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A STUDY OF TEMPORALLY BASED SUBJECTIVE COLOUR PHENOMENA

BY

JOHN ROBERT JARVIS

A THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
TO THE CITY UNIVERSITY, LONDON.

1974

ABSTRACT

The main concern of this research is an investigation of the perception of colour from achromatic flicker, particularly the colours observed on many black and white rotating patterned discs. The first chapter is an attempt to review, in a critical manner, the literature available on this subject and to discuss general and relevant topics on human colour vision. The second chapter deals with the apparatus developed. Included in this chapter is a description of a white light modulator, which was used in most of the experimentation. It was found, using two of these modulators, that the colour effects observed on many rotating patterned discs could be reproduced in a static stimulus display. Necessary for the evocation of the colours, was that the visual field should comprise two intermittent regions; one region (defined as the target) in which the colours were produced, and the other defined by the areas surrounding the target. Initial experiments employed a grating type of stimulus (see figure 36, Chapter 3) and the colours induced in the stimulus were measured with a binocular matching technique. The second experiment shows that the full gamut of subjective colours observed as rotating patterned discs cannot be reproduced in a single intermittent light by a manipulation of flicker waveform. One of the commonly held theories of the subjective colours is suggested as untenable from this result. The general conclusion from most of the experimental work is that colour coded ganglion cells in the retina, whose receptive fields have a centre-surround spatial configuration, are the most likely candidates for the visual mechanisms responsible for the subjective colours. A theory is given which suggests possible ways in which the dynamic behaviour of such cells can account for the subjective colours. Data are also obtained which possibly reflect the sizes of some colour coded ganglion cell receptive fields. Finally, an electrophysiological experiment is performed to find possible reflections in human electroretinographic and evoked potential data, of subjective colour inducing

mechanisms. The results of this experiment are, on the whole, rather inconclusive.

ACKNOWLEDGMENTS

I would like to express my sincere thanks to Dr. C.A. Padgham for supervising this project and to [REDACTED] [REDACTED] [REDACTED] for the helpful advice he has offered me on many occasions. I would also like to thank [REDACTED] [REDACTED] [REDACTED] for assistance in the construction of the light modulator and [REDACTED] [REDACTED] [REDACTED] for patiently typing this thesis.

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A note to the reader

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THE PERCEPTION OF COLOUR FROM ACHROMATIC FLICKER

INTRODUCTION

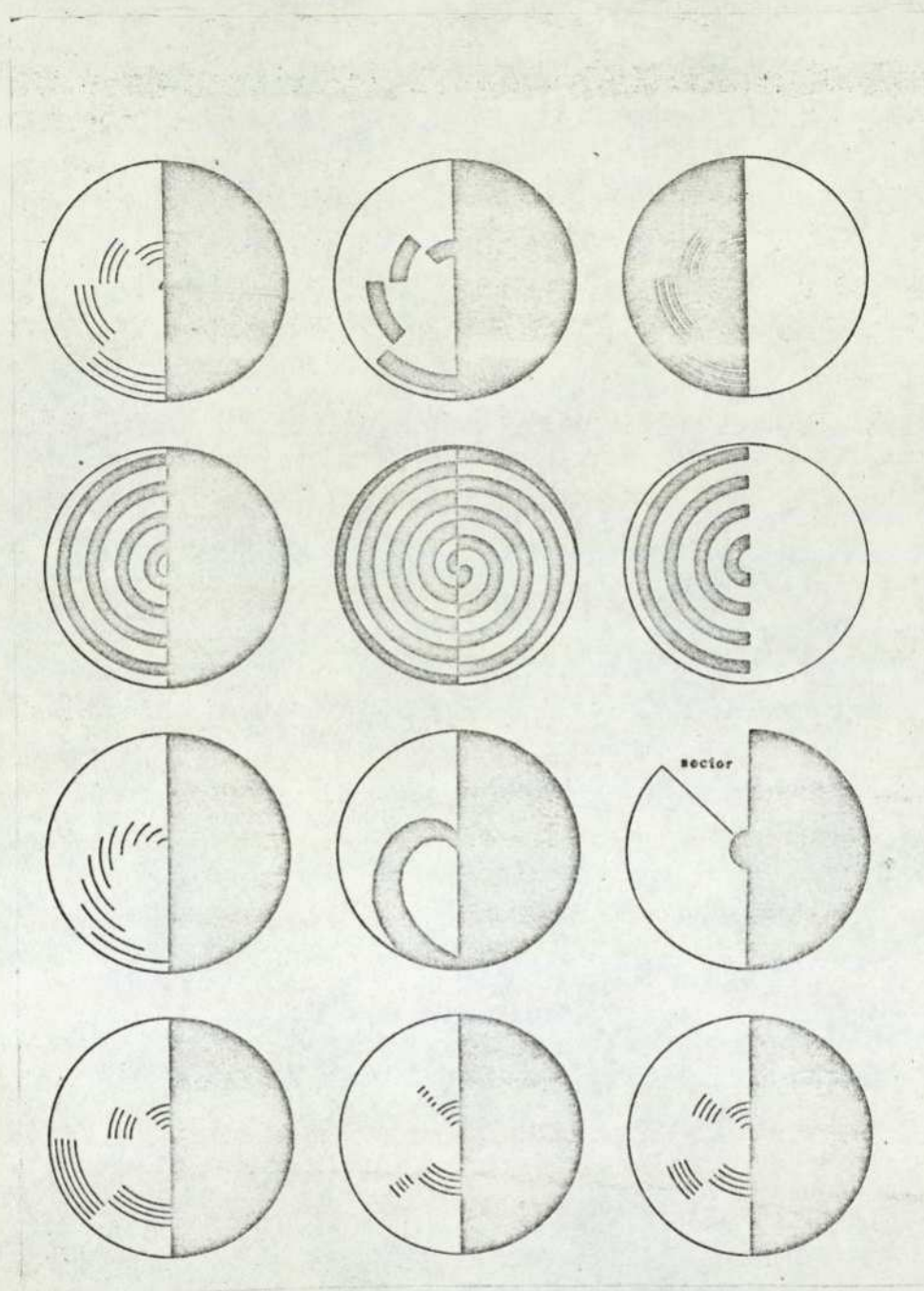
Colour sensations aroused from intermittent achromatic stimuli have been studied for well over 100 years. From the many investigations of such phenomena, little information has emerged concerning the dynamic properties of the colour mediating mechanisms of the human eye, which are clearly involved. One of the main aims of this research is to obtain from experimental work and from the literature available on temporally based subjective colour phenomena, a more full understanding of these dynamic features.

Although most of this literature survey is concerned with studies of the perception of colour from achromatic flicker, a discussion is also given of our present understanding of human colour vision in general. (Gordon 1968).

1) Colour from black and white patterned discs

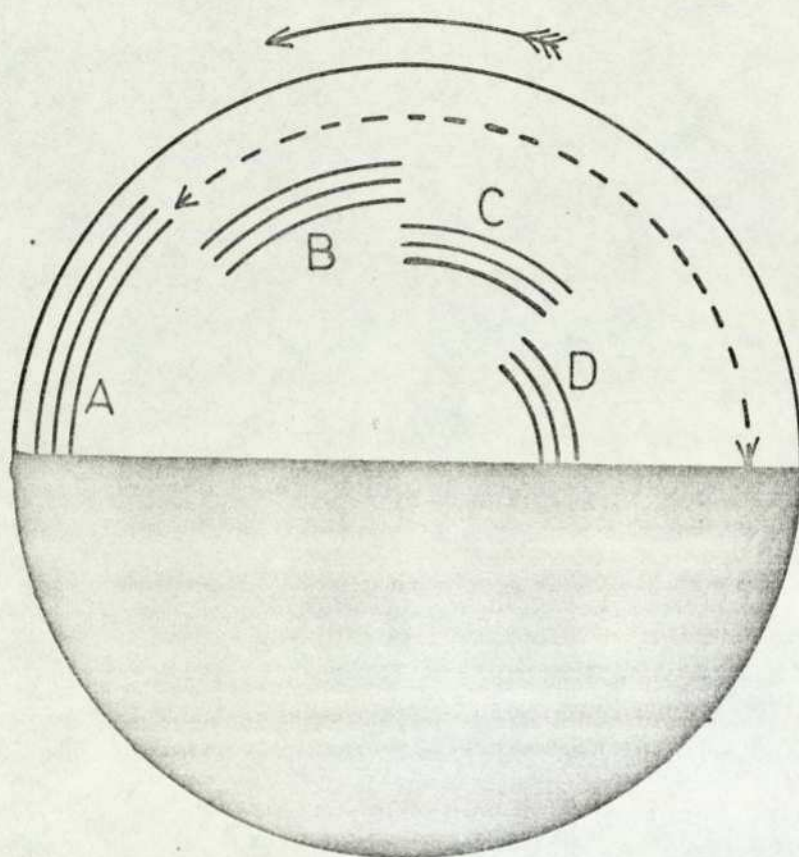
The discovery of subjective colour from an intermittent achromatic stimulus is usually credited to PREVOST (1826), who observed a full spectrum of colours by oscillating a rectangular piece of cardboard through a ray of white light. The first report of colour from a rotating black and white cardboard patterned disc, however, came from FECHNER (1838) and almost all studies since then on the induction of colour from a flickering achromatic stimulus have used such discs. Figure 1 shows examples of this kind of stimulus, all of which have been claimed to induce subjective colours of one sort or another. Most of the pre-1949 experimentation was conducted with such discs, and a review article, outlining the majority of these studies is available (COHEN and GORDON, 1949). More recent reviews of temporally based subjective colour investigations have emerged from NELSON (1971), SHEPPARD (1968) and JAMESON (1972).

The disc shown in figure 2, known as Benham's disc after the designer (BENHAM, 1894) has become the most widely used method of producing



A selection of subjective colour
producing black and white discs
(from COHEN and GORDON , 1949).

Fig.1



Benham's Disc.

Fig. 2

Fechner-Benham¹ (F-B) subjective colour, mainly since it has been reported to be the simplest of geometric designs capable of producing a full gamut of subjective colours, from blue through the spectrum to red, when rotated.

Most of the early experiments (pre-1949) carried out on rotating patterned discs, consisted of a binocular viewing situation, involving disc diameters of about 6° or 8° angular subtense. The experiments usually involved unspecified illuminants and illuminances, and the colours observed were described in terms of simple colour names. Even so, some important experimental points have emerged from this early work mainly derived from investigations of Benham's disc and adjustments made of the spatial parameters of it.

The main findings from observations made on Benham's disc are (with reference made again to figure 2), as follows;

- a) When rotated in the direction shown between 5 to 15 Hz and viewed under moderate achromatic illumination, the arc lines marked A on the disc usually appear reddish in colour. Those marked B yellowish, those marked C greenish, and those marked D dark blue or often achromatic. With reversal of the direction of rotation the spectral pattern is reversed, the D lines now appearing red, etc.
- b) The hues and saturations of the colours seen depend on the illuminance and the spectral composition of the illuminant (PIERON, 1922 a, b; VERRIEST and SEKI, 1964.)

Although as stated, early experiments on F-B subjective colour were vague in specifying stimulus parameters, KNEHR and LORENZ (1964) state a value of 55 cd.ft.^{-2} for the luminance of the white portion of a Benham's disc, required for satisfactory evocation of the colours. This would provide

FOOTNOTE 1. Since the authors Fechner and Benham may be regarded as pioneers in the study of colour effects from black and white patterned discs, the effect will be referred to as Fechner-Benham subjective colour.

an illuminance at the retina, using a monocular viewing situation without an artificial pupil of about 2500 td. Measurements by the writer (of this thesis) made on a Benham's disc illuminated by standard illuminant A showed this figure was for him, about 1200 td.

The work of Verriest and Seki, constitutes one of the few attempts to measure the colours of Benham's disc quantitatively. The general finding was that the colours seen were relatively unsaturated. Measurements were made with the disc illuminated by both standard illuminants A and C, with four values of illuminance of the white part of the disc, viz 100, 250, 300 and 1700 lux employed, for each of the two illuminants. The colour measurements were carried out by comparing colour chips from the Munsell colour atlas with the subjective colouring. A binocular viewing situation was employed and the frequency of rotation of the top was varied from 1.6 to 13 Hz. For the experimental conditions employing standard illuminant C and with 1700 lux illuminance, the Munsell matches were converted into plots on the CIE (x, y) chromaticity diagram. These results are shown in figure 3, where the numbers 1, 2, 3 denote the A, B and C lines respectively of the disc shown in figure 2 and the speed of the disc shown in revolutions per minute.

The findings of these authors confirmed the general statements made previously in this thesis as to the subjective colours. In addition, the subjective colours were seen to change in hue and saturation when the illuminant was changed from standard A to standard C. With the use of the C illuminant, not only was the saturation of all colours reduced, but little red was seen, compared with the use of illuminant A. These hue and saturation changes were interpreted as supporting the ABNEY (1895) and PIERON (1928) proposition that the subjective colours depend on the spectral composition of the illuminant rather than its colorimetric properties. This was an unjustified deduction from their data, since these differences might well have occurred from the fact that standard illuminant's A and C are not metamers.²

If F-B subjective colour differed, depending on the actual spectral

Verriest and Seki (1964)

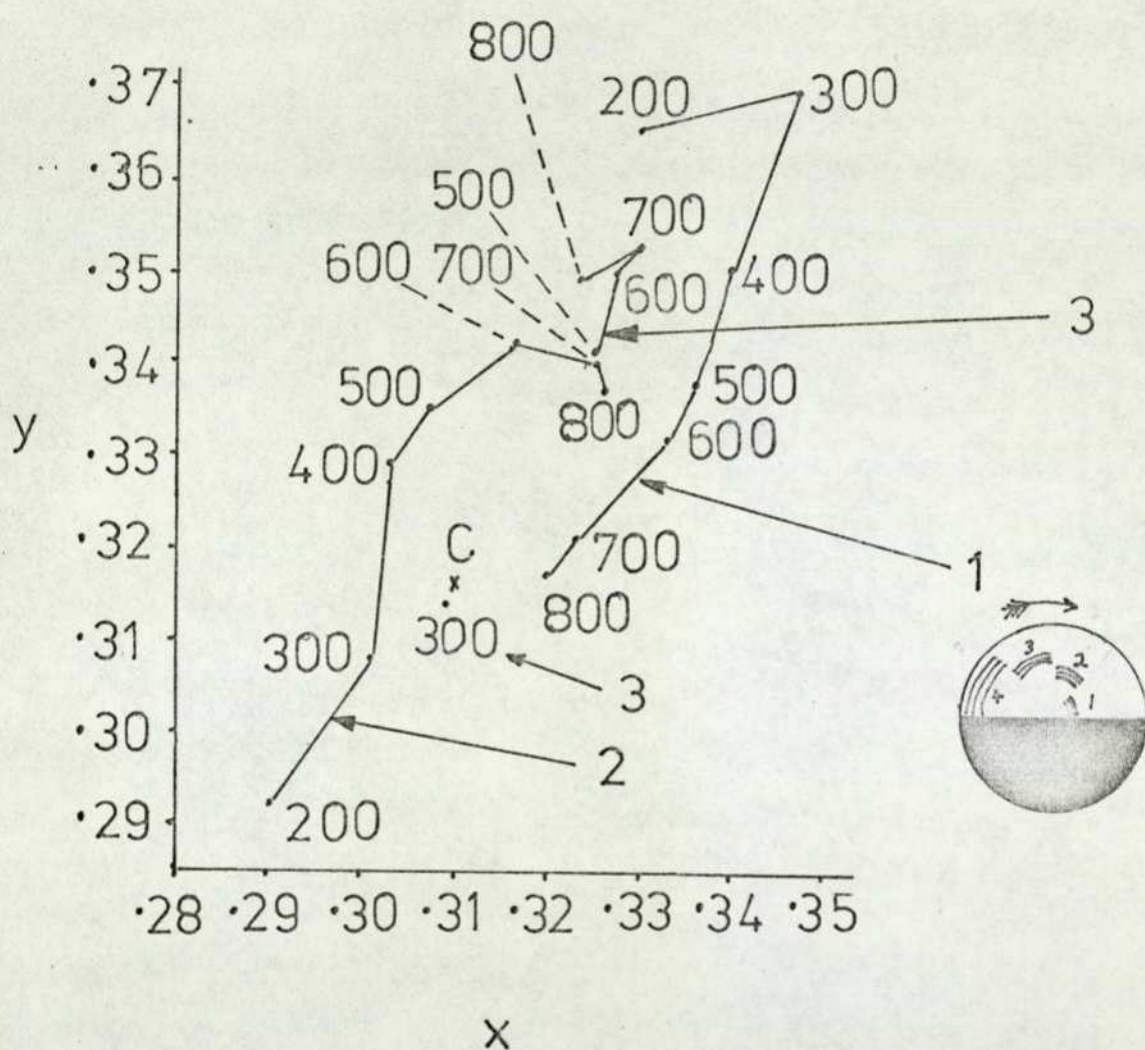


Fig.3 Colour appearance of Benham's disc illuminated by standard illuminant C and rotated at the speeds shown (revs/min)

distribution of the light stimuli, even when the stimuli are metameric, then one of the basic concepts of colour theory would be undermined (JAMESON, 1972). It is generally agreed amongst colour vision theorists that for two given metamers, the outputs from the receptor cells are identical. Thus, it would be expected that the colours of Benham's disc would be the same under illumination from metameric light sources. CAMPENHAUSEN (1969) re-examined this question and using nine different pairs of metamers showed no differences in the colours matched for each metameric pair. Campenhausen suggested that the successive comparison method used in the earlier studies, was inadequate to ensure precise colour matches between the lights which would have been identical in appearance when viewed under steady conditions. Additional findings from the Verriest and Seki study were that the lines marked D appeared achromatic under all the viewing conditions used (direction of rotation of the disc as shown in figure 2). Also, for the lines marked A, the speed of rotation of the disc and illuminance were found to be related by the expression:

$$f = k (I)^{\frac{1}{4}} \text{ --- (1)}$$

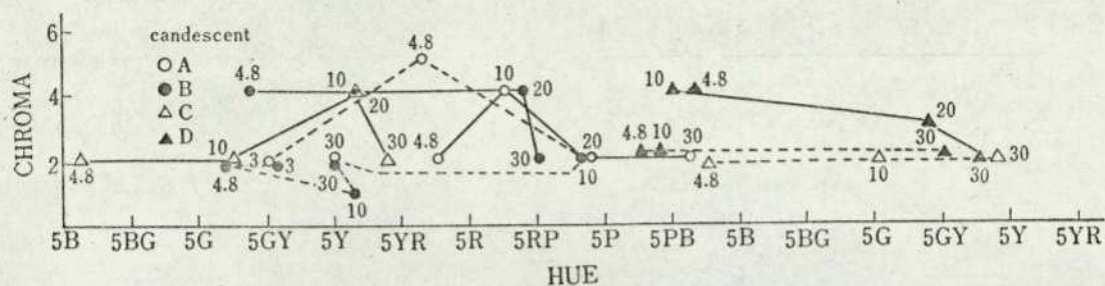
(where k = a constant), to give a particular hue. (The disc rotating in the direction shown in figure 1). This finding agreed well with the findings of PIERON (1922a), who also found this expression applicable to the other sets of arc lines.

A study similar to that made by Verriest and Seki has been carried out more recently by HASEGAWA (1971). Again, the colours observed were specified in terms of the Munsell colour naming system. The results are shown in figure 4. The groups of arc lines A, B, C and D and the direction of rotation of the disc are as in figure 2. The disc was 30 cm in diameter and viewed from a distance of 1.5 mm; the arc lines were 4 mm in width and the illuminance of the white portion of the disc was 300 lux.

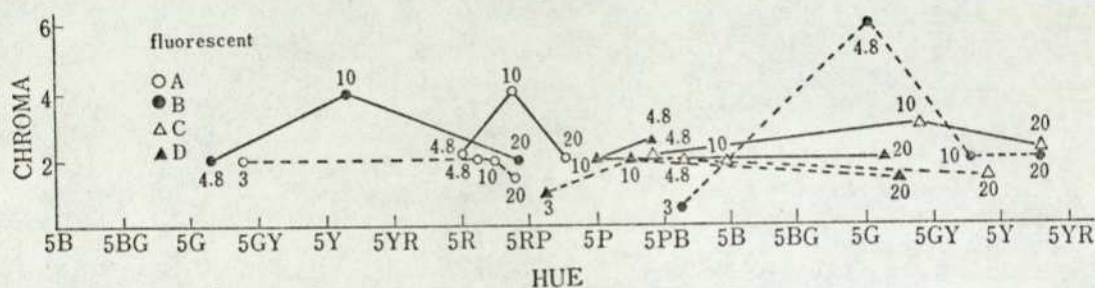
Other recent investigations of Benham's disc involving colour

FOOTNOTE 2. Two light stimuli are said to be 'metamers' if they have different spectral energy distributions but the same colorimetric co-ordinates.

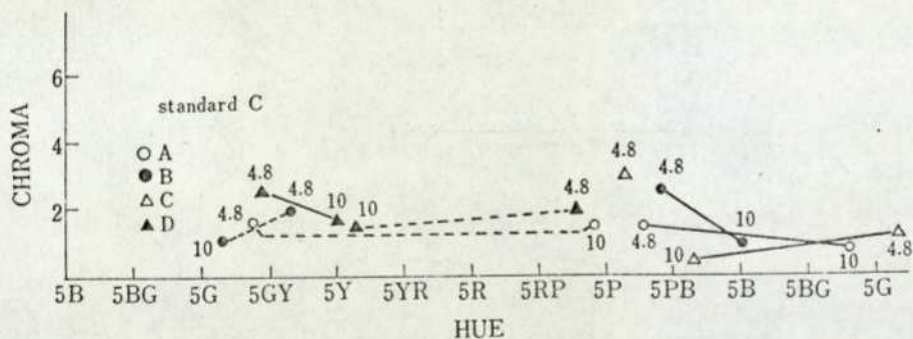
HASEGAWA (1971)



(a) under candescent light



(b) under fluorescent light



(c) under standard source C

Fig. 4. Munsell hue and chroma of the perceived colors plotted on the Cartesian co-ordinates. Symbols $\circ$, $\bullet$, $\triangle$ and $\blacktriangle$ mean the group of the stripes A, B, C and D respectively. Numerals attached to the plots indicate the rotating speed in frequency. Subjects are HSG (.....) and IWT (—).

naming procedures (rather than a colour matching technique) include those made by ROELOFS and ZEEMAN (1957, 1958), who emphasized the necessity of sharp contours in any colour inducing patterned disc, and by CAMPENHAUSEN 1968(a). All these experiments produced data similar to those of Verriest and Seki and Hasegawa.

c) The colours are affected by modifying the spatial pattern of Benham's disc.

Qualitative assessments made by Hasegawa on how arc line width affects the colours showed that for lines subtending about $18'$ at the eye, the colour extended from the edge into the central region of each line. For lines subtending $90'$ arc at the eye, the colour effect was confined to on and around the edge of the line, in a similar fashion to Mach bands occurring at a boundary in a static spatial black and white pattern. These results agreed with the theoretical curves drawn by CAMPENHAUSEN (1968a) to describe such distributions in the subjective colour. These curves, which were not based on experimental data, were considered to illustrate the fact that lateral inhibition might play a role in the colour induction, since he also noted the similarity between the subjective colour which was observed to "cling" to an edge, and Mach bands. The cause for Mach bands is generally assumed to be lateral inhibition within the retina (FIORENTINI, 1972).

The Campenhausen 1968a study, also included data on the effect of eccentricity of the retinal image of the arc lines on the colours perceived. Fourteen subjects were used, and the most important finding was that for eccentricities of about 20° on either side of the fovea, all the subjective colours were less saturated than for other retinal areas stimulated. Campenhausen interpreted this as due to the fact that at about 20° from the fovea rods are greatest in number in the retina and the ratio between rods and cones the greatest (OSTERBERG, 1935).

BAGLEY (1902) and PIERON (1922 a, b,) extended the study of varying the spatial parameters of Benham's disc by investigating the effect of changing the relative portions of black and white on the disc and also

the arc line lengths. General conclusions from these authors and as summarised by SHEPPARD (1968), were that;

- (i) the optimum length of an arc line on Benham's disc such that red, green, yellow and blue are seen simultaneously is $45^{\circ} - 60^{\circ}$. Line lengths departing from this figure result in subjective colours which are less bright although not necessarily less saturated.
- (ii) The length of the white portion of the disc following an arc line³ has little effect on the colour seen.
- (iii) The length of the white sector preceding an arc line determines the colour evoked, except for blue. As this white portion increases (from zero in the case of the A lines in figure 2) to 180° , the colours emerging on the lines pass through the spectrum from red to blue.

In a recent study of spatial changes in the pattern of Benham disc type stimuli, CAMPENHAUSEN (1973), using a rotating modification of the disc showed that slight spatial shifts of the arc lines in the pattern led to perceptible changes in the appearance of these. The detection of such a small spatial shift meant that the observer was detecting a correspondingly small time difference. The rotating disc used, and Campenhausen's interpretation of the stimulus in terms of luminance vs. time functions are shown in figure 5.

Now, Campenhausen regarded such a rotating disc to produce firstly an intermittent surround region in the stimulus, (formed by the black and white quarters of the patterns) as shown in the row marked (1) in figure 5 and two intermittent target regions where the pulses of this flicker sequence are defined by the white spacings between the ends of one set of arc lines and the beginnings of the next as shown in rows 11a and 11b in figure 5.

Thus figure 5 (b) shows the total stimulus presented to the eye in terms of temporal luminance changes for one revolution of the disc. Note

FOOTNOTE 3. For example in figure 2, the white portion indicated by the dotted arrowed line is considered to "follow" the arc lines A.

CAMPENHAUSEN (1973)

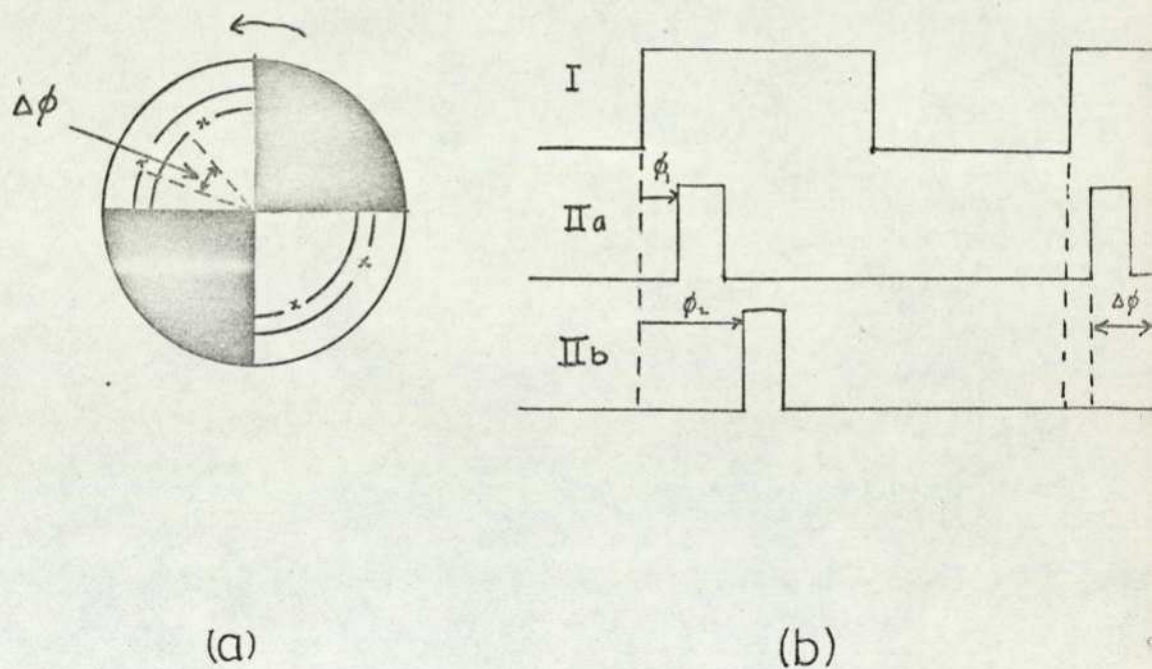


Fig.5 a) Experimental disc. b) The pulse stimuli as emitted by the white portions of the disc I and as emitted by the gaps (x) between the outer IIa and inner IIb black arcs

that for the outer and inner sets of arc lines, a phase difference $\Delta\phi$ exists between the pulses generated.

If the frequency of the flicker is f Hz (where f is twice the rotation frequency of the disc), then the time difference between these pulses, separated by the phase angle $\Delta\phi$ is given by:

$$t = \frac{\Delta\phi}{2\pi f}$$

By firstly fixing $\Delta\phi$ in the stimulus pattern and asking the observer to adjust f until a perceptible difference between the two sets of arc lines could be detected, t values were found as small as 1msec. This finding was interpreted as supporting the idea that the visual mechanism responsible for F-B subjective colour lay in the retina. The argument proposed was that to detect such short time delays, the information on the time relationships of the stimulus at the site of the subjective colour producing visual mechanism must be available with a high degree of accuracy. Thus, since information on the temporal properties of a stimulus undergoes various degrees of attenuation as it is conducted on through the receptor→cortex pathways, then this mechanism is likely to be located at the periphery of the visual system (i.e.) somewhere in the receptor→ganglion cell neural network. The flicker frequencies employed by the observers varied from between 20 - 50Hz, which is a frequency band greater than that normally associated with F-B subjective colour (that being about 5 - 15Hz). Thus, the visual mechanism responsible for the detection of such short time delays may not be that associated with the subjective colour effects.

(iv) Dichoptic presentation of F-B colour inducing stimuli modifies the colours seen. CAMPENHAUSEN (1968b), used the patterned disc shown in figure 6a, and found that the arc band appeared red-brown in colour when rotation was anticlockwise. Monocular and binocular viewing showed qualitatively, the same results. Then, by presenting the disc shown in figure 6(b) to the left eye and that shown in figure 6(c) to the right eye,

CAMPENHAUSEN (1968b.)

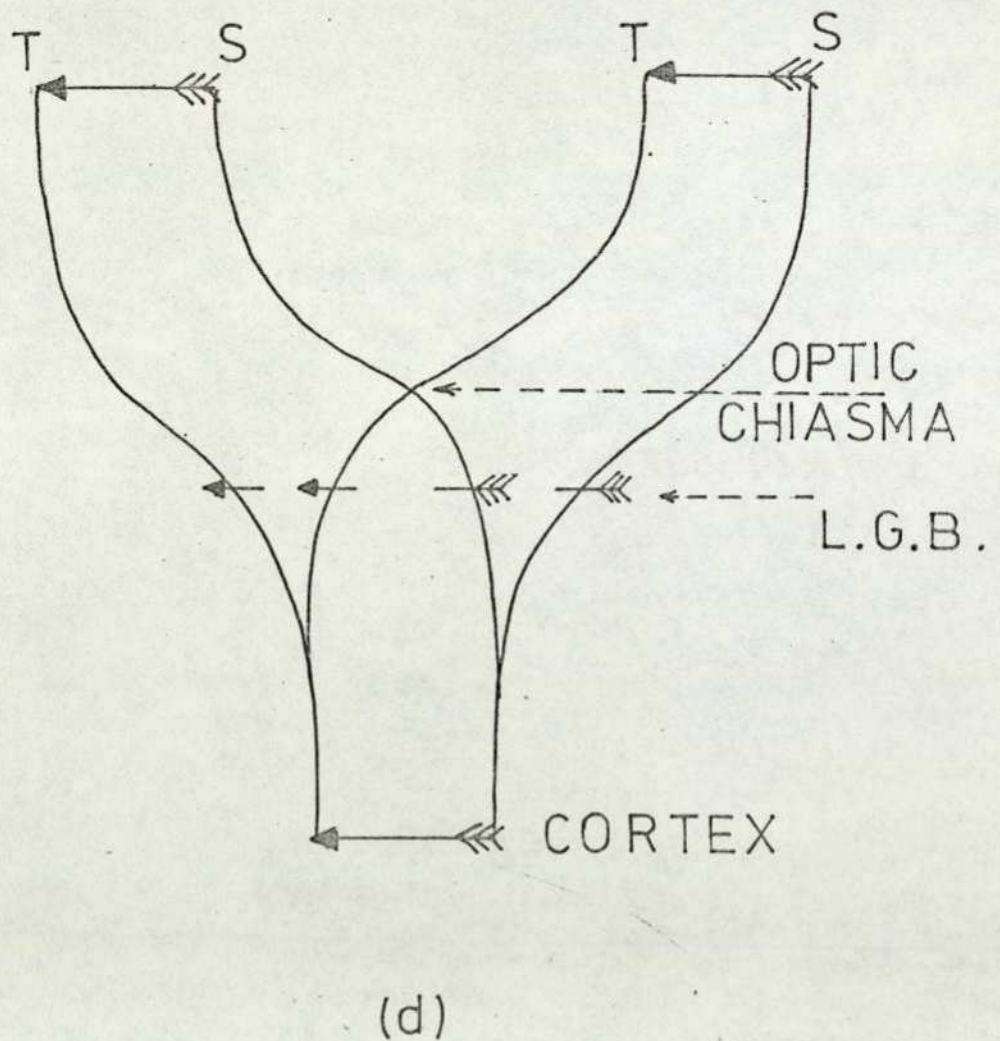
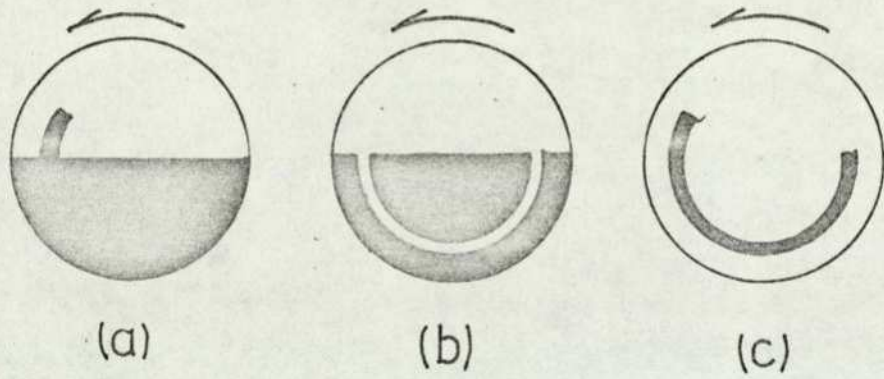


Fig. 6. a,b,c, represent the experimental discs. d represents retina→cortex pathways

no colour was observed when the discs were rotated, even though the fused images resulted in the observer seeing a disc identical with that in figure 6a.

The interpretation of the data was that since dichoptic presentation of the stimulus resulted in no colours being seen, then the locus for the cause of the colour effects occurs before the nerve pathways from the two eyes join together (i.e.) either in the retina or possibly the lateral geniculate body (see figure 6d for a schematic representation of the organisation of optic nerve fibres from each retina.) The arrow TS represents the retinal image produced from an object in space and the neural information stemming from this image is transported to the cortex in two distinct groups as shown. (on the left the arrow head; on the right the arrow tail). Performing a similar experiment, GREGORY (1968) and HESS (1952) arrived at this same conclusion.

Campanhausen also investigated the effect of presenting the stripe of the disc shown in figure 6a through a small aperture so that it was seen either passing vertically or horizontally through the aperture. In both cases, qualitative estimates of the colours seen were the same. Campanhausen was further led to the conclusion that the visual mechanisms responsible for the induced colours lay in the retina and not the alternative L.G.B. The argument stemmed from the theory of F-B subjective colour advanced by Campanhausen (see later in this chapter for a full discussion of this). The postulate was that both an intermittent target area (the arc lines of a Benham's disc) and an intermittent surround (the remaining black and white portions of the disc) are both necessary to produce the colours (i.e.) two adjacent flickering fields in the stimulus are necessary. The colours are formed, according to Campanhausen, by a lateral inhibitory interaction occurring within the visual system between the neural activity resulting from stimulation by the surround region of the stimulus and that arising from stimulation of the target. Now the dividing line between that half of the retina leading to stimulation of the ipsilateral portion of the brain from that part leading to stimulation of the contralateral part

of the brain is a vertical trough through the fovea (POLYAK, 1957). Also, the neighbouring cells between which a target-surround interaction could take place for a vertical stripe stimulating the centre of the fovea are next to each other in the retina, whereas in the L.G.B. they lie separated in the right and left halves of the brain. From these facts, Campenhausen maintained that if the lateral interactions occur in the L.G.B., then the colour appearance of the stripe would be likely to depend on the orientation of the stripe, relative to the fovea. Such was not the case as mentioned previously.

d) Miscellaneous Factors

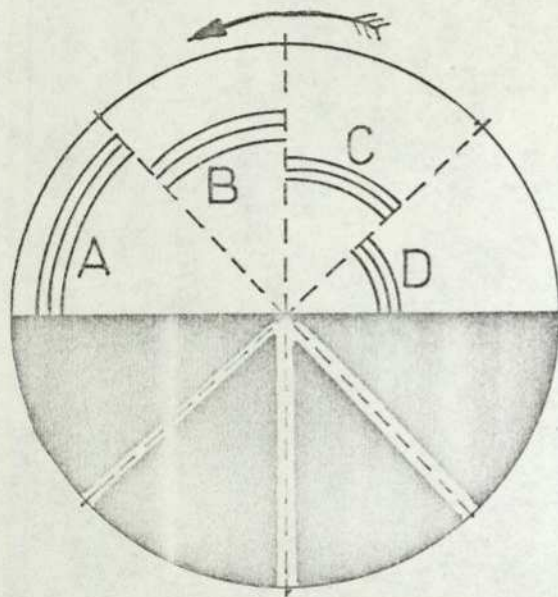
(i) Individual differences occur in the hues and saturations of the colours. KNEHR (1953), for example, showed that amongst the 25 observers tested with a Benham's disc, differences occurred, as marked as one observer describing a set of lines as blue-purple which were observed by another observer as olive-green. Munsell matches were made in this experiment, and care must be taken in interpretations of the data, since no details were given regarding the conditions of the observers colour vision.

(ii) Eye movements are irrelevant in the production of F-B subjective colour. TRINCKER, (1968) showed that the colours of a Benham's disc were qualitatively the same following paralysis of the eye muscles by curare.

(iii) Flicker adaptation enhances F-B subjective colour according to HELMHOLTZ (1860). BAGLEY (1902), however, found that continued viewing of a Benham's disc did not produce such an affect.

e) Other methods of producing F-B subjective colour.

HANSEL (1957), SHEPPARD (1968) and BUTTERFIELD (1967, 1970), described Benham's disc in terms of eight segments as shown in figure 7a. The stimulus sequence to produce red on the A lines was interpreted as comprising four black segments (B), followed by one segment of black (B) lines on a white background (O), followed by three segments of white (W). Similar interpretations of the stimulus coding required to elicit the other subjective colours were given. Thus a tabulation was made of these requirements in terms of B, O, and W components (see figure 7b).



(a)

<u>LINE</u>	<u>'STIMULUS SEQUENCE'</u>	<u>COLOUR</u>
A	B-B-B-B-O-W-W-W	RED
B	B-B-B-B-W-O-W-W	YELLOW
C	B-B-B-B-W-W-O-W	GREEN
D	B-B-B-B-W-W-W-O	BLUE

(b)

An interpretation of Benham's disc. Each 'stimulus sequence' letter represents one frame of a television film. (see text for further details.)

Fig. 7

Following this interpretation of Benham's disc, television films designed to produce subjective colour from black and white flicker were produced. Each of the B, O and W components was made into a single frame of the film and the sequence was continually repeated. An interesting feature of this mode of producing subjective colour was the fact that the O segment or film frame could comprise almost any black object on a white background. Providing the black object was not too large, F-B subjective colouring was observed when the film speed was about 30 frames/sec, this being equivalent to 5Hz rotation frequency on a Benham's disc.

Since in this mode of producing F-B subjective colour, the stimulus appears as a static flickering field, it seems that motion across the retina is not important in producing the colours. This has been confirmed by SILVESTRI (1965), who pulsed black and white photographs with white light and observed the subjective colours and BRIGNER (1971) who produced the colours using a tachistoscopic presentation of a black and white scene.

Reports of subjective colour induced in a single pulsed achromatic light have also appeared in the literature. A detailed experiment investigating such colour effects (FESTINGER, ALLYN & WHITE, 1971) will be discussed later, and only the more minor studies will be mentioned here.

As in the case of experiments involving the viewing of rotating patterned discs, many of the investigations of colours induced in a pulsed light have involved simple colour naming procedures, and the apparatus usually employed either a strobe light or a light chopping disc, both providing a square waveform to the flickering stimulus. In this category of experimentation comes work from FRY (1933a, b), PIGGINS, KINGHAM and HOLMES (1972) and CRAIG (1973). The general conclusion from all of these studies was that subjective colour can be produced from a single flickering achromatic light over a range of frequencies from 1Hz to fusion and over a range of retinal illuminances from 600 to 1700 td^4 . Unfortunately no quantitative relationships between any of the variables tested in these experiments have emerged.

Also, BURNHAM (1964), using both binocular and monocular viewing situations, observed subjective colours in a pulsed achromatic light under the binocular situation only (No data on the luminances employed were given).

Whether or not all the experiments quoted, concerning subjective colour induced in a single flickering light, reflect the manifestations of F-B subjective colour is open to some dispute, since firstly 1700 td produced from a stimulus is considerably greater than that provided by any colour inducing patterned rotating disc, and secondly F-B subjective colour is produced from both monocular and binocular viewing situations.

A brief note on the basic mechanisms of human colour vision is now given, mainly to define terms and descriptions used later in this thesis.

2. A Note on the Mechanisms of Colour Vision

Over the years many reviews on this subject have appeared. Among the most recent, are those by ABRAMOV (1972) and MACNICHOL, FEINBERG, and HAROSI (1973).

Human perception of light is divided into two aspects; luminosity and colour, where both are functions of the energy and of the wavelength of the light falling on the retina. Luminosity is a function of the total energy that is effective in stimulating the retinal receptors, whereas colour is dependent upon the wavelength distribution of the light. Colour has two dimensions; hue, which is related to the predominant wavelength of the colour and saturation which is related to the amount of the predominant wavelength in the colour.

The first neurons in the chain of neurons comprising the visual system are the photoreceptors. Each photoreceptor secretes a light-sensitive substance (photopigment), which is broken down when acted upon by light (see WRIGHT, 1946 for a discussion). Through this decom-

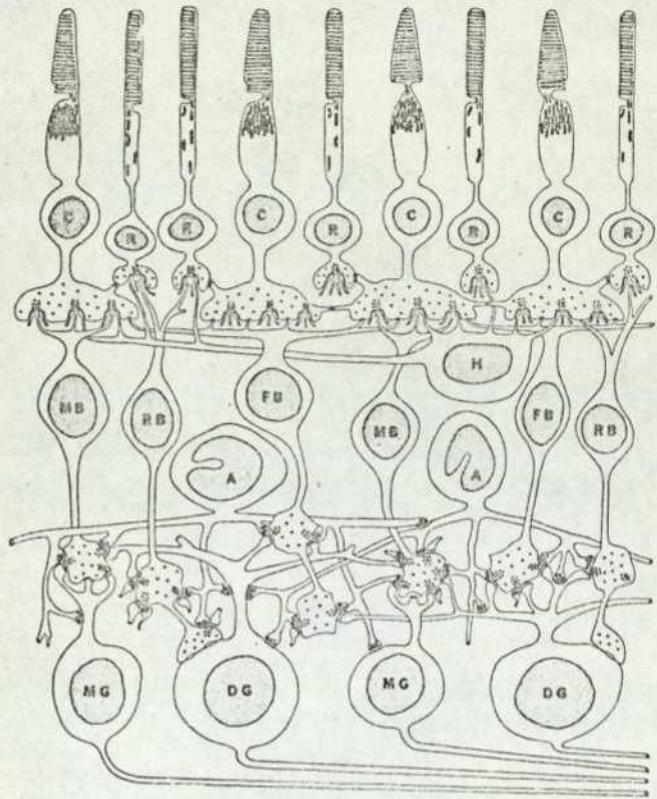
FOOTNOTE 4. These figures are approximate and were derived from data quoted in FRY (1933a).

position, nerve currents are produced which travel via the neurons of the retina and on to the brain. Figure 8, shows the retinal neurons in the visual system of a typical vertebrate retina (DOWLING and BOYCOTT, 1966). Structurally, two distinct photoreceptor types are seen; cones, which function in daylight conditions (photopic vision) and are concerned with colour vision and rods which function under low levels of illumination (scotopic vision) and give vision only in shades of grey⁵.

