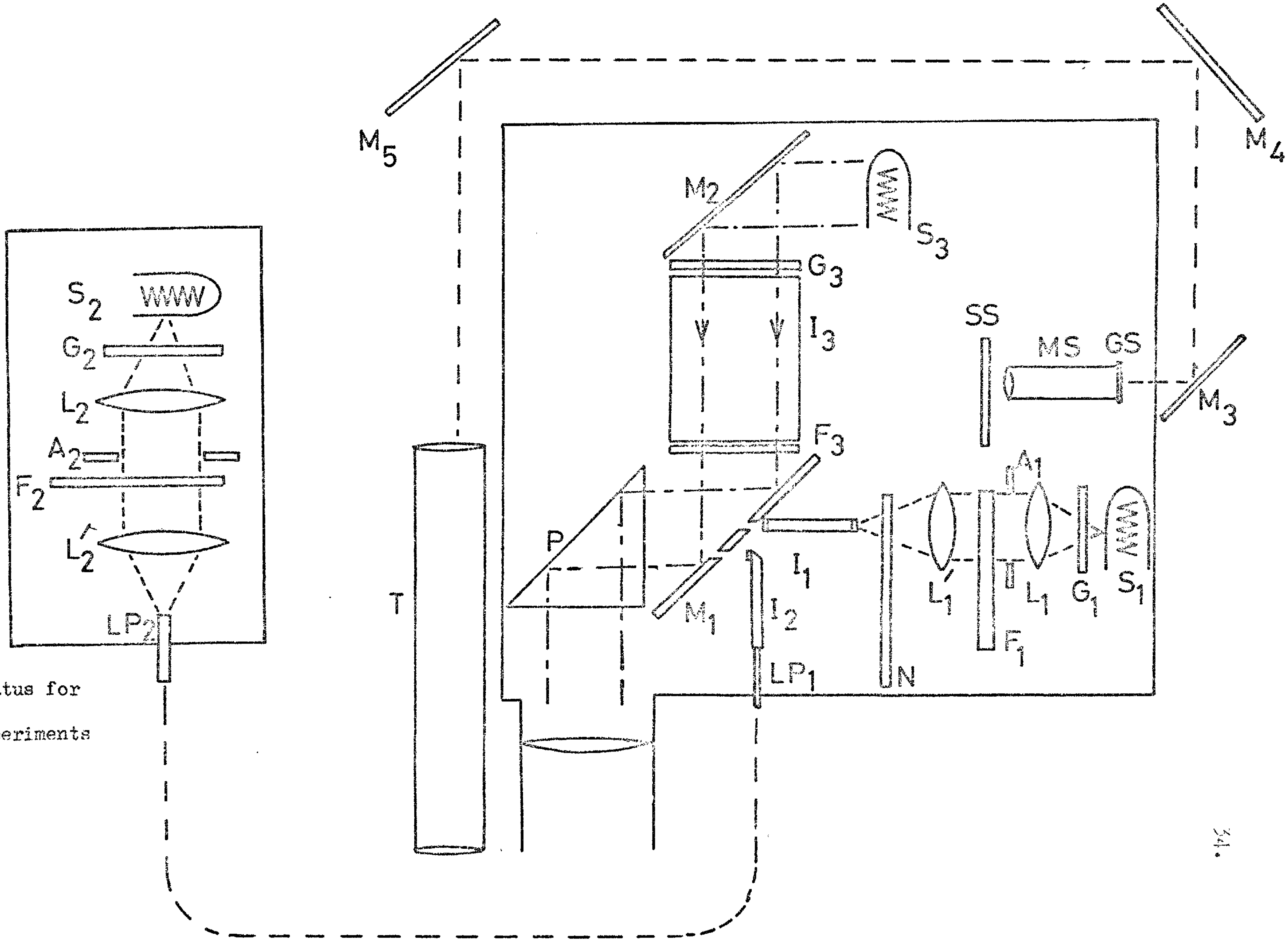


Fig 2.2

Plan of the Apparatus for Discrimination Experiments

This consisted of a piece of clear 'Perspex' of 0·25 inch cross-section and about 1·5 inches in length. Small pieces of opalised 'Perspex' were stuck to each end of the bar to act as diffusers to the ingoing and outgoing light. The light was sufficiently scrambled in this integrating bar to give a uniform field on its exit end. This method of adding the components of the incident light beam is very efficient in terms of additivity but it is not very efficient in terms of overall light transmission.

Between the condenser lenses L_1 and L_1' and covering a square aperture A_1 of side 1·5 inches was a filter assembly F_1, as shown in Figure 2.3, consisting of red, green and blue areas. These were provided by Wratten filters No. 29(Red), No. 58(Green) and No. 47(Blue). They were mounted between two 3·25 by 3·25 inch cover glasses. This filter assembly was mounted on a microscope cross-slide and by moving the cross-slide relative to the aperture a very convenient additive colorimeter was obtained. A neutral density wedge N, (Figure 2.2), was mounted close to the entrance end of the optical integrating bar. The position of the filter assembly and the neutral density wedge were controlled by three knobs mounted conveniently close together.

2.4 The Adaptation Field

The source was another 150 Watt Truflector lamp S_3. The aluminium mirror M_2 reflected the beam through a heat absorbing glass filter G_3, similar to G_1, and into a mirror box I_3. This consisted of four silvered mirrors, two mounted horizontally and two mounted vertically, with pieces of ground glass mounted at each end to form a complete box. This served to provide a surface of overall even illumination with no apparent texture for the

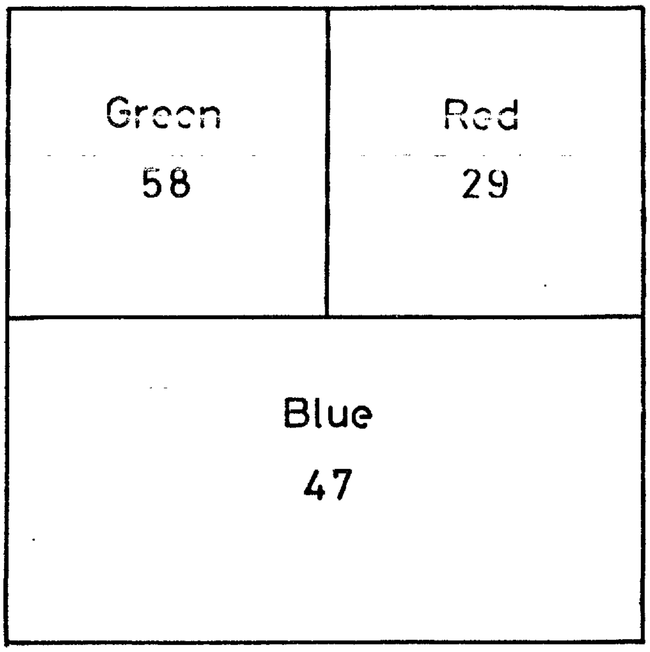


Fig 2.3 Filter Pack

adaptation field. The light then passed through a filter F_3 that was used to obtain the required colour temperature for adaptation. Coloured filters could also be mounted in this position to provide adaptations of various colours.

The beam was then reflected by mirror M_1 into a silvered prism P to be reflected into the eyepiece to give an adapting field of 15 degrees angular subtense. The visual field beyond this appeared black. The mirror M_1 had a small hole in the centre drilled at 45 degrees to its surface to enable light from the end of the optical integrating bar to be viewed. This provided the standard test field of 1·6 degrees angular subtense.

The above two units were mounted in an aluminium box with a lid with the controls for the microscope cross-slide and the neutral density wedge accessible on the outside. A fan, mounted in the bottom of the box, was used to provide forced convection cooling for the two lamps inside the box. The transformers, rheostats and voltmeters for these two lamps were mounted in a separate box connected to the colorimeter by a multi-way cable.

2.5 The Reference Field

The reference field was similar in construction to the standard field and it was mounted in a separate box. It consisted of a source S_2, heat absorbing glass G_2, lenses L_2 and L_2' and a filter assembly F_2 with aperture A_2. The source had a 'Variac' variable voltage transformer in the a.c. supply to its transformer so that the running voltage and hence the brightness of the lamp could be varied. Cooling was provided by a small fan mounted directly behind the source. The second lens L_2' focussed an image of the source filament on to a piece of incoherent fibre optic light guide LP_2 (Rank Precision Industries Ltd., 'Fibrox' Light Pipe). This was necessary because the box containing the reference field apparatus could not be mounted in a position close to the mirror M_1. The light pipe was 2·0ft in length and the transmitting bundle 0·125 inches in diameter. The other end of the light pipe LP_1 was taken into the box containing the standard and adaptation sources and butt jointed to an optical integrating bar I_2. This was similar in construction to the other optical integrating bar I_1 except that it had one end shaped to bend the light through a right angle. This was so that the reference field could be mounted close to the standard field in the rather confined space available in this part of the apparatus. It meant, however, that this integrating bar was less efficient than the straight type I_1. There was a second hole in the mirror M_1 through which the end of the optical integrating bar I_2 was viewed.

Thus the field of view, as shown in Figure 2.4, contained two separate fields, each subtending 1·6 degrees and separated by 1·5 degrees, surrounded by an adaptation field subtending 15 degrees. The standard field was on the right hand side of the field of view and the reference field on the left hand side.

All three lamps required a maximum of 21·5 volts. This was supplied by three separate transformers which were in turn supplied by a constant voltage transformer used to smooth out any fluctuation in the a.c. mains supply.

The complete apparatus was mounted on a table such that the observer could sit comfortably with his head resting on the rubber surround of the eyepiece. The controls of the apparatus were mounted such that those of the standard field were operated

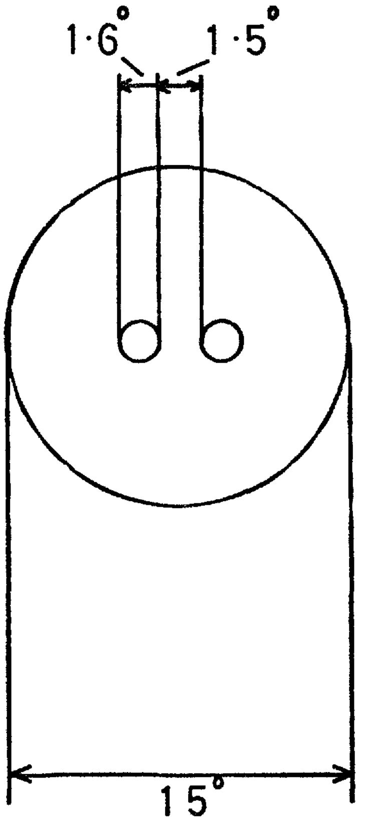


Fig 2.4 Field of View

by the right hand and those of the reference field by the left hand.

2.6 The Theory of the Apparatus

The experimental procedure required that all measurements be made using the standard field with the filter assembly F_1. The calculation of chromaticity coordinates required a knowledge of the horizontal and vertical positions of the filter assembly relative to the aperture against which it was mounted.

Let the vertical movement of the filter assembly be represented by a scale V ranging from 0·0 to 1·0 and the horizontal movement by a scale H having the same range. The three filters are arranged so that the scale V is at 1·0 and the scale H at 1·0 for 100% red, scale V is at 1·0 and scale H at 0·0 for 100% green, scale V is at 0·0 and scale H at 0·0 for 100% blue and scale V is at 0·0 and scale H at 1·0 also for 100% blue. The proportional contribution of each filter to any given mixture is given by:-

$$R = V \,.\, H$$

$$G = V \,.\, (1 - H)$$

$$B = (1 - V) \,.\, (1 - H) + (1 - V) \,.\, H$$

$$= (1 - V)$$

where R, G, B are the proportional amounts of red, green and blue colours in any mixture respectively.

Thus for any given mixture:-

$$C = R + G + B$$

$$C = V \cdot H + V \cdot (1 - H) + (1 - V)$$
$$= 1$$

The measurements H and V were obtained from a scale slide SS, illustrated in Figure 2.5, that was attached to the side of the filter assembly. This was viewed through a low power microscope MS with a ground glass screen GS in place of the eyepiece. A set of cross-wires was engraved on the screen. So that measurements could be taken while the observer remained adapted a mirror system M_3, M_4, M_5 was arranged on the outside of the box containing the standard field apparatus and its associated adaptation field. A telescope T was used to image the ground glass screen in the left eye. A neutral density filter (1·0) was inserted in the beam of light in the telescope to ensure that the luminance was considerably less than that seen by the right eye. To avoid writing down the measurements as they were observed a tape-recorder and microphone were used, the tape-recorder being operated by a foot switch every time a reading was recorded. Thus it was possible to take as many readings as desired without spoiling the adaptation of the right eye.

Thus the apparatus consists of two independently controllable fields composed of a mixture of red, green and blue lights surrounded by an adaptation field of varying colour temperature and colour quality. The apparatus has the added advantage that the observer can record his own observations while his observing eye remains adapted.

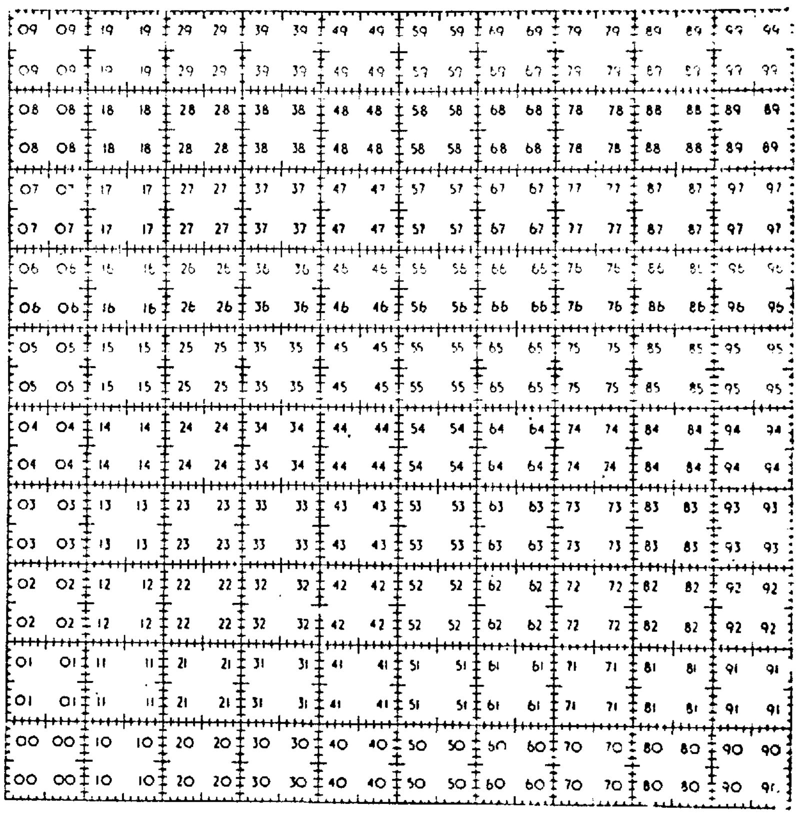


Fig 2.5 Scale Slide

Chapter 3

The Calibration of the Apparatus

3.1 Introduction

The parts of the apparatus requiring calibration were the filters used in the filter assembly to obtain the red, green and blue lights. There were two sets of filters; one providing the standard field and the other the reference field. Only those providing the standard field needed calibration because all measurements were taken using these filters. The reference field was used solely as a reference and no measurements were taken from it.

The filters used to raise or lower the colour temperature of the adaptation source had to be constructed to give the required colour temperatures for adaptation and to keep the luminance of the adaptation source constant as the colour temperature was varied. Filters were also required to change the colour of the source light, also maintaining constant luminance, for work under coloured adaptations. A measure of the level of luminance was also required.

The efficiency of the transfer of coloured light from the filters through the optical integrating bar was also investigated.

3.2 The Calibration of the Filters

The CIE tristimulus values X, Y and Z of a given colour mixture are found from the computed tristimulus values of the three primaries and the proportional contributions of the primaries to the mixture:-

$$X = R.X_r + G.X_g + B.X_b$$

$$Y = R.Y_r + G.Y_g + B.Y_b$$

$$Z = R.Z_r + G.Z_g + B.Z_b$$

where:-

X_r, Y_r, Z_r are the tristimulus values of the red filter.

X_g, Y_g, Z_g are the tristimulus values of the green filter.

X_b, Y_b, Z_b are the tristimulus values of the blue filter.

R, G, B are the proportional amounts of the red, green and blue colours in the mixture respectively.

Thus we need to know the tristimulus values of each filter in the standard filter assembly.

The method used was to derive the tristimulus values from the spectral composition of the light transmitted by the filter P_λ. Generally:-

$$X = \Sigma(P_\lambda \cdot \bar{x}_\lambda)$$

$$Y = \Sigma(P_\lambda \cdot \bar{y}_\lambda)$$

$$Z = \Sigma(P_\lambda \cdot \bar{z}_\lambda)$$

where $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$ are the tristimulus values, or distribution coefficients, for wavelengths λ in the equal energy spectrum. The spectral composition P_λ is a function of the source used to illuminate the filter and can split into two functions, S_λ and

P_λ, where S_λ is a measure of the energy distribution of the source. Thus:-

$$X = \Sigma(P_\lambda \cdot S_\lambda \cdot \bar{x}_\lambda)$$

$$Y = \Sigma(P_\lambda \cdot S_\lambda \cdot \bar{y}_\lambda)$$

$$Z = \Sigma(P_\lambda \cdot S_\lambda \cdot \bar{z}_\lambda)$$

Tables of values of $S_\lambda.\bar{x}_\lambda$, $S_\lambda.\bar{y}_\lambda$ and $S_\lambda.\bar{z}_\lambda$ are available for the Standard Illuminants S_A, S_B and S_C (Wright, 1969). These tables have the advantage of using the Y tristimulus value to give the percentage luminance of the surface or filter directly.

The spectral transmission of the three filters was measured over the wavelength range from 380nm to 740nm, in steps of 10nm, using the Wright Non-Recording Spectrophotometer available in the laboratory.(Wright, 1953). The light transmitted by the filter at each wavelength was measured using a photomultiplier tube, with a suitable 1kV power supply, connected to a digital voltmeter. Readings were also taken without a filter in the apparatus to enable the absolute transmission of the filter to be calculated. The transmission curves of the red, green and blue filters are shown in Figure 3.1. The multiplication, wavelength by wavelength, was performed using a computer and the tristimulus values X, Y and Z found for each filter. It was necessary to add neutral density filters to the red and green filters so that a change in the position of the filter assembly relative to the aperture did not produce an overall change in the amount of light transmitted by the filters. The values of the neutral density required were calculated using information supplied by the filter manufacturer.

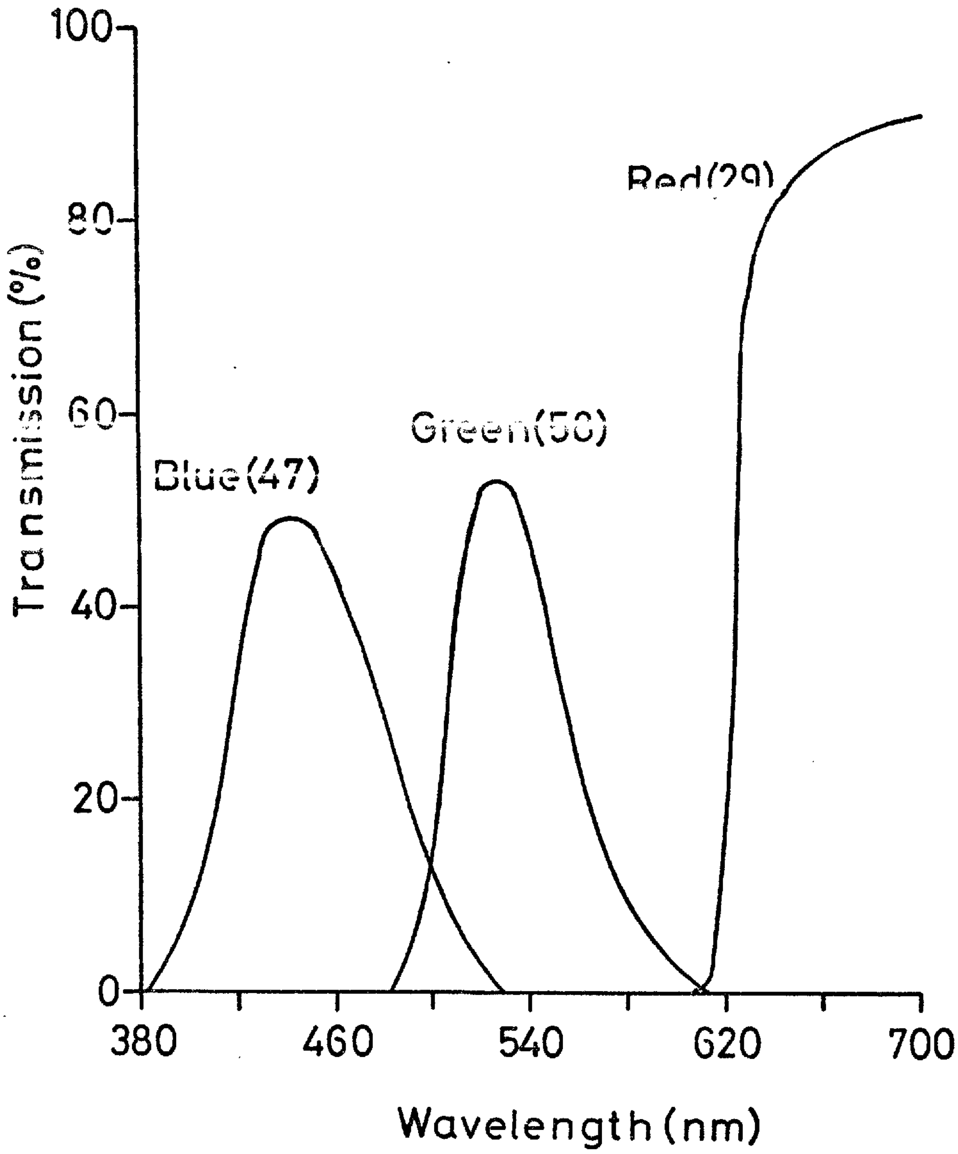


Fig 3.1 Filter Transmission

(Kodak, 1969). It was required to make the Y tristimulus value of each filter approximately the same with no filter being added to the blue filter which was the densest filter. The required neutral density for the red filter D_{red}, was given by:-

$$D_{red} = \log_{10} \frac{Y(\text{Blue})}{Y(\text{Red})} \doteq 1 \cdot 0$$

Similarly for the green filter:-

$$D_{green} = \log_{10} \frac{Y(\text{Blue})}{Y(\text{Green})} \doteq 1 \cdot 2$$

Thus a neutral density of 1·0 was bound in with the red filter and a neutral density of 1·2 was bound in with the green filter. This was done before the tristimulus values of the filters were found. The corresponding chromaticity coordinates were found using the equations:-

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = 1 \cdot 0 - x - y$$

The results for the three filters were:-

Red	X = 1·8124	x = 0·7082
	Y = 0·7467	y = 0·2918
	Z = 0·0001	z = 0·0000

Green	X = 0·2697	x = 0·2603
	Y = 0·7170	y = 0·6921
	Z = 0·0493	z = 0·0476
Blue	X = 1·6506	x = 0·1368
	Y = 0·8808	y = 0·0730
	Z = 9·5350	z = 0·7902

The chromaticity coordinates were plotted in the 1931 CIE (x,y) chromaticity diagram, as shown in Figure 3.2, to give the colour triangle which defines the gamut of colours which can be matched using the colorimeter with these particular filters. It is seen that the triangle excludes some areas of the space within the spectrum locus especially in the blue-green region. This could be overcome by using a fourth cyan filter (e.g. a Wratten No. 75) in place of half of the large blue filter.

The coloured light had to pass through a glass lens and the optical integrating bar before it was viewed. It was assumed that the absorption of light in the lens would be negligible. The absorption of 'Perspex', the material from which the integrating bar was made, is stated by the manufacturer to be uniform throughout the visible spectrum and less than 0·5% per inch thickness of material. This absorption component was also ignored because it was small compared with the overall filter transmissions.

3.3 The Filters for the Adaptation Source

The colour temperature of the adaptation source needed to be changed to five different values:-

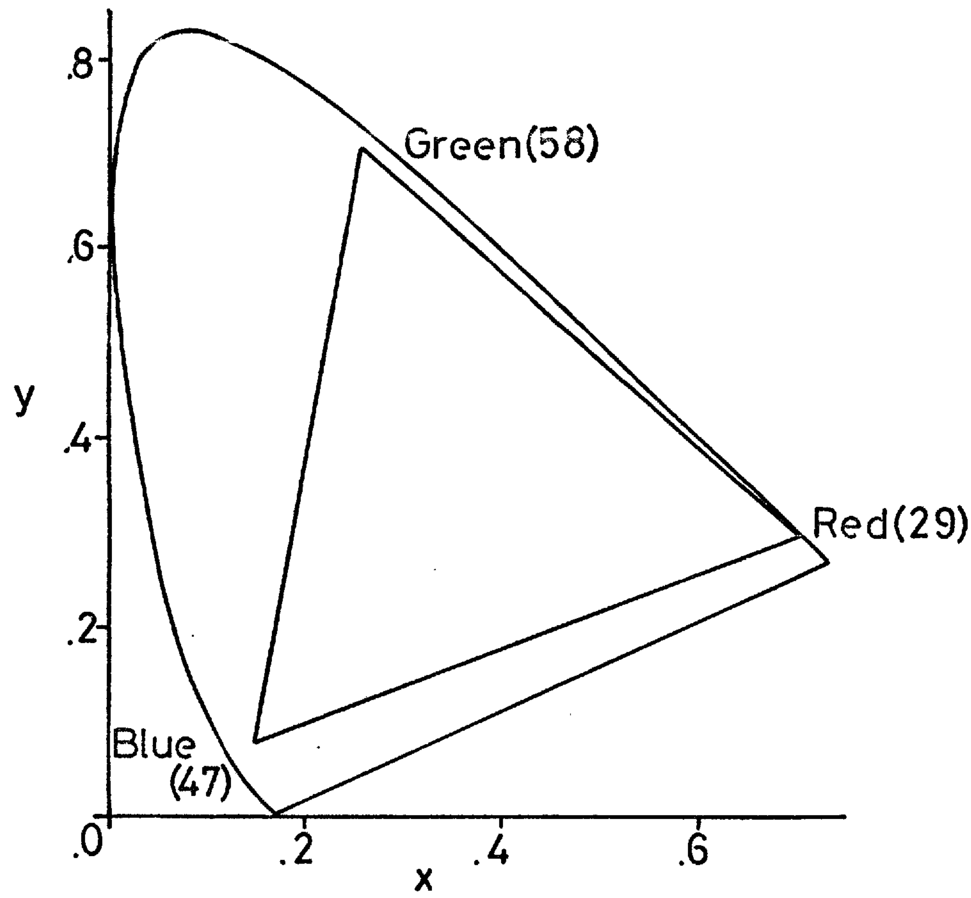


Fig 3.2 Colour Triangle

6500°K corresponding to Standard Illuminant D_{65}, typical average daylight.

5500°K corresponding to typical sunlight plus skylight.

4000°K corresponding to a typical fluorescent tube.

2856°K corresponding to Standard Illuminant S_A, tungsten illumination.

2000°K corresponding to something approaching candle-power.

It was also desired that the adaptation be as bright as possible and so initially the lamp was set to run at the highest possible voltage. This still involved slight under running (4%) to prolong the life of the lamp. The approximate colour temperature of the filament, as seen in the eyepiece of the apparatus, was measured using a Megetron Colour Temperature Meter. This colour temperature was converted to its mired value, (10^6/colour temperature), and the mired shift to the required colour temperature calculated. A set of fourteen Chance OB8 glasses, each 2·0 by 2·0 inches, was available. These had thicknesses ranging from 0·85mm to 4·60mm and gave corresponding mired shifts of -47M to -233M. The nearest piece of glass giving the required mired shift was selected and placed in front of the adaptation source. The standard field was then used to match the surround. From the readings obtained the chromaticity coordinates were calculated. The x,y coordinates first calculated were converted to their corresponding u,v coordinates using the equations:-

$$u = \frac{2x}{6y - x + 1{\cdot}5}$$

$$v = \frac{3y}{6y - x + 1{\cdot}5}$$

The use of the 1960 CIE u,v chromaticity coordinate system had the advantage that lines of correlated colour temperature are perpendicular to the black body locus. Thus the colour temperature of the source plus filter could be found.

The filter needed to convert the source to a colour temperature of 6500°K was found first since this would be the densest filter. This set the highest available brightness level. The required filter was a piece of Chance glass 2·74mm in thickness.

The filters for the other colour temperatures were then found using the same technique. Gelatine neutral density filters were used to keep the brightness constant. When a piece of Chance glass of the required thickness was not available the one nearest to it was taken and the filter trimmed to the required mired shift by using Kodak Wratten Series 82 (Bluish) filters to raise the colour temperature or Kodak Wratten Series 86 (Yellowish) to lower the colour temperature.

The red, green and blue adaptations were provided by filters similar to those used in the standard field filter assembly. The brightness was adjusted by colour matching the filter with the respective colour in the standard field and adjusting the voltage of the adaptation source to give a brightness match. In the case of the green filter a neutral density filter had to be added in front of the adaptation source for a match to be obtained. The dark surround was obtained by switching off the adaptation source and blanking off the end of the mirror box with a piece of black card.

The final filter combinations were bound between two cover glasses. Their make-up is shown in the table in Figure 3.3. The

Colour Temperature Conversion Filters

6500°K	One piece of Chance OB8 glass 2·74mm thick
5500°K	One piece of Chance OB8 glass 2·40mm thick + 2 Cover glasses
4000°K	One piece of Chance OB8 glass 1·50mm thick + Wratten 82A + Neutral density 0·1 + 2 Cover glasses
2856°K	One piece of Chance OB8 glass 0·85mm thick + Neutral density 0·4 + 2 Cover glasses
2000°K	Wratten 81C + Neutral density 0·5 + 2 Cover glasses

Fig 3.3

position of the chromaticities of each filter relative to the black body locus is shown on the u,v chromaticity diagram in Figure 3.4. The positions of the coloured adaptations are also shown.

The lamp had a colour temperature of approximately 2750°K when it was being under-run by 4% for the adaptations of different colour temperature. Thus the filter combinations for 6500°K, 5500°K, 4000°K and 2856°K raised the colour temperature and were therefore blue while the filter combination for 2000°K had to lower the colour temperature and was therefore yellow.

3.4 The Luminance of the Adaptation Field

This was measured using a flicker photometric method. The layout of the additional apparatus needed is shown in Figure 3.5. A motor M with a white sector W attached to it was placed in front of the eyepiece of the apparatus E. A standard source S_5 was mounted on a length of optical bench B at 45 degrees to the viewing axis V. A screen SC, with a small central hole, was mounted at the instrument end of the bench to limit the area of the light falling on the sector. A tube T, containing a pin-hole at the observation end and an iris diaphragm at the instrument end, was set up along the viewing axis. The iris diaphragm was stopped down until an area of the adaptation field could be seen that did not include the standard or reference fields. A screen was set up between the viewing arm and the optical bench to prevent any light entering the observer's eyes directly from the standard lamp. The sector was then set in motion and the distance of the standard source from the sector adjusted, by sliding the source holder

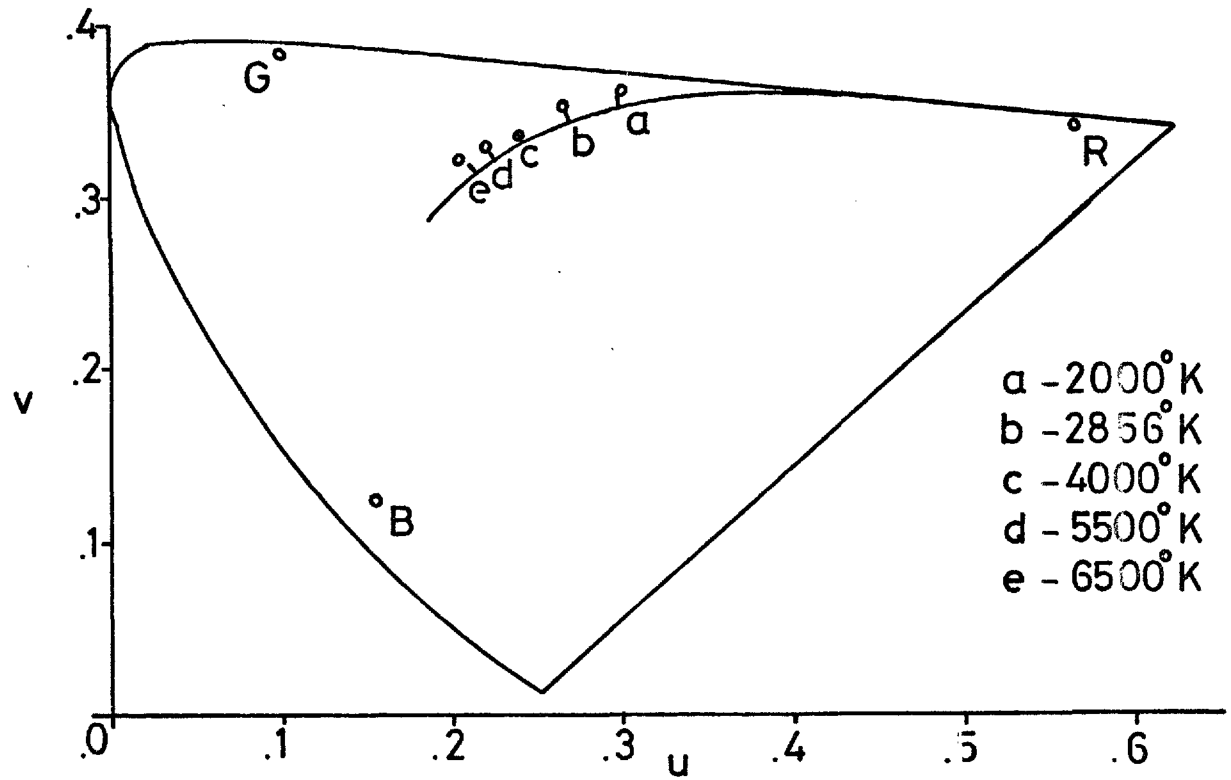


Fig 3.4 Colour Temperature Conversion Filters

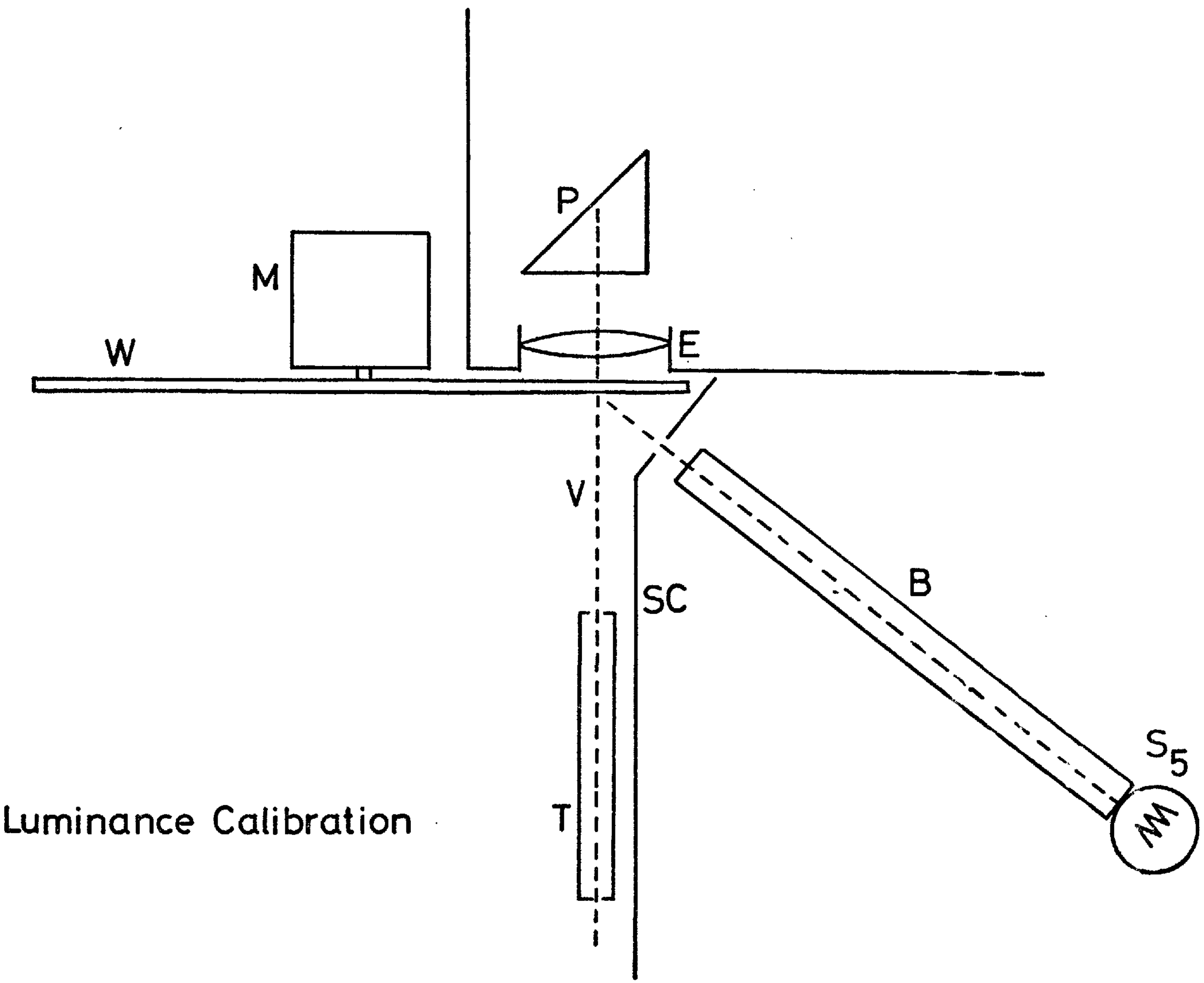


Fig 3.5 Luminance Calibration

along the optical bench, until the appearance of flicker disappeared. In this position the stimuli were equally bright. This measurement was repeated several times.

The illumination L on the sector is given by:-

$$L = \frac{I \cos a}{r^2} \qquad \text{lumens cm}^{-2}$$

where I = the intensity of the standard source in candelas.

a = the angle subtended between the source and the sector.

r = the distance of the source from the sector in centimetres.

The standard source was a 1000 Watt tungsten filament lamp rated at 240 Volts but under-run at 186 Volts to give a filament colour temperature of 2856°K and a corresponding intensity of 1360 candelas. The mean value of r was found to be 28cms giving a value for the illumination L of 1·23 lumens cm^{-2}.

A surface, of luminance factor R, which equalled 0·9 for the white sector, under an illumination of L lumens cm^{-2}, has a luminance given by:-

$$B = \frac{L \cdot r}{\pi} \qquad \text{candela cm}^{-2} \text{ (stilb)}$$

therefore the luminance of the adaptation field was 0·35 stilbs. Since 1·0 stilb is equal to 929π foot-lamberts, the luminance of the adaptation field can be expressed as approximately 1000 foot-lamberts.

3.5 The Luminance of the Standard Field

The surround adaptation field, with the filter to raise the colour temperature to 6500°K inserted in front of it, was matched using the standard field. The neutral density wedge was also used to make this match. The 5500°K filter was inserted in place of the 6500°K filter and the standard field matched to the surround. This was possible without altering the position of the neutral density wedge. A similar situation was found for all the other filters. This was to be expected since all the filters were constructed to be of the same luminance. Thus, with the neutral density wedge set in this position, the standard field had the same luminance as the adaptation fields no matter which colour temperature conversion filter was inserted. The neutral density wedge was left in this position for all the experimental work.

3.6 The Efficiency of the Optical Integrating Bar

The transfer of light from the aperture plate, through the filters, and then through the integrating bar via the focussing lens represents a reduction in the area of the beam of 36 to 1. A situation could be reached where the light beam was composed of, for example, predominantly blue light with a small line of green light and a spot of red light. The calculation of the tristimulus values of the mixture includes these small contributions of light but the question must be asked as to whether they are actually reaching the optical integrating bar. To investigate this the green and the blue filters of the standard field filter assembly were masked off with black paper to leave only the red filter exposed to the light from the aperture. A photomultiplier tube, connected to a suitable high voltage power supply, was placed at the eye-piece of the colorimeter. The output of the photomultiplier was connected to a digital voltmeter. With only the standard field source switched on the filter assembly was set to transmit the maximum amount of red light. This corresponded to a scale reading of 0·0. The amount of red light transmitted was then reduced and voltmeter readings taken at scale readings up to 10·0, in steps of 0·5, when no light was transmitted. Three sets of readings were taken and the mean of these normalised to give a maximum at 1·0. The experiment was then repeated with the red and the blue filters masked off so that only green light was transmitted. The results, plotted in Figure 3.6, show that, on addition of the red and green component, the overall light level stays constant indicating that the light from very small areas of the filter is being transferred to the integrating bar. Similar results were obtained for the red-blue combination and the green-blue combination of filters. Thus it would appear that the optical transfer of light through the filters to the integrating bar is complete.

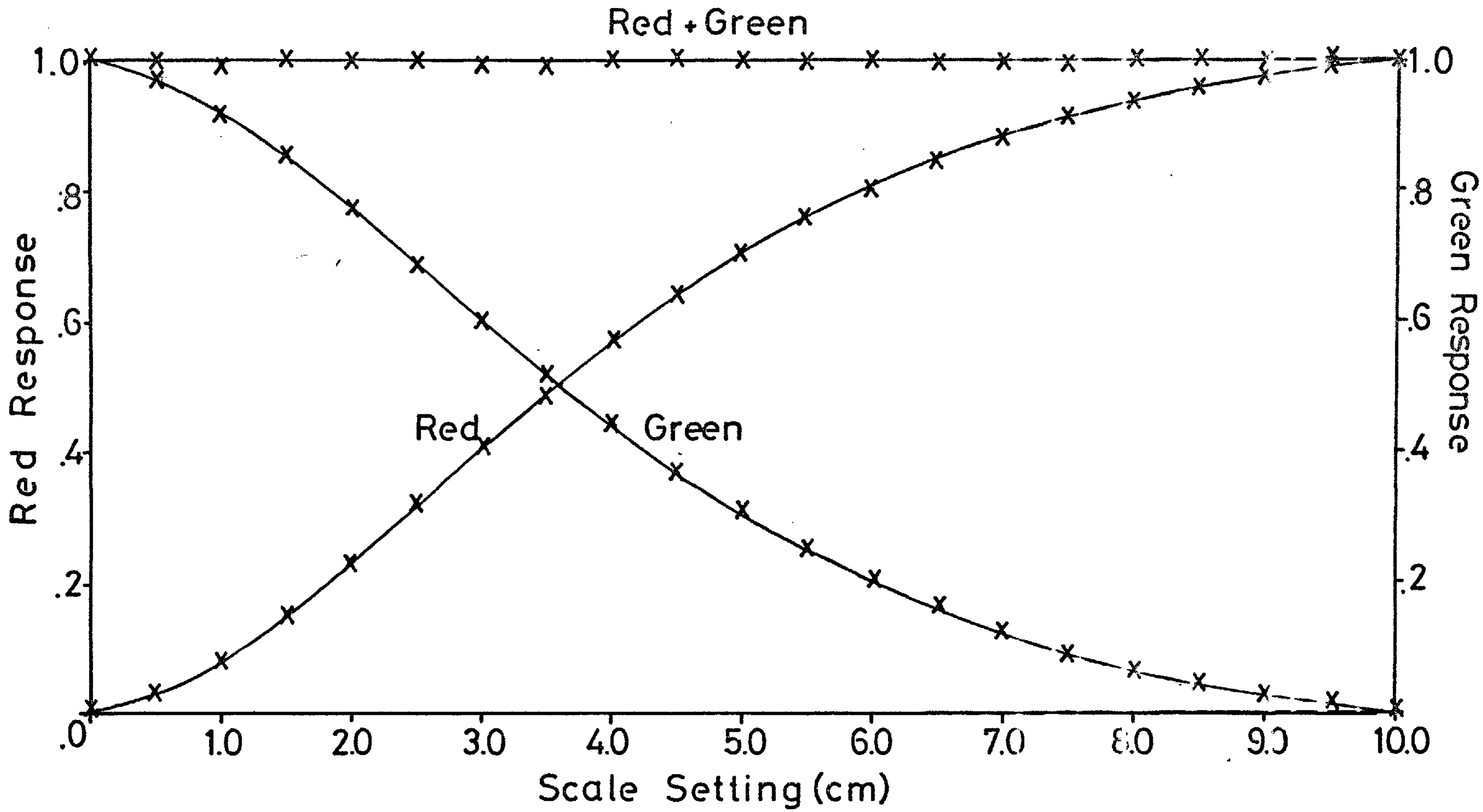

Red + Green
Red
Green
Red Response
Green Response
1.0
.8
.6
.4
.2
.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Scale Setting (cm)

Fig 3.6

Chapter 4

Experimental Procedure

4.1 Introduction

One advantage of a colorimeter of the Burnham type is that there are only two controls, instead of the usual three, for changing the colour content of any particular colour mixture. The third degree of freedom is provided by the neutral density wedge but in work carried out at constant luminance this ceases to be a variable provided that the filters used to give the colorimeter primaries are designed to transmit similar quantities of light. Having only two controls means that, in a mixture of three colours, the amounts of only two of the colours may be set independently; the third is then automatically set. With the filter arrangement shown in Figure 2.3 movement in one direction varies the proportion of red to green (or red-blue to green-blue) and movement in the other direction varies the proportion of blue to the red-green mixture. Hence the two controls on the instrument enable the chromaticity diagram to be traversed in two directions as shown by the grid of lines in Figure 4.1.

4.2 The Choice of Grid Lines

The lines were chosen to give convenient readings on the instrument scales and to cover the available area of the chromaticity diagram in a fairly uniform manner. Regard was given to the closer spacing of colours in the yellow region of the u,v chromaticity diagram compared with the much larger region given to the blue and magenta colours. The red-green to blue 'vertical' direction

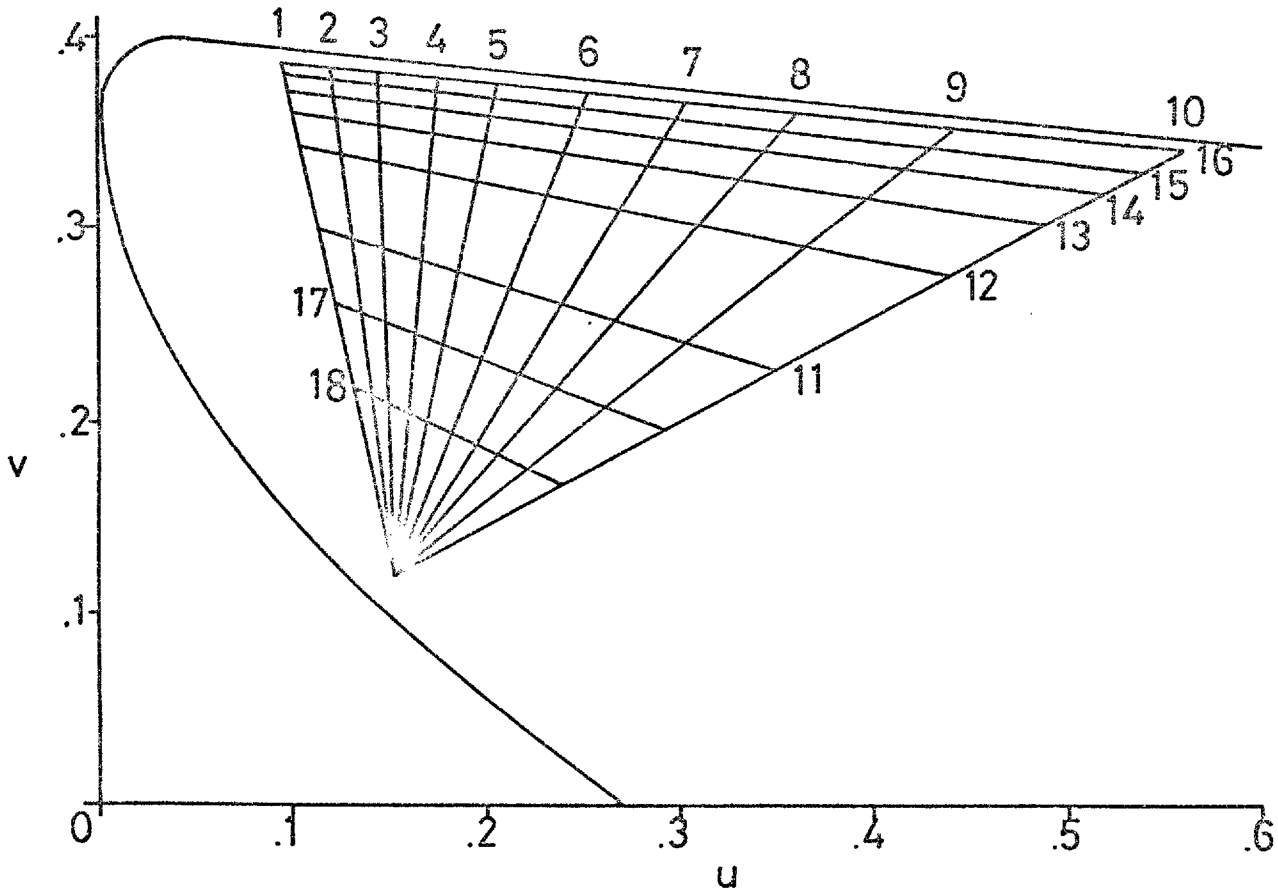


Fig 4.1   Grid Lines

was divided into ten lines and the green-blue to red-blue 'horizontal' direction divided initially into six lines. At a later stage in the experimental work a new brighter quartz halogen lamp was put into the apparatus to replace the source S_2 that provided the reference field light. This lamp gave more light than the old tungsten lamp especially in the blue region of the spectrum. The loss of light with the old source was probably due to the lowering of the transmission of the light pipe in the blue region of the spectrum and to the fact that a smaller aperture plate had to be fitted to the microscope cross-slide for the reference field filter assembly. This was due to the smaller traverse of the microscope cross-slide compared with that of the cross-slide used for the standard field filter assembly. Two more lines were added in the blue region for experimental work using the new source.

Each line was numbered to facilitate the handling and inter-comparison of the data to be obtained. The numbers used are shown in Figure 4.1. Line 1 went from pure green to pure blue, line 10 from pure red to pure blue and line 16 from pure green to pure red. The chromaticity coordinates of the end points of the lines together with the intersection points of the grid of lines are given in Figure 4.2a and 4.2b.

4.3 Experimental Procedure

All experimental work was carried out with the apparatus in a darkened room. The main set of observations were made by the author who had normal colour vision. Each observing session commenced with a period of approximately 15 minutes dark adaptation

Line No.		1	2	3	4	5
16	U =	0.0966	0.1195	0.1452	0.1741	0.2068
	V =	0.3851	0.3833	0.3808	0.3782	0.3753
15		0.0976	0.1202	0.1453	0.1736	0.2055
		0.3801	0.3778	0.3753	0.3725	0.3693
14		0.0993	0.1212	0.1456	0.1729	0.2035
		0.3725	0.3699	0.3670	0.3637	0.3601
13		0.1016	0.1227	0.1460	0.1719	0.2019
		0.3613	0.3583	0.3549	0.3512	0.3470
12		0.1058	0.1252	0.1446	0.1701	0.1961
		0.3418	0.3381	0.3341	0.3296	0.3247
11		0.1152	0.1310	0.1480	0.1663	0.1861
		0.2974	0.2928	0.2879	0.2827	0.2769
17		0.1232	0.1357	0.1491	0.1632	0.1783
		0.2602	0.2556	0.2507	0.2454	0.2399
18		0.1322	0.1410	0.1503	0.1599	0.1700
		0.2180	0.2140	0.2097	0.2053	0.2008
		0.1530	0.1530	0.1530	0.1530	0.1530
		0.1201	0.1201	0.1201	0.1201	0.1201

Fig 4.2a

	6	7	8	9	10	Line No.
U=	0.2524	0.3019	0.3608	0.4303	0.5578	16
V=	0.3713	0.3669	0.3617	0.3547	0.3442	
	0.2499	0.2977	0.3544	0.4296	0.5420	15
	0.3648	0.3600	0.3543	0.3468	0.3355	
	0.2469	0.2915	0.3450	0.4153	0.5190	14
	0.3551	0.3497	0.3434	0.3359	0.3228	
	0.2405	0.2827	0.3318	0.3956	0.4878	13
	0.3412	0.3352	0.3281	0.3188	0.3055	
	0.2314	0.2682	0.3103	0.3639	0.4393	12
	0.3180	0.3110	0.3031	0.2929	0.2786	
	0.2121	0.2385	0.2676	0.3031	0.3505	11
	0.2694	0.2518	0.2534	0.2431	0.2295	
	0.1976	0.2167	0.2373	0.2617	0.2929	17
	0.2328	0.2257	0.2181	0.2091	0.1976	
	0.1826	0.1948	0.2076	0.2223	0.2405	18
	0.1950	0.1894	0.1836	0.1769	0.1686	
	0.1530	0.1530	0.1530	0.1530	0.1530	
	0.1201	0.1201	0.1201	0.1201	0.1201	

Fig 4.2b

followed by a period of 5 minutes adaptation to the light of the surround field. The observer was required to let his gaze wander around the viewing field and so no fixation points were provided. This served to minimise any effect of local adaptation to the two coloured fields which could otherwise be a nuisance with the very bright fields used. If the observer were to fixate on one of the fields the perceived saturation would, by the effect of local adaptation, decrease until the observer ceased to fixate or blinked. The amount of this decrease in saturation is large and can easily be ten times the just noticeable difference in saturation. If however the observer scans from one field to the other and also takes in the surround field in his random scanning each field is seen to be more saturated than the other in turn and the saturation difference corresponding to the comparison of the two fields by equally adapted retinal areas is largely obscured. This effect is also reduced by having the luminance of the surround field and the two matching fields approximately equal.

After the initial adaptation periods a match of the surround was made using the standard field. This served as a check against fading of the filters used in the standard field filter assembly. It was not necessary to make a similar check on the reference field filters since they were not used for any measurements.

The standard field was then set to the required starting point and the colour of the reference field matched to it. One of the controls of the standard field was then changed until a difference in colour could just be detected between the two fields. The position of the scale was recorded. The controls of the reference field were then used to obtain a colour match with the standard field. The reference field had three controls; two controls for the positioning of the microscope cross-slide containing the filter assembly and the 'Variac' controlling the lamp voltage and hence the lamp brightness. The controls of the standard field were then moved again until another just noticeable colour step could be detected. This procedure of alternate matching and just noticeable difference observation was repeated along the line until, in the case of the 'vertical' lines it was not possible to obtain a match or, for 'horizontal' lines, the end of the line was reached. The line was then traversed in the reverse direction back to the starting point again alternately matching and observing just noticeable differences.

The work on all eighteen lines was divided into four groups:-

Group 1 : Lines 1, 5, 10, 12, 14, 16

Group 2 : Lines 2, 4, 6, 8, 15

Group 3 : Lines 3, 7, 9, 11, 13

Group 4 : Lines 17, 18

Measurements on the lines in each group were taken in two daily sessions for two and a half days. This meant that each line was traversed twice in each session (once in each direction) and ten times over the two and a half day period. All work on one group was finished before going on to the next although the order in which the lines were taken in any particular session was changed. Therefore all work on one adaptation took ten working days. Each observing session was timed and, initially, a large variation in time was found for successive sessions. As the observer became more practised the times for the observing sessions became more uniform. The earlier sets of readings were discarded and these lines repeated at a later date. The groups were repeated for nine different states of adaptation: the five white light adaptations, dark adaptation, and three coloured adaptations; red, green and blue.

The two controls of the microscope cross-slide carrying the standard field filter assembly had gearing of different ratios. It was thought that this may have some psychological effect on the size of the just noticeable colour difference that was observed in the two directions. To investigate this the filter assembly was turned through a right angle and some of the measurements repeated. This meant that, for example, line 1 now involved horizontal movement of the microscope cross-slide whereas before it involved vertical movement. Very little difference was found between the readings obtained for the two directions and the differences were less than or at least not greater than the spread of results for any particular line. Consequently the filter assembly was returned to its original position and left there for all subsequent measurements.

4.4 The Spread of Experimental Readings

The agreement between the readings for the same line measured at a different time was thought to be good. The nature of the observations was such that exact reproduceability could not be expected. Figures 4.3 and 4.4 show the instrument readings plotted as a function of the step number for lines 1 and 10 respectively. They are shown as recorded with adaptation of 6500°K colour

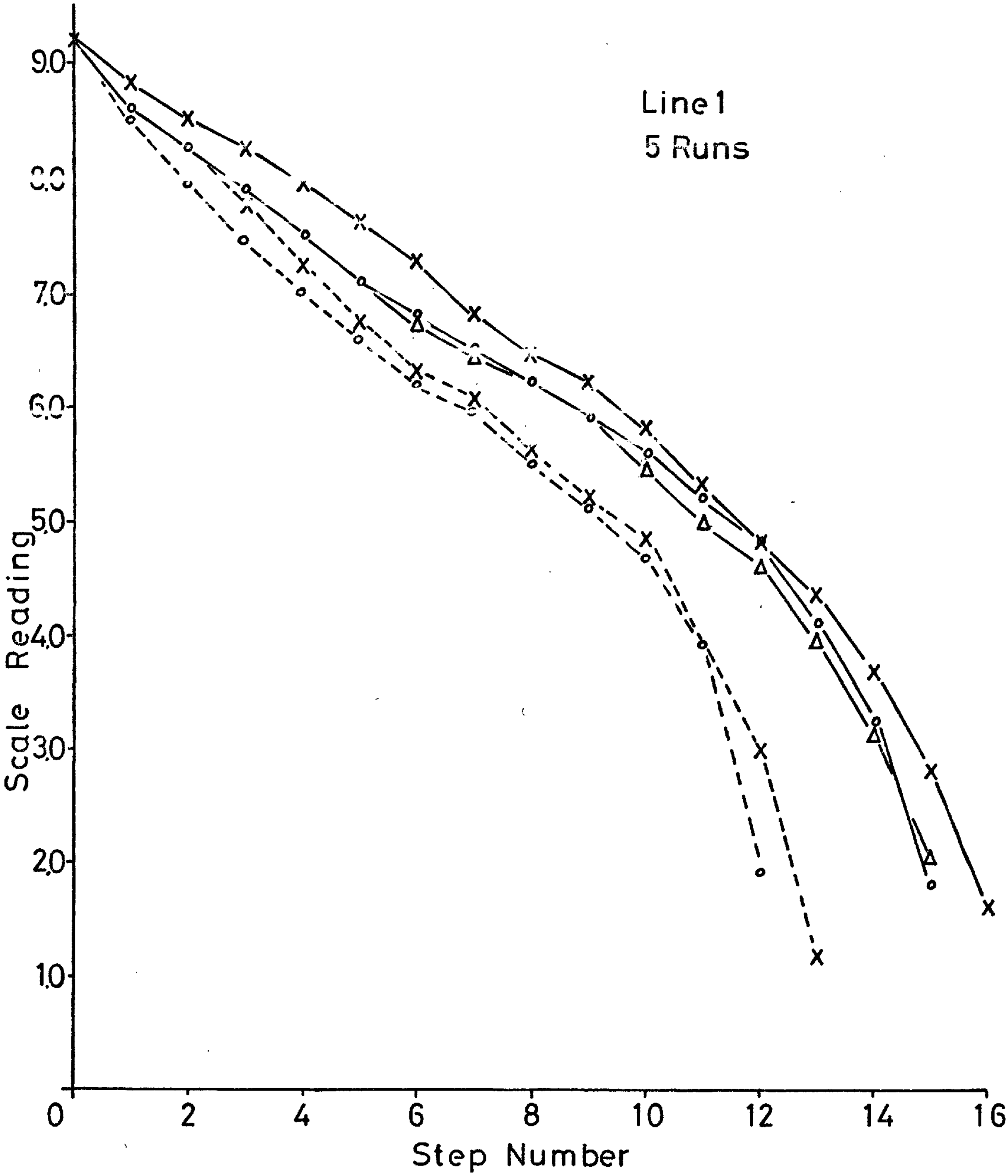

Line 1
5 Runs
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
Scale Reading
0
2
4
6
8
10
12
14
16
Step Number

Fig 4.3

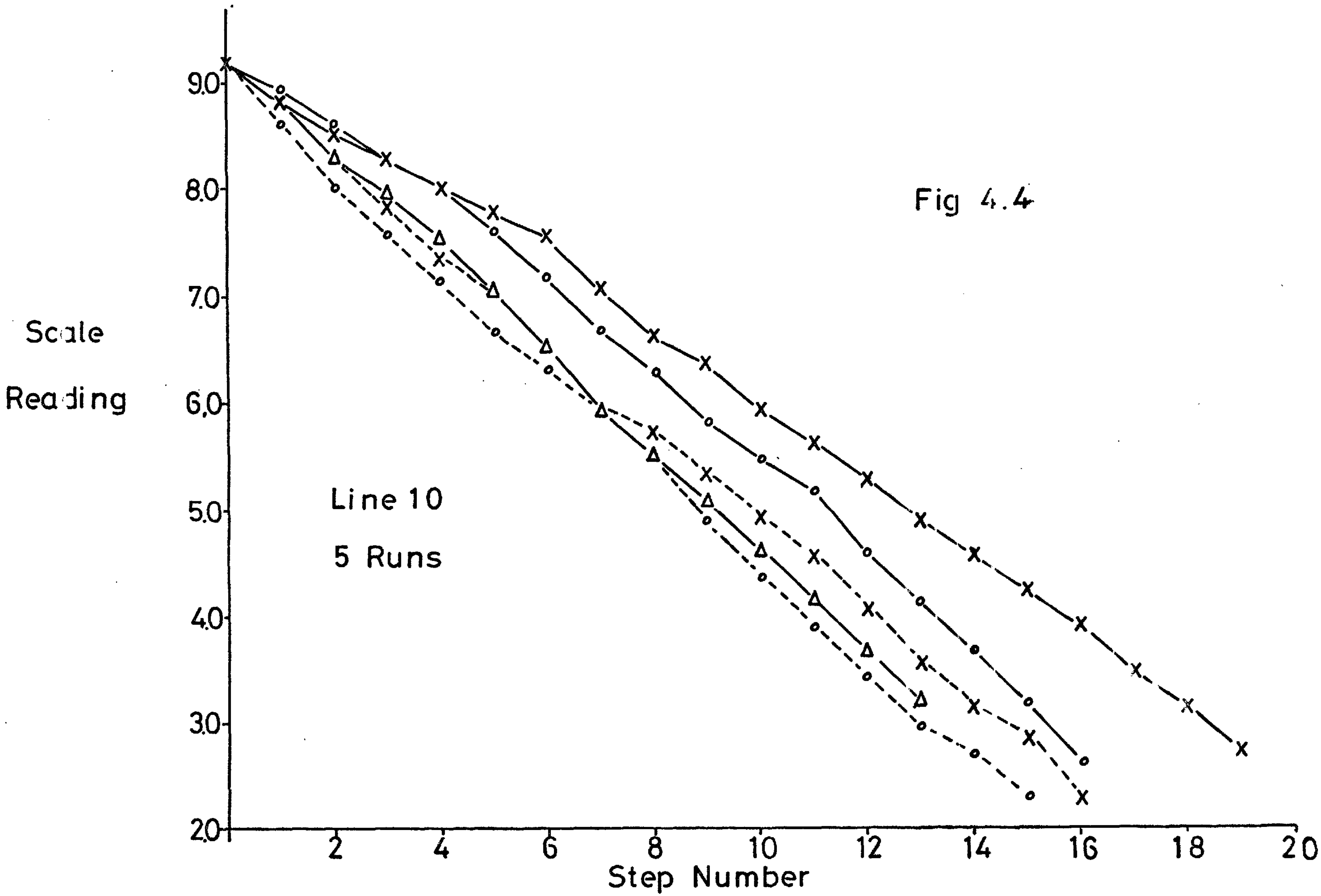


Fig 4.4
Scale Reading
Line 10
5 Runs
Step Number
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
2
4
6
8
10
12
14
16
18
20

temperature. Only readings for one direction were plotted. These graphs are representative of similar graphs for all the other data, both for other lines and other adaptations. There were usually more steps in the green-red direction than in the green-blue or red-blue direction but this was to be expected because the gamut of colours between green and red is larger than that between green and blue or red and blue.

4.5 The Analysis of the Results

The readings obtained in each session for each separate line were written down on play back of the tape and then transferred to computer punch cards. An IBM 7094 computer, using a programme written by the author was used to calculate the u,v chromaticity coordinates of each recorded point and the geometric distance between them for each line: i.e. for two points u_1, v_1 and u_2, v_2 the separation was given by:-

$$\Delta l = ((u_1 - u_2)^2 + (v_1 - v_2)^2)^{\frac{1}{2}}$$

The 1960 CIE u,v chromaticity diagram was chosen as the means of initially representing the data because of its supposed uniformity. It was felt that as discrimination data ~~was~~ were being observed something approaching a uniform chromaticity diagram should be used. A disadvantage was that the CIE defined the diagram for use where better uniformity than that given by the 1931 CIE x,y diagram was required, 'for specimens subtending between 1 degree and 4 degrees having negligibly different luminances and surrounded by an area of chromaticity not much different from that of the CIE Standard Source C.'(CIE, 1959). Thus the diagram may not be valid as a uniform chromaticity diagram for surrounds (adaptations) other than those approximating to daylight.