Colour mixture experiments illustrate the fact that most colours can be reproduced by an additive mixture of only three radiations, such as a monochromatic red, green and blue. From this fact psychophysicists have deduced that three distinct cone photopigments exist in the human retina and the whole range of colour sensations can be produced from these. The hypothesis that at the most peripheral region of the visual system colour vision is trivariant, (three photopigments) became a reality from the spectrophotometric studies of BROWN and WALD (1964) and MARKS, DOBELLE and MACNICHOL (1964), who made measurements of photopigment spectral absorption curves in man. Unfortunately, due to scatter in the data points, the exact form of these spectral absorption curves and the exact values of the absorption maxima are still uncertain. Approximately, these maxima lie at about 440 nm (blue region of the spectrum), 530 nm (green) and 565 nm (orange). These values are consistent with the data provided by both Brown and Wald and Marks et al.

It is also generally proposed that for the human, each of these photopigments is contained within separate single cones. These three distinct cone types have often been referred to as red (R), green (G), and blue (B) cones, since their absorption spectra peak in long, middle and short wavelength regions of the visible spectrum, as mentioned above.

FOOTNOTE 5. Rods may be active under photopic conditions however, augmenting the blue mechanism of the eye (see for example, TREZONA, 1970).



Schematic diagram of synapses in a typical vertebrate retina. R rods, C cones, H horizontal cells; MB, FB, and RB bipolar cells; A amacrine cells; MG and DG ganglion cells. (From Dowling and Boycott, 1966.)

Fig. 8

Strictly speaking, such colour names should not be given to the cones but it does provide a useful shorthand method of writing.

From the output of the three cones there is evidence to suggest that distinct colour information and luminosity information channels are formed. Psychophysical evidence that this is so came from PIERON (1939) who showed that the luminosity⁶ curve changes only slightly after moderate chromatic adaptation, and WEALE (1953) who showed that the luminosity curve of cone-monochromats is virtually the same as that of normal trichromats.

Electrophysiological work on the macaque⁷ monkey has also provided evidence for the separation of colour channels from a luminosity channel. Cells in the lateral geniculate nucleus of this monkey have been extensively studied (DE VALOIS and JACOBS, 1968) and two main types have been distinguished according to their response to monochromatic stimuli. Cells of one type, (spectrally non-opponent cells) show an increase in firing rate to stimulation by all wavelengths, whereas cells of the other type, (spectrally opponent cells) respond with excitation to wavelengths in one part of the spectrum and inhibition to wavelengths in another. The opponent cells are purveyors of colour information, whereas the non-opponent cells lie in the luminosity channel. A similar state of affairs has been found to exist at the ganglion cell level in the macaque (GOURAS, 1968).

The finding of spectrally opponent cells also gave support to the postulate of HERING (1872), who believed that colour opponent processes exist within the human colour visual system, in which a red

FOOTNOTE 6. The luminosity curve for the eye is a measure of its sensitivity to each wavelength in the visible spectrum. Two curves are given; one for photopic vision, the other for scotopic vision.

FOOTNOTE 7. There is good experimental evidence available to suggest that the human and macaque monkey have identical colour vision.

vs. green mechanism and a blue vs. yellow mechanism exist. The spectrally opponent cells found by De Valois and Jacobs can be divided into two groups; those which handle information from the red and green cones and those which handle information from the red and blue cones.

With regards to the development of models designed to describe human colour vision (see WALRAVEN, 1973 for a review), perhaps the most widely accepted is that proposed by WALRAVEN (1962, 1973). This model is shown in figure 9. The stage A of the model shows the initial trivariant nature of human colour vision. From the three cone outputs R, G and B, distinct colour channels (R vs G, B vs Y) and a luminosity channel L are formed. Now Walraven interpreted $Y=R+G$ (the R and G symbols here of course refer to the neural activity stemming from the red and green cones) which is in disagreement with the electrophysiological data collected at the retina and L.G.N. of the macaque described earlier. Here, the opponent processes do not show a Y signal stemming from an addition of red and green cones, but a signal arising from only the red cones. Nevertheless, this model has been used successfully in describing many psychophysical phenomena, including the Bezold-Brucke effect.

A model of human colour vision not discussed by WALRAVEN (1973) and mentioned, but not fully discussed by ABRAMOV (1972) is the "Modulation" theory first proposed by TROLAND (1921). Since this theory forms the basis of one of the theories of F-B subjective colour discussed later, it must be examined now.

The theory postulates that colour information is signalled in a temporal code form, by a modulation of the spike discharge frequency in optic nerve fibres, hue depending on the waveform of the spike frequency vs. time function, saturation by the amplitude and luminosity by the fundamental frequency of the function. The theory was extended by FRY (1945, 1965), who in the first of these two papers illustrated plausible modulation waveforms and their corresponding sensations (see

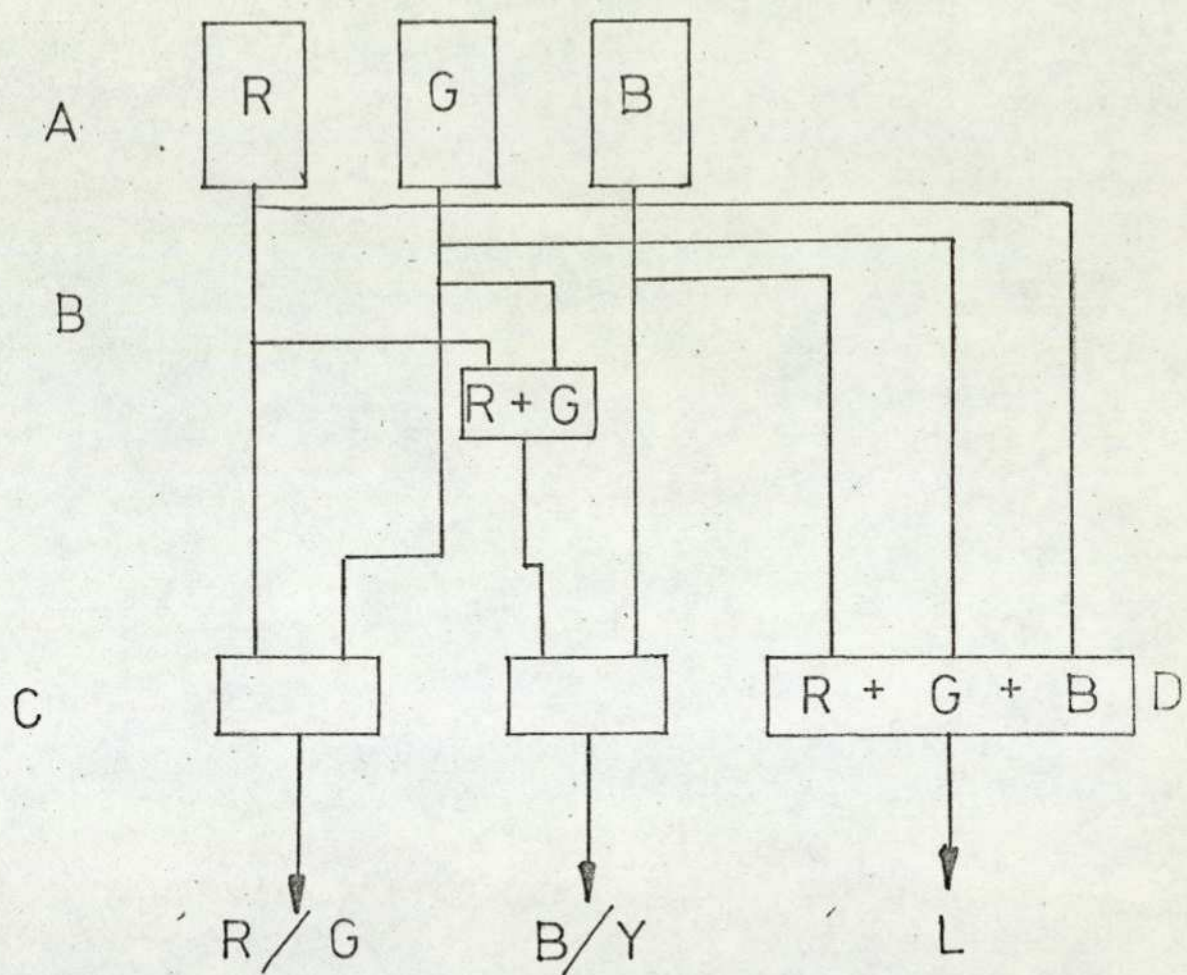


Fig.9 The Walraven zone model

figure 10). The waveforms for complementary colours were assumed to have complementary shapes by FRY (see p.273, FRY, 1965) as shown in figure 10. Fry maintained that the Benham's disc phenomenon provided some experimental justification for the waveforms chosen, but the connection is not immediately obvious (but see later when the "Morse Code" theory of F-B subjective colour is discussed).

On this basis, the frequency of modulation for all the colour coded modulation waves was suggested to lie in the 4-10 Hz frequency band and they may be superposed on a basic frequency of between 10 to 300 impulses per second.

In its original form, the theory postulated nerve impulse (spike) outputs from photoreceptors and so was criticised for this fact, since such neural behaviour is not found until the ganglion cell layer in the retina (see NELSON, 1971). Nelson, however, appeared to be unaware of the fact that FRY (1965) had revised the theory to allow for this fact, and now postulated that the colour coded modulation patterns first appear at the ganglion cell level following interactions between the three steady potentials generated by the three cones.

The mechanisms for producing the characteristic modulation waveforms were assumed to be arranged in pairs; the mechanisms responsible for the red and green modulation patterns are arranged together and produce opposite modulation effects (see figure 10). The mechanisms responsible for the yellow and blue modulations are arranged together and the yellow mechanism is considered to have an input from both red and green cones. A major criticism of this theory is that it does not discuss possible physiological processes which constitute the modulation mechanisms, located at or near the ganglion cell level. These must be capable of producing the modulation patterns from steady stimuli.

In summary, this particular theory acknowledges the existence of a trivariant level in the colour visual system followed by a Hering type opponents system (as in the Walraven model), but also includes a

FRY (1965)

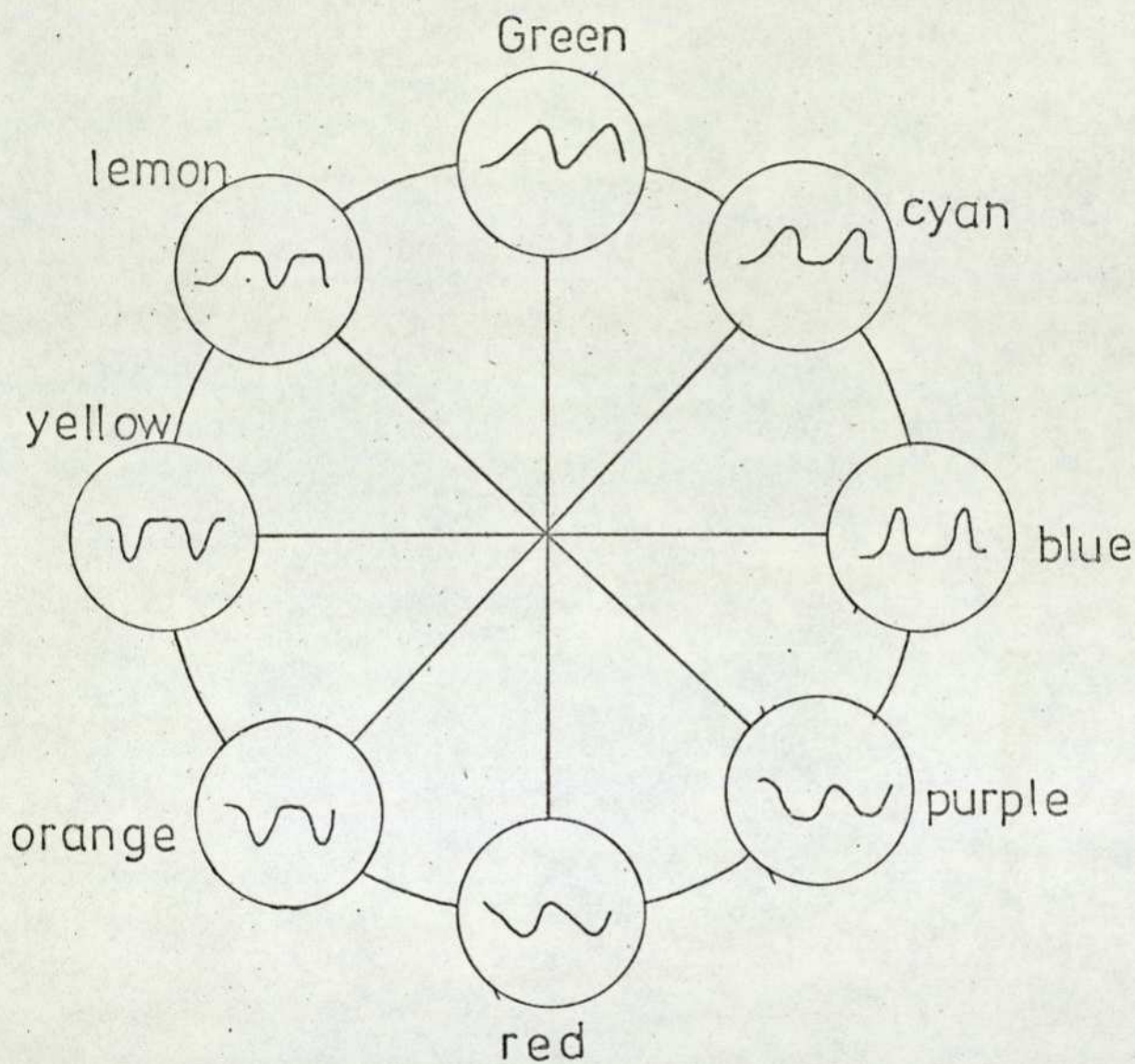


Fig. 10 Hypothetical modulation waves
(The "Modulation theory")

temporal aspect to the colour information in the form of modulation effects in the ganglion cell discharge patterns.

The theory has never gained much support from electrophysiological findings. The opponent ganglion cells found by GOURAS (1968) for example, appear to show a maintained steady discharge (apart from an initial on-transient when the stimulus is first delivered) to a maintained light stimulus, whereas on the basis of the "Modulation" theory, the appropriate colour coded continuous modulation effects would be expected to be observed.

KOZAK and REITBOECK (1973), however, have recently found colour coded modulation patterns of the ganglion cell discharge frequency in the cat, and claimed that this supports the "Modulation" theory.

3) Theoretical Interpretations of F-B subjective colour

Emerging from the extensive research in F-B subjective colour comes three commonly held theories;

- a) The "Fechnerian" Theory (FECHNER, 1838) which has been supported and developed by PIERON (1922, 1957).
- b) The "Phase Sensitive Lateral Inhibition" theory proposed by CAMPENHAUSEN (1968a, b, 1969).
- c) The "Morse Code" theory, proposed by ROELOFS and ZEEMAN (1957, 1958) FRY 1933 (a), (b) and BUTTERFIELD (1970).

a. The "Fechnerian" Theory

This theory takes its name after Fechner, who was the first to suggest that the colours of Benham's disc were due to the fact that the colour mediating mechanisms of the eye respond with different latencies. The theory was explored a little more by Pieron and his conclusions were based on his own observations on Benham's disc (see above cited references). The explanation is that basically Benham's disc represents a flickering (square wave) stimulus. For the lines marked A in figure 2, it was stated previously that for the direction of rotation indicated, these normally appear red in colour. The A lines coincide with the beginning

of one of the flicker pulses and in this theory the red colour mechanism of the eye is supposed to reach a peak in neural activity with a shorter latency than the other colour mechanisms (green being next and blue having the longest latency). According to Pieron, this red peak coincides with the A lines, these as mentioned occurring at the very beginning of the light pulse. Thus, following what Pieron unconvincingly described as a "diffusion of excitation" from retinal regions stimulated by the light pulse onto retinal regions stimulated by the A lines, these are made to appear red in colour. Similar explanations were given for the colours emerging on the other arc lines, and a diagram illustrating the theory is shown in figure 11. The curves shown in figure 11, represent theoretical interpretations of the time courses of the three colour mechanisms. The ordinate for each curve is a measure of sensation magnitude, stemming from each of the cone derived signals. Why the presence of black lines on a Benham's disc should lead to the observer distinguishing each colour component of the white pulse is not discussed by any of the advocates of this theory.

Implicit in this theory, in summarising, are the following points;

- i) the colour mediating mechanisms of the eye possess different time constants.
- ii) the phenomenon is produced from a single white light pulse.
- iii) a lateral excitation effect is involved.

The theory also accounts for the changes in colour of the arc lines, observed by Pieron, as the illuminance of Benham's disc was changed. PIERON (1922^{a,b}) in fact believed that the time constants of the colour mechanisms are inversely related to the illuminance (or level of light adaptation). Figure 12 shows how the colour sensation curves are shifted when the illuminance is raised. Since, according to Pieron the latencies of the colour mechanisms must now all be shortened the curves are shifted toward the pulse onset.

As mentioned previously, optimum coloration on a Benham's disc occurs about 7Hz, which means a light pulse length of about

PIERON (1957)

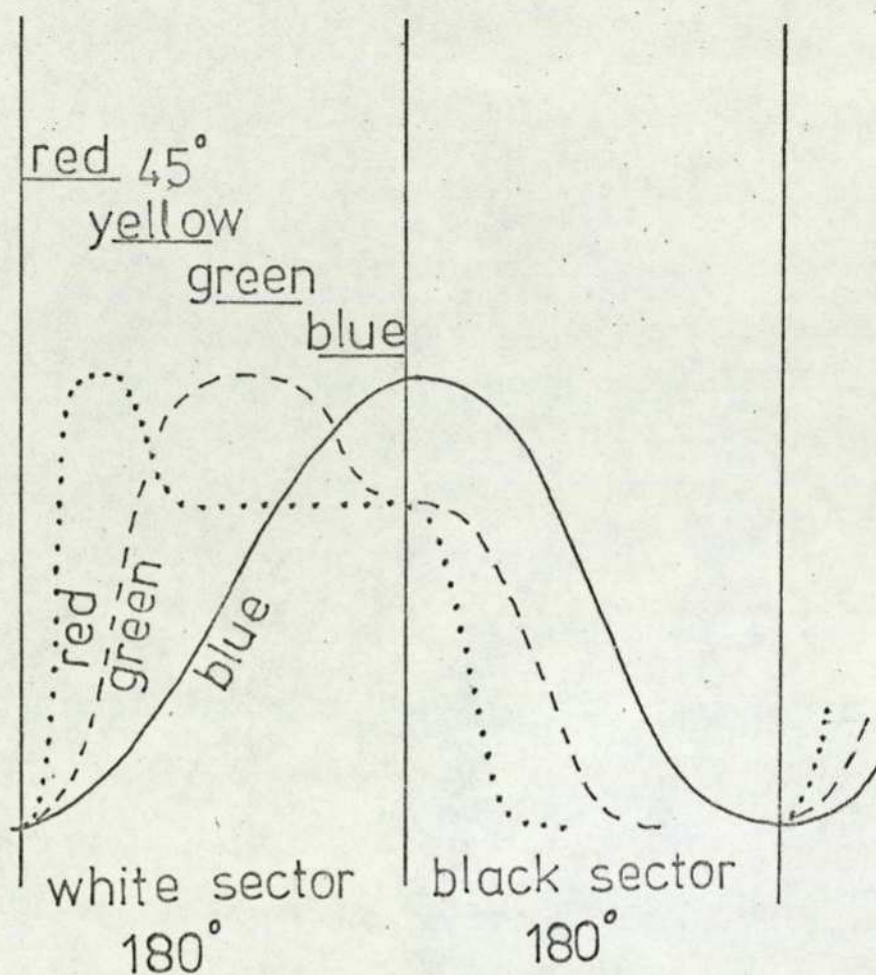


Fig.11 Schema of the time courses of the three chromatic systems, explaining the colourations of the rings produced by the curved stripes during the rotation of Benham's disc.

PIERON (1922 a)

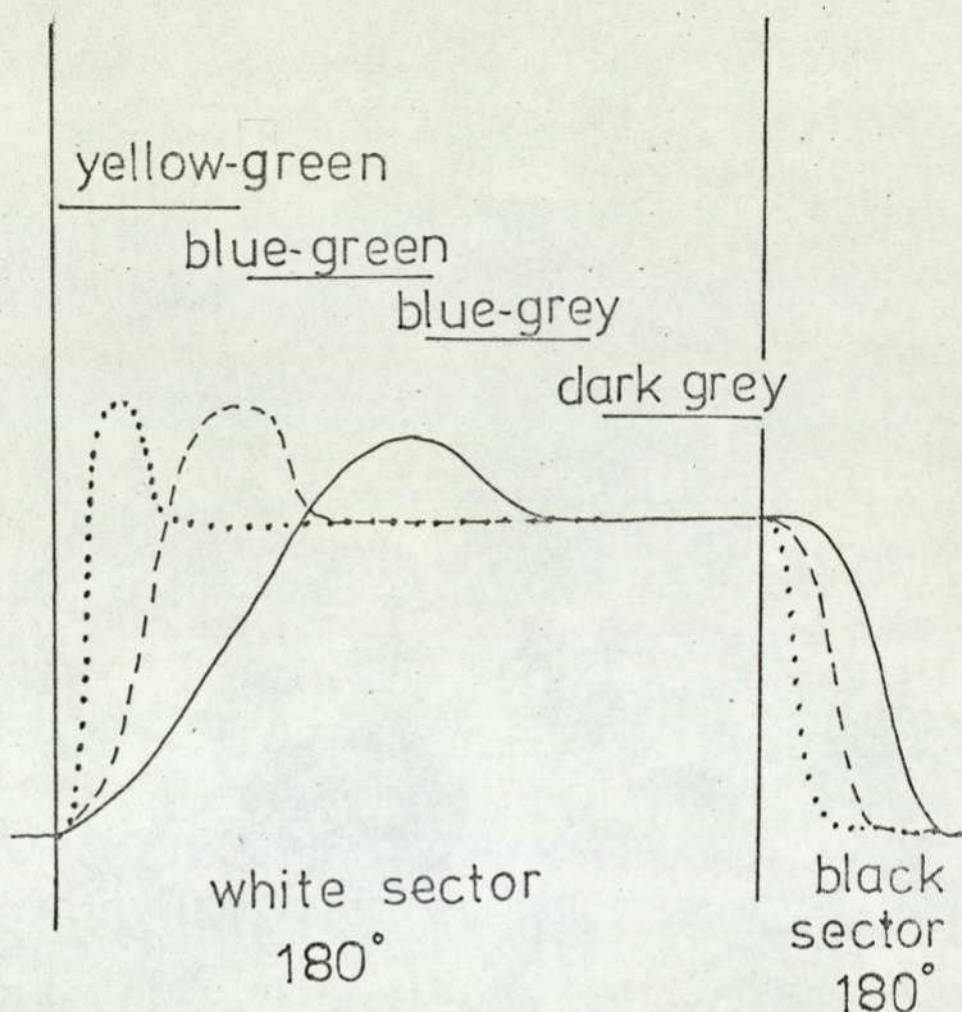


Fig.12 As for figure 11, with the speed of rotation reduced or with the disc illuminance increased.

70 msec. The differences between the peaks of the curves shown in figure 11 would then be about 30 msec. The question now raised in connection with the "Fechnerian" theory is what experimental evidence exists to support the existence of differences in latency of such an order of magnitude? Experimental estimates of latency times for the colour mechanisms have been derived from a variety of psychophysical procedures and the results have been ambiguous and confusing. On the one hand, LIT, YOUNG and SHAFFER (1971) measuring reaction times to monochromatic stimuli and GUTH (1964), using a moving bipartite target failed to find differences between wavelengths at photopic levels.

On the other hand, PIERON (1932a, b) found reaction times to red pulses slightly shorter than for blue. In most of the studies of reaction time, monochromatic stimuli of suprathreshold intensity presented on achromatic backgrounds have been used. Such stimuli are only likely to isolate a single colour mechanism under a very limited number of conditions.

In order to investigate the colour mechanisms of the eye in isolation, MOLLON and KRAUSKOPF (1973), measured reaction times to threshold and slightly suprathreshold intensity light flashes presented on monochromatic adapting fields. The adapting field acted to depress the sensitivity of the colour mechanisms derived from two cone types, so that the detection of the flash was mediated by just one colour (π) mechanism, derived from the third class of cone. The method used was the "two-colour increment threshold" technique developed by STILES (1939, 1953, 1959). A major point emerging from Stiles theories and worthy of mention here, is that the state of adaptation of a particular colour (π) mechanism was found to be ^{almost} independent of the adaptive states of the other π -mechanisms.

The salient findings of the Mollon and Krauskopf study were that not only did reaction times decrease when the level of adaptation of the mediating colour mechanism increased, but also reaction time was found

to be greatest when detection was mediated by the blue (Π_1) mechanism, and least for the red (Π_5) mechanism. Reaction times for detection mediated by the green (Π_4) mechanism lay between these two. Also found was that reaction time was dependent on the state of adaptation of the mediating mechanism only, and not on the adaptive state of the retina as a whole. Since interactions between colour mechanisms within ganglion cell receptive fields have been found to occur (GOURAS, 1968), Mollon and Krauskopf interpreted this finding as suggesting that changes in the time constants of colour mechanisms associated with changes in adaptive state arise at a very peripheral stage in the visual system.

Also investigated by these authors was the effect of raising the test flash intensity (keeping the adapting field unchanged) to slightly suprathreshold levels. Reaction time was then found to first decrease as test flash intensity was raised and then remain constant as test intensity was further raised. The results showed that the asymptotes differed by as much as 50 msec between the Π_1 reaction time curve and the Π_5 (red mechanism) curve.

Estimates of a latency difference between two "black boxes" in a system can be obtained from a knowledge of phase shift difference occurring between them, using as a stimulus for example, sinusoidally flickering light. DE LANGE (1958a) reported that when red and green stimuli are sinusoidally modulated in anti-phase, the observer detected a residual brightness flicker that could not be eliminated by varying the relative intensities of the two stimuli. If in addition, however, the phase relationship between the two flicker trains was varied, this residual flicker was eliminated. In this way a phase shift difference occurring between the responses to the two stimuli was compensated for. WALRAVEN and LEEBEEK (1964) measured the change in phase between the two stimuli Δt needed to eliminate residual brightness flicker for a large number of wavelength combinations and for flicker frequencies up to 10Hz. Their experimental findings (which have been confirmed by REGAN (1973a)) were used to calculate a phase shift difference $\Delta\theta$, supposed to exist

between the red and green cone colour mechanisms. The existence of $\Delta\theta$ as a linear function of flicker frequency was interpreted as indicating a latency time difference of about 30 msec between the red and green cone derived neural signals. Furthermore, such a latency difference seems likely to be established at or by the point D on the Walraven model (see figure 9), which represents the beginning of the luminosity channel in which the red and green cone derived outputs share a common path.

It is of interest to note at this point that colour dependent phase shifts in the visual system can be caused by the existence of rectifier elements rather than the existence of latency differences. For example, to explain the large phase differences found to occur between particular frequency components of the evoked potentials (E.P.'s) recorded from red and yellow flicker, REGAN (1973a) postulated the existence of such colour dependent rectifiers. Regan illustrated by way of an example, how the phase shifting properties of each rectifier depends on the slope of the characteristic curve (figure 13). As can be seen, sinewave inputs give distorted outputs (illustrating the non-linear behaviour of the rectifier) which are shown in terms of the fundamental frequency and second harmonic of the Fourier series. A change in slope leads in this particular example, to a 180° phase shift in the fundamental as shown. Regan suggested that if the slope of the characteristic was a function of wavelength then the phase shifting observed in his experiment would be accounted for.

There is in fact electrophysiological evidence to link rectifier elements with the activity of ganglion cells, at least in the goldfish (SPEKREIJSE, 1969). Again strong electrophysiological evidence that a latency difference exists between the red and green colour mechanisms in the goldfish has been produced by SPEKREIJSE and VAN DEN BERG (1971). These authors examined ganglion cells which received a $(-R+G)^8$ input to the centre and $(+R-G)$ input to the surround of their receptive fields. In order to investigate the nature of the interactions occurring

REGAN (1973a)

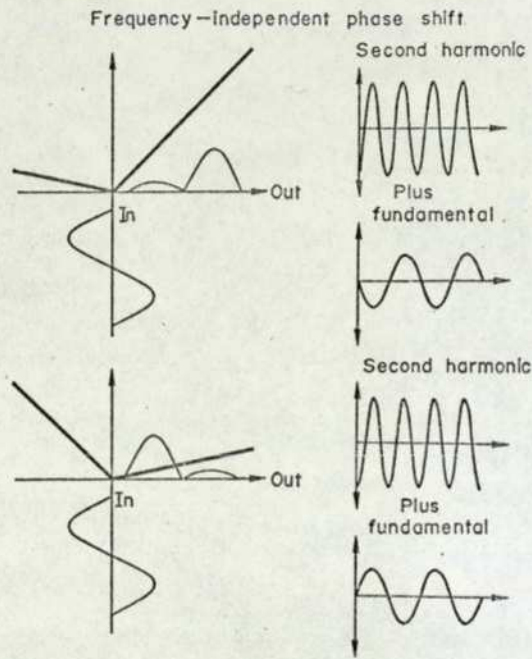


Fig. 13 180° colour-dependent phase shift of fundamental frequency component. Left side illustrates hypothetical rectifier-like properties of a peripheral stage in the visual pathway for long-wavelength light (upper plot) and short-wavelength light (lower plot). Sinewave inputs of frequency F Hz and a second harmonic component of frequency $2F$ Hz. By comparing the upper and lower halves of the figure it can be seen how a change in the relative slopes of the two branches of the rectifier results in a 180° phase change in the fundamental component of the output waveform.

between the red and green mechanisms in the centre of the receptive field, superposed sinusoidally flickering red and green lights arranged in anti-phase were used. The stimuli were chosen with the assumption that each stimulated the red and green mechanisms separately. To produce no output from the ganglion cells, an extra phase angle had to be introduced between the stimuli. That no output at all could be produced by manipulating the phase difference showed that the interaction between the red and green mechanisms occurred before the non-linear rectifier stage. Furthermore, the results indicated that the necessity for this extra phase angle stemmed from the existence of a latency difference, between the red and green mechanisms, existing before the rectifier stage. From these authors data it is a simple matter to calculate this figure, being about 30 msec. |(i.e.) phase shift $\Delta\phi$ and latency Δt are related to each other by the expression $\Delta\phi = 2\pi (\text{frequency}) \Delta t$ |.

On the role of the receptors themselves in determining latency differences between colour mechanisms, WHITTEN and BROWN (1973) have shown that the late receptor potential of the blue cone in the macaque monkey has a longer latency than in the red and green cones. The blue cone L.R.P., in fact resembles the rod L.R.P., in which latencies were found to vary from 60 - 120 msec, depending on the intensity of the light stimulus. Latencies in red and green cone L.R.P.'s were never found to exceed about 20 msec.

Recent analysis of human EP's derived from stimulation of single colour mechanisms (Stiles technique used with slightly suprathreshold test flashes) has also provided information on latency differences (KRAUSKOPF, 1973). From his experimental findings, Krauskopf showed that latency differences between the blue (π_1) mechanism were on average (50-75) msec longer than for either the red or green mechanisms. A glance at the data in fact shows that differences as large as 100 msec were

FOOTNOTE 8. The nomenclature used here is as follows; -R means an inhibitory input from the red mechanism, and +R means an excitatory input. Similar meanings apply to the G symbols.

manifested in the E.P. data. This author speculated that such differences arise in the retina.

The experimental evidence and speculations on the existence of different response latencies amongst the colour mediating mechanisms so far reviewed, generally support the suggested order of magnitude as shown in figure 11, for Benham disc type stimuli. Furthermore, as discussed, these latency differences may well be formed by retinal processes.

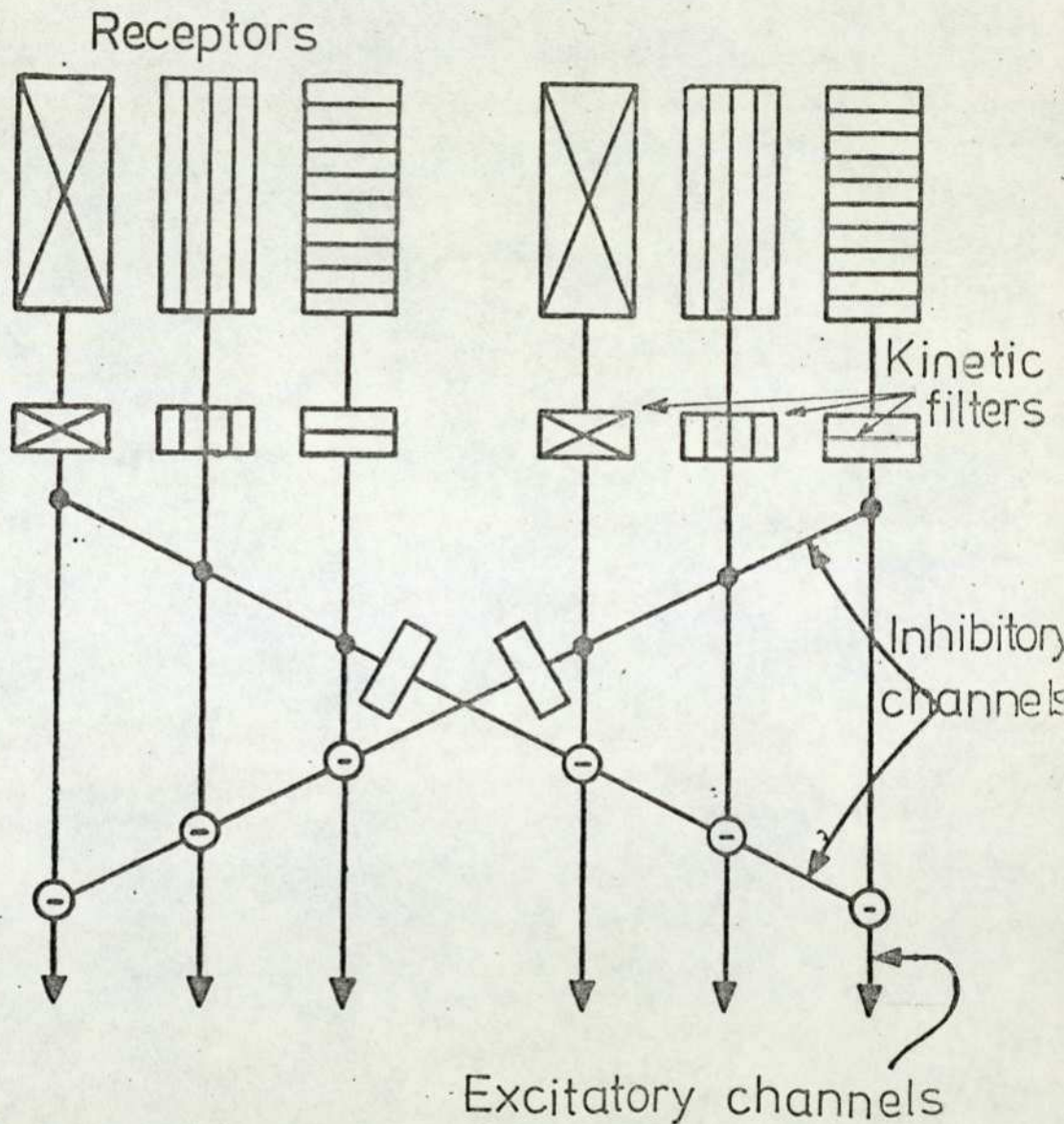
b) "The Phase Sensitive Lateral Inhibition" Theory

A summary of this theory is available in English (JAMESON, 1972). The theory constitutes speculations made by Campenhausen from a series of experiments carried out on rotating patterned discs, and as mentioned previously this author maintained that both an intermittent target and surround region are necessary to induce the colours. From this fact, and also the belief that lateral inhibition plays a role, the existence of a subjective colour producing mechanism was postulated as shown in figure 14. Excitatory signals produced from the three cone types are assumed to be modified in their temporal characteristics by "kinetic filters", each specific to a cone type. Lateral inhibition to and from neighbouring excitatory channels acts to modify the excitatory signals (two channels are assumed, since two signals from adjacent retinal areas are assumed necessary to produce the colours). It has already been seen how Campenhausen interpreted Benham disc type stimuli, in terms of target and surround signals (figure 5). Thus, for the Benham disc shown at the left of figure 15 (which comprises three sets of arcs instead of four), the interpretations of the red, green and blue inducing components are shown in column a. Notice that the "red" signal is similar to that shown in figure 5 and it is a simple matter to interpret the "green" and "blue" signals as illustrated.

According to Campenhausen, when for example a red inducing signal is applied (see figure 15 col. a, row 1), the interactions between

CAMPENHAUSEN (1968 a)

Fig.14 Schematic representation of Campenhausen theory



the two channels selectively favour the output from the red cones. The main reason for Campenhausen postulating inhibition as the lateral interacting signal has been discussed previously ((~~ie~~) the similarity between the spatial distribution of the colour and the spatial distribution of Mach bands). Not only is the colour inducing signal assumed to be peripheral in the visual system, but Campenhausen maintained that the interconnections shown in his model represent horizontal cells. A main point in this theory is that lateral inhibitory interactions can occur between colour mechanisms. ^(although this fact is frequently disputed) Figure 14 shows that in the model, all possible lateral linkages between cone types via the horizontal cells are possible. Recent electrophysiological evidence obtained on S-potentials, which are now known to represent the activity of horizontal cells, suggests a model proposed by GOURAS (1972), in which lateral inhibition is not conveyed between similar cone types through colour-coded horizontal cells, but always between cones of different spectral types. A similar state of affairs was found by GOURAS (1968) at the ganglion cell level, in an analysis of lateral inhibition conveyed between ganglion cell receptive field surrounds and centres. These facts alone suggest that Campenhausen's model is grossly oversimplified.

c) The "Morse Code" theory

This theory was first postulated by FRY (1933a, b). FESTINGER, ALLYN and WHITE (1971), however, were the first to explore the theory experimentally. The theory has for its foundation, the "Modulation" theory of colour vision outlined previously, and it explains F-B subjective colour in very simple terms: "The temporal succession of black and white stimulation (of a Benham's disc) creates a sequence of neural events that mimics the true temporal code (for the particular colour sensation evoked)". (FESTINGER, ALLYN and WHITE, 1971).

For example, in figure 2, the part of Benham's disc comprising the A lines, which appear red in colour when direction of rotation is as shown, and the black and white semi-circular areas of the disc, together

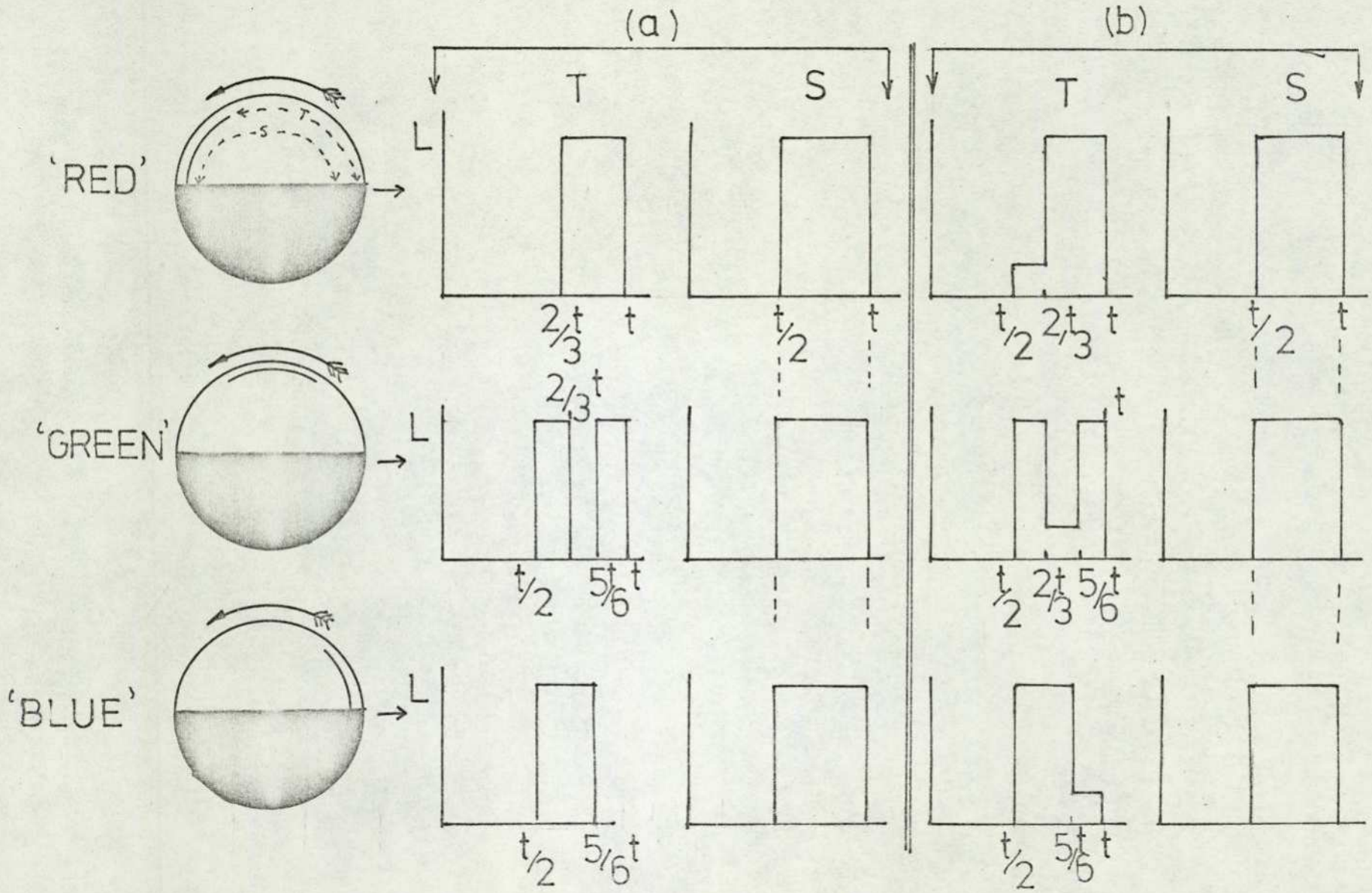
constitute an achromatic intensity vs. time relationship which brings about the temporal pattern in ganglion cell discharge frequency which characterises red. The same explanation holds for the other arc lines. Thus, argued Festinger et al, it should be possible to produce a full gamut of subjective colours from a single flickering achromatic stimulus by manipulation of the waveform of the flicker. A waveform producing, for example, a red sensation would be the waveform necessary to force the appropriate ganglion cells into discharging with a red characteristic pattern. Since the Festinger et al study constitutes the only major quantitative investigation of F-B subjective colour, a discussion of the results will now follow.