A sampling technique was then applied to the ten sets of data for each line to give a mean set of data. The sampling points used were the points of intersection of the grid of lines as tabulated in Figure 4.2a and 4.2b. For a 'vertical' line (numbers 1 to 10) the nearest experimental point above and below the sampling point was found for each of the ten sets of data. In Figure 4.5 the results for one run of one line are shown plotted on the u,v chromaticity diagram together with the sampling points. The lengths used to obtain the mean set of data are also shown. The separation of each pair of points was given by the computer output and the average of the ten lengths was found. For a 'horizontal' line (numbers 11 to 18) the nearest experimental point on either side of the sampling point was taken as shown in Figure 4.6. Occasionally the situation arose where there was no experimental point between two sampling points. In this case the particular set of data had to be discarded for those sampling points.

Thus a mean set of data was obtained for each line observed under each of the nine adaptation conditions. These results could be plotted in the u,v chromaticity diagram where a length Δl could be used to represent the just noticeable colour difference on either side of the sampling point.

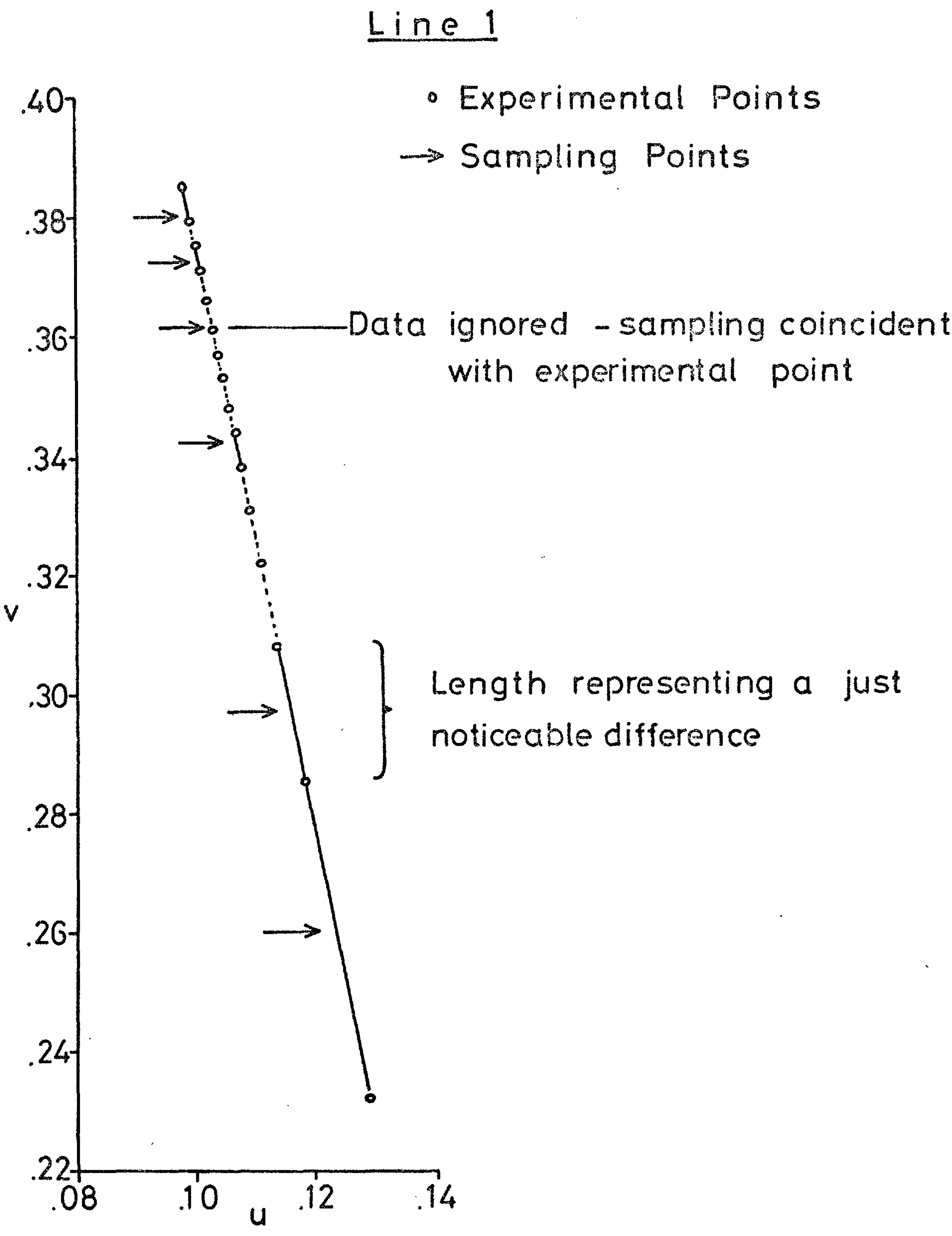

Line 1
Experimental Points
Sampling Points
Data ignored - sampling coincident with experimental point
Length representing a just noticeable difference
.40
.38
.36
.34
.32
.30
.28
.26
.24
.22
v
.08
.10
.12
.14
u

Fig 4.5

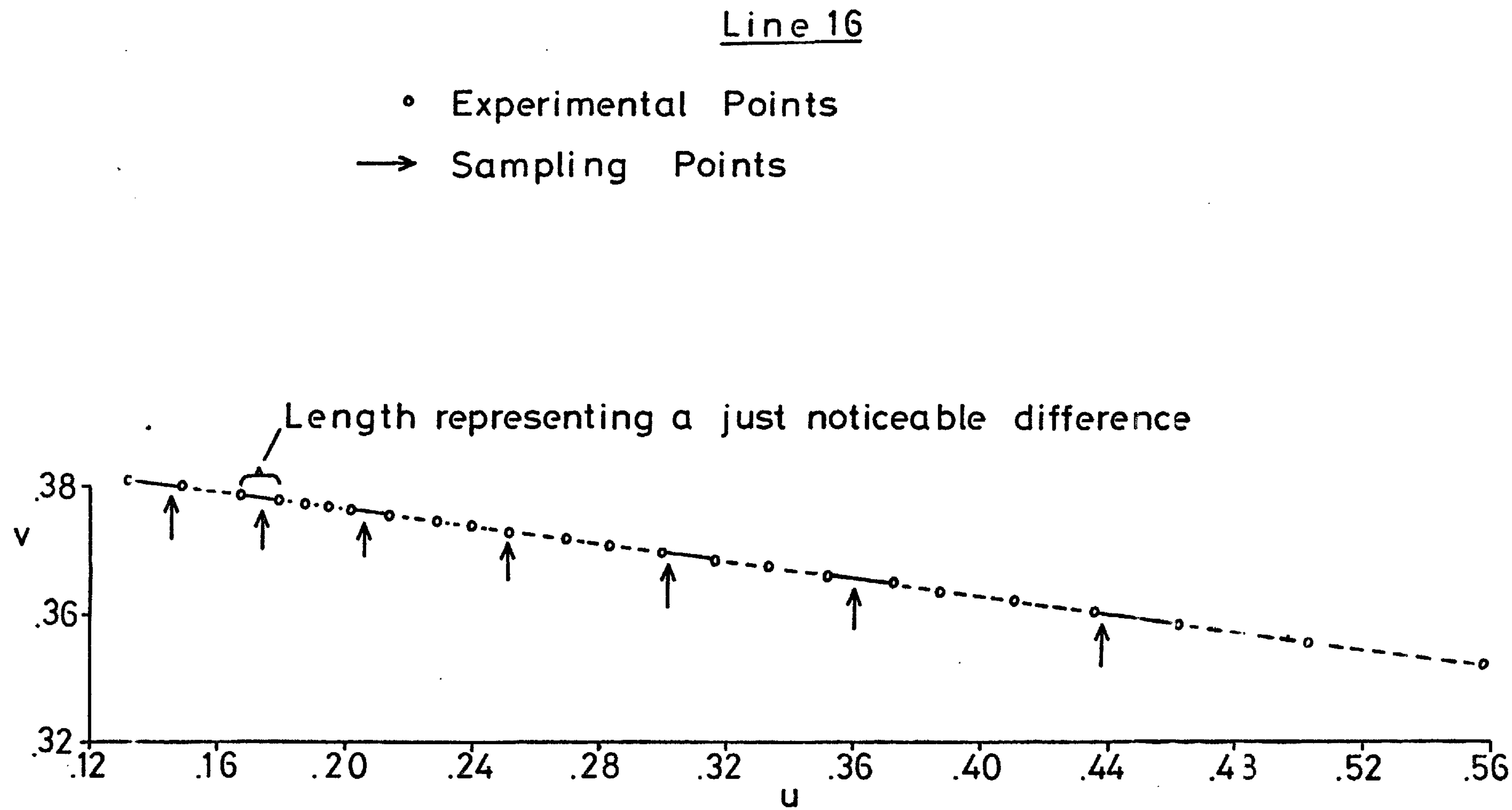

Line 16
Experimental Points
Sampling Points
Length representing a just noticeable difference
.38
.36
.32
v
.12
.16
.20
.24
.28
.32
.36
.40
.44
.43
.52
.56
u

Fig 4.6

Chapter 5

The Results for White Light Adaptations

5.1 Presentation of Results

The results of the experimental discrimination work are presented in two ways:-

(i) The overall results are plotted on separate graphs for each adaptation using the u,v chromaticity diagram. The just noticeable colour differences are represented by bars drawn symmetrically about the sampling points.

(ii) The results for individual lines are compared for all five white light adaptations. Δl, the mean length representing the just noticeable colour difference, is plotted as a function of the v chromaticity coordinate of the sampling point for the 'vertical' lines (numbers 1 to 10), and as a function of the u chromaticity coordinate of the sampling point for 'horizontal' lines (numbers 11 to 16).

Some importance should be placed on the fact that the conclusions drawn from a particular set of results depend entirely on how the difference in physical quality between two colours is described. The 1960 CIE u,v chromaticity diagram is just one of many graphical methods that could be used to represent the results diagrammatically.

5.2 The Overall Results

The overall results for adaptation to a surround with a colour temperature of 6500°K, 5500°K, 4000°K, 2856°K and 2000°K are shown tabulated in Figures 5.1 - 5.5 respectively. The tables show the length in the u,v chromaticity diagram representing the just noticeable colour difference for each sampling point. The rows of results for lines 1 to 10 give the results in descending order (from red-green to blue or descending value of the v chromaticity coordinate) and the rows for the lines 11 to 18 give the results from left to right (green-blue to red-blue or ascending value of the u chromaticity coordinate). The overall results are plotted in the u,v chromaticity diagram in Figures 5.6 - 5.10 respectively.

The most striking observation is that the results do not show a great amount of uniformity over the area enclosed by the colour triangle. The ratio of the longest bar to the shortest bar is about 7:1. However, the uniformity in the central region of the colour space is considerably better than this being less than 2:1. The length of the lines increases and hence discrimination gets poorer in going from any mixture of red and green towards the blue region; the longest lines being found in the blue region for mixtures of pure green and blue and pure red and blue. The shortest lines, and hence the best discrimination, are found in the 'white' region of the chromaticity diagram where the colours are least saturated. The reason for this is not immediately obvious because, although the surround field appears to be an acceptable white when seen on its own, (except the field representing an adaptation of 2000^{o}K colour temperature which has a distinct orange appearance), the best discrimination is in the region of the white point x = 0·333, y = 0·333 equivalent to u = 0·211 and v = 0·316 and not in the region of the surround field chromaticity as night be expected. However, when the standard

6500°K Adaptation

Line	ΔI							
Line 1	·006	·005	·007	·007	·020	·035	·038	
Line 2	·006	·005	·006	·007	·016			
Line 3	·007	·006	·006	·007	·016			
Line 4	·006	·006	·006	·008	·015	·026	·030	
Line 5	·007	·006	·007	·007	·016			
Line 6	·006	·006	·008	·009	·012			
Line 7	·009	·008	·009	·011	·015	·017	·022	
Line 8	·008	·009	·011	·012	·013			
Line 9	·013	·013	·015	·015	·019			
Line 10	·020	·022	·021	·019	·023	·022	·025	
Line 11	·018	·016	·015	·013	·012	·012	·019	·027
Line 12	·018	·011	·008	·008	·008	·010	·016	·023
Line 13	·021	·016	·015	·015	·016	·019	·027	·040
Line 14	·020	·014	·010	·090	·010	·015	·019	·028
Line 15	·021	·015	·012	·014	·013	·017	·023	·038
Line 16	·022	·015	·011	·012	·013	·017	·021	·037
Line 17	·012	·011						
Line 18	·012	·009						

Fig 5.1

5500°K Adaptation

Line	ΔI							
Line 1	·006	·006	·006	·007	·024	·035	·034	
Line 2	·007	·006	·007	·008	·021			
Line 3	·007	·006	·007	·008	·016			
Line 4	·006	·006	·008	·009	·018	·022	·033	
Line 5	·007	·005	·007	·009	·015			
Line 6	·008	·008	·008	·009	·014			
Line 7	·010	·010	·011	·012	·016	·017	·022	
Line 8	·009	·011	·011	·013	·015			
Line 9	·011	·014	·016	·016	·019			
Line 10	·021	·018	·020	·022	·024	·022	·023	
Line 11	·019	·014	·013	·011	·011	·012	·019	·021
Line 12	·021	·013	·011	·010	·010	·014	·018	·029
Line 13	·021	·015	·013	·015	·016	·020	·030	·041
Line 14	·026	·015	·012	·013	·014	·015	·026	·038
Line 15	·028	·018	·015	·016	·016	·020	·029	·043
Line 16	·026	·019	·014	·015	·015	·019	·026	·038
Line 17	·014	·012						
Line 18	·010	·009						

Fig 5.2

4000°K Adaptation

Line	ΔI							
Line 1	·007	·005	·007	·008	·025	·032	·045	
Line 2	·006	·006	·005	·008	·018			
Line 3	·006	·006	·006	·008	·016			
Line 4	·006	·007	·007	·010	·018	·027	·028	
Line 5	·006	·006	·008	·011	·015			
Line 6	·008	·007	·009	·010	·013			
Line 7	·009	·008	·011	·012	·016	·018	·023	
Line 8	·009	·010	·012	·013	·017			
Line 9	·012	·014	·017	·017	·021			
Line 10	·016	·020	·025	·022	·027	·023	·023	
Line 11	·017	·015	·014	·012	·011	·103	·107	·038
Line 12	·025	·014	·011	·012	·013	·016	·019	·029
Line 13	·020	·015	·015	·016	·016	·022	·029	·045
Line 14	·026	·017	·013	·015	·014	·018	·027	·049
Line 15	·025	·019	·017	·017	·016	·023	·035	·050
Line 16	·030	·019	·016	·016	·016	·022	·029	·037
Line 17	·014	·012						
Line 18	·012	·011						

Fig 5.3

2856° K Adaptation

Line	ΔI							
Line 1	·006	·006	·008	·010	·028	·023	·041	
Line 2	·007	·006	·007	·009	·019			
Line 3	·006	·006	·007	·010	·019			
Line 4	·007	·007	·007	·010	·019	·021	·026	
Line 5	·008	·008	·010	·011	·020			
Line 6	·008	·009	·009	·012	·016			
Line 7	·008	·010	·011	·012	·016	·017	·021	
Line 8	·011	·012	·012	·012	·019			
Line 9	·012	·014	·017	·016	·020			
Line 10	·018	·022	·027	·024	·027	·023	·022	
Line 11	·019	·015	·015	·015	·012	·014	·018	·024
Line 12	·029	·020	·013	·013	·013	·018	·021	·034
Line 13	·020	·020	·016	·017	·018	·020	·032	·041
Line 14	·036	·018	·018	·016	·016	·020	·028	·042
Line 15	·025	·021	·016	·016	·017	·021	·034	·046
Line 16	·033	·023	·019	·017	·019	·022	·029	·039
Line 17	·015	·012						
Line 18	·012	·012						

Fig 5.4

2000°K Adaptation

Line	ΔI							
Line 1	·006	·007	·007	·010	·026	·034	·040	
Line 2	·006	·006	·007	·009	·020			
Line 3	·006	·007	·008	·012	·020			
Line 4	·006	·007	·009	·011	·022	·026	·025	
Line 5	·007	·007	·010	·012	·023			
Line 6	·008	·008	·010	·011	·018			
Line 7	·008	·009	·011	·012	·017	·018	·021	
Line 8	·018	·014	·014	·012	·011			
Line 9	·012	·016	·017	·017	·021			
Line 10	·019	·021	·030	·027	·025	·021	·023	
Line 11	·017	·015	·014	·013	·012	·013	·018	·023
Line 12	·032	·023	·021	·016	·015	·017	·024	·040
Line 13	·021	·018	·014	·016	·015	·020	·029	·038
Line 14	·035	·025	·021	·016	·018	·020	·026	·047
Line 15	·027	·023	·018	·017	·019	·026	·033	·049
Line 16	·038	·029	·022	·018	·019	·026	·030	·045
Line 17	·018	·015						
Line 18	·018	·012						

Fig 5.5

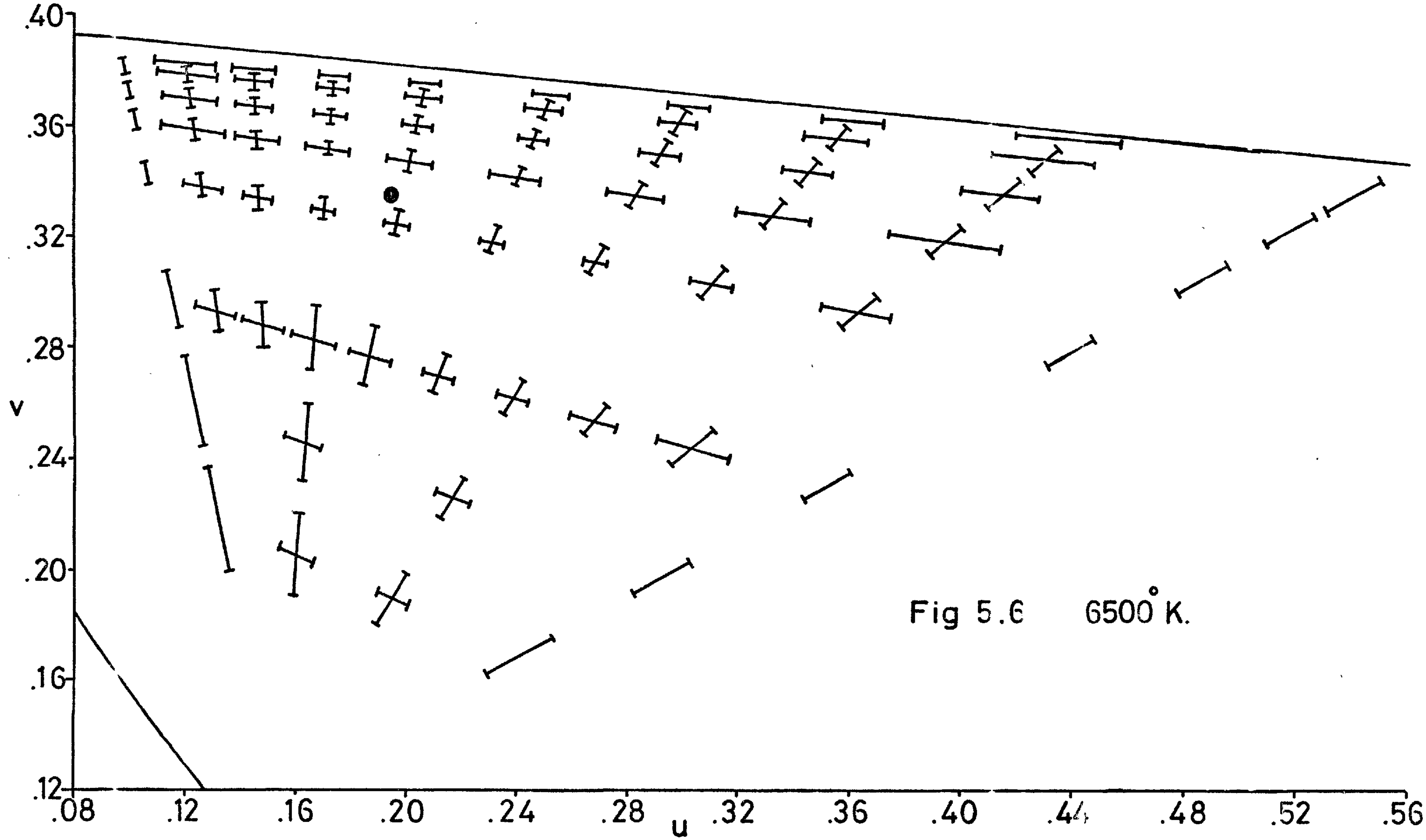


Fig 5.6 6500° K.

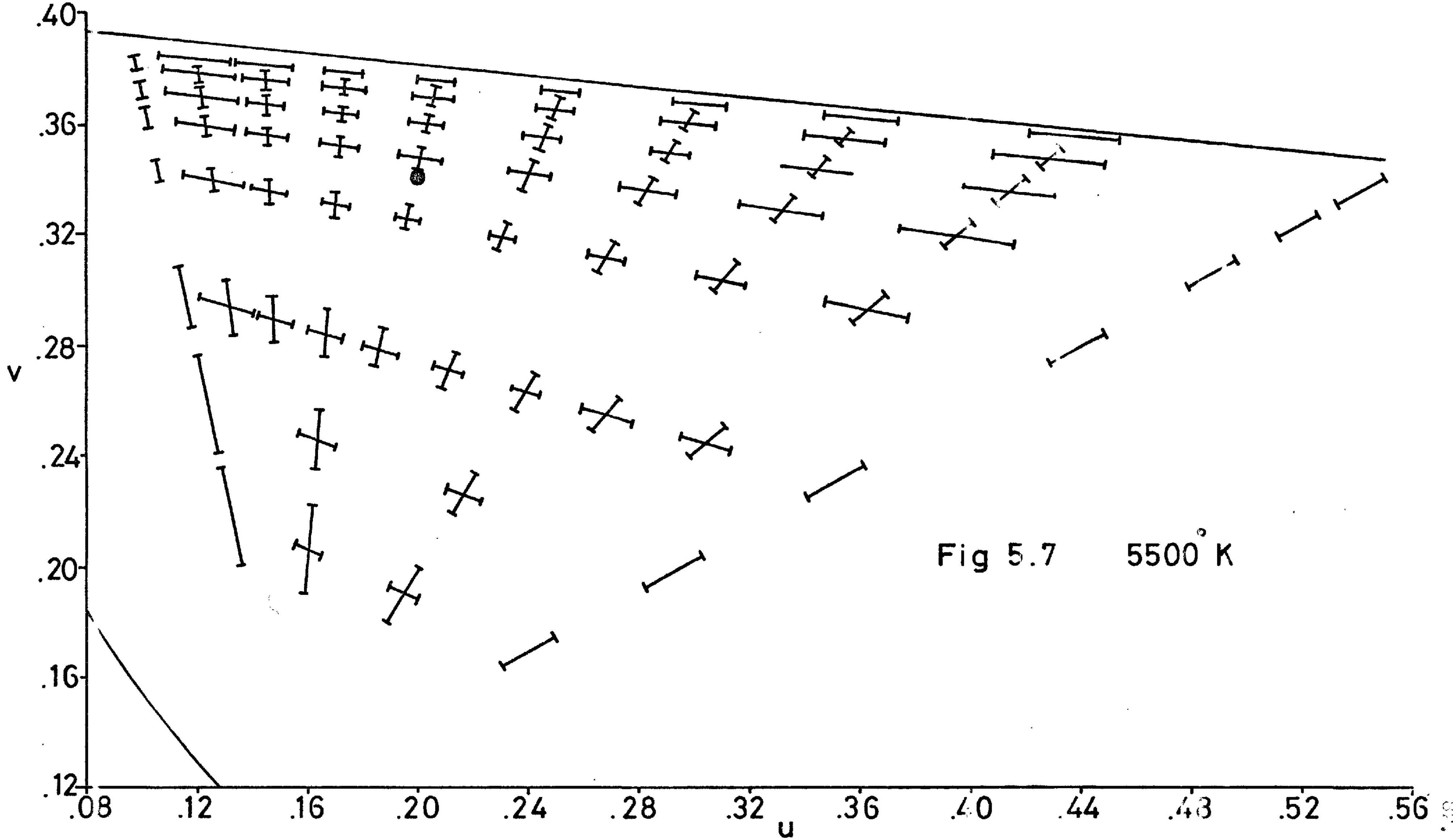


Fig 5.7   5500°K

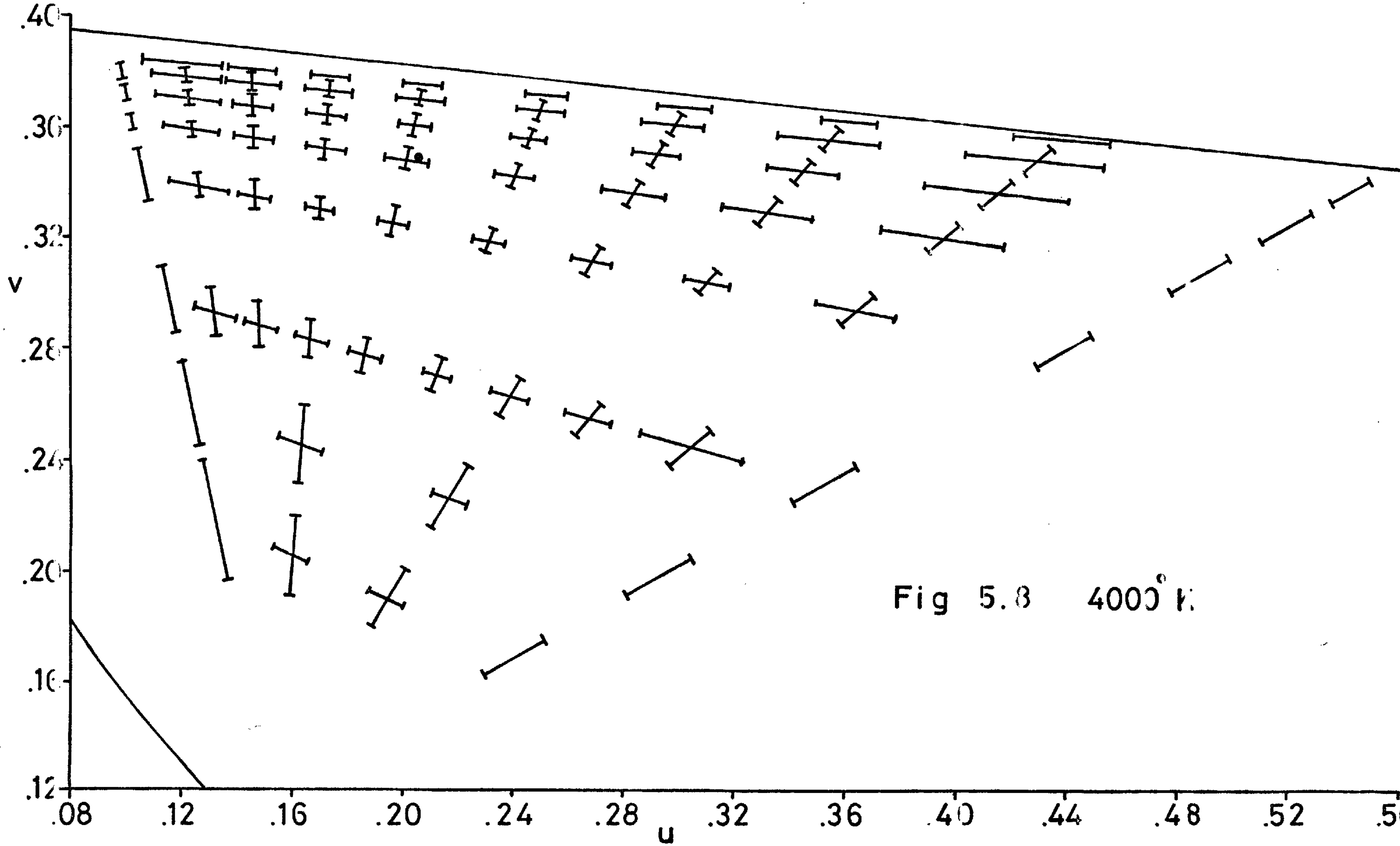


Fig 5.8 4000°K

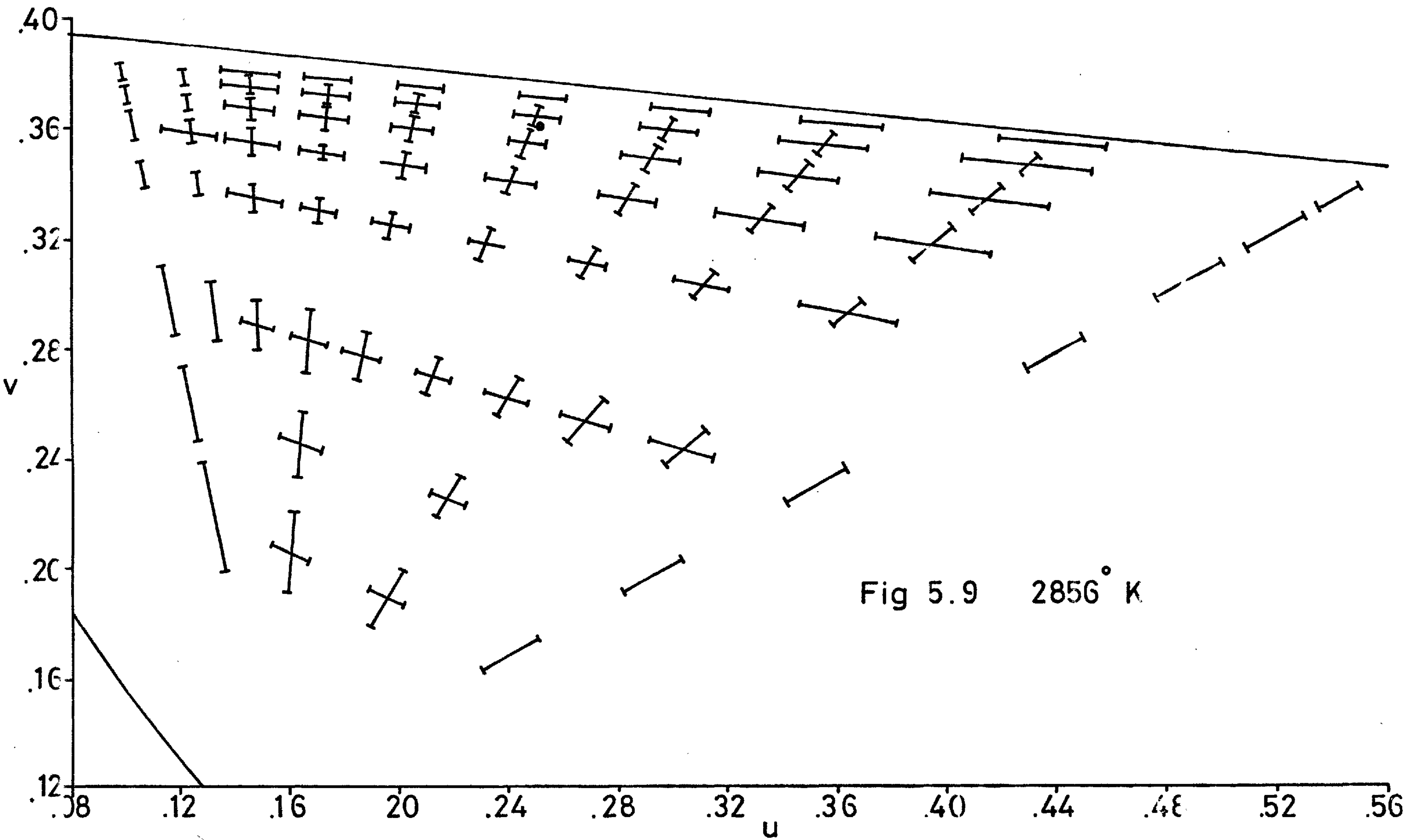


Fig 5.9 2856° K

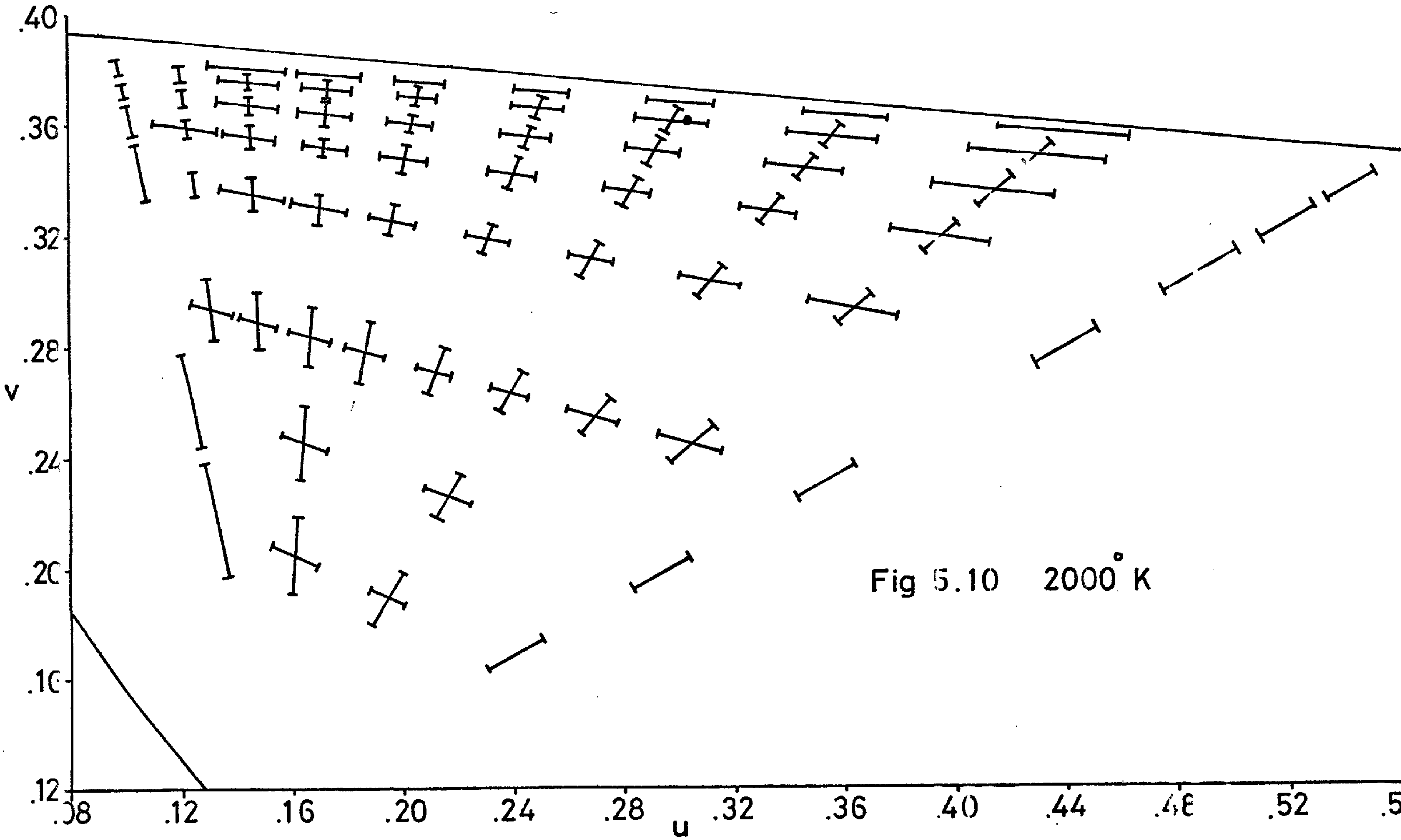


Fig 5.10 2000° K

and reference fields have approximately the same chromaticities as the surround field the effect is to increase the overall field size and, over this small region of the u,v chromaticity diagram, the observer is effectively performing large field observations. He is now more influenced by the surround when he makes the just noticeable difference observation and this would tend to improve his discrimination powers.

Generally it was found to be more difficult to make just noticeable difference observations near the ends of the lines where the colours observed are more saturated than those in the central region. This was found to be especially true for colours in the blue region. If the two fields differed in the peripheral sense (red to green) rather than in the radial sense (mixtures of red and green to white) the disturbing influence of the white light surround seemed to be less. This is shown by the fact that lines representing just noticeable differences in the peripheral direction are relatively longer than those in the radial direction. This may be due to the fact that the effect of local adaptation of the retina is playing an important part. As the fovea and para-fovea become more and more adapted to the mean value of the chromaticities of the two fields and the surround between the two fields the hue difference becomes more apparent. This means that one would expect poorer discrimination in the direction not involving white light where this mean chromaticity was more remote from the chromaticity of the surround adaptation field.

Comparison of the results of observations using adaptations of different colour temperatures does not show any immediate differences when they are represented graphically in this manner, except that there is a very gradual lengthening of the lines as the colour temperature is decreased. Figures 5.11 - 5.16 show the results plotted in the second way. The length of the bar representing the chromaticity difference in the u,v chromaticity diagram, as defined by:-

$$\Delta l = ((u_1 - u_2)^2 + (v_1 - v_2)^2)^{\frac{1}{2}}$$

is plotted as a function of the v chromaticity coordinate of the sampling point for lines 1 to 10 and as a function of the u chromaticity coordinate for lines 11 to 16. The individual experimental points have been joined together with straight lines. This is merely for clarity and does not imply any continuity in the values along the lines. The results for lines 17 and 18 are not plotted in this way since they involve only two points for each colour temperature. These graphs show that there were some spurious readings that did not follow the overall trend of the results. These can usually be accounted for in that for some sets of readings there were only four or five out of a possible total of ten readings. This was either because there were two sampling points between a pair of readings or because a reading and a sampling point coincided. In both cases the data for the sampling point concerned had to be ignored because it could not be used to assign a sensible just noticeable difference value to that sampling point. The overall effect of poorer discrimination with decreasing colour temperature of adaptation now becomes more obvious. However, the amount by which the discrimination has deteriorated is very small.

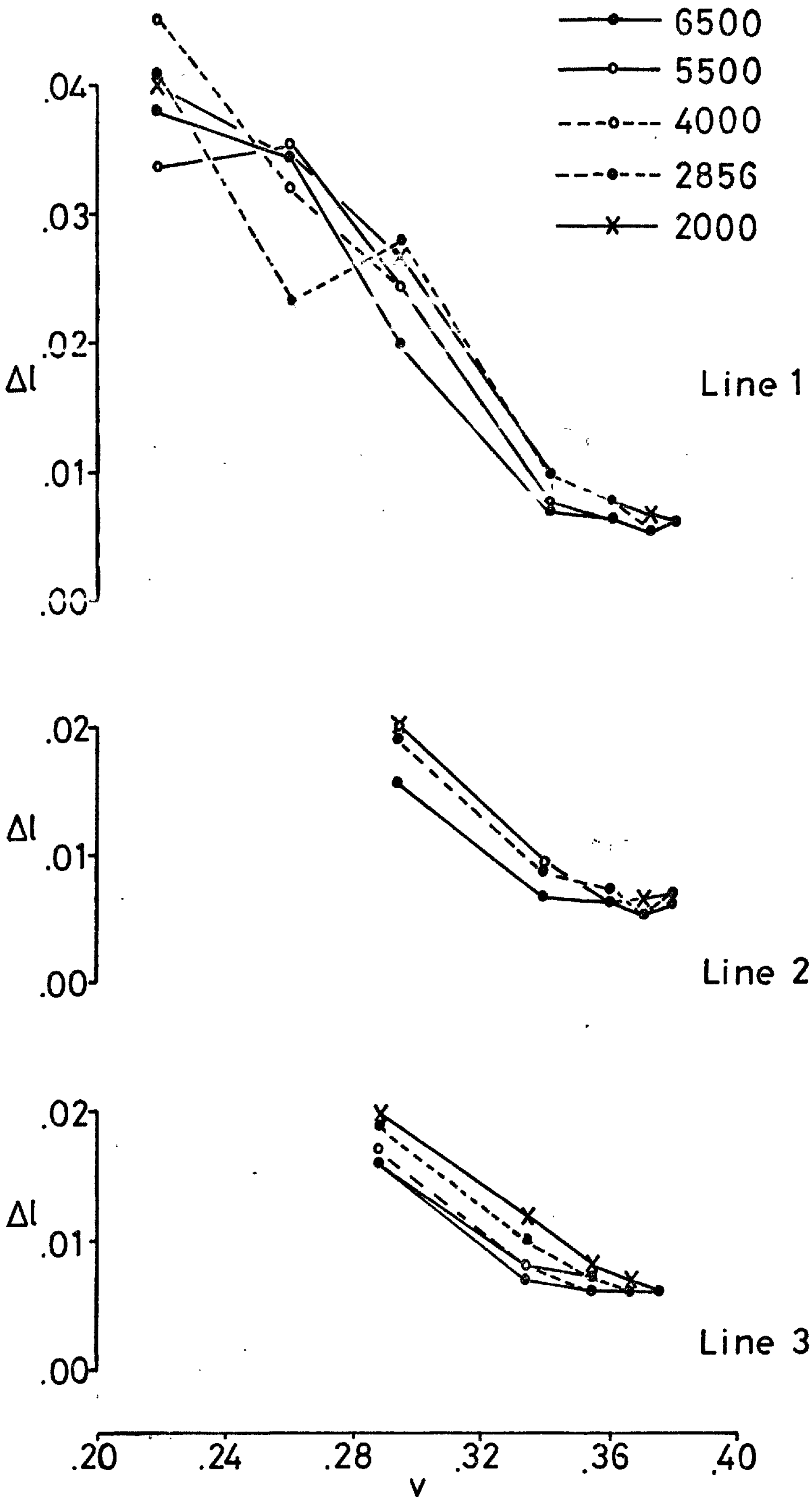

6500
5500
4000
2856
2000
.04
.03
.02
.01
.00
Δl
Line 1
.02
.01
.00
Δl
Line 2
.02
.01
.00
Δl
Line 3
.20
.24
.28
.32
.36
.40
v

Fig 5.11

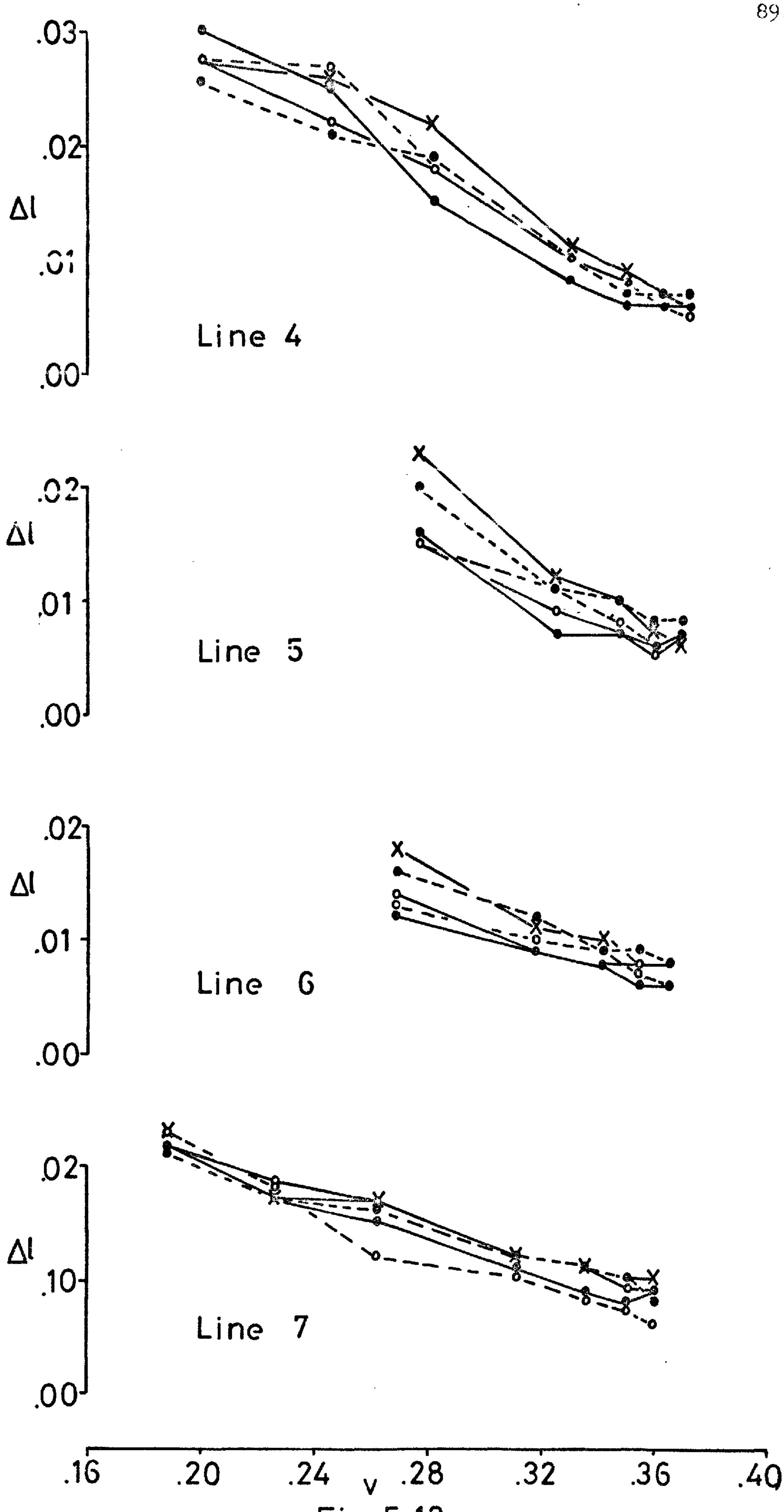

.03
.02
Δl
.01
Line 4
.00
.02
Δl
.01
Line 5
.00
.02
Δl
.01
Line 6
.00
.02
Δl
.10
Line 7
.00
.16
.20
.24
v
.28
.32
.36
.40

Fig 5.12

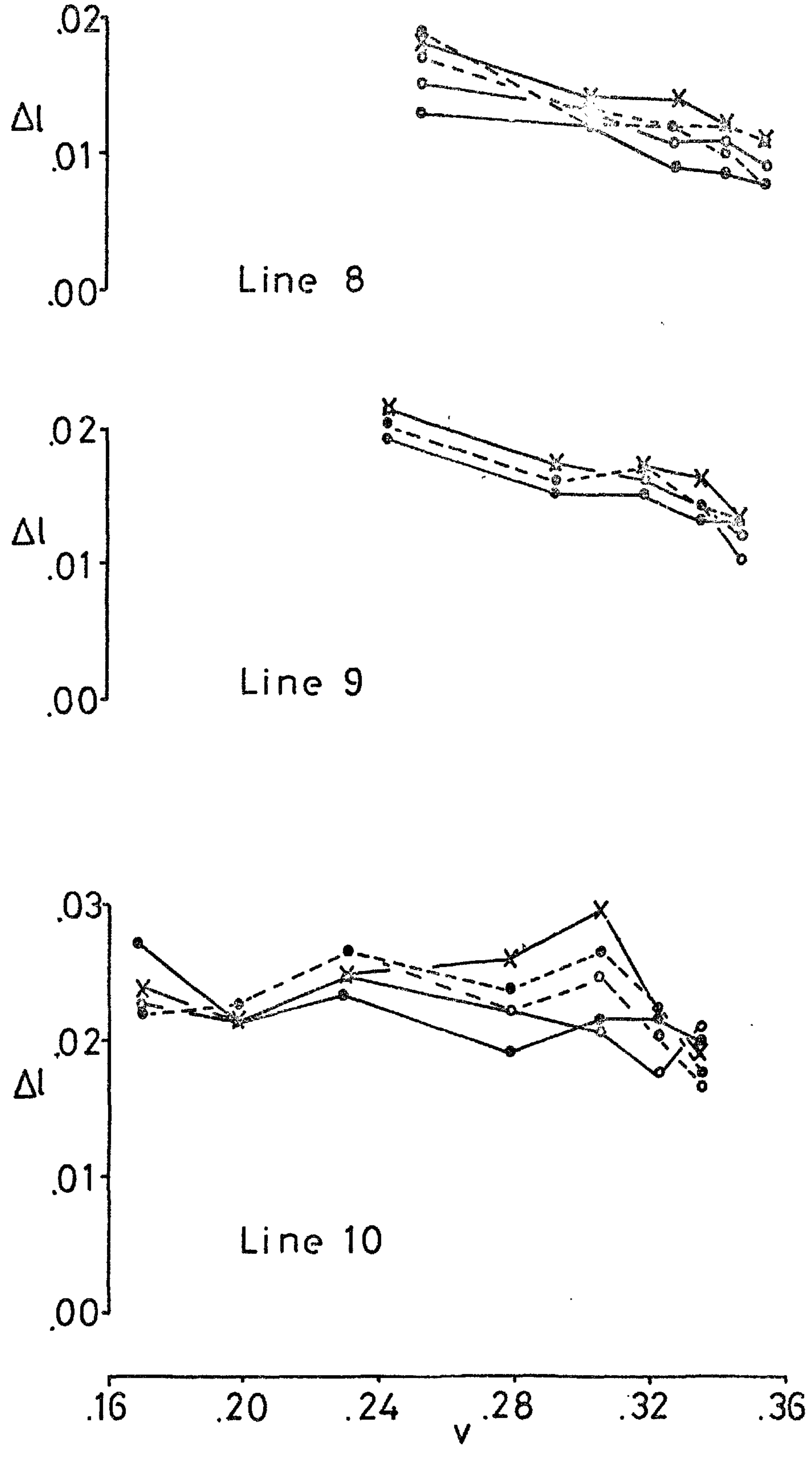

.02
ΔI
.01
.00
Line 8
.02
ΔI
.01
.00
Line 9
.03
.02
ΔI
.01
.00
Line 10
.16
.20
.24
.28
.32
.36
V

Fig 5.13

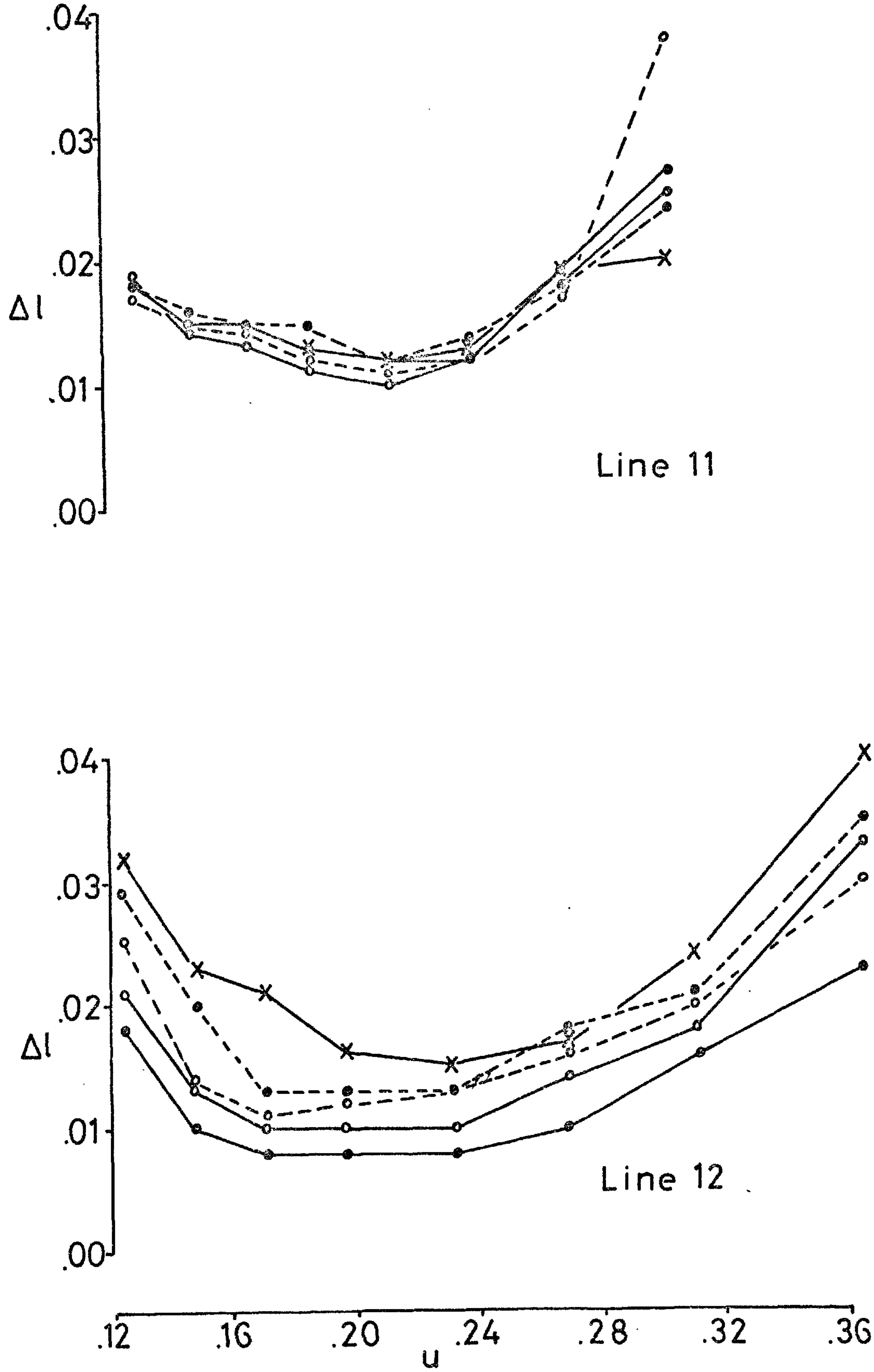
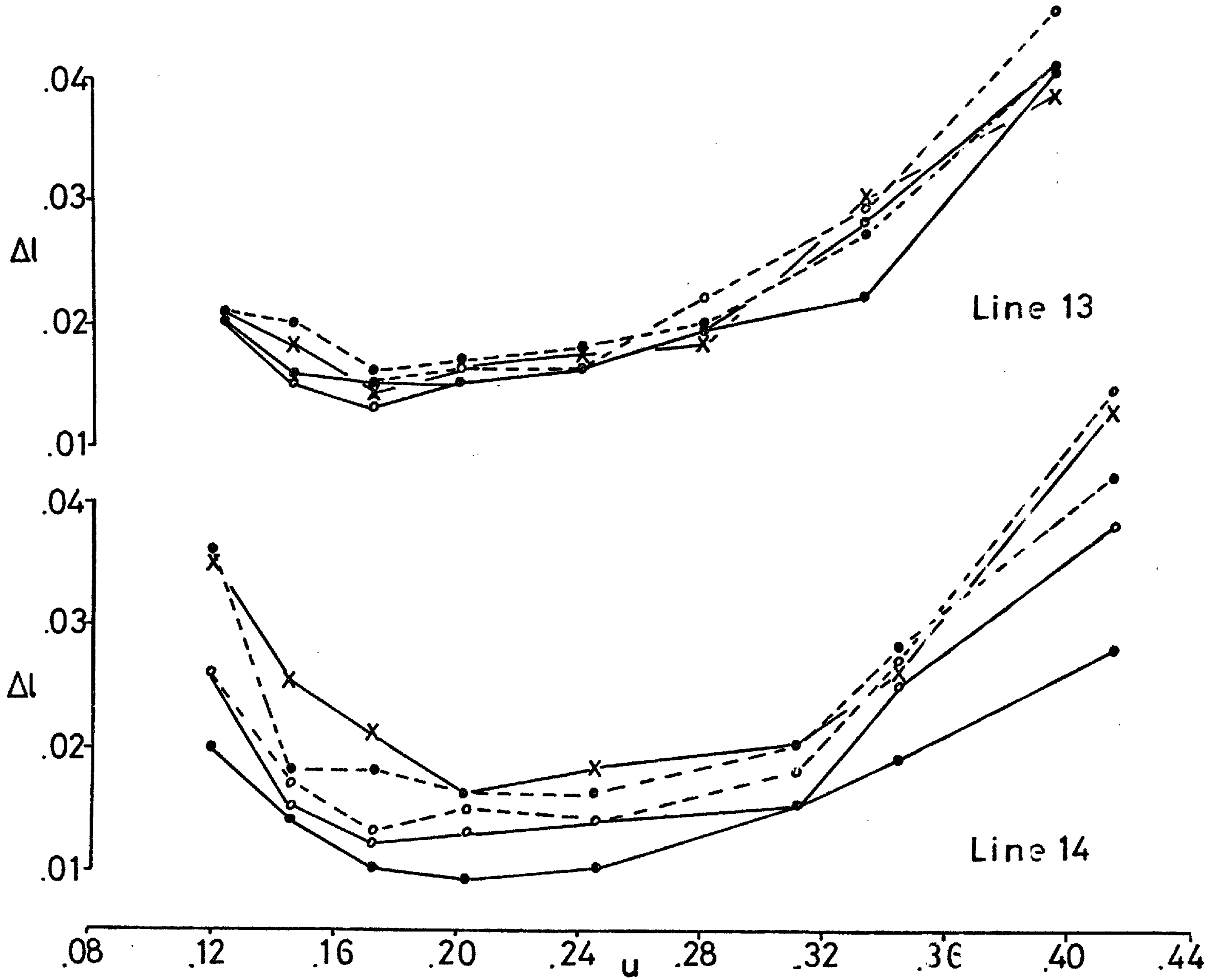

.04
.03
.02
Δl
.01
.00
Line 11
.04
.03
.02
Δl
.01
.00
Line 12
.12
.16
.20
.24
.28
.32
.36
u

Fig 5.14



.04
.03
.02
.01
Δl
Line 13
.04
.03
.02
.01
Δl
Line 14
.08
.12
.16
.20
.24
u
.28
.32
.36
.40
.44

Fig 5.15

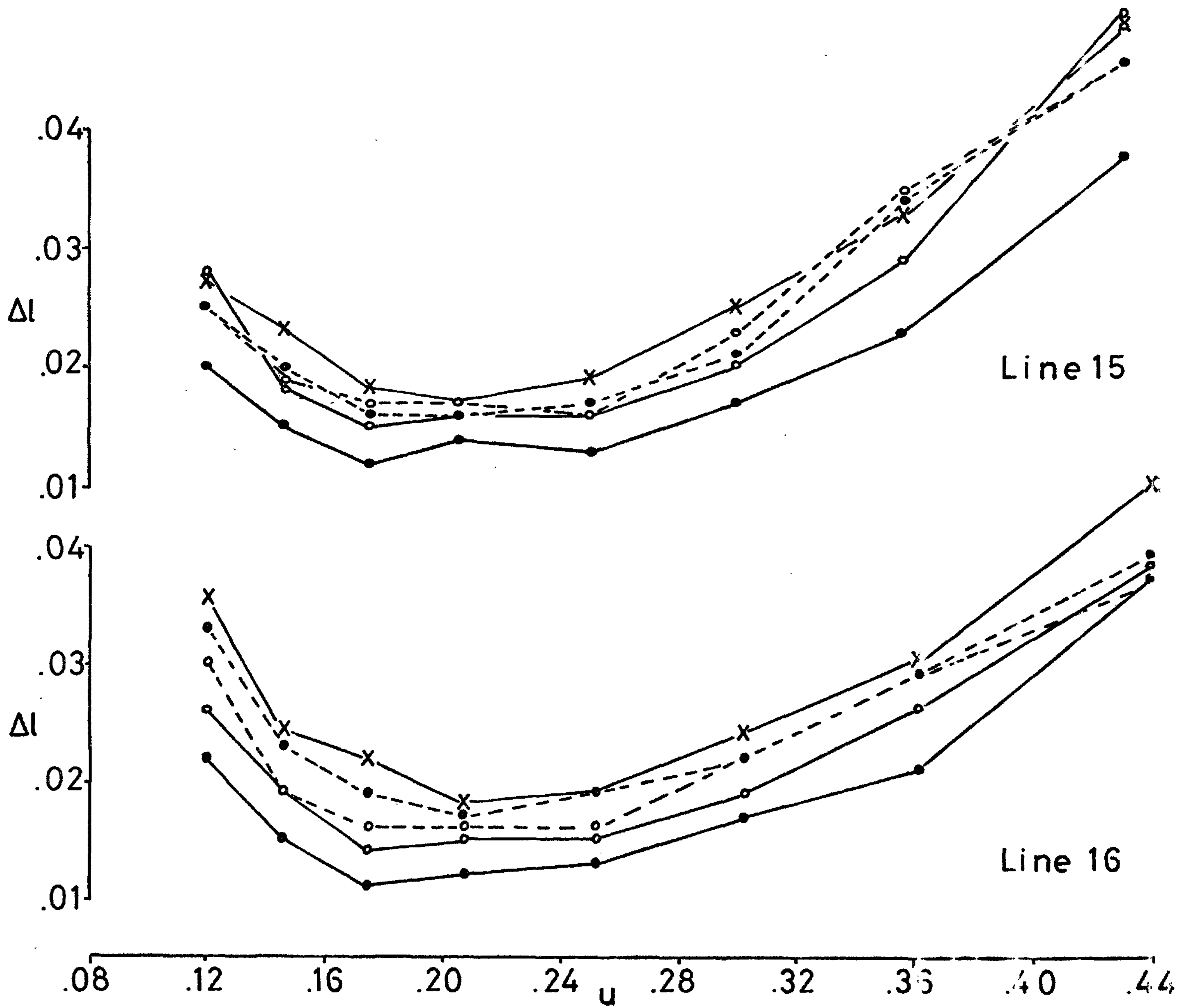

.04
.03
Δl
.02
.01
Line 15
.04
.03
Δl
.02
.01
Line 16
.08
.12
.16
.20
.24
u
.28
.32
.36
.40
.44

Fig 5.16

In general:-

$$\Delta l = ((\Delta u)^2 + (\Delta v)^2)^{\frac{1}{2}}$$

where Δu is the difference in the u coordinate of the points representing the ends of the line Δl.

Δv is the difference in the v coordinate of the points representing the ends of the line Δl.

or, if we consider a change in one direction only:-

$$\Delta l = \Delta u$$

Now the mean value of Δl for all sampling points under 6500°K adaptation subtracted from the mean value of Δl under 2856°K adaptation is 0·004. This can be thought of as a chromaticity shift of only ± 0·002 in the u coordinate with the v coordinate held constant. This is smaller than the smallest observed just noticeable colour difference. Thus it seems justifiable to say that, for example, the results for the daylight adaptation (6500°K) are similar in magnitude to the results for tungsten adaptation (2856°K). This will be justified further when the spread of results is considered in the next section.

5.3 The Spread of the Results

Each length Δl representing a just noticeable colour difference was usually the mean of ten experimental readings. To give an idea of the spread of the results the maximum and minimum readings for each sampling point were found for each adaptation and the mean spread, defined as the mean of the maximum and minimum readings, was found for each sampling point. This spread was plotted as an error bar on the data for adaptation with a colour temperature of 6500°K. Figures 5.17 and 5.18 show the 6500°K adaptation results, with error bars, and the 2856°K adaptation results plotted together. Results for lines 1 and 10 are plotted in Figure 5.17 and results for lines 11 and 16 in Figure 5.18. The results shown for these four lines are typical of the spread of the results obtained for the other lines. It is seen that the spread of the results defined in this way is quite large and can be as high as 50% of the size of the just noticeable colour difference. If the error bars were added to the 2856°K adaptation results as well considerable overlap with the 6500°K data would be obtained. It must be remembered however that the error bars represent the mean maximum overall spread of the results for any particular sampling point. A more meaningful picture of the spread would be obtained by taking the spread of each set of ten results for each sampling point and weighting the mean spread according to the frequency of occurrence of any reading.

5.4 The Results for a Second Observer

The second observer, IIM, also had normal colour vision. He had some experience of colour matching work although not on the apparatus used by the author. The nature of the experiment was explained to him before observations commenced and he was allowed to familiarise himself with the controls of the instrument and their associated effects. The observing sessions commenced, as for the author. with a period of 15 minutes dark adaptation

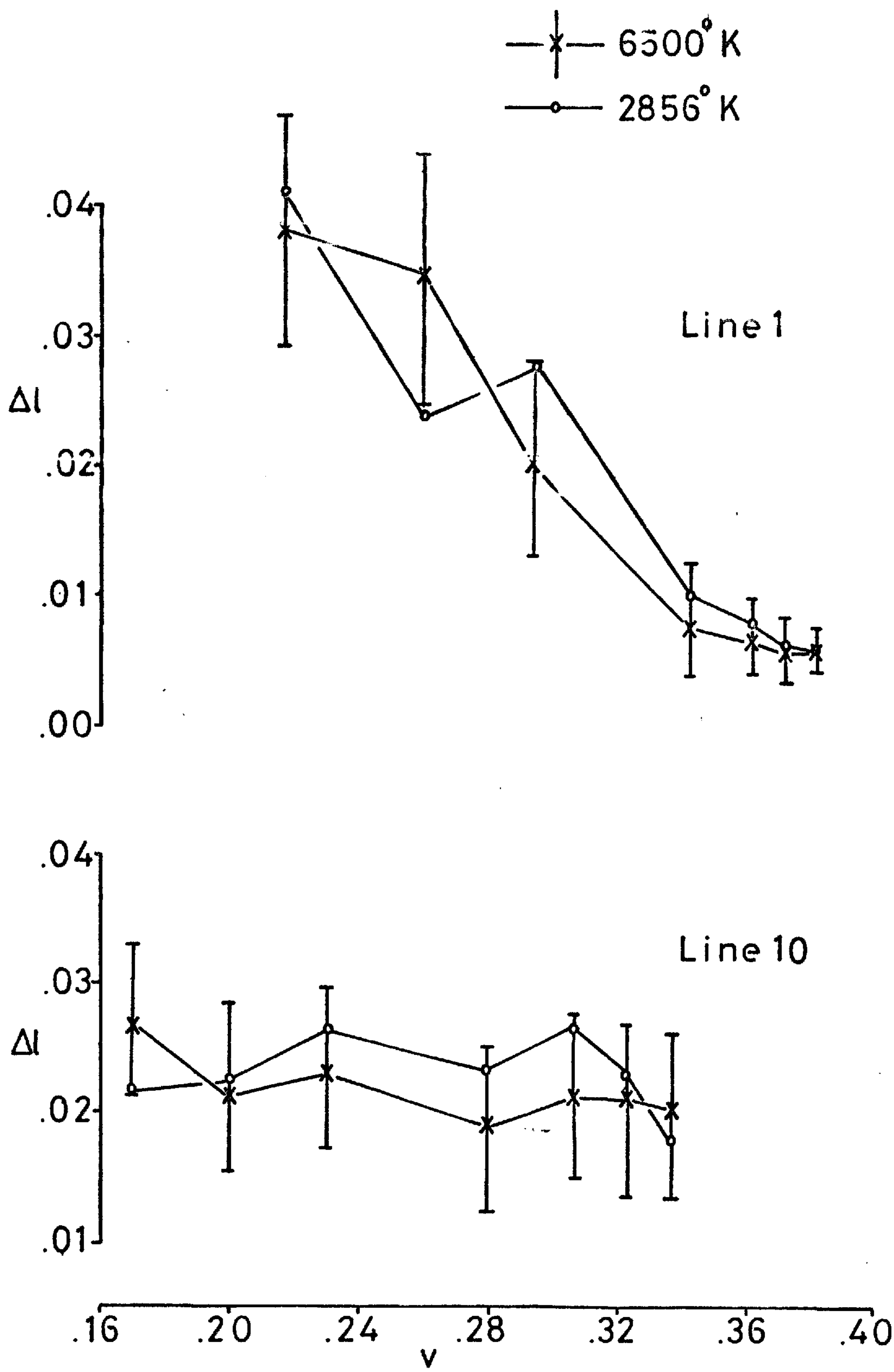

6500° K
2856° K
.04
.03
.02
.01
.00
Δl
Line 1
.04
.03
.02
.01
Δl
Line 10
.16
.20
.24
.28
.32
.36
.40
v

Fig 5.17

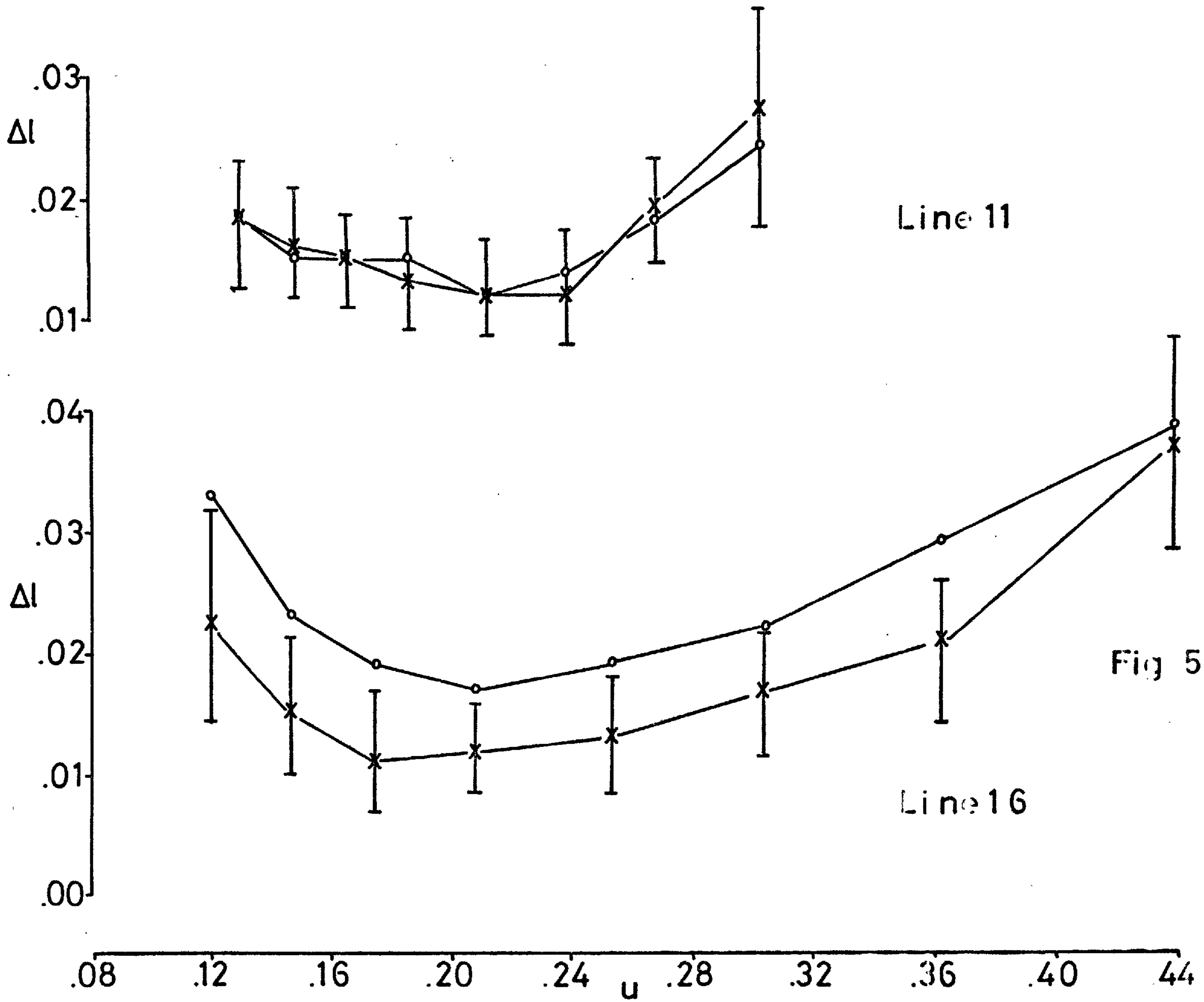

.03
Δl
.02
.01
Line 11
.04
.03
Δl
.02
.01
.00
Line 16
.08
.12
.16
.20
.24
u
.28
.32
.36
.40
44

Fig 5.18

followed by a period of 5 minutes adaptation to the light of the surround field. The author then set the starting colour and the observer commenced the series of alternate matching and just noticeable difference observation. The telescope, used by the author in his experimental work to read the instrument scale, was removed from the side of the apparatus and mounted on an optical bench some distance to the left of the observing position. Refocussing enabled the instrument scale to be read by the author to record the observations. The observer's left eye looked into an eyepiece, similar to that of the telescope, which was blanked off with black card.

The observer recorded seven sets of readings using 6500^{o}K adaptation. He only recorded data for lines 1, 6, 10, 11, 13 and 16 taking each set over two sessions; lines 1, 10 and 13 in the morning and lines 6, 11 and 16 in the afternoon session. The first two sets of data for each line were regarded as practice runs and the readings were discarded, although the observer was not told of this until all experimental work was finished.

The analysis of the second observer's results is summarised in Figures 5.19 and 5.20 where Δl, the length representing the just noticeable colour difference in the u,v chromaticity diagram, is plotted as a function of the v chromaticity coordinate, for lines 1, 6 and 10, and as a function of the u chromaticity coordinate for lines 11, 13 and 16. The comparable results of the author are also plotted.

Considering the nature of the experimental observations and the fact that the observer IBM had considerably less experience in colorimetry work than the author the agreement between the two

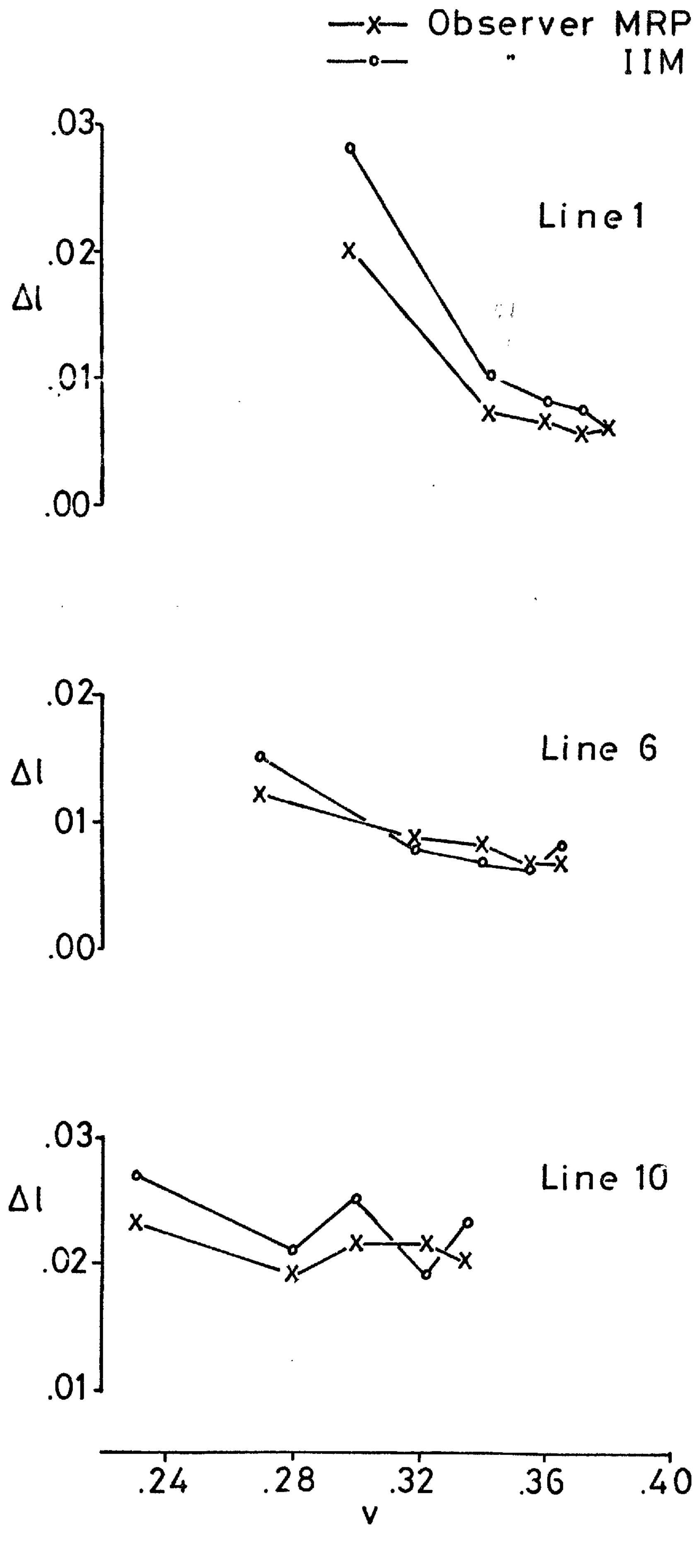

—x— Observer MRP
—o— " IIM
Line 1
Line 6
Line 10
Δl
.03
.02
.01
.00
.24
.28
.32
.36
.40
v

Fig 5.19

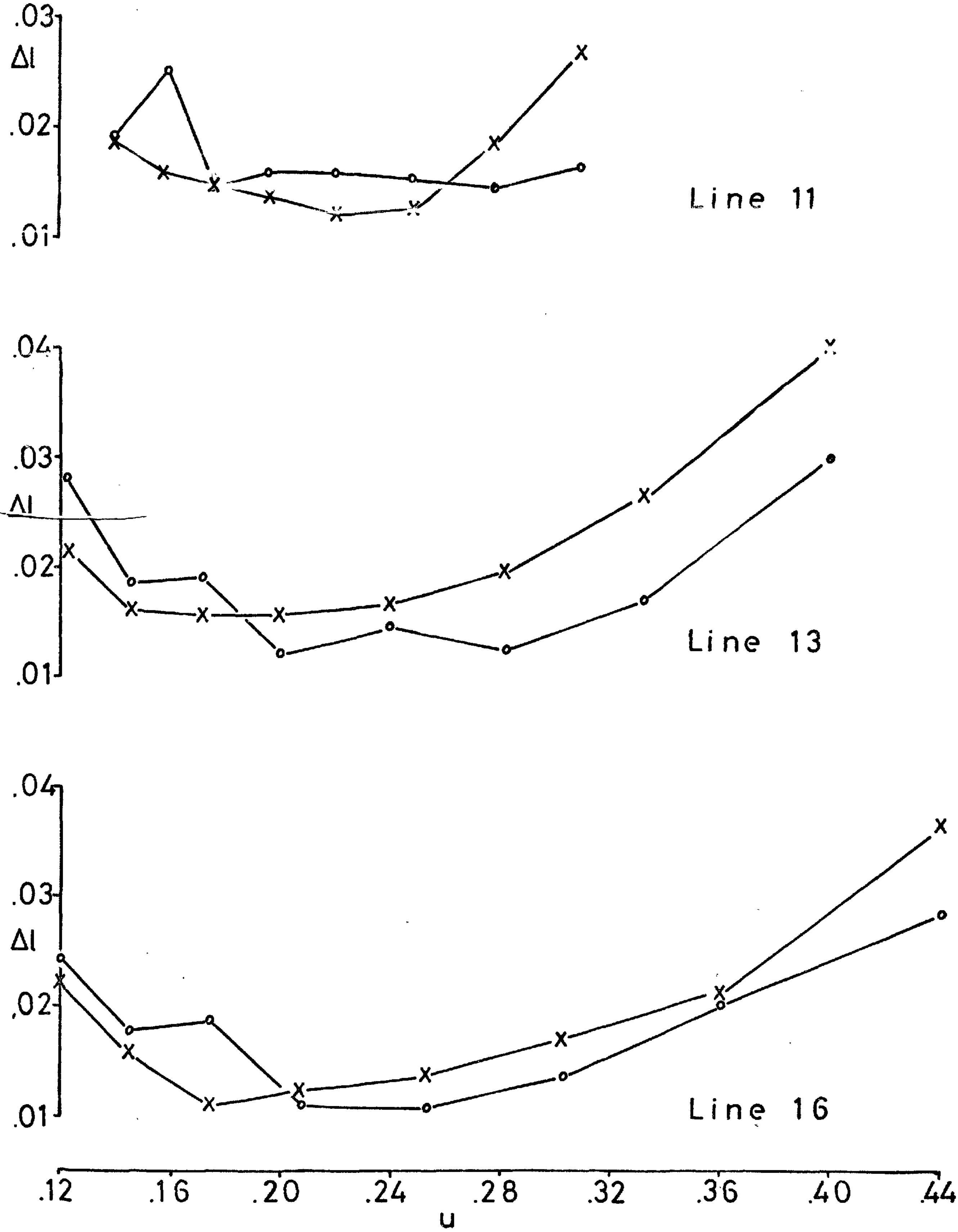

.03
ΔI
.02
.01
Line 11
.04
.03
ΔI
.02
.01
Line 13
.04
.03
ΔI
.02
.01
Line 16
.12
.16
.20
.24
.28
.32
.36
.40
.44
u

Fig 5.20

sets of data is considered very good. Indeed in the red region of the u,v chromaticity diagram the second observer's results were consistently slightly smaller than those of the author indicating a greater sensitivity to change in colour in this region.

5.5 The Mean Set of Data

A mean set of data was obtained by averaging the sets of data for the five white light adaptations. These data are shown tabulated in Figure 5.21 and they will be used for comparison with the data obtained using coloured adaptations and dark adaptation.

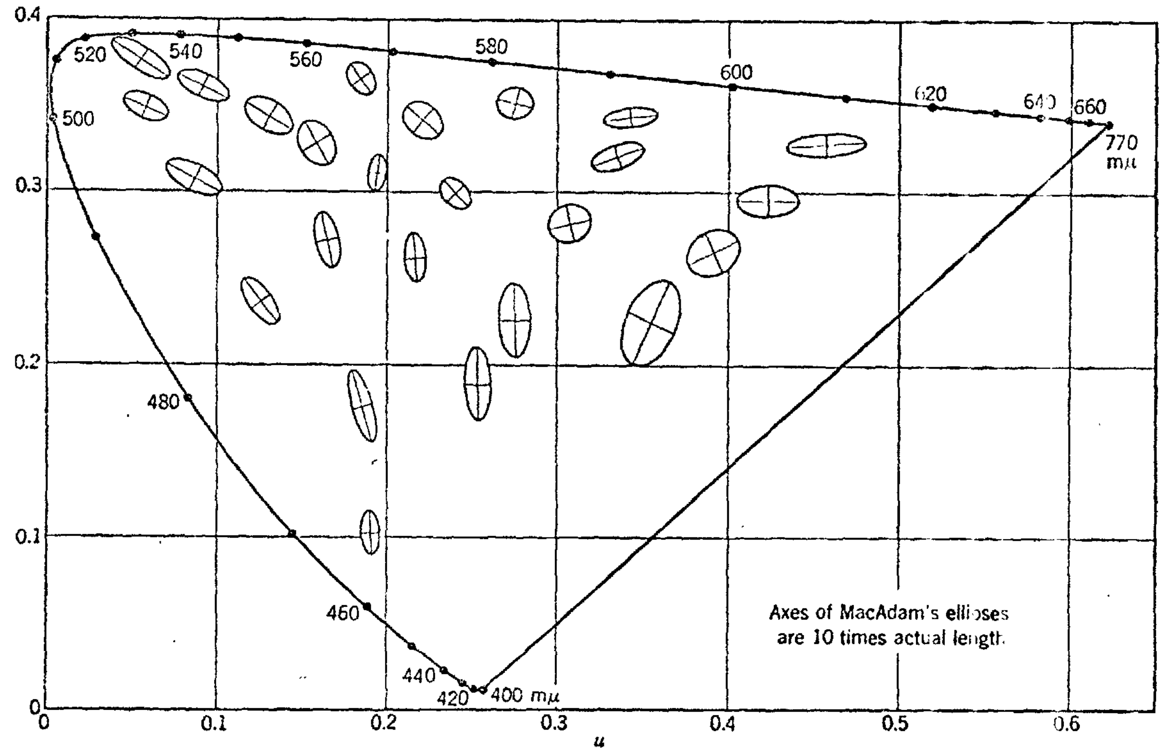
5.6 Comparison with Other Data

The largest set of data with which relevant comparison can be made is that of MacAdam (1942). He used the standard deviation of a set of colour matches, observed with a white light (Standard Illuminant S_C) adaptation, as the criterion for visual sensitivity and obtained the well known set of ellipses shown plotted in Figure 1.2. Judd (1963) has transformed these ellipses into the u,v chromaticity system and the resulting ellipses are shown plotted in Figure 5.22. The overall results show the same effects as those of the author. There is a general decrease in discrimination with increasing saturation of the test colour; the discrimination is poorest in the blue region of the chromaticity diagram especially in the blue-green direction. The MacAdam ellipses are plotted ten times their correct size and so the author's results show that the standard deviation of colour matching gives a measure of the visual sensitivity that is considerably smaller than a colorimetrically

Mean 'White' Data

Line	ΔI							
Line 1	·006	·006	·007	·008	·026	·032	·040	
Line 2	·006	·006	·006	·008	·019			
Line 3	·006	·006	·007	·009	·017			
Line 4	·006	·007	·007	·010	·018	·024	·029	
Line 5	·007	·006	·008	·010	·018			
Line 6	·008	·008	·009	·010	·015			
Line 7	·009	·009	·011	·012	·016	·018	·022	
Line 8	·010	·011	·012	·013	·017			
Line 9	·012	·014	·016	·016	·020			
Line 10	·019	·021	·025	·023	·025	·022	·023	
Line 11	·018	·015	·014	·013	·012	·013	·018	·027
Line 12	·025	·016	·013	·012	·012	·015	·020	·031
Line 13	·021	·017	·015	·016	·016	·020	·029	·041
Line 14	·029	·018	·015	·014	·015	·018	·025	·041
Line 15	·025	·019	·016	·016	·016	·021	·031	·045
Line 16	·030	·021	·016	·016	·016	·021	·027	·039
Line 17	·015	·012						
Line 18	·013	·011						

Fig 5.21



1960 CIE-UCS diagram showing MacAdam's (1942) ellipses of observer P.G.N.

Fig 5.22 (from Judd, 1963)

observed step. The ratio of the longest to the shortest ellipse radius is about 7:1 in the u,v chromaticity diagram which is compatible with the ratio obtained by the author.

Brown later expanded the work of MacAdam to take in twelve observers (Brown, 1952), but he used a larger, 10 degree, field for his colour matching. His results were in general agreement with those of MacAdam although there were some significant discrepancies. He found that his observers, who started making observations as unskilled observers, gradually became more skilled in that the size of the standard deviation of a series of colour matches decreased when a set of observations was repeated. It was this learning process that led the author to discard the first set of results for 6500°K adaptation and repeat them at a later date. Brown found that the same mean length of the semi-major axes of the colour matching ellipses of his twelve observers differed from the corresponding weighted mean length by 23%.

Chapter 6

The Results for Dark Adaptation and Coloured Adaptation

6.1 Introduction

The results of the experimental work using a dark surround and three coloured surrounds (red, green and blue) are presented in two ways as were the results for the white light adaptations. The mean set of data obtained from the results of the white light adaptation discrimination data is used for comparison.

6.2 The Results for Dark Adaptation

The overall results of discrimination observations made using a dark surround are shown tabulated in Figure 6.1. The bars representing the just noticeable colour difference are shown plotted in the u,v chromaticity diagram in Figure 6.2. Comparison with the mean set of data for white light adaptation shows that the lengths of the bars representing just discriminable colours are slightly shorter when a dark surround is used. This indicates that the power of discrimination is better with the dark surround. This is shown more clearly in Figures 6.3 - 6.8 where Δl, the length of the bar representing the just noticeable colour difference in the u,v chromaticity diagram, is plotted as a function of the v chromaticity coordinate of the sampling point (for lines 1 to 10) and as a function of the u coordinate of the sampling point (for lines 11 to 16). The results for lines 17 and 18 are not plotted in this way. The points on the graphs have been joined together to facilitate discrimination between the two different sets of data. This does not necessarily imply any continuity in the data.

Line	ΔI							
Line 1	·006	·007	·008	·010	·019	·027	·037	
Line 2	·006	·007	·007	·011	·016			
Line 3	·006	·007	·008	·011	·017			
Line 4	·005	·006	·007	·008	·012	·016	·025	
Line 5	·005	·007	·007	·010	·012			
Line 6	·006	·007	·008	·009	·012			
Line 7	·006	·007	·008	·010	·012	·016	·020	
Line 8	·008	·010	·011	·011	·016			
Line 9	·008	·011	·013	·013	·016			
Line 10	·015	·018	·021	·019	·022	·021	·024	
Line 11	·014	·011	·009	·009	·010	·011	·013	·020
Line 12	·015	·012	·012	·010	·012	·014	·016	·023
Line 13	·012	·010	·011	·010	·011	·012	·017	·032
Line 14	·016	·013	·012	·012	·012	·014	·021	·035
Line 15	·016	·013	·012	·013	·012	·013	·021	·038
Line 16	·021	·015	·014	·013	·014	·016	·024	·045
Line 17	·011	·012						
Line 18	·010	·009						

Fig 6.1

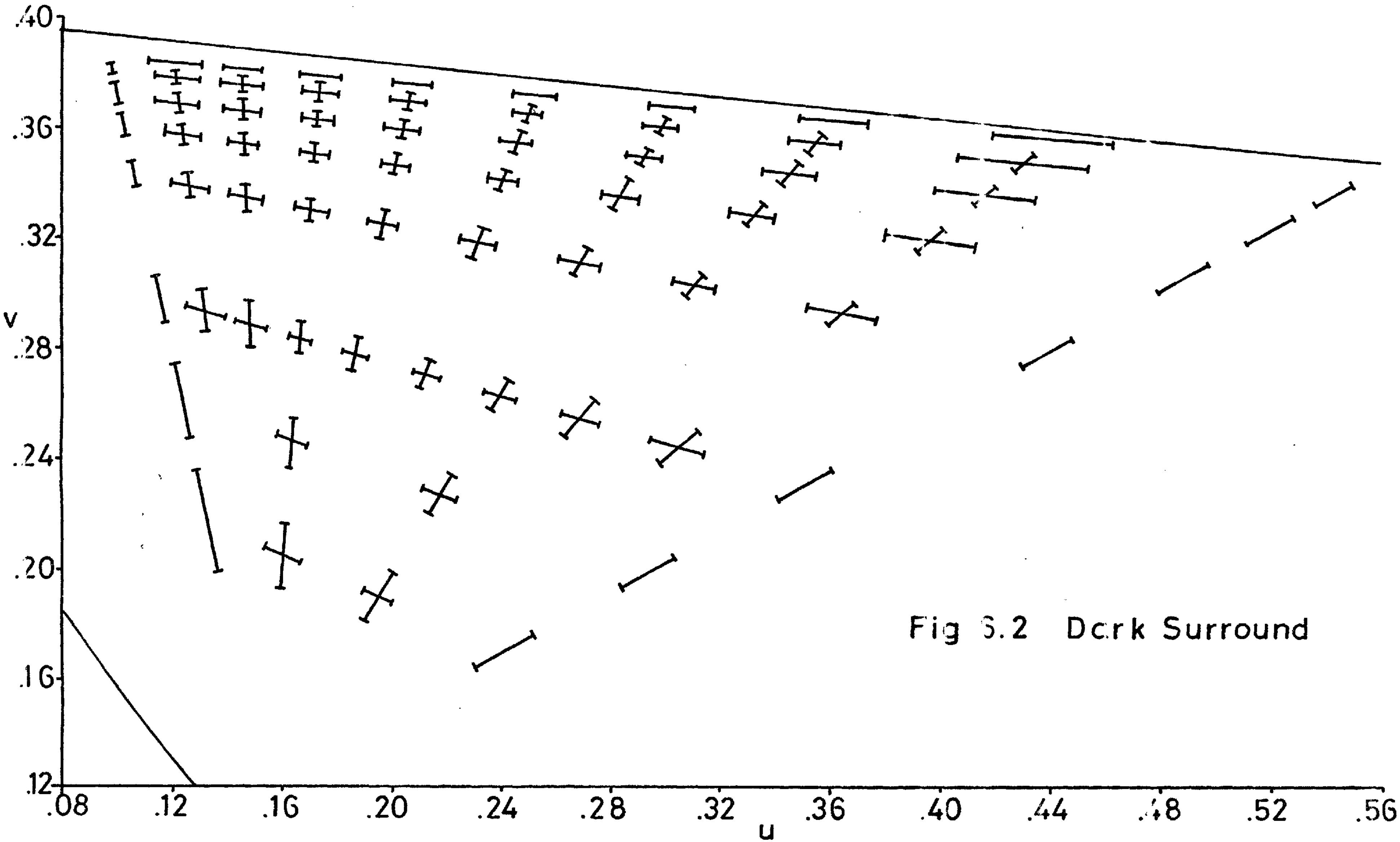
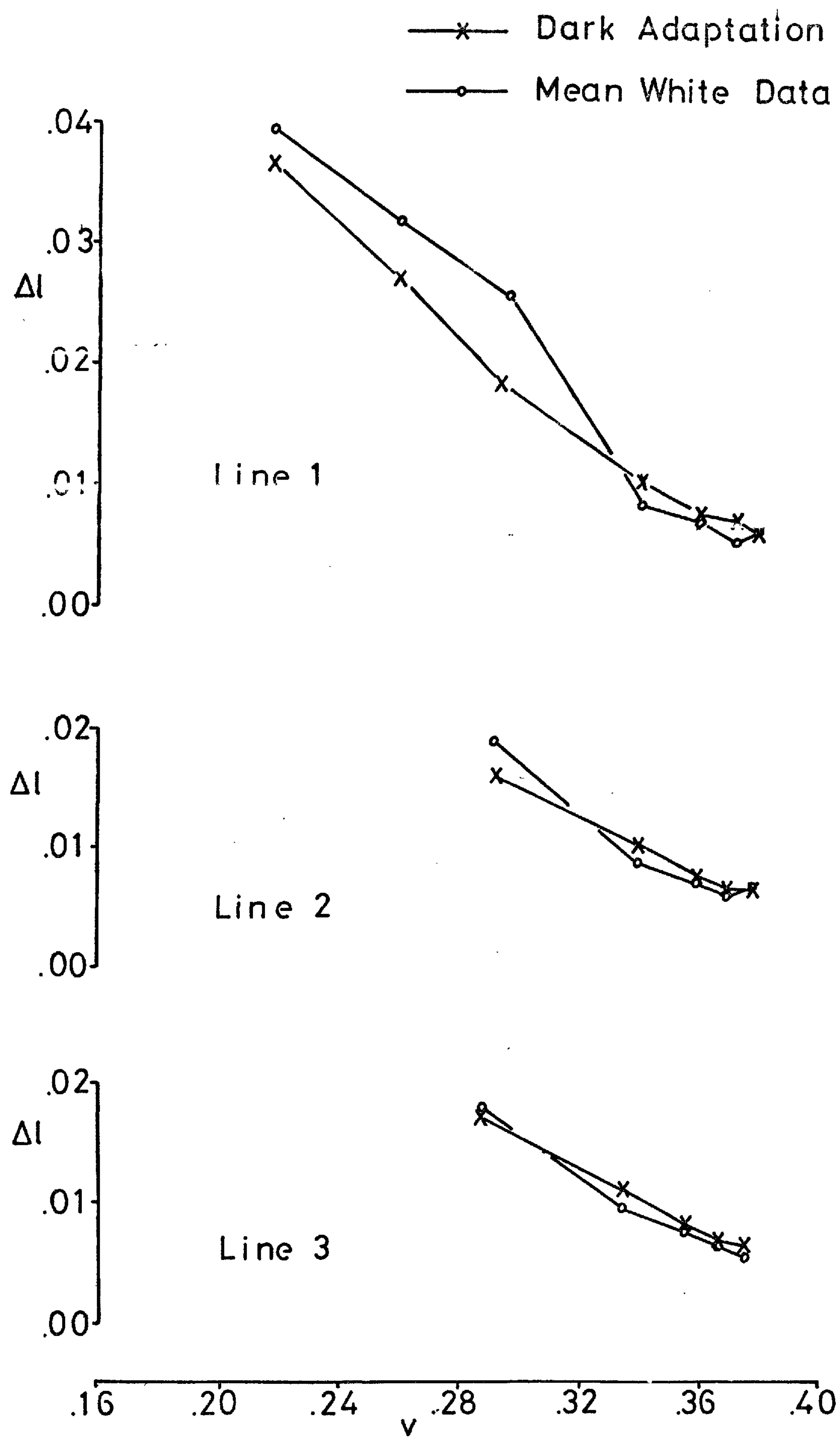


Fig 6.2 Dark Surround



Dark Adaptation
Mean White Data
ΔI
.04
.03
.02
.01
.00
Line 1
Line 2
Line 3
.16
.20
.24
.28
.32
.36
.40
v

Fig 6.3

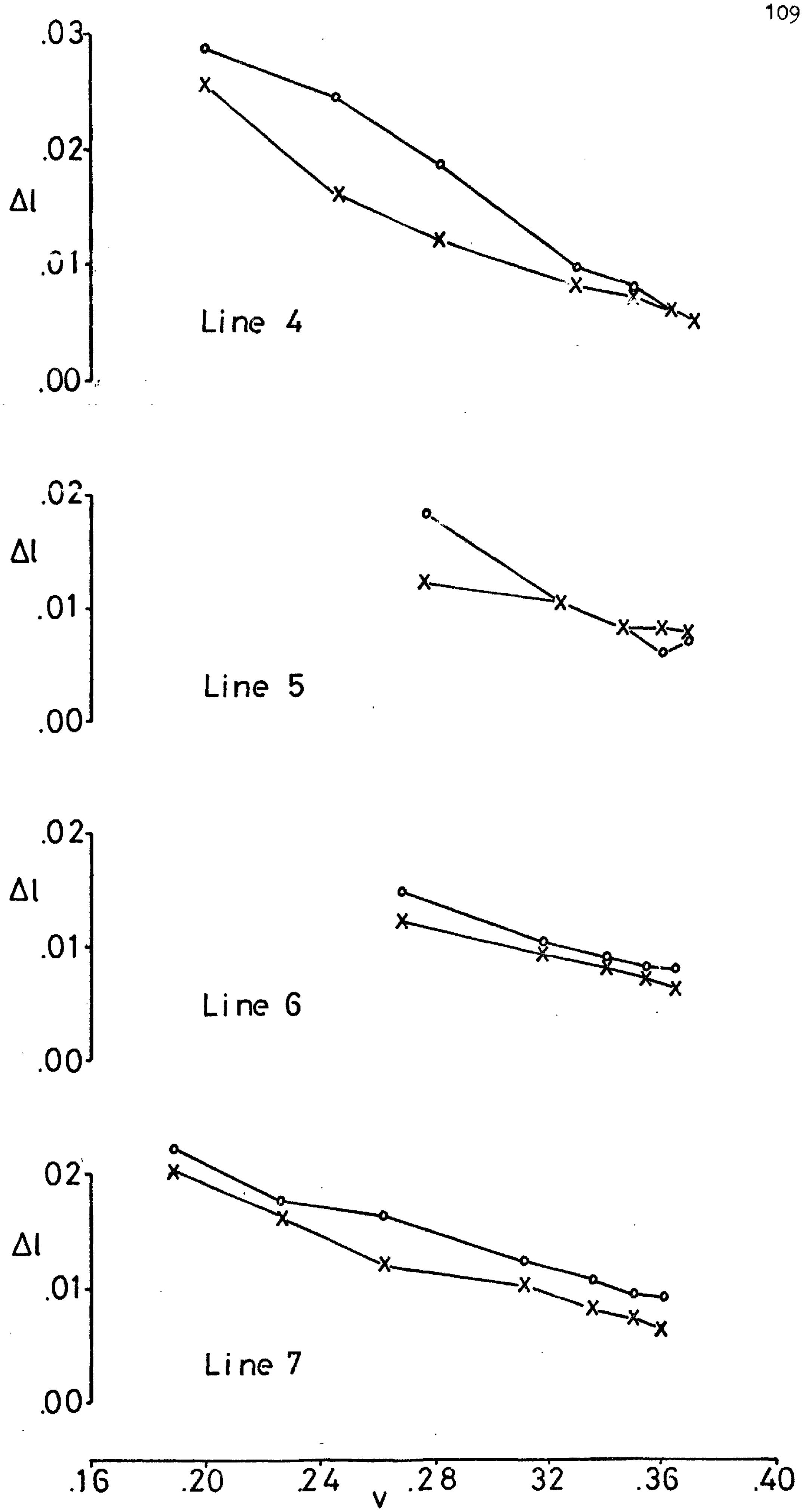

.03
.02
Δl
.01
.00
Line 4
.02
Δl
.01
.00
Line 5
.02
Δl
.01
.00
Line 6
02
Δl
.01
.00
Line 7
.16
.20
.24
.28
32
.36
.40
v

Fig 6.4

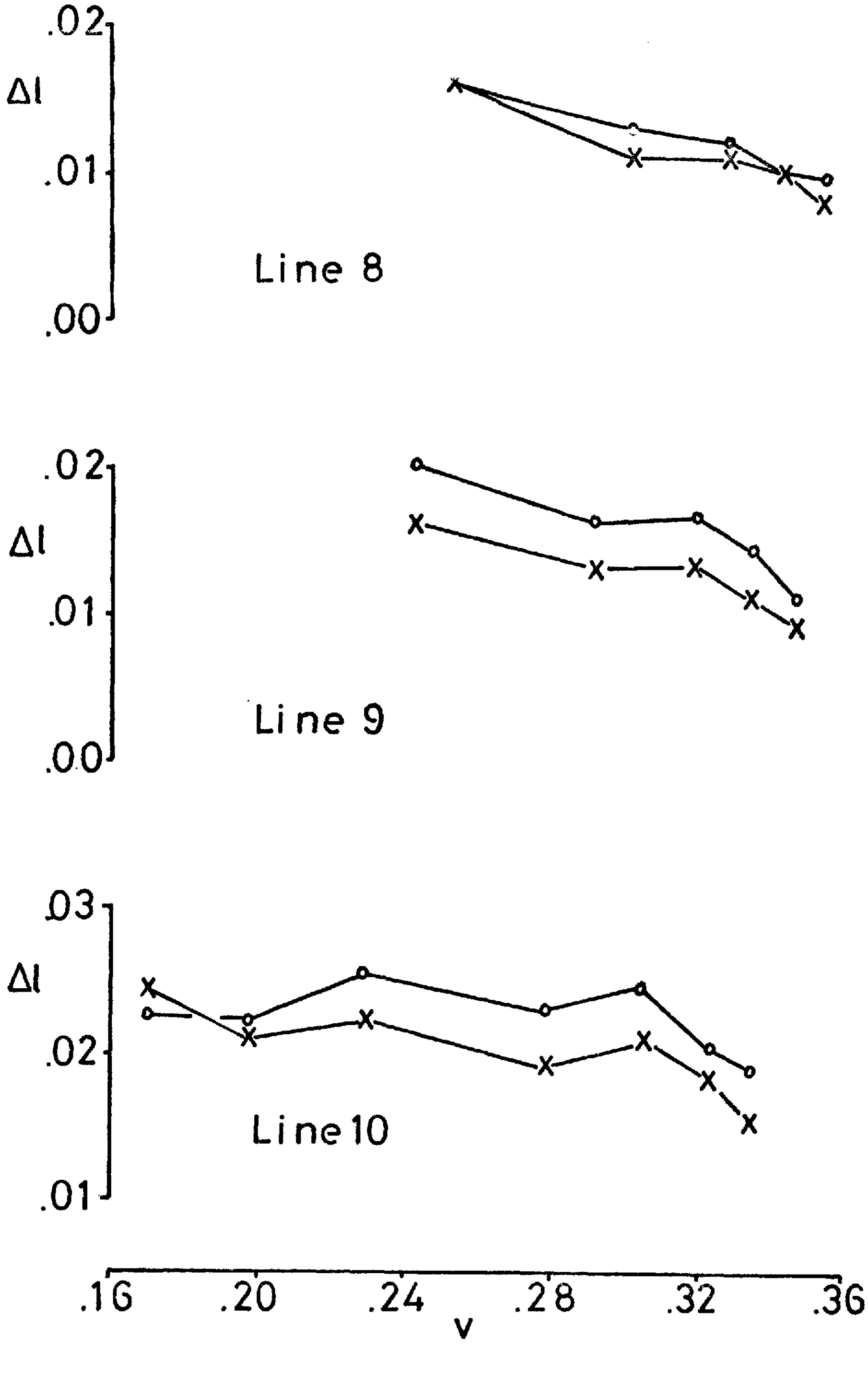

.02
ΔI
.01
Line 8
.00
.02
ΔI
.01
Line 9
.00
.03
ΔI
.02
Line 10
.01
.16
.20
.24
.28
.32
.36
v

Fig 6.5

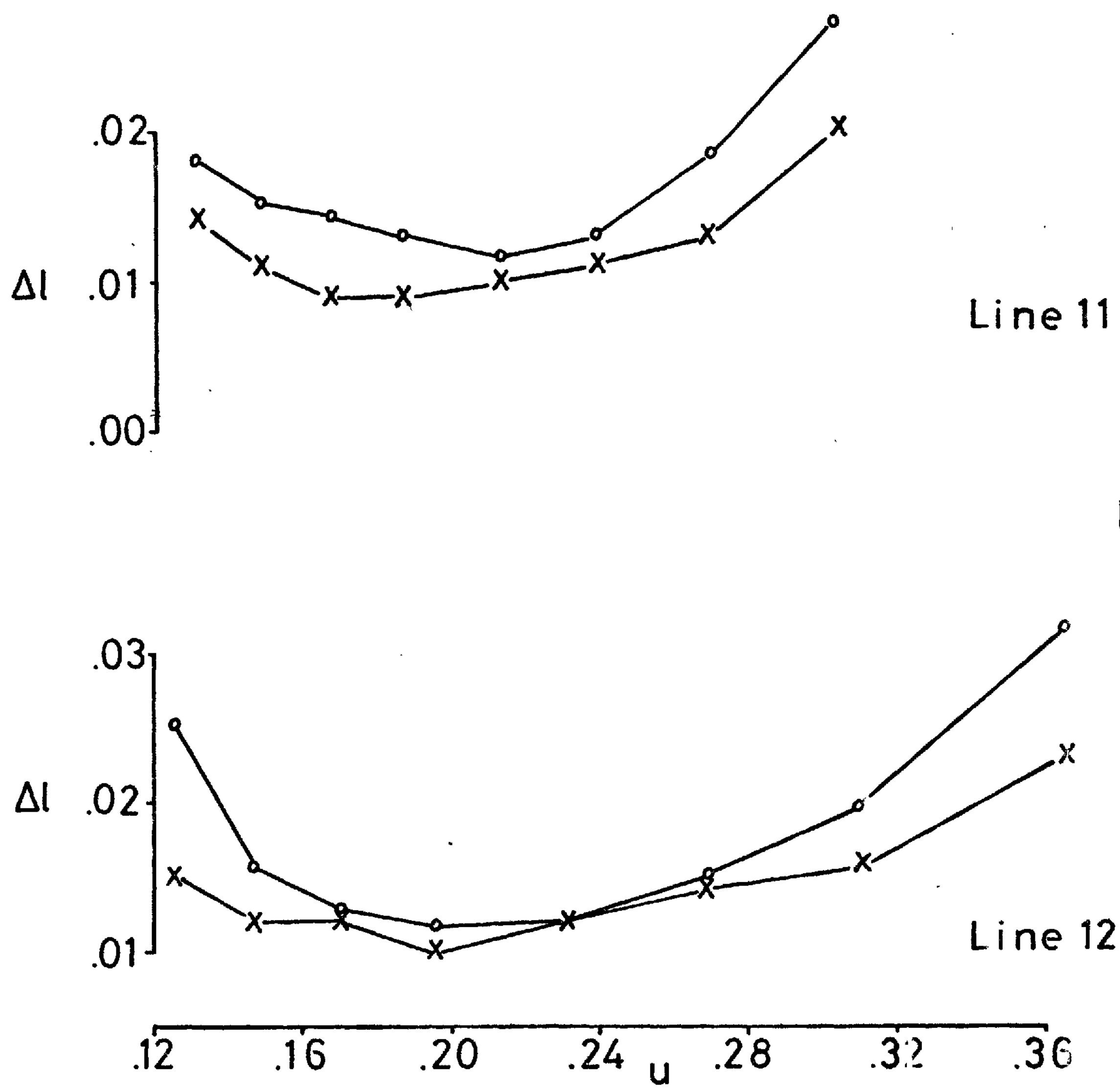


Fig 6.6

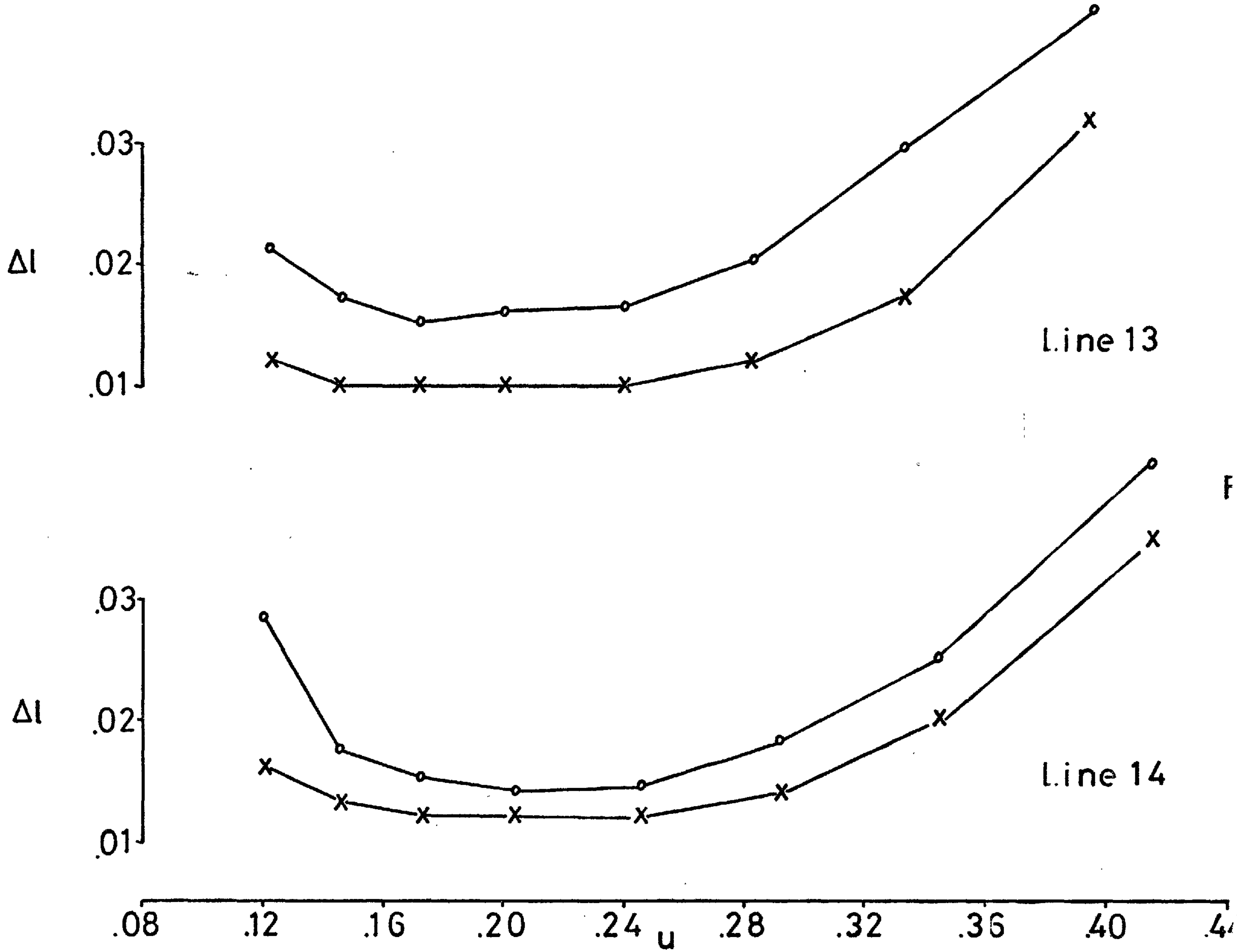


Fig 6.7

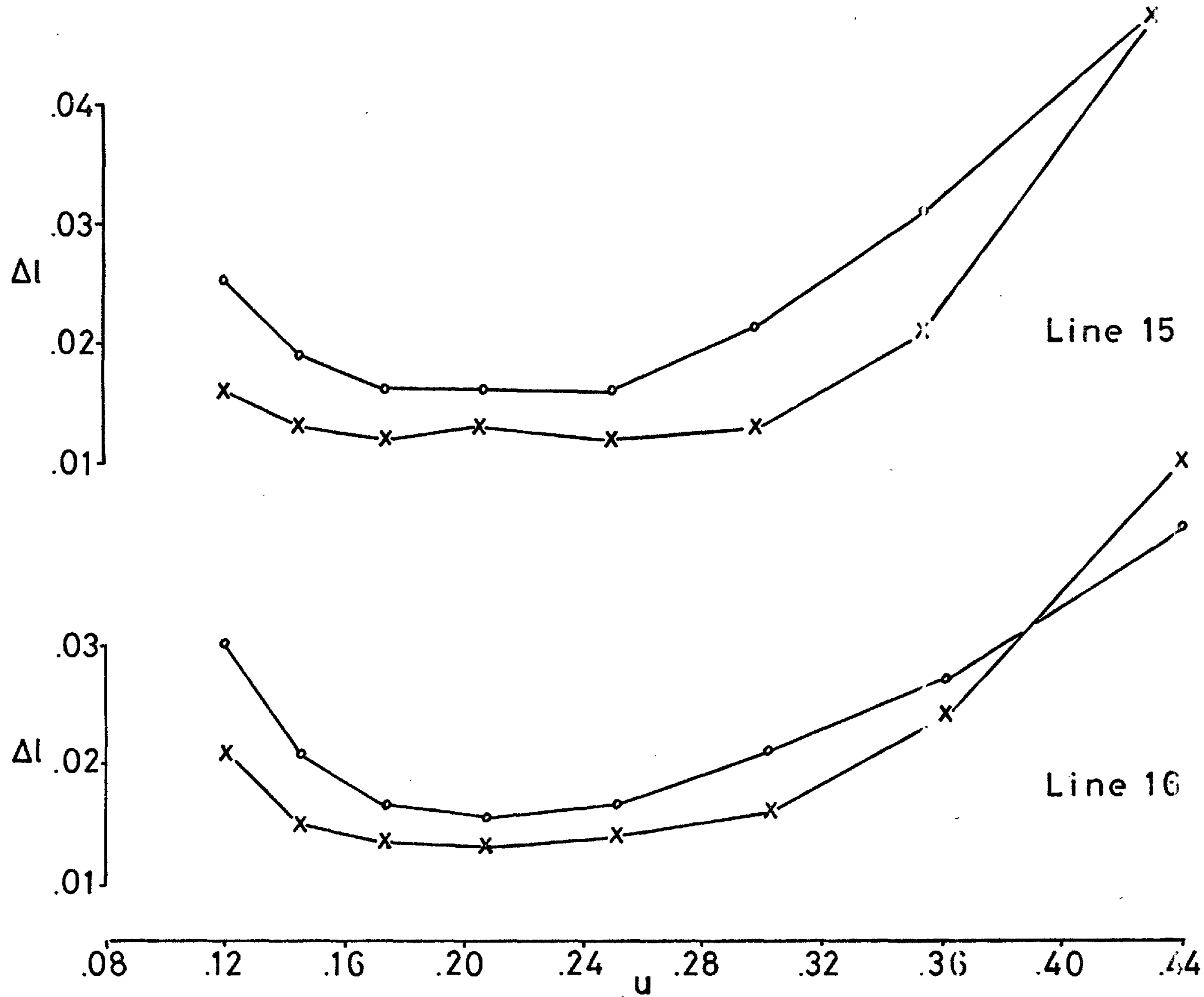

.04
.03
.02
.01
Δl
Line 15
.03
.02
.01
Δl
Line 16
.08
.12
.16
.20
.24
.28
.32
.36
.40
.44
u

Fig 6.8

The mean difference between the two sets of results, expressed in terms of Δl, is 0·003 which is smaller than the minimum observed discrimination step. The ratio of the length of the longest bar to the length of the shortest bar is about 7:1 and so the relative uniformity is no better with a dark surround than with a white surround. The best discrimination is still in the white-yellow region of the chromaticity diagram but only for mixture of green or green-yellow with blue.

The reasons for better discrimination with a dark surround may be due to the effect of simultaneous contrast. The dark surround makes the test colours appear relatively less saturated and, as was observed for desaturated colours with a white surround, it was easier to make observations in these conditions. This is confirmed by the overall effect of better discrimination with relatively desaturated test colours.

6.3 Comparison with Previous Data

The above results can be compared with those of several previous workers. The data of Wright(1941), who was working at a brightness level two orders of magnitude lower than that used by the author, were converted from the x,y coordinate system to the u,v coordinate system. This had to be done semi-graphically because only the lengths of the bars representing the just noticeable differences were available and not the sampling points. These latter were found graphically and the transformation calculations performed using a computer. The results are shown plotted in Figure 6.9. The bars are drawn three times their correct size and only those bars falling within the area of the chromaticity

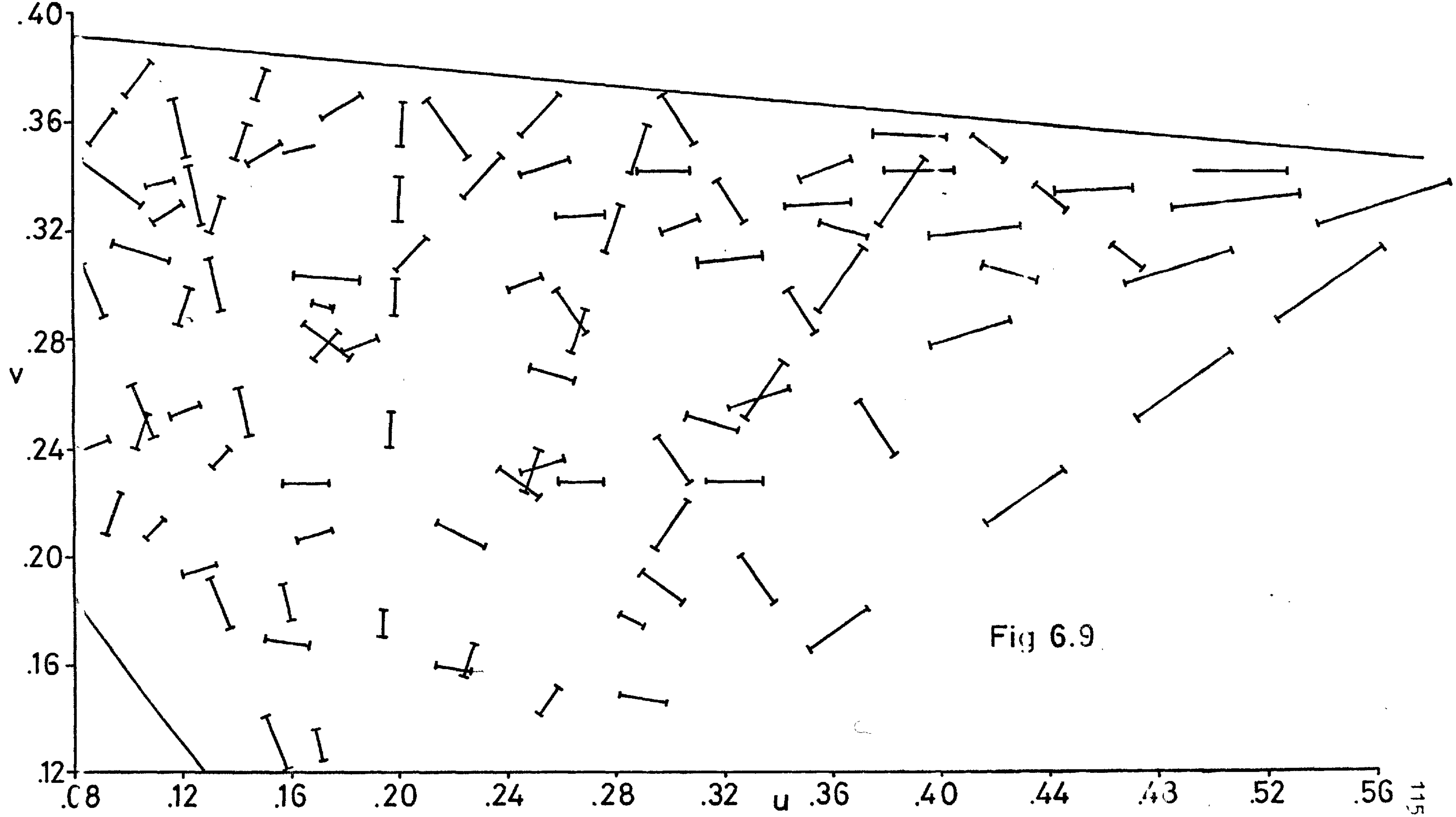


Fig 6.9

diagram used by the author in his experiments are shown. The spread of the results appears to be a lot more random than that of the author. The best discrimination appears to be in the blue region of the diagram although there is a trend for the best overall uniformity to be in the centre of the diagram. This would agree with the author's findings.

The results also show the same trends as the constant luminance cross-sections of discrimination ellipsoids computed by Brown and MacAdam (1949) from the statistically analysed results of numerous colour matches made by two observers.

6.4 The Results for Coloured Adaptations

The results for the red, green and blue adaptations are shown tabulated in Figures 6.10 - 6.12 respectively. They are then shown plotted in the u,v chromaticity diagram in Figures 6.13 - 6.15 respectively. Comparison of the three sets of results is easier using Figures 6.16 - 6.21 where the length Δl representing the just noticeable colour difference is plotted as a function of the v chromaticity coordinate of the sampling point for lines 1 to 10 and as a function of the u chromaticity coordinate of the sampling point for lines 11 to 16. Again no data are shown plotted for lines 17 and 18 since these only comprise two points. These figures show that the discrimination step size is usually longest and hence discrimination poorest with red adaptation. The discrimination with red adaptation is also considerably poorer than that obtained with the white light adaptations especially in the blue region of the chromaticity diagram. An exception to this is in the red region of the diagram where the chromaticity of the test colour

Red Adaptation

Line	ΔI							
Line 1	•006	•007	•010	•014	•026	•030	•042	
Line 2	•006	•007	•010	•013	•026			
Line 3	•006	•007	•010	•014	•021			
Line 4	•006	•007	•010	•013	•022	•023	•029	
Line 5	•007	•009	•011	•014	•028			
Line 6	•006	•008	•011	•018	•024			
Line 7	•008	•010	•012	•015	•025	•019	•023	
Line 8	•008	•011	•013	•016	•024			
Line 9	•011	•013	•017	•019	•027			
Line 10	•015	•018	•020	•022	•033	•024	•028	
Line 11	•026	•023	•024	•025	•031	•035	•039	•050
Line 12	•024	•023	•024	•021	•022	•024	•027	•033
Line 13	•028	•027	•022	•024	•021	•025	•029	•039
Line 14	•033	•029	•024	•025	•024	•023	•023	•030
Line 15	•027	•026	•025	•024	•021	•024	•025	•037
Line 16	•035	•030	•028	•026	•025	•024	•031	•031
Line 17	•016	•017						
Line 18	•014	•015						

Fig 6.10

Line	ΔI							
Line 1	·005	·008	·009	·016	·027	·025	·034	
Line 2	·005	·006	·008	·011	·020			
Line 3	·005	·007	·008	·012	·018			
Line 4	·005	·007	·009	·011	·018	·017	·022	
Line 5	·005	·007	·009	·011	·014			
Line 6	·007	·009	·010	·012	·019			
Line 7	·007	·010	·011	·014	·016	·016	·017	
Line 8	·009	·012	·014	·017	·020			
Line 9	·011	·014	·017	·020	·020			
Line 10	·015	·020	·023	·026	·027	·023	·022	
Line 11	·018	·016	·014	·013	·012	·016	·018	·028
Line 12	·023	·019	·014	·015	·016	·022	·028	·038
Line 13	·023	·017	·014	·014	·017	·020	·027	·044
Line 14	·023	·019	·017	·016	·019	·025	·033	·044
Line 15	·022	·016	·016	·018	·021	·025	·032	·047
Line 16	·023	·018	·018	·021	·021	·026	·038	·048
Line 17	·014	·013						
Line 18	·013	·009						

Fig G.11

Line	ΔI							
Line 1	·007	·007	·008	·011	·016	·021	·031	
Line 2	·006	·007	·007	·008	·014			
Line 3	·008	·008	·008	·010	·015			
Line 4	·006	·007	·007	·009	·013	·016	·020	
Line 5	·007	·007	·009	·010	·014			
Line 6	·006	·008	·008	·011	·013			
Line 7	·012	·011	·012	·013	·015	·016	·020	
Line 8	·011	·010	·012	·014	·015			
Line 9	·016	·016	·018	·017	·020			
Line 10	·022	·023	·024	·025	·024	·025	·024	
Line 11	·019	·016	·016	·013	·014	·015	·019	·027
Line 12	·022	·017	·017	·016	·016	·019	·022	·039
Line 13	·022	·019	·017	·019	·020	·025	·031	·045
Line 14	·020	·020	·016	·017	·018	·022	·029	·044
Line 15	·018	·017	·014	·016	·018	·019	·024	·042
Line 16	·018	·018	·016	·021	·018	·025	·034	·045
Line 17	·012	·013						
Line 18	·012	·010						