Apart from studying the hypothesis that waveform of a flickering light source can determine the subjective colour experience, these authors also investigated the Campenhausen interpretation of Benham disc type stimuli in terms of intermittent target and surround regions. The stimulus employed is shown in figure 16. This experiment was the first attempt to induce F-B subjective colour from a static stimulus display, which comprised a tripartite visual field viewed monocularly (no fixation point was employed). The colour inducing stimulus consisted of 17' horizontal bars (the target) and gaps of 65' (see figure 16). The bars were representative of the arc lines of a Benham's disc and the colours induced in these were matched by adjusting the colour and luminosity properties of the colorimeter field (c). The colorimeter employed was a Burnham filter colorimeter (BURNHAM, 1952). The colour inducing stimuli used (which were slightly different from the Campenhausen suggestion) are shown in figure 15, column b. The stimuli were derived from consideration of a Benham's disc having three sets of arc lines (see figure 15 column a for Campenhausen's interpretation of such a disc).

The Festinger et al interpretation of this disc, although basically similar to the Campenhausen interpretation, included a small

T - target t - periodic time
S - surround L - luminance

Fig. 15. a) Campenhausen's, b) Festinger's interpretation of the discs shown



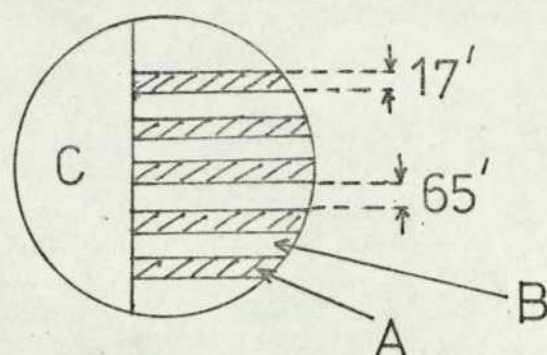


Fig 16 Stimulus field. A; target, B; surround, C; colorimeter

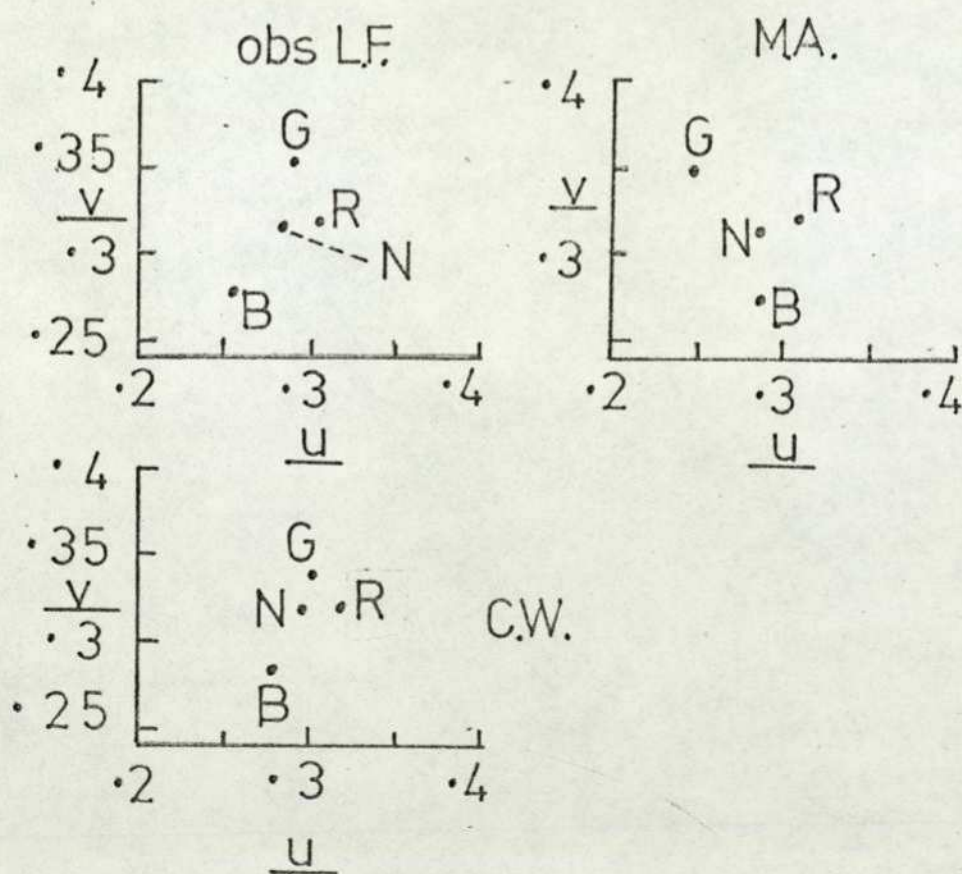


Fig 17 Results for three observers. (C.I.E. u, v)
 (see figure 15 for the temporal features of the stimulus.). N-neutral sq wave signal.
 R, G, B — red, green, blue signals

step in the target pulses for the blue and red signals. The inclusion of this small step was to allow for the effects of light spread from the white portion of a Benham's disc onto the black lines, which has the effect for narrow lines of increasing the effective retinal illuminance. They argued, to achieve the same effect for wider lines, some light must be present in the part of the stimulus period corresponding to the arc lines. Furthermore, if this is done, the colour inducing effects may well be independent of arc line width. (In an auxiliary experiment using a Benham's disc with wide grey bands these authors found this to be so). Thus, achromatic stimuli derived from their interpretations of Benham's disc, were investigated and the colours induced were measured. Data were reported for one temporal frequency (7Hz), since it has often been suggested that F-B subjective colour observed on rotating patterned discs has near optimum saturation at this frequency of rotation. The results indicated that the luminance vs. time functions chosen for the target and surround were good interpretations of the stimulus sequences represented by the Benham's disc considered. The data were shown on the C.I.E. (u, v) diagram (see figure 17). The hypothesis that similar colours could be induced from a single isolated flickering light source was investigated next. The stimuli used are shown in figure 18. The mathematical representation of these stimuli were not given and the drawings shown, were described as "smoothed approximations" to the temporal signals used. The maximum retinal illuminance of any pulse was 5000 td. and the stimuli were presented either as circular fields or as rectangular bars. The target had a constant surround providing a retinal illuminance of 750 td. and the flicker frequency was 7Hz. The light sources used throughout the experiment were Sylvania glow modulator tubes and the waveforms shown were approximated by groups of large numbers of small pulses. Subjective colour impressions were found to occur for each of these waveforms as indicated. The exact data are shown in chapter 4 of this thesis.

Waveforms similar to the blue, red and magenta inducing signals shown in figure 18, had been suggested earlier in speculations made by FRY (1945, 1965) on the requirements in a photic achromatic stimulus to produce subjective colour. ROELOFS and ZEEMAN (1957) were of the opinion, following inspection of various rotating black and white discs that a temporal increase in luminosity (an up ramp waveform in the flicker pulse) enters consciousness as red or yellow and a temporal decrease in luminosity as green, blue or violet. These ideas are in general agreement with the data obtained from Festinger et al, using the signals shown in figure 18. Others to suggest that pulse profile may play a role in F-B subjective colour were COLENBRANDER (1933), and NELSON (1971) in his review article cited earlier. Using a static stimulus display, with a temporal modulation of the intensity of a white light to induce F-B subjective colour is far more satisfactory than experiments involving rotating patterned discs. With such discs, inhomogeneity in the reflecting properties is likely to occur and a careful study of the temporal properties of the stimulus is difficult. Complex motion across the retina also occurs from such stimuli, the effects of which would be difficult to interpret theoretically.

The experimental design of the Festinger et al study is also open to serious criticism. Firstly, doubt must be cast at the glow modulator tube as a white light source. The action of this device is to convert variations in electric current into approximately corresponding variations in light output, the spectral composition of the output depending on the type of gas used (neon, argon and mercury being typical gasses). PUGSLEY (1972) using English Electric glow modulators reported that at low currents when the discharge is maintained by the gas filling, the colour is pinkish. At higher currents, the light output is produced by mainly ionised electrode material and the blue content becomes higher. BUCKMAN-OLSEN and ROSENFALCK (1957), determined the spectral composition of the light output for several Sylvania glow modulators and found that

FESTINGER et al (1971)

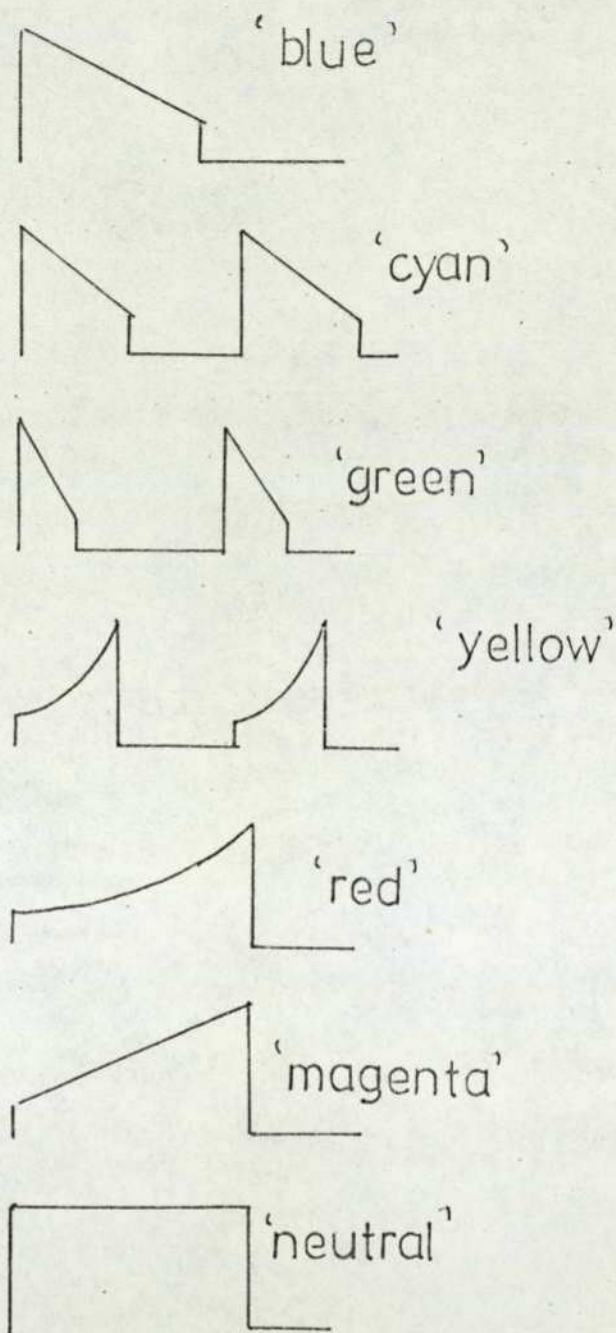


Fig.18 Smoothed approximations to temporal signals used with constant background (Exact details of the waveforms are not given)

this varied as a function of peak current.

Since F-B subjective colour effects are relatively unsaturated, such shifts in the spectral composition of the light source, even though these may be small, are likely to lead to considerable inaccuracies in the colour measurements. A second criticism of this study is the use of a colorimeter light patch viewed adjacent to, and by the same eye as, the target area in which the subjective colour is induced. With such an arrangement, contamination of the F-B subjective colour by a colour contrast effect due to the presence of the colorimeter may occur. More information on the waveforms shown in figure 18 is also necessary if this data is to assist in a quantitative theory of the subjective colours. The fact, for example, that different colour effects may occur for an up ramp and an exponential rise (which according to figure 18, have roughly similar profiles) suggests that the mechanism responsible for the subjective colour is sensitive to small temporal variations in the light stimulus. (That the mechanism may be sensitive in this manner has been suggested previously). Thus, the noise which must be superimposed on a waveform which is described as a "rough approximation" to the desired stimulus may be an unknown and uncontrollable variable effecting the colour induction.

To conclude this literature survey, the suggestions emerging from previous investigators regarding further experimentation, will now be discussed. The result that F-B subjective colour can be induced in a single flickering light by a manipulation of the waveform can certainly be explained readily, by the "Morse Code" theory and further research is clearly necessary into the effect of stimulus waveform. Also, following the discussion on glow modulator tubes, there is the possibility that some of the colours reported were instrument artefacts. If Campenhausen is correct in postulating that both an intermittent target and intermittent surround are necessary to produce F-B subjective colour, then the colour effects observed by Festinger et al are either artefacts or not F-B

subjective colour. The "Morse Code" theory will thus be re-examined as well as the plausibility of the theories developed by Campenhausen and Fechner.

CHAPTER II

APPARATUS DEVELOPED

Introduction

To make the necessary study of stimulus flicker waveform as a Fechner-Benham (F-B) subjective colour inducing parameter, a light modulator is required which can provide accurately, a large variety of temporal variations in the intensity of a white light stimulus, without a temporal change in spectral composition. This fact is clearly necessary following the remarks made in the discussion of the apparatus used by FESTINGER, ALLYN and WHITE (1971). A light modulator able to achieve this requirement has not previously been developed, although vibrating shutters (REGAN, 1970) and also rotating sector discs (placed in the light path) have been used successfully to produce rectangular and sinusoidal flicker. These methods have the advantage that the spectral composition of the light stimulus remains constant with time.

Apart from its use in studying F-B subjective colour, a white light modulator capable of accurately producing most mathematically specified waveforms would be a useful piece of laboratory equipment to develop, finding an application in most flicker experiments. The first stage in this research is concerned with the development of such an apparatus.

1. A METHOD OF CHANGING THE TIME PATTERN OF A LIGHT STIMULUS WITHOUT A TEMPORAL CHANGE IN SPECTRAL COMPOSITION

a) Construction and general principle of the light modulator

A technical note describing the basic principles of the modulator is provided at the back of this thesis (JARVIS, 1973).

A schematic diagram of the optical arrangement of the modulator is shown in figure 19, and this was used to test the basic principle behind the modulation process. The basic principle is to produce a temporal variation in the total quantity of light flux, from a 6V tungsten ribbon filament lamp (T.R.F.). This light flux then enters a mirror integrating box (M.I.B.). The temporal flux variation is achieved by the use of a rotating mask attached to a 1mm thick clear perspex disc D, placed adjacent to a slit S as shown. The end Y of M.I.B. gives a uniform light patch, the luminance of which varies in accordance with the variation in the total quantity of light flux incident on end X. The details of the components of the modulator are as follows; the slit S forms part of a sector of angle α and whose centre coincides with the centre O of the disc D. Figure 20 shows the arrangement. The sector slit S is formed by positioning two metal straight edges S.E., on an aperture (shown as a hatched line in figure 20) in a metal plate M. By making elongated holes in the metal plate for the screws fixing the straight edges, fine adjustments could be made in the positioning of these. The metal plate M was rigidly fixed in the apparatus, so that the orientation of the slit S, relative to the disc D was as shown in figure 20. This was achieved by small adjustments to the screws fixing the plate M to its support. To ensure that the centre of the sector slit coincided with the centre of the driving axle O (for the rotating disc), a clear perspex disc with a radial line scribed on it was positioned along each straight edge in turn. Fine adjustments to the metal plate were then made until this radial line accurately lay along the straight edge. Dimensions of the slit are as follows; the outer boundary of S is

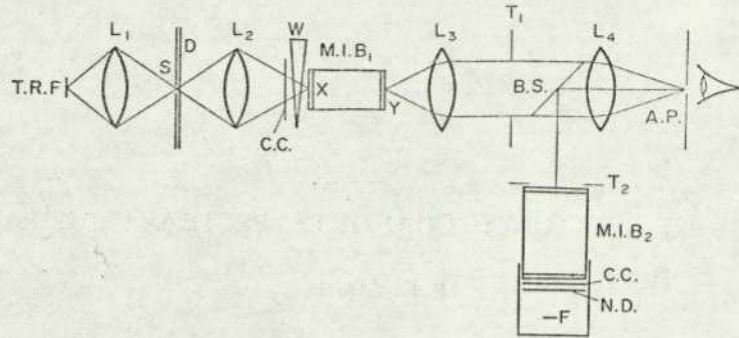


Fig 19.

Schematic diagram of the light modulator. T.R.F. = tungsten ribbon light source; M.I.B. = mirror integrating box; L = achromatic lens; W = neutral density wedge; CC = colour correcting filter; S = sector slit; D = rotating disc; B.S. = beam splitter; N.D. = neutral density filter; F = 12V, 24W Mazda filament lamp; T = adjustable diaphragm; A. P. = artificial pupil.

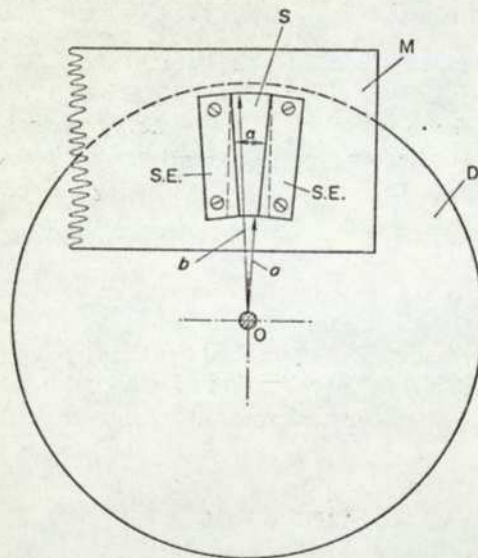


Fig 20.

The orientation of the slit S relative to the centre O of the rotating disc. M = metal plate; S.E. = metal straight edge; D = perspex disc; S = sector slit; $a = 1.5^\circ$; $b = 11.9$ cm; $a = 6.9$ cm.

formed by part of a circle, with centre O and radius b ($= 11.9$ cm). The inner boundary of S is formed by part of a circle with centre O and radius a ($= 6.9$ cm). The angle α is 1.5° . A magnified image of the filament of lamp T.R.F. is produced on the slit S such that S is completely covered by this image. The light flux from S is collected by the lens L_2 , which produces an image of S on the end X of the mirror box M.I.B.,. The disc D has attached an opaque mask whose outline determines the temporal change in the total amount of light flux which is allowed to pass through the slit S, as D rotates. The theory of the shape of this mask will be discussed later, together with details of how a computer graph plotter was used in its construction. Parts of the clear perspex disc which are not covered by this mask are thus free to transmit light. The disc is mounted on a lightweight axle driven by a stepper motor and such a device can drive the disc at any required frequency of rotation from 0 to ~ 60 Hz. In most of the experimentation reported in this thesis, two modulator discs, both mounted on the same axle, were employed. Constructional details of how the stepper motor was used to achieve this are given later in this chapter. The motor used throughout all the experimental work was a P.D. 20, 8-phase unit, supplied by Impex Electrical Ltd., Richmond.

The electrical connections between the electronic drive unit and the motor are shown in Appendix 1. The speed of rotation of the motor axle (and thus the disc D) was measured with a frequency counter, which responds to the small electrical pulses issued by the drive unit. These pulses correspond to each step made by the motor, there being 96 steps per revolution. By setting the motor to 1 Hz rotation ((i.e.) 96 pulses were counted per second by the counter), variations shown by the counter, away from this figure, never exceeded 1 per cent. It was also found that for higher frequencies, this figure was never exceeded. To obtain greatest stability from the motor throughout the frequency range (0-60) Hz, it was found advisable to incorporate three pre-set potentiometers, P_1 ($5k\Omega$), P_2 ($10k\Omega$) and P_3 ($20k\Omega$) for use with speeds in the

bands (60-40) Hz, (40-10) Hz and (10-0) Hz respectively (see Appendix 1).

The mirror integrating box M.I.B.₁, was constructed from four front surfaced mirrors cemented with their reflecting surfaces facing inward, and pieces of translucent perspex, acting as diffusers, attached to both ends. In order to provide a constant component to the light stimulus, a mirror integrating box (M.I.B.₂) of similar construction to M.I.B.₁ was used. This mirror box shown in figure 19, had attached, a box containing a 12V, 24W filament lamp F, which provided the necessary light source. Control of the luminance of the end of M.I.B.₂ was provided by inserting neutral density filters inside the attached box. For the trials with this modulator, the extent of the stimulus was defined by two adjustable apertures T₁ and T₂ as shown in figure 19, where the light flux passing through T₂ was superimposed upon that from T₁ by means of a beam splitter B.S. The apertures were placed at a focal point of the lens L₄, so that infinitely distant images of these were seen by the observer. Also, the Maxwellian view optics employed, ensured that the aperture T₁ appeared completely and uniformly filled with light.

Both the lamps used were run on a d.c. battery supply to eliminate any temporal variations in light output caused by the electrical supply. (Details of how several heavy duty 6V batteries were used when two tungsten ribbon filament lamps were employed, are given later in this chapter).

b) Theory of the light modulator

The slit S may be considered to be a uniform light source, and the luminance of end Y of M.I.B.₁ is clearly proportional to the amount of light flux emerging from the slit S (at any instant in time). Thus, a rotating disc D with an attached mask, will produce a temporal change in the luminance of the mirror box, since it produces a temporal change in the area of the slit S which is allowed to pass light.

Let the required temporal variation in the luminance of end Y of the mirror box M.I.B.₁ be; $L(t) = I(A_1 + A_2 \sin (wt + P_1))$

$$+ A_3 \sin(2\omega t + P_2) + \dots A_{n+1} \sin(n\omega t + P_n))$$

$$\text{-----} 2$$

Where $A_1, A_2, \dots, A_{n+1}$, and $P_1, P_2, \dots, P_n$ are all constants, 1 denotes luminance, $\omega = 2\pi \times \text{frequency}$, and t denotes time.

The theory of the shape of the mask required to produce this luminance variation is developed by considering the sector slit S relative to two axes as shown in figure 21.

The total extent of the slit is defined from radii of angular separation α , and the curves RS and PQ , where;

PQ is part of a circle centre O and radius b .

RS " " " " " " " " " " a .

Let the inner edge of the mask required to produce the luminance vs. time function given by equation 2 be given by;

$$r = f(\theta) \text{-----} 3.$$

Let the area of the sector slit S bounded by the function $f(\theta)$ and which allows light flux to pass be denoted by $E(\theta)$, where;

$$E(\theta) = \frac{E_{\max}}{P} \left[A_1 + A_2 \sin(\theta + P_1) + A_3 \sin(2\theta + P_2) + \dots A_{n+1} \sin(n\theta + P_n) \right]$$

----- 4.

where P = the maximum value of the function given in the brackets.

$E_{\max}$ = the maximum value of $E(\theta)$

$$(i.e.) \quad E_{\max} = \left(\frac{(b^2 - a^2)}{2} \right) \alpha$$

The introduction of P in equation 4 ensures that when the function given in the brackets takes its maximum value, the slit is just fully unmasked. Clearly, the variation in $E(\theta)$ given by equation 4 will lead to the required luminance vs. time function given by equation 2⁹, when θ is given by the expression;

$$\theta = \omega t.$$

FOOTNOTE 9. The theory supposes that the slit "moves" under the curve $f(\theta)$ as θ varies. In practice, of course, the slit remains stationary and $f(\theta)$ is rotated around the slit.

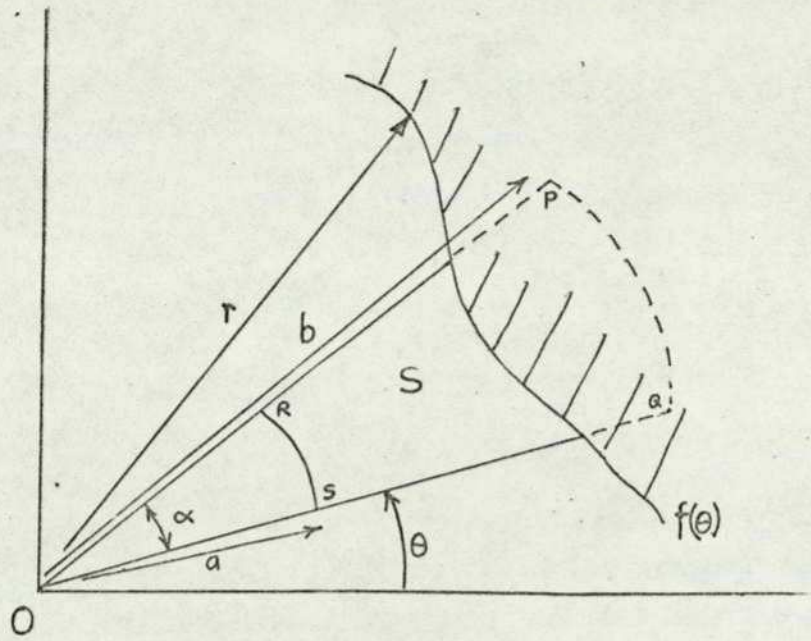


Fig. 21 The sector slit relative to the mask $[f(\theta)]$.

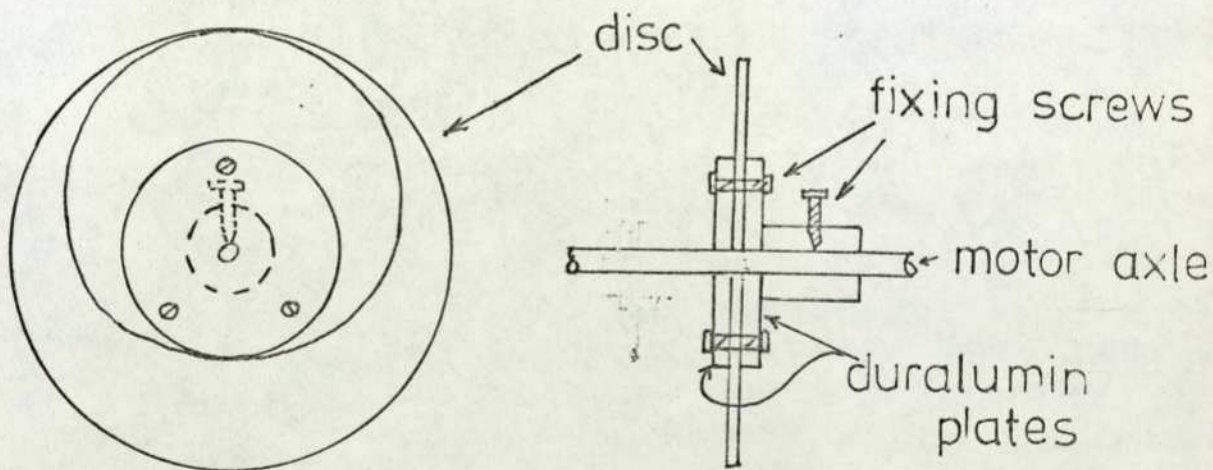


Fig. 22 Details of the rotating disc mounting

Also, $E(\theta)$ is given by;

$$E(\theta) = \int_{\theta}^{\theta+\alpha} \frac{[f(\theta)]^2}{2} d\theta - \frac{a^2\alpha}{2} \quad \text{5.}$$

Combining equations 4 and 5;

$$\int_{\theta}^{\theta+\alpha} \frac{[f(\theta)]^2}{2} d\theta = \frac{E_{\max}}{P} \left[A_1 + A_2 \sin(\theta+P_1) + \dots + A_{n+1} \sin(n\theta+P_n) \right] + \frac{a^2\alpha}{2} \quad \text{6.}$$

To find the equation of the mask $r = f(\theta)$, consider the function $g(\theta)$;

$$g(\theta) = \left[\frac{(b^2-a^2)}{P} \left[A_1 + A_2 \sin(\theta+P_1) + \dots + A_{n+1} \sin(n\theta+P_n) \right] + a^2 \right]^{\frac{1}{2}} \quad \text{6a.}$$

$$\begin{aligned} \text{Now } \int_{\theta}^{\theta+\alpha} \frac{[g(\theta)]^2}{2} d\theta &= \frac{1}{2} \int_{\theta}^{\theta+\alpha} \left[\frac{(b^2-a^2)}{P} (A_1 + A_2 \sin(\theta+P_1) + \dots + A_{n+1} \sin(n\theta+P_n)) + a^2 \right] d\theta \\ &= \frac{1}{2} \left[(kA_1\theta + kA_2 [-\cos(\theta+P_1)] + \dots + \frac{kA_{n+1}}{n} [-\cos(n\theta+P_n)]) + a^2\theta \right]_{\theta}^{\theta+\alpha} \end{aligned}$$

$$\text{where } k = \frac{b^2-a^2}{P}$$

$$\begin{aligned} (\text{i.e.}) \int_{\theta}^{\theta+\alpha} \frac{[g(\theta)]^2}{2} d\theta &= \frac{1}{2} \left[kA_1\theta + kA_1\alpha - kA_2 \cos(\theta+\alpha+P_1) \right. \\ &\quad + \dots + \frac{-kA_{n+1}}{n} \cos(n\theta+n\alpha+P_n) \\ &\quad + a^2\theta + a^2\alpha - kA_1\theta + kA_2 \cos(\theta+P_1) \\ &\quad + \dots + \frac{kA_{n+1}}{n} \cos(n\theta+P_n) - a^2\theta \left. \right] \\ &= \frac{1}{2} \left[kA_1\alpha + 2kA_2 \sin(\theta+P_1 + \frac{\alpha}{2}) \sin \frac{\alpha}{2} \right. \\ &\quad + \dots + \frac{2kA_{n+1}}{n} \sin(n\theta+P_n + \frac{n\alpha}{2}) \sin \frac{n\alpha}{2} \\ &\quad \left. + a^2\alpha \right] \end{aligned}$$

$$\begin{aligned} (\text{i.e.}) \int_{\theta}^{\theta+\alpha} \frac{[g(\theta)]^2}{2} d\theta &= \frac{1}{2} \left[kA_1\alpha + 2kA_2 \sin \frac{\alpha}{2} (\sin(\theta+P_1) \cos \frac{\alpha}{2} + \sin \frac{\alpha}{2} \cos(\theta+P_1)) \right. \\ &\quad + \dots + \frac{2kA_{n+1}}{n} \sin \frac{(n\alpha)}{2} (\sin(n\theta+P_n) \cos \frac{n\alpha}{2} \\ &\quad \left. + \sin \frac{n\alpha}{2} \cos(n\theta+P_n)) + a^2\alpha \right] \end{aligned}$$

6b.

If α is small, and integer n is limited to values such that;

$$\sin \left(\frac{n\alpha}{2} \right) \approx \left(\frac{n\alpha}{2} \right)$$

equation 6b becomes;

$$\begin{aligned} \int_{\theta}^{\theta+\alpha} \frac{[g(\theta)]^2}{2} d\theta &= \frac{1}{2} \left[\left(\frac{b^2-a^2}{P} \right) \alpha A_1 + \left(\frac{b^2-a^2}{P} \right) A_2 \alpha \sin(\theta+P_1) \right. \\ &\quad + \dots \frac{2(b^2-a^2)}{P \cdot n} A_{n+1} \left(\frac{n\alpha}{2} \right) \sin(n\theta+P_n) \\ &\quad \left. + a^2 \alpha \right] \\ &= \frac{E_{\max}}{P} \left[A_1 + A_2 \sin(\theta+P_1) + \dots A_{n+1} \sin(n\theta+P_n) \right] + \frac{a^2 \alpha}{2} \end{aligned}$$

Now, compare the right hand side of equation 6 with this result.

Clearly;

$$g(\theta) \equiv f(\theta)$$

Thus, to produce the luminance v.s. time function given by equation 2, for the end Y of the mirror box M.I.B.₁, $f(\theta)$ is given by;

$$f(\theta) = \left\{ \left(\frac{b^2-a^2}{P} \right) A(\theta) + a^2 \right\}^{\frac{1}{2}} \quad \text{--- 7.}$$

where $A(\theta) = A_1 + A_2 \sin(\theta+P_1) + \dots A_{n+1} \sin(n\theta+P_n)$.

Now, for the n th sinusoidal term of equation 2, the integer n represents the number of cycles of the sinusoidal luminance variation for that term, which occur for each revolution of the disc. The function $L(t) = 0.51 [1 + \sin 2\omega t]$, for example, will undergo two sinusoidal luminance vs. time cycles for each revolution of the disc. Following a consideration of the approximation made in the mathematics v.i.z. $\sin \left(\frac{n\alpha}{2} \right) \approx \left(\frac{n\alpha}{2} \right)$, since $\alpha = 1.5^\circ$, sinusoidal terms involving n greater than about ten, will become progressively more difficult to generate, as n increases.

Luminance vs. time relationships other than sinusoidal functions can be produced from the modulator. A sawtooth waveform, for example, with a P.C.F. = $10 = \frac{1}{2}$ will be obtained, if $A(\theta) = \left(\frac{\theta}{\Pi} \right)$. A rectangular waveform can be obtained by using a simple sector disc. The rise and fall times

FOOTNOTE 10. P.C.F. = Pulse to cycle fraction and represents the ratio between the time of duration of the light pulse and the periodic time.

of the rectangular pulse will then be $\frac{\alpha}{(2\pi f)}$, where f is the rotational frequency of the disc D. Expressed as a percentage of the periodic time of the waveform, rise and fall times will be less than 0.5 per cent.

c) Apparatus designed for testing the light modulator and construction of the modulator masks.

A measure of the accuracy with which a required luminance vs. time relationship can be generated, was established using a photodiode and an ultra-violet (U.V.) sensitive recorder. The details of the apparatus employed, are as follows;

- (i) An Advance function generator, type S.G. 72 (assumed to have no error).
- (ii) A 1706 Visicorder (U.V. recorder) from Honeywell Controls Ltd. This device produces traces of a time varying voltage input on ultra-violet sensitive paper.
- (iii) A Mullard B.P.Y. 13 photodiode.
- (iv) Two computer generated masks.
- (v) The apparatus employed in the development of the B.P.Y. 13 photodiode, as a linear photodetecting device (see later in the text).

Methods

The main aim of the investigation was to see how accurately the modulator could produce the luminance vs. time functions;

$$L(t) = 0.51 [1 + \sin(2\pi ft)] \quad \text{_____} \quad 8.$$

$$L(t) = 0.51 [1 + \sin(20\pi ft)] \quad \text{_____} \quad 9.$$

Thus, two masks were constructed, using a computer graph plotter. Appendix 2 gives details of all the computer programmes used throughout the experiments reported in this thesis and examples of the computer generated masks.

Having obtained these outlines, the areas required to be opaque were painted with indian ink. The masks were then cemented to perspex discs with a rubber based adhesive, and then a scapel was used to remove all parts of the paper mask not painted black, so that these were

free to transmit light. Figure 22 shows the mask used to generate the function shown as equation 8.

When in use, each perspex disc mounted mask was rigidly clamped between two duraluminum plates, which could be fixed to the stepper motor axle (see figure 22). All rotating masks used in the experiments, were constructed and fixed in place in this manner.

The light output from the modulator was monitored using the B.P.Y. 13 photodiode placed at the artificial pupil of the apparatus (see figure 19). The manner in which the photodiode was used is shown in figure 23 (the photovoltaic-linear mode of operation).

The current output from the photodiode was amplified by the operational amplifier (FET OPA). The gain depends on the feedback resistance employed, and it was decided that for the range of illuminances, likely to be encountered, (0-1000 Lux), feedback resistances of $1M\Omega$ and $1000k\Omega$ would be suitable. To prevent the possibility of oscillations in the feedback resistance employed, a $100pF$ capacitance was connected as shown. The null circuit enabled the voltage output from the photodetecting device to be zero, with zero light flux incident. The voltmeter employed, was an 'Advance' digital voltmeter. To confirm that the photodetector responded linearly to incident light flux, the device was compared with a G.E.C. "Physical Eye" photometer, which is known to respond linearly with light flux input. The method employed was as follows;

Both photodetectors (the photodiode and the G.E.C. instrument) were arranged adjacently at one end of a photometric bench as shown in figure 24.

A 40W filament bulb was placed at a distance of $1m$. from the detectors and an opal diffusing plate placed in front of the bulb. A variable aperture A was placed between the diffuser and the detectors. Screens were placed as shown to ensure that no stray light from the laboratory was incident on either of the detectors.

Initially, the B.P.Y. 13 photodetector was used with a $1M\Omega$

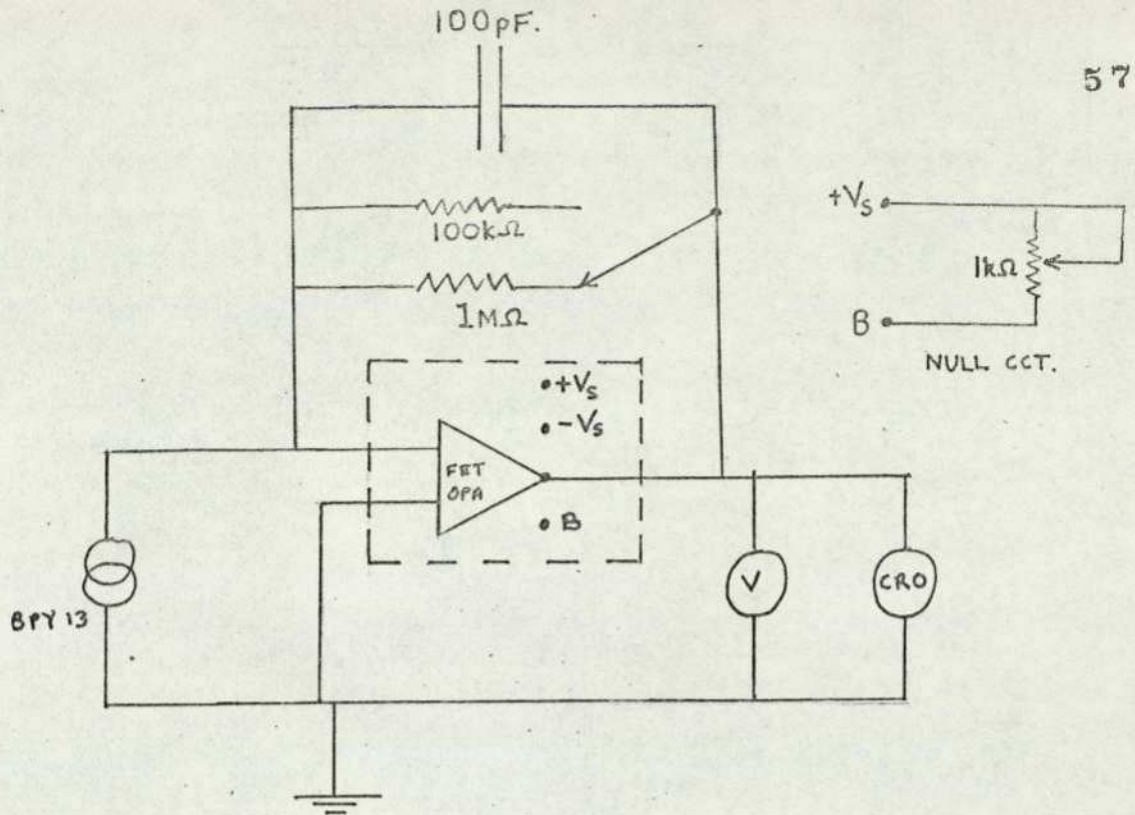


Fig.23 Photodetector circuit

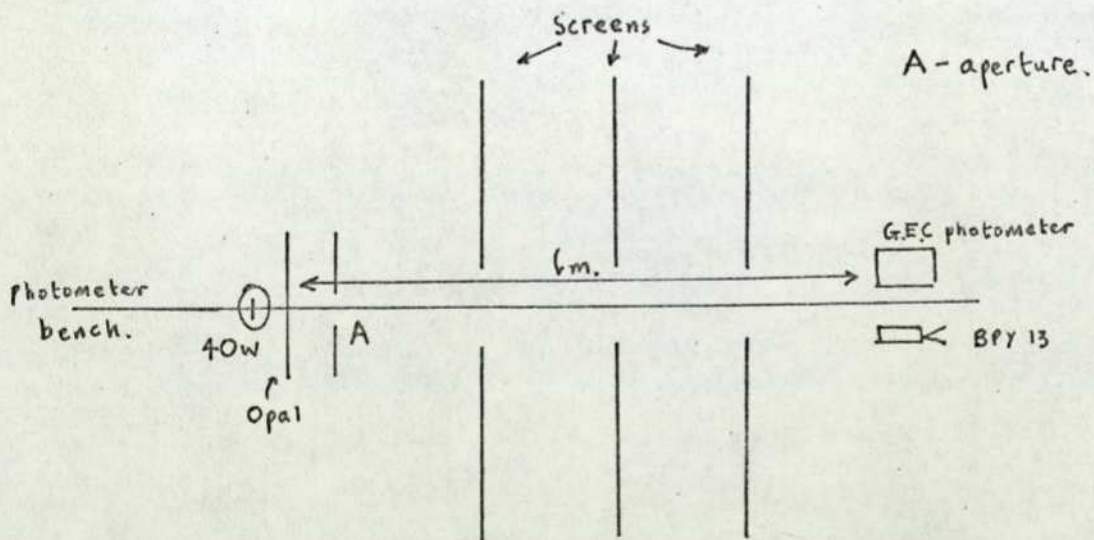


Fig.24 Apparatus used to determine the voltage output vs. light input relationship for the B.P.Y. 13 photodetector

feedback resistance and the output (V volts) recorded on the voltmeter. For this resistance, $l = 2m$, and the aperture A was adjusted until the voltmeter recorded 1.538v. This value was taken since with the photodiode in place at the artificial pupil of the modulator, the voltmeter recorded about 1.6V, with the maximum light flux transmitted.

In this experiment the G.E.C. photometer was used as a null instrument i.e. the resistance box in the G.E.C. photometer auxiliary circuit (not shown here) was adjusted to a value $R\Omega$ such that the galvanometer used in this circuit gave a zero reading. By adjusting R to $kR\Omega$ (k an integer) and then reducing the aperture A until the galvanometer again recorded no deflection, it is clear that the total amount of light flux incident on the G.E.C. photometer had been reduced by a factor k. Thus the total amount of light flux incident on the B.P.Y. 13 photodiode had been reduced by a factor k. If the voltage V_v , recorded by the voltmeter in the photodiode circuit is a linear function of flux input, then a plot of the value of k against V_v will be linear.

The above procedure was repeated for the $100\ k\Omega$ feedback resistance and l adjusted to 1.5m. Plots of relative light flux incident vs. Vvolts (or mvolts) are shown in figure 25. In the case of the $1M\Omega$ feedback resistance, unity on the relative light flux axis corresponds to $R = 1839$. For the case with the $100k\Omega$ resistance employed, unity corresponds to $R = 2219$. For a given value of R, the illuminance at the photometer, under the conditions in which it was employed, is given by;

$$E = (R \times .00323) \text{ Lumens. (ft)}^{-2}$$

For absolute determinations of illuminance, the G.E.C. photometer is quoted as being accurate to about 1 per cent.

The results showed that the photodiode apparatus operating in the photovoltaic mode (as shown in figure 24), responded linearly with respect to incident light flux, over the full range of illuminances encountered at the artificial pupil of the modulator.