Fig 6.12

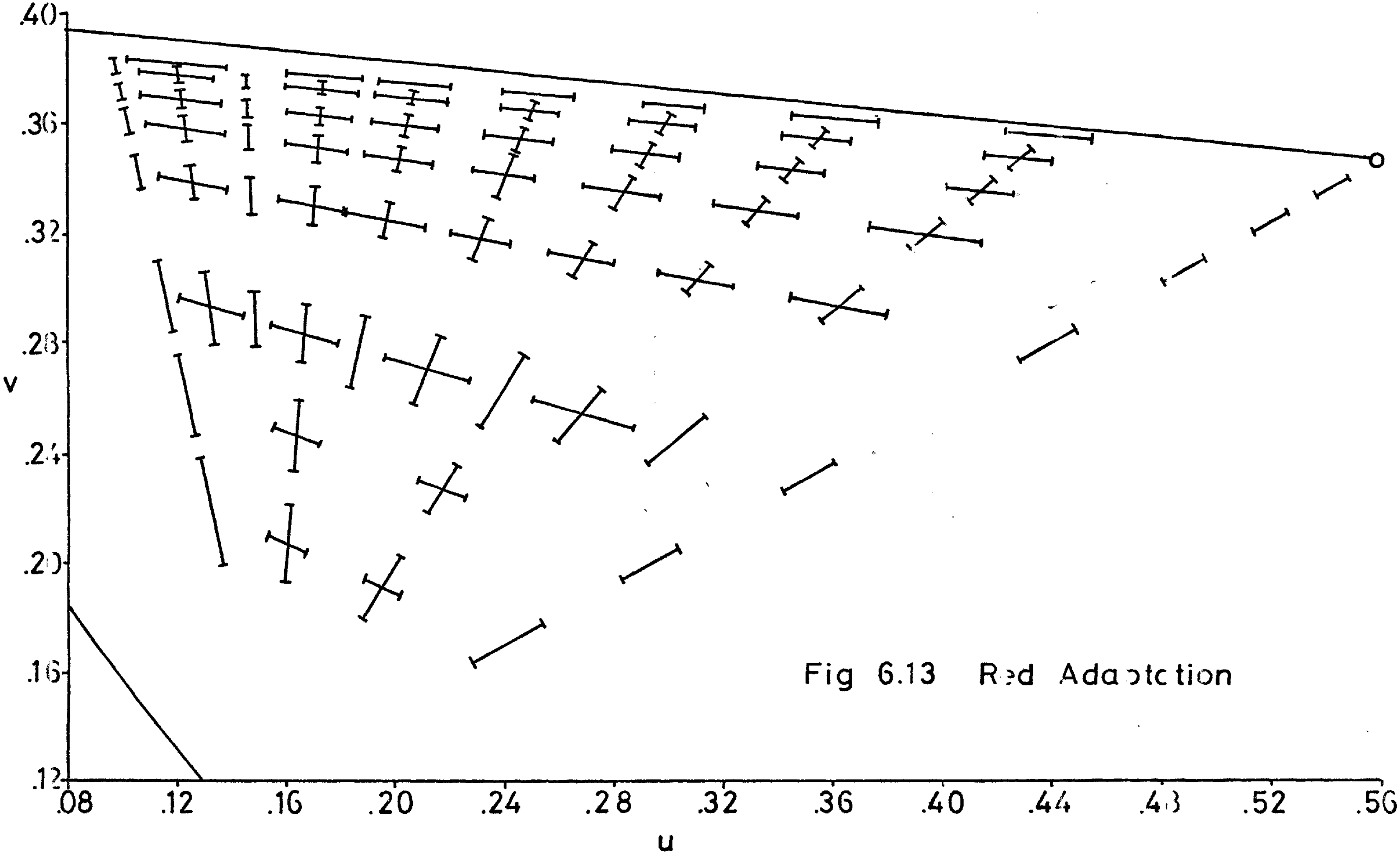


Fig 6.13 Red Adaptation

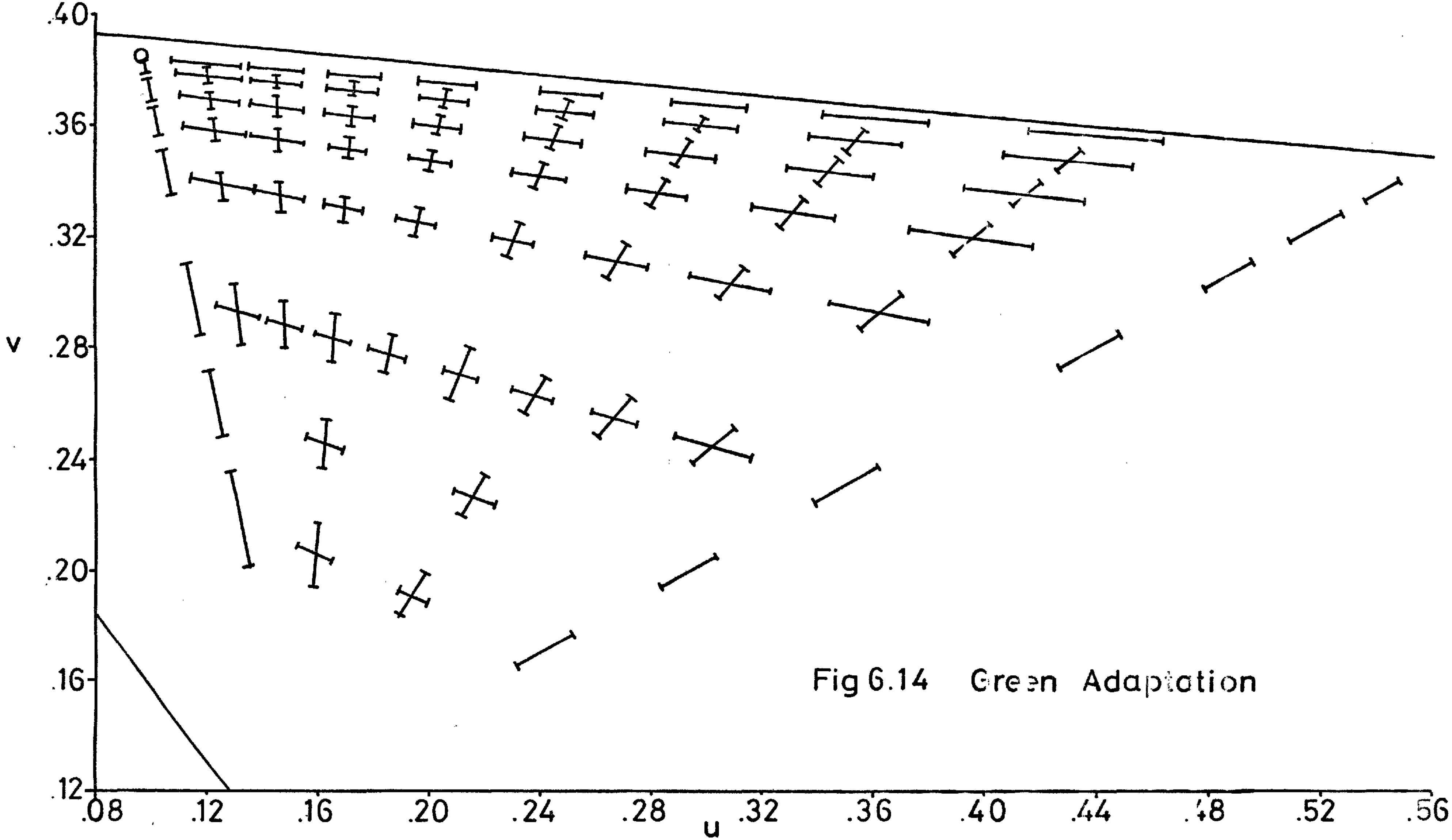


Fig 6.14 Green Adaptation

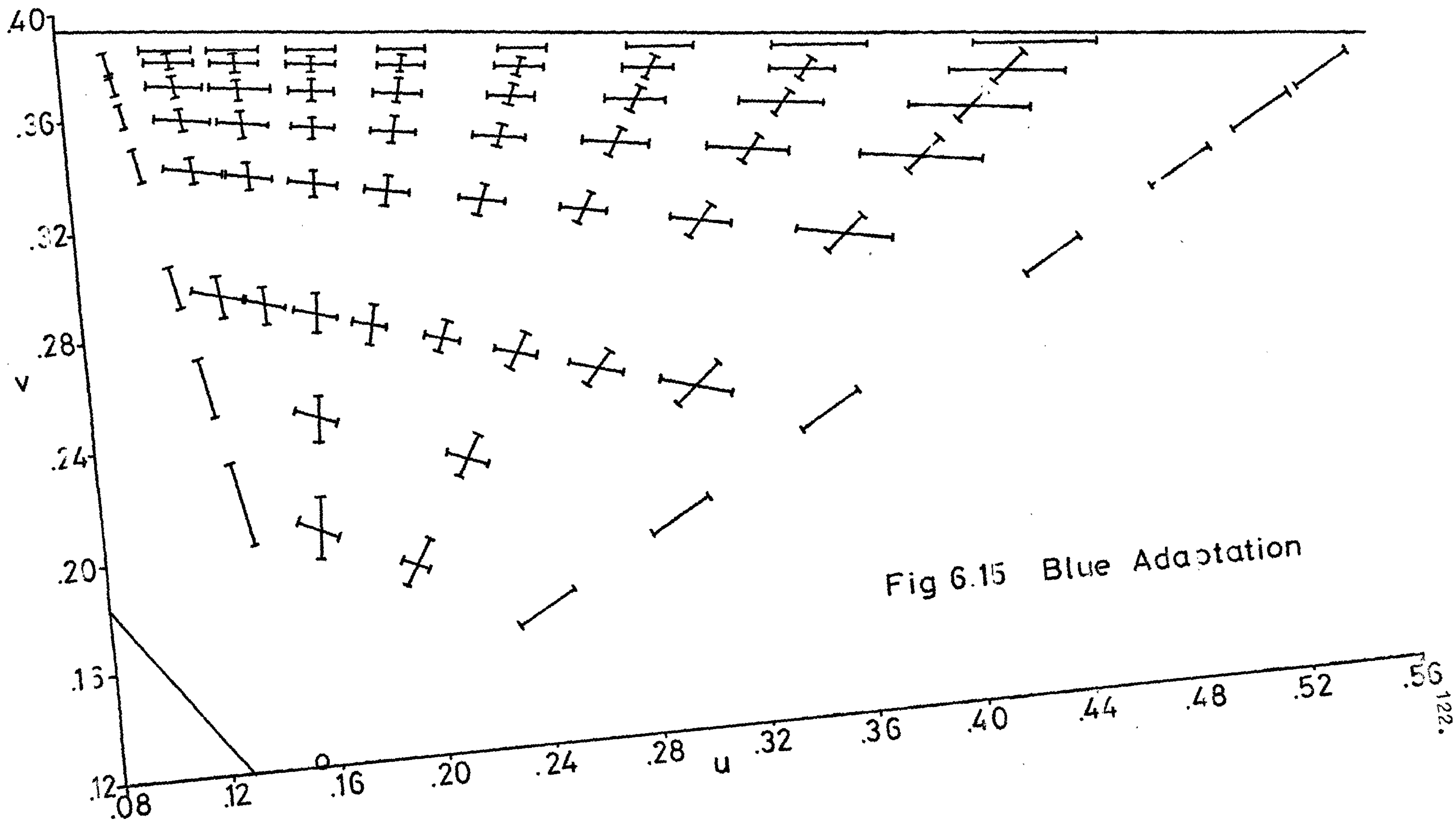
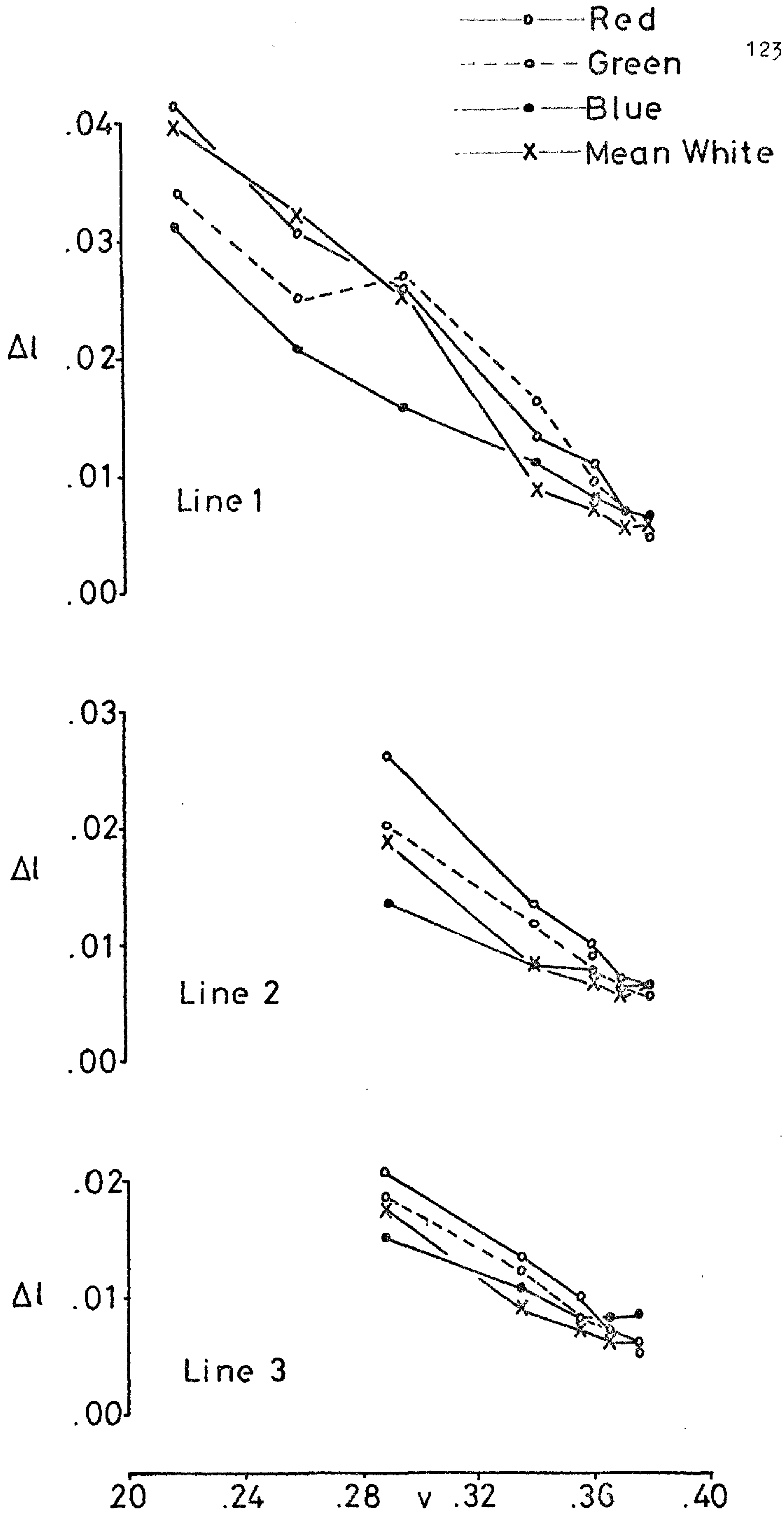


Fig 6.15 Blue Adaptation


Red
Green
Blue
Mean White
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.03
.02
.01
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ΔI
Line 1
.03
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ΔI
Line 2
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.01
.00
ΔI
Line 3
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.24
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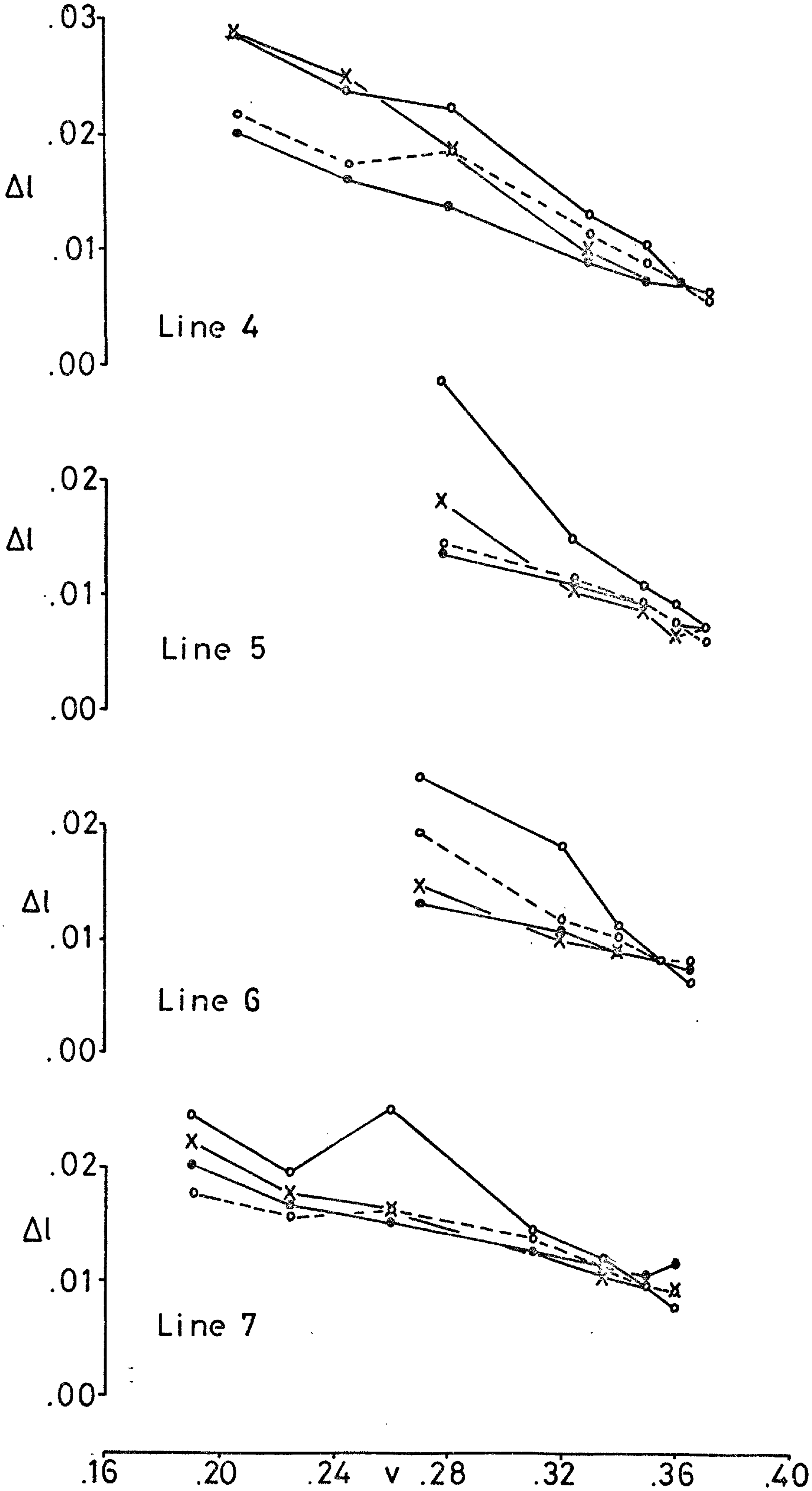
v
.32
.36
.40

Fig 6.16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Line 6
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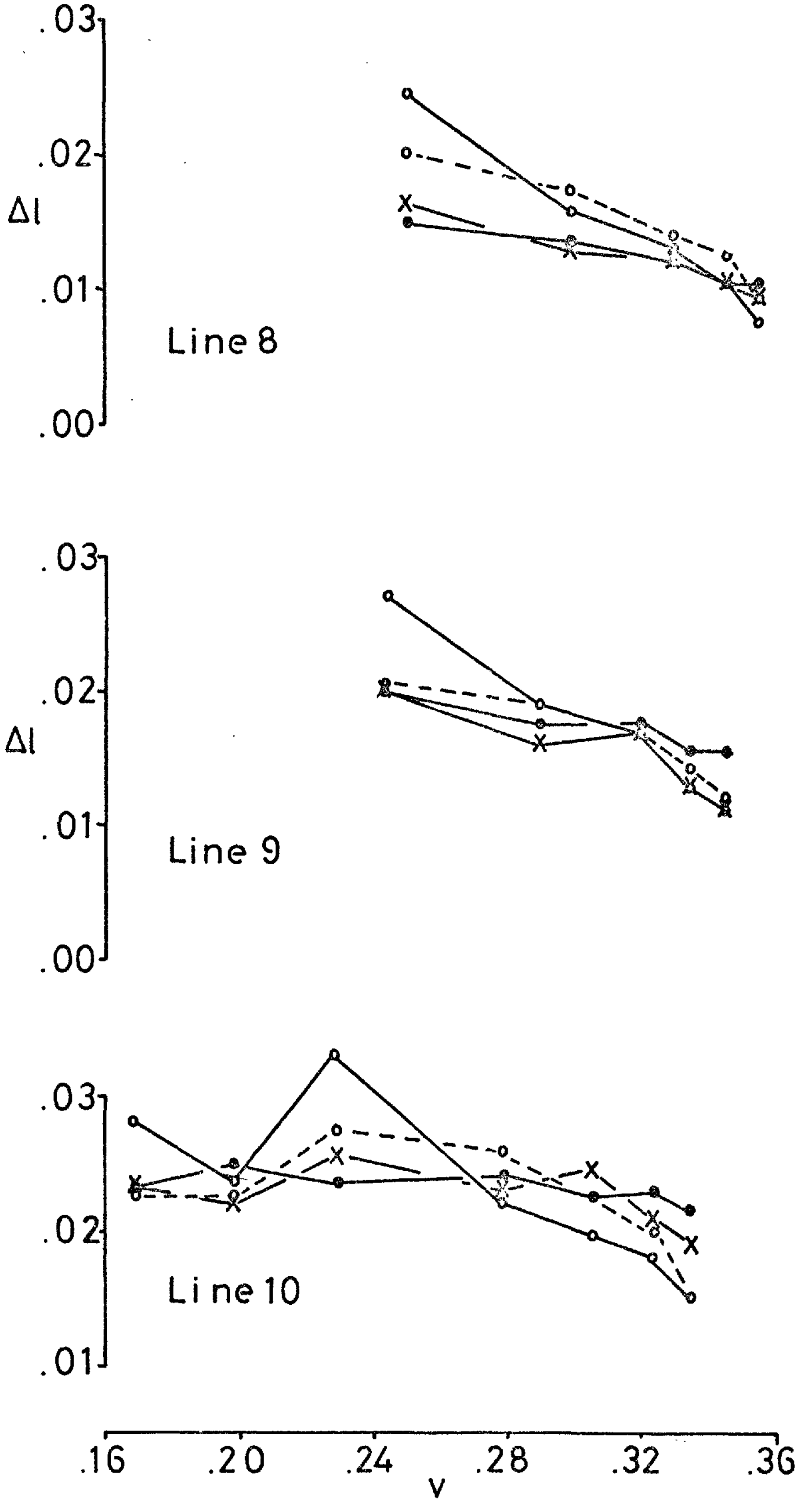
Fig 6.17


.03
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ΔI
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.36
V

Fig 6.18

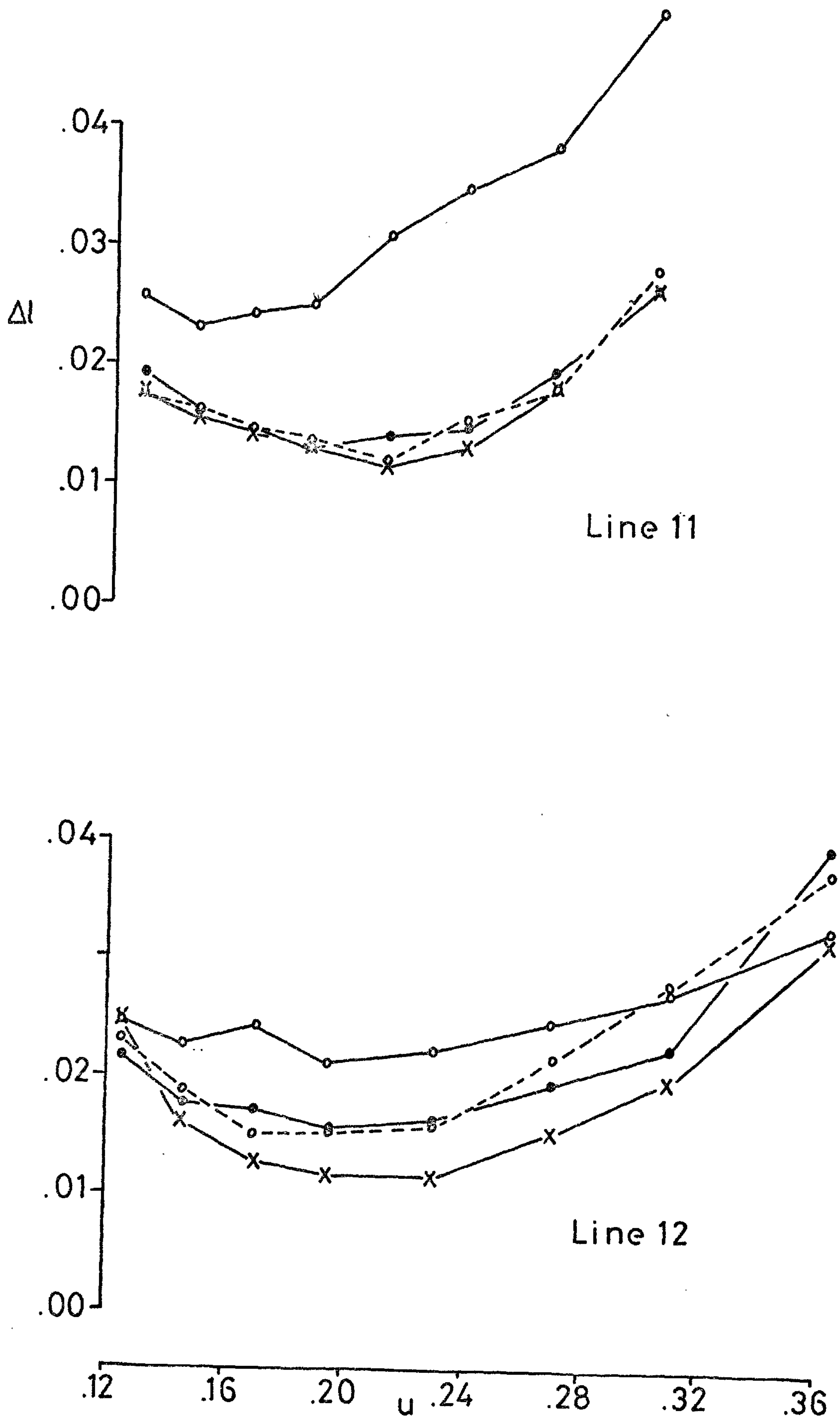
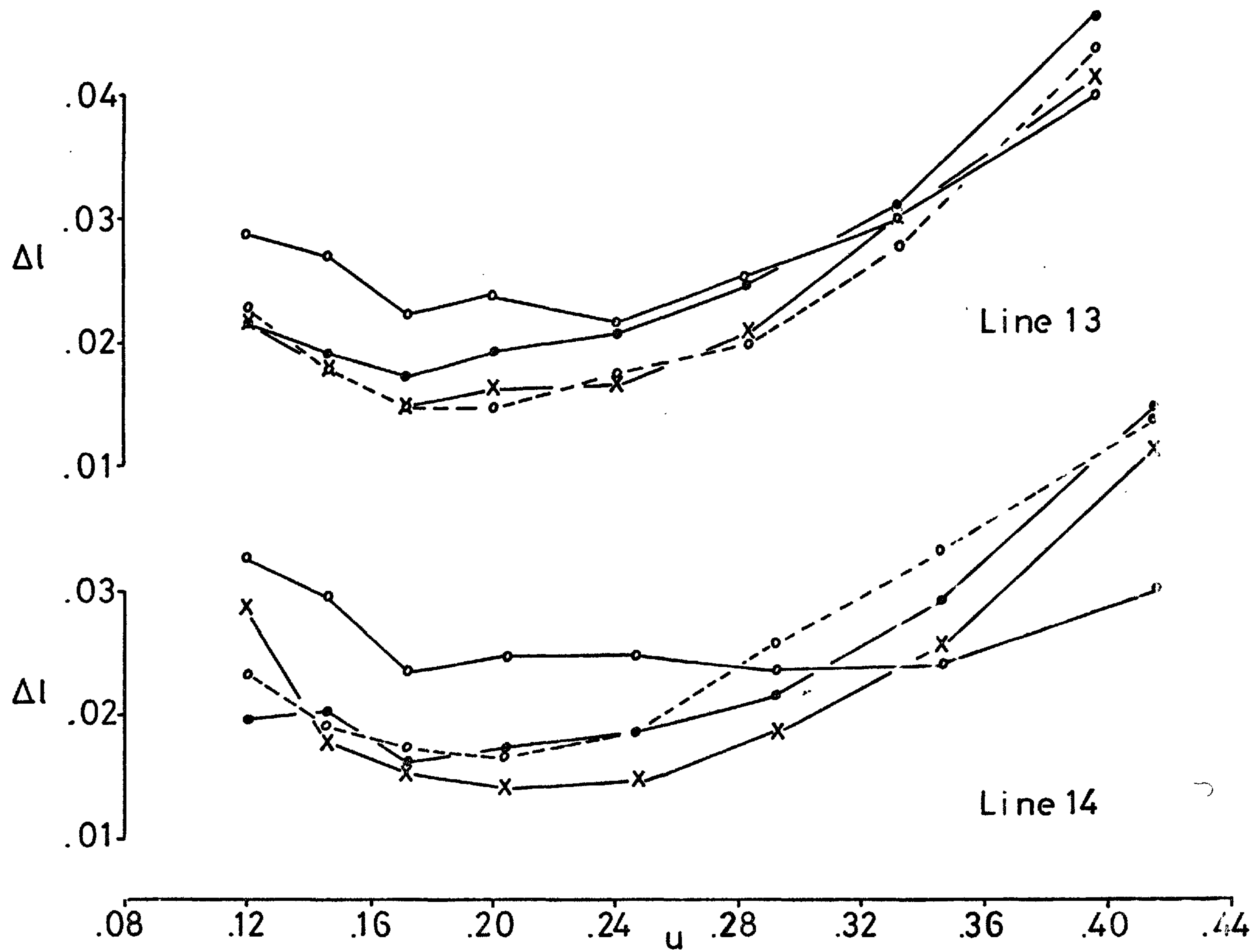


Fig 6.19


.04
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Δl
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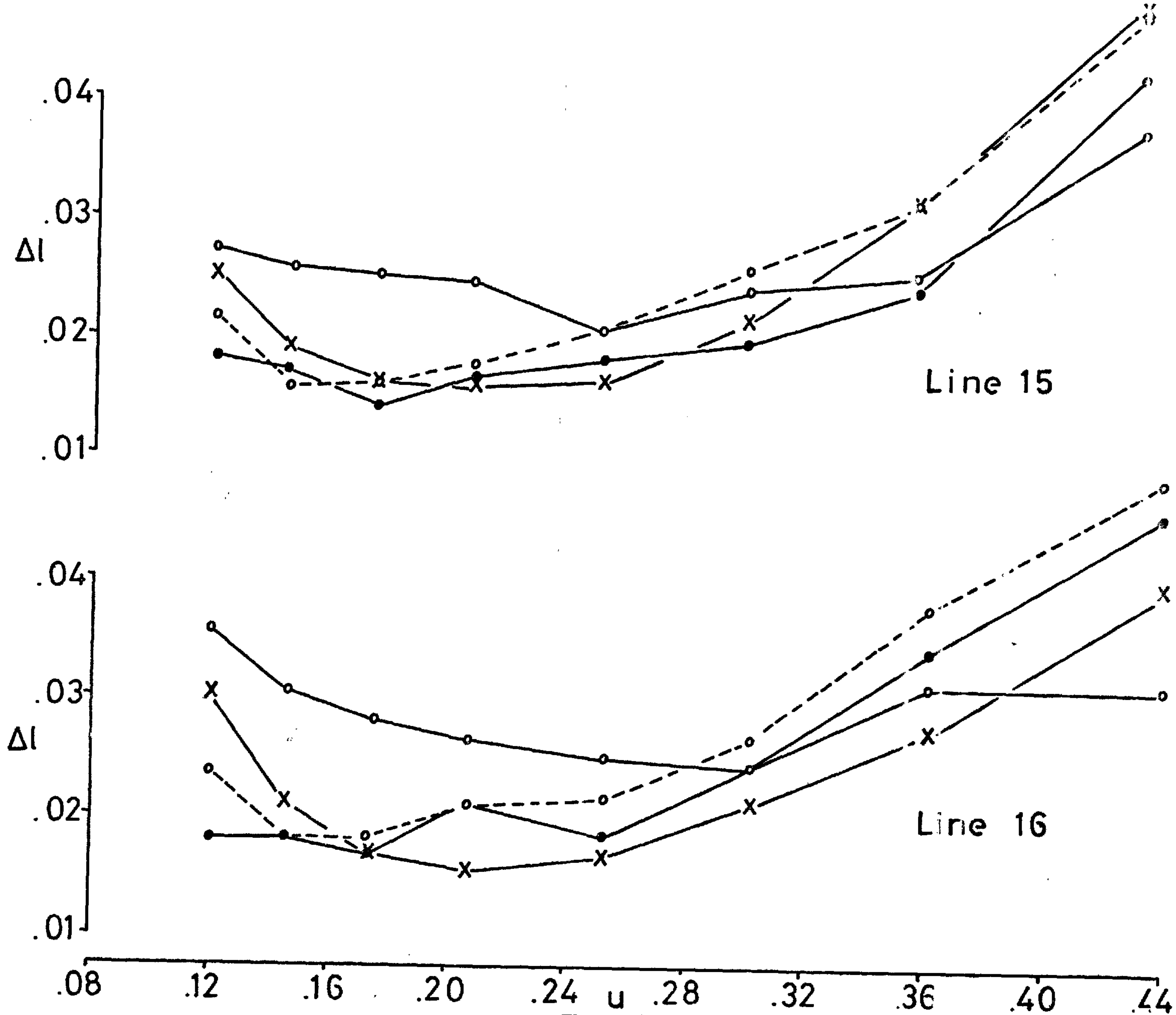
Fig 6.20



.04
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.32
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.40
.44

Fig 6.21

approaches that of the adaptation colour. Here the discrimination step became smaller than that obtained with green or blue adaptation and smaller than that of the mean white adaptation. The discrimination step size is usually smallest, and hence the discrimination most sensitive, for the blue adaptation. For colours involving a mixture of red-green and blue it is smaller than the step size obtained from the mean white data. For the blue adaptation there is a significant decrease in step size as the chromaticity of the test colour approaches that of the adaptation. This effect was present for the green adaptation and the step size dropped below that obtained from the mean white data in the green corner of the chromaticity diagram.

However, the overall shape of the curves for lines 11 to 16 for the individual sets of data was such that there was a definite minimum in the central region of the chromaticity diagram. This was also true for the various white light adaptations.

6.5 Comparison with Previous Data

The largest set of data with which comparison can be made is that of Brown (1952). The main feature of his results, which were similar in many respects to those of the author, was that discrimination was best when the test field had the same chromaticity as the adaptation or surround field. However, Brown found that the highest overall sensitivity was obtained with a red surround whereas a red surround gave the lowest relative sensitivity in the author's results. This ambiguity is possibly explained by the fact that Brown was using a statistical analysis of many colour matches and not the direct observation of the just noticeable colour difference as his criterion. Also he used only one red test colour and this had the same chromaticity as the surround providing the adaptation. The author's white light adaptation results showed that the power of discrimination was better for higher colour temperature adaptations, which were more blue in appearance, than the low colour temperature adaptations. On these grounds it might be expected that a pure blue adaptation would give more sensitive discrimination than pure red adaptation.

Brown obtained the best discrimination for a pure green test field with a dark surround, and similarly for the blue test field. This is in agreement with the general trends of the author's results. The poorest discrimination for a red test field was obtained with a blue surround, for a green test field with a blue surround and for a blue test field with a green surround. This was also in general agreement with the results obtained by the author although for a blue test field a red surround generally gave poorer discrimination. For a white test field the best discrimination was given by having a dark surround and the poorest discrimination with a blue surround. The former is true for the author's results but not the latter.

MacAdam (1955) also reported that the overall effect of the power of chromatic discrimination being maximum when the colour of the surround is close to being equal in chromaticity to the discriminated colours.

6.6 The Spread of the Results

It is difficult to place any meaning on the spread in the results due to the nature of the experimental observations. The spread for the coloured adaptations was similar to that obtained with the white light adaptations. Whereas with the white light adaptations it was easier to make observations with desaturated test colours, with the coloured adaptations it was easier to make observations when the surround and the test fields had very similar chromaticities.

However, the spread of the readings obtained with dark adaptation was slightly less than that obtained with the white light adaptations. This agrees with the finding that just noticeable difference observations are generally harder to make with saturated test colours and a white surround than with desaturated test colours and a dark surround. This is the effect of simultaneous contrast which has already been observed. The colour with a dark surround has the same chromaticity as when it is viewed with a white surround but it will appear relatively desaturated. This also appears to make just noticeable difference measurements in colour easier to make with a good degree of consistency.

Chapter 7

Uniformity of Chromaticity Diagrams and Colour Appearance

7.1 The Ideal Uniform Chromaticity Diagram

It would be very convenient if a uniform chromaticity diagram could be devised on which a given distance from any point and in any direction always corresponded to an equal subjective colour step. This is not true of the 1931 CIE chromaticity diagram since its aim was to describe colour matching data in a convenient way and no thought was given at the time to the spacing of colours on it. One of the major uses of a Uniform Chromaticity Scale Diagram (UCS Diagram) would be to simplify the specification of colour tolerances allowing a tolerance to be expressed, in the simplest case, as the radius of a circle drawn about the required point on the UCS Diagram. It would simplify the interpretation of colour errors in industrial processes if equal distances on the diagram always referred to the same subjective error.

The concept of the equality of distance on the Diagram and the subjective colour difference cannot be the whole story because it is not possible to lay down all the criteria mathematically. This is because, in industrial manufacturing or processing, colour differences in one direction may be judged to have more weight than those in another. Thus even though the colour differences may be equal in size they are not necessarily equal in importance. An example of this is in colour photography, where it is recognised that the eye will accept differences in saturation but relatively smaller differences in hue will cause a print to be rejected as not being a faithful reproduction.(Hunt, 1967).

7.2 Practical Uniform Chromaticity Scale Diagrams

Present evidence is that observers' judgments of differences in chromaticity do not accurately satisfy the requirements for constructing an ideal uniform scaling system; the limited accuracy with which visual assessment can be measured, the variation of criteria defining what is just noticeable to different observers, the variety of viewing conditions and the varied uses to which the uniform scale would be put, do not really justify a complex scaling system. Of the so-called Uniform Chromaticity Scale Diagrams devised so far each constructor has managed to devise a scaling system that is best suited to his own purposes. This is an obvious approach and its use is not to be shunned.

However, Silberstein (1943), using the results of MacAdam's investigation into visual sensitivity (MacAdam. 1942), has given a rigorous mathematical proof that no linear transformation of the 1931 CIE x,y chromaticity diagram can exactly represent small visually perceived colour intervals in an equal way. The geometry of colour space is almost certainly not Euclidian. However, it is wrong to conclude that a Euclidian approximation to uniform colour scaling is of no practical use.

The 1960 CIE u,v chromaticity diagram was originally developed as a uniform representation of colours by MacAdam (1937). It is based on earlier theoretical work by Judd (1935) which in turn is based on the experimental work of several workers (reviewed by Judd, 1963). It has the advantage that it is a linear transformation of the 1931 x,y coordinate system and that the transformation coefficients are all simple integers.

One reason for objecting to the use of the u,v coordinate system as a uniform system is that the corresponding chromaticity diagram gives a rather distorted mapping of colours. In particular the colours in the yellow-orange region of the diagram are very cramped compared with the blue-magenta region. It would appear from the author's experimental work that giving more space to the yellow colours and less to the blue-magenta colours would improve the linearity of the discrimination data. This would, however, distort the diagram and probably lead to a non-linear transformation. Recent work carried out by the Optical Society of America Committee on Uniform Colour Scales to find loci of constant saturation has shown that such a locus, when plotted in the u,v chromaticity diagram, bears a remarkable resemblance to a circle. The work involved assessing painted chips viewed in daylight against a grey background, and one hundred observers took part. These observing conditions were considered to correspond most closely to those encountered in industry and thus it can be concluded that the 1960 u,v chromaticity diagram provides a uniform chromaticity spacing for industrial applications and for samples viewed by reflection. This does not seem to be true for self-luminous samples.

Several attempts have been made to find, by a non-linear transformation, a coordinate system that would yield essentially the same chromaticity spacing as that provided by the coloured chips used in the Munsell Atlas. The most popular transformation of this type is that known as the Adams Chromatic Value System. (Adams, 1942). This system has been accepted in a slightly modified form by the Colour Measurement Committee representing the British textile industry. (McLaren and Coates, 1971). It yields a very uniform spacing of colours which agrees very well with the Munsell spacing.

7.3 The Adams Chromatic Value Diagram

In the Adams Chromatic Value transformation the relation between the tristimulus value Y of samples which are equally spaced in lightness and their corresponding Munsell value V are used to derive a function $(V_x - V_y)$ which is then plotted against a similar function $0{\cdot}4(V_z - V_y)$ where the Munsell value is defined by the quintic equation:-

$$Y_c = 1{\cdot}2219V_y - 0{\cdot}23111V_y^2 + 0{\cdot}23951V_y^3 - 0{\cdot}021009V_y^4 + 0{\cdot}0008404V_y^5$$

This was shortened by Ladd and Pinney (1955) to become:-

$$V_y = 2{\cdot}468\ Y_c^{\frac{1}{3}} - 1{\cdot}636$$

Where:-

V_x is the Munsell value found from the Munsell value function by substituting X_c for Y_c and V_x for V_y.

V_z is the Munsell value found from the Munsell value function by substituting Z_c for Y_c and V_z for V_y.

X_c is the ratio X/X_s.

Y_c is the ratio Y/Y_s.

Z_c is the ratio Z/Z_s.

X_s, Y_s, Z_s are the tristimulus values of the source. This transformation is such that the point representing the source is at the origin of the diagram. The colours radiate out from the origin with increasing saturation. Figure 7.1 shows the position of the principle hue planes.

The author's results for the discrimination experiments taken using daylight (6500°K) and tungsten light (2856°K) adaptation were transformed to the Adams Chromatic Value System and the results are shown in Figure 7.2 (daylight) and Figure 7.3 (tungsten light). These graphs show an improvement in the uniformity of the lines representing the just noticeable colour differences. The ratio of the length of the longest line to the length of the shortest line is about 3:1 which is an improvement on the value of 7:1 obtained with the u,v chromaticity diagram. The overall effect of a decrease in discrimination with increasing saturation is again shown in these diagrams.

7.4 Uniformity and Appearance

As has already been stated the 1960 u,v chromaticity diagram, which has been used to present the results of the discrimination experiments, was only defined by the CIE for comparison of differences between object colours of the same size and shape viewed in identical white to middle grey surroundings. The observer was to be adapted to a field whose chromaticity approximately represented daylight. However, results for adaptations other than daylight have been plotted using the u,v chromaticity system. While it is not incorrect to represent the data in this way and then draw comparisons between different sets of data, it is only

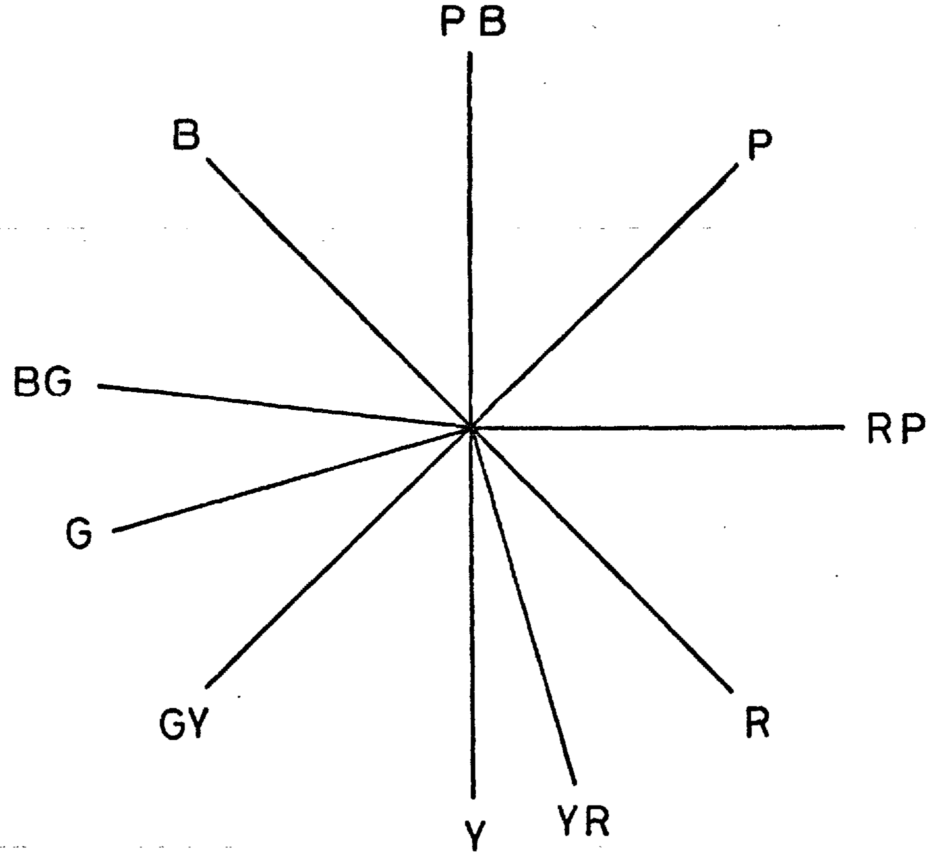


Fig 7.1

The Position of Hue Planes

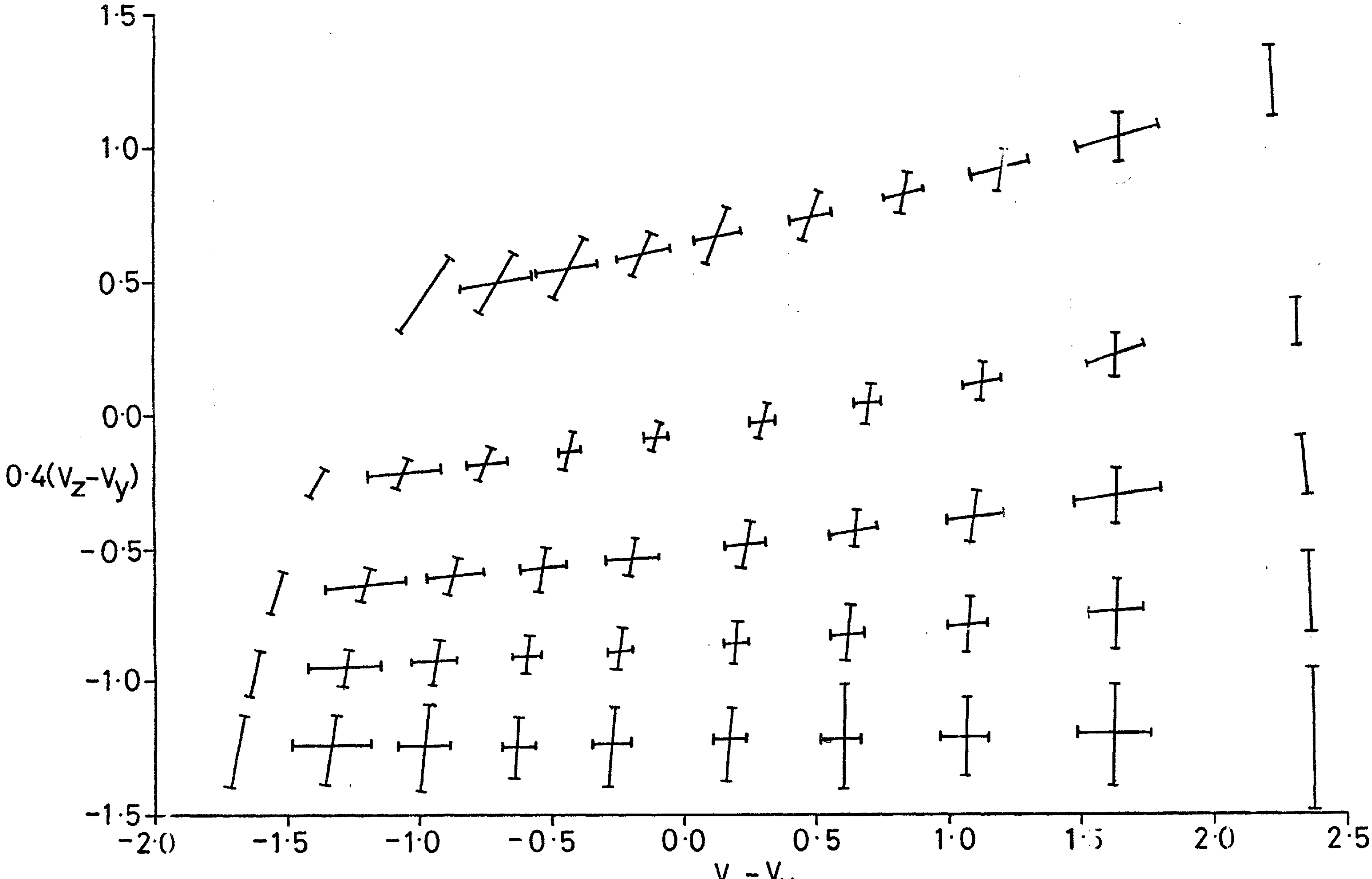


Fig 7.2 Adams Chromatic Value Diagram – 6500°K. Adaptation

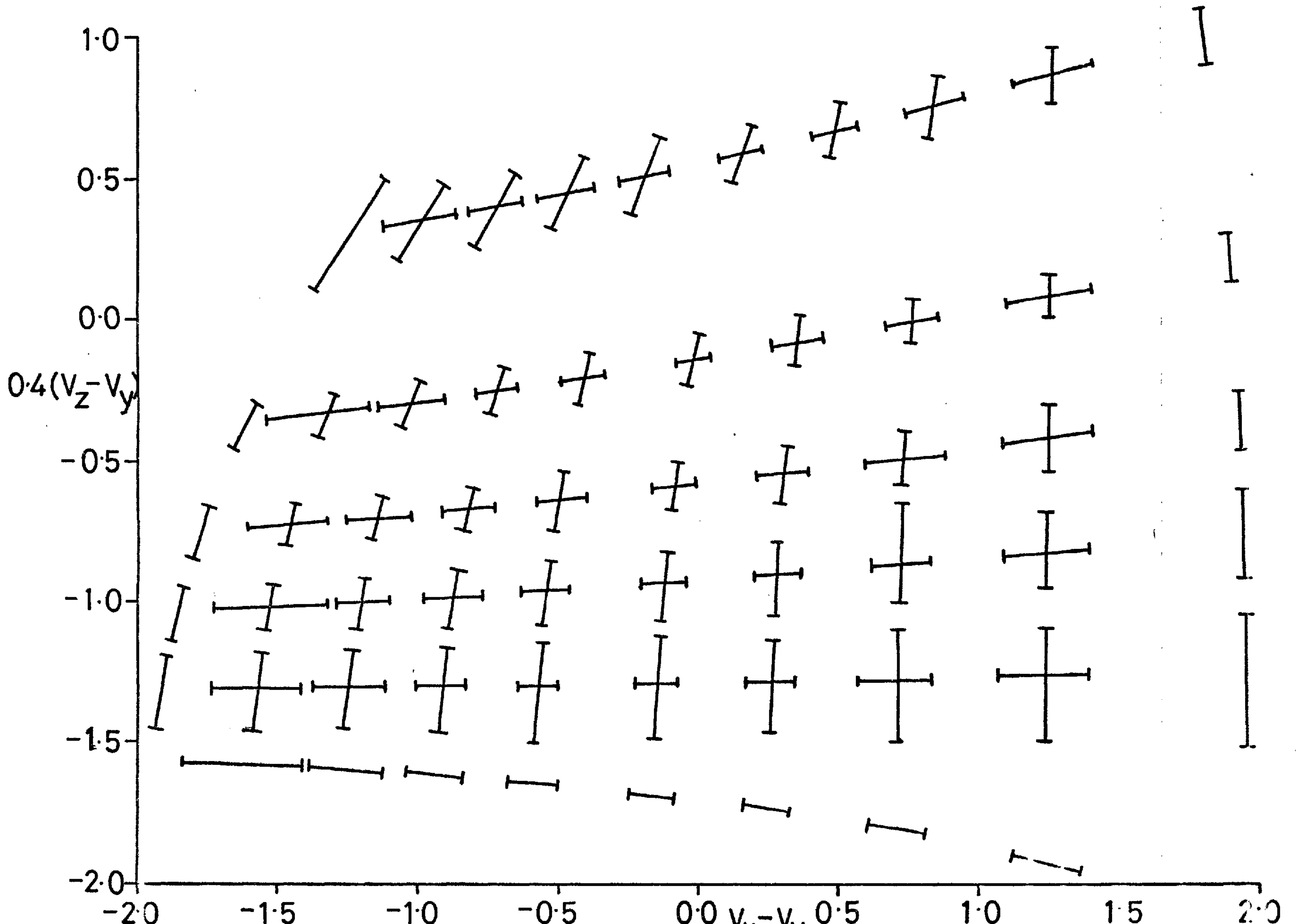


Fig 7.3 Adams Chromatic Value Diagram – 2856°K. Adaptation

correct to compare the uniformity of the different sets of data with that obtained using a daylight adaptation. It is not possible, within the terms of the definition of the u,v chromaticity diagram, to state any conclusions about the absolute uniformity of any particular set of data other than that obtained using daylight adaptation.

One of the most important properties of the human visual system is its ability to maintain the same overall image even though the composition of the light that enters the eye changes over quite a large range. A practical example of this is that of a coloured slide taken of an outdoor scene in bright sunlight and projected in a darkened room by a projector with a tungsten lamp. Both the illumination and the surround viewing conditions are very different but the average amateur photographer considers that he is able to judge the slide to be a good or bad reproduction of the original scene. If, however, it were possible to place the slide and the corresponding original scene side by side a large difference between corresponding colours would be seen. A similar effect, that does not rely so much on colour memory, can be observed in passing from natural daylight to a room illuminated by incandescent lamp. Objects that reflect green light in daylight will appear to reflect a yellow-green light in tungsten light; purple objects will now appear to reflect more red light. This change in perceived colour does not, however, appear to apply to the object. We recognise that the illuminant has changed from being relatively blue to a red-yellow and perceive that the object colour has changed relative to this; i.e., green or purple just as it was in daylight. This is an effect known as colour constancy.

After a small length of time our visual system is able to adapt to the new illuminating conditions and the yellow-green light seen at first reflected from the green object in the tungsten light will revert back to appearing green. Similarly the purple object that appeared more red will revert to looking purple.

The length of time involved for this effect to take place is the subject of much discussion. Experiment shows that the adaptation process is relatively slow but natural observation dictates that it must be almost instantaneous. For example, a white object viewed under sodium street lighting immediately looks white when it is seen on coming out of a house although the illuminating source is virtually monochromatic. It appears that there may be some psychological influence speeding up the formation of the visual image. This may be especially true if the observer is also aware of the colour of the object in daylight.

The adaptation process is not, however, complete. There remains a residual colour shift which is not accounted for. The size of this shift depends on the illumination change and the particular colours involved. Thus, generally, colours will look slightly more red under tungsten illumination compared with their appearance under daylight or, vice versa, will look slightly more blue when viewed under daylight compared with tungsten light.

The resultant colour shift perceived after adaptation to the chromatic illumination can be considered to have two components:-

i) A colorimetric shift which is due to the change in the spectral composition of the light reflected from the sample.

ii) The adaptive shift which is caused solely by the chromatic adaptation and usually shows a general tendency towards the original colour perceived.

Thus, if we wish to talk about the uniformity of the discrimination data, taken under any adaptation other than daylight, in absolute terms the effect of colour appearance shifts must be taken into consideration. The data that should be plotted in the u,v chromaticity diagram are not the data as observed under the chromatic adaptation but the data observed and then corrected to give their relative appearance in daylight adaptation. The data plotted in this way can then be discussed in terms of absolute uniformity since they are complying with the definition of the use of the u,v chromaticity diagram.

7.5 The Measurement of Colour Appearance Shifts

By using simple conditions of illumination and observation it is possible to measure the resultant colour appearance shift and express it in terms of, for example, chromaticity coordinates or Munsell notation. There are three basic methods of measuring the appearance shifts: the memory method, the binocular method and the method of local adaptation.

The memory method was used in an extensive study by Helson, Judd and Warren (1952). The observer first had to learn how to describe surface colours, which were Munsell chips, in terms of hue, lightness and saturation, corresponding to Munsell hue, Munsell value and Munsell chroma. After practice the observer memorised hue, lightness and saturation scales and was then able to describe, with reasonable accuracy, the colour of any object he might perceive. The observer then viewed a set of Munsell chips illuminated with the various chromatic lights in turn after his eyes had been adapted to daylight. He was asked to describe the colour he saw in terms of the scales that he had memorised. Typical results are illustrated in Figure 7.4. Results are shown for six observers viewing samples illuminated firstly with Standard Illuminant S_C and then with light corresponding to Standard Illuminant S_A. The arrows go from the points representing the samples as judged by the observer in S_C illumination to the point representing the sample in S_A illumination. The samples were viewed against a white or grey background representing extremes of reflectance. The results showed that the change in background gave colour appearance shifts as great as those due to the change from daylight to tungsten illumination. The overall results showed that definite colour shifts do occur when the illuminant is changed. These shifts were greatest for the red-purple colours, and for some very desaturated colours (low Munsell chroma) the shifts were nearly non-existent.

A slightly different memory method of measurement was used by Sproson (1953). He was interested in finding the area on the chromaticity diagram which represented colours accepted as white by the average observer, and also in determining the effects of tungsten and daylight adaptation on this area. The white point has considerable importance in the field of colour television since it is used to determine the colour balance of the overall television picture. The observers were asked to make a white using two controls of a tricolorimeter, the third control being fixed. Using red, green and blue controls as the fixed control in turn

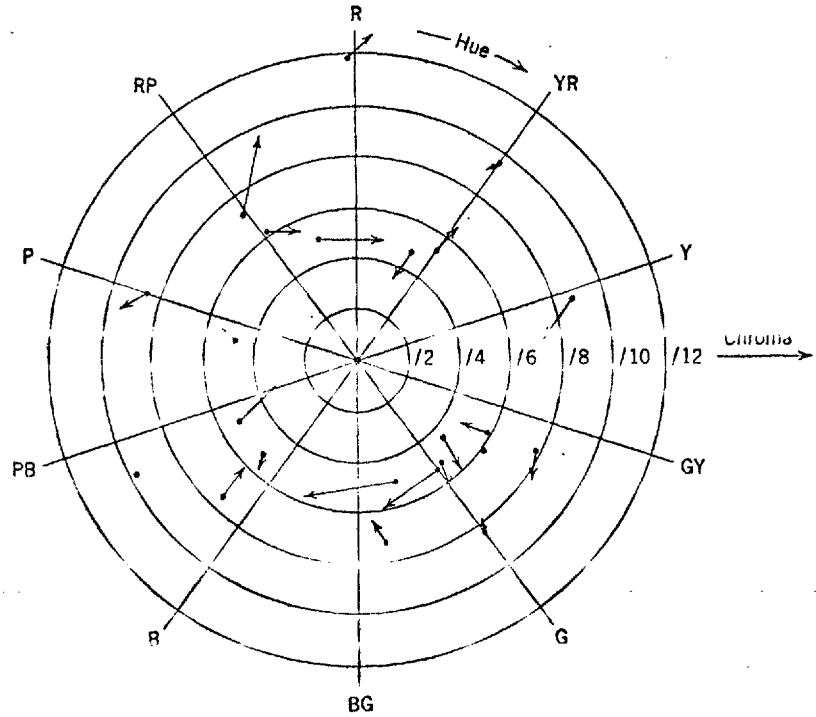


Fig 7.4 (from Helson, Judd & Warren, 1952)

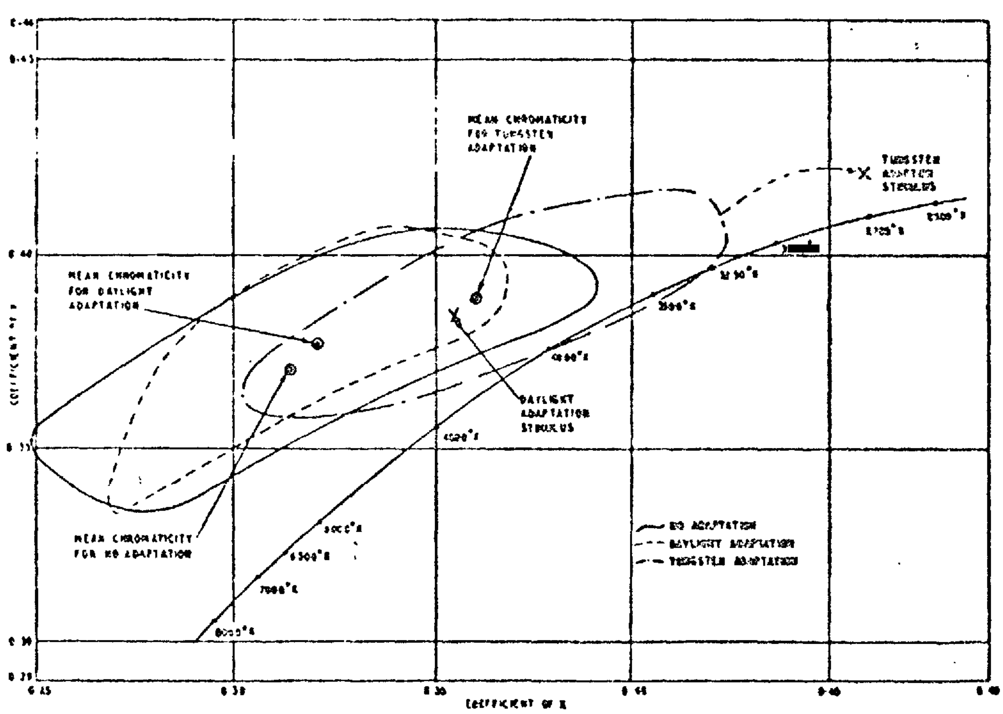


Fig 7.5 (from Sproson, 1953)

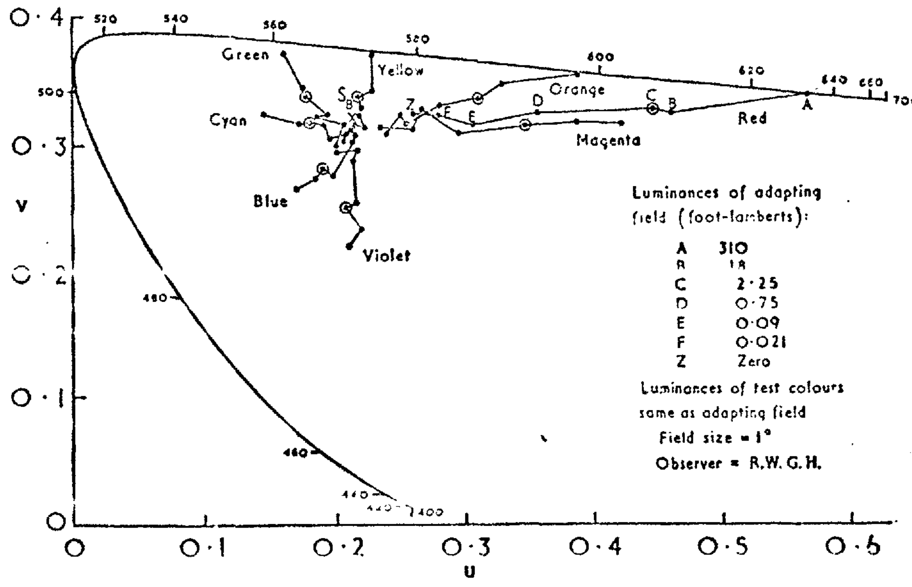
gave three sets of readings for the chromaticity that the observer considered white. The adaptation was then changed and three more sets of readings taken. The mean results for the twelve observers are shown plotted in the x,y chromaticity diagram in Figure 7.5. These results show the characteristic shift towards the blue region for daylight adaptation relative to tungsten adaptation. It is also interesting to note that the observers showed a greater sensitivity to changes in the green-magenta direction compared with changes in the direction of the black body locus.

The binocular septum matching method for the observing of adaptation processes in the eye was pioneered by Wright in his early investigation into the foveal adaptation process. (Wright, 1934, 1936). In this method one test field is viewed by the left eye and another by the right eye. The two stimuli are displaced vertically such that horizontal binocular convergence assures that the two coloured patches are perceived one above the other and separated by a small gap. The fields are located in the middle of a surround field.

A determination of pairs of aperture colours which appear the same with adaptation to tungsten light and artificial daylight was made by Burnham, Evans and Newhall (1952) using this binocular technique. The two test fields were matched with both eyes adapted to the same illuminant and then the match re-established with one eye adapted to a different illuminant. Plots of the data obtained, in terms of x,y chromaticity coordinates, indicate a systematic shift in colour appearance when the adaptation was changed from daylight to tungsten light. An important distinction must be drawn between aperture colours and surface colours. The colour appearance change in aperture colours is primarily the result of modification of the sensitivities of the retinal receptors, whereas with surface colours the energy distribution of the stimulus also changes.

Hunt (1949, 1950) used the binocular matching technique to study the effects of daylight and tungsten adaptation on the saturation and hue of aperture colours. The results showed that there appeared to be a marked increase in the saturation of the test colours when the adaptation was changed from a dark to a light surround. The effect was further investigated (Hunt, 1952, 1953) using an improved version of the earlier colorimeter which provided test fields of 20 degrees and one degree both with a 60 degree adapting field. Various effects were investigated including the effect of the change in intensity level of the adapting light. Binocular matches for eight different test colours were obtained with the left eye adapted in turn to seven different intensity levels, while the right eye was adapted to a constant level of illumination. The results are shown in Figure 7.6 for an intensity range of 1200 ft.candles(A) to 0·1 ft.candles(F). The lines joining the results are for identification purposes only.

Winch and Young (1951) report the changes in colour appearance of a series of dyed material swatches using Standard Illuminants A, B and C. They also give results using adaptations produced by fluorescent tubes of five different colour temperatures that were intermediate between those of daylight and tungsten light illumination. They used a binocular matching technique, the swatches being presented to the left eye and a field produced by a tricolorimeter being



Variation in the appearance of eight different test colours as the adapting luminance is varied from 310 foot-lamberts (outer points, A) to zero (inner points, Z). Intermediate levels (in foot-lamberts) 18, 2.25, 0.75, 0.09, and 0.021 (Hunt, 1952 and 1953). If the average reflectance of a typical scene is taken as 25 per cent, these luminance levels are approximately equivalent to the following levels of illumination in foot-candles (ft.-c.):

A. 1200 ft.-c.: cloudy daylight or operating theatre.
B. 70 ft.-c.: dull daylight or drawing office.
C. 10 ft.-c.: twilight or corridors.
D. 3.0 ft.-c.: twilight or good street lighting.
E. 0.4 ft.-c.: poor street-lighting.
F. 0.1 ft.-c.: ten-times full moonlight.

Fig 7.6 (from Hunt, 1967)

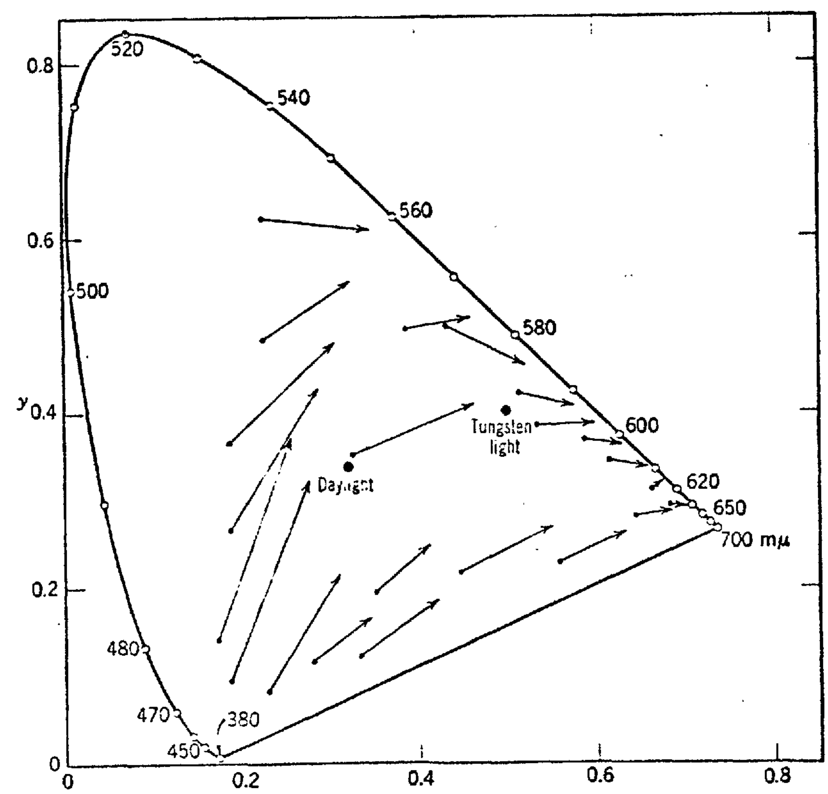


Fig 7.7 (from MacAdam, 1956)

presented to the right eye. The results show that the colour shifts for the fluorescent tube adaptations fall inbetween those obtained for the Standard Illuminants as would be expected from previous work.

Similar experiments were conducted by Wassef (1955) using Munsell chip samples illuminated by Standard Illuminant A, B or C. However, in this case Munsell samples were also used to make the match. These matching chips were illuminated by Standard Illuminant A. This use of fixed reference conditions enabled a comparison to be made between the results obtained for the various illuminants. The principle results showed that the changes in the colour appearance of different hues under either illuminant C or B were similar in that the directions of change were consistent but that there was a variation in the magnitude of the change. The results suggested that there might be a hue in the blue region of colour space which does not change its colour when seen under illumination corresponding to Standard Illuminant A, B or C as long as the sample is viewed against a white background.

The local adaptation method involves using a tristimulus colorimeter. The two halves of the colour comparison field are filled with different adapting lights. Every ten seconds, and for one second only, the two adapting lights are replaced by a test colour in one half of the field and an additive mixture of the three primary lights in the other half of the field. The observer fixates on the centre line dividing the two halves of the field with both eyes and adjusts the controls of the colorimeter to obtain a colour match between the two halves. This can usually be obtained after a few cycles of the presentation of the test and mixture fields. This method of observation was used by MacAdam (1956) who determined the appearance shifts of twenty-two test colours when the adaptation was changed from daylight to tungsten illumination. Two observers were used and the results for one of the observers are shown in Figure 7.7. Each vector shows the change in chromaticity required to maintain a colour match between the two colorimetric fields when one part of the central retina was adapted to daylight illumination and an adjacent part of the retina to tungsten illumination.

These results, representative of those obtained by different investigators, show similar trends in colour appearance shifts when the adaptive state of the eye is changed, no matter which method of observation is used. There are, however, some discrepancies between different sets of results. The majority of experimental work done in the past has involved measuring the colour appearance shifts observed on changing the colour temperature of the adapting light from daylight to tungsten light, although Burnham, Evans and Newhall (1957) used a green adaptation and MacAdam (1956) used several coloured adaptations.

However, no method of measurement is perfect and all three can be held open to criticism. The memory method relies on the training and temperament of the observer, both of which are immeasurable qualities. The binocular matching method assumes that there is no transfer of information between the two eyes that could affect the match made by the observer. Similarly the local adaptation method assumes that there is no transfer of information between adjacent parts of the retina that would affect the colour match. Factors such as the field size, the luminance or reflectance of the samples and their surround and the differences between individual observers are other factors that could explain some of the differences between different sets of results.

7.6 The Mathematics of Colour Appearance

The simplest formula for predicting the change of appearance of test colours when the adaptation is changed is that based on the von Kries coefficient law. This in turn is based on the Young-Helmholtz theory of colour vision.

Briefly, this theory postulates that, as well as rod receptors used in twilight vision, there are three types of cone receptors used for colour vision. Each type is characterised by a particular spectral response function that is correlated with one of the three fundamental colour sensations, namely red, green and blue (or possibly violet), and all visual sensations are compounded of varying amounts of the responses from these three excitory systems. The resulting sensation of colour is a function of the relative values of the three responses and the resulting sensation of brightness is a function of the linear combination of the three responses.

This theory is derived directly from the basic trichromatic data of colour matching, i.e. that all visible hues can be matched by suitable proportions of only three stimuli. To explain the effects of adaptation von Kries further postulated that, although the responses of the three cone mechanisms would be affected by the chromatic adaptation in a different way, the relative spectral sensitivity of each cone mechanism would remain unchanged. Using the fact that there are three fundamental primaries corresponding to the three cone mechanisms the von Kries hypothesis may be stated as follows: 'The tristimulus values of all colours, expressed in terms of the fundamental primaries of the Young-Helmholtz theory, for one adaptive state of the eye bear fixed ratios to the corresponding tristimulus values of the visually equivalent colours observed under another adaptive state of the eye.' (Judd, 1963)

This can be summed up by the equation:-

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = K \begin{pmatrix} R \\ G \\ B \end{pmatrix} \qquad 7.1$$

where R, G, B are the tristimulus values of the colour as perceived under the original adapting light.

R', G', B' are the tristimulus values of the colour as perceived under another adapting light.

K is a third order diagonal matrix, the coefficients of which are the von Kries coefficients corresponding to the reduction in sensitivity of the three cone mechanisms due to the change in adaptation.

The tristimulus values R, G, B can be related to the CIE tristimulus values X, Y, Z by a three-by-three linear matrix A:-

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = A \begin{pmatrix} R \\ G \\ B \end{pmatrix} \qquad 7.2$$

Inversely:-

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = A^{-1} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad 7.3$$

Similarly for another adaptation:-

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = A \begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} \qquad 7.4$$

Substituting for R', G', B' from equation 7.1 and using the result of equation 7.3 gives:-

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = M \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad 7.5$$

where M is a three-by-three matrix given by:-

$$M = A\,K\,A^{-1} \qquad 7.6$$

Thus we have an equation that relates the CIE tristimulus values before and after a change in adaptation by a matrix M. The matrix M may be found in two ways. The practical way is to obtain the X, Y, Z and corresponding X', Y', Z' tristimulus values for at least three colours. This gives a set of nine equations which can be solved to give the coefficients of the matrix M. The alternative theoretical method is to consider the components of the matrix M as defined by equation 7.6. The coefficients of the matrix A can be found by adopting a particular set of fundamental primaries. The set adopted by many workers is the so-called P, D, T primaries due to Judd. However, as outlined by Terstiege (1971), there exists at least twenty-six different sets of fundamental primaries. Most workers agree on the position of the red and the blue primary but there is much controversy as to the position of the green primary.

To find the coefficients of the matrix K requires a knowledge of at least one pair of corresponding colours. When appearance changes corresponding to a change of adaptation from tungsten light to daylight are being considered a convenient pair of corresponding colours can be the two adapting lights whose tristimulus values are usually known. Experiment shows that spectrally non-selective objects are perceived closely as grey by an observer adapted to a chromatic light even if the adapting light is quite different from daylight quality (Helson and Michels, 1948). Thus it is safe to assume without serious error that colour constancy holds strictly for spectrally non-selective objects.

The tristimulus values of the pair of corresponding colours are converted into their respective fundamental values using equation 7.3. Let these values be K_r, K_g, K_b before the change of adaptation and K_r', K_g', K_b' after the change in adaptation respectively. The coefficients of the matrix K are then given by:-

$$K = \begin{pmatrix} K_r/K_r' & & \\ & K_g/K_g' & \\ & & K_b/K_b' \end{pmatrix} \quad 7.7$$

The agreement between the observed colour shifts and those predicted on the basis of colour theory is by no means perfect but Helson, Judd and Warren (1952), using Munsell samples, found good general agreement between the predicted and observed values of the colour appearance shifts. Burnham, Evans and Newhall (1957) compared the predicted colour appearance shifts with those measured by a binocular matching technique and found that there were some differences between the two sets of data. However, the predictive errors were small compared with the variation in repeated instrument matches which were several times the predictive error. Burnham (1959) compared the predictions of Burnham, Evans and Newhall (1957) with the experimental results of Wassef (1955). The results obtained in this comparison suggested that a linear adjustment might improve the fit of the data. Consequently a function of the difference in chromaticity coordinate between each pair was added to the Burnham, Evans and Newhall data to give a much better agreement with the Wassef data. Prediction equations were also derived from Wassef's data and the two sets of prediction equations then applied to a range of Munsell samples. Considering the great differences between the experimental technique and the different samples used to derive the equations the comparison was considered to be reasonably good.

Probably the most common use of the von Kries hypothesis has been an extension of the above experimental work to determine the fundamental response mechanisms. If valid, the hypothesis would reduce the problem of chromatic adaptation to determination of the way in which the coefficients of the K matrix, defined by equation 7.1, depend on the experimental adaptation conditions.

Most quantitative work has shown that, even if the hypothesis is not perfect, it is capable of predicting qualitatively the kind of changes of perceived colours due to adaptational changes. MacAdam (1961) postulated a non-linear hypothesis to try to overcome some of the discrepancies between theoretical predictions and experimental results. The basis of his theory is a non-linear relationship between the tristimulus values of the perceived colour and the fundamental primaries of the visual system which is given in the form of a power law, each of the three cone mechanisms being governed by a different exponent which is dependent on the adaptation.

7.7 The u,v Chromaticty Diagram and Colour Appearance Shifts

Ouweltjes (1965, 1969), in considering the colour rendering properties of light sources of various colour temperatures, again points out the limitation of the u,v chromaticity diagram to use as a means of representing data observed in daylight conditions only. Figure 7.8 shows the chromaticity coordinates of eight Munsell samples plotted in the u,v chromaticity diagram. They are plotted in two ways; firstly as direct Munsell renotation (for daylight illumination as defined in Stiles and Wyszecki, 1967) and then with the Munsell renotation corrected to give the relative appearance under tungsten illumination. This correction

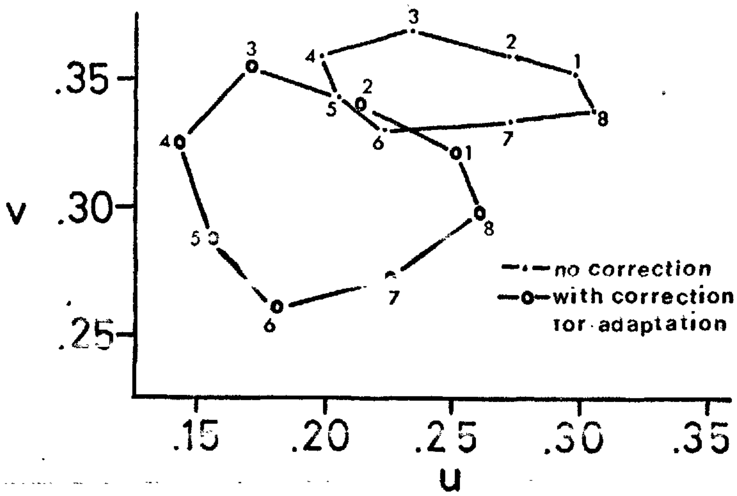


Fig 7.8 (Ouweltjes,1965)

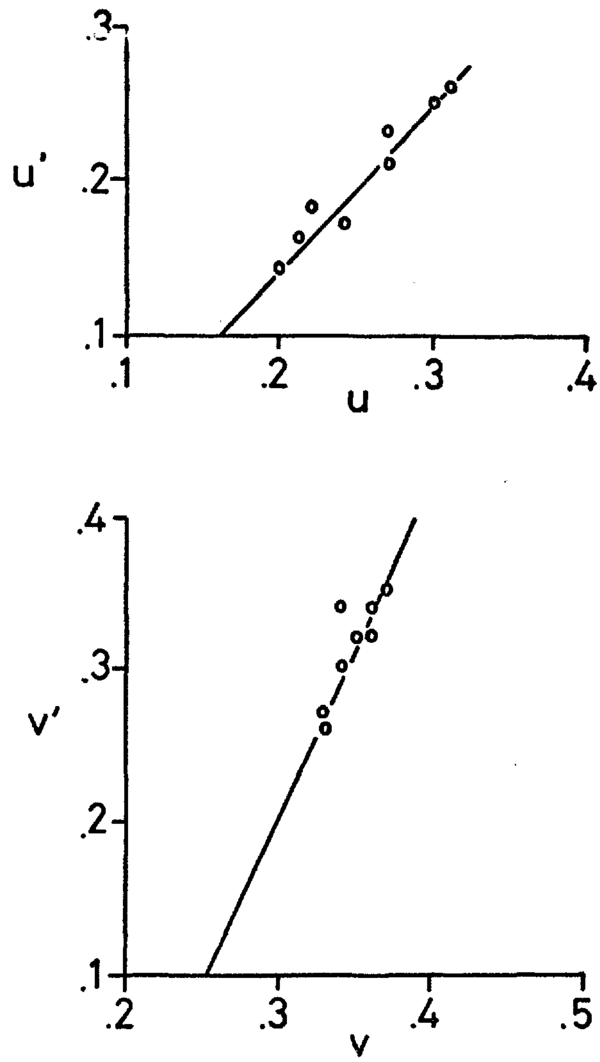


Fig 7.9

The Chromaticity Coordinates Before and After Appearance Transformation was obtained by using a transformation of the von Kries type and the Judd P, D, T primaries. The coordinates in daylight are u,v and the coordinates after transformation to tungsten light are u', v'. The data is shown again in Figure 7.9 plotted in a different way. The u coordinate before transformation is plotted as a function of the u coordinate after transformation. A similar graph is plotted for the v coordinate. Two straight line graphs are obtained, the first having a gradient of approximately unity and the second having a gradient of approximately two. The respective intercepts are c_1 and c_2, i.e.:-

$$u' = 1{\cdot}0u + c_1$$
$$v' = 2{\cdot}0v + c_2$$

This implies that, in considering colour differences under tungsten illumination, values of Δv, the change in the v chromaticity coordinate, should be about twice those calculated for daylight illumination, whereas values of Δu, the change in the u chromaticity coordinate, remain the same.

This may be considered in another way. If the usual u,v chromaticity diagram is used to represent colour differences as observed in daylight illumination, then to represent similar differences as observed in tungsten illumination it is required that the v axis of the diagram, the ordinate, has its scale compressed by a factor of two. (Ouweltjes, 1971).

Chapter 8

The Observation and Measurement of Colour Appearance Shifts

8.1 Introduction

It would be possible to assess the uniformity of the discrimination data obtained under an adaptation with a colour temperature other than that corresponding to daylight by measuring or calculating the colour appearance shifts of the sampling points used in the discrimination experiments. The perceived colour shifts observed when the adaptation is changed to daylight enable the results to be plotted in the u,v chromaticity diagram and the data to be considered in terms of absolute uniformity within the definition of the u,v chromaticity diagram.

The author's apparatus was modified to allow such measurements to be made using the binocular matching technique. The results of the observations were analysed statistically to give a three-by-three linear matrix that could be applied to the discrimination data to transform it to its relative daylight appearance. This involved transforming the sampling points and the chromaticity coordinates of the end points of the bars representing the just noticeable colour differences to enable the length of the bar to be calculated under the different adaptation.

8.2 Modifications to the Apparatus

The basic modification that had to be made to the apparatus was to remove the reference field from the field of view of the right eye and place it so that it could be seen with the left eye.

An adaptation field also had to be built to provide adaptation for the left eye.

A plan of the complete, modified apparatus is shown in Figure 8.1. The plan of the right hand side of the apparatus is the same as before. The source S_1 provides the standard field via some heat absorbing glass G_1, collimating lens L_1, filter pack F_1, aperture A_1, focussing lens L_1', neutral density wedge N and optical integrating bar I_1. The mirror M_1 had to be remade with only one hole passing through its centre at 45 degrees to the surface to provide the 1·6 degree standard field. The adaptation field was provided by the source S_3, mirror M_2, heat absorbing glass G_3, mirror box I_3, colour temperature conversion filter F_3, mirror M_1 and prism P. The mounting of the conversion filter F_3 was modified so that the filter could be changed conveniently. The two filters corresponding to the adaptation under test and to daylight were taped together and suspended in front of the mirror box I_3 by a wire. The wire was run up to a pulley fixed to the ceiling of the room and then down to a crank handle. By turning the handle one revolution the filters could be raised or lowered and hence the colour temperature or colour of the adaptation changed.

The reference field was provided by source S_2, heat absorbing glass G_2, collimating lens L_2, filter pack F_2, aperture A_2, focussing lens L_2' and fibre optic light pipe LP_2. The other end of the light pipe LP_1 was butt jointed to a 'Perspex' optical integrating bar I_2. This optical integrating bar was similar in construction to the integrating bar I_1. The reference field adaptation surround was provided by source S_4, light from which

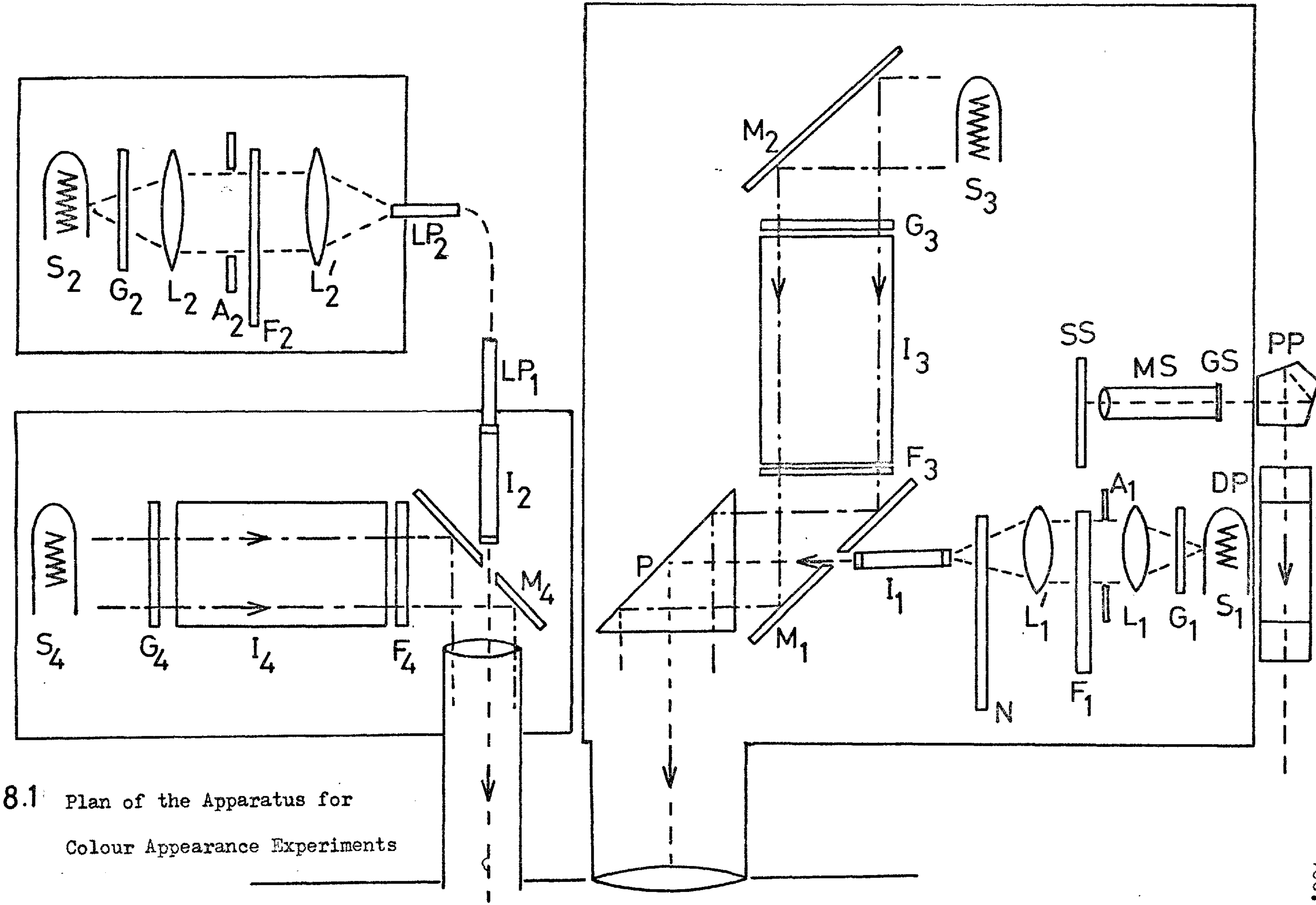


Fig 8.1 Plan of the Apparatus for Colour Appearance Experiments

passed through several strips of heat absorbing glass G_4 into a mirror box I_4. This mirror box was similar in construction to the other mirror box I_3. The source was a 240 Volt, 250 Watt projector lamp of the tungsten type run via a rheostat that enabled the applied voltage, and hence the brightness of the lamp, to be controlled. Thus the two adaptation fields could be matched for brightness. The lamp was coolled by a fan mounted immediately behind it.

The filters F_4 were used to change the colour or colour temperature of the lamp and were of similar construction to the filters F_3. The surround was viewed with the left eye via an aluminium mirror M_4 which had a small hole in the centre similar to the mirror M_1. This permitted the viewing of the end of the optical integrating bar I_2. The left eyepiece consisted of a simple telescope. This was necessary to make the two surround fields appear to be the same distance away from the observer. All the apparatus for the new surround field was contained in a metal box mounted on a small table whose height was adjustable. The complete field of view is shown in Figure 8.2. The reference and standard field subtended 1·6 degrees at the eye and each had a 15 degree surround adapting field. The areas beyond this were black. The two eyepieces were surrounded by a large piece of cardboard, sprayed matt black, that also formed a hood over the observer to shield his eyes from the stray light coming from the apparatus. It was no longer possible to record the observations using the left eye because it was now being used to make a colour match. As adaptation no longer had to be maintained it was more convenient to read the instrument scale from outside

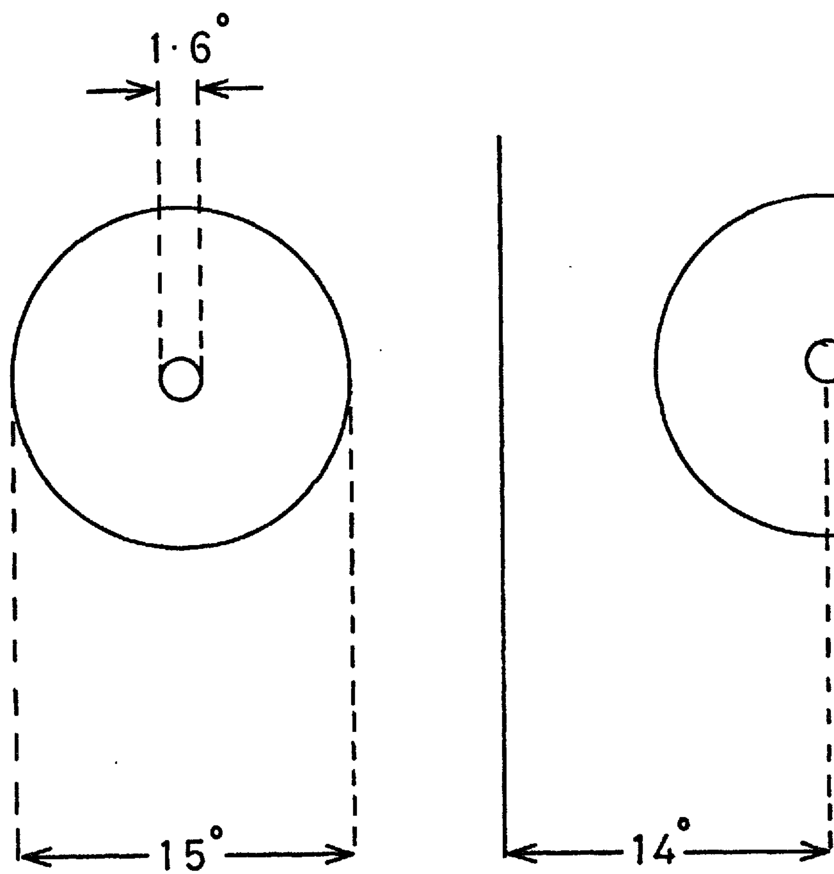


Fig 8.2

Field of View

the box, as before, but from the right hand side of the apparatus and not the left. As shown in Figure 8.1 the microscope MS was used to focus an inverted image of the scale SS that was attached to the filter assembly on to a piece of ground glass GS which had a set of cross-wires engraved on it. The image was then reflected through 90 degrees using a penta prism PP. This prevented lateral inversion of the image by utilizing a double reflection. A dove prism DP was then used to re-invert the image so that the scale could be read in its correct form.

No further calibration of the apparatus was necessary.

8.3 Experimental Procedure

The filters F_3 and F_4 were selected to give the required adaptation and the filter that gave simulated daylight was attached to the bottom of the filter F_3. The brightness of the left adaptation field was then matched to the brightness of the right adaptation field by adjusting the voltage applied to the source S_4. Since the filters F_3 and F_4 were similar in construction the colour temperature of each surround field ought to be similar when the brightness of each field is the same. This was easily checked by manouvering the two fields so that they could be seen side by side and checking that their respective colours matched.

All observations were made by the author. Each observing session commenced with a period of ten minutes dark adaptation. The observer then set the controls of the standard field filter assembly to give the required test colour. The colours used as test colours were those corresponding to the intersection points of the grid of lines 1 to 16 used in the discrimination experiments.

Only colours which fell within the colour triangle were used because a preliminary study had shown that there was often great difficulty in matching the saturated colours that lay on the colour triangle. This gave an array of forty test colours whose u,v chromaticity coordinates are shown tabulated in Figure 8.3. The numbers of the corresponding lines are also shown in this Figure.

With similar adaptation for both the right and left eyes the colour of the reference field was matched to that of the test colour in the standard field. The technique used for matching was slightly different from that usually applied in binocular matching experiments. The separation of the eye-pieces on the apparatus, about 28 degrees as shown in Figure 8.2, was greater than the interocular separation. This meant that, when the direction of gaze of the observer was directed to the right hand field, the left eye saw the black surround of the fields. Similarly when the observer's gaze was directed towards the left hand field, using the left eye, the right eye saw the black surround of the two fields. Thus by moving the head from side to side the observer was able to view the two fields alternately. This method of observation tended to create the impression that the two fields were located side by side with very little separation. It also ensured that the viewing of the standard and reference fields was by intermittent glancing. This decreased the likelihood of after images and local adaptation effects occuring. The reason for choosing this method of observation was a practical one in that the two fields could not be brought close enough together to enable them to be seen at the same time, without considerable

Row		2	3	4	5	6	7	8	9
15	U =	0.1202	0.1453	0.1736	0.2055	0.2499	0.2977	0.3544	0.4296
	V =	0.3778	0.3753	0.3725	0.3693	0.3648	0.3600	0.3543	0.3468
14		0.1212	0.1456	0.1729	0.2036	0.2460	0.2915	0.3450	0.4153
		0.3699	0.3670	0.3637	0.3601	0.3551	0.3497	0.3434	0.3350
13		0.1227	0.1460	0.1719	0.2008	0.2405	0.2827	0.3318	0.3956
		0.3583	0.3549	0.3512	0.3470	0.3412	0.3352	0.3281	0.3188
12		0.1252	0.1466	0.1701	0.1961	0.2314	0.2682	0.3103	0.3639
		0.3381	0.3341	0.3296	0.3247	0.3180	0.3110	0.3031	0.2929
11		0.1310	0.1480	0.1663	0.1861	0.2121	0.2385	0.2676	0.3031
		0.2928	0.2879	0.2827	0.2769	0.2694	0.2618	0.2534	0.2431

Fig 8.3 Chromaticity Coordinates of the Forty Test Colours

rebuilding of the casing of the apparatus and repositioning of some of the optical components. One of the observers used by Hunt in his colour appearance investigations used this technique and two other observers used a more normal technique whereby a shutter was rotated in front of the two fields so that the observer saw the fields alternately without moving his head. Each field was viewed for about ten seconds. Hunt did not think that the results obtained by the observers using these two methods differed significantly.(Hunt, 1964).

When the two fields had been matched for colour the adaptation of the right hand field was changed by inserting the filter simulating daylight adaptation. A shift in colour appearance was observed between the two fields. The controls of the standard field were then used to re-establish the match and the scale position recorded. The tape recorder was again used to record the readings in order that the room lights need not be put on. The adaptation of the right eye was then changed back again and the controls of the standard field set to the next test colours. The appearance shifts of all forty test colours were measured in one session of about two-and-a-half hours duration. The appearance shift of each test colour was measured five times spread over five separate observing sessions, the colours being taken in a different order in each session.

8.4 Analysis of the Results

The calculations involved in the analysis of the results and in the conversion of the discrimination data were made using an IBM 7094 computer with a programme written by the author. The appearance shift of each test colour relative to daylight adaptation had been measured five times for each initial adaptation used. The corresponding instrument readings were converted into tristimulus values using the equations:-

$$X = R.X_r + G.X_g + B.X_b$$

$$Y = R.Y_r + G.Y_g + B.Y_b$$

$$Z = R.Z_r + G.Z_g + B.Z_b$$

where the terms are as defined in Section 3.2.
From these values an average set of tristimulus values, X', Y', Z', was found. The tristimulus values of the initial test colour, X, Y, Z, were also found. These computations continued for each test colour to give two arrays of tristimulus values representing the test colours before and after the observation of the colour appearance shift respectively.

A method of least squares was then applied to these corresponding pairs of tristimulus values to find the coefficients of the matrix M as defined by the equation 7.5. The coefficients of the matrix M are:-

$$M = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix}$$

The values of the coefficients m_{11}, m_{12}, and m_{13} are found as solutions to the following equations:-

$$(\Sigma X_i \cdot X_i) \cdot m_{11} + (\Sigma X_i \cdot Y_i) \cdot m_{12} + (\Sigma X_i \cdot Z_i) \cdot m_{13} = \Sigma X_i' \cdot X_i$$

$$(\Sigma Y_i \cdot X_i) \cdot m_{11} + (\Sigma Y_i \cdot Y_i) \cdot m_{12} + (\Sigma Y_i \cdot Z_i) \cdot m_{13} = \Sigma X_i' \cdot Y_i$$

$$(\Sigma Z_i \cdot X_i) \cdot m_{11} + (\Sigma Z_i \cdot Y_i) \cdot m_{12} + (\Sigma Z_i \cdot Z_i) \cdot m_{13} = \Sigma X_i' \cdot Z_i$$

where all the summations, Σ, are taken from $i = 1$ to $i = 40$, the number of test colours.

To find the values of the coefficients m_{21}, m_{22} and m_{23}, these quantities replaced m_{11}, m_{12} and m_{13} on the left hand sides of the equations and the right hand sides were replaced by $\Sigma Y_i' \cdot X_i$, $\Sigma Y_i' \cdot Y_i$ and $\Sigma Y_i' \cdot Z_i$ respectively.

The value of the coefficients m_{31}, m_{32} and m_{33} were found similarly, with $\Sigma Z_i' \cdot X_i$, $\Sigma Z_i' \cdot Y_i$ and $\Sigma Z_i' \cdot Z_i$ on the right hand sides of the equations respectively. This method of least squares is due to Brewer, 1954. The coefficients of the matrix M, which could be used to transform tristimulus values, were then transformed into an equivalent set of coefficients, b_j, where $j = 1$ to 9, which could be applied to chromaticity coordinates. These were given by:-

$$b_1 = m_{11} - m_{13}$$

$$b_2 = m_{12} - m_{13}$$

$$b_3 = m_{13}$$

$$b_4 = m_{21} - m_{23}$$

$$b_5 = m_{22} - m_{23}$$

$$b_6 = m_{23}$$

$$b_7 = (m_{11} + m_{21} + m_{31}) - (m_{13} + m_{23} + m_{33})$$

$$b_8 = (m_{12} + m_{22} + m_{32}) - (m_{13} + m_{23} + m_{33})$$

$$b_9 = (m_{13} + m_{23} + m_{33})$$

The corresponding transformation equations are:-

$$x' = \frac{b_1.x + b_2.y + b_3}{b_7.x + b_8.y + b_9}$$

$$y' = \frac{b_4.x + b_5.y + b_6}{b_7.x + b_8.y + b_9}$$

where x,y are the chromaticity coordinates of the test colour as seen under the test adaptation and x', y' are the chromaticity coordinates of the colour as seen under daylight adaptation.(Hunt, 1967).

This matrix was applied to the test colours to give a smoothed set of colour appearance shifts. It was then applied to the discrimination data to give the lengths of the lines representing just noticeable colour differences as measured under one adaptation but transformed to the size that they would appear to be under daylight adaptation. This process was complicated by the fact that only the lengths of the lines were known and not the coordinates of their end points. These coordinates had to be computed using a subroutine within the main programme. After appearance transformation the new length could be easily calculated.

Thus the results of a colour matching experiment under two different states of adaptation have been used to find a transformation matrix that can be applied to further experimental data.

Chapter 9

The Results of Colour Appearance Experiments I

9.1 Introduction

The main set of observations involved measuring the change in colour appearance of the test field when the surround was changed from giving tungsten adaptation to giving daylight adaptation. The matrix derived was applied to the discrimination data obtained using tungsten light adaptation to give a set of data corrected to its daylight appearance. This was then plotted in the u,v chromaticity diagram and compared with the discrimination data before transformation. Colour appearance changes of the test field were also observed when the surround was changed from giving dark adaptation to giving daylight adaptation.

9.2 Results for a Change from Tungsten Adaptation to Daylight Adaptation

The transformation matrix derived from the instrument readings was:-

$$M = \begin{pmatrix} 0{\cdot}963 & -0{\cdot}040 & 0{\cdot}078 \\ 0{\cdot}016 & 1{\cdot}037 & -0{\cdot}053 \\ 0{\cdot}026 & 0{\cdot}022 & 0{\cdot}951 \end{pmatrix}$$

This corresponds to a pair of transformation equations:-

$$x' = \frac{0{\cdot}885x - 0{\cdot}118y + 0{\cdot}078}{0{\cdot}029x + 0{\cdot}043y + 0{\cdot}976}$$

$$y' = \frac{0{\cdot}069x + 1{\cdot}090y - 0{\cdot}053}{0{\cdot}029x + 0{\cdot}043y + 0{\cdot}976} \qquad 9.1$$

where x', y' are the chromaticity coordinates of the test colour (in the XYZ system) corresponding to daylight adaptation and x,y are the chromaticity coordinates corresponding to tungsten adaptation.

This set of equations, after transfer to a corresponding set of u,v transformations, was applied to the array of test colours in Figure 8.3. The array of transformed chromaticity coordinates is shown tabulated in Figure 9.1. The two arrays of chromaticity coordinates are shown plotted in the u,v chromaticity diagram in Figure 9.2. This diagram shows the expected shifts in colour appearance when the illuminant or adaptation is changed from being yellow to being relatively blue.

By assuming a set of fundamental primaries, e.g. the Judd P, D, T set suggested by Judd(1963), and taking the adapting surrounds as a pair of complimentary colours, it is possible to calculate values for the three coefficients of the K matrix as defined by equation 7.1. Thus it is possible to predict the expected general changes in colour appearance.

Using the P, D, T primaries in Equation 7.3 gives:-

$$R = Y$$

$$G = -0{\cdot}46.X + 1{\cdot}367.Y + 0{\cdot}10.Z$$

$$B = Z$$

U=	0.1042	0.1275	0.1535	0.1828	0.2232	0.2667	0.3179	0.3853
V=	0.3777	0.3752	0.3724	0.3693	0.3649	0.3603	0.3547	0.3475
	0.1080	0.1308	0.1563	0.1849	0.2243	0.2663	0.3156	0.3709
	0.3701	0.3672	0.3640	0.3605	0.3555	0.3503	0.3441	0.3361
	0.1136	0.1358	0.1604	0.1880	0.2257	0.2657	0.3122	0.3723
	0.3587	0.3554	0.3517	0.3475	0.3419	0.3359	0.3289	0.3198
	0.1235	0.1445	0.1678	0.1935	0.2283	0.2648	0.3065	0.3596
	0.3385	0.3344	0.3299	0.3250	0.3182	0.3112	0.3031	0.2928
	0.1470	0.1651	0.1847	0.2059	0.2340	0.2626	0.2944	0.3334
	0.2907	0.2854	0.2798	0.2736	0.2655	0.2572	0.2481	0.2368

Fig 9.1

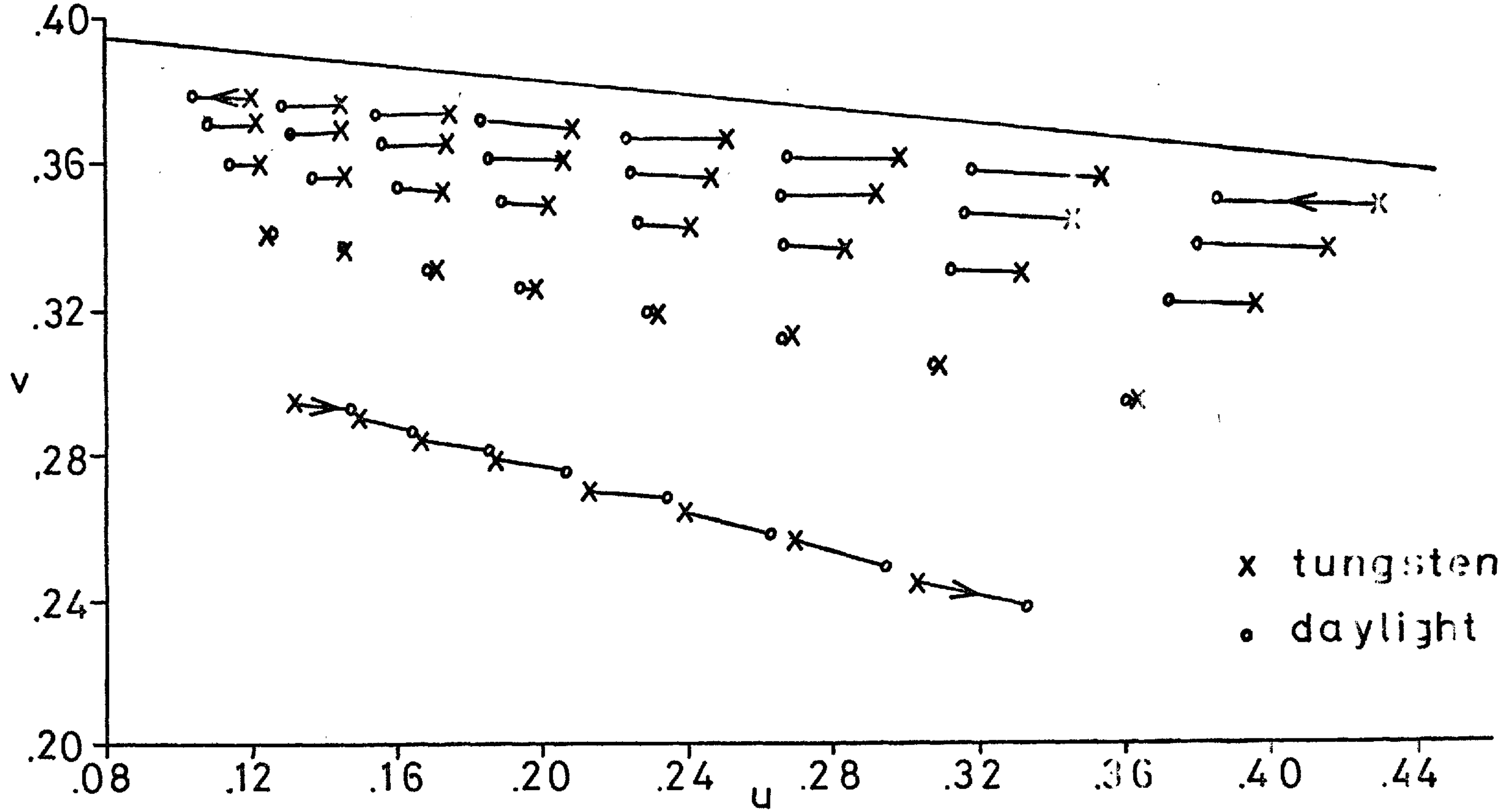


Fig 9.2 Colour Appearance Shifts

The tristimulus values of the CIE Standard Sources are given by Stiles and Wyszecki(1967) as:-

$$X_c = 0{\cdot}980 \qquad X_a = 1{\cdot}098$$

$$Y_c = 1{\cdot}000 \qquad Y_a = 1{\cdot}000$$

$$Z_c = 1{\cdot}181 \qquad Z_a = 0{\cdot}035$$

using the above equations for R, G and B with the notation defined by Equation 7.7. gives:-

$$K'_R = 1{\cdot}000 \qquad K_R = 1{\cdot}000$$

$$K'_G = 1{\cdot}027 \qquad K_G = 0{\cdot}089$$

$$K'_B = 1{\cdot}181 \qquad K_B = 0{\cdot}035$$

Therefore the matrix K is given by:-

$$K = \begin{pmatrix} 1{\cdot}000 & & \\ & 1{\cdot}150 & \\ & & 3{\cdot}330 \end{pmatrix}$$

Substituting into Equation 7.1 gives:-

$$R' = 1{\cdot}00R$$

$$G' = 1{\cdot}15G$$

$$B' = 3{\cdot}33B$$

This implies that, on changing adaptation from tungsten to daylight and assuming no relative change in the sensitivity of the red cone mechanism, there will be a slight increase in the sensitivity of the green cone mechanism and approximately a three-fold increase in the sensitivity of the blue cones.

Figure 9.2 shows that red colours move towards the orange region, yellow colours become slightly green, green colours become more saturated and blue colours move to the deep blue to magenta region of the chromaticity diagram. The overall effect is of a distortion of colour space, putting the point representing the chromaticity of the tungsten adaptation at the point representing the chromaticity of the daylight adaptation. Corresponding to this all the other colours are pulled round in a general anticlockwise direction.

The complete set of observations for the tungsten adaptation to daylight adaptation shift was repeated. The second set of results gave a matrix similar to the first:-

$$M = \begin{pmatrix} 0{\cdot}956 & -0{\cdot}024 & 0{\cdot}068 \\ 0{\cdot}019 & 1{\cdot}026 & -0{\cdot}045 \\ 0{\cdot}021 & -0{\cdot}001 & 0{\cdot}980 \end{pmatrix}$$

This corresponds to the transformation equations:-

$$x' = \frac{0{\cdot}888x - 0{\cdot}092y + 0{\cdot}068}{-0{\cdot}007x - 0{\cdot}001y + 1{\cdot}003}$$

$$y' = \frac{0{\cdot}064x + 1{\cdot}071y - 0{\cdot}045}{-0{\cdot}007x - 0{\cdot}001y + 1{\cdot}003}$$

The subsequent array of transformed test colours were found to be so similar to those shown in Figure 9.2 that it was not possible to plot them on the same diagram in a distinguishable way.

These results are in general agreement with those of previous workers and also agree with the results obtained by applying the matrix K and the P, D, T primaries used to give the theoretical matrix:-

$$M = \begin{pmatrix} 1{\cdot}154 & -0{\cdot}458 & 0{\cdot}473 \\ 0{\cdot}000 & 1{\cdot}000 & 0{\cdot}000 \\ 0{\cdot}000 & 0{\cdot}000 & 3{\cdot}327 \end{pmatrix}$$

This gives a corresponding set of transformation equations:-

$$x' = \frac{0{\cdot}681x - 0{\cdot}931y + 0{\cdot}473}{-2{\cdot}646x - 3{\cdot}258y + 3{\cdot}800}$$

$$y' = \frac{y}{-2{\cdot}646x - 3{\cdot}258y + 3{\cdot}800}$$

When applied to the chromaticity coordinates of the test colours the array of shifted coordinates shown in Figure 9.3 is obtained. These coordinates are shown plotted in the u,v chromaticity diagram in Figure 9.4.

u =	.0379	.0665	.0986	.1347	.1847	.2384	.3618	.3854
v =	.3637	.3608	.3576	.3540	.3490	.3437	.3374	.3290
	.0508	.0779	.1079	.1414	.1872	.2357	.2919	.3644
	.3398	.3360	.3317	.3269	.3203	.3134	.3053	.2949
	.0677	.0926	.1198	.1499	.1903	.2322	.2799	.3400
	.3088	.3039	.2985	.2926	.2847	.2764	.2670	.2552
	.0926	.1139	.1369	.1618	.1945	.2277	.2643	.3089
	.2630	.2573	.2511	.2444	.2356	.2266	.2167	.2047
	.1341	.1487	.1642	.1804	.2009	.2210	.2423	.2670
	.1869	.1813	.1755	.1694	.1616	.1540	.1460	.1366

Fig 9.3

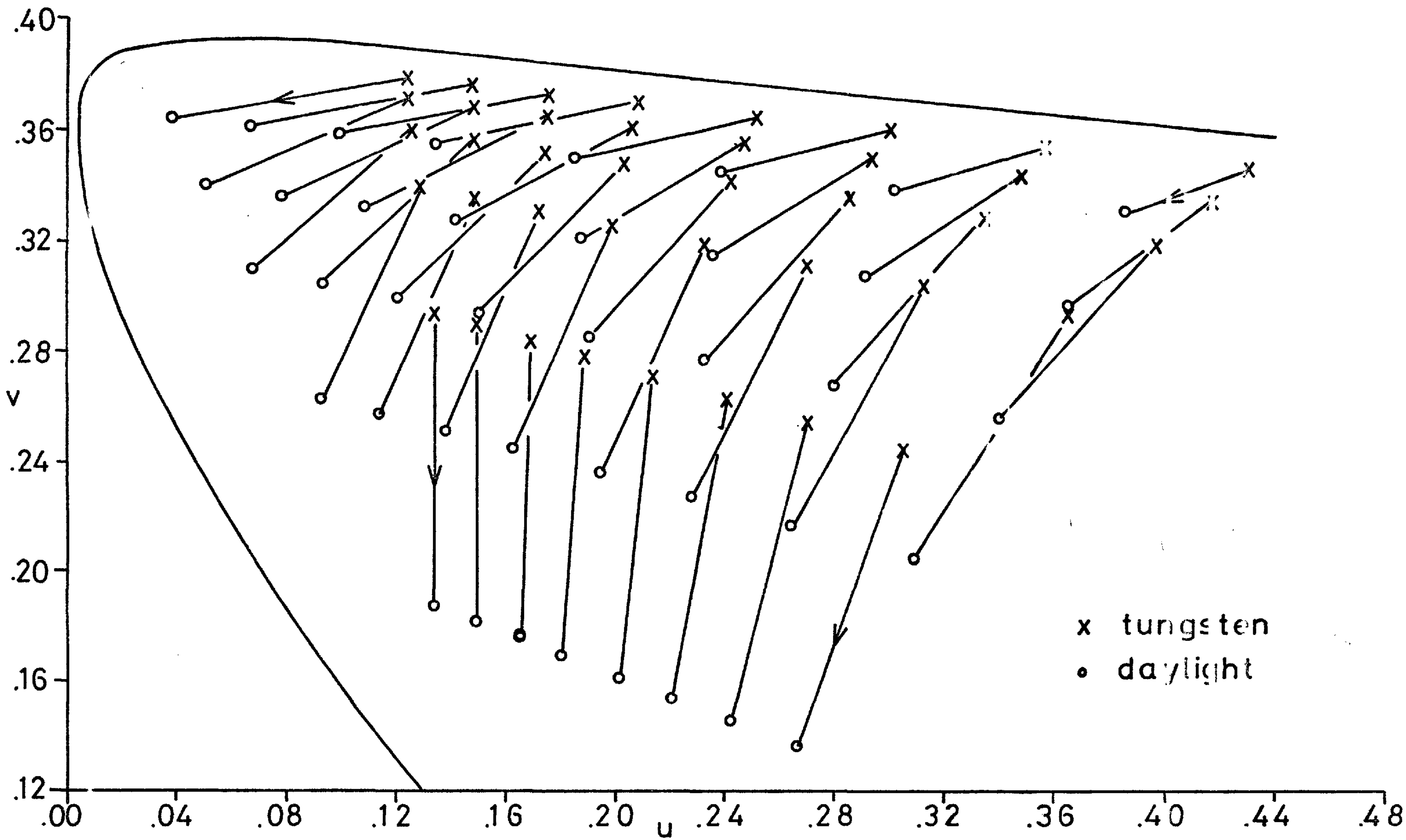


Fig 9.4 Theoretical Colour Appearance Shifts

9.3 Application to Discrimination Data

The transformation equations 9.1 were then applied to the discrimination data obtained with tungsten adaptation, and shown tabulated in Figure 5.4, to give the lengths of the lines representing just noticeable colour differences as they would appear in daylight adaptation. The resulting lengths are shown tabulated in Figure 9.5. As before, the rows of lengths for lines 1 to 10 give the results in descending order (from red-green to blue) and the rows for lines 11 to 18 give the results from left to right (from green-blue to red-blue). The lengths are shown plotted in the u,v chromaticity diagram in Figure 9.6.

It is now possible to assess the discrimination data in terms of absolute uniformity within the definition of the u,v chromaticity diagram. Figure 9.6 shows that the data are not uniform throughout the chromaticity diagram and the ratio of the length of the longest bar to the length of the shortest bar is about 7:1. This is, however, no worse than the corresponding ratio obtained from the same data before appearance transformation. It is also the same as the ratio obtained from the data observed under daylight adaptation conditions. The uniformity over the central region of the diagram, representing relatively desaturated colours, is considerably better than 7:1, being less than 2:1.

Figures 9.7 - 9.12 show the transformed results plotted in another form. The length of the line representing the just noticeable colour difference is plotted as a function of the v chromaticity coordinate of the sampling point for lines 1 to 10 and as a function of the u chromaticity coordinate of the sampling point for lines 11 to 16. The data for lines 17 and 18 are not

Tungsten (2856°K.) Adaptation

Line	ΔI							
Line 1	·007	·007	·009	·011	·034	·030	·057	
Line 2	·007	·006	·008	·010	·023			
Line 3	·006	·007	·007	·011	·022			
Line 4	·007	·008	·008	·011	·022	·026	·035	
Line 5	·008	·008	·010	·011	·022			
Line 6	·007	·008	·008	·011	·017			
Line 7	·007	·008	·010	·011	·016	·018	·024	
Line 8	·008	·009	·010	·010	·017			
Line 9	·008	·010	·012	·012	·017			
Line 10	·011	·014	·018	·017	·021	·019	·020	
Line 11	·020	·016	·016	·016	·013	·015	·020	·027
Line 12	·029	·020	·013	·013	·013	·018	·021	·034
Line 13	·019	·019	·015	·016	·017	·019	·031	·039
Line 14	·034	·017	·017	·015	·015	·019	·026	·039
Line 15	·023	·019	·015	·015	·016	·019	·031	·041
Line 16	·030	·021	·017	·016	·017	·020	·026	·034
Line 17	·013	·018						
Line 18	·015	·015						

Fig 9.5

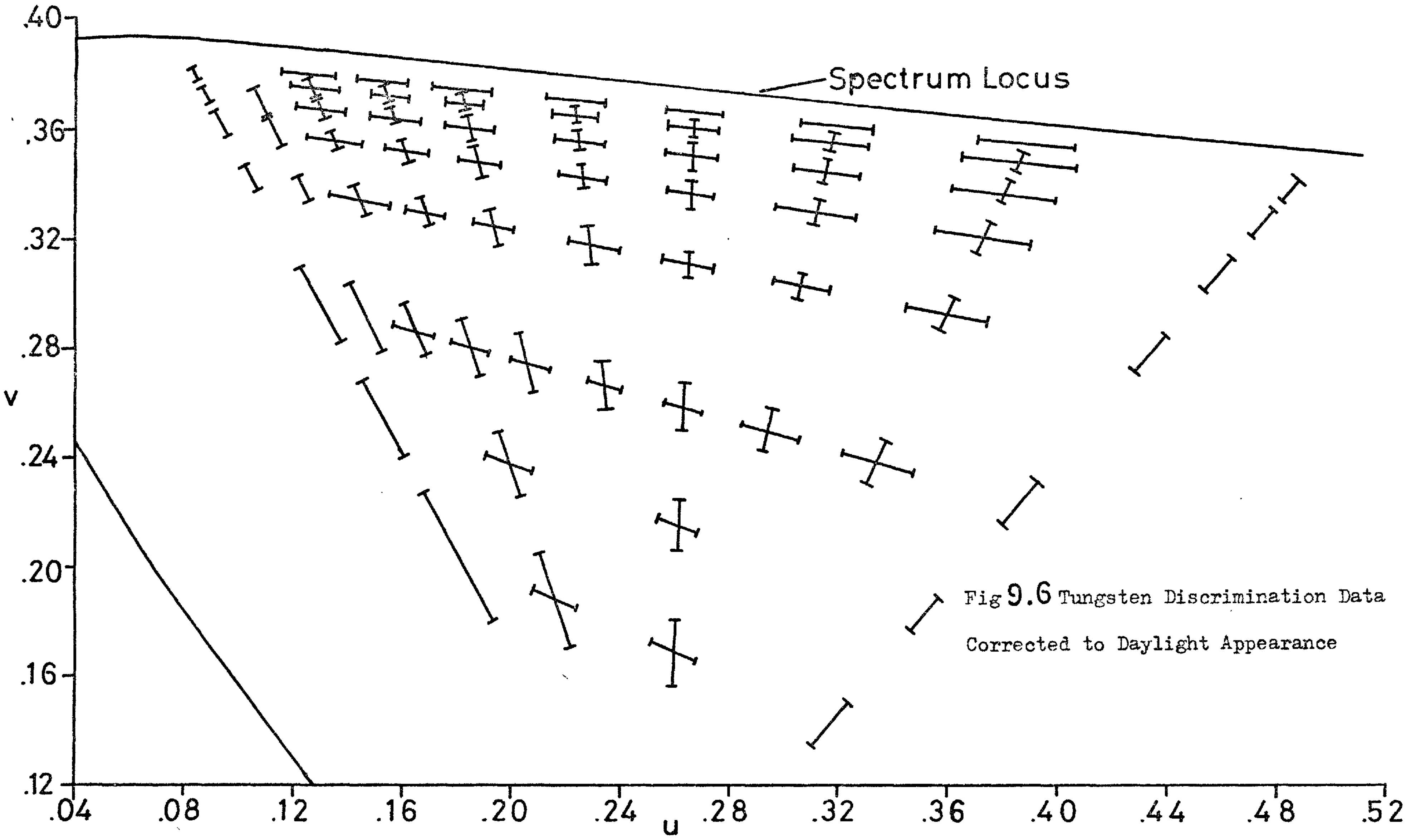
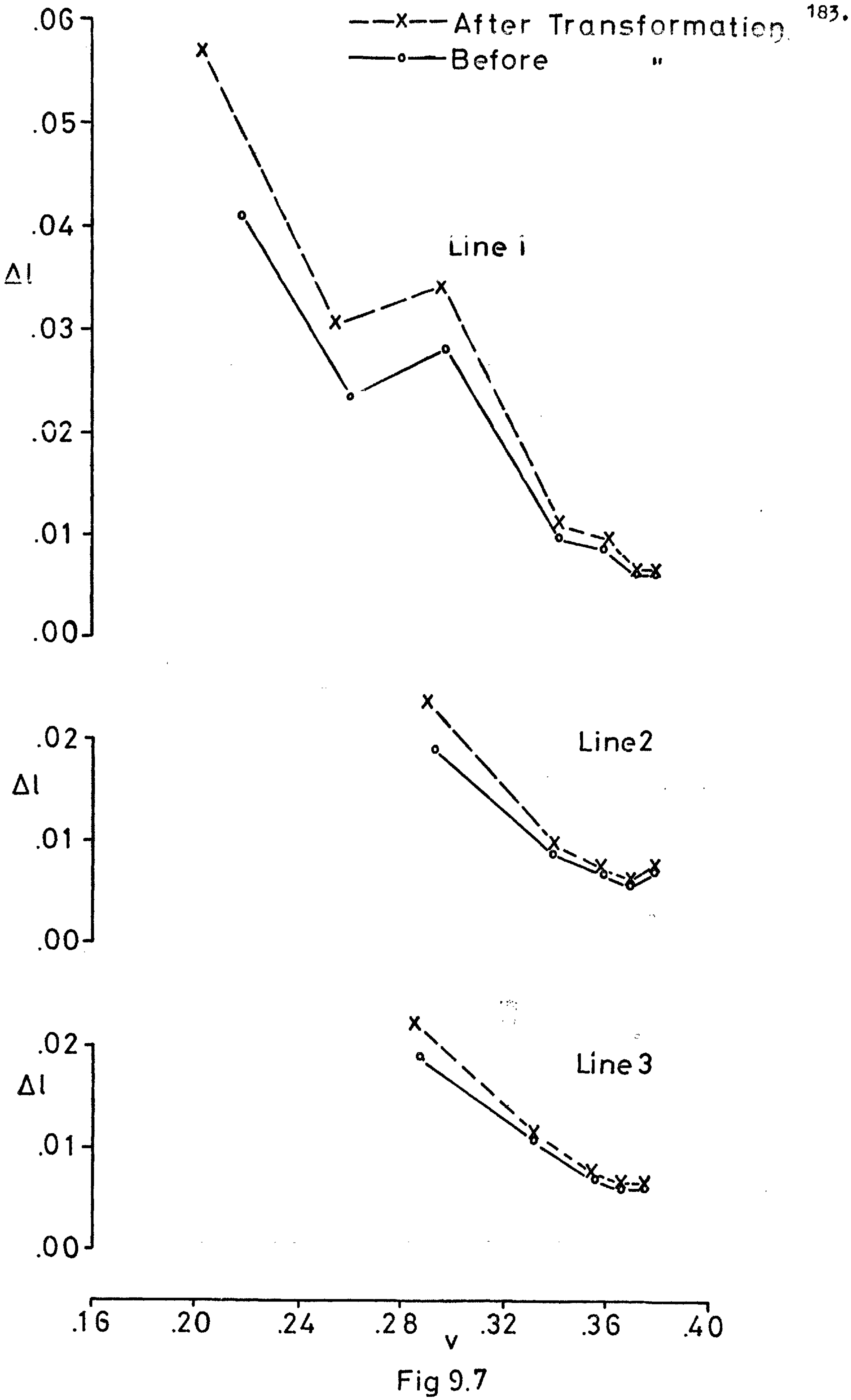


Fig 9.6 Tungsten Discrimination Data
Corrected to Daylight Appearance



--x-- After Transformation
—o— Before "
Line 1
Line 2
Line 3
ΔI
.06
.05
.04
.03
.02
.01
.00
.16
.20
.24
.28
.32
.36
.40
v

Fig 9.7

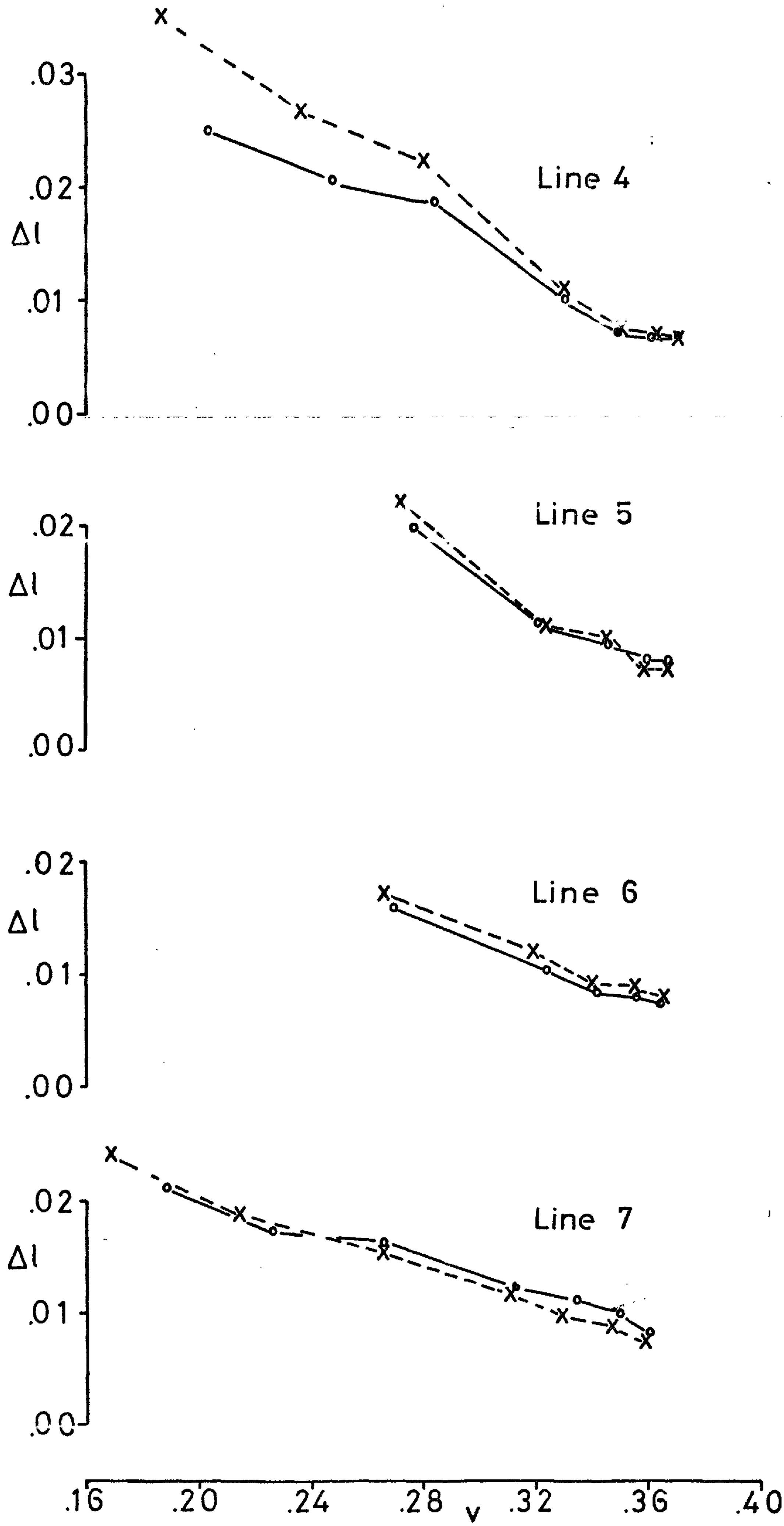


Fig 9.8

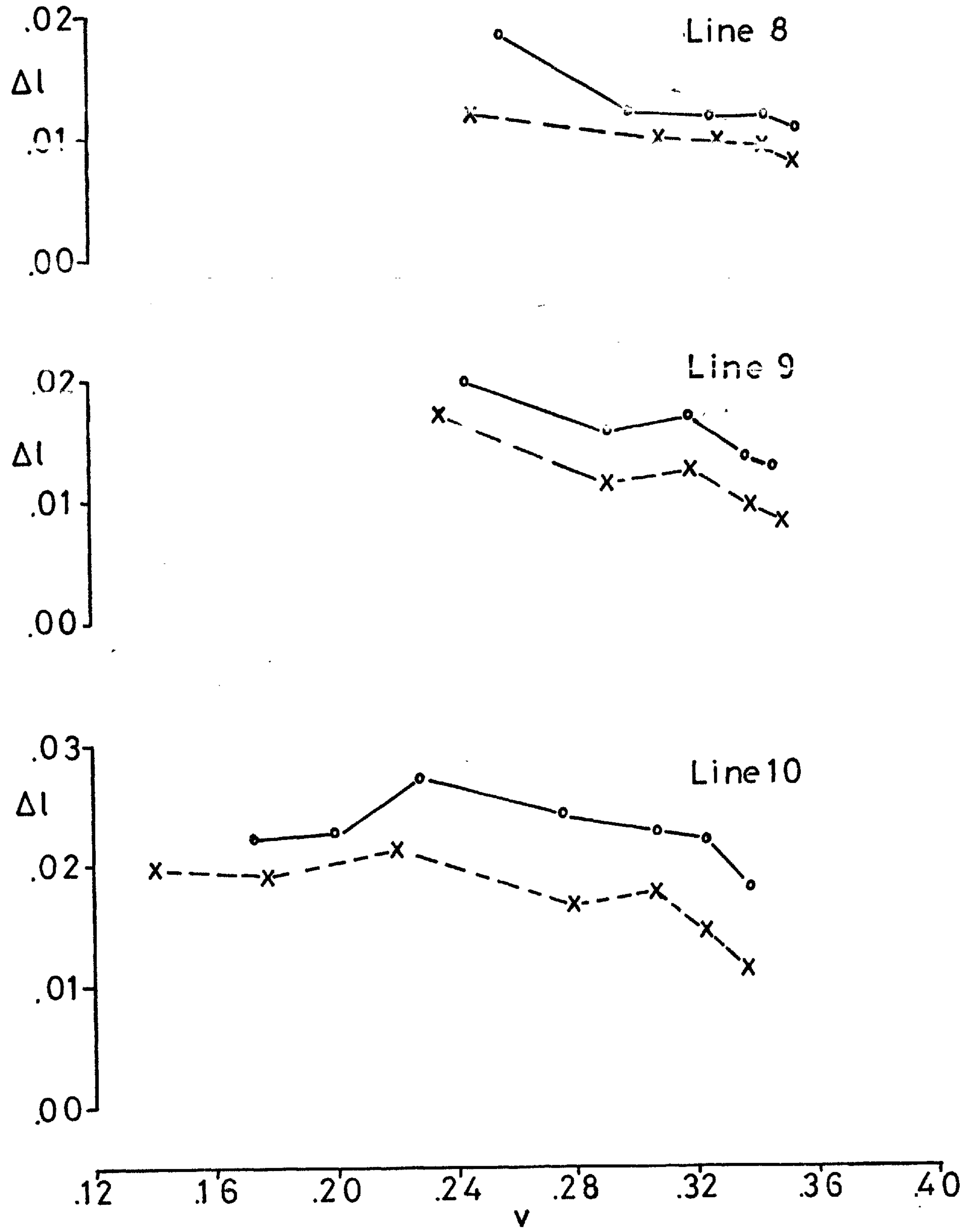

.02
Δl
.01
.00
Line 8
.02
Δl
.01
.00
Line 9
.03
Δl
.02
.01
.00
Line 10
.12
.16
.20
.24
.28
.32
.36
.40
v

Fig 9.9

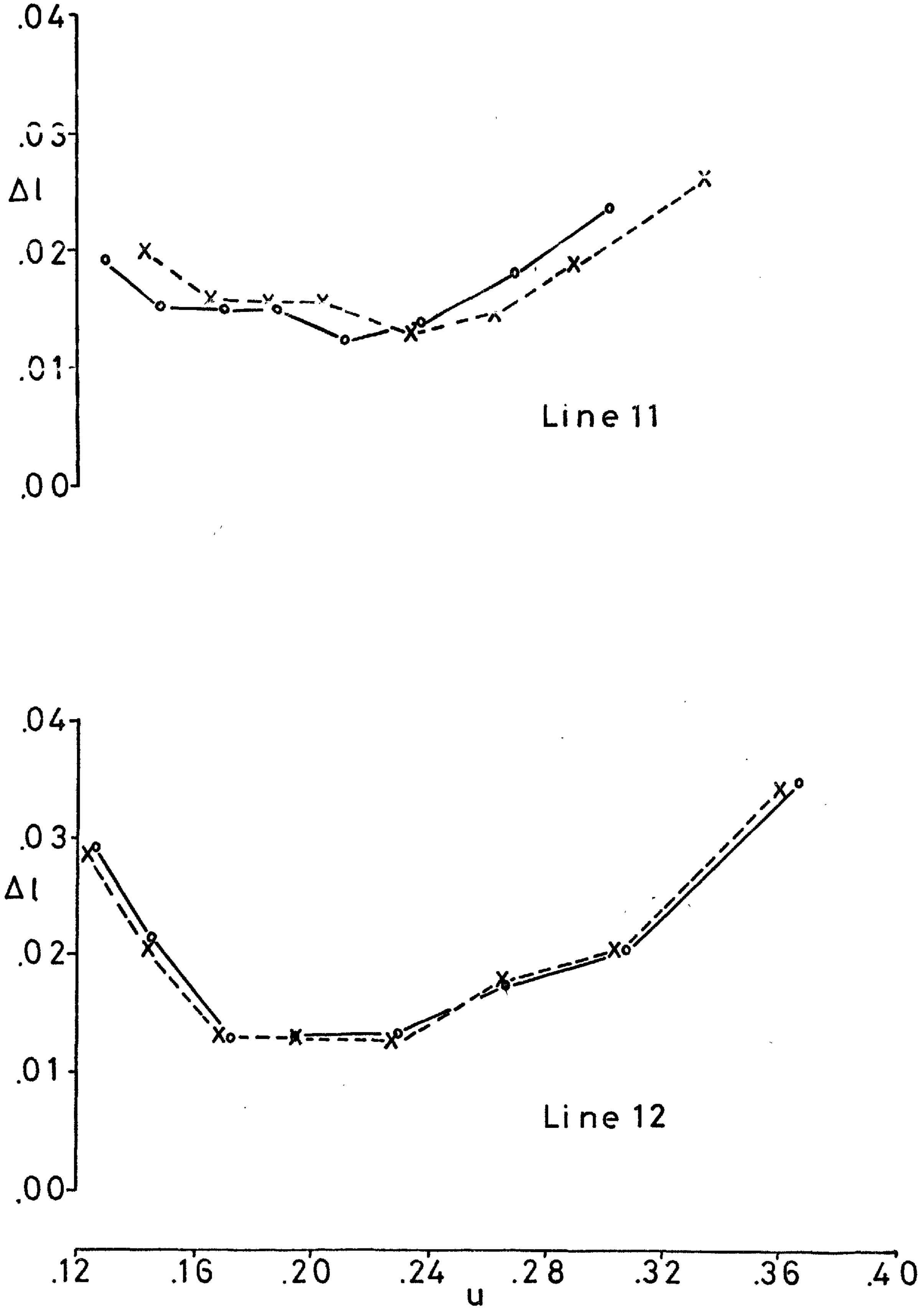

.04
.03
Δl
.02
.01
.00
Line 11
.04
.03
Δl
.02
.01
.00
Line 12
.12
.16
.20
.24
.28
.32
.36
.40
u

Fig 9.10

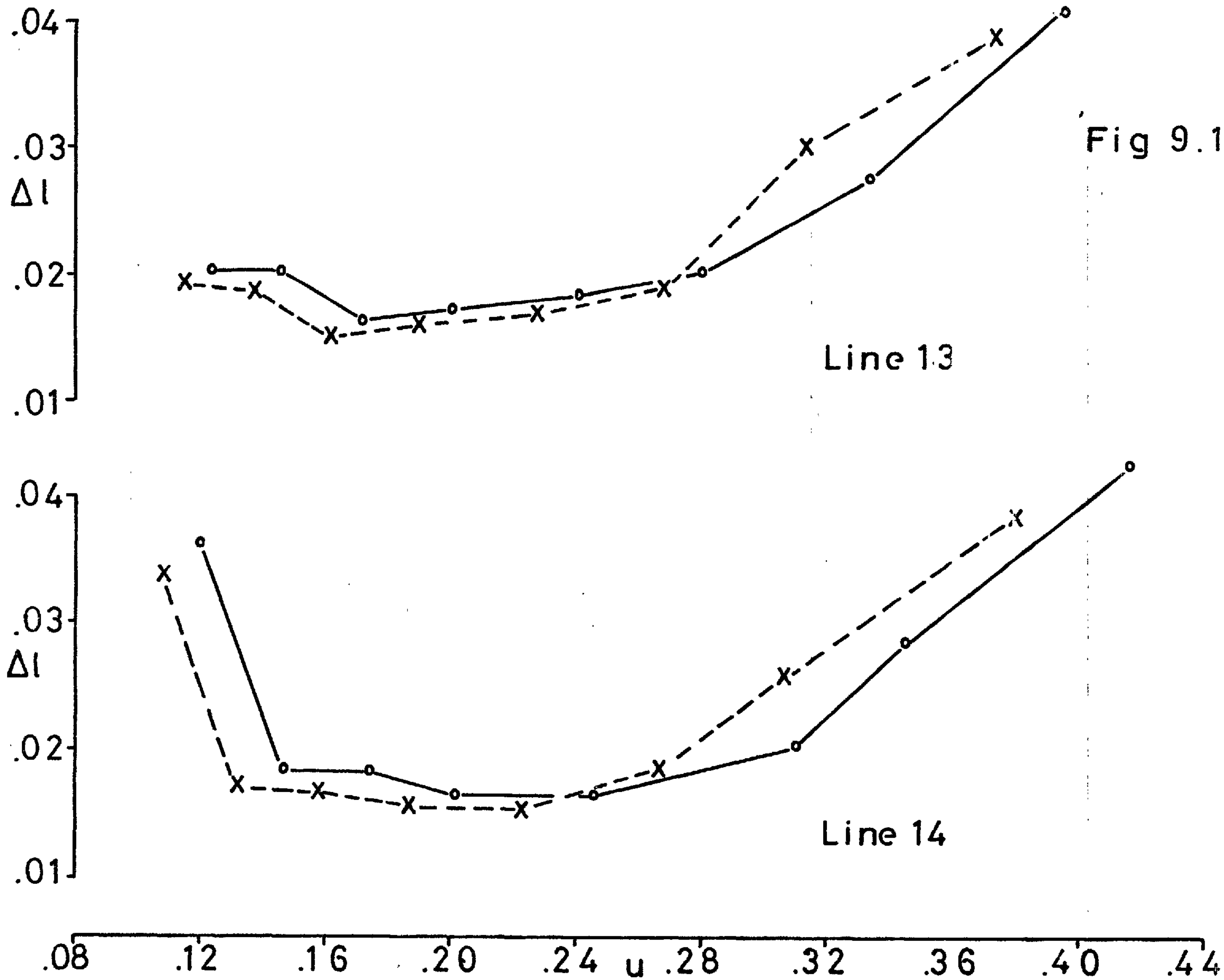

.04
.03
ΔI
.02
.01
Line 13
.04
.03
ΔI
.02
.01
Line 14
.08
.12
.16
.20
.24
u
.28
.32
.36
.40
.44

Fig 9.11

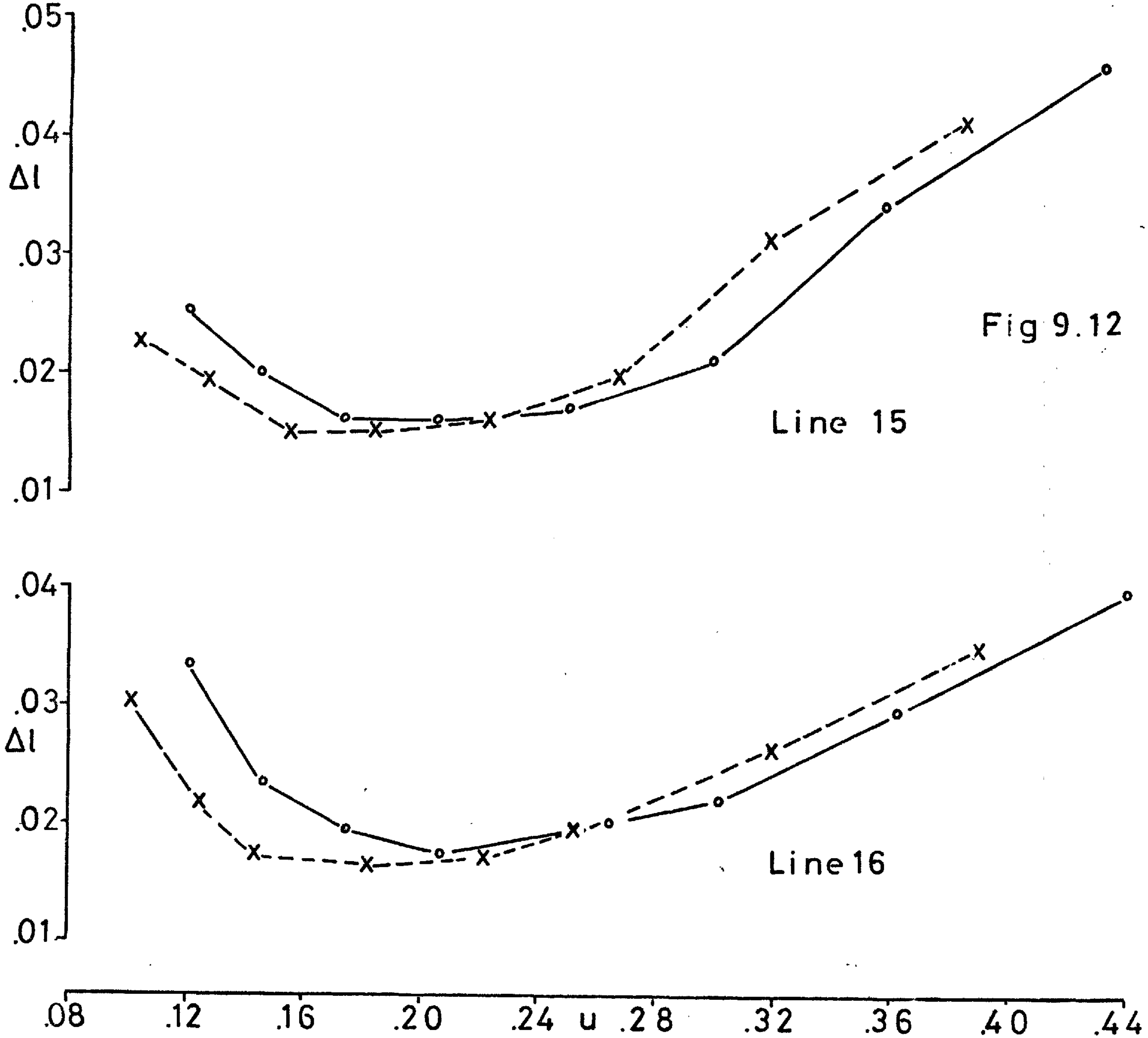

.05
.04
Δl
.03
.02
.01
Line 15
.04
.03
Δl
.02
.01
Line 16
.08
.12
.16
.20
.24
u
.28
.32
.36
.40
.44

Fig 9.12

plotted in this way since they consist only of two points. The data for tungsten adaptation after transformation to their relative daylight appearance are shown compared with the data before transformation. When the nature of the two different experiments is taken into consideration it is thought that the similarities between the two sets of data are very good. This is particularly true for the positions of the graphs representing colours in the central region of the chromaticity diagram. As before, the experimental points have been joined together to give clarity to the graphs. This similarity between the two sets of data implies that the discrimination data, plotted in this way, are invariant to the change in adaptation and any changes in coordinate of the sampling point are compensated for as a change in the size of the just noticeable colour difference at that point. This leads to the postulate that discrimination data recorded in tungsten adaptation conditions can be plotted in the u,v chromaticity diagram and the resulting plot considered to be as uniform as that obtained with discrimination data recorded in daylight adaptation under otherwise similar experimental conditions.