The accuracy with which the u.v. sensitive recorder responded

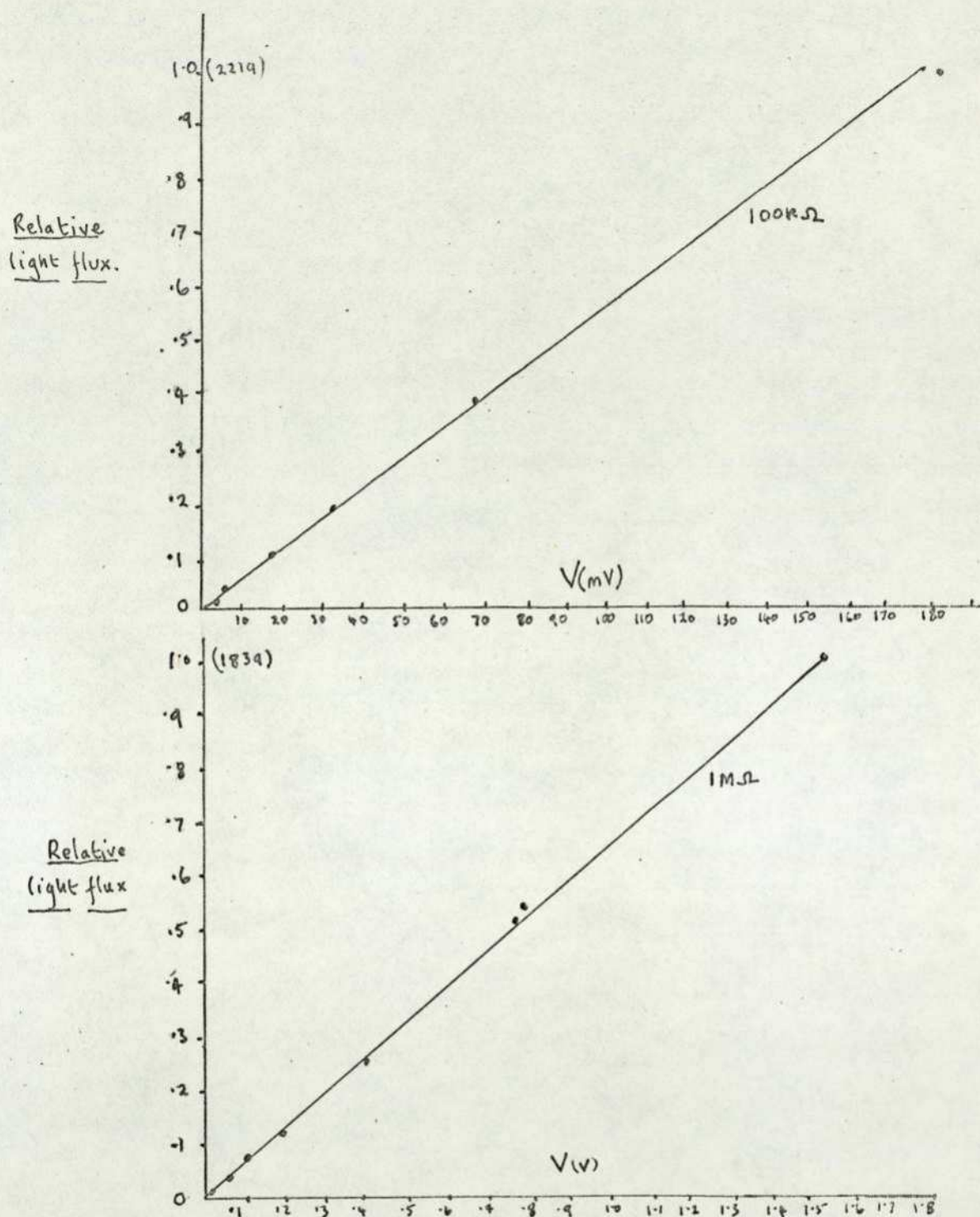


Fig. 25 Relative light flux vs. voltage plots for the B.P.Y. 13 photodetector

to a sinusoidally time varying voltage input was next established. The source of the voltage input was the Advance function generator, and a potentiometer was employed (see figure 26), to control the amplitude of the trace obtained from the recorder. The potentiometer was adjusted so that the complete width of the u.v. recorder paper was employed in obtaining the trace.

The function generator supplied a 4Hz sinusoidal input to the recorder, the trace obtained from this was described in terms of x and y coordinates as shown in figure 26. The method employed to determine the accuracy of the u.v. sensitive recorder was as follows;

- (i) The amplitude A of the trace was determined using a travelling microscope i.e. the peak to peak value was measured and halved.
- (ii) The wavelength of the trace was then measured.
- (iii) One half cycle of the sinusoidal trace was then divided into ten increments in y' and using the travelling microscope, the distance $2x$ (as shown) was measured for each of these increments.

This procedure was repeated for the other half cycle and the measuring technique was assumed to produce a negligible error. Now, referring to figure 26, $y = A - y'$ and $y = A \cos \left(\frac{2\pi x}{\lambda} \right)$, where λ is the wavelength of the sinusoidal trace. Let $Y = \frac{y}{A}$. Two values for Y can thus be obtained; one value for the measured values of x (Y_m) from the actual wave trace, and the other (Y_t) from the values of y calculated from the values taken of y' . The difference between the value of Y_m (obtained from the recorder trace) and the theoretical value Y_t was then calculated i.e. $Y_t - Y_m = dY$.

It was found that for all points examined on the wave trace, dY was at most 0.3 per cent of the amplitude A. Thus, the error produced by the u.v. recorder in producing a graphic record of a 4Hz sinusoidally varying voltage input is very small and is considered negligible.

The u.v. sensitive recorder was then used to obtain a measure of the accuracy of the light modulator. With the mask designed to produce the luminance vs. time relationship given by equation 8, a 4Hz (100 per cent

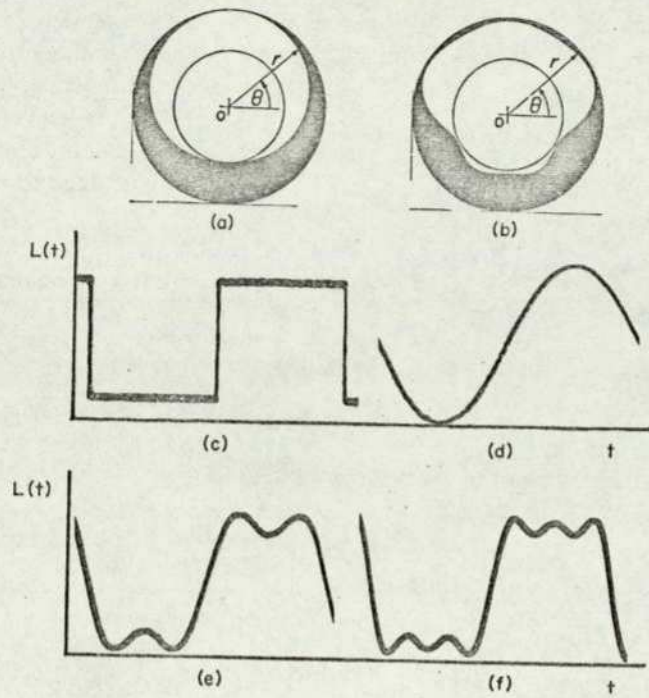
modulation) sinusoidal light input to the detector was established. The output from the photodetector was then fed into the u.v. recorder, as shown in figure 26. By adjusting the potentiometer across the recorder, a wave trace was obtained, extending across the total width of the paper. An estimate of the accuracy with which the modulator could produce such a sinusoidal light output was then determined in an identical fashion to that employed in determining the accuracy of the u.v. recorder. The results obtained showed that the deviation of the recorder trace from a true sine wave was at most 0.85 per cent of the peak amplitude A . When the mask designed to yield the luminance vs. time relationship given by equation 9 (40Hz) was employed, the corresponding figure was found to be 1.33 per cent.

As predicted from the theory, for sinusoidal waveforms, as n increases, the accuracy of the modulator decreases. As an exercise in the use of the modulator, the luminance vs. time relationships shown in figure 27 (c-f) were produced. The outlines shown in this figure were obtained from photographs taken of the oscilloscope trace for each of the flicker waveforms. Figure 27c represents one cycle of a square waveform ($P.C.F. = \frac{1}{2}$). The optical channel containing M.I.B.₁ (see figure 19) provided a temporal change in luminance from 0 to 21 cd. m^{-2} , during the cycle and the channel containing M.I.B.₂, provided a steady luminance component 1s. Actual values for 21 and 1s were 680 cd. m^{-2} and 91.8 cd. m^{-2} respectively, and 1s = 0.271. (The method of measuring these values will be discussed later).

The first four terms of the Fourier expansion of the square wave function shown are;

$$1.271 + 1.271 \sin wt + 0.42441 \sin 3wt + 0.25461 \sin 5wt.$$

Using equations 2 and 7, the appropriate masks were constructed so that the waveforms shown in figure 27 d, e, and f were obtained. The waveform shown in figure 27d is the Fourier fundamental of the square wave. The waveform shown in figure 27e represents a synthesis of the first three



(a) The computer plotted mask required to generate the sinusoidal luminance vs time function shown in (d). (b) The mask required to generate the luminance vs time function shown in (f). This function represents a synthesis of the first five harmonics of the Fourier expansion of the square waveform shown in (c). (c), (d), (e) and (f) are oscilloscope traces for four luminance vs time relationships (see text for details).

Fig. 27

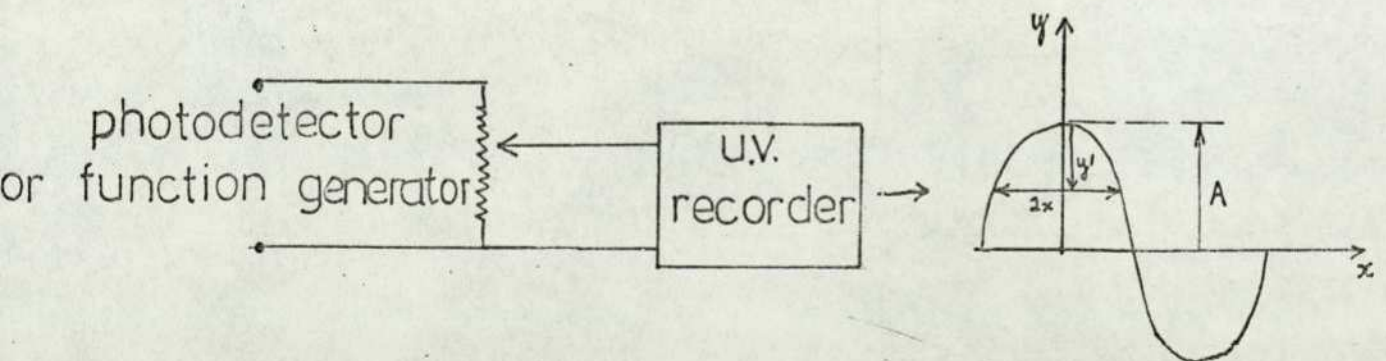


Fig.26. Determining the accuracy of the modulator

terms in the Fourier expansion and that in figure 27f a synthesis of the first four terms. Figure 27b shows the mask required to generate the waveform shown in figure 27f. The appropriate function $A(\theta)$ for the synthesis of the first four Fourier terms is;

$$1.27 + 1.27 \sin \theta + 0.4244 \sin 3\theta + 0.2546 \sin 5\theta.$$

The greatest value of $L(t)$ encountered for any of the four waveforms shown in figure 27 (c-f) is 2.541 (i.e.) twice the amplitude of the Fourier fundamental. Thus the P value in this example is 2.54.

The computer programme used to obtain the mask outlines for this analysis of a square wave is given in Appendix 2.

d) Discussion

It was emphasized previously, that one of the most important features of the modulator is that no temporal change in the spectral composition of the light output must occur. A slight modification of the spectral composition of the tungsten white light will occur, however, due to the use of mirror integrating boxes. It was found, for example, that the low-density translucent perspex diffusers used, led to a removal of a certain amount of the short wavelength region of the light energy. Such a modification of the spectral composition of the light was tolerable, since the perceptible chromatic change which occurred in the white light remained constant with time and was readily corrected for by using Wratten colour correcting filters. If no modification at all of the spectral composition is desired, then the apparatus may be altered to achieve this by removing the mirror boxes and producing a small image of slit S in the plane of the observer's pupil. (see again figure 19). A uniform field of view will still be maintained, the luminance of which undergoes the required temporal variation. With this modification, however, unless the image of S is sufficiently small, consideration may have to be given to the Stiles-Crawford effect.

The calculation and construction of the modulator is also more straightforward if the slit S is an approximation to a radius of the disc

D. (The outer and inner bounds still being of length b cm and a cm, respectively). This would have the disadvantage, however, that the total amount of light flux transmitted by the modulator will be considerably reduced, since in order to achieve the desired accuracy in the modulation process, the slit would have to be extremely narrow. Also, the extra optical channel included to provide a steady luminance component is not essential, since provision for this can be made in the channel containing M.I.B., by arranging that part of the slit S remains completely unmasked. This would be achieved if the required value of P is made greater than the maximum value of $A(\theta)$.

2. APPARATUS FOR THE INITIAL EXPERIMENTS IN FECHNER-BENHAM SUBJECTIVE COLOUR

The basic structure of the apparatus developed to study Fechner-Benham (F-B) subjective colour in detail, consisted of two modulators of the type outlined in the last section of this chapter, to provide the necessary colour inducing stimuli and a binocular matching colorimeter. (see figure 28 for a schematic diagram of the apparatus). Two modulator channels were constructed, since this would enable an investigation of the suggestion made by CAMPENHAUSEN (1968a) that both intermittent target and surround regions in the stimulus field are necessary. Also, by imaging the colorimeter field in the eye not stimulated by the subjective colour inducing stimuli, contamination by a static colour contrast effect from the colorimeter would be eliminated. (There is evidence that such colour contrast effects are retinal in origin. (WALRAVEN, J. 1973).)

a) Details of the components of the subjective colour inducing apparatus

Refer to figure 28. The colour inducing stimuli were imaged in the plane of a 1.5 mm diameter artificial pupil placed in front of the observer's right eye. The spatial configuration of the stimuli was defined from positive and negative pairs of black and white transparencies placed at a focal point of the last lens in the system, so that an

Fig.28. The main apparatus.

S=lamp; D=rotating disc; M = double sided mirror; CC= colour correcting filter;

ND= neutral density filter; MIB= mirror

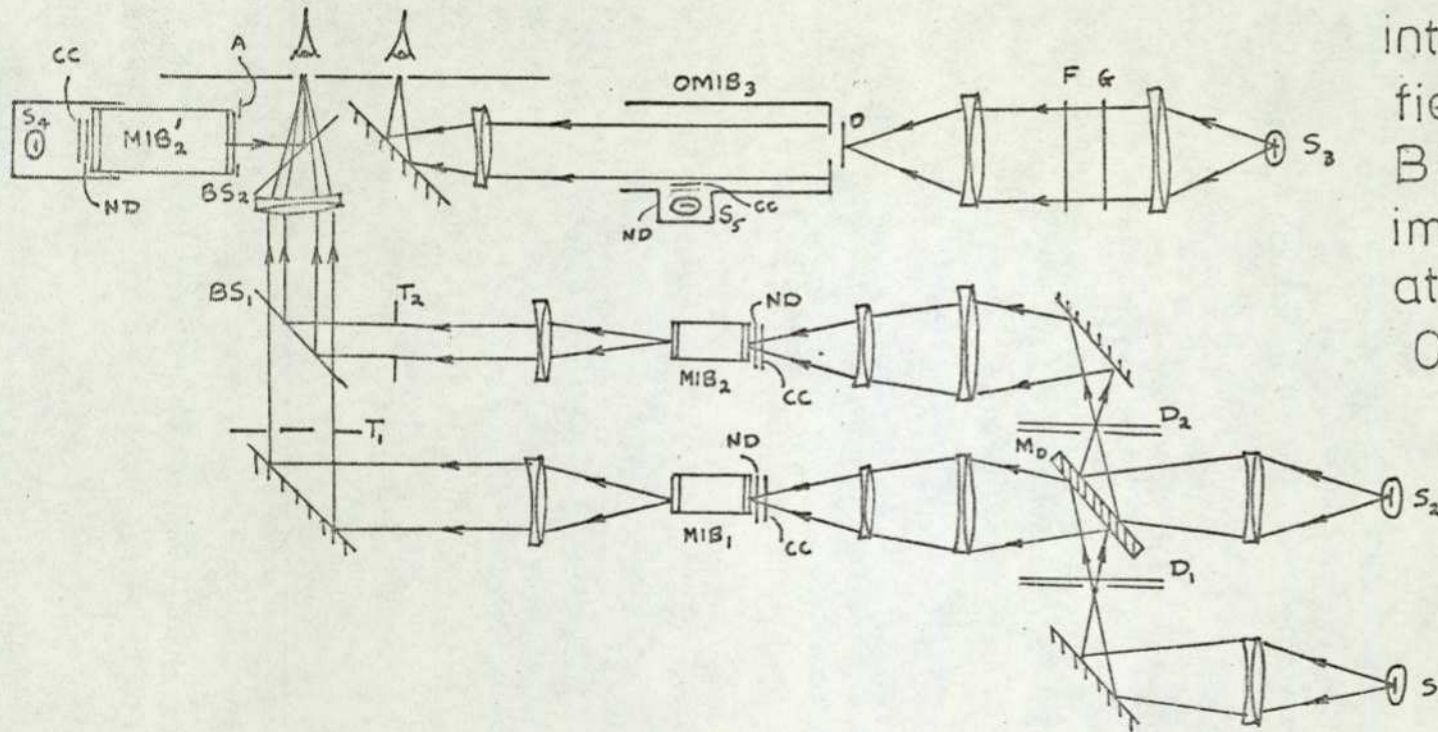
integrating box; T= visual field transparency;

BS = beam splitter; F = colorimeter filters; G= gauze attenuator (see expt 3);

OMIB=open ended mirror box

O= perspex diffuser

A= variable aperture



infinitely distant image of the stimulus field was viewed. Beam splitter B.S.₁ was used to combine the light flux from the two mirror boxes M.I.B.₁ and M.I.B.₂ and the manner in which T₁ and T₂ were used to form a target and surround region in the stimulus field can be readily understood from figure 28. T₂ was mounted on a microscope stage, which enabled small adjustments to the appropriate transparency to be made, in a plane perpendicular to the optic axis. This was necessary to ensure that T₁ and T₂ were correctly aligned relative to each other. As a large variety of stimulus field shapes and sizes were used throughout the experimental work of this project, further details of T₁ and T₂ will be given when each experiment is described. Beam splitter B.S.₂ enabled light from M.I.B.₂¹ (of the same construction as M.I.B.₂ described in the first section of this chapter) to be superimposed on that from the modulator channels. The cross sectional area of M.I.B.₂¹ was sufficiently large enough to enable light from it to be superimposed upon the whole of the stimulus field defined from T₁ and T₂. Further control on the amount of this light superimposition was achieved from the variable aperture shown. The role of M.I.B.₂¹ was both to provide a steady component to the light stimulus and also to provide a means of calibrating the apparatus. Methods employed to achieve this calibration will be discussed later. To increase the maximum luminance obtainable from the modulator channels, mirror boxes M.I.B.₁ and M.I.B.₂ were constructed with a small cross sectional area¹¹ and it was found necessary to incorporate extra lenses between these and the sector slits in order to produce images sufficiently small, that all the light flux passed into the mirror boxes. The actual dimensions of M.I.B.₁ and M.I.B.₂ are; length = 6cm, width = 1cm and height = 1cm.

The two light modulating discs D₁ and D₂ were fixed on a light steel axle driven by the stepper motor, and the arrangement of these

FOOTNOTE 11. Now, luminance $\propto \frac{\text{Light flux}}{\text{area}}$. For a given amount of light flux entering a mirror box, it follows that the luminance produced will increase if the cross sectional area is reduced.

and the two sector slits is shown in the photographs given as figures 29 and 30. Note the two modulator discs (sinusoidal waveform generators) and the two metal plates M (in which the sector slits are formed), fixed together as a single assembly supported as shown on a small optical bench.

The two lamps S_1 and S_2 (see again figure 28) were wired in series, together with a heavy duty rheostat capable of passing 18A. Three heavy duty 6v. batteries, themselves wired in series, were connected across the lamps and rheostat. In this way, a constant voltage of 12v. could be maintained for a relatively long time across both lamps by adjusting the rheostat to compensate for the decay of the batteries. The decay period of the batteries was measured in a separate experiment by wiring all three of them across three tungsten ribbon filament lamps and recording the voltage over three hours. The results are shown in Appendix 1. The voltage across both S_1 and S_2 was continuously monitored throughout all the experimental work, since it is well known that a small change in voltage leads to a large change in light flux output for a lamp. (flux output $\propto (\text{voltage})^3$). The colorimeter lamp S_3 was wired in series with another heavy duty rheostat and a stabilised 12v. d.c. supply connected across these. Again, adjustment of the rheostat ensured that the voltage across the lamp was always 6v. The supply for the other two lamps S_4 and S_5 was obtained from two small stabilised d.c. units.

b) Calibration of the subjective colour inducing apparatus

It was decided that a maximum retinal illuminance of about 1200 td would initially be used in the subjective colour inducing stimuli. This value was found to produce good subjective colour from a Benham's disc as mentioned in Chapter 1. It was also desired that the achromatic light used, should have the same chromaticity as standard illuminant A. Due to some non-neutral filtering (particularly from M.I.B.₁ and M.I.B.₂), the light output from each modulator channel needed to be corrected to achieve this, with Wratten colour correcting (C.C.) filters, placed as shown in figure 28. To produce the required stimulus luminance and colour

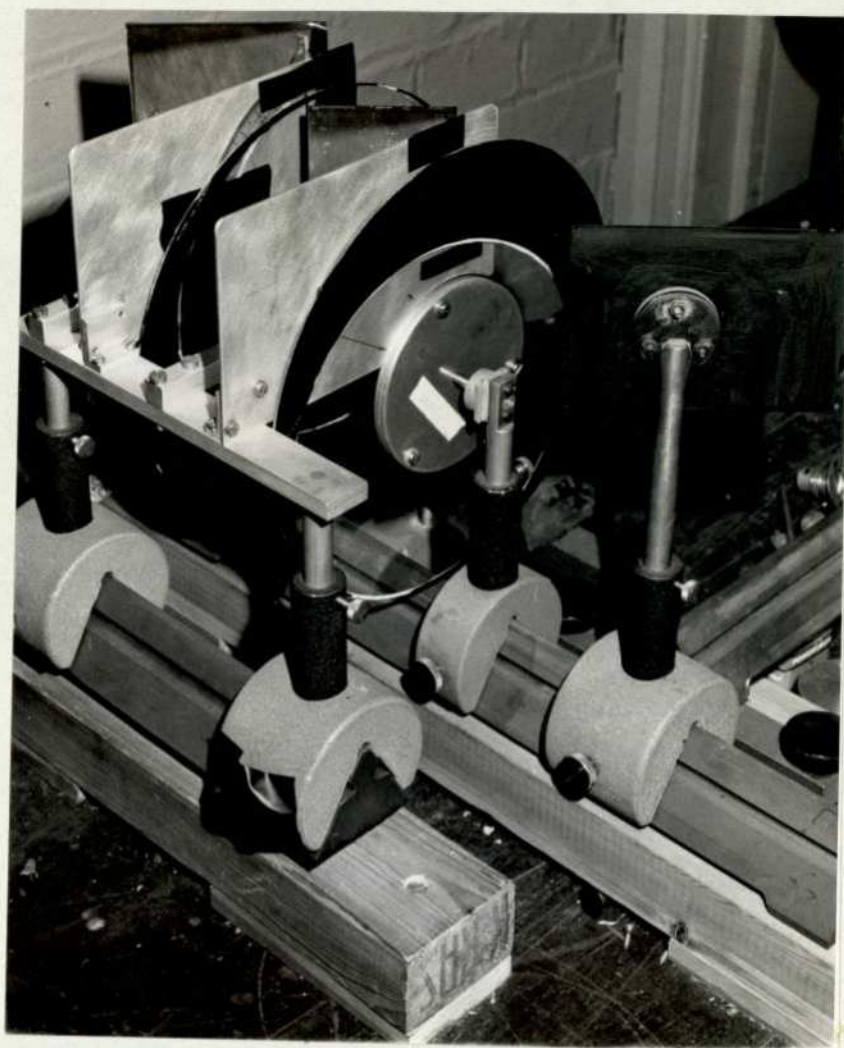


Fig 29 Two light modulator discs
and supporting axle

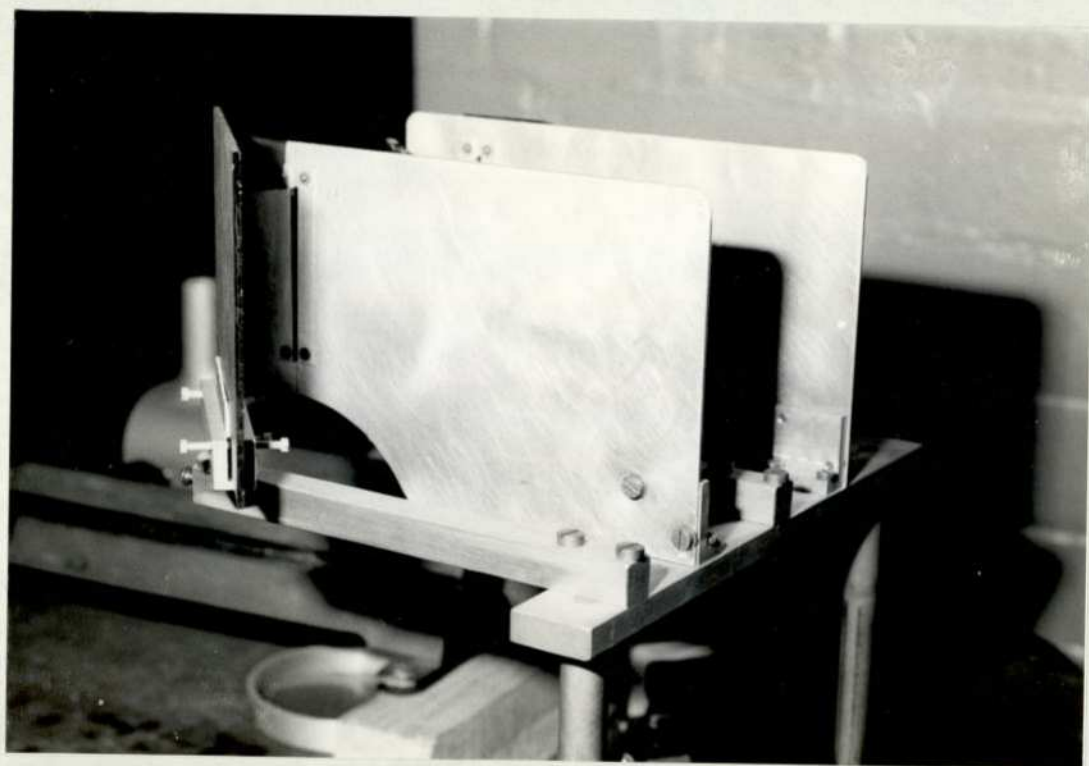
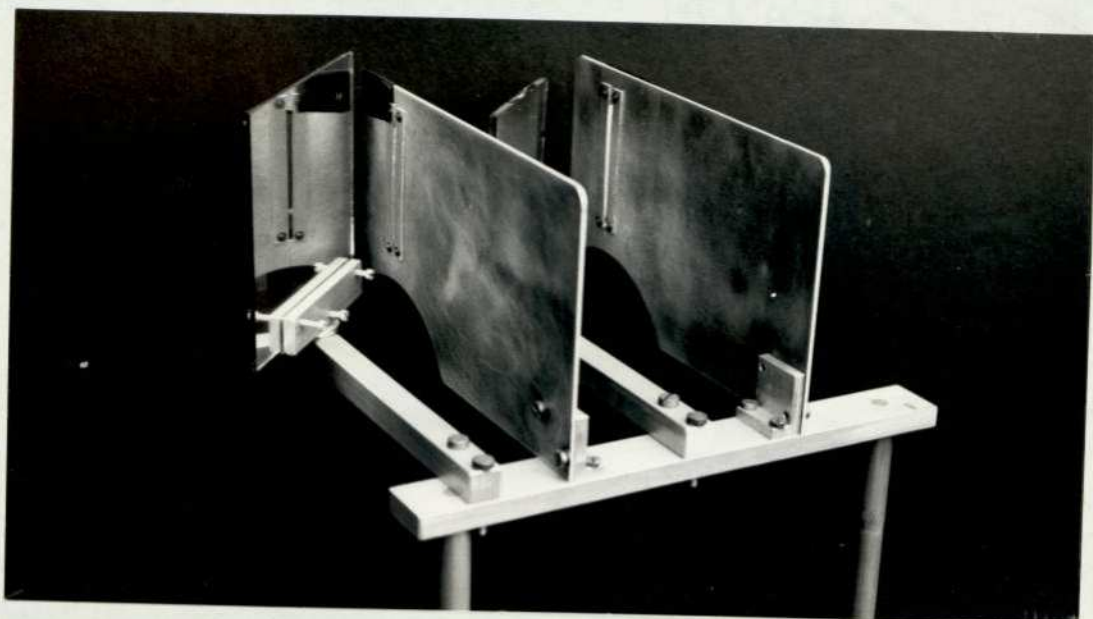


Fig 30 The metal plate M and sector slits contained in both modulator channels

properties of M.I.B.₂, use was made of M.I.B.₂¹ (whose luminance and colour temperature were previously determined) as shown in figure 31a.

Both A and T₂ shown in this figure, consisted of semi-circular apertures arranged so that a bipartite field was observed as shown in figure 31b. By placing either a Macbeth illuminometer or a Joyce-Loebel telecolorimeter at the location normally occupied by the artificial pupil, luminance and colour measurements were made on M.I.B.₂¹, after the light had been reflected by B.S.₂. By a method of trial and error, using both Wratten neutral density (N.P.) and colour correcting (C.C.) filters, the required luminance and colour appearance (as defined by a plot on the C.I.E. (x, y) diagram) of M.I.B.₂¹ were obtained. The mean values of (x, y) as calculated from four sets of readings were found to correspond to illuminant A to within 0.004 in chromaticity units. The luminance was found to be about 680 cd.m⁻².

A comparison was then made between the stimulus field derived from M.I.B.₂ and that derived from M.I.B.₂¹ and the luminance and colour appearance of the former adjusted with N.D. and C.C. filters until both the luminosity and colour appearance of each appeared the same. It was then assumed that both fields had the same luminance and chromaticity.

By a similar comparison technique, a visual field derived from light from M.I.B.₁ was compared with the field derived from M.I.B.₂, and the M.I.B.₁ channel corrected with N.D. and C.C. filters until both fields appeared identical.

c) Constructional details of the Colorimeter (with reference to figure 28)

To measure the subjective colours induced from the stimuli presented to the observer's right eye, a tristimulus colorimeter was employed. The colorimeter light patch was viewed by the observer's left eye. The three primary red, green and blue filters (F in figure 28) were placed in parallel light and a final image of the filament S₃ produced on a single diffusing sheet of perspex O. By adjusting the relative

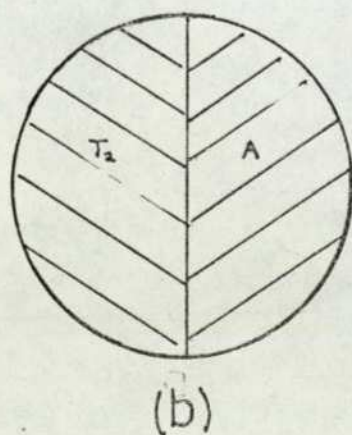
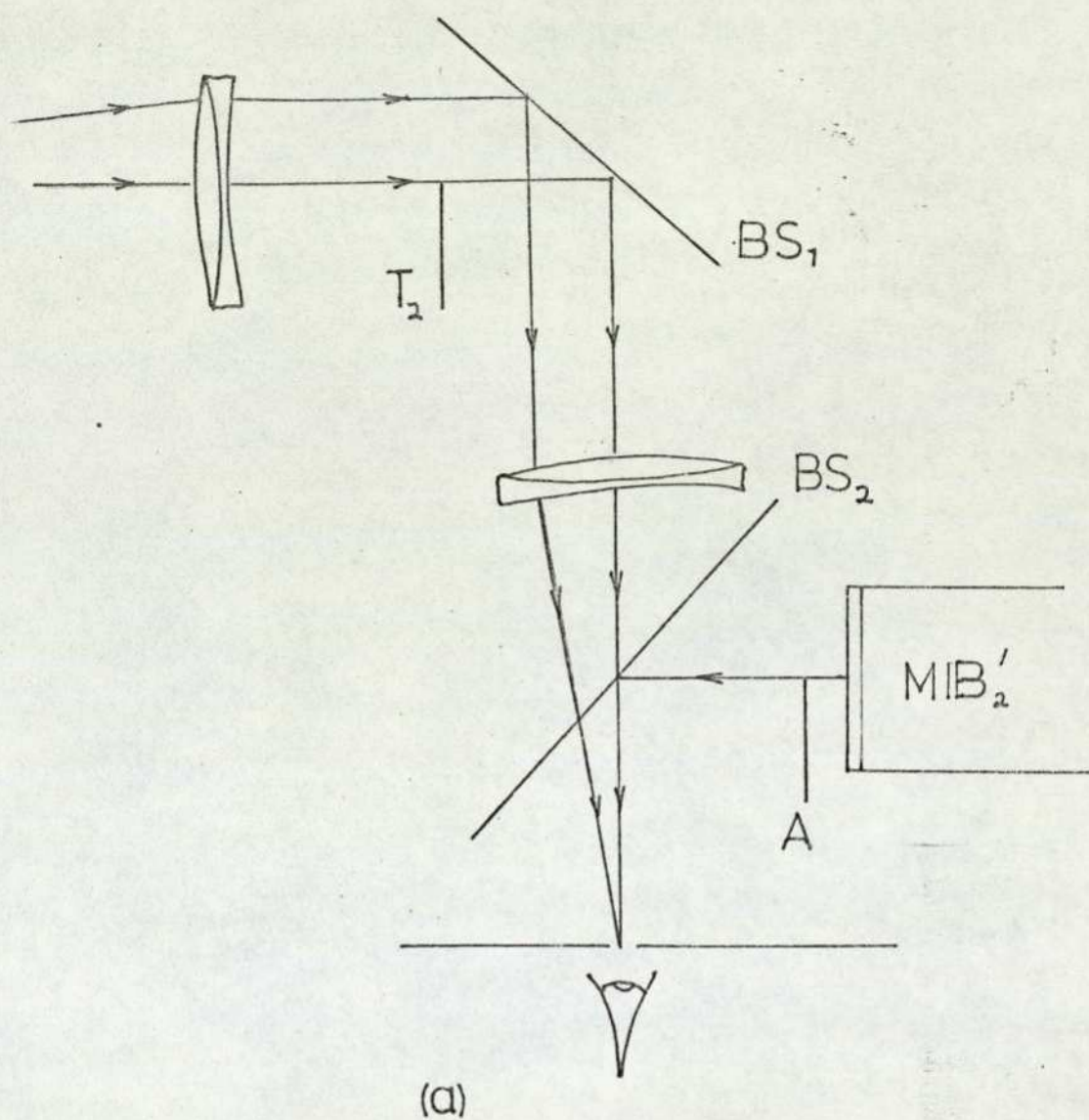


Fig. 31 a) Calibrating the apparatus with MIB'_2 (symbols as defined in fig 28)
 b) The field of view; T_2 , A are semi-circular apertures

amounts of the red, green and blue filters allowed to pass light flux, an additive mixture of red, green and blue light was obtained at the perspex diffuser, which matched the subjective colour experienced. In its original version, the colorimeter channel did not include the mirror box O.M.I.B.₃ and an infinitely distant image of the diffuser O was viewed by the observer in a completely dark surround. When trial experiments were carried out with signals of the type shown in figure 15, it was found that for some of these, the induced colours had such a low luminosity, that the matching procedure was difficult. With the addition of a surround of uniform luminance, to the colorimeter light patch, the matching task was found easier due to the extra brightness contrast produced from the surround. This surround was provided by the open ended mirror box O.M.I.B.₃, the construction of which is illustrated in figure 32. The end of O.M.I.B.₃ nearest the colorimeter filters F consisted of a white screen (forming the surround) in which a rectangular aperture was cut. This aperture defined the extent of the colorimeter field. Light from a 6v, 6w, filament lamp S₅, illuminated the surround. The function of the four mirrors of O.M.I.B.₃ was to ensure that the light from S₅ had undergone multiple reflections before arriving at the surround, which was thus, evenly illuminated. The light from lamp S₅ entered the mirror box through an aperture cut in the top mirror as shown. The end of the mirror box nearest the observer was open, so that an unrestricted view of the colorimeter field was obtained. Such a mirror box device was found necessary to produce an evenly illuminated surround to the colorimeter light patch, mainly due to lack of space in the apparatus. The luminance of the surround was fixed at approximately half that of the colorimeter light patch (viewed without a surround), which matched a 1200 td light patch presented to the observer's right eye. The chromaticity of the surround, as judged from colorimeter measurements, was fixed at ^{approximately standard illuminant A.} To achieve these luminance and chromaticity settings, Wratten N.D. and C.C. filters were used, placed between S₅ and the mirror box. The perspex diffuser O, was placed

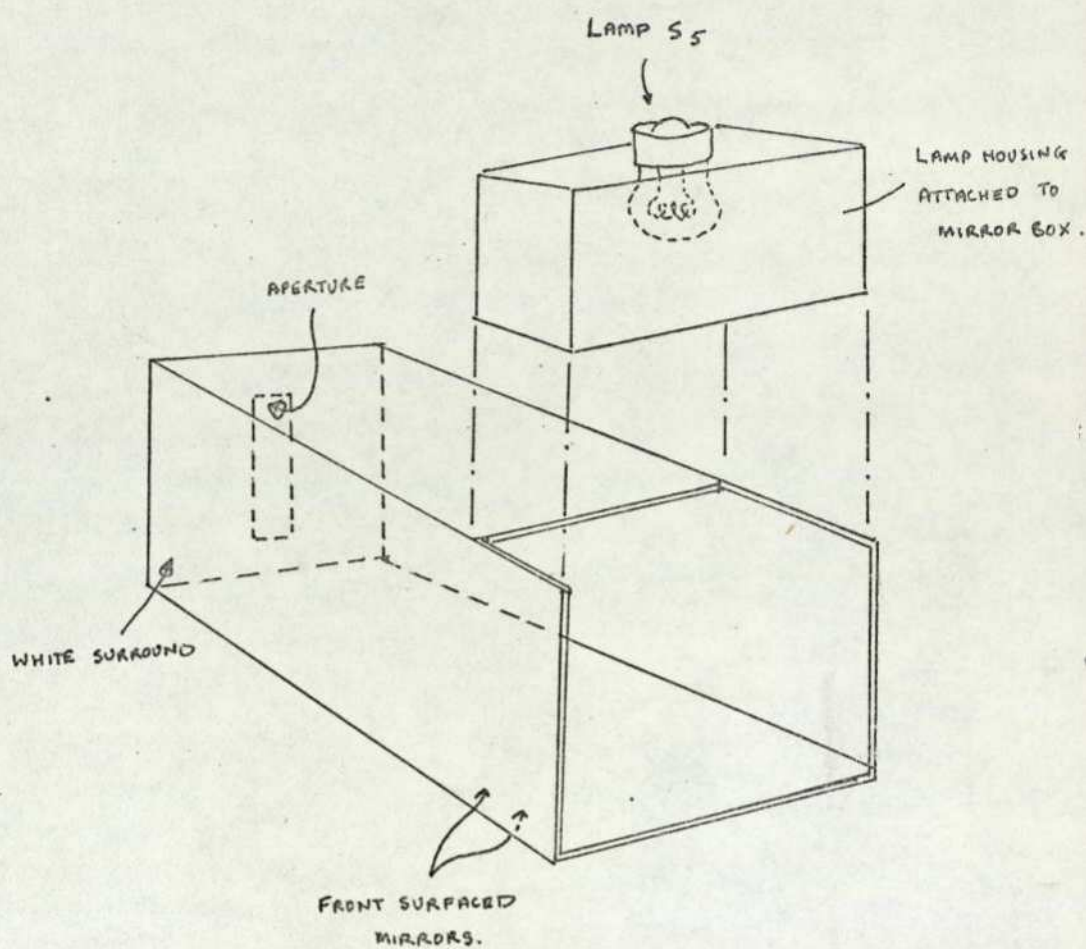


Fig. 32 Construction details of the open ended mirror box OMIB₃ (see fig 28)

slightly away from O.M.I.B.₃ to reduce the amount of light from S₅ reaching its surface. With the addition of O.M.I.B.₃ in the apparatus, the observer viewed an infinitely distant image of the aperture in the white screen.

When the right and left eye fields were presented simultaneously, the observer on fusing the two fields, viewed the colorimeter light patch vertically above and almost adjacent to the colour inducing stimulus. A small gap was introduced between the two fields, the reason for which will be given later in this chapter.

The filters used as the colorimeter primaries were Cinemoid primary red, green and blue. The C.I.E. (x, y) chromaticity coordinates of these are shown in figure 33. Only colours confined to within the triangle drawn through the locations of the primary filters R, G and B can be matched by the colorimeter.

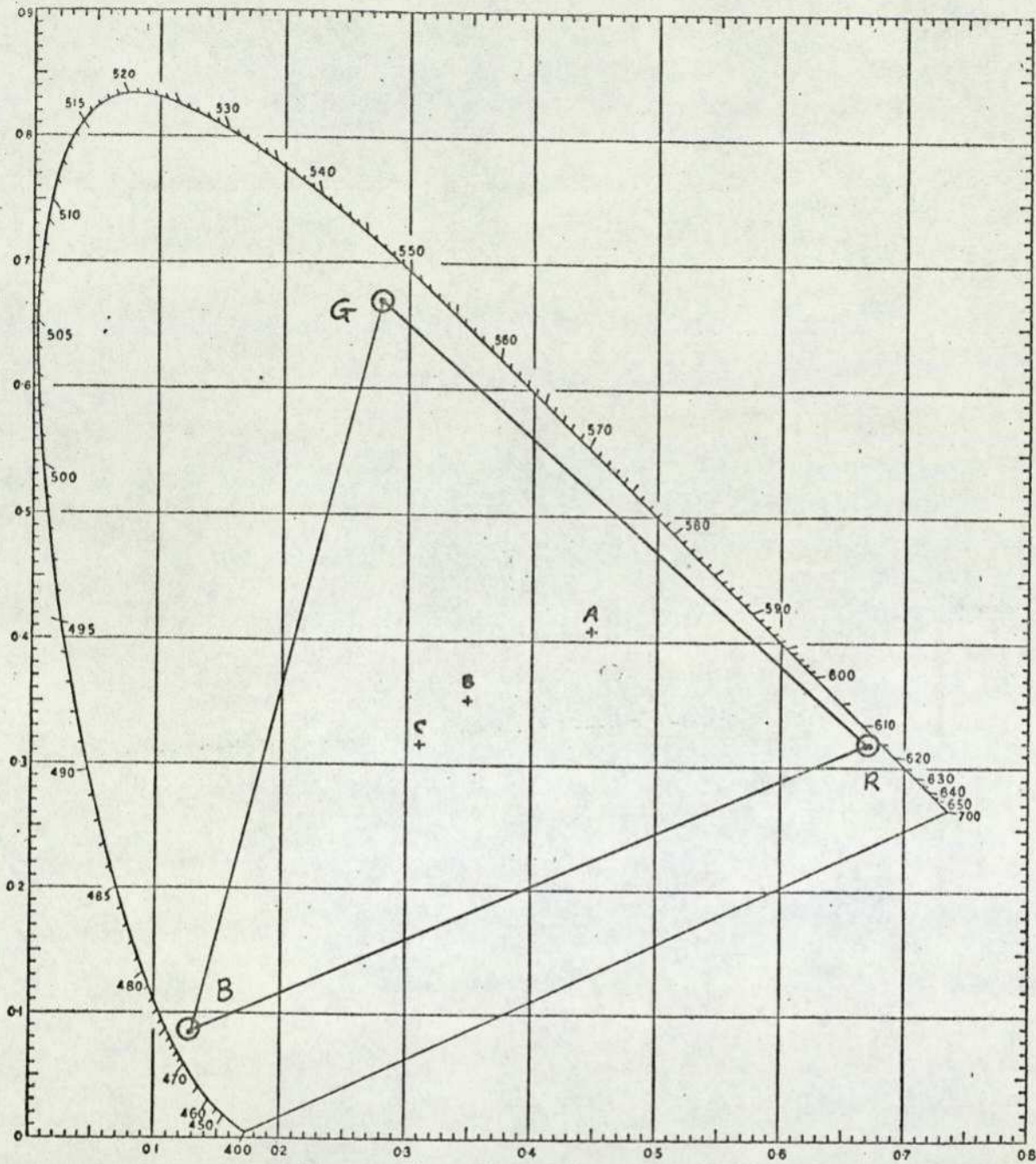
Control of the amounts of the primary filters allowed to pass light flux was provided by three shutters as shown in figure 34. Manipulation of these shutters was provided by three control knobs placed within easy reach of the observer's left hand. A scale was provided on each shutter, so that the amounts of each filter exposed could be recorded. From these readings and using a desk computer, the C.I.E. (x, y) chromaticity coordinates and Y-tristimulus value of the colorimeter light patch were calculated.