The only exception to this postulate seems to be in the red region of the diagram where, for lines 9 and 10, there appears to be some discrepancy between the two sets of data. However, this discrepancy may possibly be traced to a fault in the least squares fitting theory and its subsequent application. The equations applied to the experimental appearance observations yield a matrix which is then applied to the sampling points of the discrimination experiments. Some of these sampling points lie outside the quadrilateral defined by the sampling points used in the appearance experiments. This extrapolation assumes that the appearance shifts that would be observed for these more saturated sampling points follow the general trends of the experimentally obtained data. For the linear hypothesis to hold this extrapolation must be valid but this may not be a justified assumption in practice. Indeed, the failure of Burnham, Evans and Newhall to obtain consistent estimates of the fundamental primaries indicates that the linear model of the visual processes is an over-simplification. Burnham(1959), in his comparison between the experimental data obtained by Wassef using surface samples and the theoretical predictions of Burnham, Evans and Newhall, shows discrepancies between theory and experiment in the red, yellow-red and red-purple hue planes of Munsell colour space. Similarly MacAdam(1956), in his investigations using the local adaptation method of observation, found that the least squares fitting technique failed to give results consistent with observation in the red region of the chromaticity diagram.

9.4 Further Consideration - Colour Differences

The postulate cited above can be considered in another way. Following the ideas of Ouveltjes outlined in Section 7.7, the u coordinate of each test colour after transformation, u', was plotted as a function of the u coordinate before transformation, u, as shown in Figure 9.13. The result is a series of lines corresponding to lines 11 to 18 as shown. The corresponding pairs of chromaticity coordinates were applied to a least squares fitting computer programme that gave as its output the gradient and intercept of the straight line that best fitted the points,

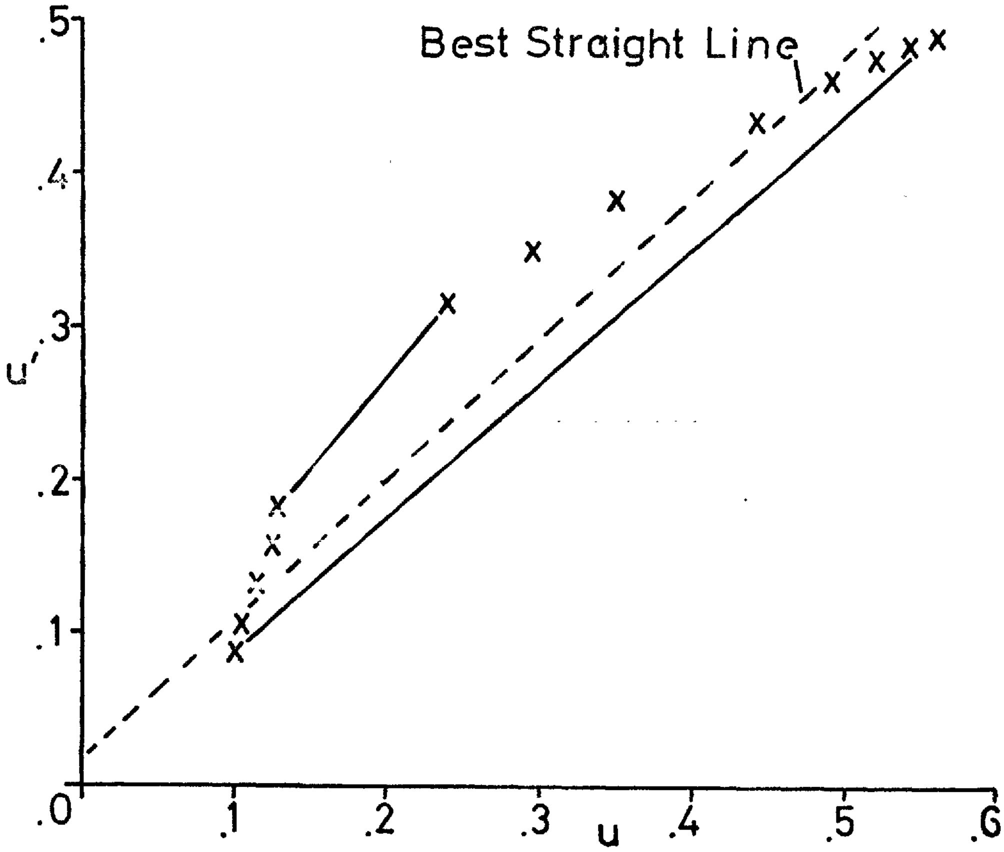


Fig. 9.13

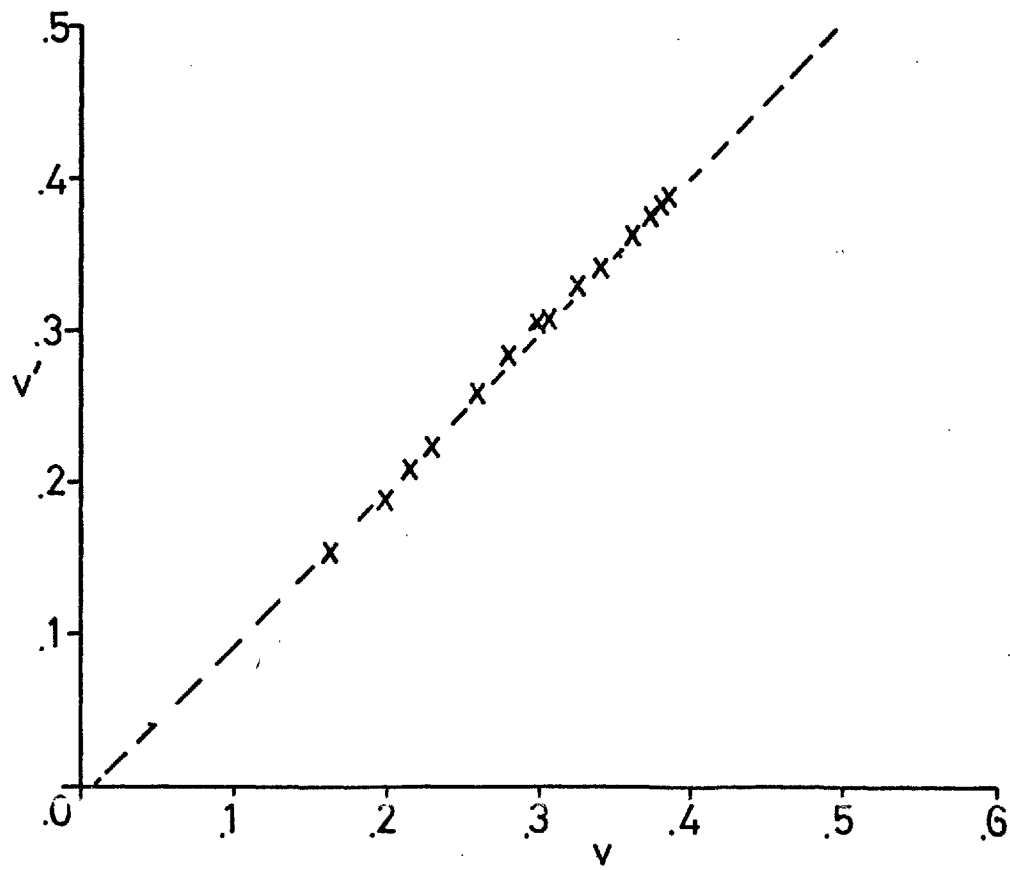


Fig. 9.14

together with the errors associated with these constants. The line obtained in this way is also shown on the diagram. It has a gradient of $0{\cdot}92 \pm 0{\cdot}03$. Thus it is possible to write:-

$$u' = 0{\cdot}92u + C_1$$

where C_1 is the intercept of the line with the ordinate. Figure 9.14 shows a similar graph with the v coordinate after transformation, v', plotted as a function of the v coordinate before transformation, v. The result in this case is a series of short lines again corresponding to lines 11 to 18. For clarity only the sampling points at the ends of these lines are shown. Again the straight line that is the best fit to the points is shown. This line has a gradient of $1{\cdot}02 \pm 0{\cdot}01$. This leads to the equation:-

$$v' = 1{\cdot}02v + C_2$$

where C_2 is the intercept of the line with the ordinate. The above pair of equations is very closely related to the corresponding pair of equations that is implied by the invariance of the discrimination data to the appearance transformation when the u,v chromaticity diagram is used:-

$$u' = 1{\cdot}00u + C_1$$

$$v' = 1{\cdot}00v + C_2$$

In terms of colour differences this means that the difference between two colours with chromaticity coordinates u_1', v_1' and u_2', v_2' determined with daylight adaptation is similar in size to the colour difference between two colours u_1, v_1 and u_2, v_2 determined for tungsten light adaptation where u_1', v_1' and u_2', v_2' are the chromaticity coordinates of the point representing u_1, v_1 and u_2, v_2 respectively, as they appear in daylight adaptation. i.e.:-

$$\Delta E_{Daylight} = ((u_1' - u_2')^2 + (v_1' - v_2')^2)^{\frac{1}{2}}$$

$$\Delta E_{Tungsten} = ((u_1 - u_2)^2 + (v_1 - v_2)^2)^{\frac{1}{2}}$$

where $\Delta E_{Daylight}$ is the colour difference between two colours as measured in daylight adaptation and $\Delta E_{Tungsten}$ is the colour difference between two colours as measured in tungsten adaptation.

Using the experimentally determined relation between u', v' and u,v gives:-

$$\Delta E_{Daylight} = \Delta E_{Tungsten}$$

This seems to be in direct contradiction to the findings of Ouweltjes who postulated that, for tungsten adaptation, Δv values $(v_1 - v_2)$ should be twice those obtained with daylight adaptation. However it must be remembered that Ouweltjes used surface samples whereas the author has used colorimetric test fields. A change in adaptation or illumination using surface samples will give a change in the spectral composition of the reflected light as well as an appearance change. The von Kries type of transformation with the Judd P, D, T primaries as used by Ouweltjes does not take into account this change in the reflected light. With the self-luminous colorimetric fields used by the author a change in adaptation does not change the composition of the light in the test fields and so the observations as made in the experiments and the matrix subsequently derived should take into account the complete colour appearance change.

Similar graphs were plotted for the forty test colours transformed to their relative daylight appearance by using the von Kries transformation with the Judd primaries. The equations are given in Section 9.1. The results for the u and v chromaticity coordinates are shown in Figures 9.15 and 9.16 respectively. The best straight line through the points, given by the least squares method, is also shown. The gradient of this line for the u coordinate is $0{\cdot}92 \pm 0{\cdot}03$ and the gradient for the v coordinate is $1{\cdot}41 \pm 0{\cdot}04$. This leads to the equations:-

$$u' = 0{\cdot}92u + C_1$$

$$v' = 1{\cdot}41v + C_2$$

This pair of equations is not so close to the pair implied by the experimental results and would tend to agree with the findings of Ouweltjes.

Similar graphs were also plotted using a third transformation equation derived by Burnham, Evans and Newhall(1957). The matrix M

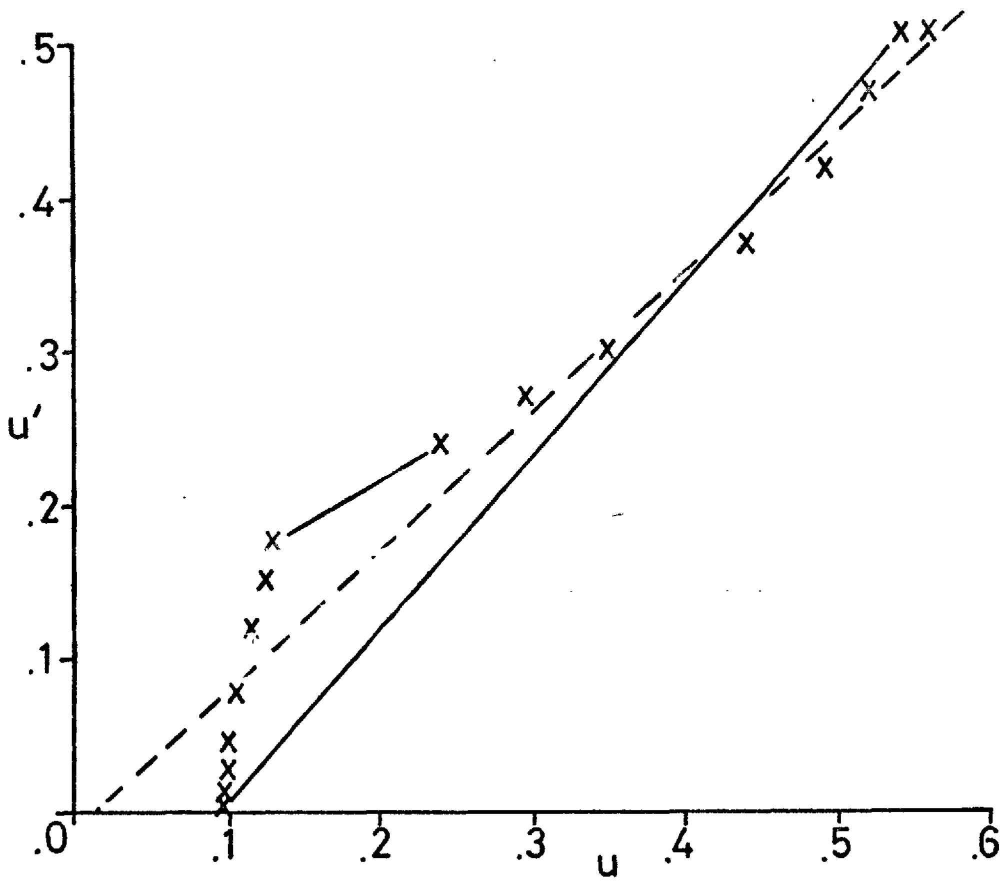


Fig 9.15

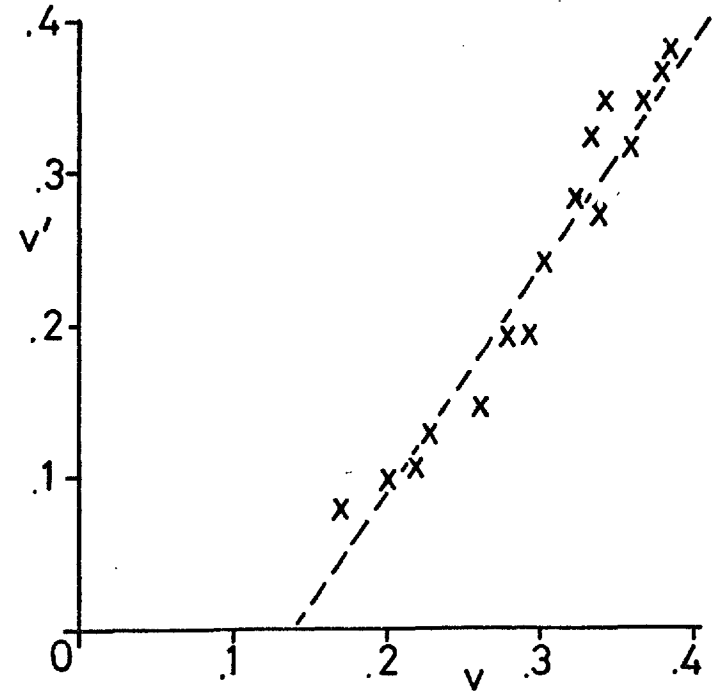


Fig 9.16

is given by:-

$$M = \begin{pmatrix} 1{\cdot}097 & -0{\cdot}405 & 0{\cdot}373 \\ -0{\cdot}030 & 0{\cdot}999 & 0{\cdot}214 \\ -0{\cdot}078 & 0{\cdot}367 & 2{\cdot}111 \end{pmatrix}$$

This matrix gives two equations for transforming x,y chromaticity coordinates:-

$$x' = \frac{0{\cdot}724x - 0{\cdot}778y + 0{\cdot}373}{-1{\cdot}709x - 1{\cdot}737y + 2{\cdot}698}$$

$$y' = \frac{0{\cdot}244x - 0{\cdot}785y + 0{\cdot}214}{-1{\cdot}709x - 1{\cdot}737y + 2{\cdot}698}$$

This transformation was derived using a technique of least squares fitting similar to that used by the author. The experimental data was obtained using the binocular matching method to determine the colorimetric specification of colours having similar appearance when the observer was adapted to tungsten, and subsequently daylight adaptation. Twelve test colours were used, four at each of three luminance levels. Three observers matched the appearance of each test colour ten times under each illuminant, and a fourth observer matched each test colour five times under each illuminant. The graph of the u coordinate before and after transformation is shown in Figure 9.17. The best straight line through the points is also shown. It has a gradient of $0{\cdot}90 \pm 0{\cdot}02$. The corresponding graph for the v coordinate before and after transformation is shown

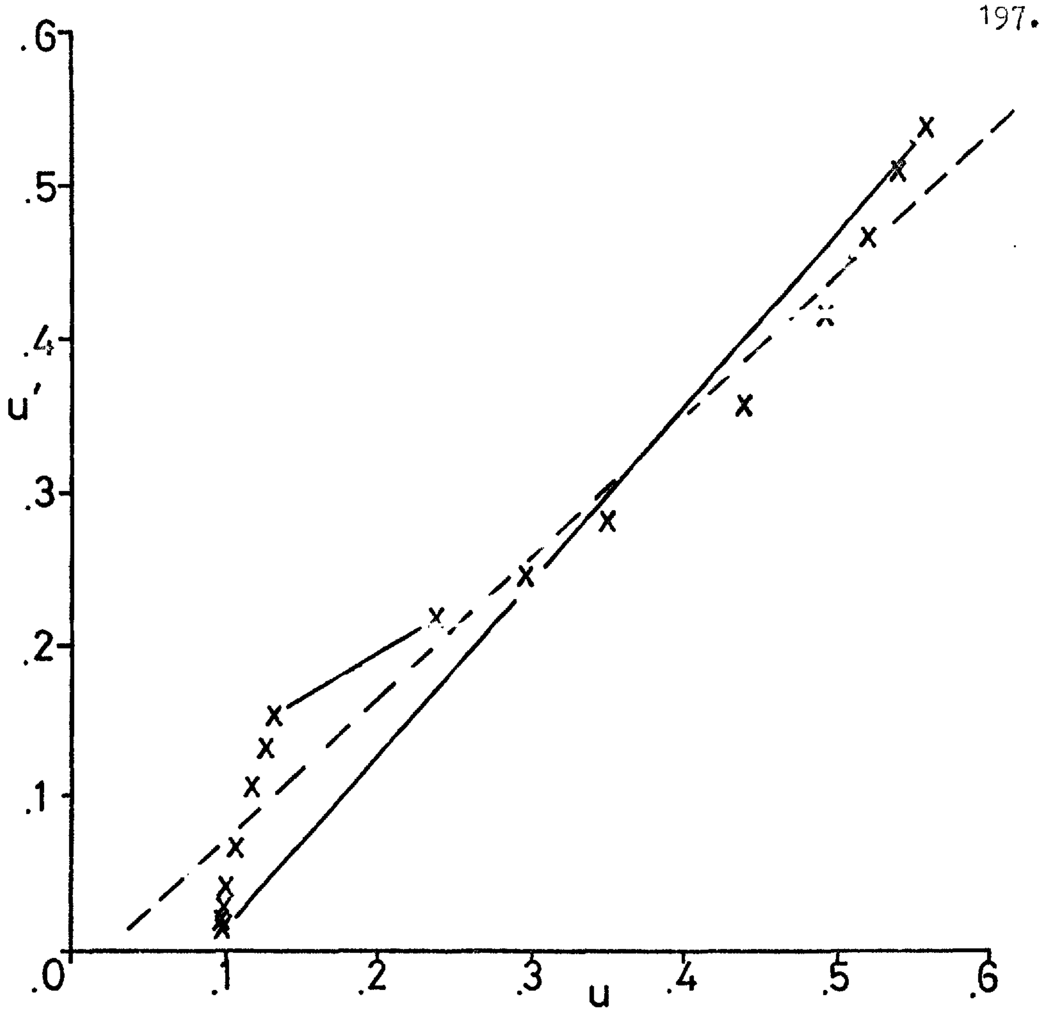


Fig 9.17

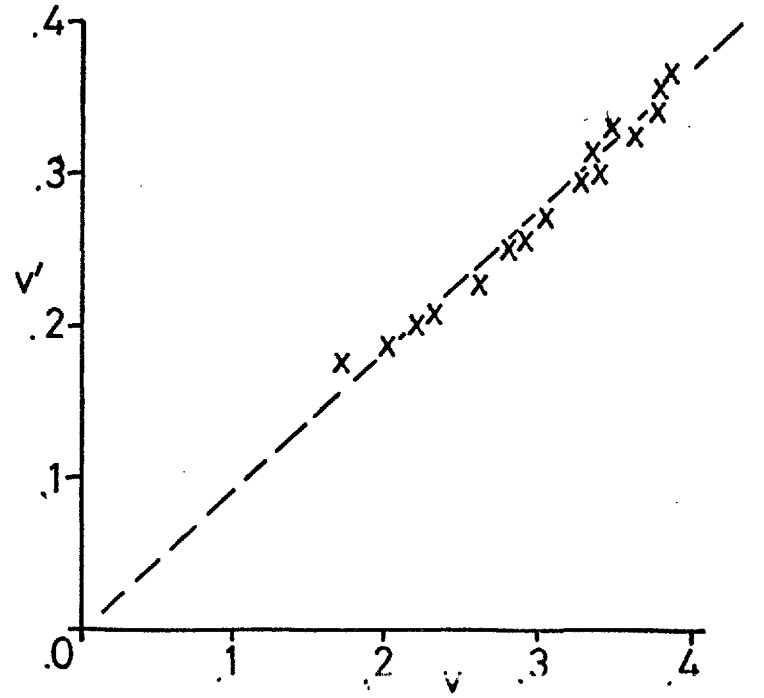


Fig 9.18

in Figure 9.18 together with the best straight line through the data. This line has a gradient of $0{\cdot}92 \pm 0{\cdot}01$. These two transformations seem to confirm the use of the equations:-

$$u' = 1{\cdot}00u + C_1$$

$$v' = 1{\cdot}00v + C_2$$

The fact that the gradients given by two of the three transformations have been less than or equal to unity agrees with the fact that the just noticeable colour differences, plotted in the u,v chromaticity diagram, observed under tungsten adaptation were slightly larger than similar just noticeable differences observed under daylight adaptation.

9.5 Other Colour Temperatures

The 1960 CIE u,v chromaticity diagram has been shown to be as uniform for data observed using tungsten adaptation as for data observed using daylight adaptation, for which it was defined. It has been shown that colour differences measured under daylight adaptation for test colours u_1, v_1 and u_2, v_2 are similar in size to colour differences measured between the same two test colours as measured under tungsten adaptation. It seems safe to assume that data obtained under adaptation conditions with other colour temperatures, but having a colour temperature between $6500^{\circ}K$ (daylight) and $2856^{\circ}K$ (tungsten light), can also be plotted using the u,v chromaticity diagram and the same conclusions drawn concerning the overall absolute uniformity and the relative size of the colour differences.

9.6 Results for a Change from Dark Adaptation to Daylight Adaptation

Measurements similar to those described for a change from tungsten adaptation to daylight adaptation were made for a change in the state of adaptation from being dark adaptation to being daylight adaptation. The transformation matrix derived by the least squares fitting programme was:-

$$M = \begin{pmatrix} 0{\cdot}901 & 0{\cdot}084 & 0{\cdot}059 \\ 0{\cdot}038 & 0{\cdot}981 & 0{\cdot}043 \\ 0{\cdot}061 & -0{\cdot}065 & 0{\cdot}898 \end{pmatrix}$$

This gave a set of transformation equations for x,y chromaticity coordinates:-

$$x' = 0{\cdot}842x + 0{\cdot}025y + 0{\cdot}059$$

$$y' = -0{\cdot}005x - 0{\cdot}937y + 0{\cdot}043$$

These equations were used to derive a similar set of equations for transforming u,v chromaticity coordinates. The equations were then applied to the array of test colours as tabulated in Figure 8.3 to give the relative appearance of the test colours in daylight. The resulting array of test colours is shown tabulated in Figure 9.19. The appearance changes are plotted in the u,v chromaticity diagram in Figure 9.20. The colour appearance changes show an overall shift towards the yellow. This is to be expected since it represents an overall decrease in sensitivity of all three cone mechanisms. Hunt(1950) suggests that the normal sensation corresponding to

U =	.1318	.1537	.1781	.2054	.2428	.2826	.3289	.3890
V =	.3804	.3777	.3747	.3714	.3669	.3620	.3564	.3491
	.1333	.1545	.1780	.2043	.2400	.2777	.3214	.3775
	.3731	.3701	.3669	.3632	.3582	.3530	.3469	.3391
	.1356	.1558	.1780	.2027	.2360	.2709	.3109	.3618
	.3625	.3592	.3556	.3515	.3461	.3404	.3338	.3255
	.1394	.1578	.1780	.2090	.2295	.2598	.2941	.3367
	.3444	.3406	.3365	.3320	.3259	.3197	.3127	.3039
	.1479	.1624	.1779	.1945	.2161	.2377	.2613	.2896
	.3048	.3005	.2960	.2911	.2847	.2784	.2714	.2631

Fig 9.19

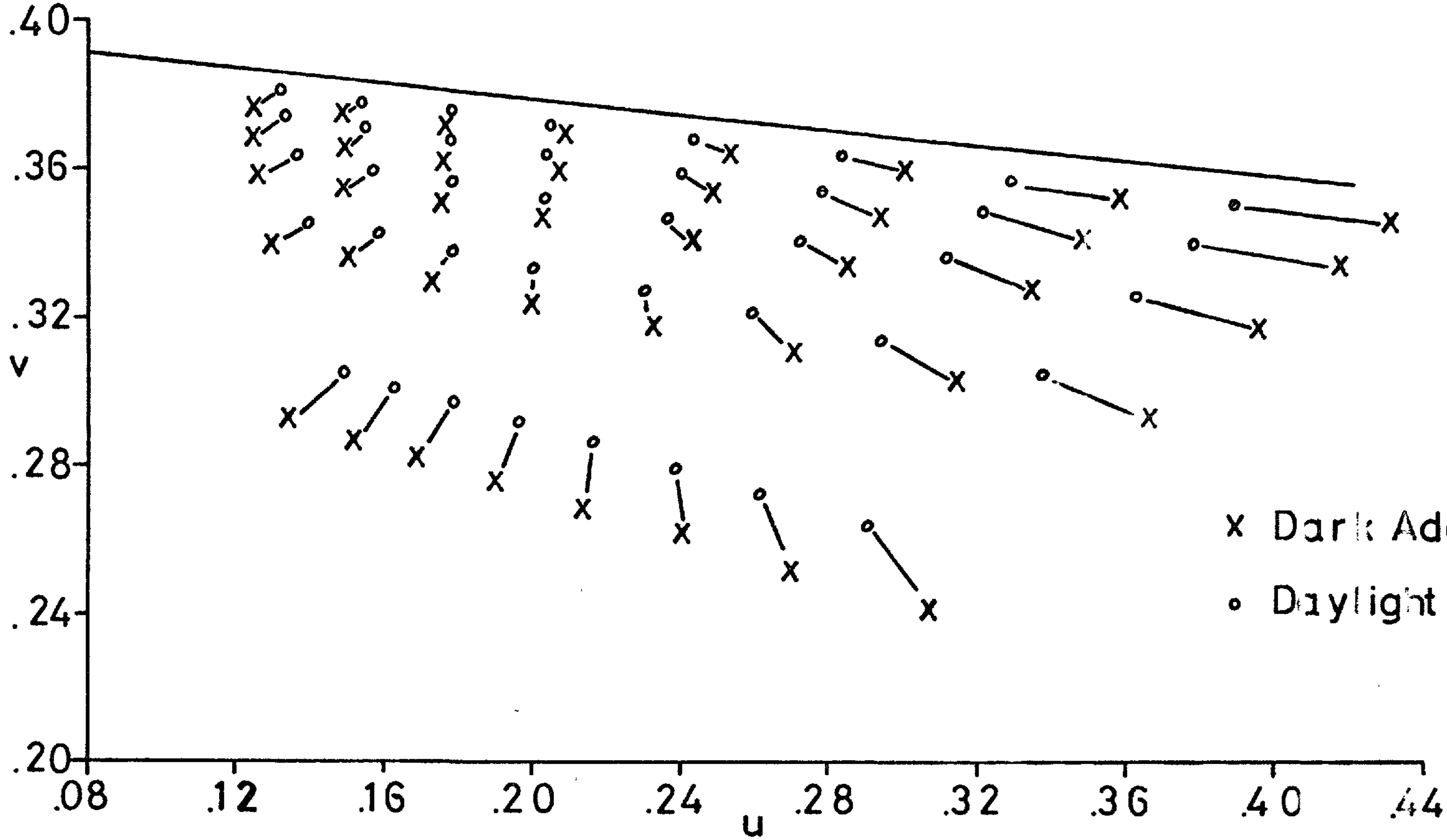


Fig 9.20 Colour Appearance Shifts

any stimulus is the saturated one which occurs under light adaptation conditions, and that when the eye is dark adapted the three cone mechanisms tend to react to decrease the differences between them, and thus desaturate the corresponding sensations. Thus when the eye is light adapted, a spectral yellow colour may produce equal red and green signals, but no blue signal, while when the eye is dark adapted, it produces red and green signals and some blue signal as well, and hence a desaturated sensation results.

The transformation equations were applied to the discrimination data obtained using dark adaptation as tabulated in Figure 6.1 to give the length representing the just noticeable colour differences corrected to their daylight appearance. These new lengths are shown tabulated in Figure 9.21 and plotted in the u,v chromaticity diagram in Figure 9.22. The uniformity of the data is shown to be good with the exception of the red region of the diagram. Even in this part of the diagram the uniformity fails only in the red-blue to green-blue direction. The lengths of the bars are shown plotted as a function of the v chromaticity coordinate of the sampling point (lines 1 to 10) and as a function of the u chromaticity coordinate of the sampling point (lines 11 to 16) in Figures 9.23 - 9.28. The data before transformation are shown compared with the data after transformation. The agreement between the two sets of data is good and it is as good as the agreement between the data obtained for tungsten adaptation before and after transformation. Thus it seems logical to assume that the 1960 CIE u,v chromaticity diagram can also be used to represent data obtained with dark adaptation conditions.

Line	ΔI							
Line 1	·006	·006	·007	·009	·017	·023	·030	
Line 2	·006	·006	·007	·010	·014			
Line 3	·005	·006	·008	·010	·014			
Line 4	·004	·005	·006	·007	·010	·013	·020	
Line 5	·004	·006	·006	·008	·010			
Line 6	·005	·006	·007	·008	·010			
Line 7	·005	·006	·007	·008	·010	·013	·015	
Line 8	·007	·008	·009	·009	·013			
Line 9	·007	·009	·011	·010	·013			
Line 10	·012	·014	·016	·015	·017	·016	·018	
Line 11	·012	·010	·007	·008	·009	·009	·010	·016
Line 12	·013	·010	·010	·008	·010	·012	·013	·018
Line 13	·010	·009	·009	·009	·009	·010	·013	·026
Line 14	·014	·012	·010	·010	·010	·012	·017	·028
Line 15	·014	·012	·011	·011	·010	·011	·018	·037
Line 16	·018	·013	·012	·011	·012	·013	·020	·035
Line 17	·009	·009						
Line 18	·007	·008						

Fig 9.21

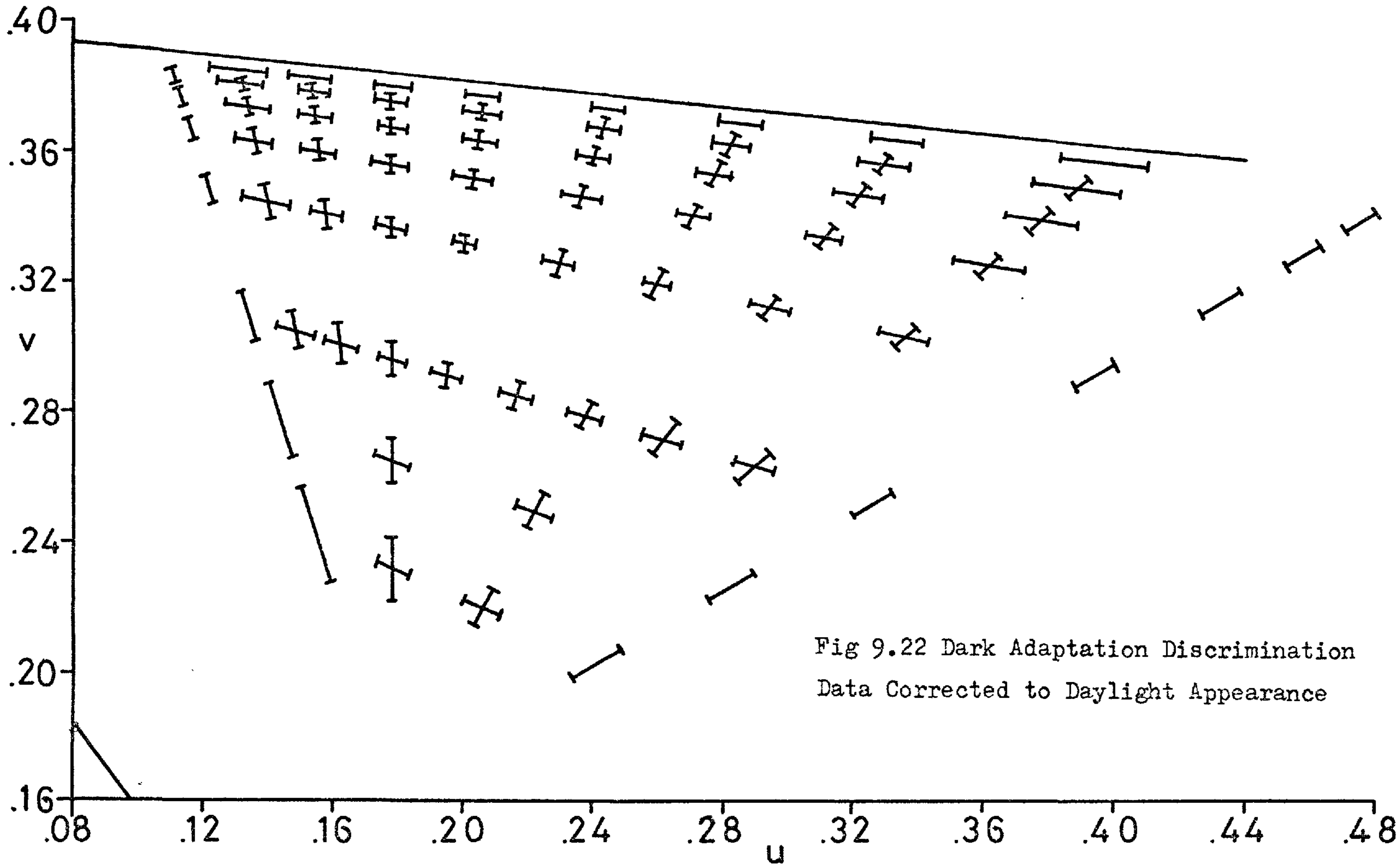


Fig 9.22 Dark Adaptation Discrimination
Data Corrected to Daylight Appearance

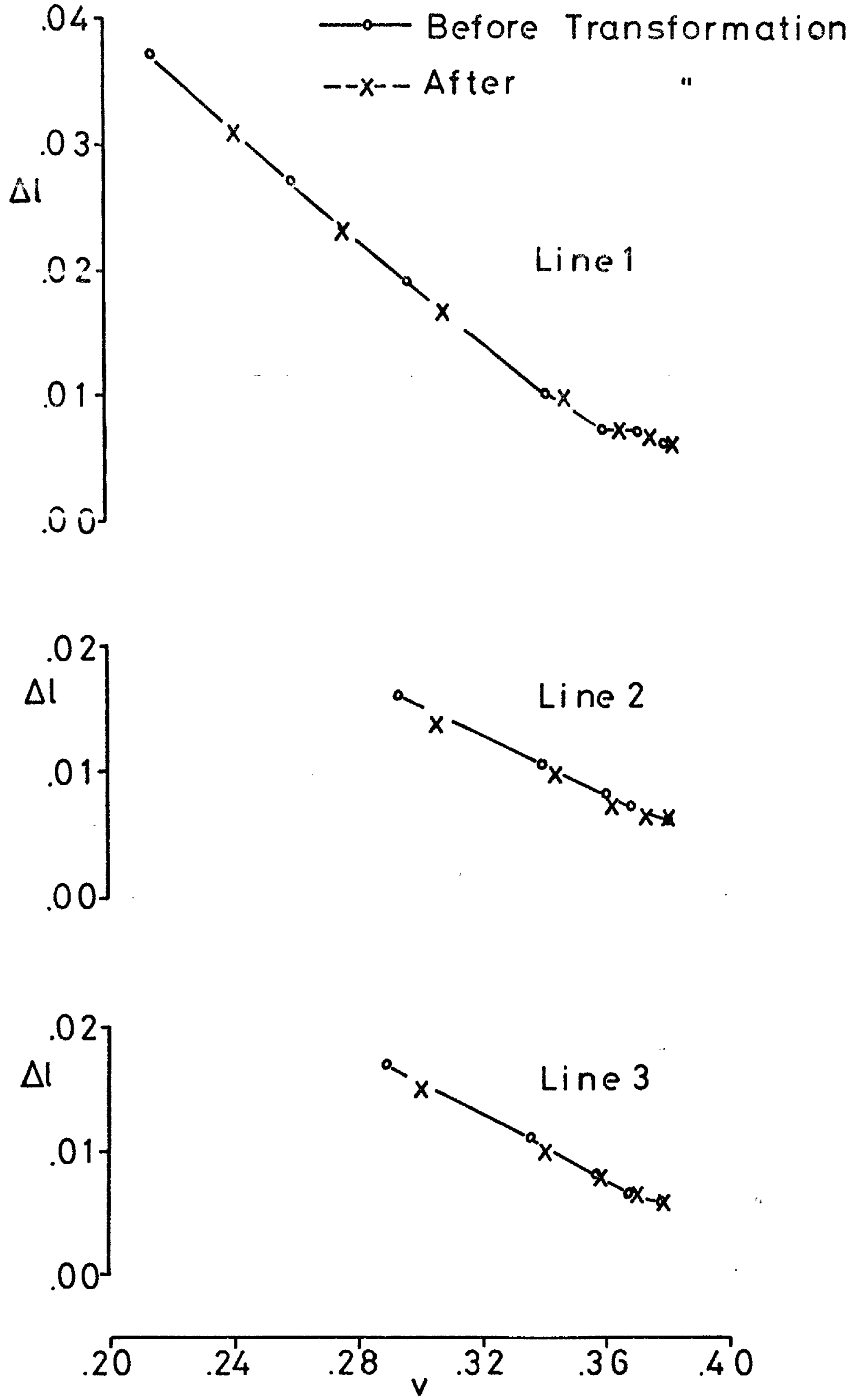

Before Transformation
After "
Δl
.04
.03
.02
.01
.00
Line 1
Line 2
Line 3
.20
.24
.28
.32
.36
.40
v

Fig 9.23

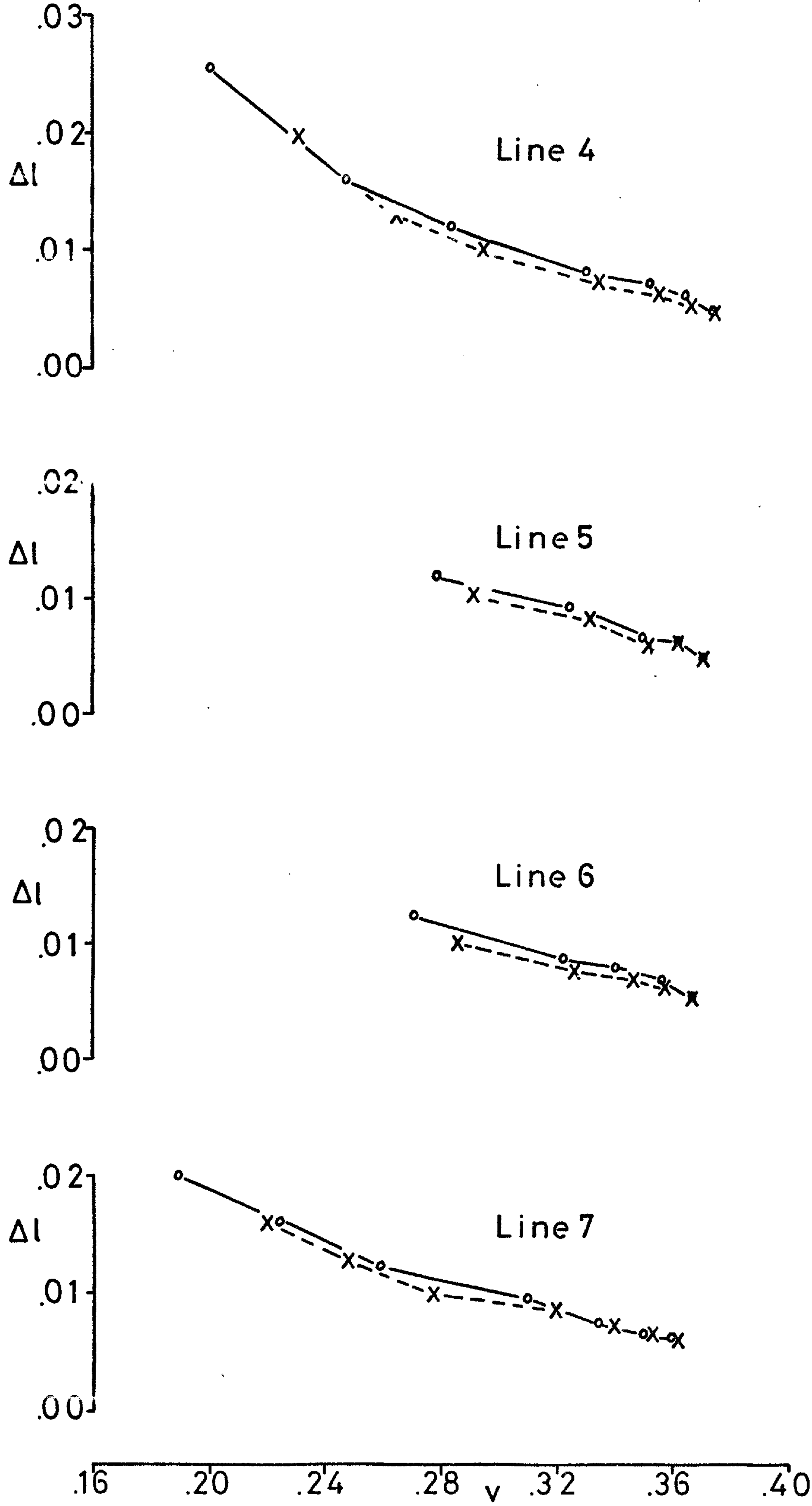
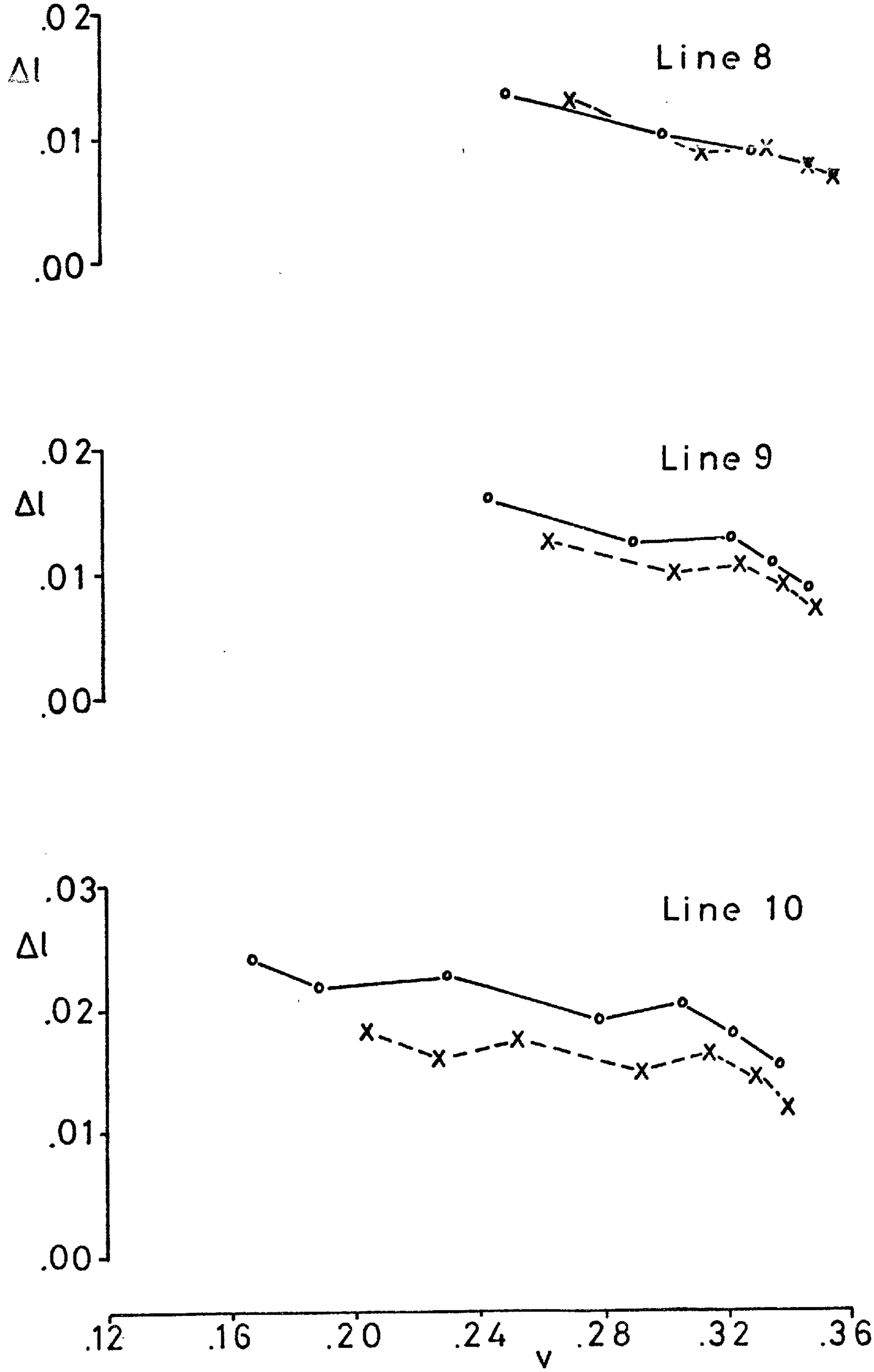

.03
.02
Δl
.01
.00
Line 4
.02
Δl
.01
.00
Line 5
.02
Δl
.01
.00
Line 6
.02
Δl
.01
.00
Line 7
.16
.20
.24
.28
v
.32
.36
.40

Fig 9.24



.02
ΔI
.01
.00
Line 8
.02
ΔI
.01
.00
Line 9
.03
ΔI
.02
.01
.00
Line 10
.12
.16
.20
.24
.28
.32
.36
v

Fig 9.25

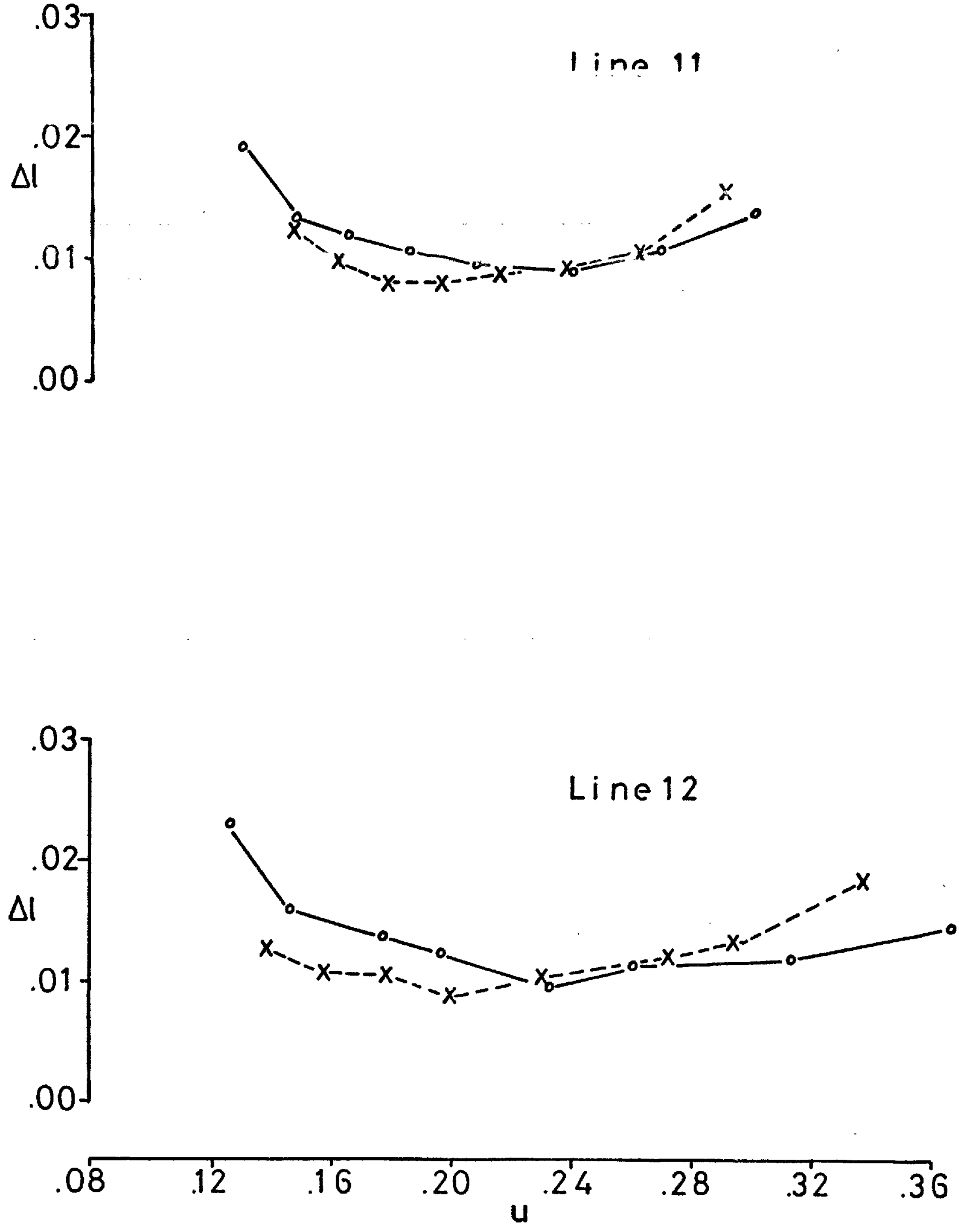
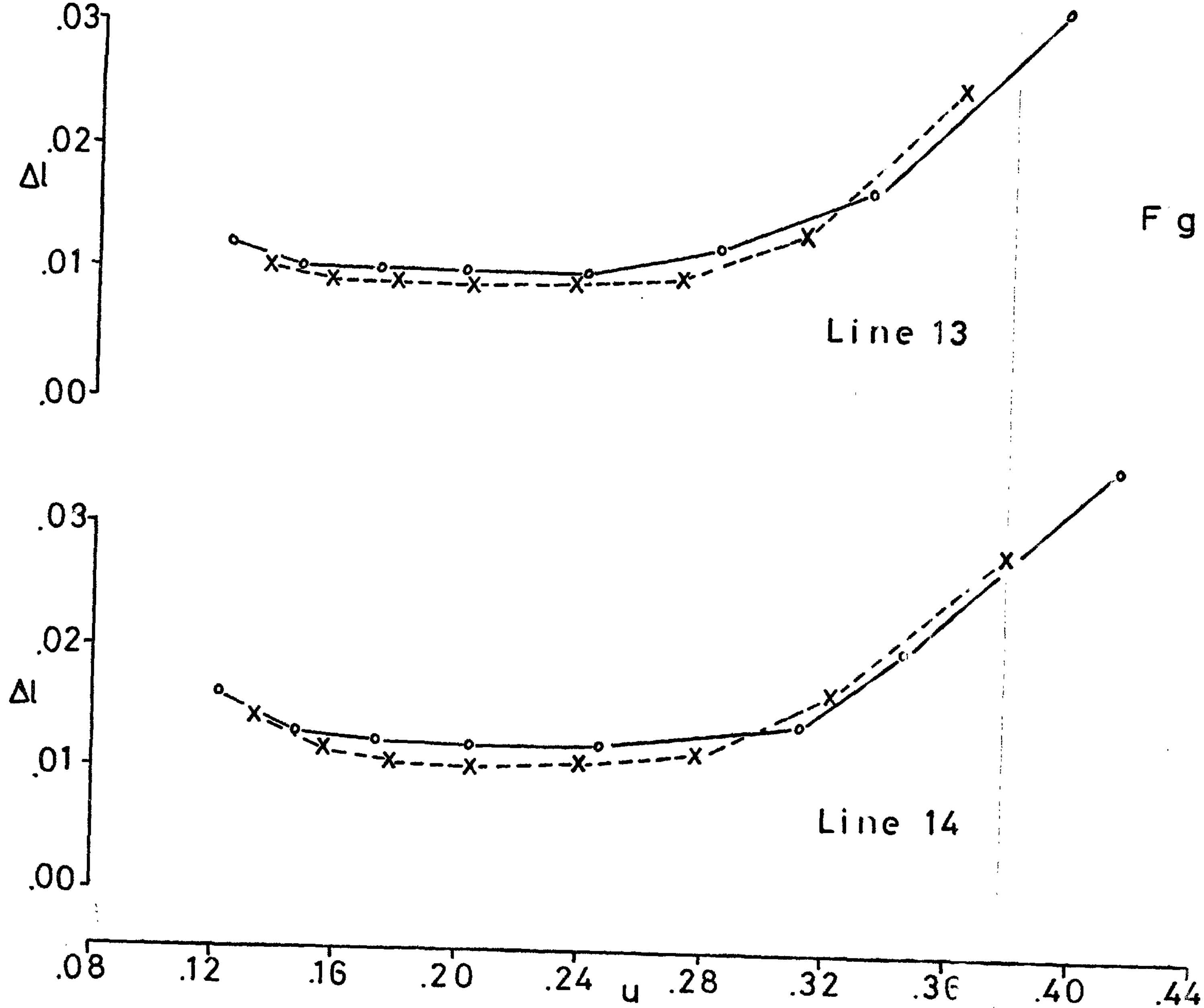


Fig 9.26


.03
.02
.01
.00
Δl
Line 13
.03
.02
.01
.00
Δl
Line 14
.08
.12
.16
.20
.24
u
.28
.32
.36
.40
.44

F g 9.27

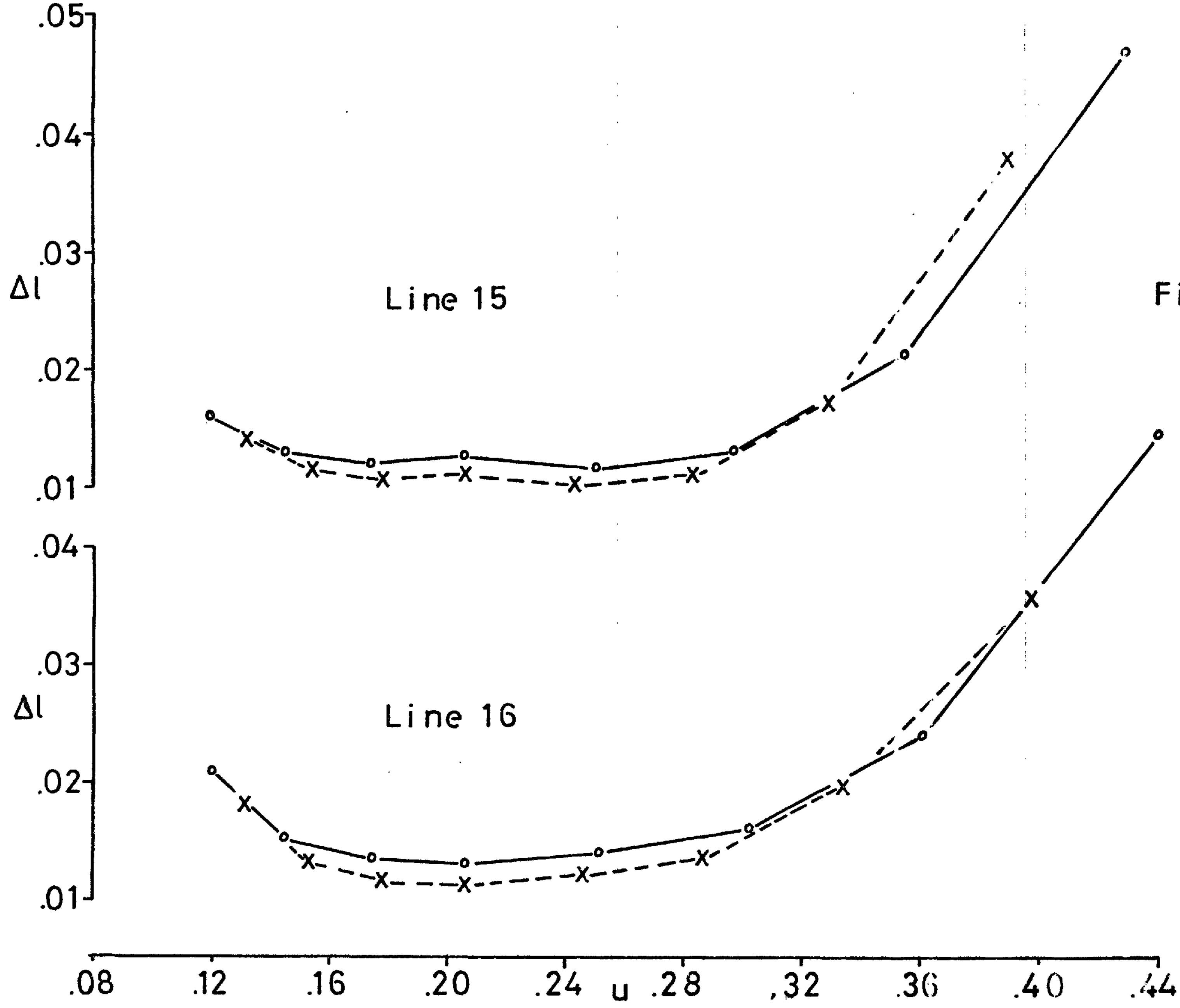

.05
.04
.03
Δl
.02
.01
Line 15
.04
.03
Δl
.02
.01
Line 16
.08
.12
.16
.20
.24
u
.28
.32
.36
.40
.44

Fig 9.28

As with the results for the colour appearance shifts observed when changing the adaptation from tungsten to daylight the u coordinate after transformation, u', was plotted as a function of the u coordinate before transformation, u, as shown in Figure 9.29. The best straight line through the points, obtained using the least squares fitting technique, is also shown. This line has a gradient of $0{\cdot}87 \pm 0{\cdot}01$. A similar graph for the v coordinate before and after transformation is shown in Figure 9.30. The best straight line through the experimental points has a gradient of $0{\cdot}98 \pm 0{\cdot}01$. This leads to the two equations corresponding to the two straight lines:-

$$u' = 0{\cdot}87u + C_1$$

$$v' = 0{\cdot}98v + C_2$$

These equations are, again, not very different from the ideal set. This means that the u,v chromaticity diagram may be considered as a uniform chromaticity diagram for colours viewed with a dark surround although considering the data in this way shows that the compatibility between the data before and after transformation is not as good as the case for tungsten adaptation.