The position of the artificial pupil in the colorimeter channel could be adjusted to allow for observer differences in interpupillary distance. When this adjustment was made, the last lens and mirror in the colorimeter channel were also adjusted to ensure that the image of the aperture in mirror box O.M.I.B.₃ was always located at infinity. artificial pupil.

d) A note on the binocular matching technique

One of the principal reasons for using this technique in experimentation, is that it is generally assumed that the main stimulus

C.I.E. CHROMATICITY CO-ORDINATES



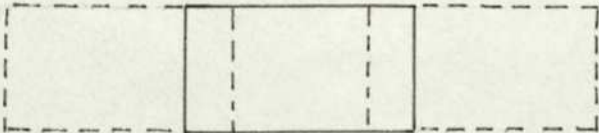
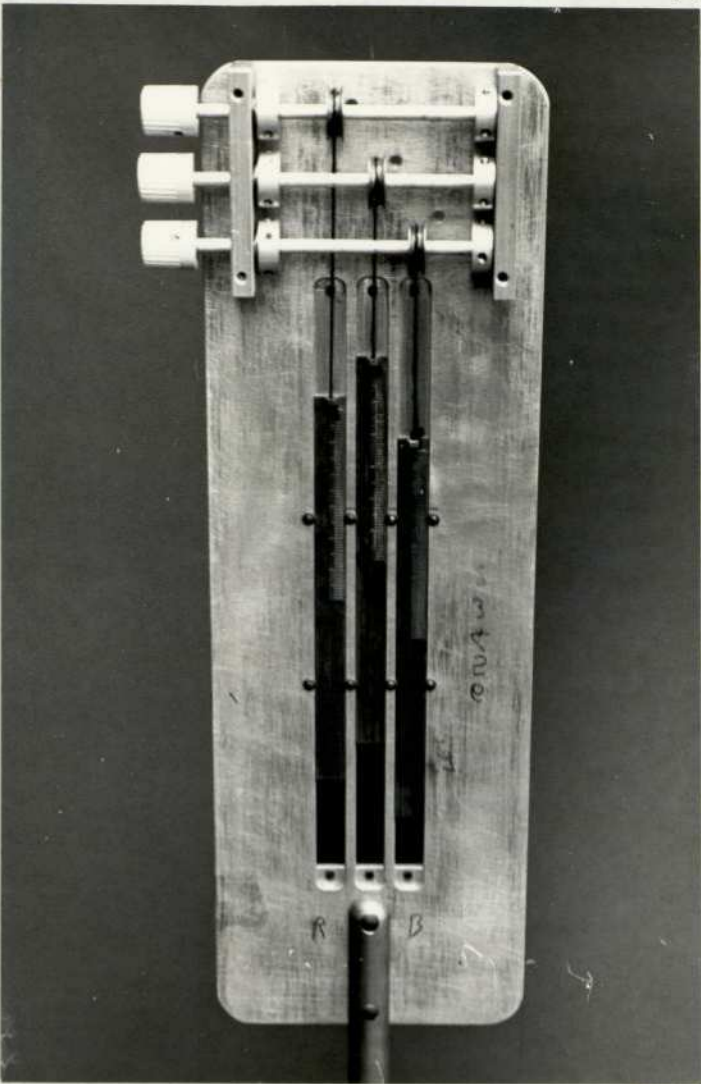
CHROMATICITIES OF COLORIMETER FILTERS.

Wavelengths marked in nanometres

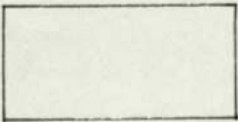
Fig.33

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THE CITY UNIVERSITY
CRANWOOD STREET, LONDON, E.C.1.

Fig 34 Colorimeter
filters and
shutters



left eye stimulus field



right eye stimulus field.

Fig 35 Fields of view in binocular
matching system

presented to one eye, does not effect the perception of the colorimeter light patch presented to the other. This assumption is not strictly correct, since adaptation of the eye in which the stimulus is presented will produce minor changes in the sensitivity of the other. WRIGHT (1946), however, in a discussion of the binocular matching technique, regarded this effect as negligible in most experimental situations. One of the reasons given for this being that adaptation of one eye, produces only very small changes in threshold measurements made with the other eye.

As stated in the previous section of this chapter, the colorimeter field appears vertically above and almost adjacent to the stimulus field, when the observer fuses the two scenes. Changes in the observer's convergence during experimentation will cause one field to move horizontally relative to the other as indicated by the dotted lines in figure 35. If the muscle balance of the observer is not quite normal, a small-angle prism can be inserted in front of the left artificial pupil to correct for either vertical or horizontal convergence (phoria). Wright also considered it necessary to provide a small separation between stimulus and colorimeter fields in such an experimental set up, to prevent the fields from fusing. In some experiments, adaptation effects in one eye, may cause a disturbance in the state of muscle balance to the extent that it is difficult to prevent the patches from merging together, even though a gap has been introduced between them.

To ensure that the artificial pupils were correctly centred on the natural pupils of the observer, a dental bite was provided throughout the experimentation.

The binocular matching technique has been employed successfully in the measurement of subject colour effects. Three examples being work by KINNEY (1965a), in the measurement of induced colour from static colour contrast situations and PADGHAM (1953, 1968) in the measurement of colour and luminosity changes in the decay of positive after images produced from white light.

CHAPTER III

EXPERIMENT 1

AN INTERPRETATION OF BENHAM'S DISC TYPE STIMULI IN TERMS OF

LUMINANCE VS. TIME FUNCTIONS

a. Introduction

It has been suggested that Benham's disc can be interpreted in terms of luminance vs. time functions of the type shown in figure 15, chapter 1, by CAMPENHAUSEN (1968a), and FESTINGER, ALLYN and WHITE (1971). One of the aims of this initial experiment is to verify that such interpretations are correct and to quantitatively measure the luminosity and colour properties of the subjective sensations using the binocular matching technique, as the temporal frequency of the stimuli is changed.

It will be recalled that HANSEL (1957), SHEPPARD (1968), and BUTTERFIELD (1967, 1970) interpreted Benham's disc in terms of eight segments (see figure 7, Chapter 1). If each of these segments is made into a single frame of a black and white television film, subjective colours are seen when the film is viewed. (BUTTERFIELD, 1967, 1970). This interpretation of Benham's disc is in fact another way of expressing the interpretation proposed by CAMPENHAUSEN (1968a) as shown in figure 15 chapter 1. Thus, there is some evidence that the colour inducing properties of Benham's disc type stimuli can be represented by a static stimulus display, containing both an intermittent target and surround region.

It was mentioned in Chapter 1, that Benham's disc appears to be the most satisfactory device from the viewpoint of producing a full gamut of subjective colours from a rotating patterned disc. Its spatial features are also less complicated than many of the patterned discs investigated (see figure 1, Chapter 1). Thus, an analysis of the temporal and spatial features of Benham's disc type stimuli, appears to provide the most satisfactory way of starting an investigation into possible visual mechanisms involved in producing the phenomenon. The second aim

of this experiment is to assess the accuracy of the measuring technique, with intermittent stimuli.

b) Details of the Stimuli Employed

A three bar grating with extended outer surround, provided the stimulus presented to the observer's right eye, as shown in figure 36. The three bars (shown shaded) represent the target T region in which the subjective colours were anticipated to appear, and the surround region of the stimulus S was defined by the rest of the stimulus field. Angular subtense of each component of the stimulus field is shown in figure 36. The observer fixated at the top of the middle bar of the grating and the colorimeter light patch, with its lowest edge appearing slightly above the top of the grating, was observed with the left eye. (The reason for this has been given at the end of the last chapter). To ensure the colorimeter light patch was correctly aligned relative to the grating, the mirror shown in figure 28 immediately in front of the left artificial pupil could be rotated and tilted to achieve this. For three of the four observers, these adjustments alone were sufficient to ensure correct alignment of stimulus and colorimeter fields, but for one observer (E.L.) a prism had to be placed in front of the left artificial pupil (3^Δ , base outward).

The three bar grating was chosen to represent the lines on a Benham's disc. These had a fairly small width ($10'$ arc), since it has been observed that the subjective colour on the lines of a Benham's disc spreads across the whole width of each line, for width values of this order. (CAMPENHAUSEN, 1968^g; HASEGAWA, 1971).

Initial exploration with temporal signals of the type shown in figure 15, Chapter 1, revealed that subjective colour sensations could be obtained in the three bars of the grating. It was decided from this initial work, to collect data on the signals shown in figure 37, these producing reasonably good subjective colour.

The flicker pulses of both the target and surround signals

C-colorimeter light patch (left eye)

T - target } (right eye)
S - surround }

S-surround) (right eye)

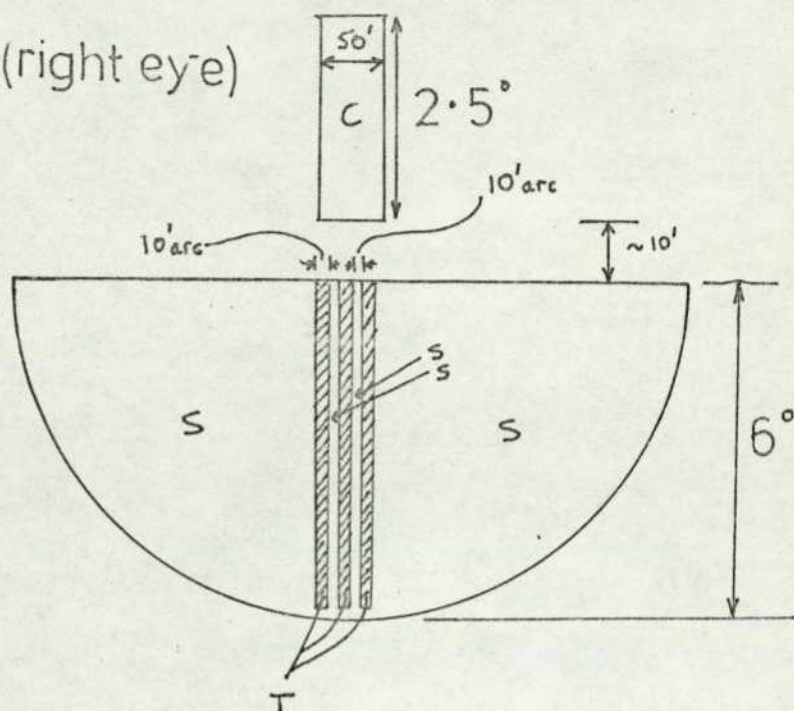


Fig. 36 Spatial features of the subjective colour inducing stimulus ($T \rightarrow S$), and the colorimeter field (C)

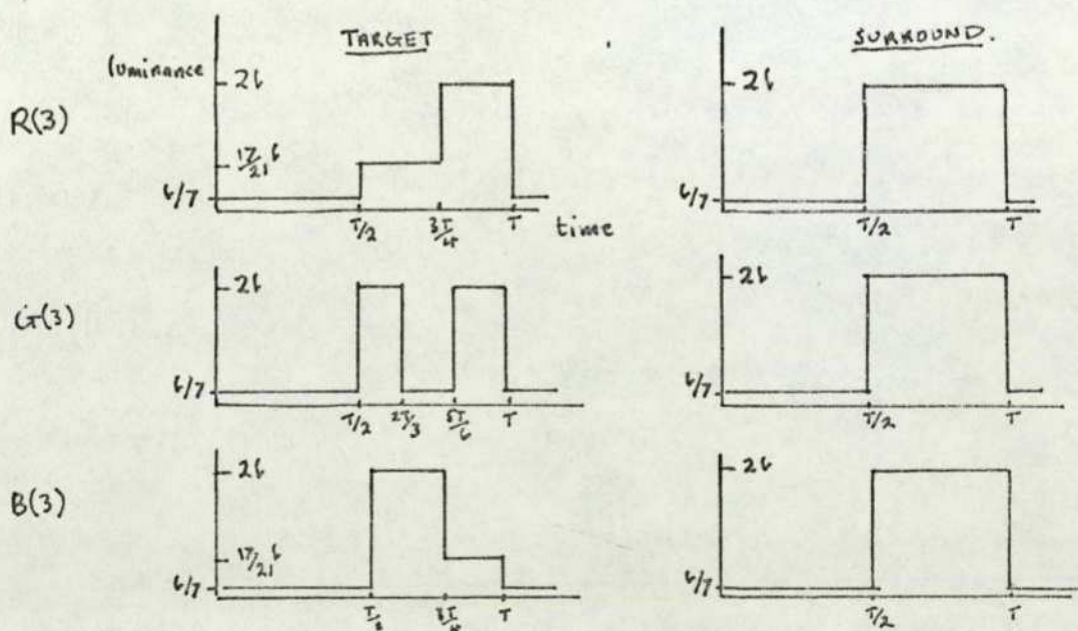


Fig.37 Temporal features of the stimulus, (single cycles). T =periodic time.

were superimposed upon a steady luminance component l_s , where $l_s = \frac{1}{7}$. The maximum luminance obtained throughout the flicker cycle (from each modulator channel was $2\frac{1}{2}$ cd. m^{-2} . The phase relationships between the target and surround flicker trains are as shown in figure 37, where each flicker sequence had a P.C.F. = $\frac{1}{2}$. The inclusion of the steady luminance component was to allow for the small luminance value of the black part of a Benham's disc. Measurements made on a Benham's disc with a Macbeth illuminometer showed that the ratio of the luminance of the white part of the disc to that of the black parts (measurements made in a direction normal to the disc) was about 14:1. Thus, l_s was made equal to $\frac{1}{7}$. The classification of the signals viz R(3), G(3) and B(3) was made to distinguish these from other signals used in subsequent experiments. The symbols R, G and B signify that these signals are associated with red, green and blue subjective colour impressions, respectively. The maximum luminance obtained from the stimulus was estimated to be 730 cd. m^{-2} .

To produce the waveforms shown in figure 37, the modulator masks were manufactured without the aid of the computer graph plotter, since in each case these were just simple sector discs. To produce the step in the R(3) and B(3) signals, a 90° segment of the appropriate mask eclipsed the bottom two thirds of the sector slit.

c) Observers

Details of the observers used throughout all the experimentation reported in this thesis are shown in Table 1.

<u>OBSERVER</u>	<u>SEX</u>	<u>AGE</u>	<u>COLOUR VISION</u>	<u>OCCUPATION</u>
J.R.J.	MALE	26	NORMAL	RESEARCH STUDENT.
C.A.P.	MALE	51	NORMAL	READER IN PHYSIOLOGICAL OPTICS
J.E.S.	MALE	33	NORMAL	LECTURER
E.L. ¹²	MALE	42	NORMAL	LABORATORY ASSISTANT

TABLE 1. The Observers

All the observers had taken part in psychophysical experiments before, C.A.P. and J.E.S. extensively. Only one observer (J.R.J.) was experienced

at matching an intermittent light source in colour and luminosity to a steady light source. All observers had normal colour vision and when necessary spectacle corrections were incorporated in the apparatus.

d) Method

Extensive trial experimentation with the temporal signals shown in figure 37, together with a variety of others (discussed in experimentation described later), was carried out where flicker frequency in the range (0-32) Hz was employed (observer J.R.J. only). For the lowest frequency settings, (0-3) Hz, it was found that the eye could easily distinguish the light and dark phases of the grating bars. All the observers were therefore instructed to make a colour and luminosity match of the grating bars for the on part of the signal only, for these low frequencies. This was considered more satisfactory than attempting to make a judgment of an average effect from the whole cycle. At higher frequencies however, the eye can produce an estimate of the colour and luminosity of the grating bars, after performing a mental averaging out process between the light and dark phases of the cycle. As soon as the observer was able to do this, the matching instruction was that he should carry out this averaging process. Such matching criteria have been employed before, in the determination of brightness enhancement of an intermittent visual stimulus, for flicker ranging from 1Hz upwards (COLGAN, 1965).

All experimental sessions lasted about an hour and only one type of temporal signal was employed in each session. Before making the luminosity and colour measurements, which were the only tasks performed by each observer, a period of about ten minutes dark adaptation was used. No more than two sessions were conducted on any one day and each session (comprising one temporal signal) was always completed in one sitting.

FOOTNOTE 12. For this observer, data were collected from only that temporal frequency band which produced the most saturated subjective colours for the other three observers.

Measurements were taken at frequency settings in the range (0-32) Hz. Four colorimeter readings were taken at each of the frequency settings; two matches were made with frequency increasing and two matches taken with frequency decreasing from 32 Hz. The colorimeter readings were converted into plots on the C.I.E. (x, y) chromaticity diagram.

Before collecting the data, a certain amount of searching for optimum conditions was carried out by each observer (i.e.) the maximum luminance was altered. It was mentioned^{previously in Chapter 1,} that good colour could be produced using a maximum retinal illuminance of about 1200 td for Benham type stimuli, involving one observer (J.R.J.). Clearly, it does not follow that this retinal illuminance will necessarily produce the best effects in the other observers. However, qualitative judgments made by each observer as maximum luminance in the stimulus field was changed away from 730 cd. m^{-2} , showed that improvements in the colour sensations, if any, were slight.

An example of the raw data is shown in Appendix 3 for the R(3) temporal signal (observer J.E.S.). Now, the degree to which subjective colour is induced will be indicated on the chromaticity diagram as a movement of the point representing the subjective colour percept away from that representing the colorimeter match made to the steady (no flicker) condition. The closer the subjective colour point is located to the spectrum locus (or line of pure purples), the greater will be the saturation of the colour. Provided that the dominant wavelength¹³ of the subjective colour varies only slightly with flicker frequency for a given temporal signal, then excitation purity values calculated for each frequency will give some indication of how the saturation changes with frequency.

FOOTNOTE 13. 'Dominant Wavelength' referred to here, is represented by the point of intersection with the spectrum locus, of the line passing through the points representing the subjective colour and the steady condition (0) match. For a subjective colour point lying in the purple region of the chromaticity diagram, this definition still holds, and in this case the dominant wavelength quoted has a small 'c' alongside.

e) Results

The colour appearance of the grating bars in terms of C.I.E. (x, y) chromaticity coordinates for the values of flicker frequency tested and for each temporal signal are shown in figure 38 (a-k) for all the observers. The plot marked (0) represents the colour appearance of the stimulus display as measured by the colorimeter, without the introduction of flicker. Each value of x and y shown in figure 38 is the arithmetic mean of four estimates obtained from the four groups of colorimeter readings taken at each flicker frequency setting. Also shown in figure 38 are sections of the spectrum locus and black body locus (shown as thick lines), and flicker frequency values (joined by hatched lines to the appropriate points). For three of the observers (J.R.J., J.E.S. and E.L.) with the R(3) signal employed, most of the data points are seen to lie within fairly narrow dominant wavelength bands. The data for observer J.R.J. for example, are confined (with one or two exceptions) to the (591-598) nm waveband. The waveband figures for the other two observers, E.L. and J.E.S. are approximately (585-590) nm and (583-591) nm, respectively. All waveband figures quoted do not include the dominant wavelength values for those data points lying outside the general spread, which as can be seen from figure 38 usually constitutes a small and confined group. For observer C.A.P., the data spread is greater than for the other observers, ranging over the (579-700) nm waveband.

For the G(3) signal the data spread is confined to fairly narrow dominant wavelength bands for all the observers. Figures for observers J.R.J., J.E.S., C.A.P., and E.L. are (581-585) nm, (580-586) nm (582-587) nm and (584-592) nm, respectively. For the B(3) signal, the dominant wavelength bands for observers J.R.J., J.E.S., C.A.P. and E.L. are about (568^C-577^C) nm, (468-577^C) nm, (568^C-579^C) nm and (450-564^C) nm, respectively.

To assign colour names to the induced colour sensations, use was made of the KELLY (1943) chart, giving colour names to each region of

the C.I.E. (x, y) chromaticity diagram. These colour names are shown in figure 39. The names of each colour (according to Kelly) represented by the data points of figure 38 are shown in Table 2, together with the dominant wavelength of each colour. When data points in figure 38 are closely grouped, a single value of dominant wavelength is taken and is obtained by considering a line joining the point (0) to the spectrum locus and which passes through the central region of the data group.

The results shown in figure 38 and Table 2, together clearly show that subjective colour sensations were aroused by the R(3) and G(3) signals and were similar sensations for each observer with a given signal employed. When the G(3) signal replaced the R(3) signal, there was a general shift in the subjective colour from orange to yellow-orange at all frequencies and for one observer a shift to the green was measured (observer J.E.S., $f = 3\text{Hz}$). There was also a tendency for the B(3) signal to make the appearance of the grating bars shift toward the purple region of the spectrum but this was slight, for two observers (J.R.J. and J.E.S.) and according to KELLY (1943), such subjective colour sensations would be termed achromatic. Greater shifts were measured by observers C.A.P. and E.L., with the B(3) signal and the colours aroused were normally pink or purple-pink, according to Kelly.

Since in general, the data points of figure 38 are confined to relatively small dominant wavelength bands for all the temporal signals and for each observer, estimates of excitation purity made for each frequency will give an approximate indication of how the saturation of the subjective colour changed as frequency changed for a given temporal signal. Excitation purities were thus obtained from the data of figure 38, where excitation purity (P_e) is given by the expression;

$$P_e = \frac{OM}{OP}$$

where OM and OP are the distances indicated on figure 39, and (0) refers to the steady condition colorimeter match. The point M represents the subjective colour whose excitation purity is to be calculated, and P

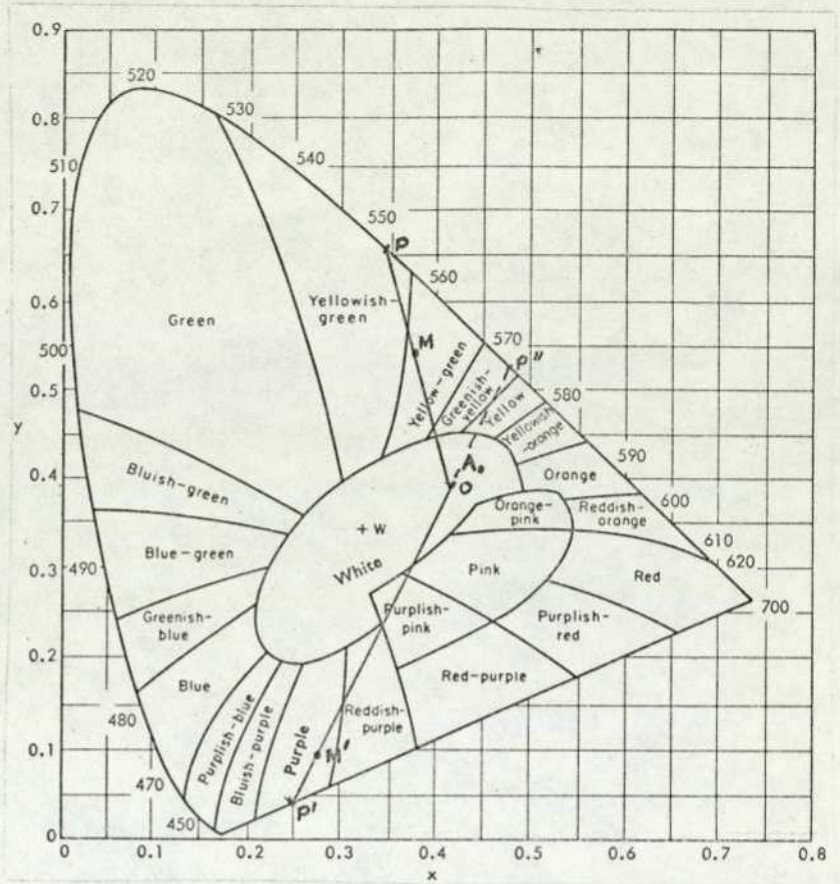


Fig 39 The colour designations of KELLY (1943)

indicates the dominant wavelength. For a purple M', the definition of Pe becomes $\frac{OM'}{OP'}$ and as mentioned previously, the dominant wavelength is represented by a point P'' on the spectrum locus. To calculate Pe, the distances OM and OP were measured directly from the chromaticity diagram¹⁴.

The values of Pe plotted against flicker frequency for the signal R(3) are shown in figure 40 (a, b) for all four observers. To provide clearer diagrams, the data have been divided into two observer groups. The functions clearly show that maximum saturation of the subjective colour occurred in the (3-16) Hz frequency band for each observer, with the peak effect occurring at about 6Hz. A secondary peak in each curve is seen to appear at about 10Hz for three observers (C.A.P., J.E.S. and E.L.) and at about 24Hz for observer J.R.J.

Values of Pe plotted against frequency for the G(3) signal are shown in figure 41 (a, b). These curves illustrate the fact that for two observers (E.L. and C.A.P.), the maximum saturation of the subjective colour occurred in a similar frequency band to the colour induced by the R(3) signal. For observer J.E.S., Pe increases as frequency increases up to about 7Hz and then remains constant. Thus, subjective colour was perceived by this observer throughout most of the frequency range examined. For observer J.R.J., the Pe vs. frequency function indicates that the maximum saturation of the subjective colour occurred at about 5Hz, with the effect diminished outside the (3-16) Hz frequency band.

The Pe vs. frequency functions for observers J.E.S., C.A.P. and E.L. with the B(3) signal all show a similar trend to that shown by the function for observer J.E.S. with the G(3) signal (see figure 42 (a, b)). For observer J.R.J., the B(3) signal produced relatively low saturation of the subjective colour throughout the frequency range.

FOOTNOTE 14. Clearly, errors are introduced into the calculation of Pe using such a measuring technique, but since Pe is considered as only an indicator of saturation, such errors were regarded as negligible.

The C.I.E. (x, y) chromaticity coordinates plotted against frequency for all the colour matches are shown in figures 43, 44 and 45, for each temporal signal. Also shown are the z values where $x + y + z = 1$. The error bars are ± 1 standard deviation, calculated from the four values of x and y for which each data point represents the arithmetic mean (see Appendix 3, for example). The range of standard deviations expressed in C.I.E. x and y chromaticity coordinates for each observer with each signal are shown alongside the data in these figures. The standard deviations are slightly greater for the B(3) signal and the matching procedure was found relatively difficult by all the observers, due mainly to the fact that the appearance of the grating bars was not uniform in either chromaticity or luminosity. Apparent movement of "blotches of colour" confined to the central region of the grating bars was reported by observer C.A.P. Although such effects in the grating bars were not reported for any other temporal signal, the surround region of the stimulus field often appeared to contain fairly desaturated purple areas, regardless of the temporal features of the stimulus. This effect was noted by all observers.

An interesting feature of the data presented in figures 43-45 is the fact that for each observer, x any y generally vary with frequency in a similar fashion, for a given temporal signal. The data for observer E.L., for example, with the R(3) signal employed clearly show this. Both curves have the same general shape, but one is displaced along the (x, y, z) axis relative to the other. The z functions are seen to lie in approximate anti-phase with the x function, for most of the data.

The luminosity of the grating bars, for each temporal signal (represented in figures 46-48) is expressed in terms of the quantity "brightness gain" G, where;

$$G = \frac{Y_s}{Y_t}$$

Y_s represents the Y-tristimulus value of the colorimeter light patch when matching the subjective colour and Y_t represents the Y-tristimulus value when the colorimeter light patch matched the grating bars for the steady

condition (no flicker), and with maximum luminance.

All the "brightness gain" curves (except that obtained from the R(3) signal and observer C.A.P.), illustrate the fact that the luminosity of the grating bars decreased as frequency increased from about 2Hz, until a frequency value was reached after which no further luminosity reduction occurred, i.e. the curves each approached an asymptote.

The value of G for this asymptote is about (0.2-0.3) for all the curves. Insufficient data are available for observer E.L., to show the complete trend illustrated by the curves for the other observers. A description of the G(3) curve for observer C.A.P. is also difficult, since the data spread is relatively large.

The R(3) signal for observer C.A.P. resulted in luminosity enhancement of the grating bars in the frequency band (2-6) Hz i.e. the grating bars appeared to have a greater luminosity than for the steady (0) condition. This is reflected in the fact that G is greater than unity in this frequency band.

Error bars shown on the "brightness gain" curves are ± 1 standard deviation calculated from the four values of G, for which each data point represents the arithmetic mean (see Appendix 3 for an example of the calculation of $G \pm 1$ std. Dev.). The range of values of the error bars are shown alongside the data in figures 46-48.

f) Discussion

The results generally support the Campenhausen-Festinger type analysis of a Benham's disc in terms of intermittent target and surround regions in the stimulus field. (see again figure 15, Chapter 1 and figure 37). Thus, F-8 subjective colour can be produced in a static stimulus display. The fact that the colour effects are relatively unsaturated is in agreement with the findings of VERRIEST and SEKI (1964), who measured the colours of a Benham's disc using Munsell colour chips. Since the colours are associated with low flicker frequencies (peak effects very often occurring in the (3-16) Hz frequency band), the calculations of

KELLY (1969), on the dynamic properties of lateral inhibition would predict this, assuming that retinal lateral inhibition plays a role in the production of F-B subjective colour. It will be recalled, (see Chapter 1), that CAMPENHAUSEN (1968a) suggested that retinal inhibitory interactions are involved.

Individual differences in the hues perceived for a given temporal signal are small, and are not as pronounced as those found in the KNEHR (1953) study. (see Chapter 1). Although undue weight must not be given to generalised statements concerning individual differences when only four observers are used, the data do give partial support to the idea that a Benham's disc may detect colour anomalies (IWAGAKI, 1968), since colour normal observers perceive approximately the same subjective hues for a given temporal signal.

A noticeable feature of all "brightness gain" curves (except that for observer C.A.P. with the R(3) signal), is the lack of a luminosity enhancement peak near about 10Hz. A luminosity increase, with respect to that produced by steady stimulation is associated with any single light source (achromatic or coloured), when presented at a flicker rate of about this value and having a similar luminance. (BALL and BARTLEY, 1966; VAN DER HORST and MUIS, 1969). Any slight enhancements which are reflected in the subjective colour "brightness gain" data (except for R(3) with observer C.A.P.) occurred at about (2-3) Hz, when the subjective colour was minimal. These enhancements may have been due to a manifestation of the Broca-Sulzer effect, associated with a single light flash.

The subjective patterning reported by observer C.A.P. (with the B(3) signal) appears to be a manifestation of the phenomenon investigated by REMOLE (1971), who measured luminance thresholds in a single flickering achromatic light for the appearance of such patterns. Subjective patterns in a single achromatic flickering light are also sometimes coloured (REMOLE, 1973a), but some of these colour effects are only seen when the stimulus is viewed binocularly (REMOLE, 1973a; BURNHAM, 1964).

FOOTNOTE 15; This author showed that retinal mechanisms responsible for lateral inhibition are insensitive to flicker frequencies greater than (10-15) Hz. It should also be noted that subjective colour was obtained using the G(3) signal (observer J.E.S.) for flicker frequencies up to 32Hz.

As discussed in Chapter 1, it is unlikely that such binocular subjective colour effects are examples of F-B subjective colour, which is produced from both monocular and binocular viewing of the stimulus.

Another effect occurring in an intermittent achromatic light (under both monocular and binocular observation) is that of "extended border enhancement", where a relatively large bright area appears to extend in toward the centre of the stimulus. The spatial extent of this subjective effect has been measured for a large rectangular light stimulus ($12^{\circ} \times 7^{\circ}$) by REMOLE (1973b), who found that border enhancement is usually maximal at about (10-18) Hz, with a secondary increase of the enhancement at about 24Hz. In this respect, the effect bears a similarity to the relationship between saturation of the R(3) induced colour and frequency, for observer J.R.J.

The border enhancement effect, together with subjective patterning in the stimulus are likely to produce difficulties in measuring F-B subjective colour under some conditions as was shown to be the case with the B(3) signal.

It is of interest, in conclusion, to consider the possibility that the F-B subjective colour effects may enhance each other, when the stimulus is a Benham's disc, because of the close spatial proximity of complementary subjective colours. It is well known, for example, that a green patch of colour surrounded by a red border, will appear a more saturated green than without the border (simultaneous colour contrast). It is plausible that visual mechanisms similar to those acting to produce simultaneous colour contrast may act to produce an enhancing effect in the colours of a Benham's disc.

Fig 38a-k

CIE(xy) chromaticity coordinates for each signal

Fig 38 a.

(figures denote flicker frequencies and dominant wavelengths)

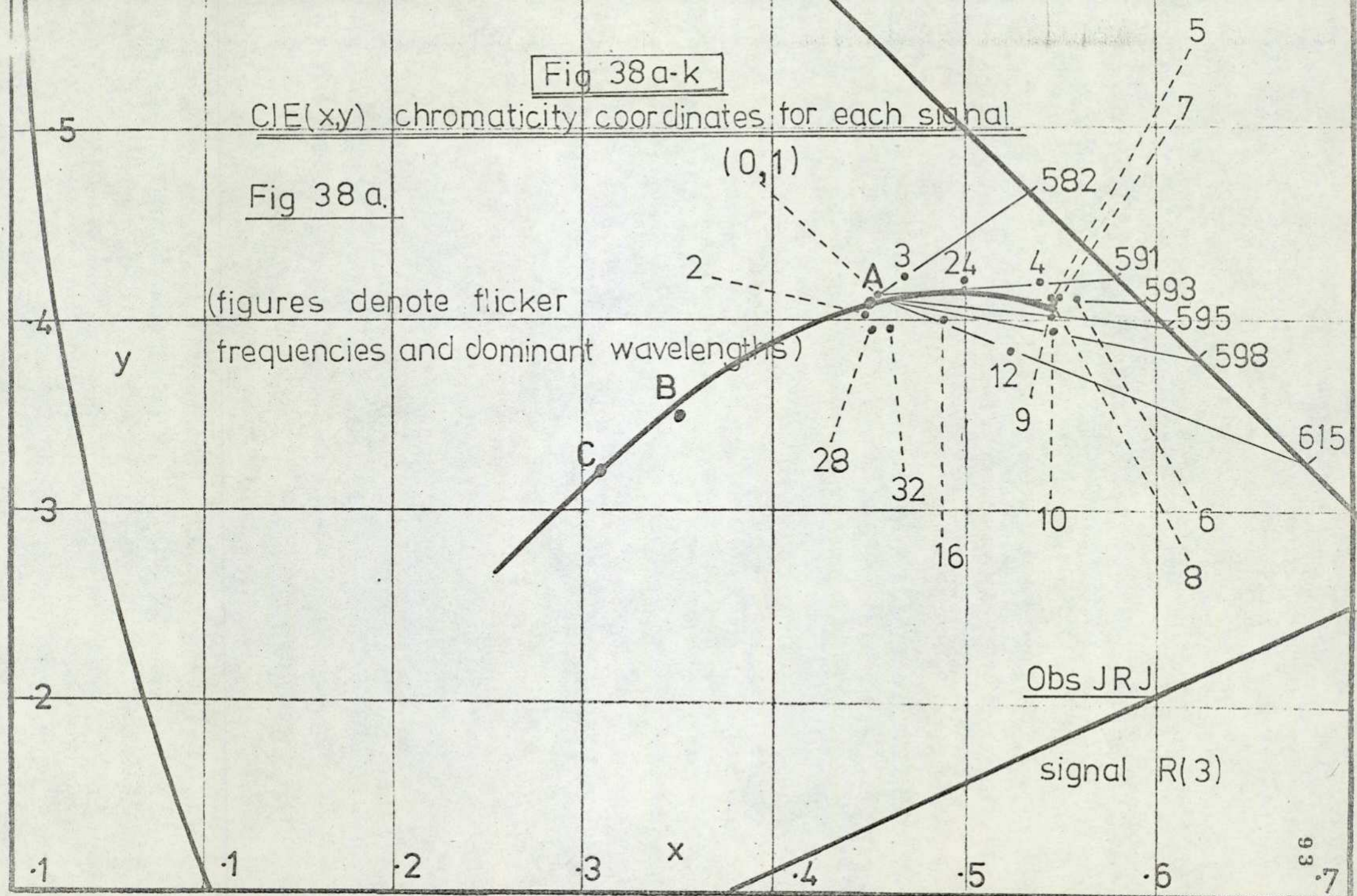


Fig 38b

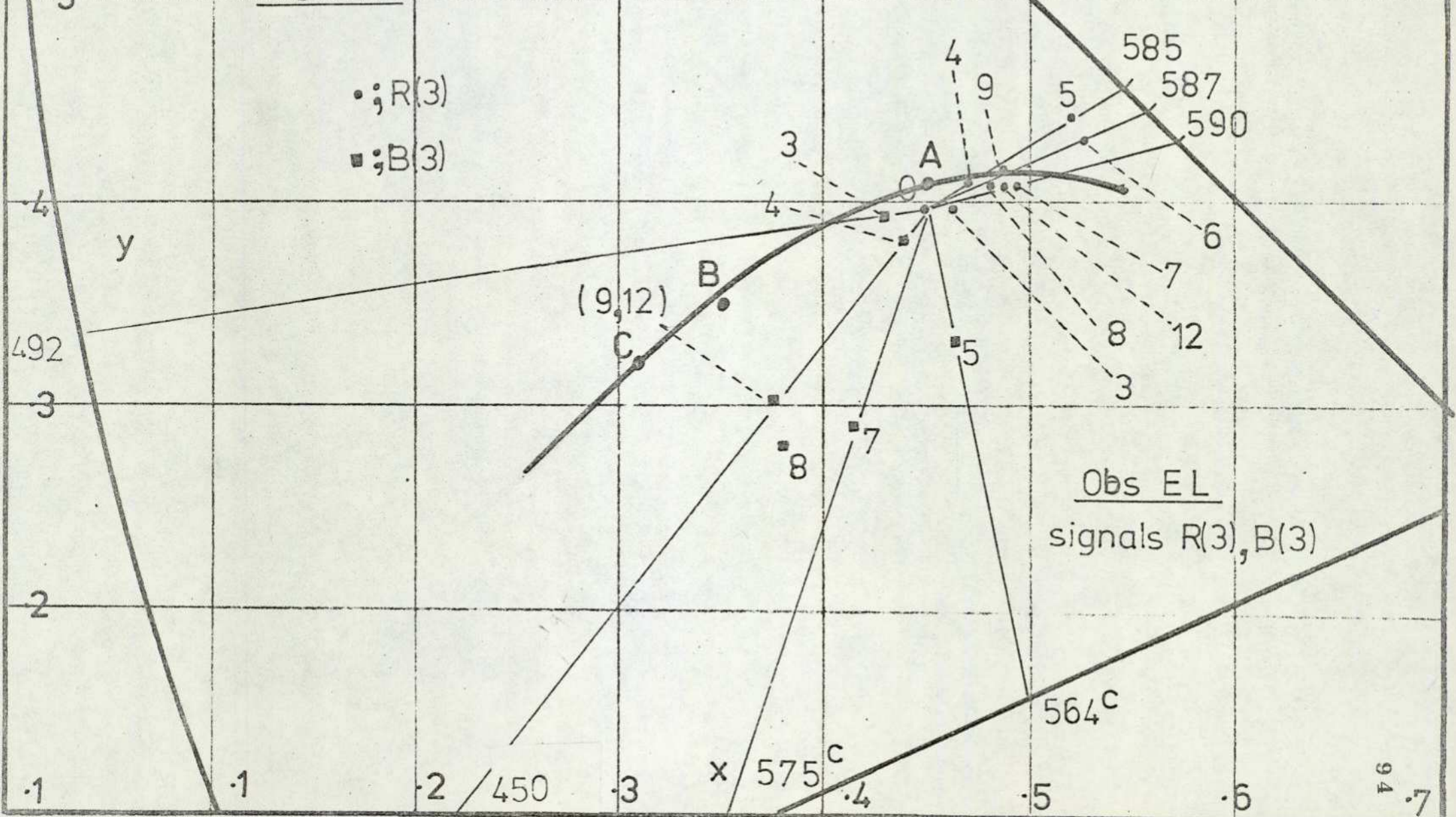


Fig 38c

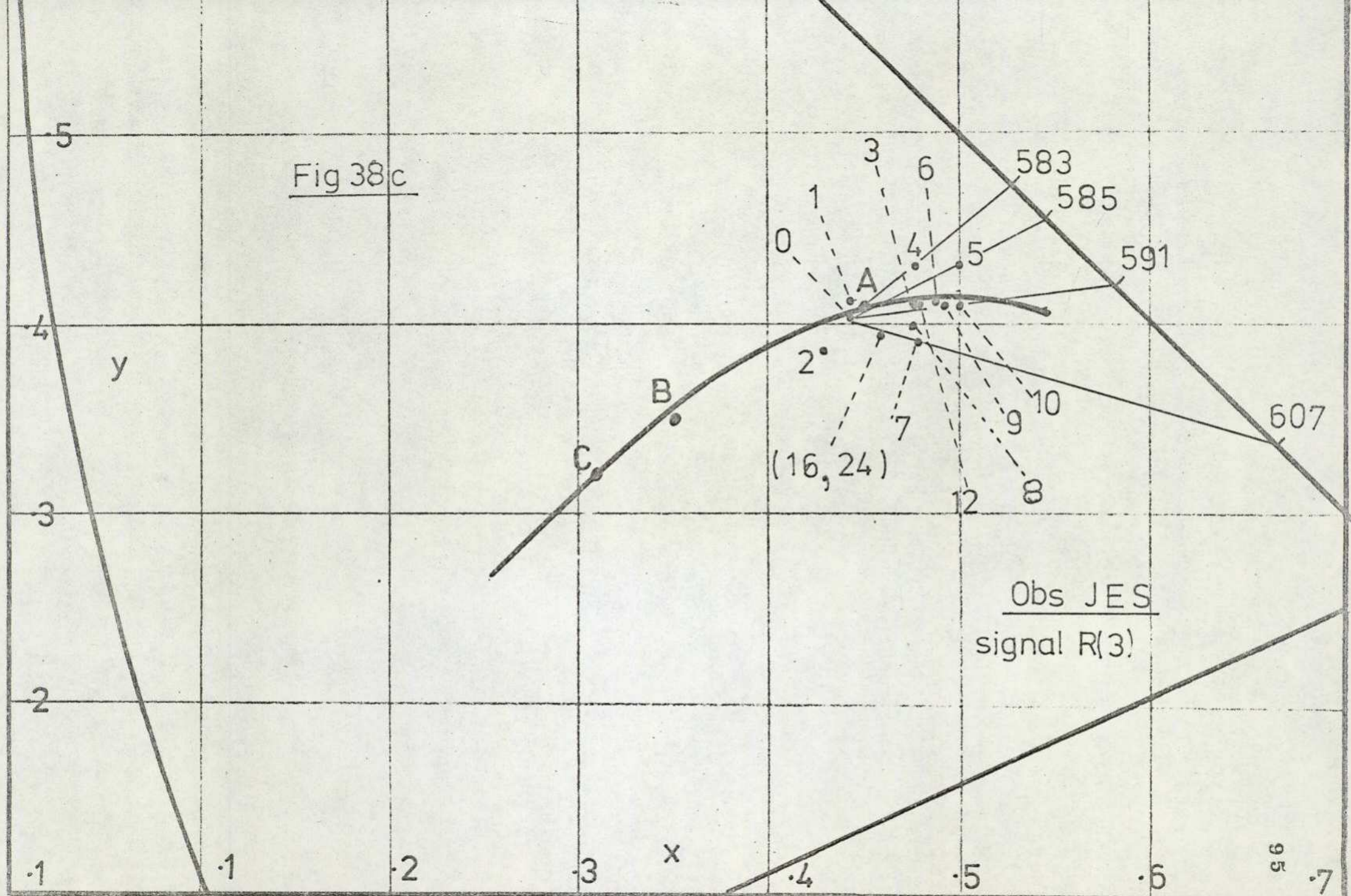


Fig 38 d

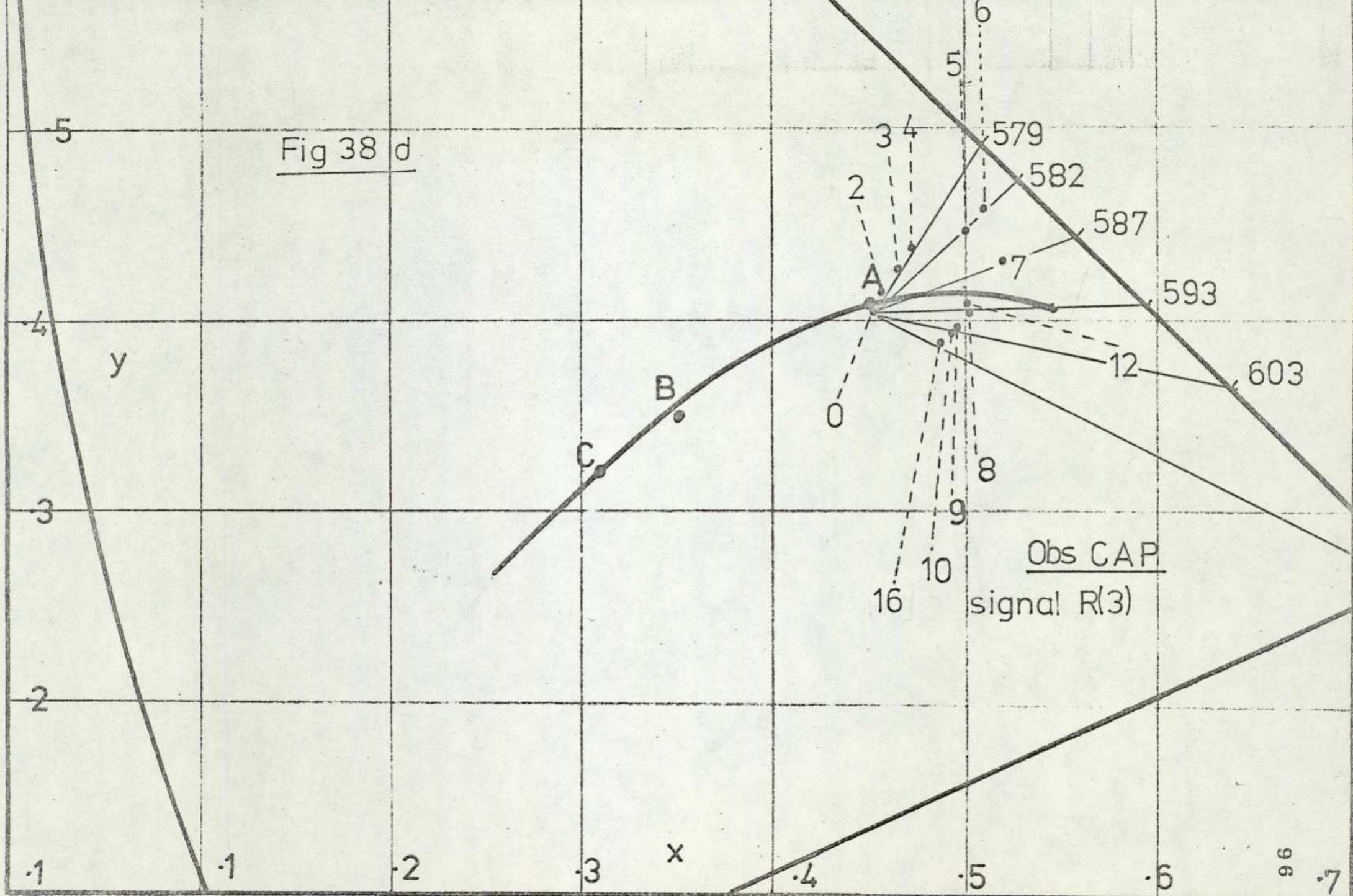


Fig. 38e

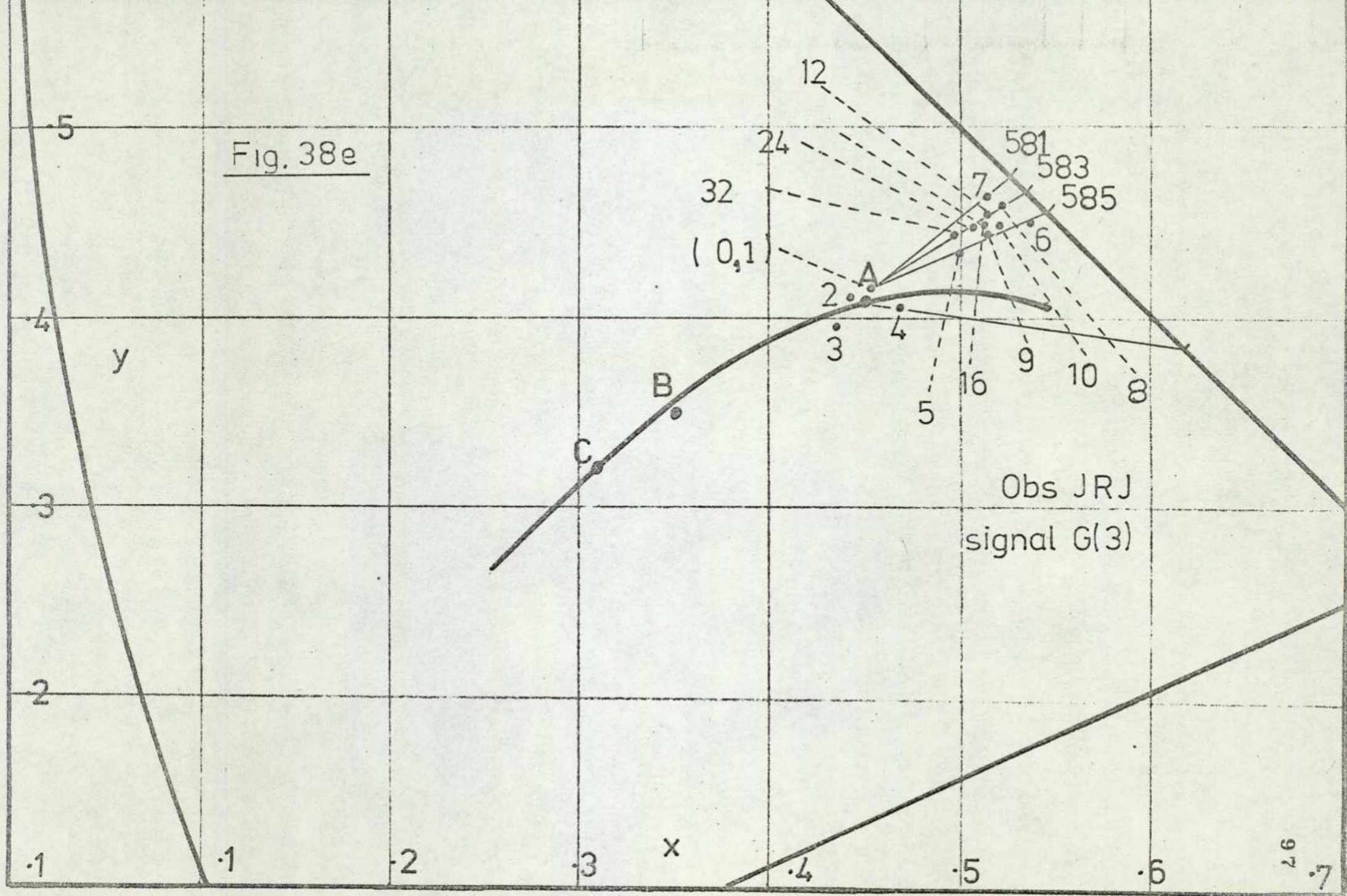


Fig. 38f

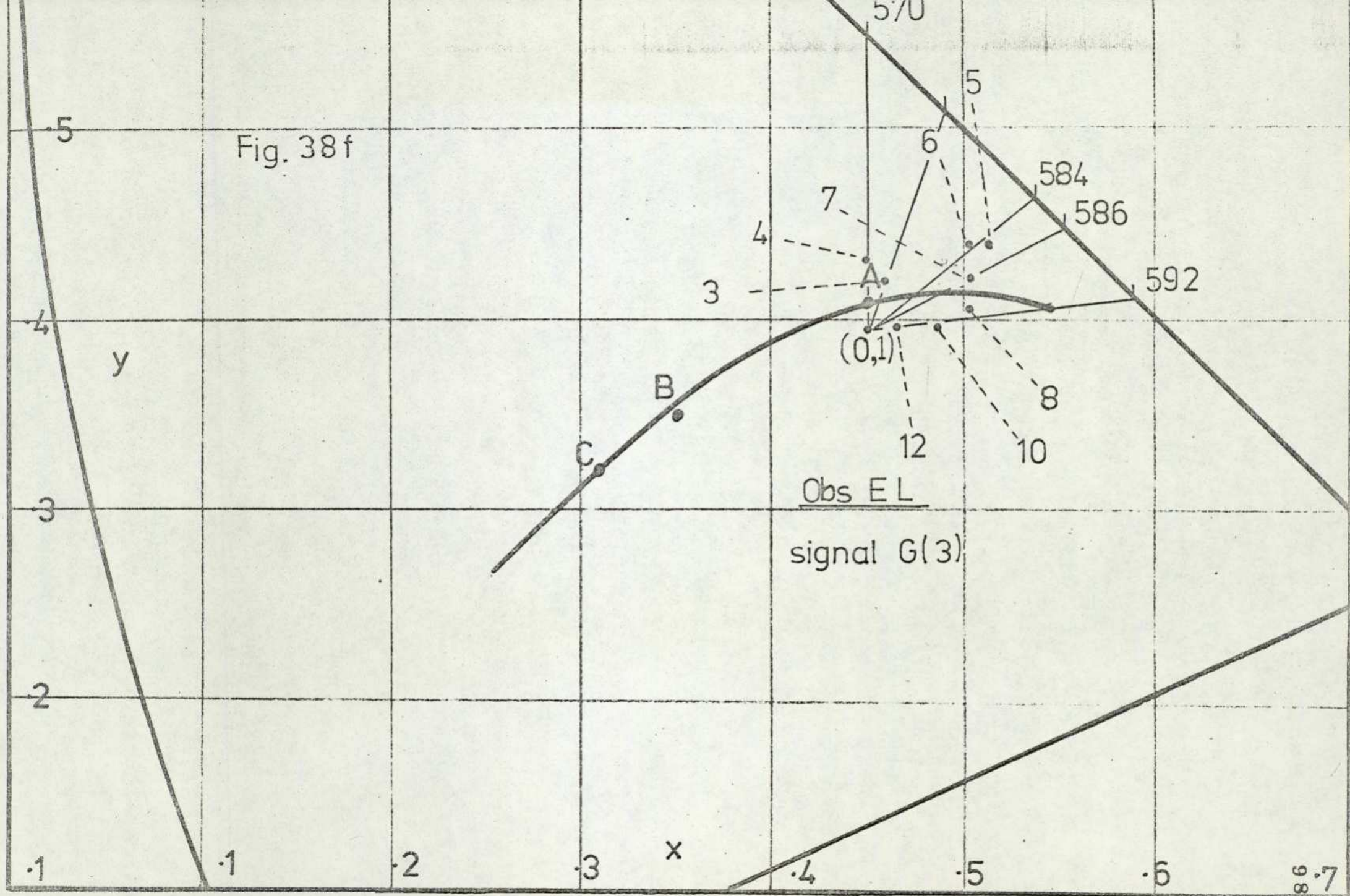


Fig 38 g

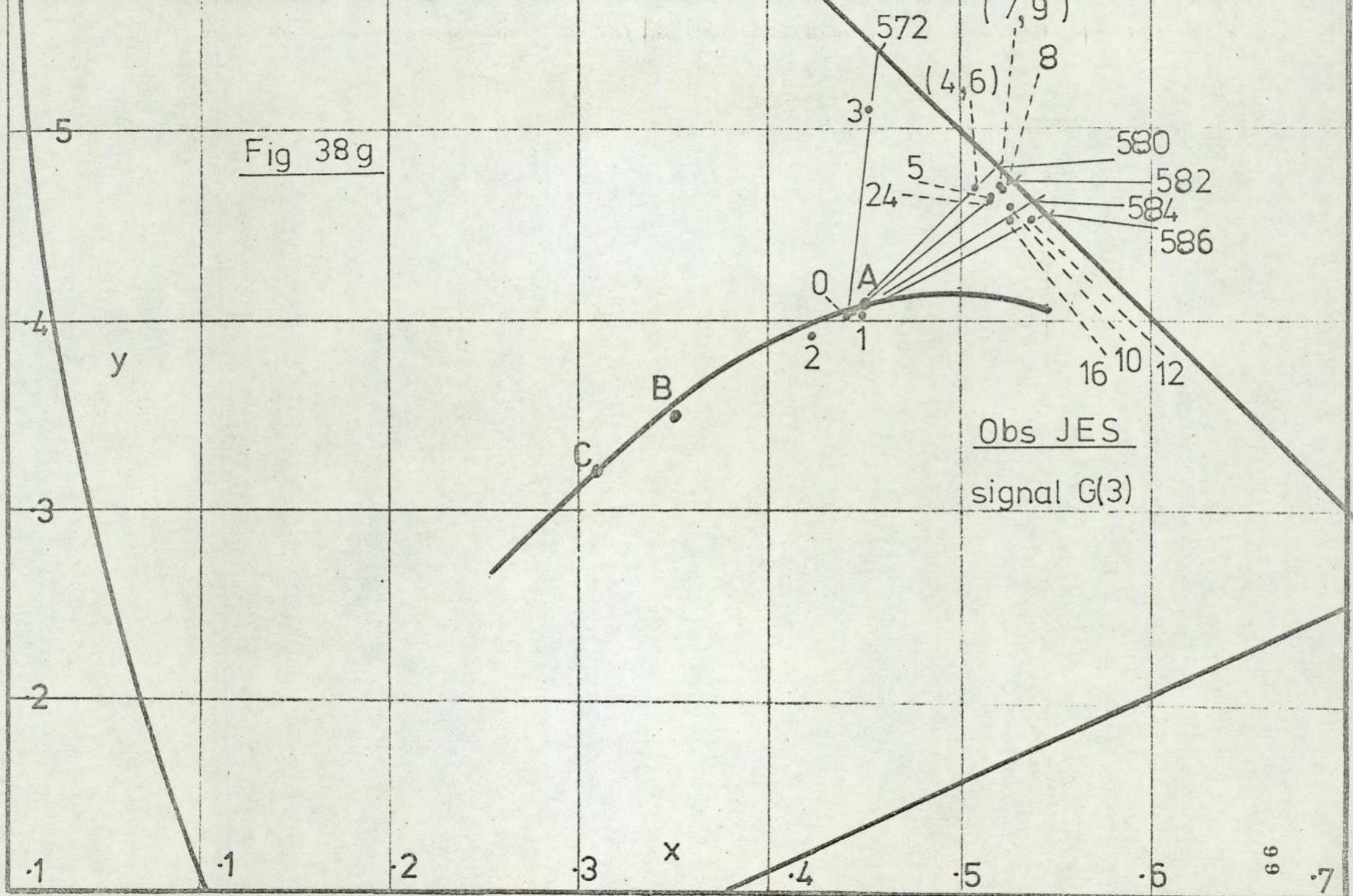


Fig 38 h

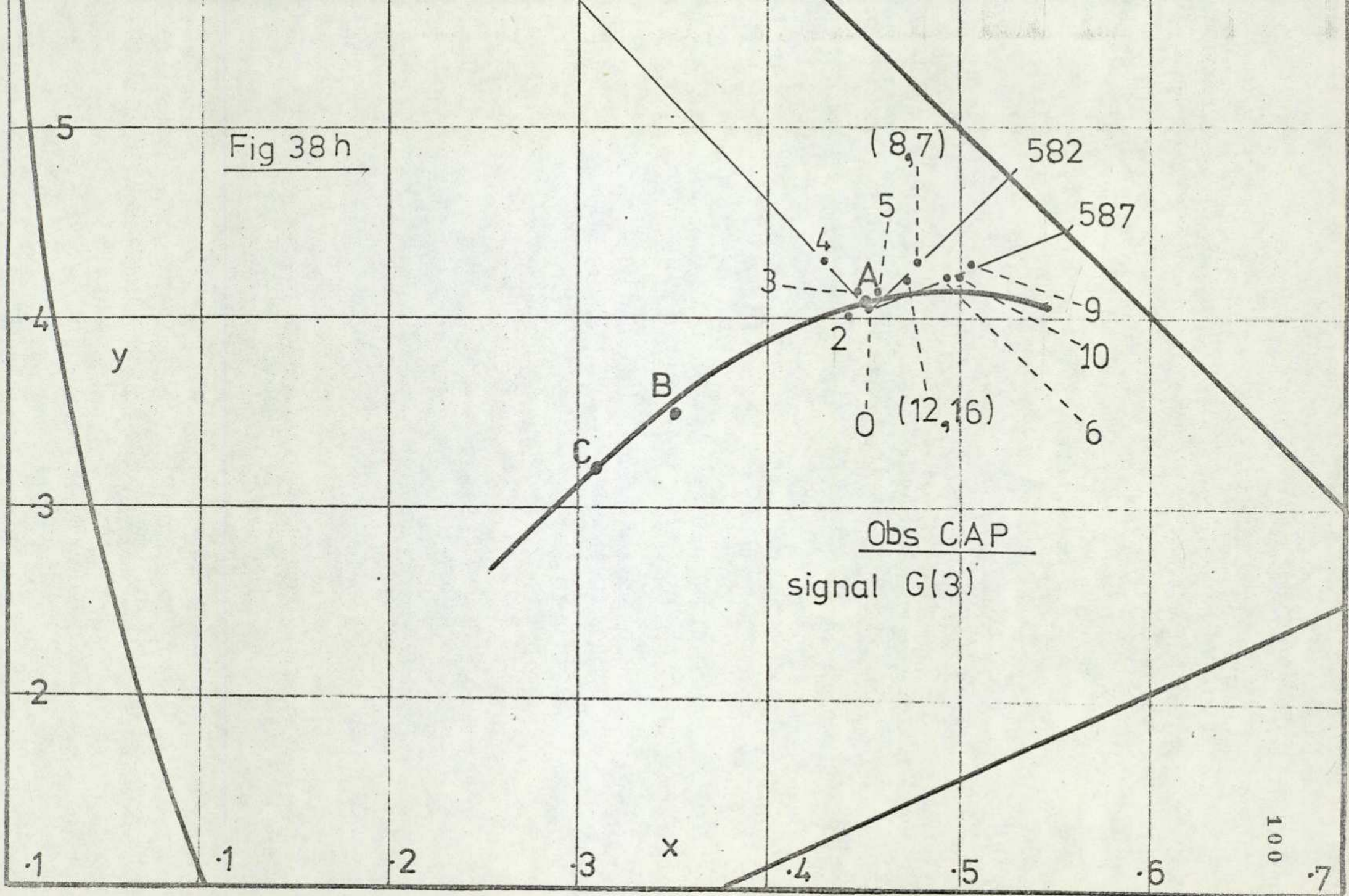


Fig 38i

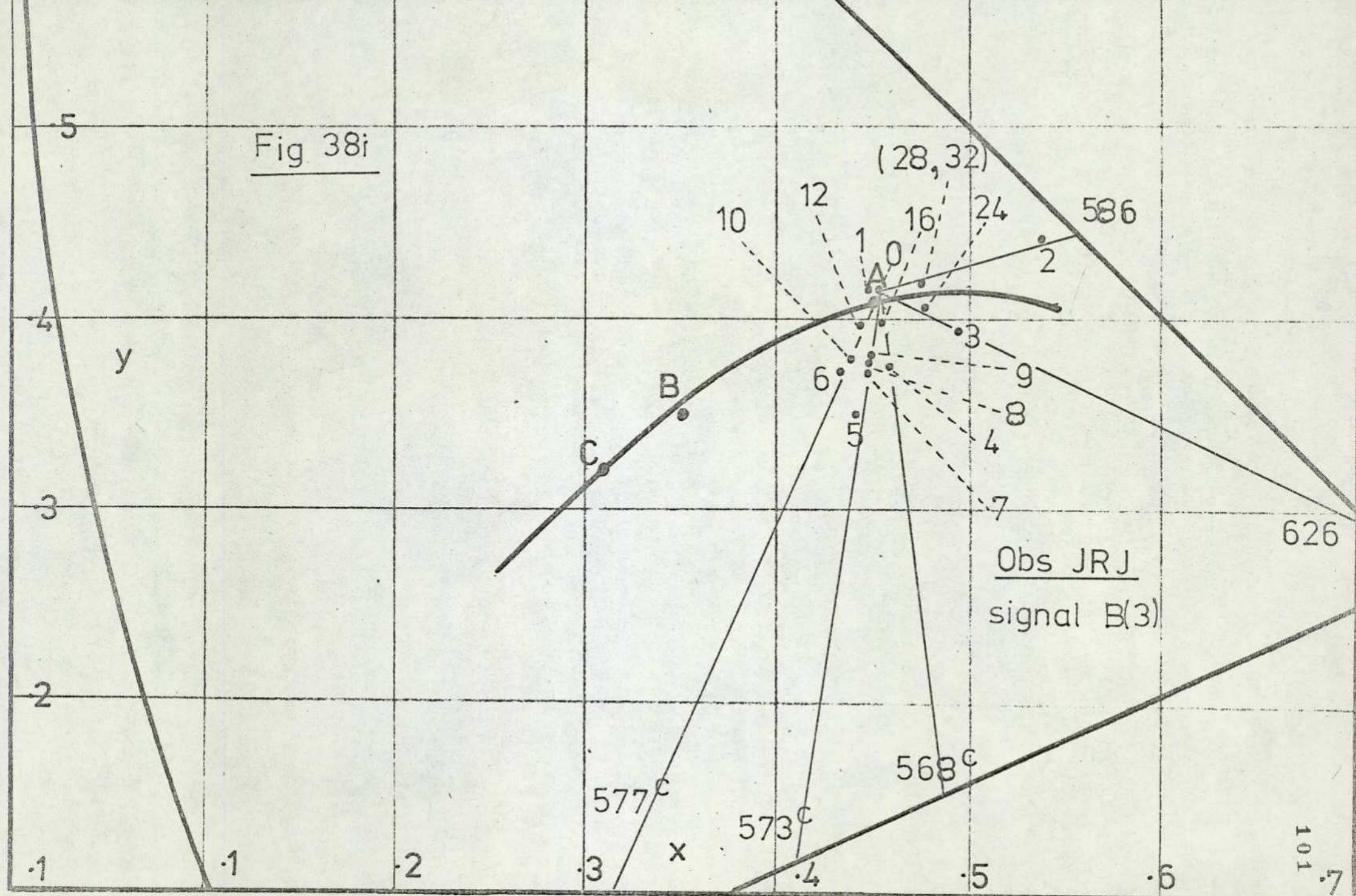


Fig 38j

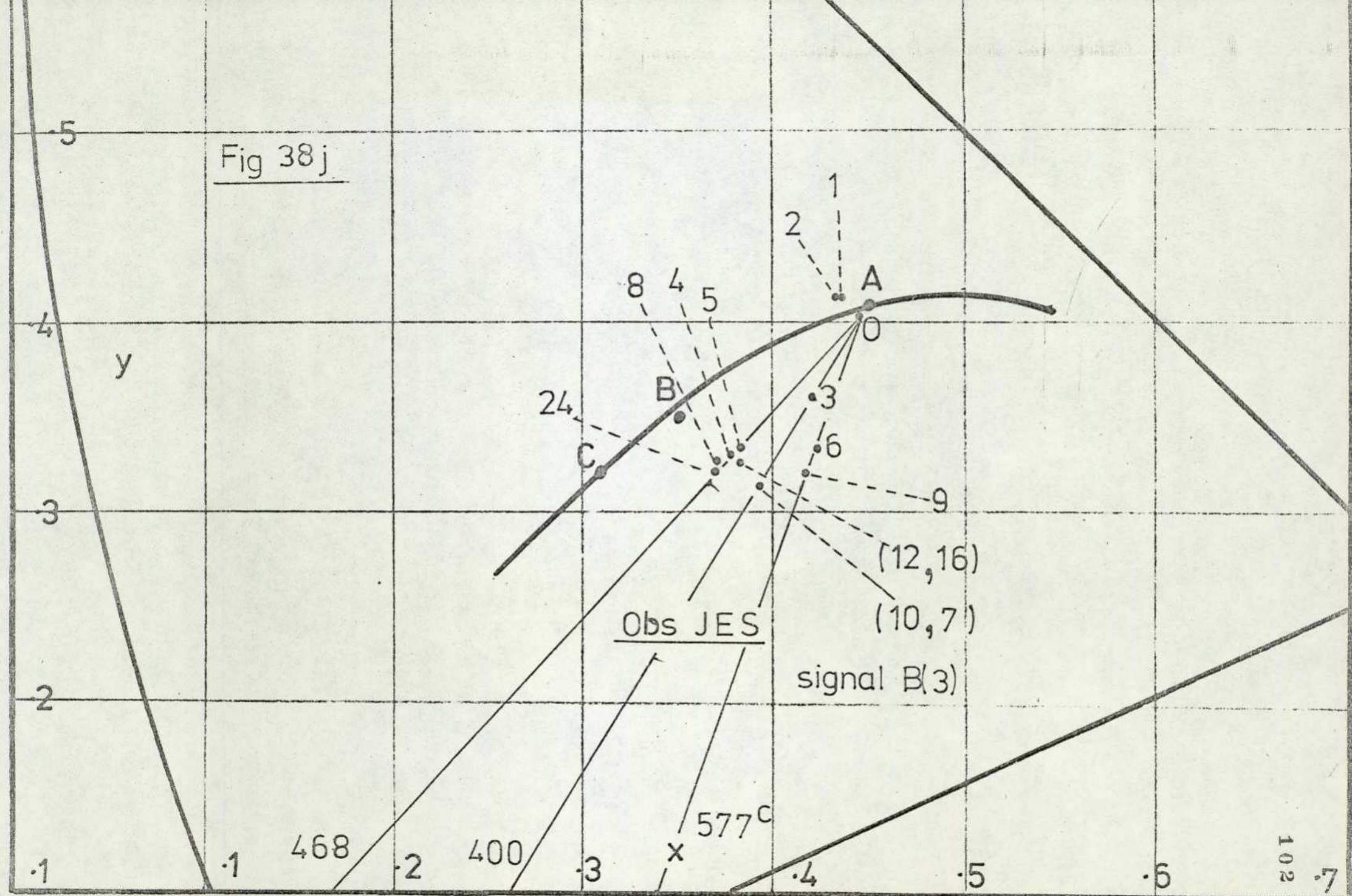
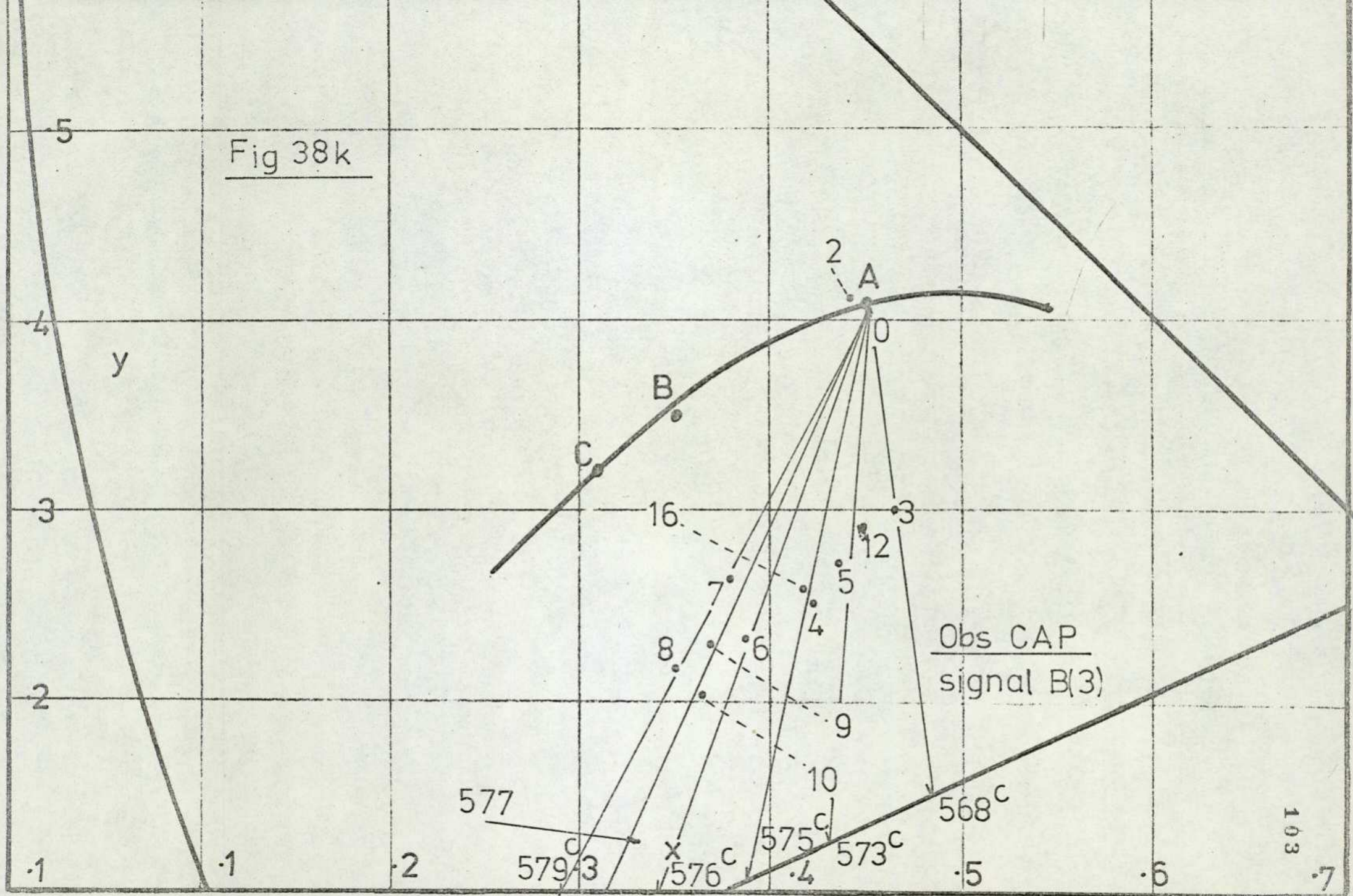
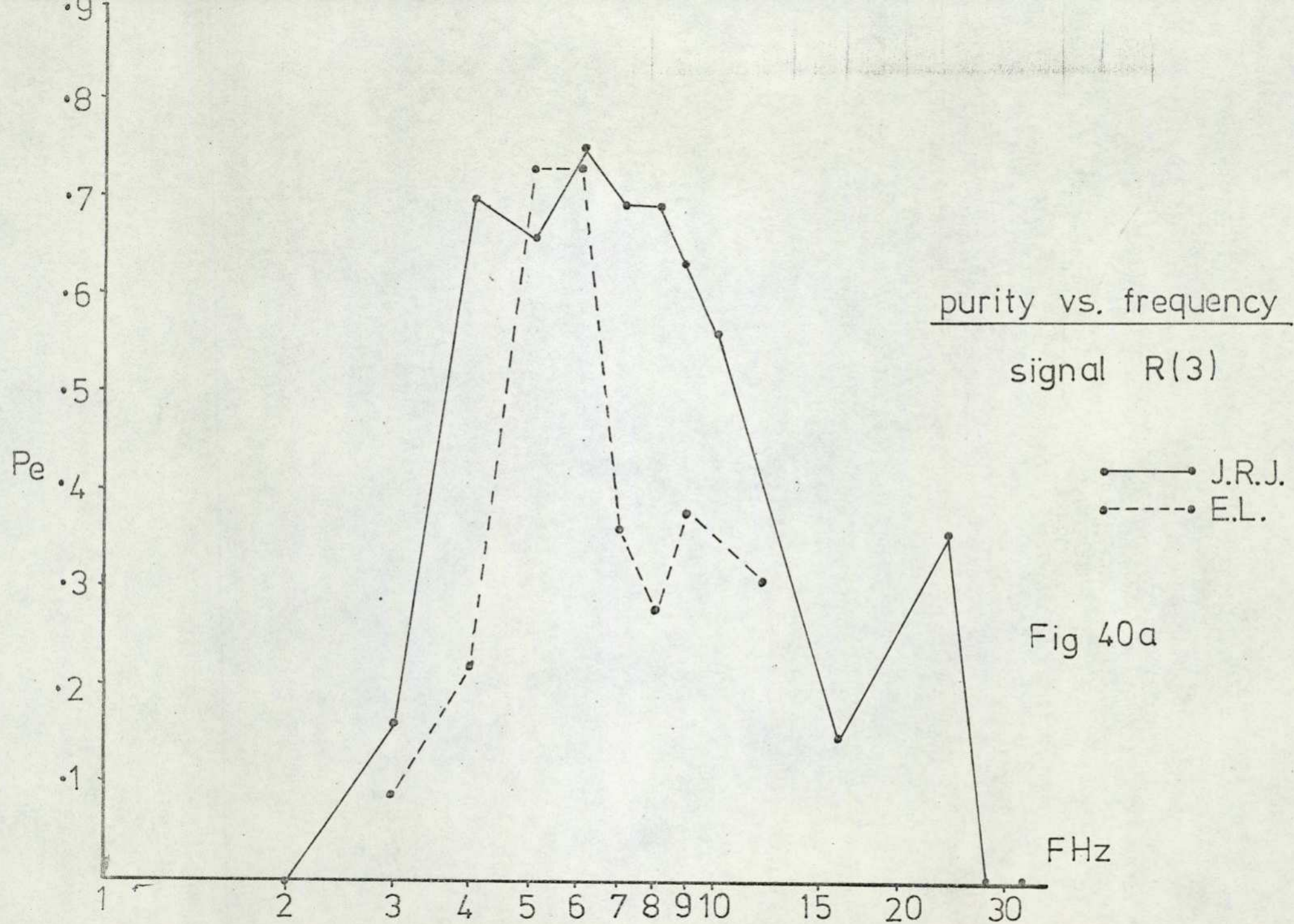
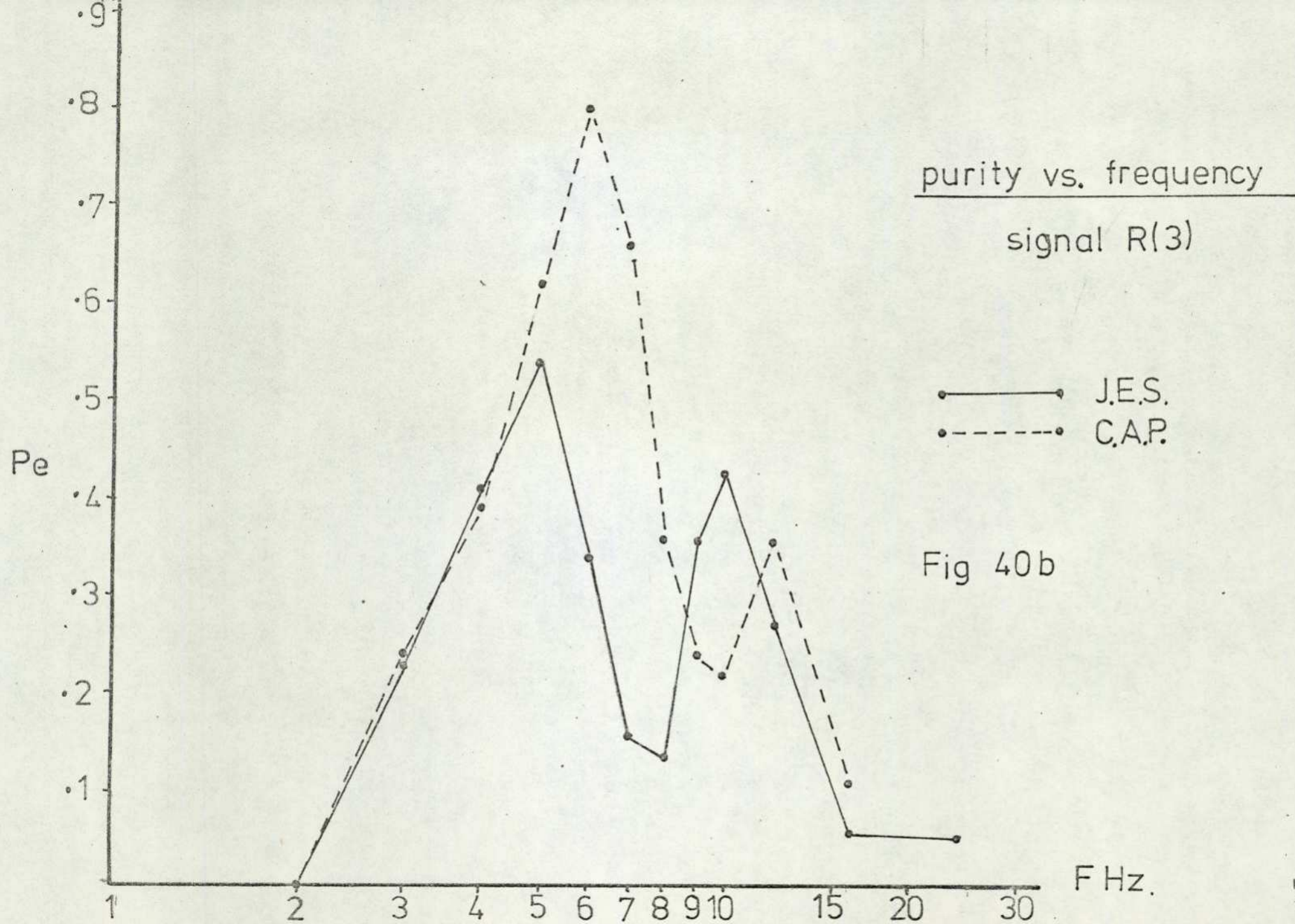
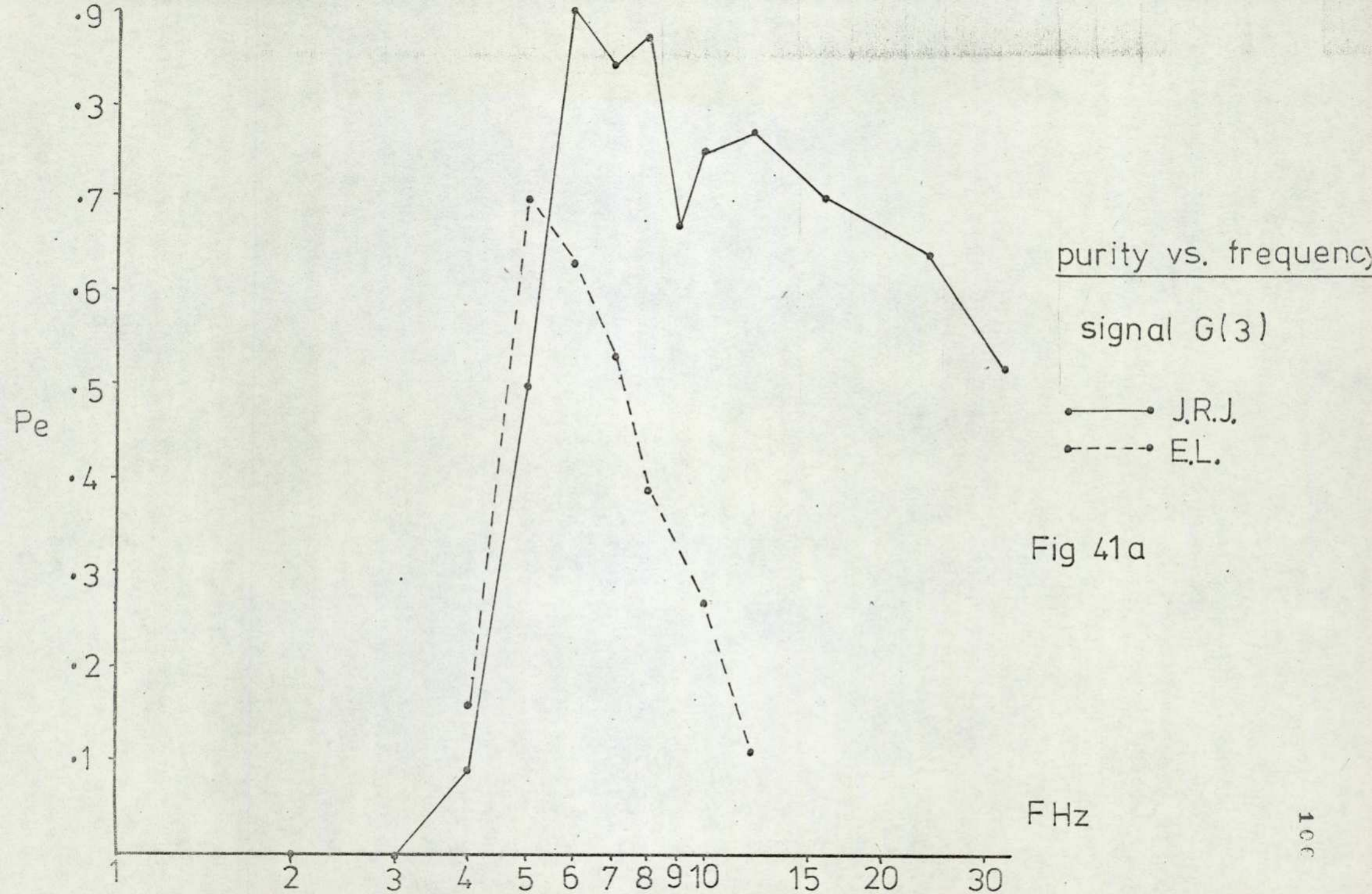