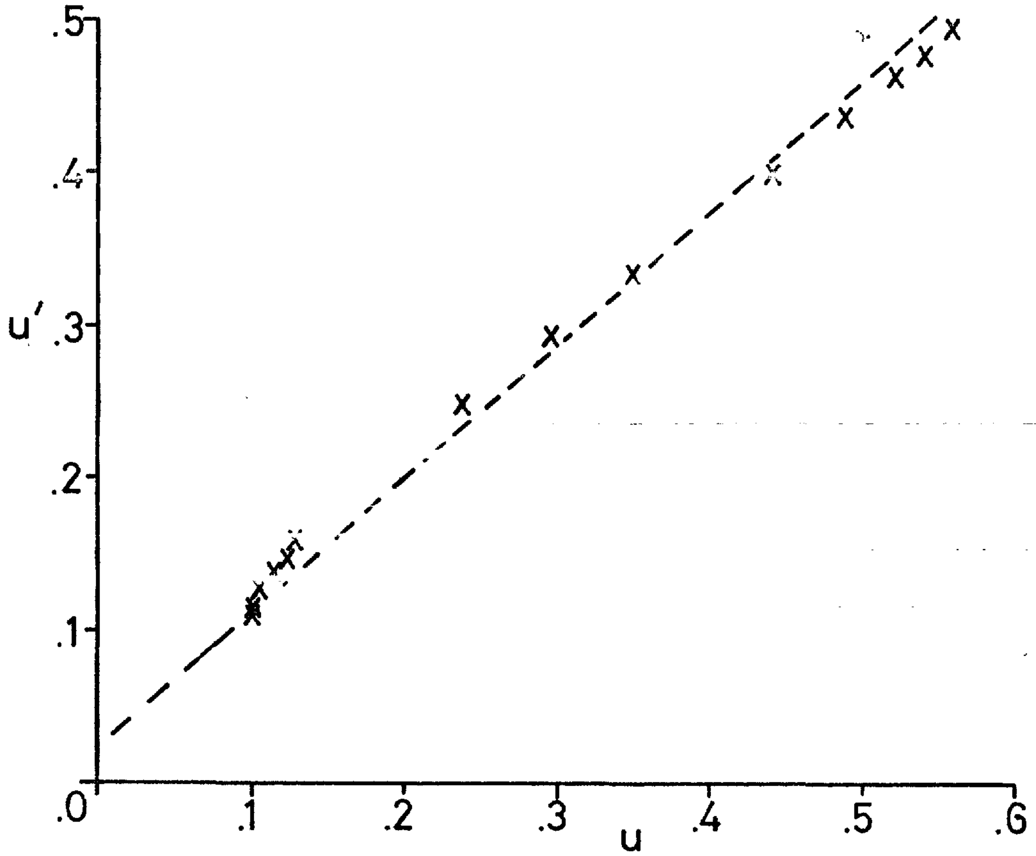


Fig 9.29

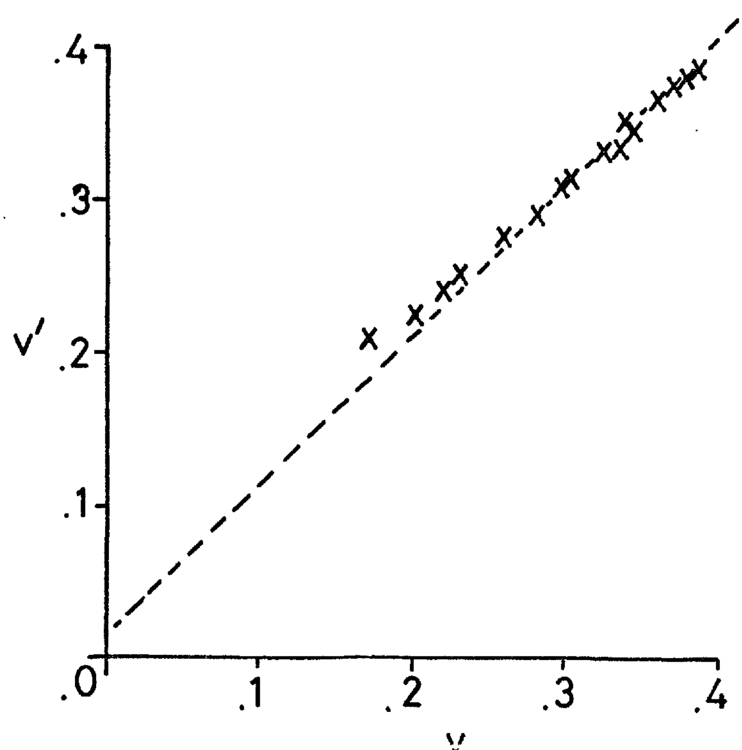


Fig 9.30

Chapter 10

The Results of Colour Appearance Experiments II

10.1 Introduction

Observations were made of the colour appearance shifts of the forty test colours when the surround adaptation was changed from being coloured to being representative of daylight. Three coloured adaptations were used corresponding to the three primaries of the colorimeter. These were defined by:-

Red	Wratten No. 29	$u = 0{\cdot}558$	$v = 0{\cdot}344$
Green	Wratten No. 58	$u = 0{\cdot}097$	$v = 0{\cdot}385$
Blue	Wratten No. 47	$u = 0{\cdot}153$	$v = 0{\cdot}120$

10.2 The Results for a Change from Red Adaptation to Daylight Adaptation

The instrument readings obtained from the observation of the colour appearance shifts of the forty test colours, perceived when the adaptation was changed from being red to representing daylight, were converted into their corresponding tristimulus values and applied to the least squares fitting programme. The resulting three-by-three matrix was then applied to the test colours to give the smoothed set of appearance shifts tabulated in Figure 10.1. They are shown plotted in Figure 10.2 using the u,v chromaticity diagram. The computed matrix was:-

U =	0.1420	0.1602	0.1801	0.2018	0.2309	0.2610	0.2948	0.3371
V =	0.3763	0.3738	0.3711	0.3681	0.3641	0.3600	0.3554	0.3496
	0.1436	0.1611	0.1803	0.2012	0.2290	0.2575	0.2895	0.3292
	0.3690	0.3663	0.3633	0.3601	0.3558	0.3514	0.3465	0.3404
	0.1458	0.1625	0.1806	0.2002	0.2262	0.2527	0.2821	0.3183
	0.3584	0.3554	0.3522	0.3487	0.3440	0.3393	0.3341	0.3276
	0.1496	0.1648	0.1810	0.1986	0.2216	0.2447	0.2701	0.3009
	0.3404	0.3371	0.3335	0.3296	0.3246	0.3195	0.3139	0.3071
	0.1578	0.1696	0.1821	0.1953	0.2122	0.2288	0.2466	0.2675
	0.3016	0.2980	0.2941	0.2901	0.2849	0.2798	0.2743	0.2679

Fig 10.1

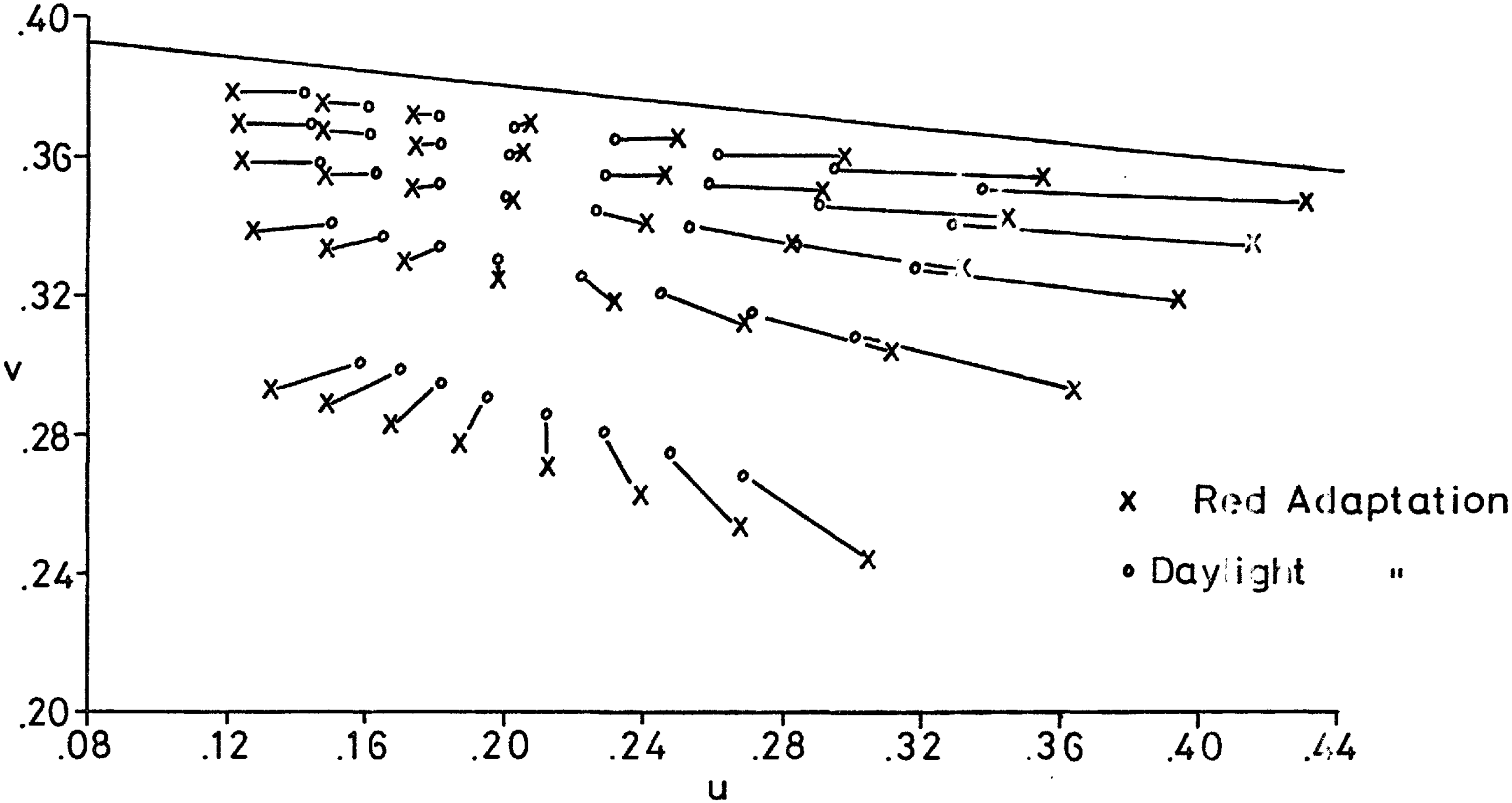


Fig 10.2 Colour Appearance Shifts

$$M = \begin{pmatrix} 0{\cdot}781 & 0{\cdot}155 & 0{\cdot}085 \\ 0{\cdot}121 & 0{\cdot}889 & 0{\cdot}043 \\ 0{\cdot}098 & -0{\cdot}044 & 0{\cdot}873 \end{pmatrix}$$

This gave a set of transformation equations for x,y chromaticity coordinates:-

$$x' = 0{\cdot}696x + 0{\cdot}070y + 0{\cdot}085$$

$$y' = 0{\cdot}078x + 0{\cdot}846y + 0{\cdot}043$$

The results show an overall decrease in sensitivity with the expected effect of a red adaptation lowering the red sensitivity more than the green. This was reported by Wright(1946) in his investigation into adaptation effects. Although the vectors from, for example, the red test colours are directed in one general direction they are not parallel, nor do they converge onto one point in the chromaticity chart. The variation about a mean direction is small but significant. The direction of the appearance shifts confirms that obtained by MacAdam(1955) who obtained his results using the local adaptation method of observation. The magnitude of the shifts reported by MacAdam is, however, much greater than that obtained by the author. This is probably due to the fact that MacAdam used a much larger ten degree field.

The transformation matrix was applied to the set of discrimination data obtained using red adaptation as tabulated in Figure 6.10. The transformed set of data is tabulated in Figure 10.3. In Figures 10.4 - 10.6 the length of the line

Red Adaptation

Line	ΔI						
Line 1	·006	·007	·010	·012	·022	·025	·032	
Line 2	·006	·007	·009	·012	·022			
Line 3	·005	·007	·009	·012	·017			
Line 4	·005	·007	·009	·011	·018	·018	·022	
Line 5	·006	·008	·009	·012	·023			
Line 6	·005	·006	·009	·014	·018			
Line 7	·006	·007	·009	·011	·018	·014	·016	
Line 8	·006	·008	·009	·011	·017			
Line 9	·007	·008	·011	·012	·018			
Line 10	·009	·010	·012	·013	·020	·015	·017	
Line 11	·018	·016	·016	·017	·020	·022	·023	·029
Line 12	·018	·016	·017	·014	·014	·015	·016	·019
Line 13	·021	·019	·015	·016	·014	·016	·017	·022
Line 14	·024	·021	·016	·017	·016	·014	·014	·017
Line 15	·020	·018	·018	·016	·013	·015	·014	·020
Line 16	·026	·022	·019	·018	·016	·015	·018	·017
Line 17	·011	·011						
Line 18	·009	·009						

Fig 10.3

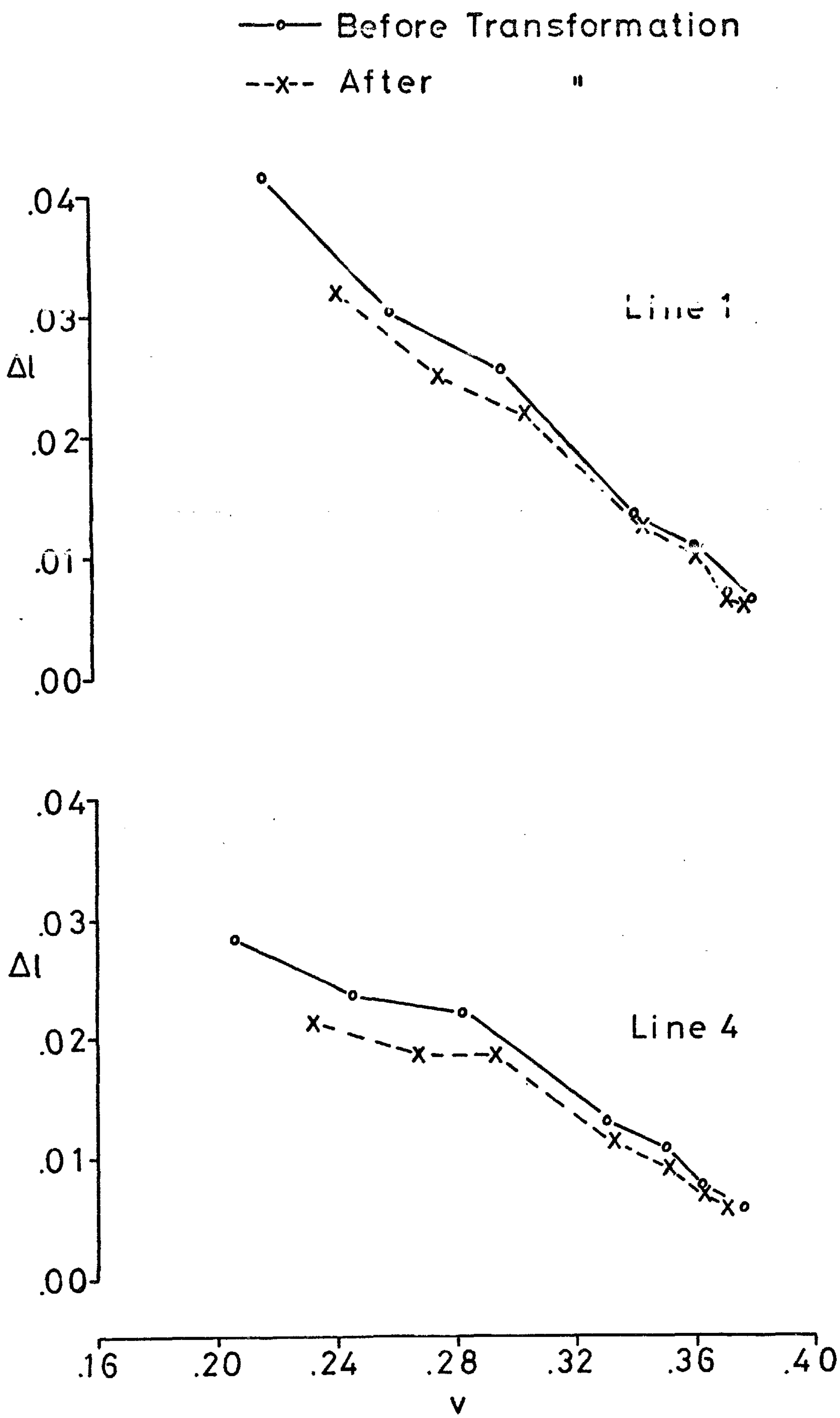

Before Transformation
After "
Line 1
Line 4
ΔI
.04
.03
.02
.01
.00
.16
.20
.24
.28
.32
.36
.40
v

Fig 10.4

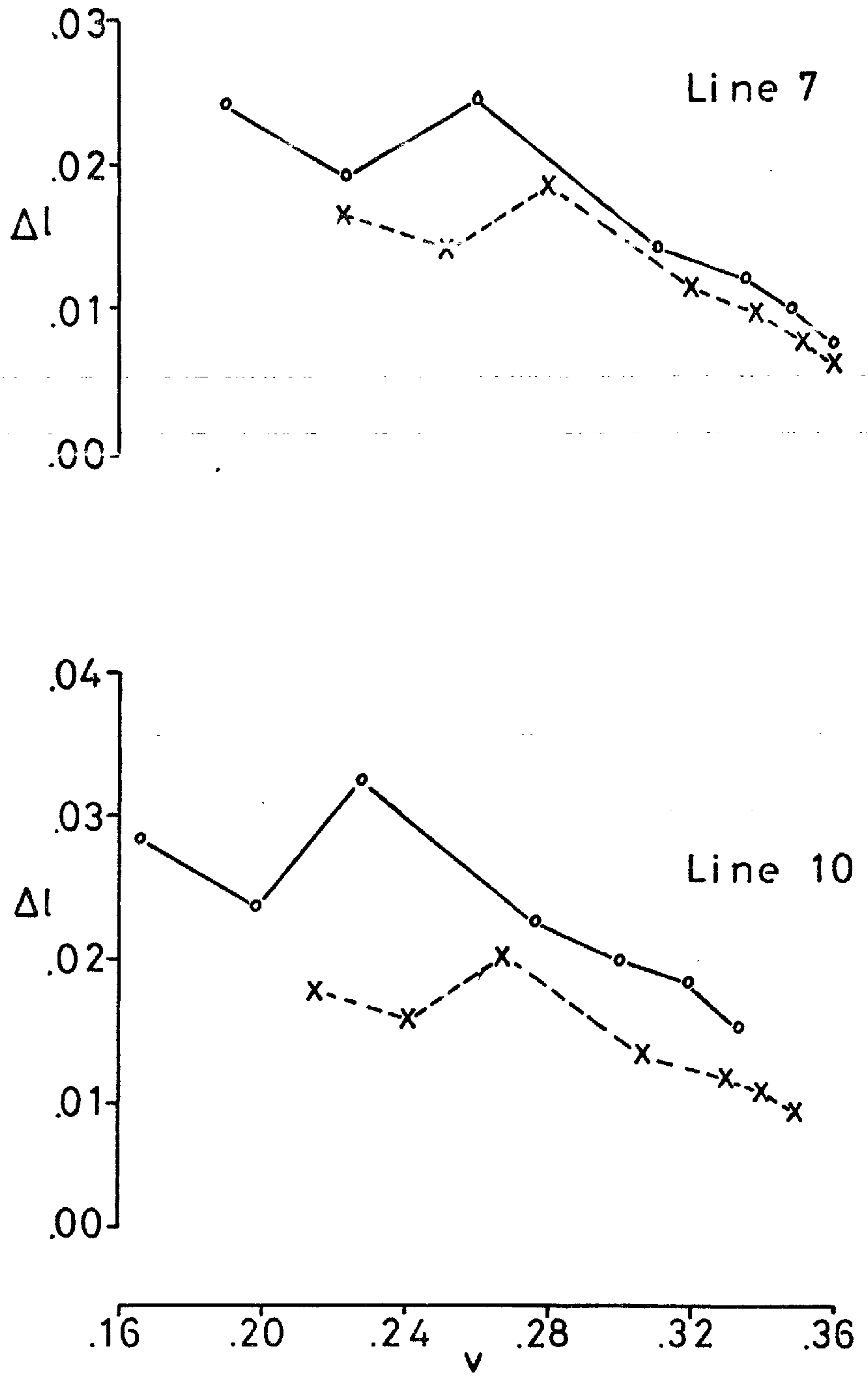


Fig 10. 5

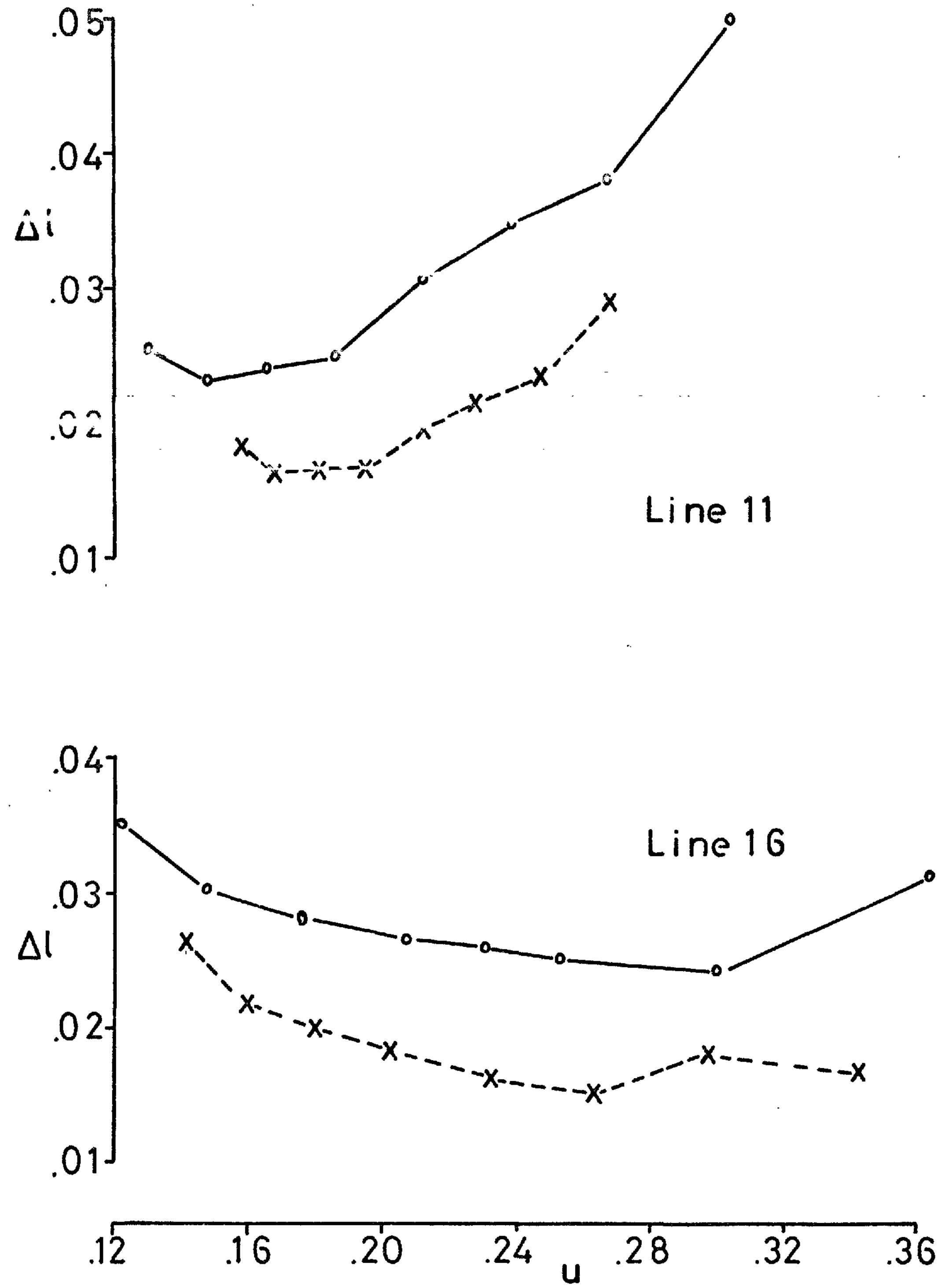


Fig 10.6

representing the just noticeable colour difference is plotted as a function of the v chromaticity coordinate of the sampling point for lines 1 to 10 and as a function of the u chromaticity coordinate of the sampling point for lines 11 to 16. The data after appearance transformation are compared with the data before transformation. Only data for lines 1, 4, 7, 10, 11 and 16 is shown plotted in this way as this is representative of the complete set. The similarity between the two sets of data is not good particularly for the data obtained from colours involving mixtures of red-blue with green-blue (lines 11 to 16) where the appearance corrected lengths are persistently smaller than the original lengths. This would imply that the u,v chromaticity diagram cannot be used directly as a means of representing data obtained under red adaptation, and the resulting graph be considered in terms of absolute uniformity. This is because the data, after appearance correction to its relative daylight appearance, is still distorted relative to the daylight adaptation results. It is probable that this distortion could be overcome by a suitable adjustment of the axis scales.

10.3 The Results of a Change from Green Adaptation to Daylight Adaptation

As before, the instrument readings obtained from the observation of colour appearance shifts of the test colours when the adaptation was changed from green to that representing daylight, were, after conversion to tristimulus values, applied to the least squares fitting programme. The resulting matrix was then applied to the test colours to give a smoothed set of appearance shifts as tabulated in Figure 10.7. The corresponding appearance shift vectors are shown plotted in the u,v chromaticity diagram in Figure 10.8. The transformation matrix given by the computer programme was:-

$$M = \begin{pmatrix} 0{\cdot}900 & 0{\cdot}108 & 0{\cdot}066 \\ 0{\cdot}022 & 0{\cdot}924 & 0{\cdot}077 \\ 0{\cdot}077 & -0{\cdot}032 & 0{\cdot}857 \end{pmatrix}$$

This gave a corresponding pair of transformation equations for the x,y chromaticity coordinates:-

$$x' = 0{\cdot}834x + 0{\cdot}042y + 0{\cdot}066$$

$$y' = -0{\cdot}055x + 0{\cdot}847y + 0{\cdot}077$$

The results again showed the expected trends with a greater overall decrease in sensitivity in the green region of the chromaticity diagram compared with the red and blue. Again the vectors are not parallel nor do they converge onto any particular point.

The transformation matrix was applied to the discrimination data obtained using green adaptation and shown tabulated in Figure 6.11 to give the lengths representing the just noticeable colour differences as they appeared in daylight adaptation. These lengths are shown tabulated in Figure 10.9. The individual lengths are shown plotted as a function of the respective coordinate of the sampling point in Figures 10.10 - 10.12. The data for lines 1, 4, 7, 10, 11 and 16 are plotted as representative of the complete

U = .1448 V = .3759	.1679 .3730	.1936 .3698	.2224 .3661	.2619 .3612	.3041 .3558	.3533 .3496	.4173 .3415
.1460 .3688	.1682 .3656	.1928 .3621	.2203 .3582	.2578 .3528	.2974 .3472	.3434 .3406	.4027 .3322
.1476 .3585	.1685 .3550	.1917 .3512	.2173 .3470	.2520 .3412	.2883 .3352	.3299 .3283	.3828 .3195
.1503 .3412	.1692 .3373	.1898 .3331	.2124 .3285	.2425 .3223	.2736 .3159	.3085 .3088	.3521 .2998
.1561 .3044	.1705 .3002	.1859 .2958	.2024 .2911	.2238 .2850	.2452 .2788	.2685 .2722	.2963 .2642

Fig 10.7

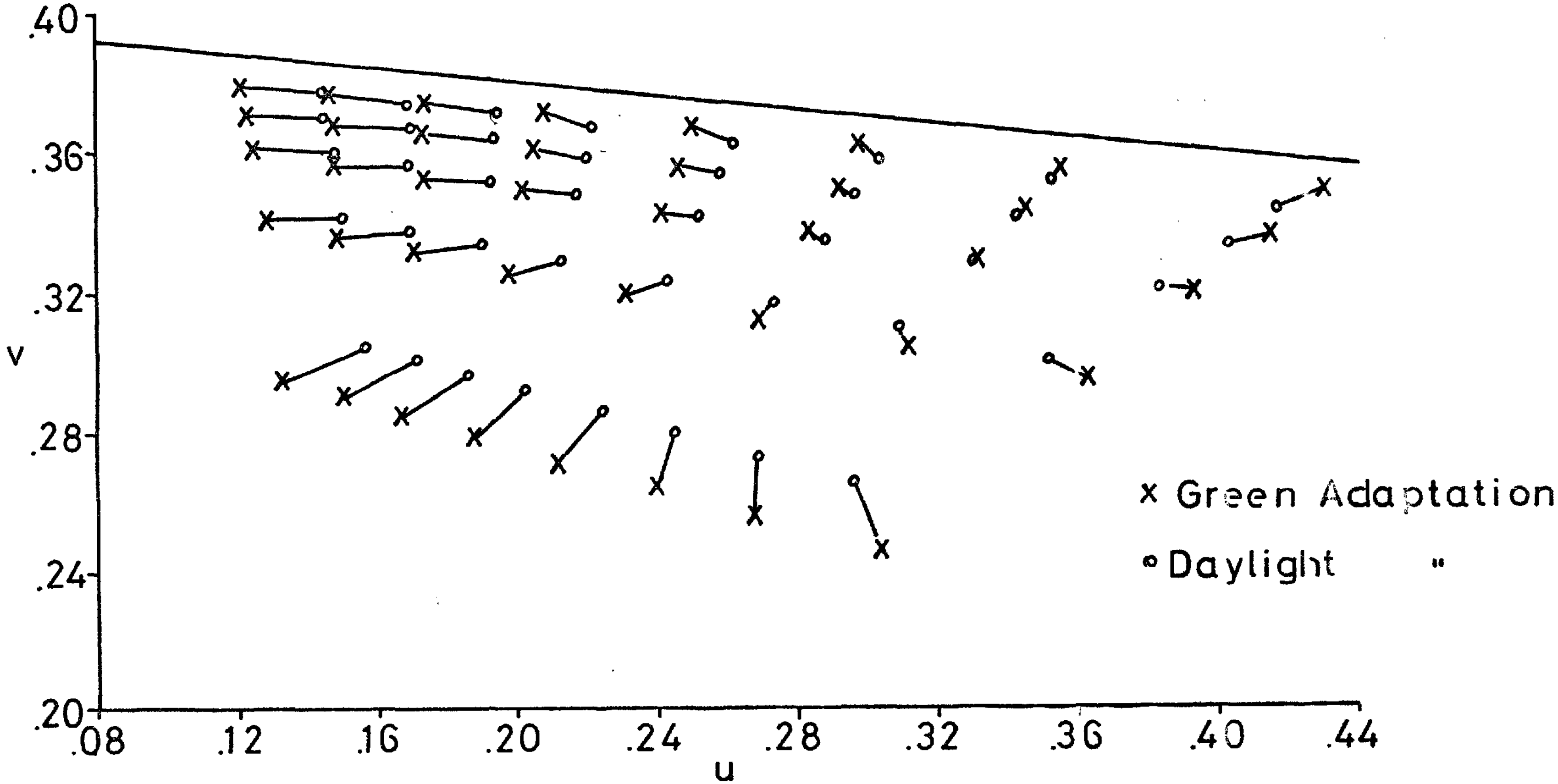


Fig 10.8 Colour Appearance Shifts

Green. Adaptation

Line	ΔI							
Line 1	·004	·007	·008	·014	·022	·019	·024	
Line 2	·005	·006	·007	·010	·016			
Line 3	·004	·006	·007	·010	·014			
Line 4	·005	·006	·007	·009	·014	·012	·015	
Line 5	·005	·006	·007	·009	·011			
Line 6	·007	·008	·009	·010	·015			
Line 7	·007	·009	·010	·012	·013	·011	·012	
Line 8	·008	·011	·013	·015	·016			
Line 9	·010	·013	·016	·017	·017			
Line 10	·014	·019	·021	·023	·022	·018	·017	
Line 11	·015	·014	·012	·011	·010	·013	·014	·022
Line 12	·021	·016	·013	·013	·013	·018	·023	·030
Line 13	·020	·016	·013	·013	·015	·017	·023	·036
Line 14	·021	·017	·015	·015	·017	·022	·028	·037
Line 15	·020	·014	·015	·016	·018	·022	·027	·040
Line 16	·022	·017	·016	·019	·019	·023	·033	·041
Line 17	·010	·011						
Line 18	·007	·010						

Fig 10.9

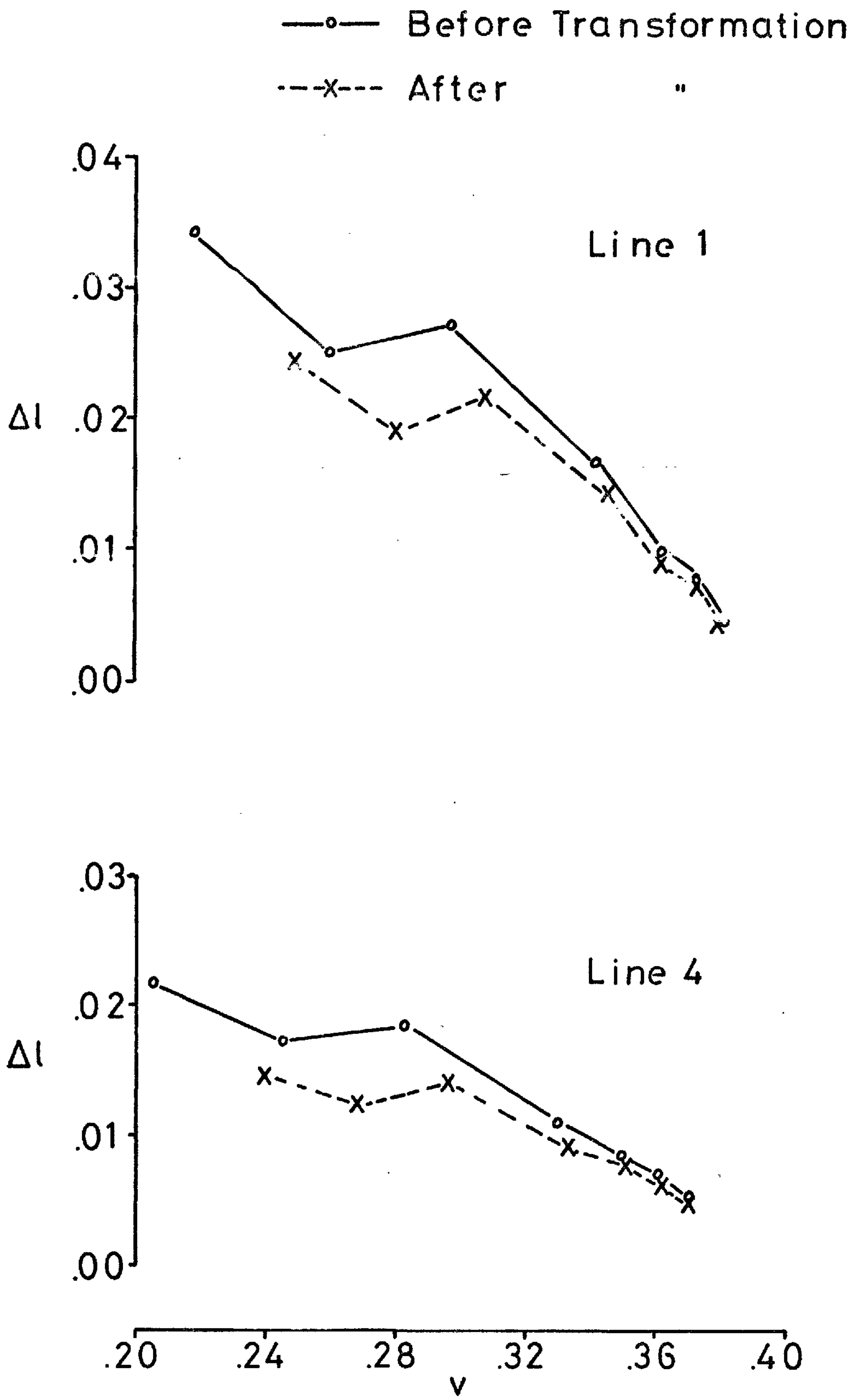

Before Transformation
After "
Line 1
.04
.03
.02
.01
.00
Δl
Line 4
.03
.02
.01
.00
Δl
.20
.24
.28
.32
.36
.40
v

Fig 10.10

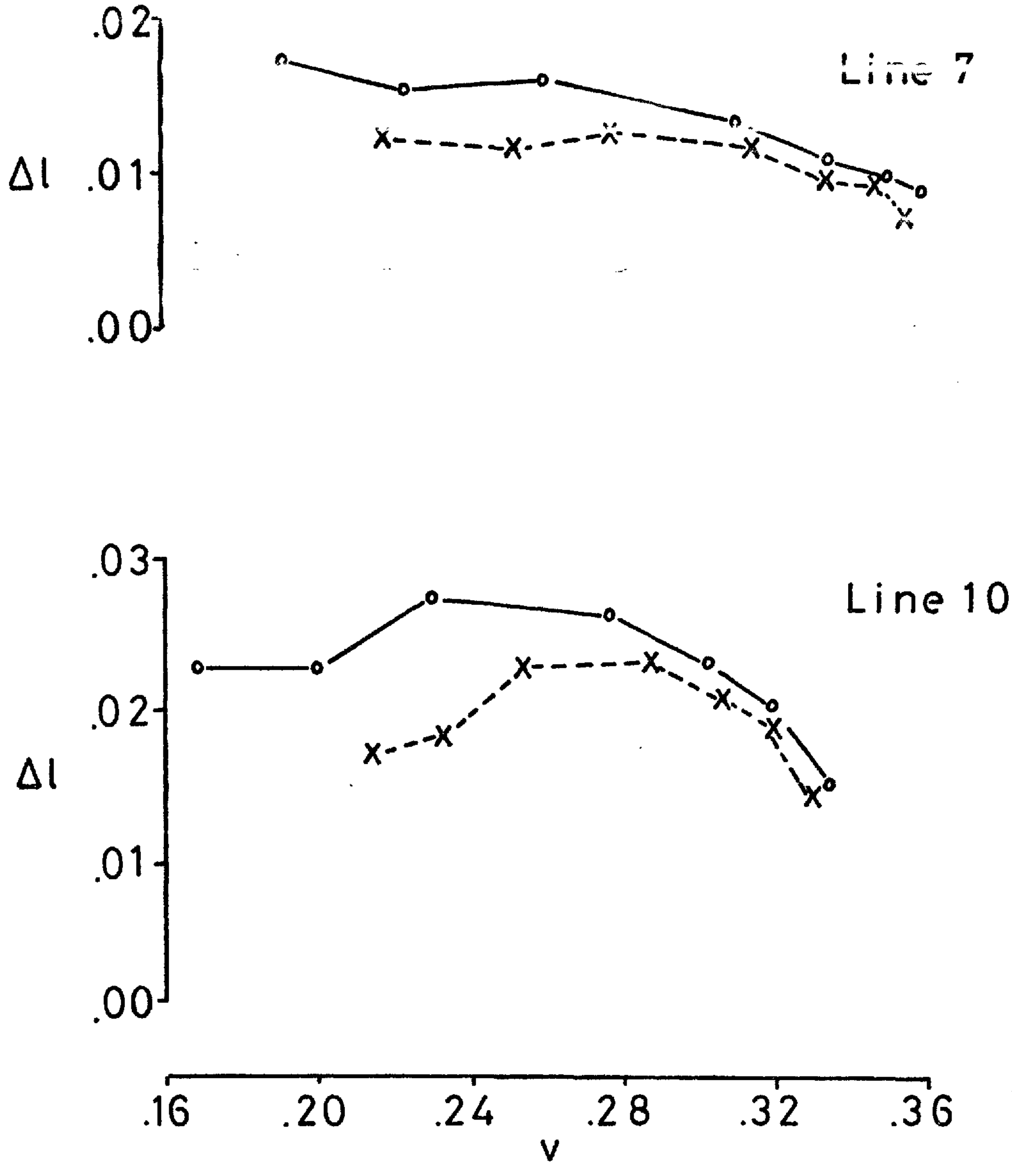


Fig 10.11

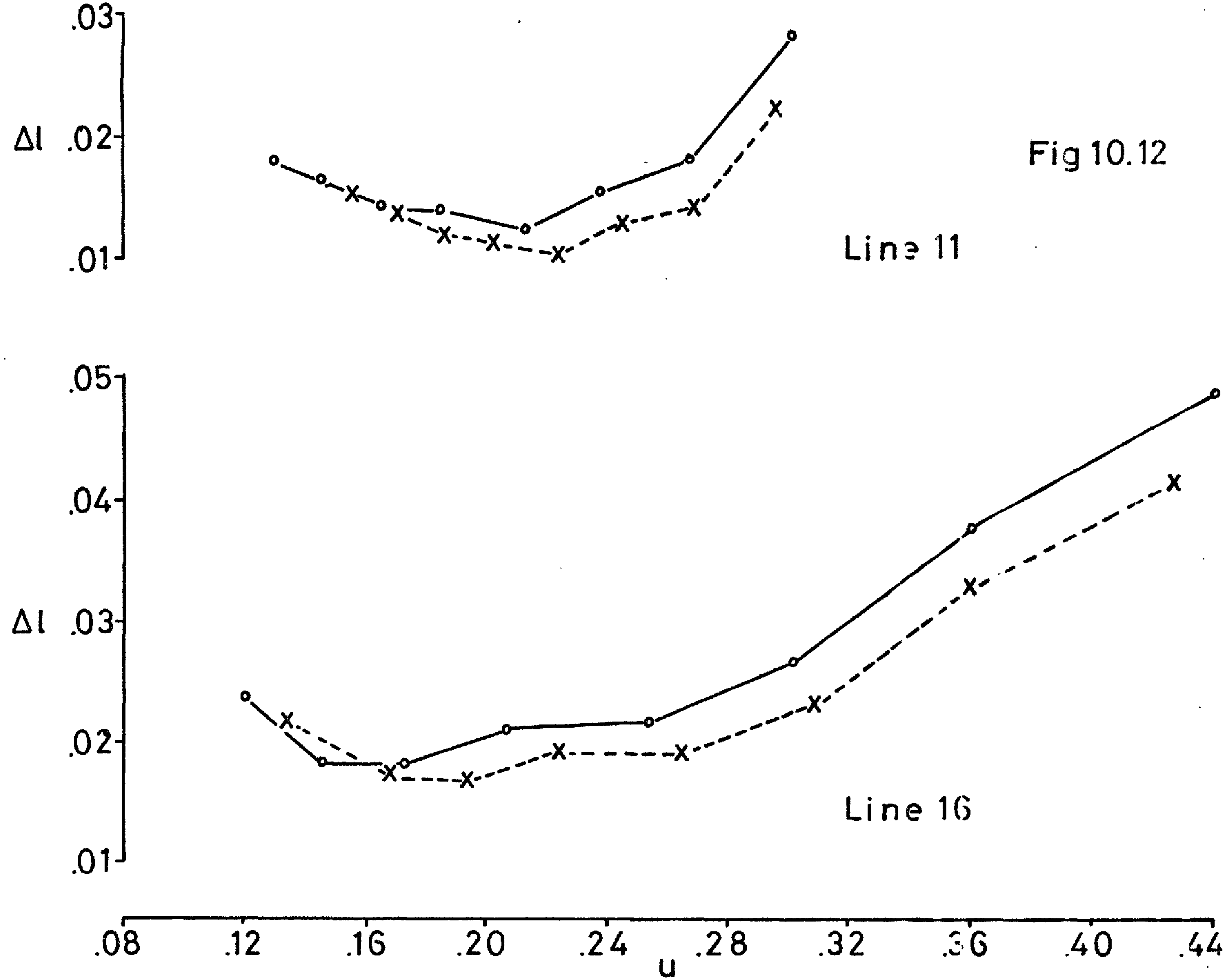


Fig 10.12
Δl
.03
.02
.01
Line 11
Δl
.05
.04
.03
.02
.01
Line 16
.08
.12
.16
.20
.24
.28
.32
.36
.40
.44
u

set of data. The data before transformation are shown compared with the data after transformation. The fit between the two sets of data is better than the corresponding fit obtained with the red adaptation but it is not as good as the fit obtained with the corresponding data for tungsten adaptation. This is especially true in the central region of colour space which represents the more common desaturated colours.

10.4 The Results of a Change from Blue Adaptation to Daylight Adaptation

As before, the smoothed set of results was obtained using the instrument readings. After conversion to tristimulus values they were applied to the least squares fitting programme. The array of appearance transformed test colours is shown tabulated in Figure 10.13 and the corresponding appearance shift vectors are shown plotted in the u,v chromaticity diagram in Figure 10.14. The transformation matrix given by the computer programme was:-

$$M = \begin{pmatrix} 0{\cdot}817 & 0{\cdot}200 & 0{\cdot}116 \\ 0{\cdot}112 & 0{\cdot}854 & 0{\cdot}139 \\ 0{\cdot}072 & -0{\cdot}053 & 0{\cdot}745 \end{pmatrix}$$

This gave a set of transformation equations for x,y chromaticity coordinates:-

$$x' = 0{\cdot}701x + 0{\cdot}084y + 0{\cdot}116$$

$$y' = -0{\cdot}027x + 0{\cdot}715y + 0{\cdot}139$$

U =	.1642	.1837	.2050	.2284	.2598	.2921	.3287	.3745
V =	.3770	.3745	.3718	.3688	.3648	.3607	.3560	.3502
	.1650	.1836	.2039	.2261	.2556	.2859	.3199	.3622
	.3707	.3680	.3651	.3620	.3578	.3535	.3487	.3428
	.1660	.1835	.2023	.2228	.2499	.2774	.3086	.3456
	.3618	.3589	.3559	.3526	.3482	.3438	.3338	.3327
	.1678	.1832	.1997	.2175	.2407	.2640	.2895	.3203
	.3471	.3441	.3408	.3374	.3329	.3284	.3234	.3174
	.1713	.1827	.1947	.2073	.2234	.2391	.2558	.2754
	.3173	.3143	.3112	.3079	.3037	.2997	.2953	.2902

Fig 10.13

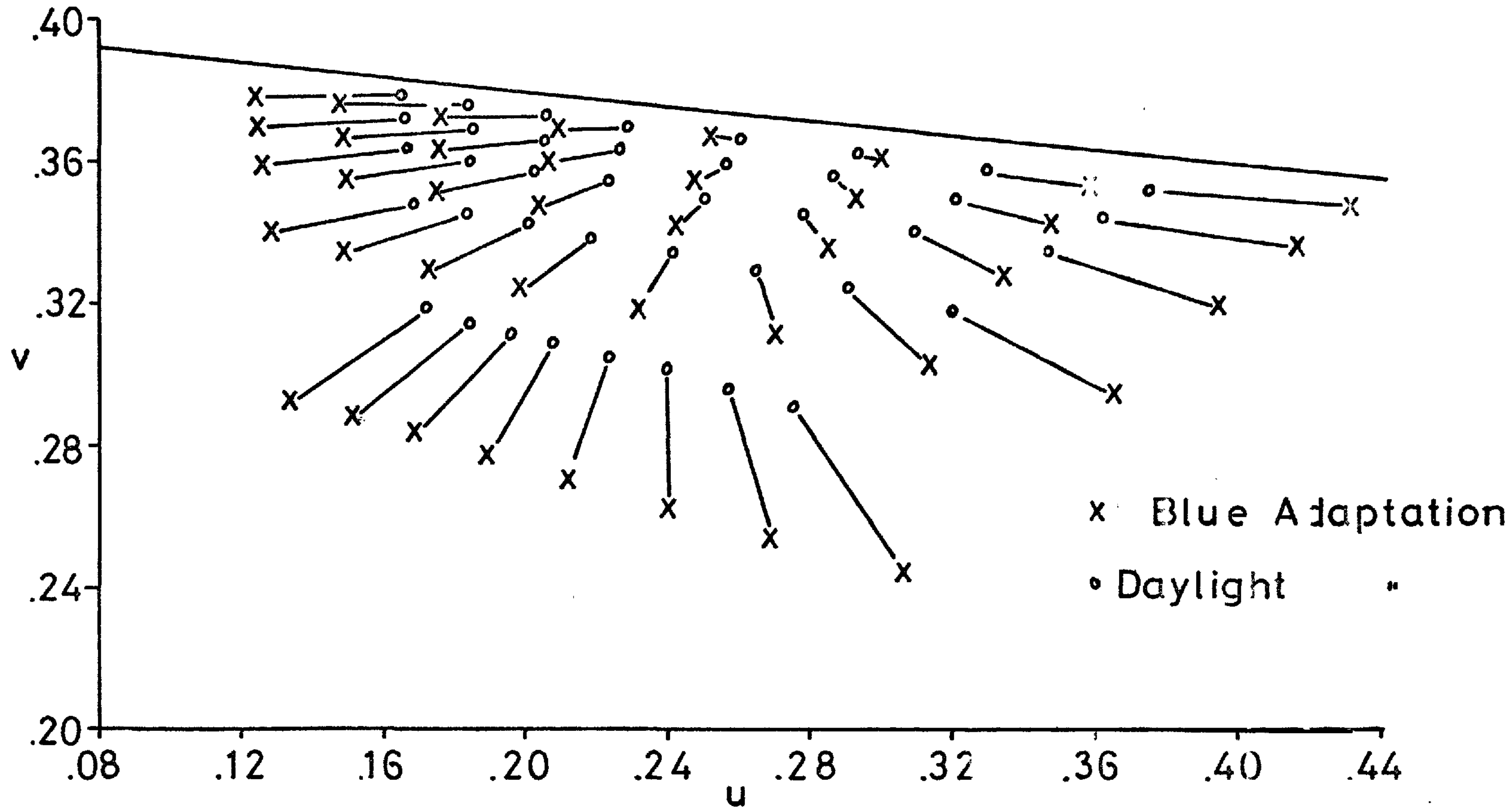


Fig 10.14 Colour Appearance Shifts

These results showed the expected overall decrease in blue sensitivity although there was a decrease in the relative sensitivity of all three mechanisms.

The transformation matrix was applied to the discrimination data obtained using blue adaptation and shown tabulated in Figure 6.12. The resulting data represented the just noticeable colour differences as they would appear with daylight adaptation. The new lengths are shown tabulated in Figure 10.15. The individual lengths for lines 1, 4, 7, 10, 11 and 16 are shown plotted as a function of the coordinate of their respective sampling point in Figures 10.16 - 10.18. The data are shown plotted together with the corresponding data before appearance transformation.

The fit between the two sets of data is not as good as any of the previous comparisons between equivalent sets of data. This is particularly true for colours in the centre of the chromaticity diagram where previous comparisons have been considerably better.

Thus it has been shown that the u,v chromaticity diagram is not a good means of representing the data obtained using green and blue adaptation as was also the case for data obtained using red adaptation. It can be noticed too, that there is little overall improvement in the uniformity of the data after they have been converted to their relative daylight appearance. If there were an improvement in the uniformity it would be expected that the graphs of the length of the bar representing the just noticeable colour difference as a function of the coordinate of the sampling point would show some signs of becoming more horizontal. With the exception of the blue adaptation results, which show slight levelling, there is no great improvement in uniformity.

Blue Adaptation

Line	ΔI							
Line 1	·006	·006	·006	·008	·010	·012	·016	
Line 2	·005	·005	·006	·006	·008			
Line 3	·007	·006	·006	·007	·009			
Line 4	·005	·005	·005	·006	·008	·008	·010	
Line 5	·006	·005	·006	·007	·008			
Line 6	·006	·006	·006	·007	·008			
Line 7	·009	·008	·009	·009	·009	·009	·011	
Line 8	·009	·008	·009	·010	·010			
Line 9	·012	·012	·013	·012	·013			
Line 10	·016	·017	·017	·017	·015	·015	·014	
Line 11	·014	·011	·009	·008	·008	·010	·011	·013
Line 12	·022	·013	·012	·011	·010	·012	·012	·016
Line 13	·026	·019	·016	·014	·013	·012	·014	·017
Line 14	·015	·015	·012	·012	·013	·014	·018	·026
Line 15	·014	·013	·011	·012	·012	·013	·015	·025
Line 16	·014	·014	·012	·015	·013	·017	·022	·027
Line 17	·007	·007						
Line 18	·005	·007						

Fig 10.15

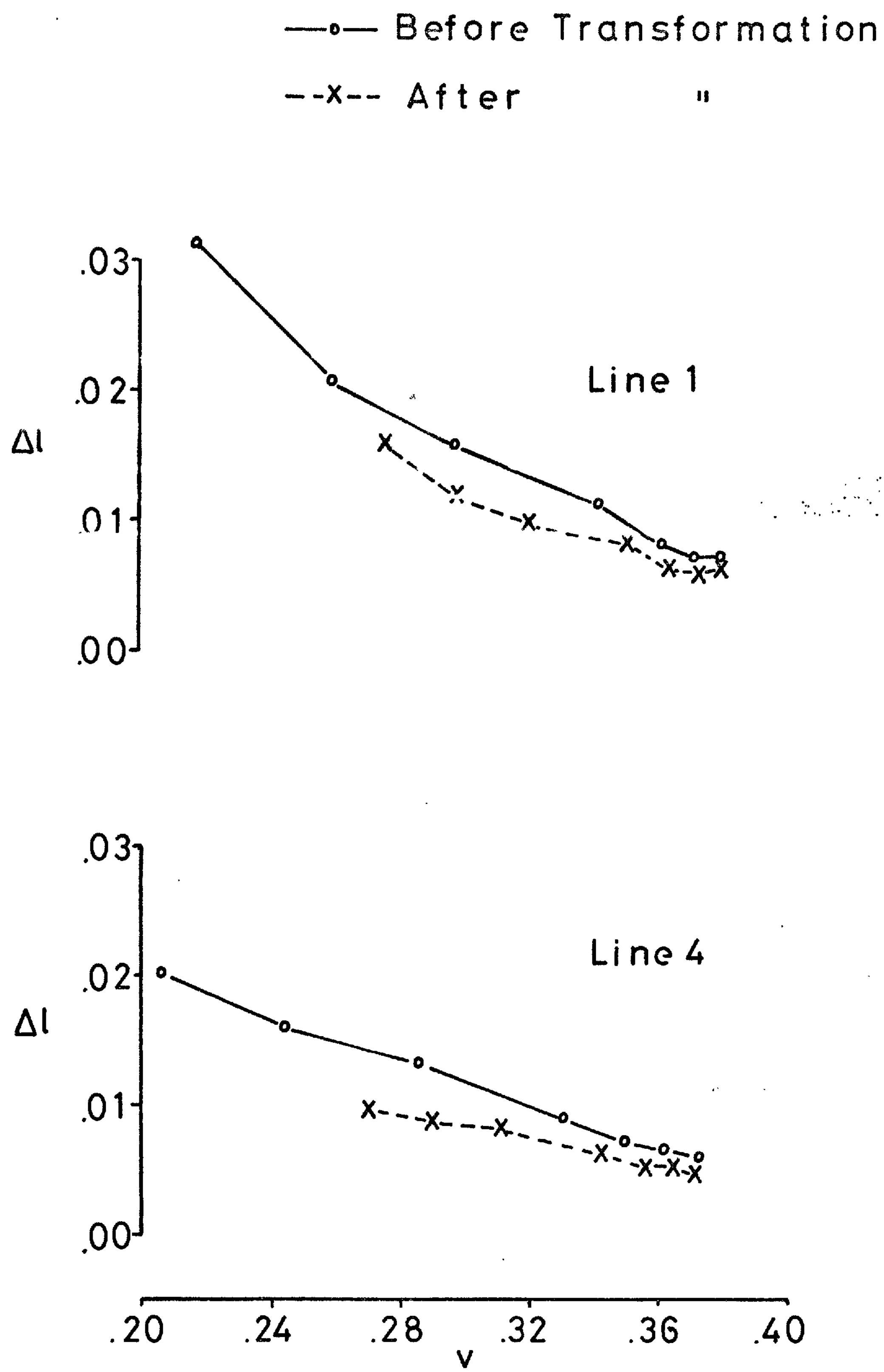

Before Transformation
After "
Line 1
Line 4
Δl
.03
.02
.01
.00
.20
.24
.28
.32
.36
.40
v

Fig 10.16

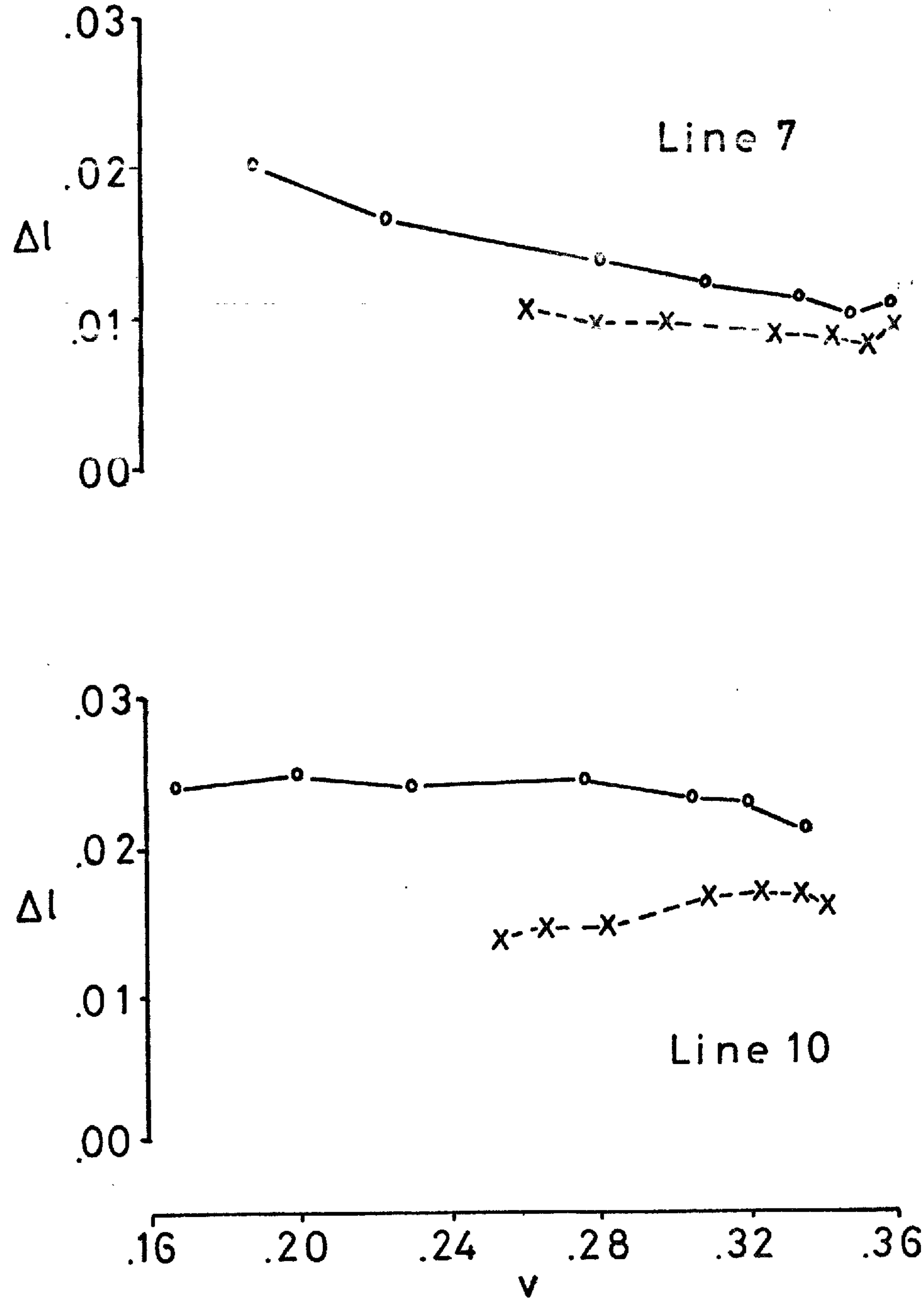


Fig 10. 17

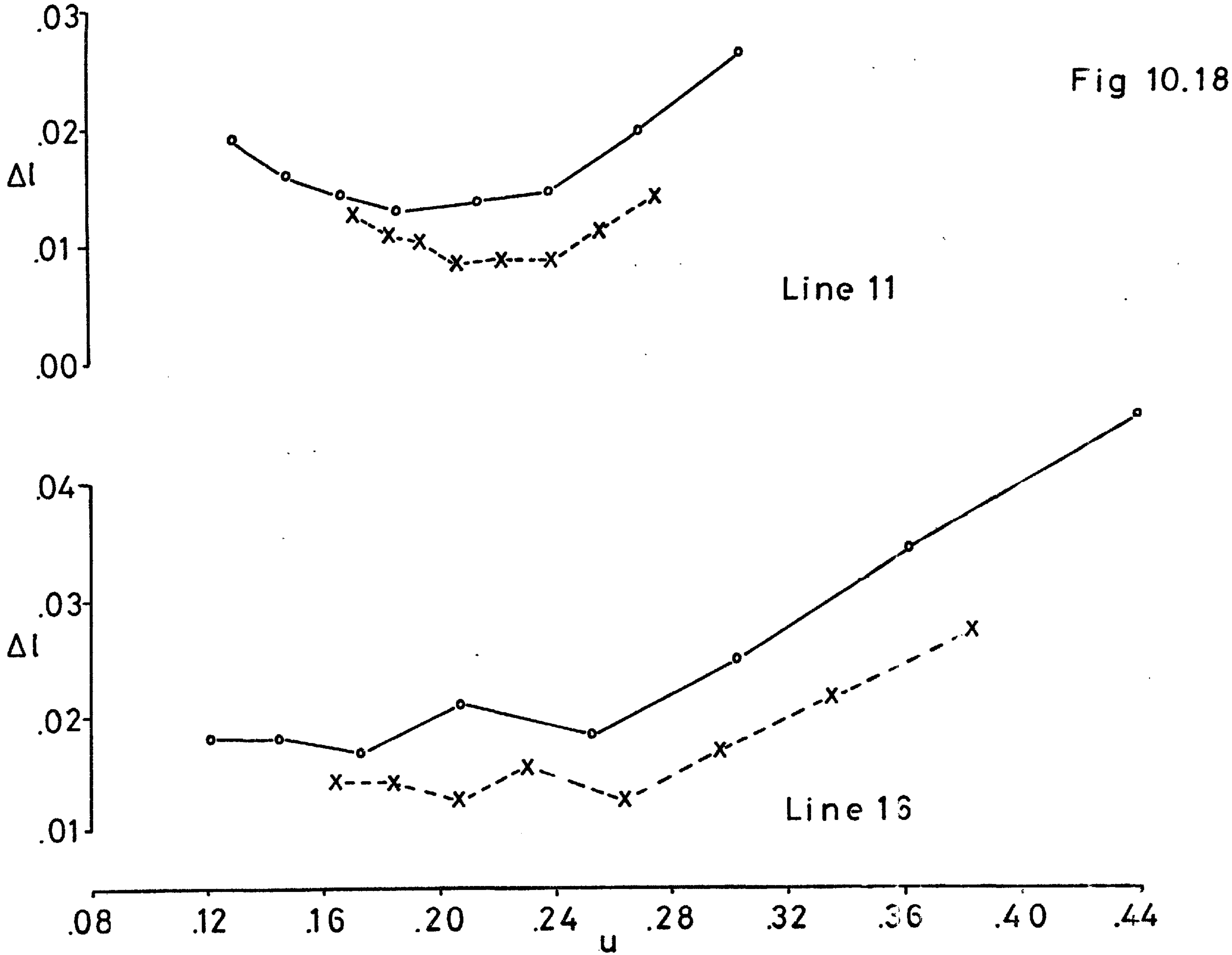


Fig 10.18
.03
.02
.01
.00
ΔI
Line 11
.04
.03
.02
.01
ΔI
Line 16
.08
.12
.16
.20
.24
.28
.32
.36
.40
.44
u

10.5 Theoretical Interpretation of the Results

These results for coloured adaptation appearance shifts relative to daylight adaptation would appear to agree with the simple theory outlined by Hunt (1950) to explain similar shifts involving a change from light adaptation to dark adaptation. The normal sensation is regarded as the saturated one which occurs under light adaptation conditions. When the state of the adaptation is changed from light to red adaptation the red sensitivity function stays relatively the same and the green and blue sensitivities increase. Thus when the eye is light adapted, a spectral yellow may produce equal red and green responses but a negligible blue signal; while when the eye is red adapted, the relative magnitude of the green and blue signals increases causing the yellow to appear much more green due to the increased green sensitivity and slightly less saturated than the original yellow due to the increased blue sensitivity. When the eye is green adapted the relative magnitude of the red and blue signals increases causing the yellow to appear more red due to the increase in red sensitivity and slightly less saturated due to the increase in blue sensitivity. For blue adaptation the relative magnitude of the red and green signals is increased causing the yellow test colour still to look yellow but to appear slightly more saturated.