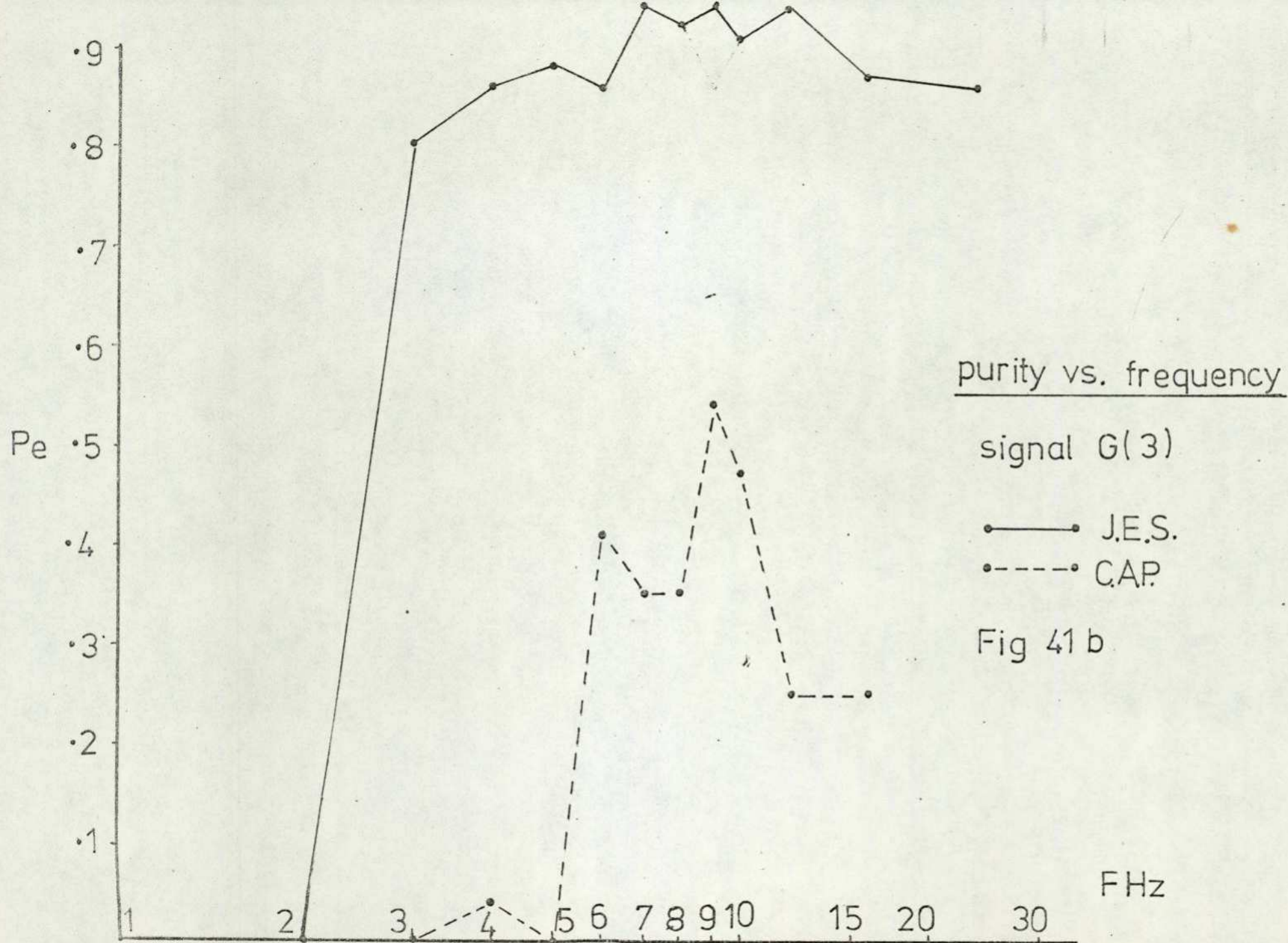
Fig 38k











Pe

4

3

2

1

1

2

3

4

5

6

7

8

9

10

15

20

30

FHz

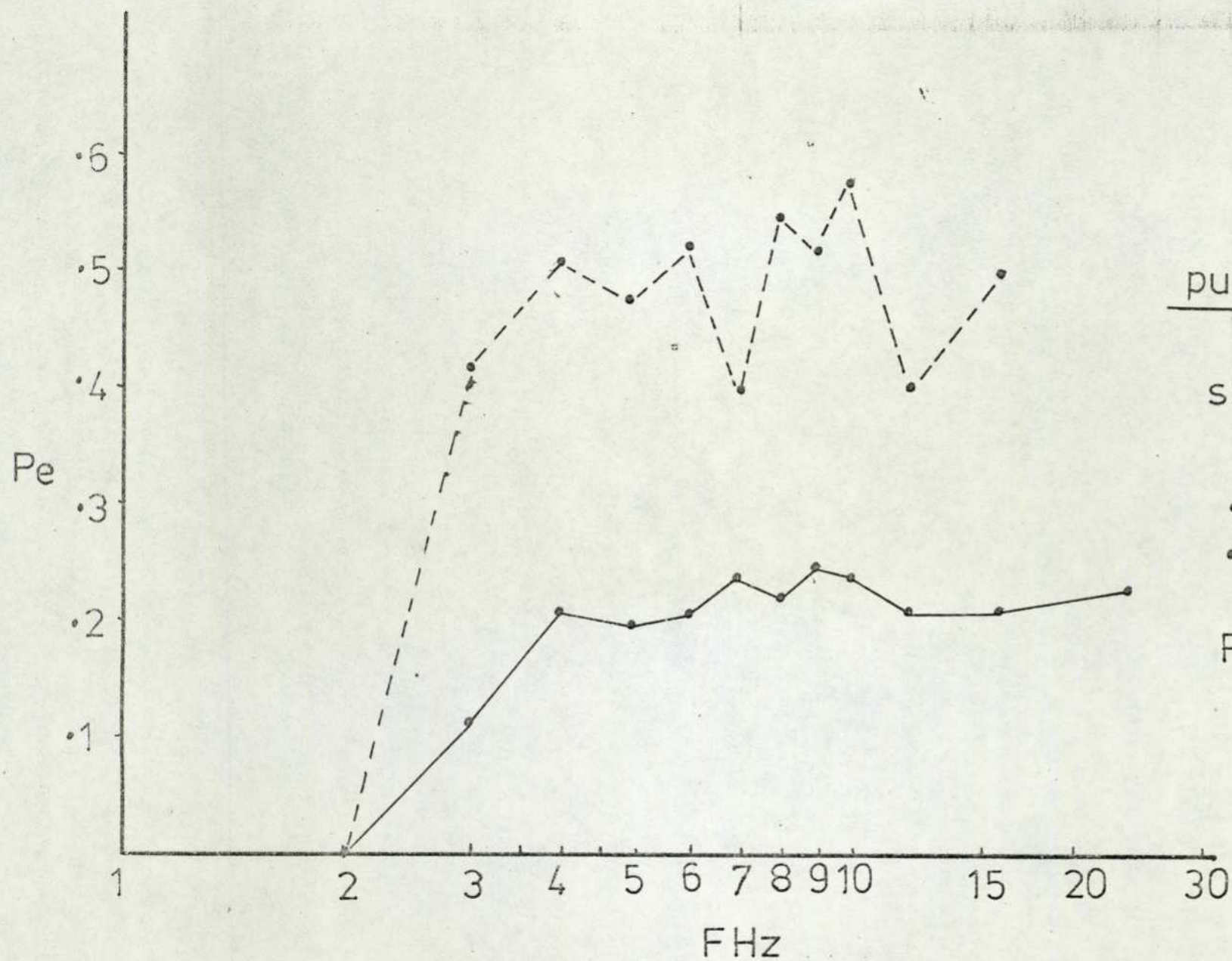
purity vs. frequency

signal B(3)

—•— J.R.J.

- - • - - E.L.

Fig 42a



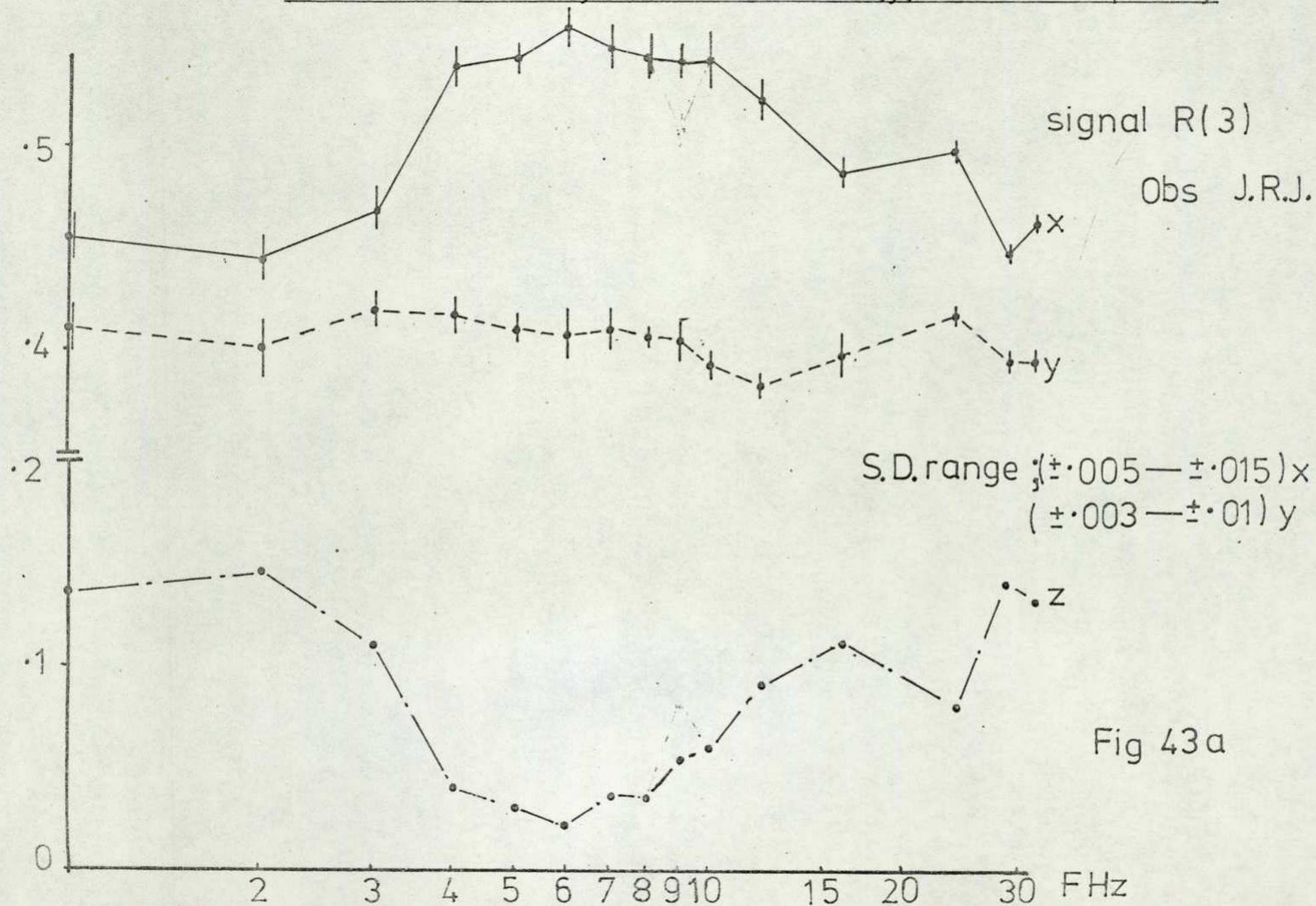
purity vs. frequency

signal B(3)

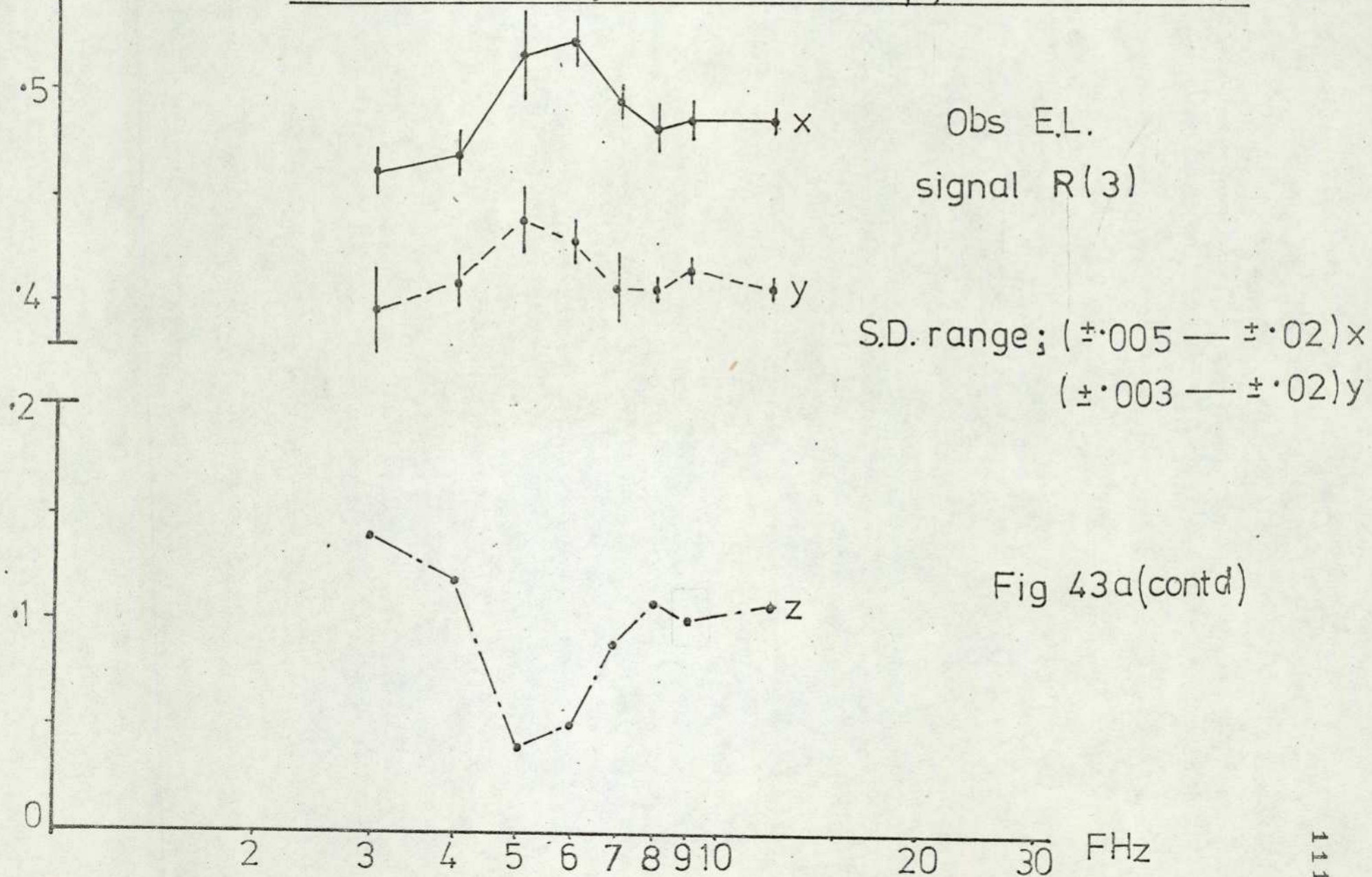
—•— J.E.S.
- - -•- C.A.P.

Fig 42b

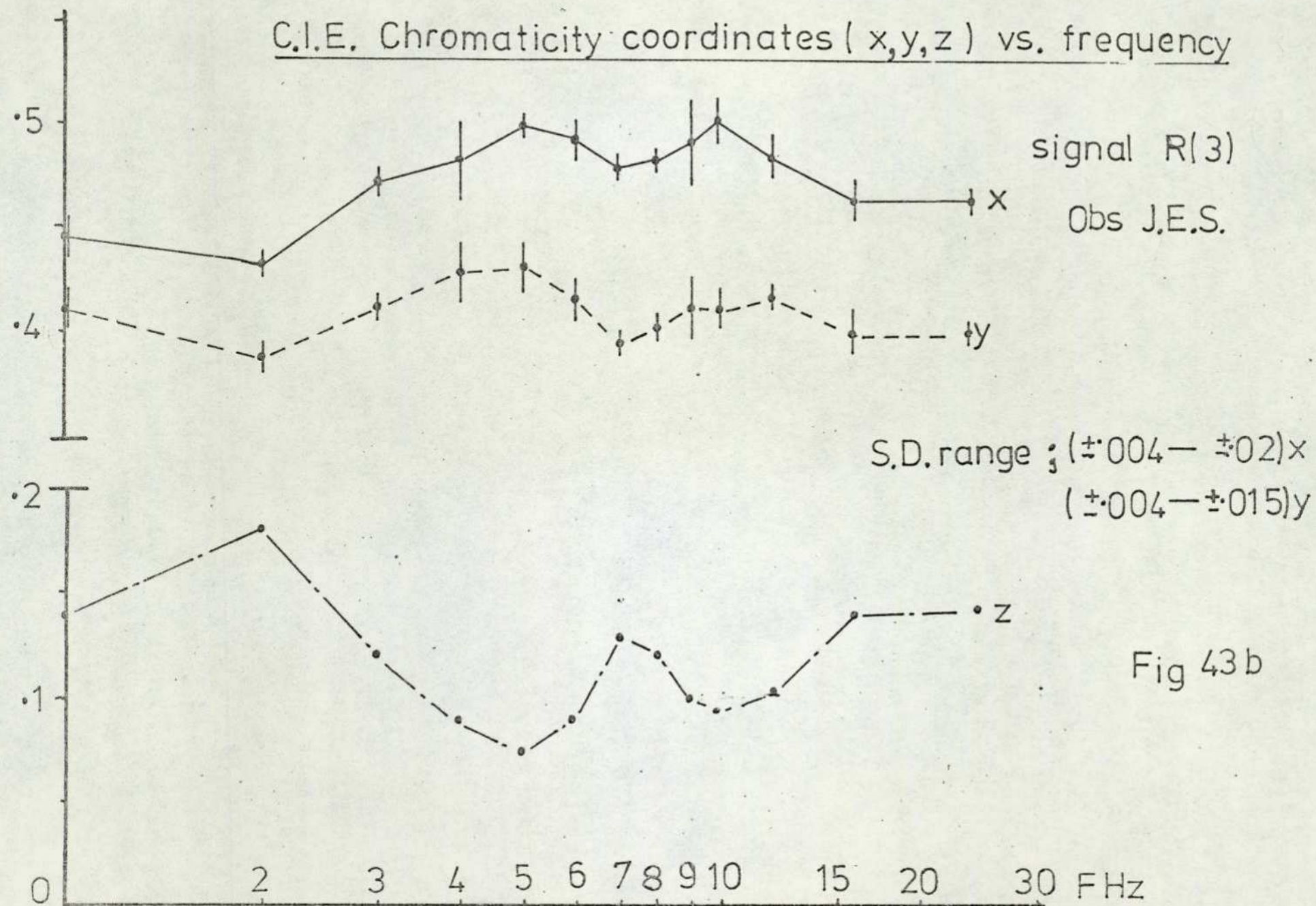
C.I.E. Chromaticity coordinates(x,y,z) vs. frequency



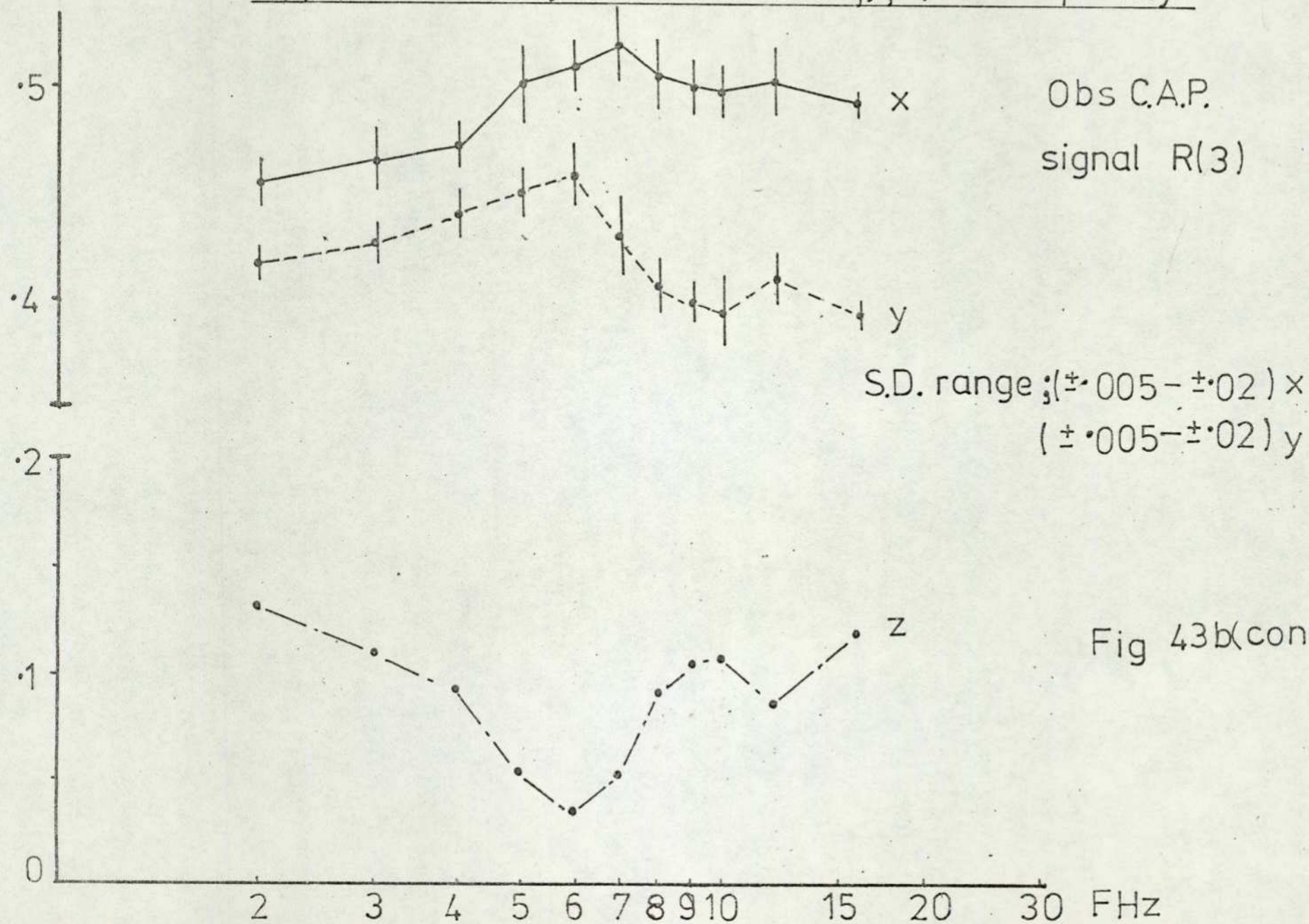
C.I.E. Chromaticity coordinates (x,y,z) vs. frequency



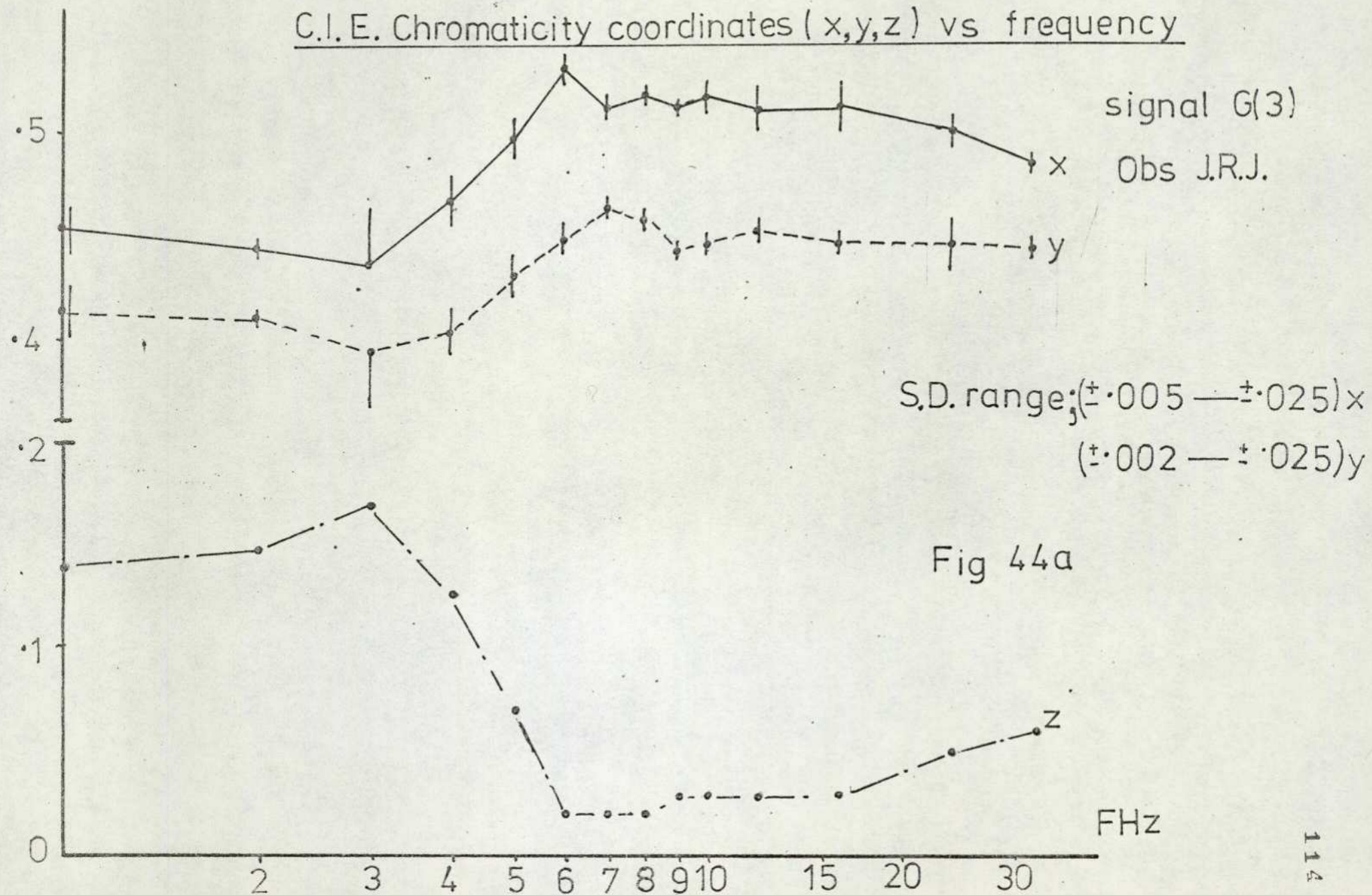
C.I.E. Chromaticity coordinates (x,y,z) vs. frequency



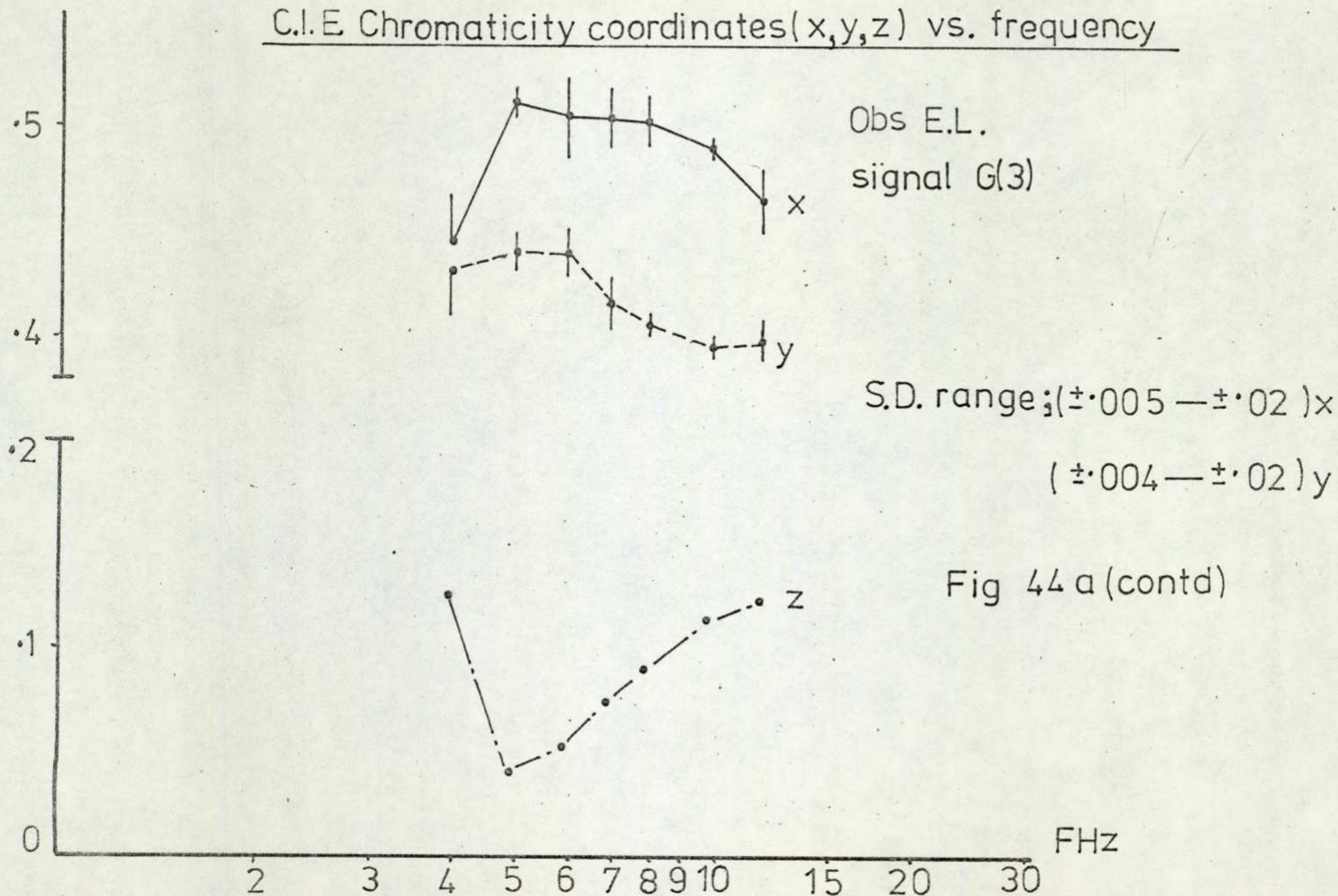
C.I.E. Chromaticity coordinates (x,y,z) vs. frequency



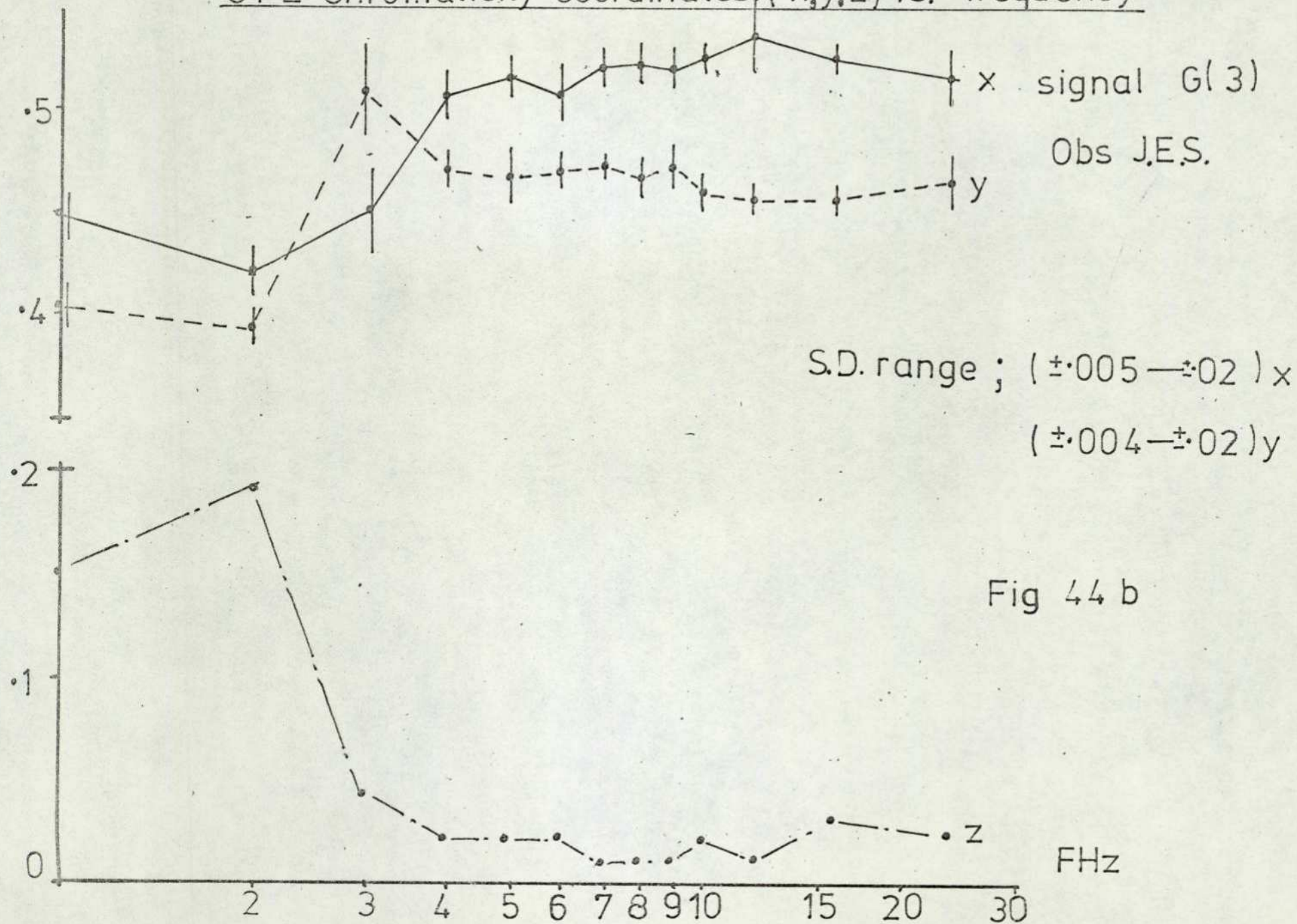
C.I.E. Chromaticity coordinates (x,y,z) vs frequency



C.I.E Chromaticity coordinates(x,y,z) vs. frequency



CIE Chromaticity coordinates (x,y,z) vs. frequency



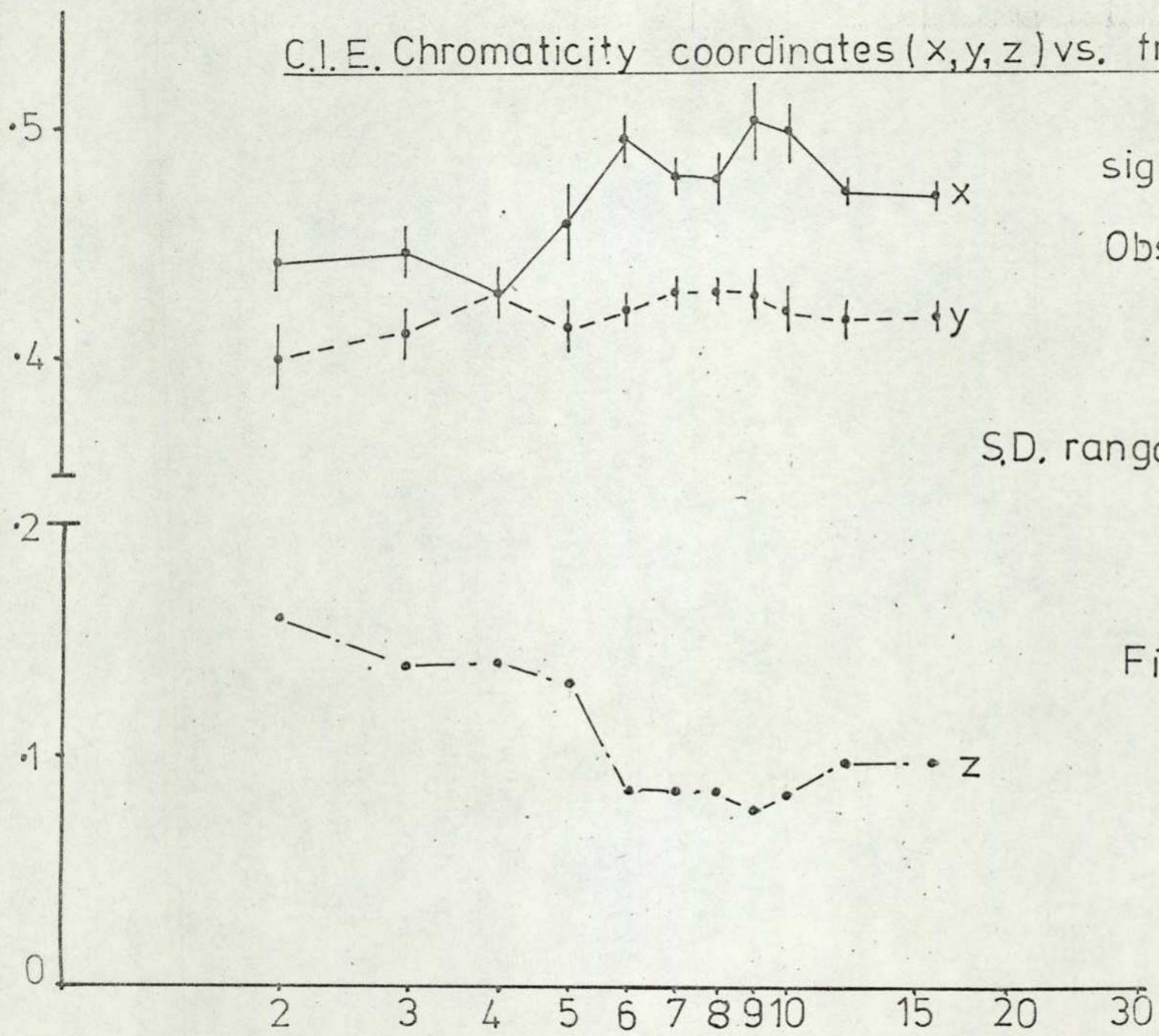
C.I.E. Chromaticity coordinates (x,y,z) vs. frequency

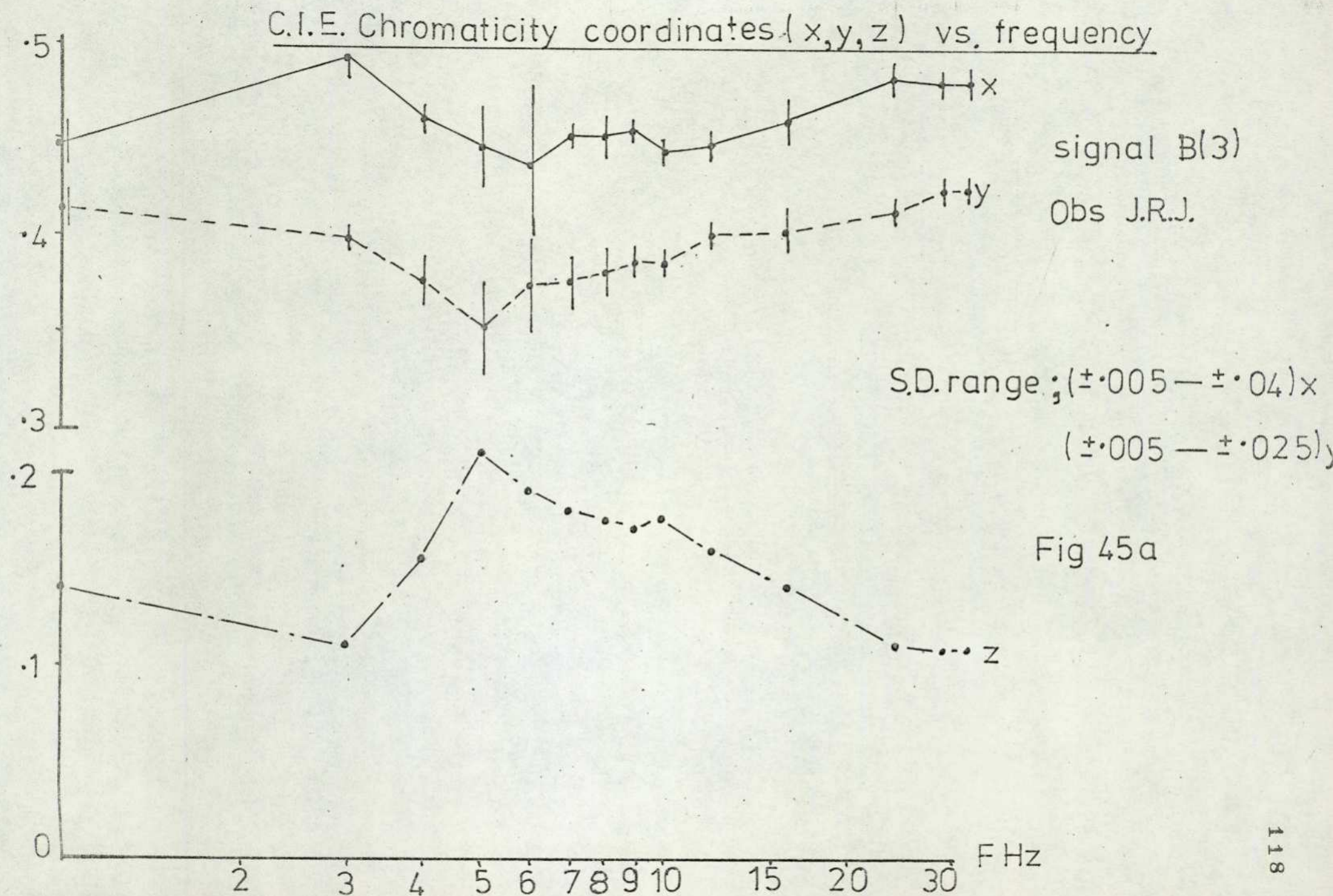
signal G(3)

Obs C.A.P.