10.6 Further Considerations

The array of u chromaticity coordinates after transformation, u', was plotted as a function of the u coordinate before transformation, u, as were the results for tungsten adaptation and dark adaptation. This was done for each of the three coloured adaptations separately.

Similarly graphs were plotted for the respective pairs of v chromaticity coordinates. These six graphs are shown in Figures 10.19 - 10.24. For clarity only the points representing the ends of lines 11 to 18 are shown. The points that lie between the end points all fall on the straight line joining the end points. The lines representing the best straight line through the points are also shown. Their gradients were:-

Red	u coordinate	$0{\cdot}59 \pm 0{\cdot}01$
	v coordinate	$0{\cdot}79 \pm 0{\cdot}01$
Green	u coordinate	$0{\cdot}86 \pm 0{\cdot}01$
	v coordinate	$0{\cdot}73 \pm 0{\cdot}01$
Blue	u coordinate	$0{\cdot}65 \pm 0{\cdot}01$
	v coordinate	$0{\cdot}56 \pm 0{\cdot}01$

None of these pairs of gradients is such that the test colours are invariant to a change of adaptation and obey the ideal equations:-

$$u' = 1{\cdot}00u + C_1$$

$$v' = 1{\cdot}00v + C_2$$

Thus this method of representing the appearance shifts would seem to add weight to the argument that the u,v chromaticity diagram cannot be used as a means of representing the above data and the subsequent plot be considered in terms of absolute uniformity.

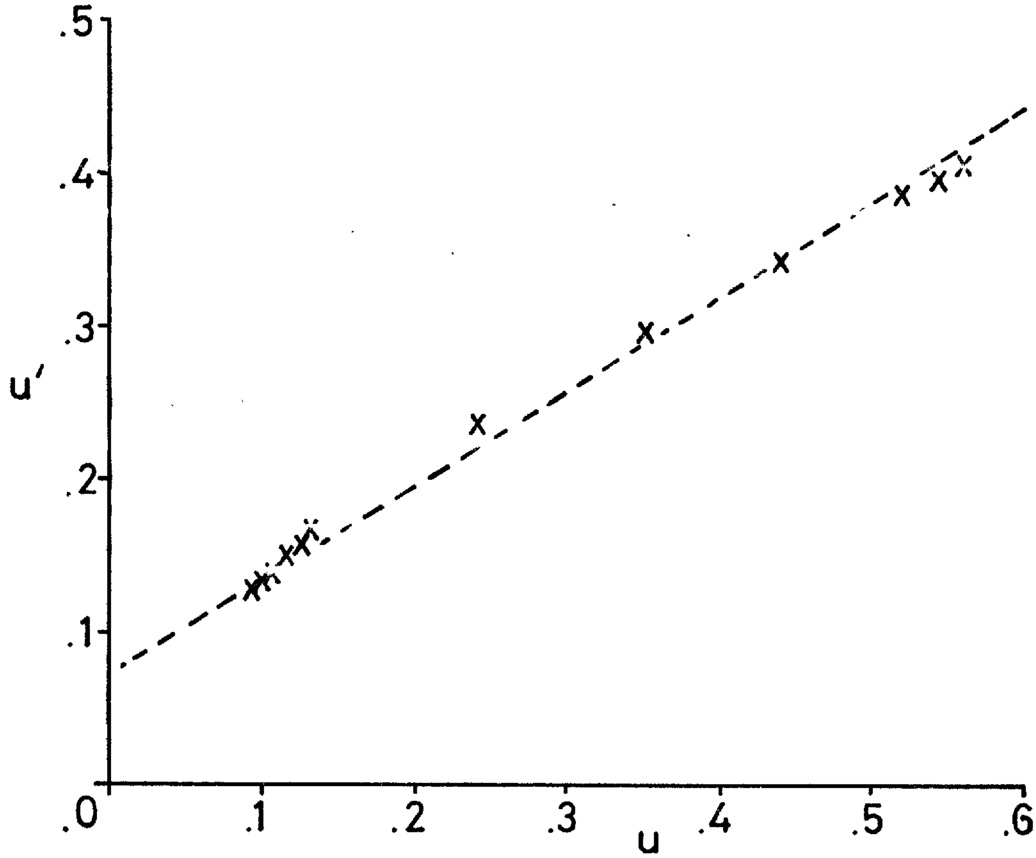


Fig 10.19

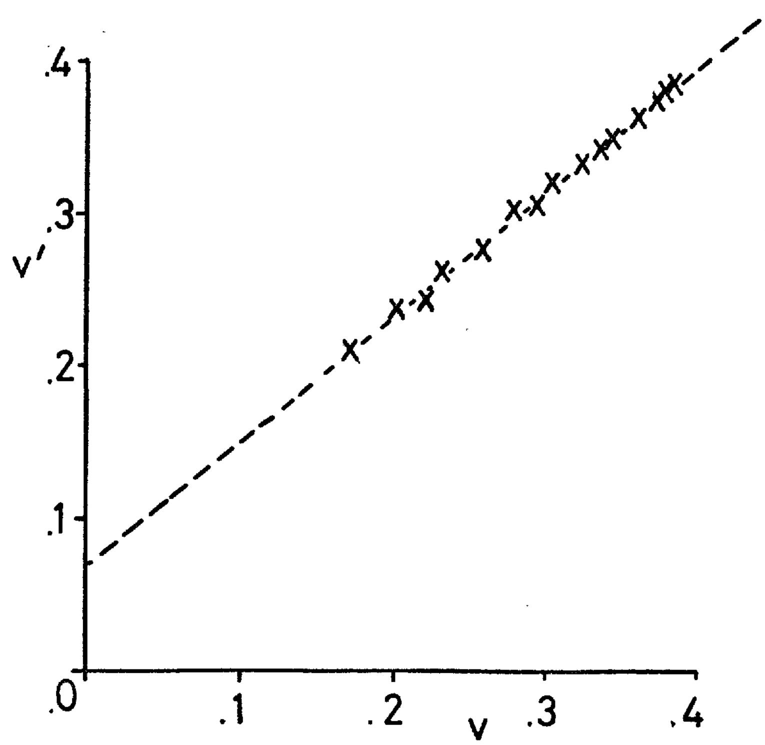


Fig 10.20

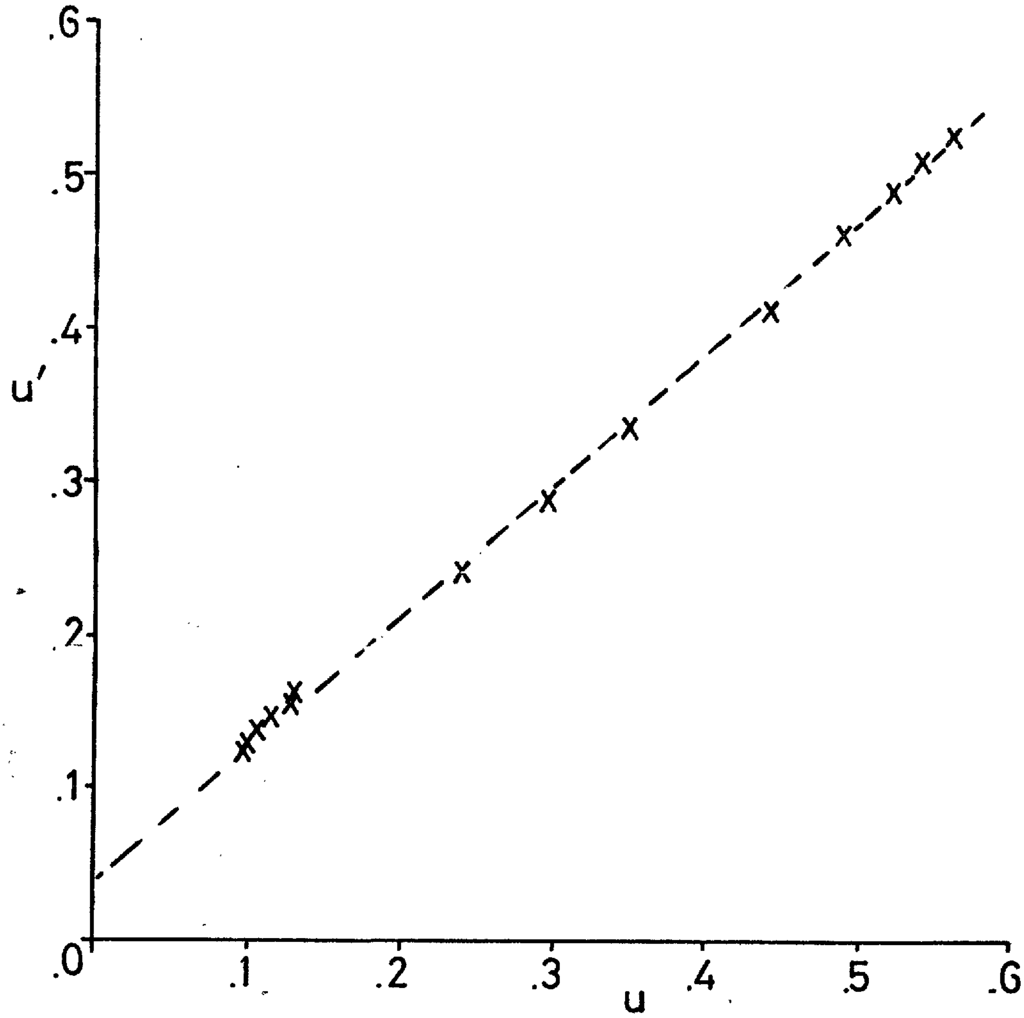


Fig 10.21

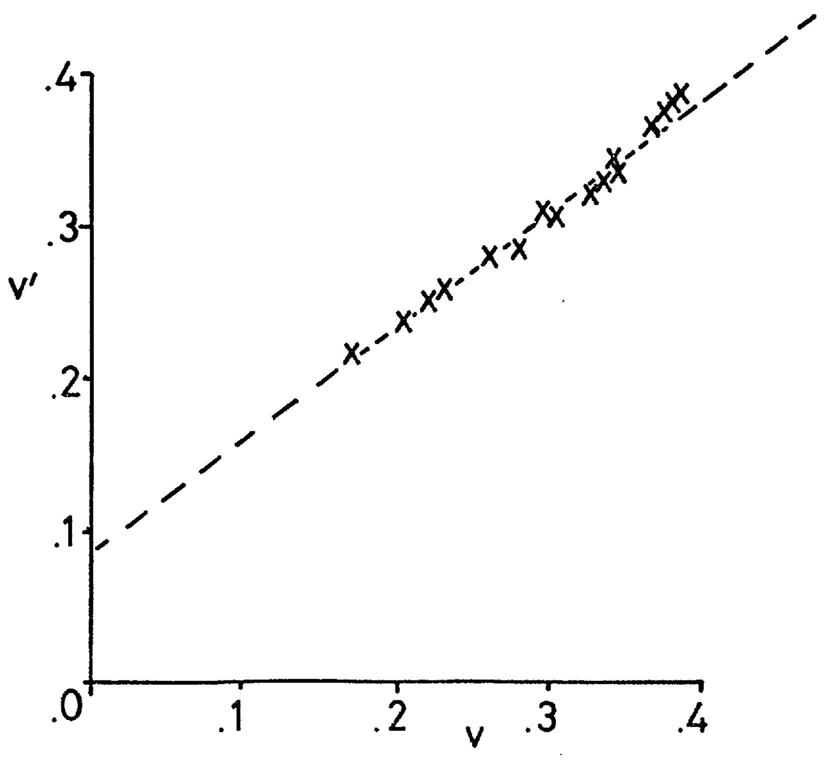


Fig 10.22

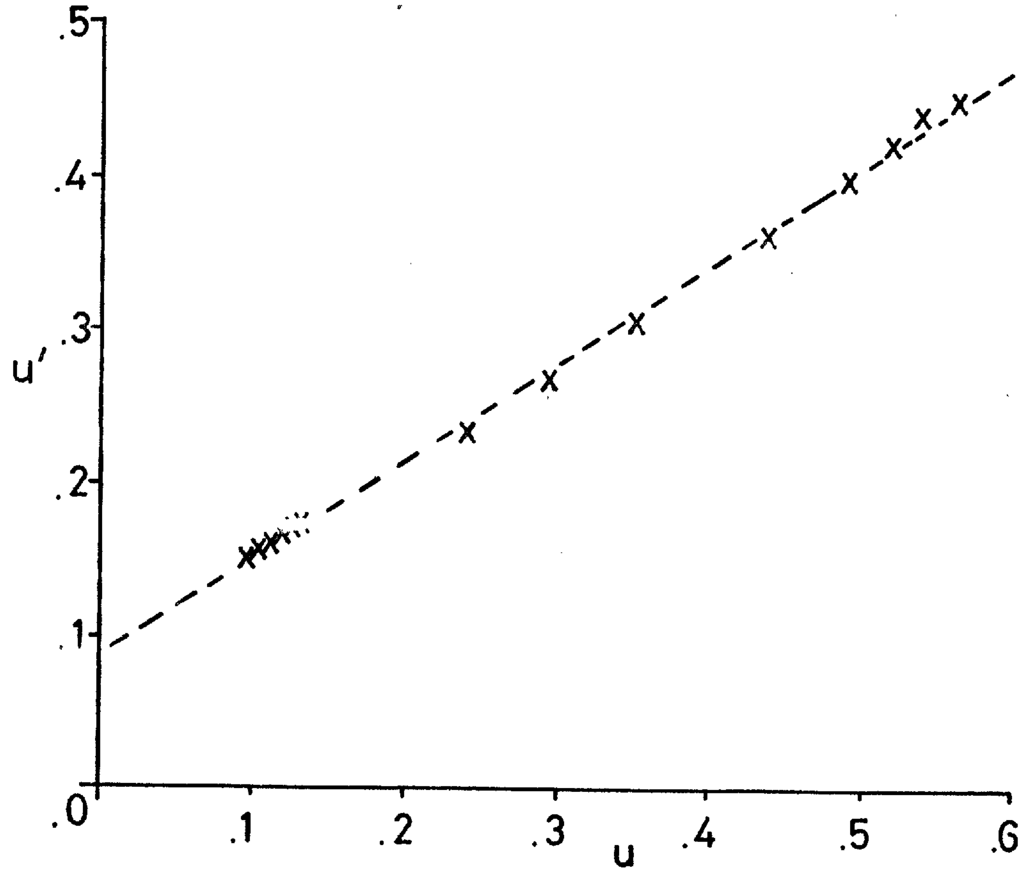


Fig 10.23

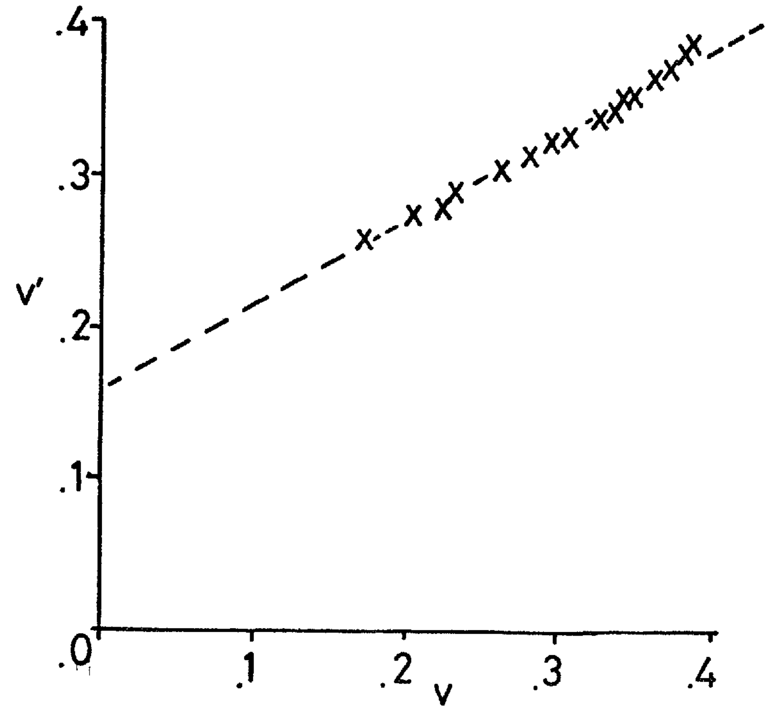


Fig 10.24

Chapter 11

Summary of Experimental Procedure, Results and Conclusions

11.1 Introduction

The results of the observation of just noticeable colour differences under various adaptation conditions are summarised. The results of the observation of colour appearance shifts of forty test colours, perceived when the state of adaptation was changed from various initial conditions to daylight adaptation, and the subsequent application of a statistically derived appearance shift matrix to the discrimination data, are also reported. The implications of this colour appearance shift with respect to the use of the u,v chromaticity diagram as a means of representing and comparing the results is discussed.

In the final section the physiological structure of the retina has been briefly outlined and the electrical response of each cell type considered. The possible levels at which adaptation, colour appearance effects and colour discrimination effects take place has been outlined.

11.2 A Summary of the Experimental Procedure

The plan of the experimental work is best described with reference to the schematic diagram shown in Figure 11.1.

Consider a stimulus with a spectral distribution P_λ. ~~This spectral distribution may be considered to consist of two components; one due to the spectral distribution of the test field, $P_{T\lambda}$ and the other due to the adaptation under which the test field is viewed, which may have a spectral distribution $P_{A\lambda}$.~~

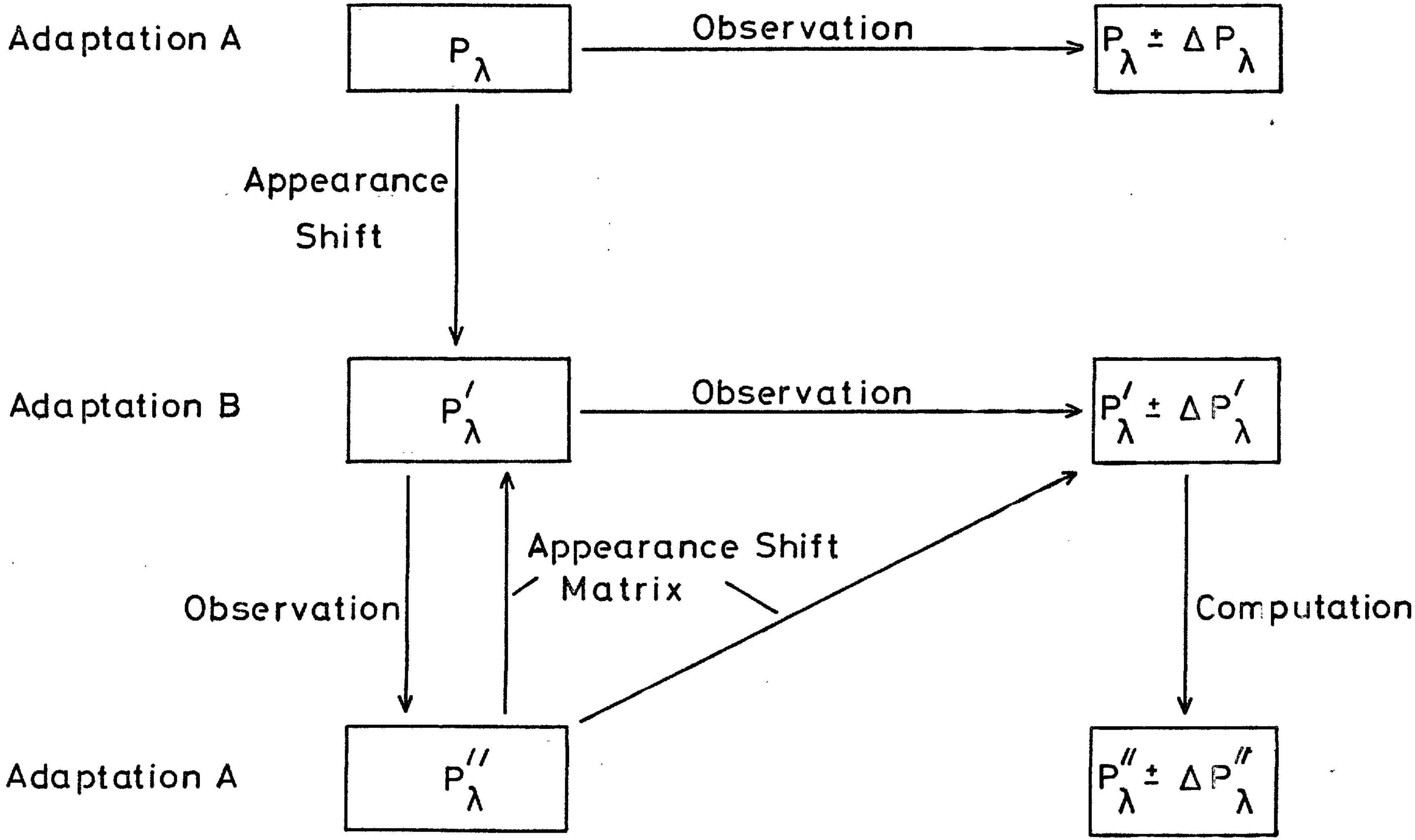

Adaptation A
P_λ
Observation
$P_\lambda \pm \Delta P_\lambda$
Appearance Shift
Adaptation B
P'_λ
Observation
$P'_\lambda \pm \Delta P'_\lambda$
Observation
Appearance Shift Matrix
Computation
Adaptation A
P''_λ
$P''_\lambda \pm \Delta P''_\lambda$

Fig 11.1

The initial adaptation, state A, was simulated daylight adaptation with a colour temperature of 6500^{o}K. ~~The component of P_λ due to the test field, $P_{T\lambda}$,~~ ρ_λ was then changed until ~~P_λ~~ it become $P_\lambda + \Delta P_\lambda$. The new stimulus $P_\lambda + \Delta P_\lambda$ was judged, by the observer, to be just noticeably different from the initial stimulus P_λ. The difference between the two stimuli, ΔP_λ, involved a change in the colour content only; the brightness of the two stimuli and the state of adaptation under which they were viewed remained constant.

This same observation could be made under a different adaptation, state B. The same initial stimulus, P_λ, while it could still be defined by the same set of chromaticity coordinates, would appear to have altered in colour. The sensation perceived has changed because of a modification in the spectral sensitivity of the response of the eye. Thus the spectral distribution P_λ has changed to P'_λ. ~~The change in colour appearance was due to the change in adaptation component of P'_λ which is $P'_{A\lambda}$.~~ As before P'_λ was changed until a colour with spectral distribution $P'_\lambda + \Delta P'_\lambda$ was obtained which was judged by the observer to be just noticeably different from P'_λ.

The first set of experiments was designed to measure the just noticeable differences ΔP_λ for many initial stimuli P_λ viewed under adaptation state A and then to measure the just noticeable differences $\Delta P'_\lambda$, for many initial stimuli P'_λ, using adaptations for state B that were all 'white' but which had different colour temperatures. The colour temperatures used were 5500^{o}K, 4000^{o}K, 2856^{o}K and 2000^{o}K. The second set of observations gave sets of just noticeable differences $\Delta P'_\lambda$ for the same stimuli P'_λ

but using dark adaptation and then three coloured adaptations: red, green and blue. This completed the first half of the experimental work in which nine sets of discrimination data were obtained.

The stimuli P''_λ were then found that, when viewed under adaptation state A, had the same colour appearance as the stimuli P'_λ viewed under adaptation state B. After statistical analysis of the results of a series of observations using the range of initial stimuli P'_λ a three-by-three linear matrix was derived which could be applied to the test colours P'_λ, and the just noticeable differences associated with them, $\Delta P'_\lambda$, as observed under the various adaptation states B. This gave the size of the just noticeable differences $\Delta P''_\lambda$ as they would appear when viewed under adaptation state A corresponding to daylight adaptation. This enables the data obtained using adaptations other than daylight to be correctly represented in the u,v chromaticity diagram within the terms of its definition.

11.3 Summary of Results

The results of the discrimination experiments using white light adaptations of various colour temperature showed that the overall power of discrimination was little affected by the change in colour temperature. If all the filters used to correct the colour temperature of the surround adaptation field were viewed together they all appeared to have different chromaticities, which indeed they had. However, when they were viewed separately in the colorimeter the observer was only aware of a white adaptation field and it was not possible to assign any specific colour temperature to it. An exception to this was the field representing a colour temperature of 2000°K which had a definite orange appearance. It is one of the remarkable features of the human eye that it exhibits this effect of colour constancy. The results show that the power of discrimination decreases very slightly with decreasing colour temperature, the difference, however, between the results for two successive colour temperatures usually being less than the observed just noticeable differences.

It is possible that these results can be explained by considering the nature of the retinal and cortical responses to the visual stimuli. When the eye is adapted to a white light all three colour channels will carry signals which will have a certain noise signal superimposed upon them. With a dark stimulus, however, the magnitude of the signals would be smaller and the magnitude of the noise signal correspondingly smaller. Thus the relatively high noise level in all three channels when viewing under white light adaptation could be such as to drown any small changes in the fundamental signals due to the change in colour temperature of the white light. This will be considered again in Section 11.4.

Experiments were also conducted with red, green and blue adaptation. The results of these experiments showed that there was usually good discrimination sensitivity for test colours with chromaticities similar to that of the adaptation. The results for blue adaptation showed that the discrimination sensitivity was usually better than that obtained from the mean set of data for the white light adaptation.

Measurements were also taken using dark adaptation. The effect of simultaneous contrast tends to relatively desaturate the test colours, and thus the relative amount of the colour diagram covered by the experimental test colours is smaller than that covered with a light adaptation. However, colour triangles show the relation between different primary stimuli and not different primary sensations.

The size of the colour gamut covered by the colour triangle was found by extrapolating from the measurement of colour appearance shifts of the test colours as outlined in the previous section. The gamut of test colours with a dark surround is compared with that obtained using a daylight surround in Figure 11.2. The gamut obtained using a tungsten light surround is also shown in this Figure. This shows the general shift in colour appearance towards the blue region when the adaptation is changed from tungsten light to daylight. The corresponding gamuts for red, green and blue adaptations are shown in Figure 11.3. The gamut for a daylight surround is also shown for comparison. This Figure shows the greater overall decrease in sensitivity for the red adaptation resulting in poorer discrimination using adaptation of that colour. The decreased sensitivity of the blue region for the blue adaptation is also clearly shown.

The uniformity of the 1960 CIE u,v chromaticity diagram has been considered in relation to its use as a means of representing data obtained under an adaptation other than daylight. The use of the appearance transformation matrix, when applied to discrimination data obtained with adaptations other than daylight, meant that the data could be plotted in the u,v chromaticity

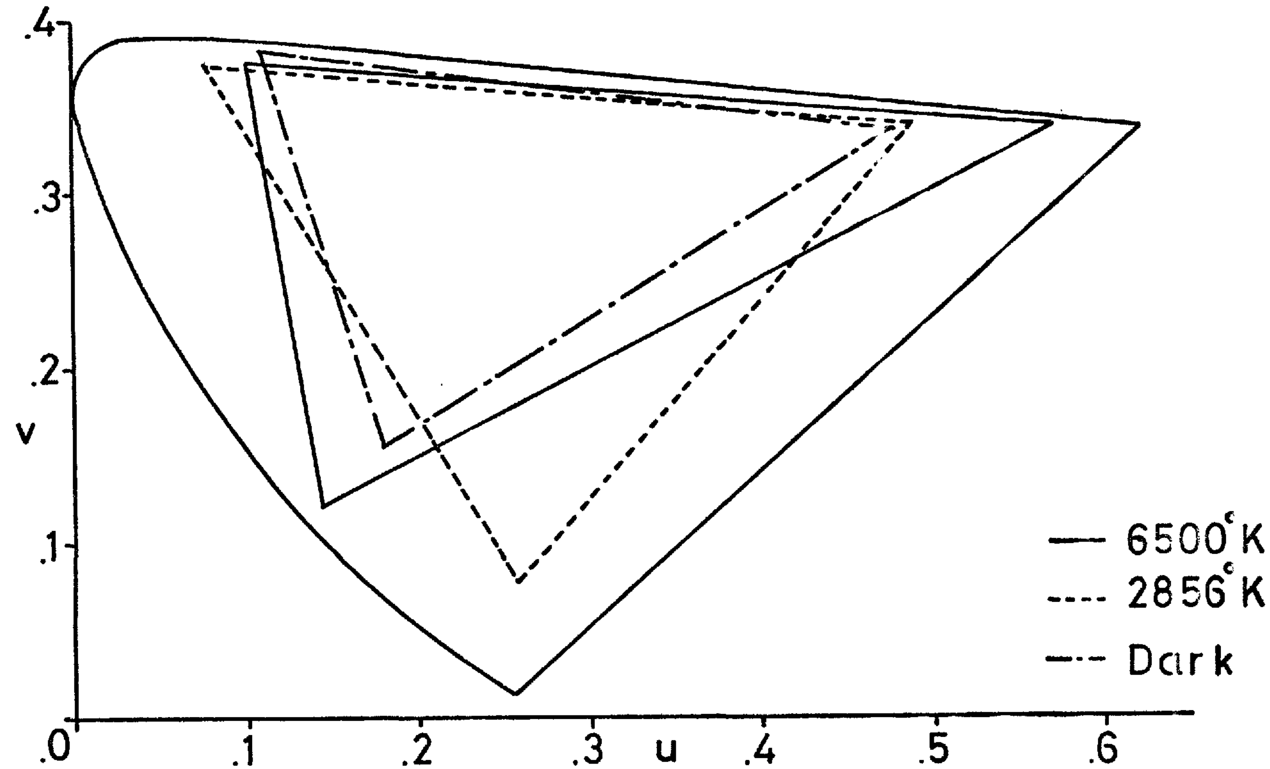


Fig 11.2

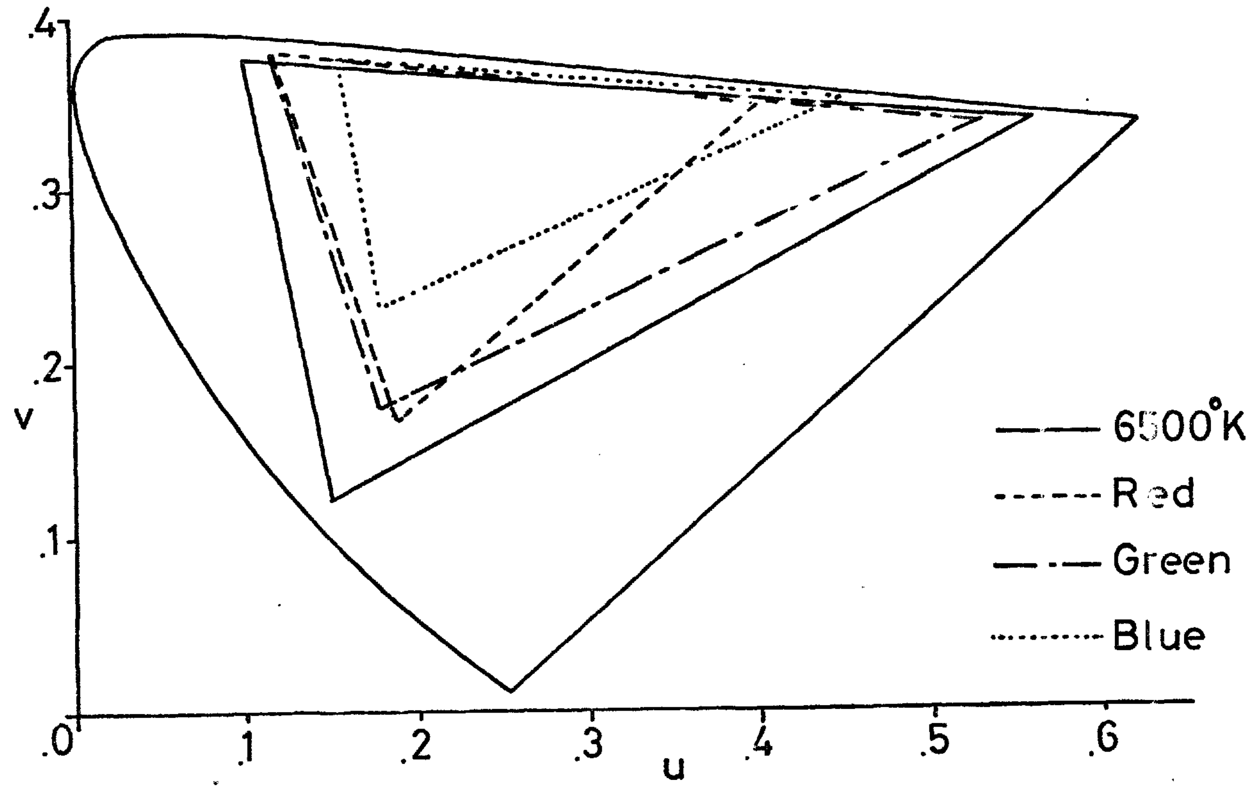


Fig 11.3

and the resulting plot considered in terms of absolute uniformity. This is because the data plotted had been corrected to its relative daylight appearance, the adaptation condition for which the u,v chromaticity diagram was defined. The results obtained show that the discrimination data obtained using tungsten adaptation and dark adaptation were invariant to the appearance transformation for any particular sampling point. This implies that the data can be plotted directly in the u,v chromaticity diagram. It is reasonable to assume that similar data obtained with other 'white' light adaptations, of different colour temperature but within the range $6500^{o}K$ to $2856^{o}K$, can also be plotted directly in the u,v chromaticity diagram, and the corresponding set of discrimination data be considered invariant to appearance transformation.

The implication of the invariance of the data, as represented in a uniform chromaticity diagram, to colour appearance transformation, is that a colour difference between two colours with chromaticity coordinates u_1', v_1' and u_2', v_2', where these coordinates have been measured under daylight adaptation, will be similar in size to the colour difference between two colours u_1, v_1 and u_2, v_2 measured under tungsten light adaptation or dark adaptation conditions. This assumes that u_1, v_1 and u_2, v_2 are represented by u_1', v_1' and u_2', v_2' respectively after appearance transformation and that the equations involving the chromaticity coordinates before and after transformation are:-

$$u' = 1{\cdot}00u + C_1$$

$$v' = 1{\cdot}00v + C_2$$

This, however, is not true for colour differences measured under adaptation conditions of saturated red, green or blue colour. In order to represent the colour differences so obtained and compare then with similar differences obtained using daylight adaptation it would be necessary to change the relative lengths of the scales used for the abscissa and ordinate of the u,v chromaticity diagram.

This has implications in the field of colour reproduction. Cine films are normally projected in situations where the level of general illumination is low. Under these conditions the light received from the actual reproduction is the only factor controlling the observer's adaptation level together with the effect of the dark surround on the picture. Similarly in colour television the reproduction on the television screen may be viewed under dark surround conditions although in this case other illuminants and surround conditions are possible. The ambient lighting may be provided by tungsten room lighting or even natural daylight. The actual picture usually has a dark grey or black surround and may form any fraction of the field of view according to the viewing distance.

In all situations, however, the cine film and the television picture will react as objects viewed in the aperture mode; that is, they react as a colour perceived to belong to a hole in a screen and are thus non-localised in depth. While there is little comparison between the fields in the author's colorimeter and the complex field described above, both fields contain colours viewed in the aperture mode. That is to say, they are not colours viewed as surface colours by reflection. Thus the results obtained in the author's experimemtal work should bear some relation to the practical situation. Therefore it should be possible to use the u,v chromaticity diagram as a means of representing colour differences as measured from a projected film or slide or from the television screen, and the differences may be considered in terms of absolute uniformity.

Similarly a colour difference between two stimuli in an actual outdoor scene may be represented in the u,v chromaticity diagram. If a photograph is then taken of the scene and the resulting picture projected using a projector with a tungsten lamp, the colour difference, as it appears on the screen, can also be represented in the u,v chromaticity diagram. These two colour differences will only be similar in size, however, if the u,v chromaticity diagram is considered to be absolutely uniform, i.e. a just noticeable colour difference observed using a red test colour is represented by the same length in the diagram as a just noticeable difference observed using any other test colour. Although some experiments, e.g. the work of the Optical Society of America Committee on Uniform Colour Scales, show that this uniformity does exist under certain conditions of adaptation and viewing, the results of the author's discrimination experiments show that the ratio of the lines representing just noticeable colour differences in the u,v chromaticity diagram is likely to vary within the ratio of 7:1.

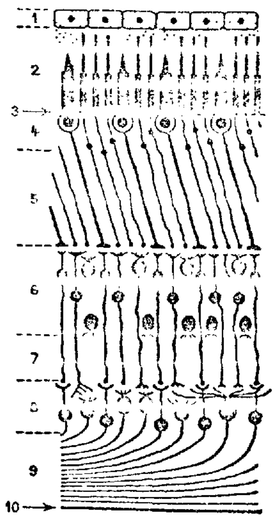
It would be convenient if the results of the author's work using an apparatus providing variable aperture colours could be compared with similar work conducted using surface colours. A set of discrimination data for daylight illumination already exists in the form of the Munsell atlas of coloured chips which were spaced visually in rows and columns. Samples in any one row were intended to be perceived as equally bright with a medium grey to white surround and samples in any one column were intended to be perceived under the same conditions as equally saturated. Unfortunately a similar set of discrimination data for tungsten adaptation does not exist. It is however, possible to derive the appearance of the Munsell samples under tungsten illumination from their daylight specification by using a theoretical transformation of the von Kries type incorporating the set of Judd P, D, T fundamental primaries. This transformation, however, does not take into account the complete change in appearance that actually occurs. It is able to correct the spectral response functions of the eye but it does not account for the change in the spectral distribution of the light coming from the sample by reflection. Attempts have been made, for example by Burnham, Evans and Newhall (1957), to derive a transformation matrix from experimental data that does take into account the change in reflected light, but what is really needed for an accurate assessment of the situation regarding surface colours to be considered, is an experimentally obtained set of discrimination data using surface samples. This in itself is no easy task since the variables involved increase rather than decrease. The Munsell samples are defined when used with a medium grey to white surround and are themselves matt. This is true of many practical situations, e.g. textiles, some paint surfaces and printed paper, but in many cases the surfaces are glossy, e.g. photographic reflection prints, some paint surfaces and some printed work. This only adds to the complexity of the experimental work that would have to be done.

11.4 Physiological Considerations

It is of interest to consider the implications of the results in terms of the physiological processes of the eye. It is generally accepted that the vertebrate retina, which constitutes the first stage of the active transmission of signals from the eye to the visual cortex, may be thought of in terms of a ten layer scheme. (Polyak, 1941). This is shown diagrammatically in Figure 11.4.

1) The pigment epithelium; a black heavily absorbing layer at the back of the retina.
2) The receptors; the light sensitive elements.
3) The outer limiting membrane.
4) The outer nuclear layer containing the receptor nuclei.
5) The outer plexiform layer, at which the receptors synapse with the horizontal cells and the bipolar cells.
6) The inner nuclear layer; containing bipolar, horizontal and amacrine cells.
7) The inner plexiform layer; containing synaptic functions between the bipolar, amacrine and ganglion cells.
8) The retinal ganglion cells.
9) The optic nerve fibres; axons of the ganglion cells.
10) The inner limiting membrane which forms the surface of the retina.

The retina is transparent. Light passes through the retina from layer 10 to layer 1 to be absorbed actively by the receptors or



Diagrammatic section of the retina. 1, Pigment epithelium; 2, outer limbs of rods and cones; 3, external limiting membrane; 4, outer nuclear layer (nuclei of the photoreceptor cells); 5, outer plexiform layer; 6, inner nuclear layer (nuclei of bipolar, horizontal and amacrine cells); 7, inner plexiform layer (axons of bipolars); 8, ganglion cells (nuclei); 9, optic nerve fibres (axons of ganglion cells); 10, internal limiting membrane. Light incident from below. (From le Grand, 1968.)

Fig 11.4

passively by the pigment epithelium. There is a dip in the retina at the visual axis where layers 7 to 10 are pulled to one side to form the fovea.

The receptor layer of the vertebrate retina constitutes the photo-transducer stage of the visual system and microscopic investigation shows that the receptors may be classified into two groups, known as rods and cones. The foveal region is found to possess only cones but, as the point of investigation is moved away from the fovea, the ratio of the number of rods to the number of cones increases rapidly. Rods are found to be grouped together to form functional units, whereas cones are in many respects independent units. Rod vision is not associated with colour response, whereas the rod-free fovea has highly developed colour discrimination, which must arise in the cones.

Colour sensation correlates closely with the wavelength of the light stimulus. Thus information about the performance of the visual system can be found by performing psycho-physical 'black box' type of experiments as discussed by Ruddock(1971). Such experiments determine input-output relations for the visual system as a whole, and make use of a constant response criterion, e.g. threshold detection or the equality between two stimuli. Conclusions from such experiments rest upon the assumption that stimuli which cause identical signals to be transmitted to the brain produce identical sensations. Colour matching experiments have shown that a test stimulus of any spectral composition may be matched by a suitable mixture of three fixed monochromatic stimuli. Because of the finite visual discriminative capacity, there is always a finite, though small, range of combinations of the three matching stimuli which match a given test colour. This trichromatic nature of colour matching implies that human colour vision requires a minimum of three independent 'colour' channels at all points in the visual system. There may be more than three independent channels at all locations preceding the three channel point, but there must be at least one level in the visual system which is trivarient. This follows from the trivariancy of the colour matching equation:-

$$c(C) = r(R) + g(G) + b(B)$$

This identity relationship represents the fact that c units of stimulus (C) are identical in appearance to a mixture of r units of (R), g units of (G) and b units of (B). If two separate matches of this type give:-

$$c_1(C_1) = r_1(R) + g_1(G) + b_1(B)$$

$$c_2(C_2) = r_2(R) + g_2(G) + b_2(B)$$

then we can mix the left hand side stimuli to give a further match:-

$$c_1(C_1) + c_2(C_2) = r(R) + g(G) + b(B)$$

Experimentally it is found that, within the limits of the errors of judgment:-

$$r = (r_1 + r_2) \ , \ g = (g_1 + g_2) \ , \ b = (b_1 + b_2)$$

This embodies the principle of additivity of colour matching, which is valid over a wide range of experimental conditions. It implies that the visual system is linear up to the point that it becomes trivariant. The linearity of the colour matching does not, however, require that the three independent channels possess linear characteristics. As long as the inputs into the corresponding channels are equal for the two halves of the field of view the outputs must be equal, whatever may be the input-output characteristics of the channels. Thus psycho-physical experiments give us information regarding the overall organisation of the human visual system but do not give details regarding neural colour discrimination mechanisms. For this to be done the electrophysiological responses of the constituent cells in the retina must be determined experimentally. This can be done by inserting microelectrodes into some pre-determined point and measuring the change in electrical potential elicited by light stimulation. Such techniques cannot, of course, be applied to the human visual system but comparison can be drawn between electrophysiological data from other mammals and human psycho-physical results. At the photo-receptor stage of the visual system, the incident light, in the form of photons, starts a photo-chemical reaction with the associated separation of electrical charge. This capture of photons is thought to be linear up to the point of saturation and the amplitude of the electrical potential associated with this reaction, the early receptor potential, has been shown to be directly proportional to the amount of the visual pigment bleached. (Cone, 1964).

Rods have been shown to contain a photosensitive pigment, rhodopsin, which has an absorption spectrum fairly close to the human scotopic relative sensitivity function.(Rushton, 1956). The information regarding cone photopigments is, unfortunately, far less certain than that concerning rhodopsin. The only pigment to be extracted with any degree of certainty is iodopsin, extracted by Wald from the cones of chicken retinae.(Wald, 1937). Ripps and Weale (1963) and Rushton (1958), using the technique of fundus reflectometry applied to the fovea, were able to show that there was more than one photopigment in this region. Recent microspectrophotometric measurements by Marks, et al. (1964) and by Brown and Wald (1964) have shown that there are three cone pigments in the primate eye with maximum absorptions at approximately 440, 530 and 570nm. They have also shown that any one cone possesses only one of these photopigment types. Physiological recordings of the responses of the cells late in the visual pathway of monkeys have revealed the presence of spectrally opponent cells which receive inputs from more than one receptor type. Selective chromatic adaptation can be used to suppress one input to reveal another. Wiesal and Hubel (1966) and Gouras (1968) have shown the presence of three underlying systems, with peak spectral sensitivities of 440, 530 and 570nm, which coincide with those of the photopigments found by spectrophotometry. Tomita, et al. (1967) recorded intracellularly from fish cones and found that each cone gave one of three different action spectra depending on the wavelength of the incident stimulus.

Clearly the photopigment first stage of the visual system must be backed by neural organisation which is capable of sorting the data from the receptors and processing it. It has been shown (e.g by MacNichol and Svaetichin, (1958) using fish retinae) that all the complex retinal processing at the pre-ganglion level takes place with graded potentials with no generation of on-off spike potentials. Spike potentials are usually associated with the transmission of information over relatively long distances and hence it is logical that they should form the output of the last cell layer in the retina, the ganglion cells.

The post receptor potentials are known as S-potentials and they may be either positive (depolarizing) or negative (hyperpolarizing) depending on the stimulus wavelength and the particular unit from which the record is obtained. It has been suggested by DeValois (1969) that this graded potential, generated in the receptor-horizontal cell complex, is quasi-logarithmically related to the light intensity of the input stimulus and that it is this logarithmic signal that forms the input to the bipolar cells. The bipolar cells are the first to show the effect of opposite types of response to different kinds of stimuli. Two main classes of S-potentials are observed. The first gives a negative potential for all wavelengths and has a broad spectral response characteristic which correlates with the luminance of the stimulus and is therefore said to originate from an L-unit. This response is shown in Figure 11.5. The other S-potentials show hyperpolarisation or depolarisation depending on wavelength. Some are associated with R-G units which are depolarised by long wavelengths and hyperpolarised by short wavelengths. Other units, Y-B units, are depolarised by yellow stimuli and hyperpolarised

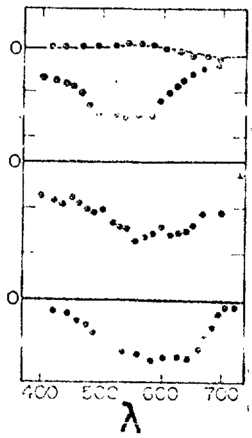


Fig 11.5

L-type S-potentials

R-G Y-B

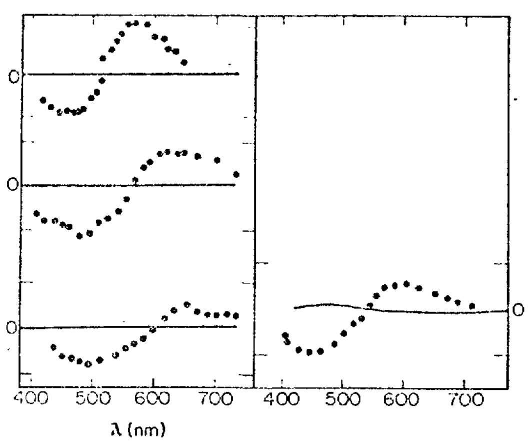


Fig 11.6

C-type S-potentials

(from Ruddock, 1971)

by blue stimuli as shown in Figure 11.6. It is these units that are obviously organized to give colour discrimination and they are known as C-units. This work of MacNichol and Svaetichin has been confirmed and extended by Naka and Rushton (1966,a,b) working on the tench.

At the ganglion cell level the electrical response to the light stimuli consists of a train of potential spikes of constant amplitude but variable frequency. Hartline (1940), and later Kuffler (1953), have shown that there are at least three types of ganglion cell response; 'on' units which discharge at the onset of the light stimulus, 'off' units which discharge at the cessation of the stimulus and 'on-off' units which discharge at both onset and termination. Studies by Wagner, et al.(1960) using the goldfish retina showed that the ganglion cells possessed the above characteristics with the addition of a response that encoded information about the stimulus wavelength. Cells were found that were inhibited by a red stimulus ('off' response) and stimulated by a green or blue stimulus ('on' response), such cells being called R-G cells. It was also shown that the response was a function of the stimulus location within the receptive field of the ganglion cell. A receptive field is defined as the relatively large region of the receptor layer which, when illuminated, gives a response in a retinal ganglion cell. A red stimulus gives an 'off' response when located in the centre of the field, but as it is moved towards the edge of the field the response changes to 'on-off' and then pure 'on'. Hubel and Wiesel (1960) and later Michael (1966) have found similar responses from ganglion cells in the mammalian visual system. Thus at ganglion cell level units giving chromatic responses are organised spatially and it is highly likely that they may be responsible for interactions between adjacent, differently coloured areas of the visual field - so called colour contrast effects. Hence a coloured spot surrounded by a simulated tungsten light surround 'looks' different from the same coloured spot surrounded by a simulated daylight surround although the tungsten light and the daylight, when seen on their own, both appear white. Thus it would appear that the colour appearance shifts observed on changing illuminants may be due to the spatially selective nature of the ganglion cells. The fact that, for commonly observed objects, the effect of colour constancy overrides this appearance shift must occur at a higher level where the psychological colour correlation between what the object actually looks like and what the brain thinks it usually looks like comes into play.

There have been a number of investigations into colour coding of spike discharges elicited in units of the lateral geniculate body of mammals, the position of which is shown in Figure 11.7. (DeValois, 1966, 1969). Early work using the cat retina has shown that almost all of the cells at the lateral geniculate nucleus (LGN) level of the visual system are of two types only. They either give an increased response to a change in stimulation at the centre of the receptive field (excitory) or they give a decreased response to a change in stimulation at the surround of the receptive field (inhibitory). The centre response usually dominates over the surround response and so the cells usually show excitation to a flash stimulus incident on the whole field. Both types of cell in the cat give responses independent of wavelength and they are therefore

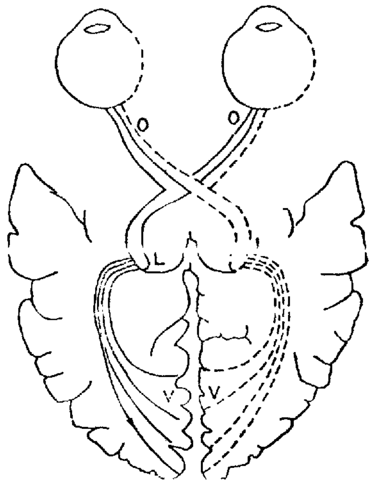
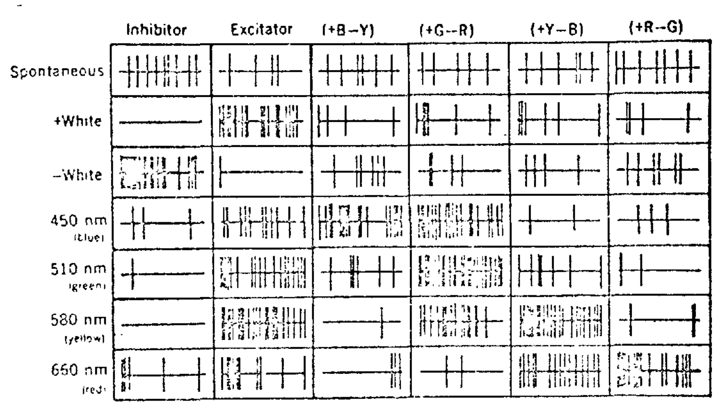


Diagram of the visual pathways showing *O*, the optic nerve; *L*, the lateral geniculate body; and *V*, the visual cortex.

Fig 11.7



A drawing of the responses of each of the six cell types in the primate visual pathway to a variety of different lights. The number of spikes in each case is based on the average firing rates of cells of that type.

Fig 11.8

(from DeValois, 1969)

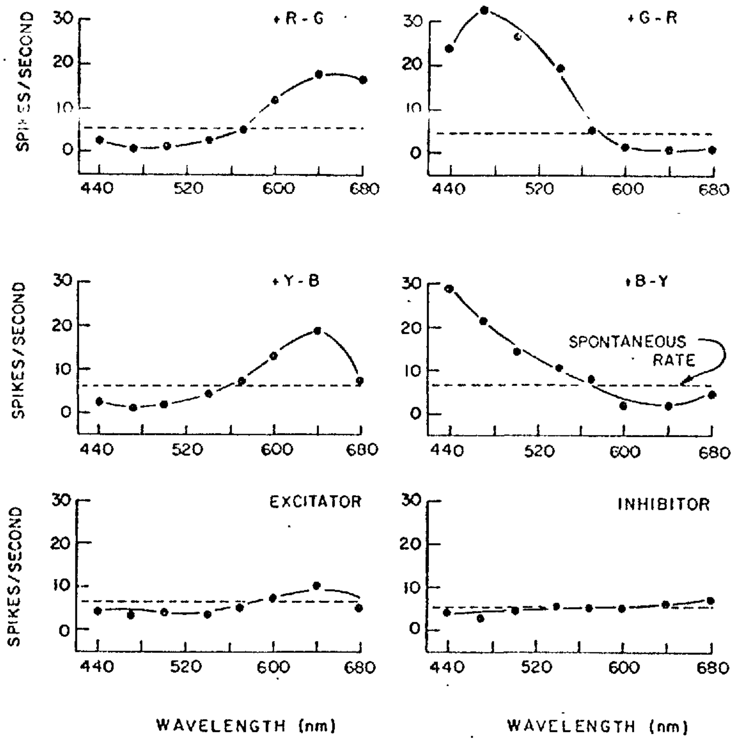
termed spectrally non-opponent cells. There are about 50% of each type of cell in the cat LGN. In the monkey LGN, however, they constitute only about 30% of the cell population. The remainder of the cells show spectrally opponent responses: some excitory and some inhibitory. DeValois (1966) has presented evidence that there are four classes of such opponent cells. These are:-

+R-G	red excitory	green inhibitory
-R+G	red inhibitory	green excitory
+Y-B	yellow excitory	blue inhibitory
-Y+B	yellow inhibitory	blue excitory

In the monkey LGN, RG cells are found somewhat more frequently than the BY cells. It would seem logical, since the monkey used for experimentation has colour vision identical to that of man, that there are six types of cell in the human LGN; two spectrally non-opponent and four spectrally opponent types.(DeValois, 1969).

Experiments have been conducted to investigate the response of the various cell types to white and monochromatic lights. DeValois and Jacobs (1968) presented a white adapting light and then changed this to a monochromatic light of equal luminance. The results are summarised in Figure 11.8 which shows the discharge patterns of the six principal types of LGN cells in response to various light flashes. The spike patterns are drawn to match the average firing rate of the large sample of LGN cells from which recordings were made. They show that the responses of the non-opponent cells to the coloured test flashes are no different from the spontaneous discharge responses. Thus they can be making no contribution to the animal's colour vision. The opponent cells, however, show large changes in their firing rate depending on the wavelength of the stimulus. In response to a shift from white to a coloured stimulus, for some wavelengths the cells show an increase in firing rate and for other wavelengths they show a decreased firing rate. At one particular wavelength there is a 'neutral' point for that cell type as shown in Figure 11.9.

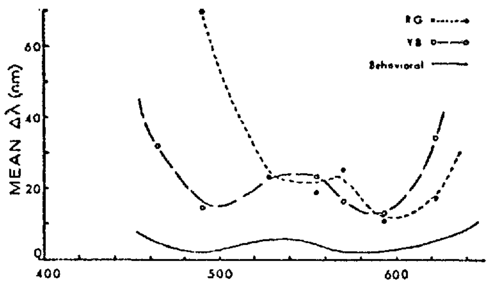
Further experiments (DeValois, 1969) were conducted using changes from white light to coloured test flashes with varying degrees of saturation. Here opponent cells showed changes in their firing rate which were systematically related to the chromatic component of the stimulus. In discrimination experiments conducted by DeValois, et al.(1967) a monochromatic light was viewed for a short time and then its wavelength shifted to be slightly higher or lower. It was found that the opponent cells had a very high sensitivity in some spectral regions, the RG cells showing optimum discrimination at approximately 590nm and the BY cells in the region of 490nm. These two wavelengths correspond to the two minima found in the human psycho-physical wavelength discrimination curve as shown in Figure 11.10. The non-opponent type cells respond to the wavelength shifts purely on the basis of the relative luminance of the different colour. They could not discriminate between two equal luminance signals. In brightness discrimination experiments it was found that, when a shift was made from white light to one of higher luminance, the non-opponent cells gave systematic increasing or decreasing responses.



The average firing rates to a shift from a white light to a monochromatic light of the same luminance. The dotted lines mark the maintained firing rate to the white adapting light from which the shift was made. It can be seen that the non-opponent cells cannot distinguish between white and monochromatic lights of the same luminance, whereas the opponent cells all do, except at their neutral points.

Fig 11. 9

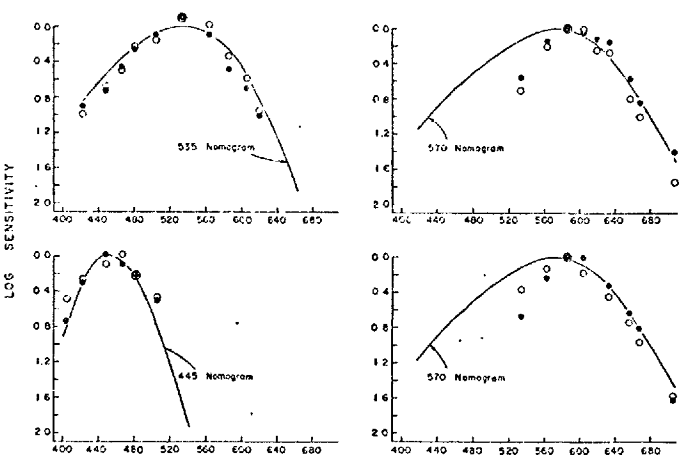
(from DeValois, 1969)



The wavelength discrimination of the different cell types compared with the overall human wavelength discrimination function. It can be seen that the RG cells discriminate between wavelengths well in the 600 nm region and poorer at longer and shorter wavelengths; the YB cells do well at 500 nm and have a second minimum at the longer wavelengths. The two humped psychophysical wavelength discrimination function is clearly the result of macaque monkeys (and humans) possessing both types of opponent cells

Fig 11.10

(from DeValois,1969)



Spectral sensitivity curves of the components isolated with the chromatic adaptation technique shown in Fig. 13. Top left: short-wavelength component from the RG cells. Top right: long-wavelength component from the RG cells. Bottom: short and long wavelength components from the YB cells. In each case, the filled circles are the excitatory and the open circles the inhibitory components from the respective mirror-image cells.

Fig 11.11

(from DeValois, 1969)

The opponent cells were, however, much less responsive. The +R-G cells showed almost no change in firing rate even to a shift in the white stimulus of more than one log unit; the +G-R cells were only slightly more responsive. The +Y-B and the +B-Y cells were intermediate between the RG cells and the non-opponent cells in their response.

It is now worthwhile considering how all the results reported above improve our knowledge of the neural organisation of the visual pathway. In the first stage of the system we have three broadly absorbing photopigments whereas at a later stage we have opponent cells with excitory and inhibitory inputs that differ in spectral sensitivity. Neither the shapes of the response curves nor the points of maximum excitation or inhibition correspond to the absorption curves of any of the photopigments. For example, in a +R-G cell the excitory influence is greater at short wavelengths and the inhibitory influence greater at long wavelengths. It must be assumed that the excitory response is not the complete excitory response but only that part of it that exceeds the long wavelength inhibition. The effect of this cancellation due to the overlap of the excitory and inhibitory systems should be detectable by selective chromatic adaptation. If the eye is adapted to long wavelength light it will adapt or desensitize the long wavelength receptors leaving the short wavelength receptors in isolation. When this is done (DeValois, 1969) and, for example, the output of the +G-R cells is recorded, the short wavelength excitation is seen to shift its maximum sensitivity towards the longer wavelengths to occur, not at 500nm as in the unadapted case, but at 530nm. Similar experiments with short wavelength adapting light reveal a long wave inhibitory system whose maximum sensitivity has shifted from 640nm, in the unadapted state, to approximately 570nm. The same shifts of the peak sensitivities are found for the +R-G cells but with reversed polarity as would be expected. Chromatically adapting the +B-Y cells reveals an excitory input peaking at 440nm and an inhibitory input peaking at 570nm. Similarly for the +Y-B cells there is a 570nm excitory input and a 440nm inhibitory input. The wavelengths at which the inputs peak, 570, 530 and 440nm, correspond quite closely to the peaks of the absorption curves of the cone pigments. These results are shown in Figure 11.11. Thus it appears that the six cell types found in the LGN have various combinations of inputs from just three cone types and these correspond closely to the three photopigments found by spectrophotometric experiments.

Three basic effects have arisen from the author's work. The overall effect of adaptation, if thought of in terms of the von Kries hypothesis, is a linear effect. It involves a linear desensitisation such that the relative spectral sensitivities of the three cone mechanisms of the visual system stay constant. The additivity of colour matches has shown that the visual system is linear up to the point that it becomes trivariant and it would appear that the trivariant point in the system is in the region of the bipolar cells. These give a wavelength independent response and two wavelength dependent responses corresponding to the R-G and Y-B opponent signals. Thus if it is correct to assume that adaptation is a linear process, it can only involve a relative desensitisation of the receptors and possibly the horizontal cells since these precede the bipolar cells. However, DeValois has suggested that the horizontal cells are responsible for forming the logarithm of the electrical signal before it goes to the bipolar cells. Thus the linear part of the visual system must consist of the receptors and their associated output signals and it is at this level that the desensitisation must take place.

The effect of the different coloured surrounds on the appearance of the coloured test fields has already been associated with the ganglion cells since these are the first group of cells to show any spatial selectivity to chromatic stimuli.(Ruddock, 1971).

The principal function of the nerve cells of the retina is probably to compress information contained in the activity of a very large number of receptors into a much smaller number of channels, the fibres of the optic nerve. In doing this they certainly discard a great deal of information. In transmitting visual information from the optic nerves to the cortex the lateral geniculate nucleus may further filter the information.(Brindley, 1970). If this effect of filtering involves a loss of colour information this would contribute to the sensitivity of colour discrimination and the fact that a just noticeable colour difference has a finite size.

The invariance of the discrimination data to the white light adaptations of various colour temperatures can possibly be traced to the response of the six types of cell in the lateral geniculate nucleus. The effects of the adaptation on the response of the visual system to the coloured field stimuli will already have been determined in the photochemical reaction and subsequent electrical signal produced in the receptors. The power of colour discrimination, however, seems to be very much controlled by the four types of spectrally opponent cells in the LGN.

It is probable that a certain amount of noise in the form of random spontaneous discharges will be superimposed on any signal and also be present as an output to any cell that is not specifically firing in response to a particular input.

It is significant that the two types of spectrally non-opponent cells, the inhibitory and excitory cells, respond to white light in a unique way. A change in the luminance of the white light, for example, does affect the firing rate of the excitory and inhibitory cells but does not affect the firing rate of the four types of opponent cell. Thus as long as the surround in the author's apparatus is seen as white the discrimination sensitivity should be affected only by noise. As shown in Figure 11.8 a change in the stimulus colour from white to red increases the firing rate significantly in the +R-G cells and to a lesser extent in the +Y-B cells as would be expected. Thus the sensitivity of discrimination should be affected as the surround colour temperature is lowered and there is more red light present causing the +R-G and then the +Y-B cells to start firing as well as the excitory and inhibitory cells. There will also be a corresponding increase in the amount of noise signal present. In the author's work it was found that the overall size of the just noticeable colour difference did increase by a small amount when the colour temperature of the adaptation was lowered.

Summarising, it would appear that adaptation, if it is assumed to be a linear effect in that it modifies the relative spectral sensitivities of the three cone mechanisms, involves an overall desensitisation of the receptors and their associated output signals; colour appearance shifts can be associated with the spatially selective ganglion cells and colour discrimination with the responses of the six types of cell in the lateral geniculate nucleus. The presence of noise in the electrical outputs of the various cells coupled with the process of information filtering must contribute to the fact that a just noticeable colour difference has a finite size.

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