S.D. range; (± 0.003 — ± 0.015) x
 (± 0.005 — ± 0.015) y

Fig 44 b(contd)

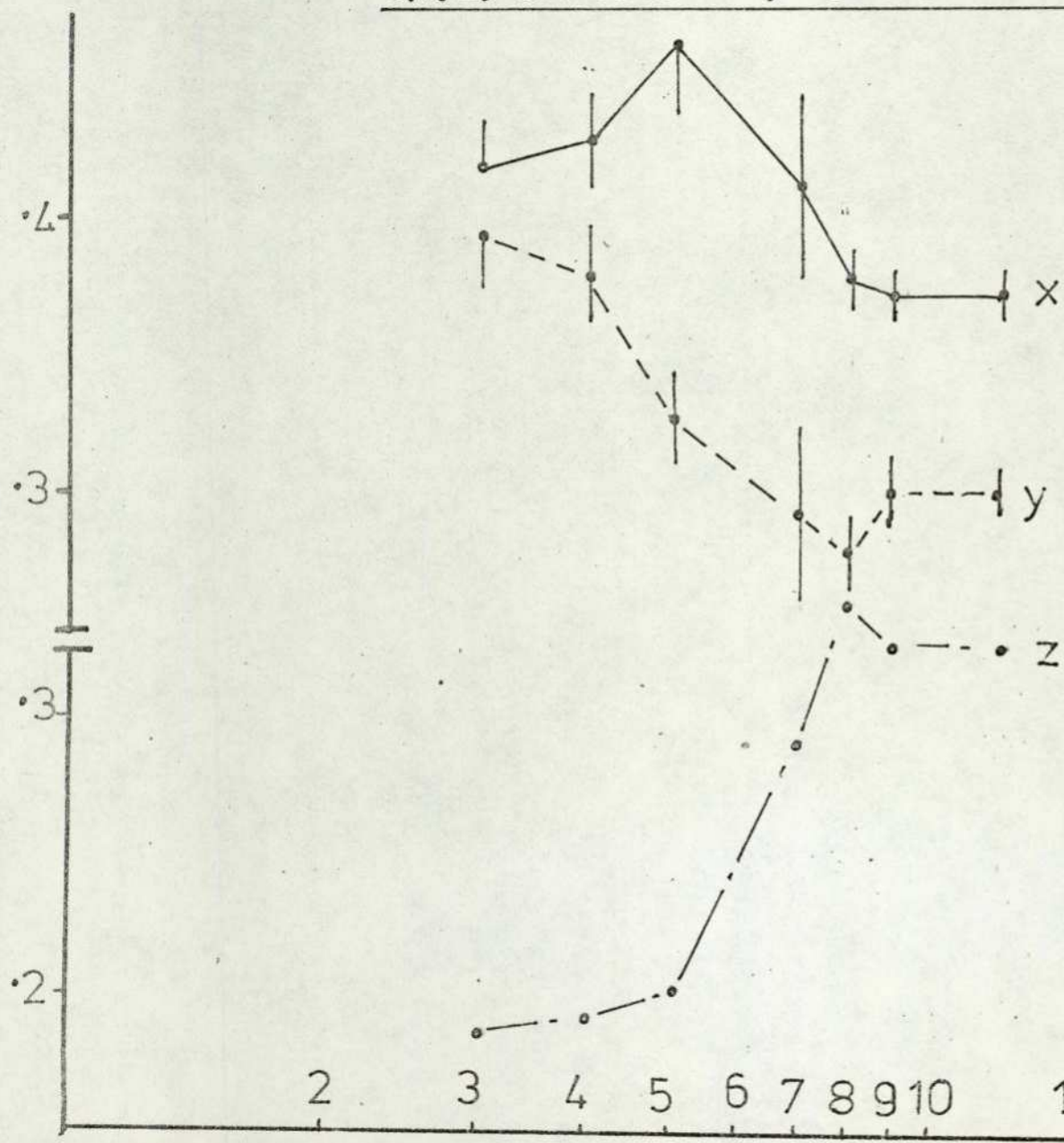




C.I.E. Chromaticity coordinates (x,y,z) vs. frequency

signal B(3)

Obs. E.L.

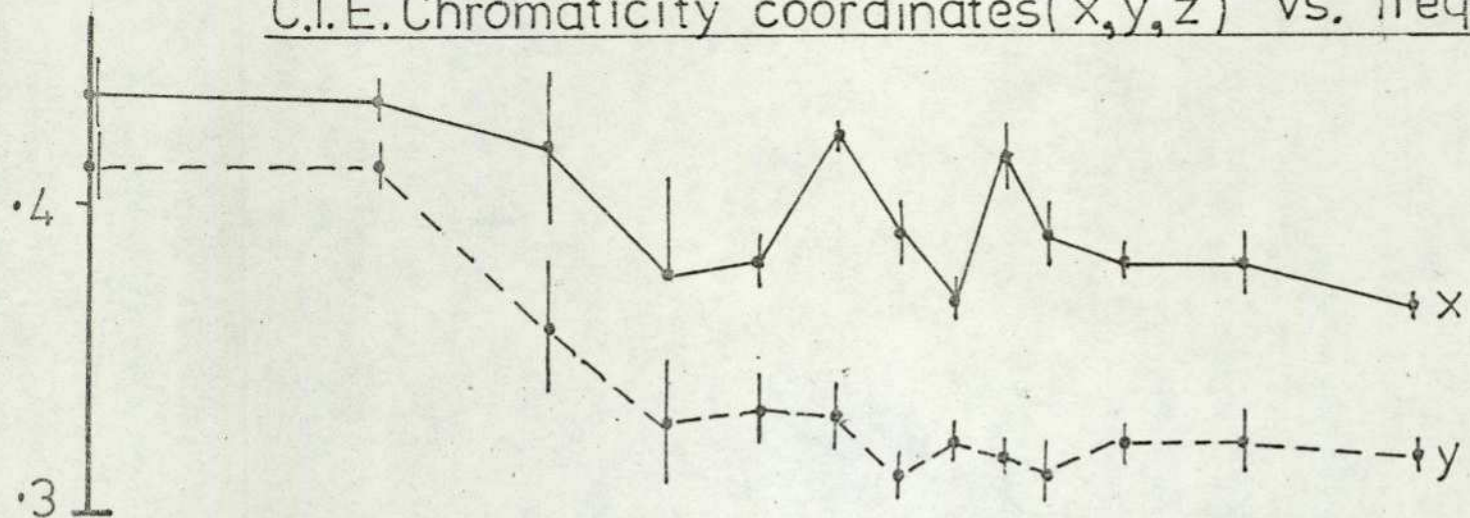


S.D. range: $(\pm 0.01 - \pm 0.04)x$

$(\pm 0.01 - \pm 0.04)y$

Fig 45a (contd)

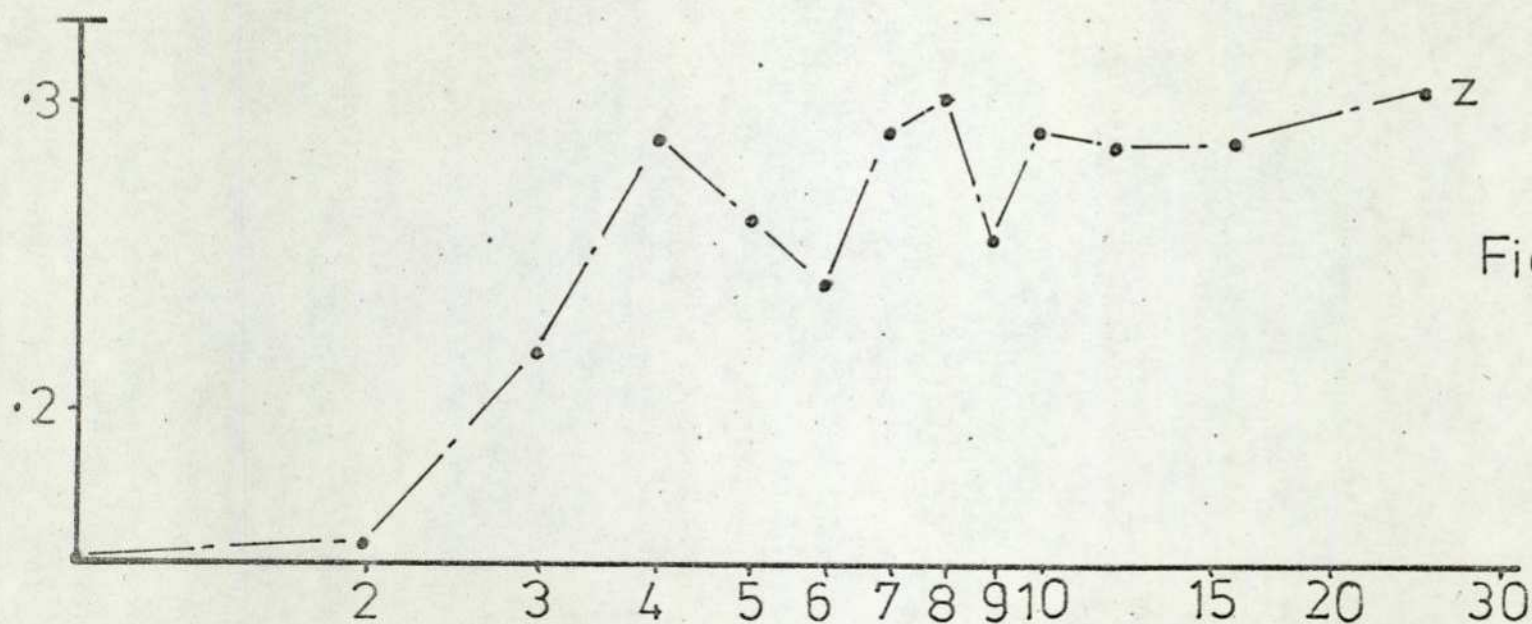
C.I.E. Chromaticity coordinates (x,y,z) vs. frequency



S.D. range ; ($\pm 0.005 - \pm 0.025$)

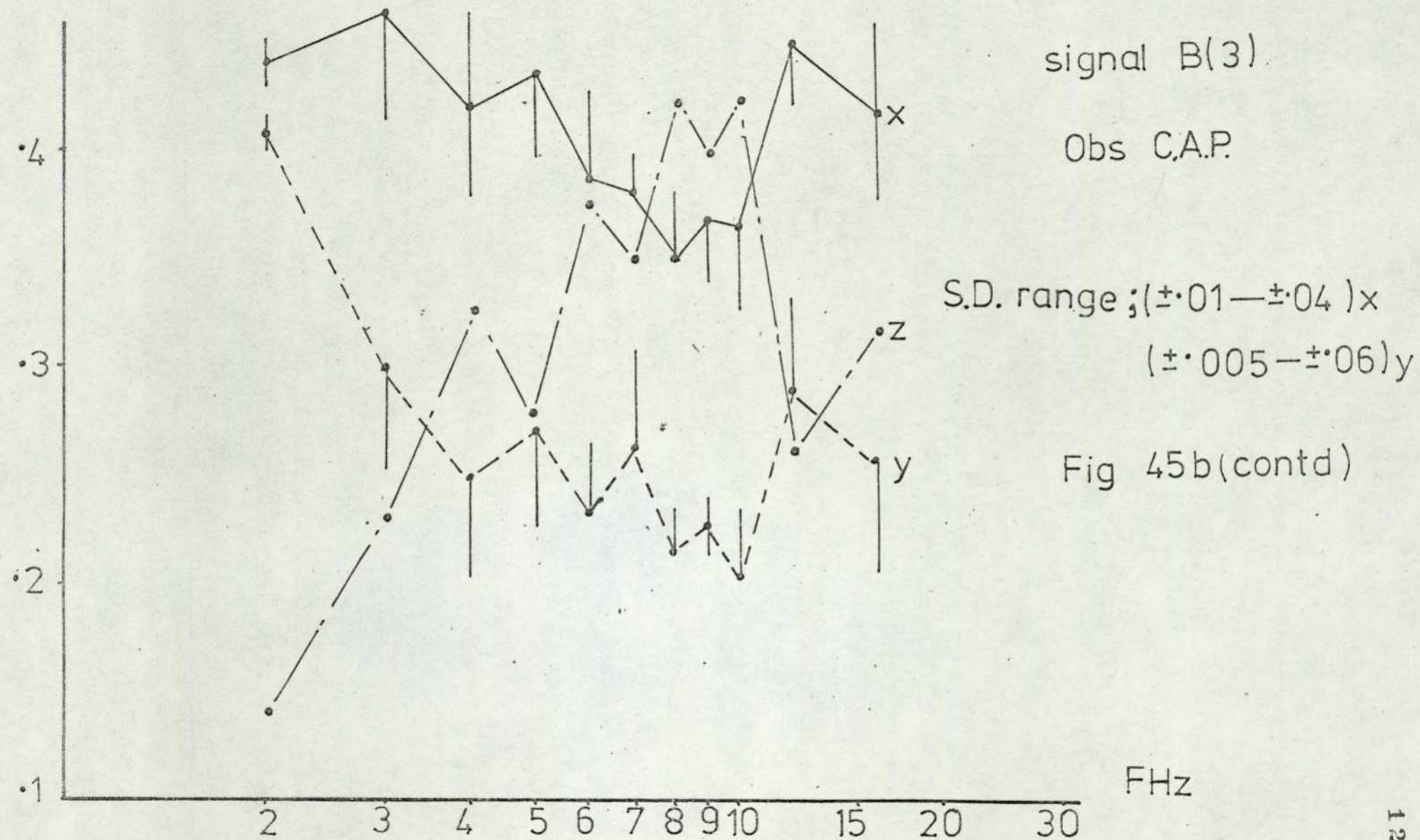
($\pm 0.005 - \pm 0.02$) y

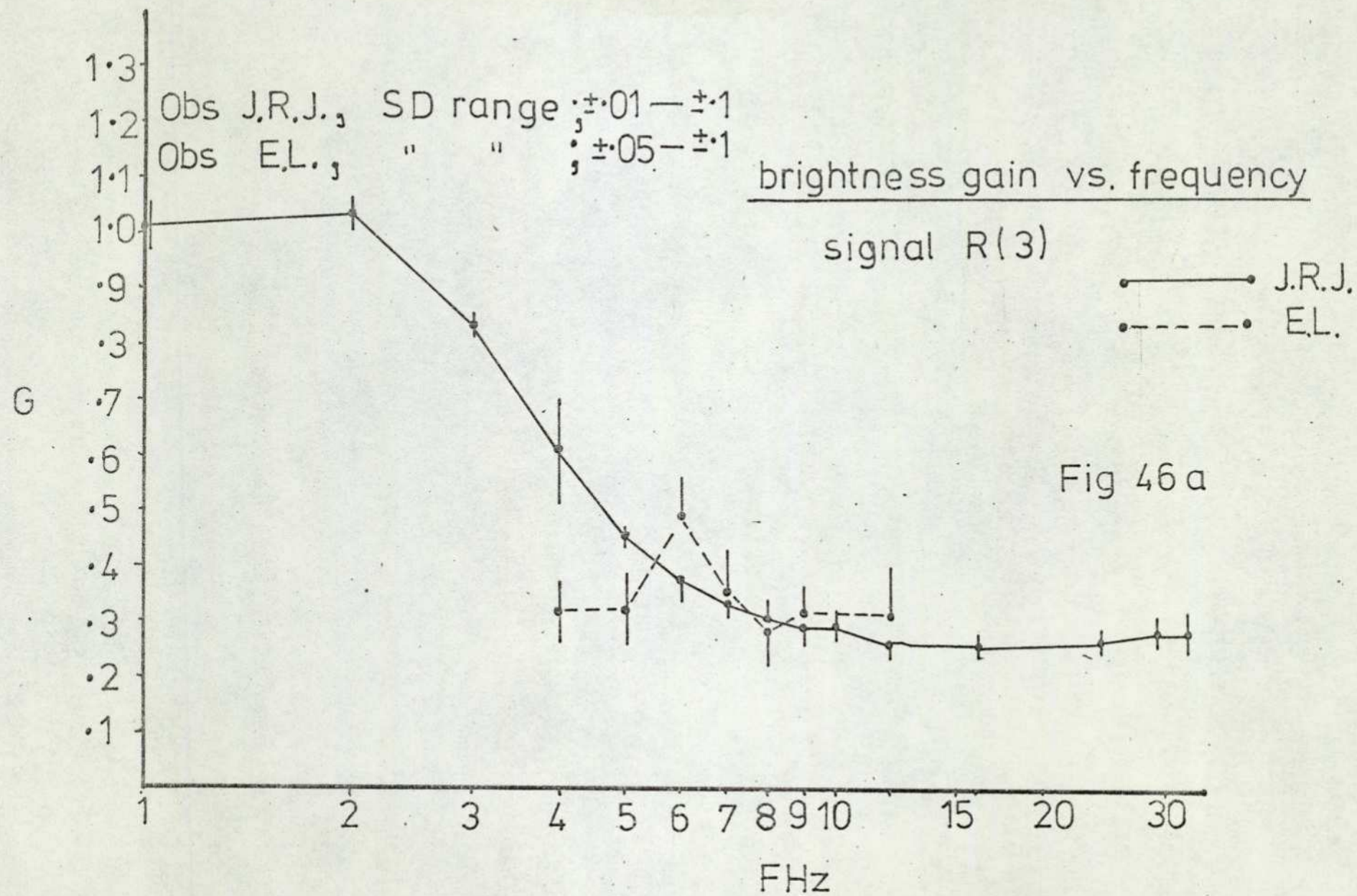
Fig 45b



FHz

C.I.E. Chromaticity coordinates (x,y,z) vs. frequency





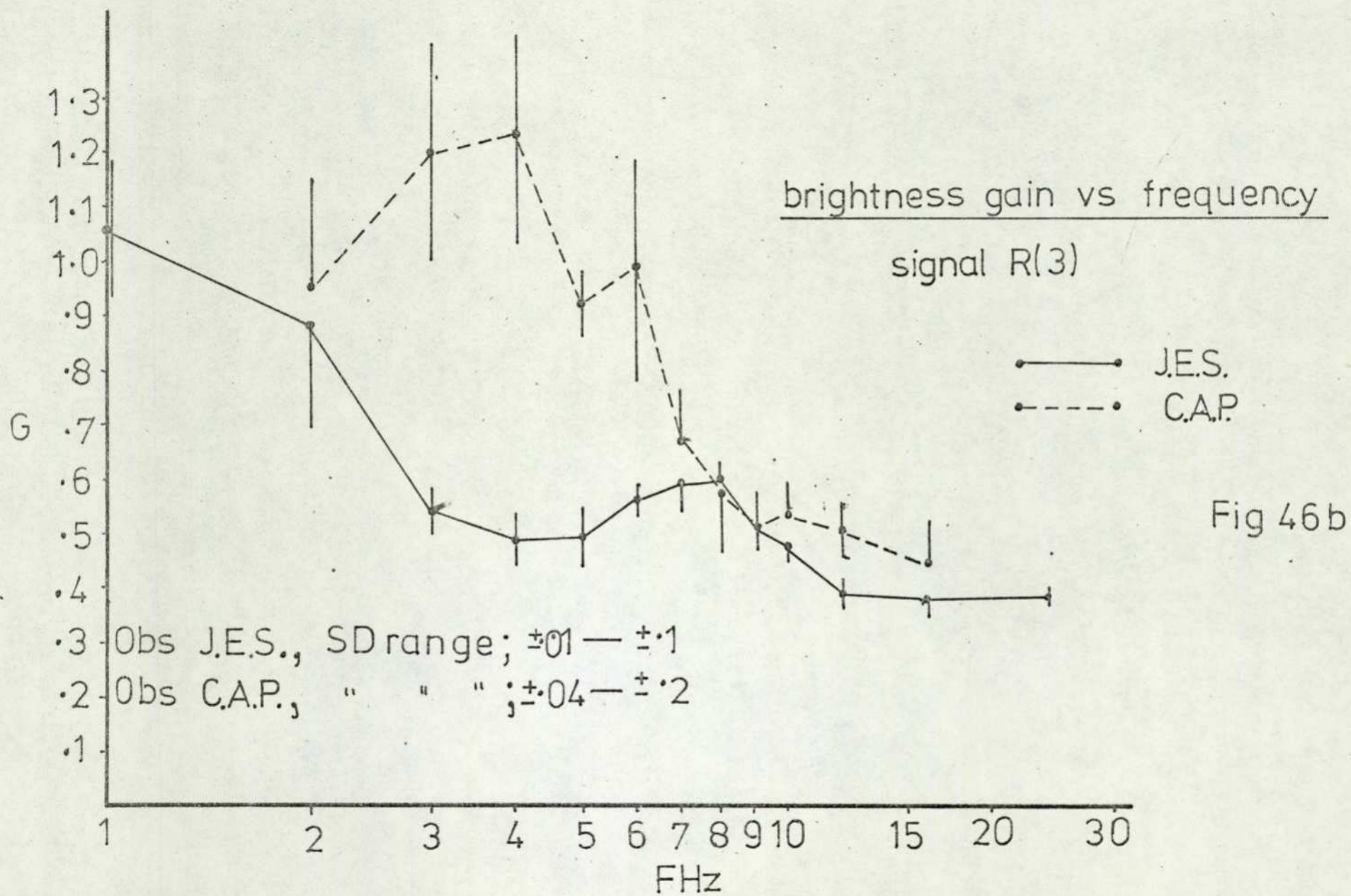


Fig 46b

Obs J.R.J., S.D. range ; ± 0.02 — ± 0.07
 Obs E.L., " " " ; ± 0.06 — ± 0.18

brightness gain vs frequency

signal G(3)

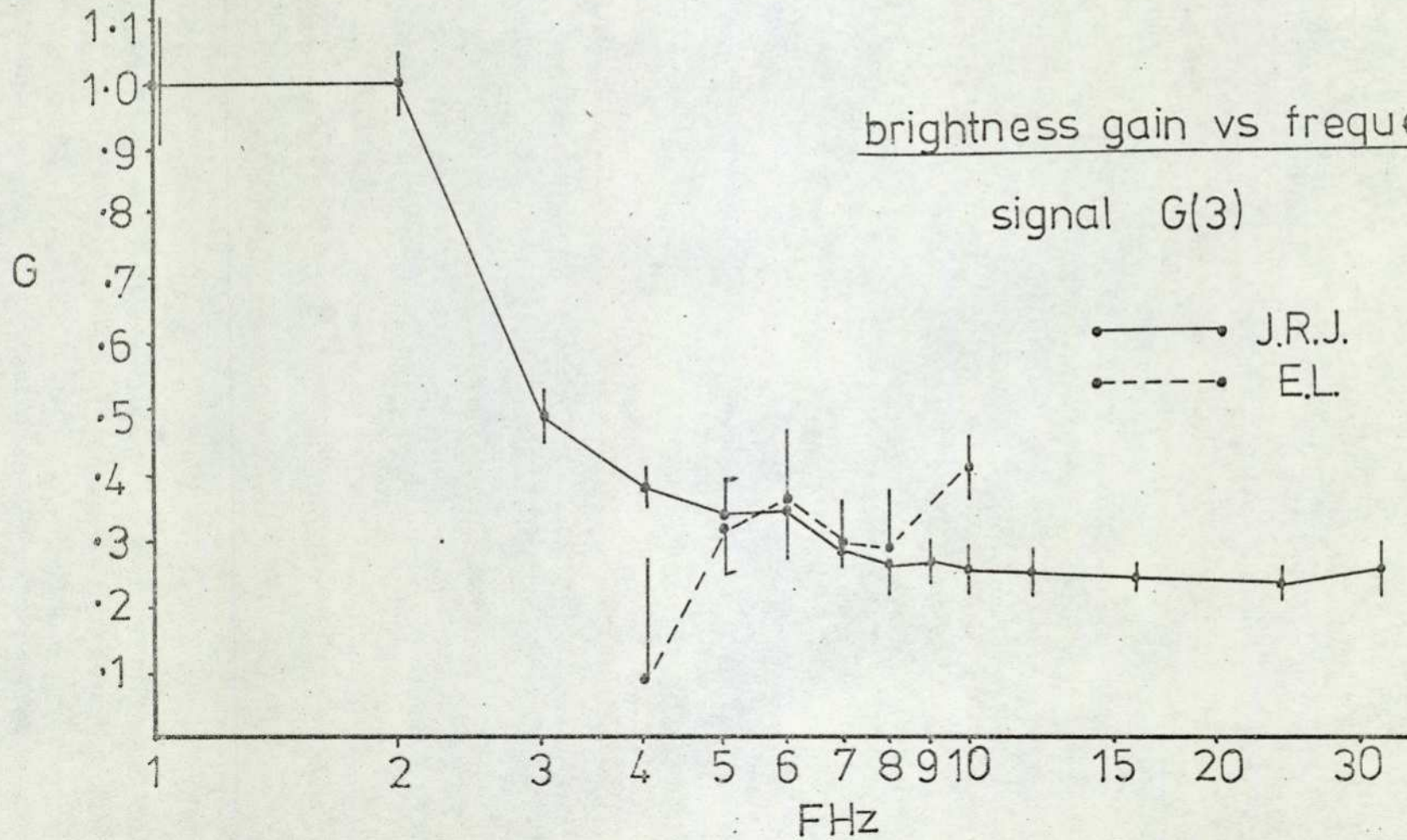


Fig 47a

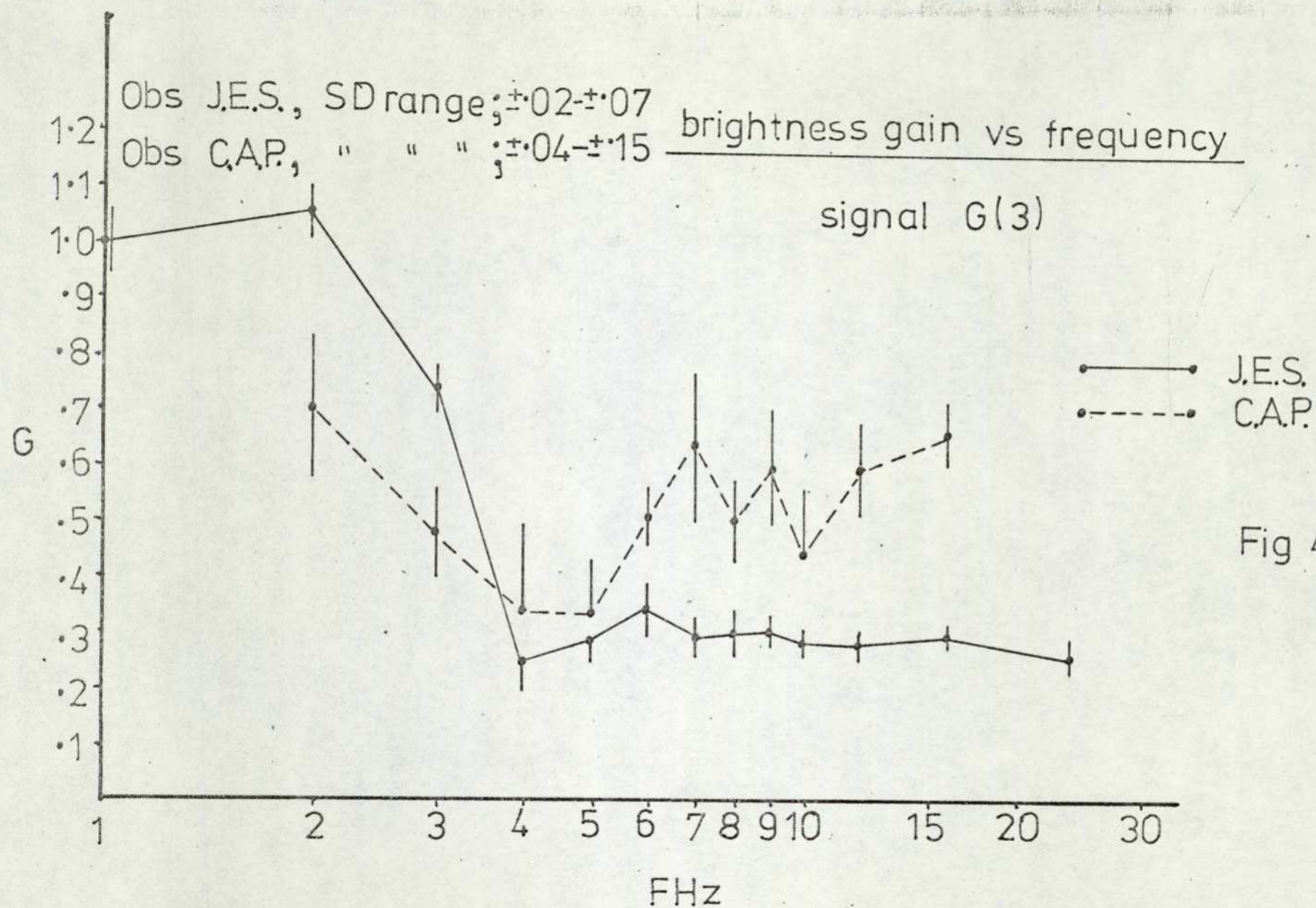


Fig 47b

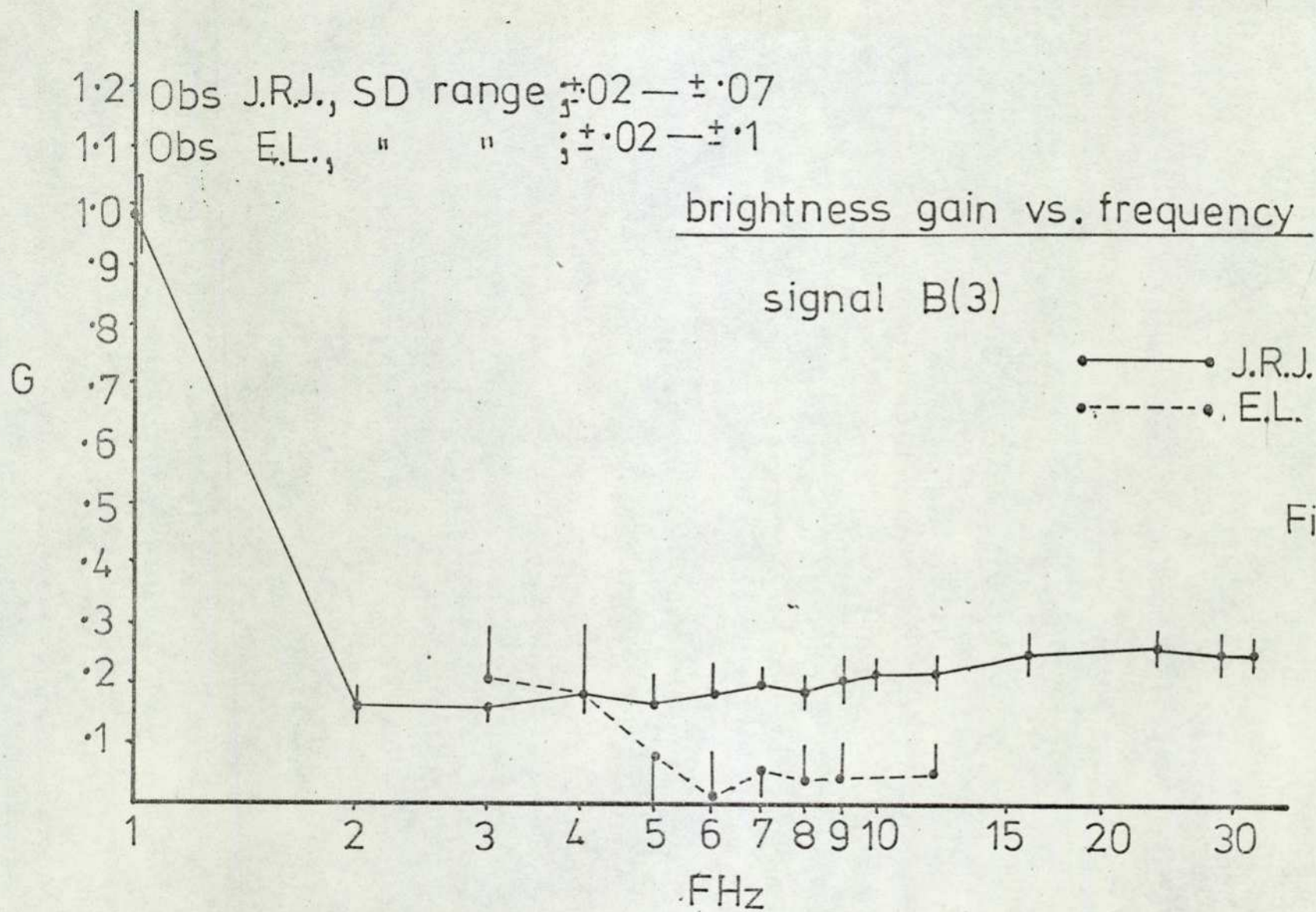


Fig 48a

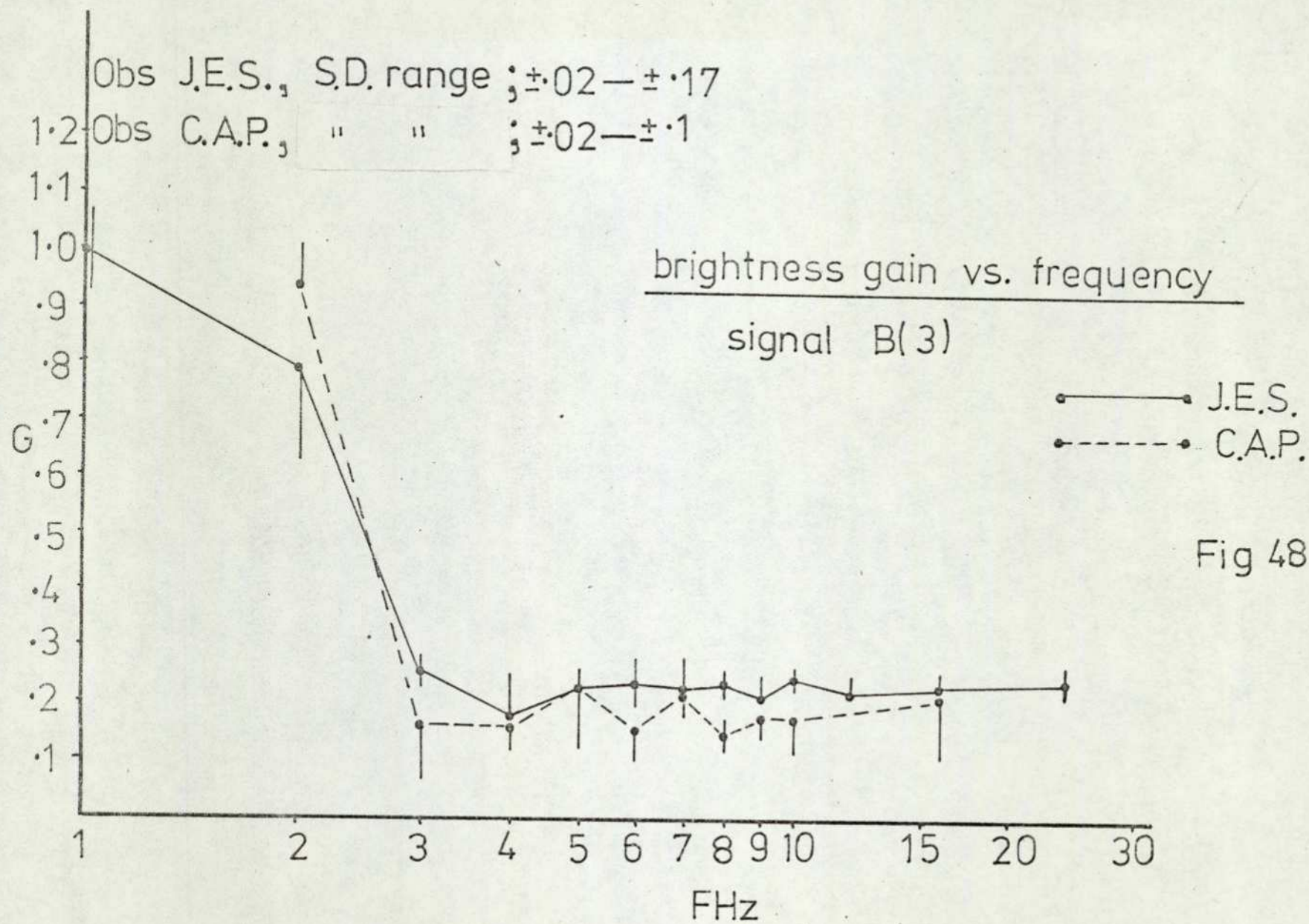


Fig 48b

TABLE 2

SIGNAL: R(3)

obs. f.Hz.	λd	J.R.J. COLOUR NAME	λd	J.E.S. COLOUR NAME	λd	C.A.P. COLOUR NAME	λd	E.L. COLOUR NAME
0	/	A	/	A	/	A	/	A
1	/	A	/	A	NO	DATA	NO	DATA
2	/	A	/	A	/	A	NO	DATA
3	582	A	591	A	579	Y-O	/	A
4	591	O	583	Y-O	579	Y-O	/	A
5	593	O	585	Y-O	582	Y-O	585	Y-O
6	593	O	591	A	582	Y-O	587	O
7	593	O	607	A	587	O	590	Y-O
8	593	O	607	A	593	O	590	A
9	595	O	591	O	603	O	587	Y-O
10	598	O	591	O	603	O	NO	DATA
12	615	O	591	A	593	O	590	A
16	615	O	607	A	700	A	NO	DATA
24	591	O	607	A	NO	DATA	NO	DATA
28	/	A	NO	DATA	NO	DATA	NO	DATA
32	/	A	NO	DATA	NO	DATA	NO	DATA

SIGNAL: G(3)

f.Hz.	λd	J.R.J. COLOUR NAME	λd	J.E.S. COLOUR NAME	λd	C.A.P. COLOUR NAME	λd	E.L. COLOUR NAME
1	/	A	/	A	NO	DATA	/	A
2	/	A	/	A	/	A	NO	DATA
3	/	A	572	G-Y	/	A	/	DATA
4	/	A	580	Y	518	A	570	A
5	585	Y-O	582	Y	582	A	584	Y-O
6	585	Y-O	580	Y	587	Y-O	584	Y-O
7	581	Y-O	582	Y-O	582	A	586	Y-O
8	583	Y-O	582	Y-O	582	A	592	O
9	585	Y-O	582	Y-O	587	Y-O	NO	DATA
10	585	Y-O	584	Y-O	587	Y-O	592	A
12	583	Y-O	586	Y-O	582	A	/	A
16	583	Y-O	584	Y-O	582	A	NO	DATA
24	583	Y-O	582	Y-O	NO	DATA	NO	DATA
28	NO	DATA	NO	DATA	NO	DATA	NO	DATA
32	583	Y-O	NO	DATA	NO	DATA	NO	DATA

SIGNAL: B(3)

obs. f.Hz.	λd	J.R.J. COLOUR NAME	λd	J.E.S. COLOUR NAME	λd	C.A.P. COLOUR NAME	λd	E.L. COLOUR NAME
1	/	A	/	A	NO	DATA	NO	DATA
2	586	Y-O	/	A	/	A	NO	DATA
3	626	A	400	A	568 ^C	P	/	A
4	568 ^C	O-P	468	A	575 ^C	PL-P	/	A
5	573 ^C	O-P	468	A	573 ^C	P	564 ^C	P
6	577 ^C	A	577 ^C	A	576 ^C	PL-P	NO	DATA
7	573 ^C	A	400	A	579 ^C	PL-P	575 ^C	P
8	573 ^C	A	468	A	579 ^C	PL-P	450	P
9	573 ^C	A	577 ^C	P	577	PL-P	450	P
10	577 ^C	A	400	A	577	PL-P	NO	DATA
12	/	A	468	A	573 ^C	P	450	P
16	/	A	468	A	575 ^C	PL-P	NO	DATA
24	626	A	468	A	NO	DATA	NO	DATA
28	/	A	NO	DATA	NO	DATA	NO	DATA
32	/	A	NO	DATA	NO	DATA	NO	DATA

KEY; λd = Dominant Wavelength.

f = frequency (Hz).

A = Achromatic, O = Orange, Y = Yellow, G = green, P = Pink, PL = Purple,

O-Y = orange-yellow, PL-P = purplish-pink.

EXPERIMENT 2 (A, B)AN INVESTIGATION OF FLICKER WAVEFORM AS A SUBJECTIVE
COLOUR INDUCING PARAMETER1) Expt. 2A An investigation of flicker waveform in a single intermittent
light sourcea. Introduction

It has been suggested that subjective colour of the type obtained from Benham's disc (Fechner-Benham (F-B) subjective colour), may be manifested in a single intermittent achromatic light source, where flicker waveform determines the colours seen. (FRY, 1933a, b, 1945, 1965; COLENBRANDER, 1933; ROELOFS and ZEEMAN, 1957; NELSON, 1971). A commonly held theory of F-B subjective colour (The "Morse Code" theory) is based on this fact, as was discussed in Chapter 1. The first experiment designed to test this theory directly, was carried out by FESTINGER, ALLYN and WHITE (1971), using a glow modulator tube to produce a variety of flicker waveforms in the stimulus. The results were considered to show that flicker waveform-dependent (F-B) subjective colours could be observed in a single achromatic light.

Since the glow modulator tube is probably unsuitable in such an experiment, due to the possibility of temporal changes in the spectral composition of the light output (see Chapter 1 and JARVIS, 1973), the postulate of flicker waveform-dependent (F-B) subjective colour (in a single light source) is re-investigated. The role of flicker waveform in a target-surround stimulus configuration is also examined (see Expt. 2B).

b. Apparatus and Methods

The apparatus of experiment 1 was employed, together with a series of computer-generated masks to provide the required temporal features of the stimulus. In this investigation two spatial stimulus configurations were used. The first was identical to that employed in experiment 1 (see figure 36), and the second consisted of a single rectangular target ($2.5^{\circ} \times 50'$), which replaced the three bars of the

grating. The longer edges of the rectangle were arranged vertically.

A target consisting of a single uniform field, of comparable dimensions to this rectangular bar target, was employed by Festinger et al in their investigation of waveform dependent subjective colour, from a single light source.

In this experiment thirteen flicker waveforms were investigated, including those suggested by Festinger et al as producing good subjective colour. The maximum retinal illuminance obtained from each target signal, and that from the constant surround were initially set at 4600 td and 650 td respectively, which are values similar to those employed by Festinger et al.

In order to achieve these values of illuminance, the T.R.F. lamps (S_1 and S_2) were run at a voltage slightly greater than the specified (12v) value. This, of course, changed the colour temperature of the lamps to a certain extent and this was not corrected for. The (0) point referred to in Chapter III (the steady condition point) was thus displaced further away from the standard illuminant A point on the C.I.E. diagram (see for example, figure 54).

Data were also collected with a maximum retinal illuminance of 1200 td provided by the target. The ratio of the maximum target retinal illuminance to that provided by the constant surround, was the same as for the other experimental condition viz. $1/7$.

Details of the temporal signals employed are shown in figure 49. Those marked (F) are those signals which Festinger et al suggested are inducers of F-B subjective colour. The other signals are variations of these and the expected subjective colour from each signal is marked; R, G, B, M, Y, C and N, representing red, green, blue, magenta, yellow, cyan and neutral (achromatic), respectively. The waveform mathematics of the Festinger (F) signals were inferred from the data supplied (see figure 18, Chapter 1). For further details of the temporal signals see figure 49, and Appendix 2 for details of the computer programs employed

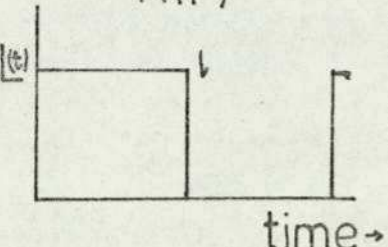
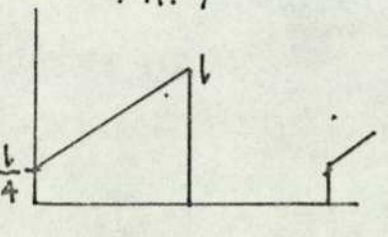
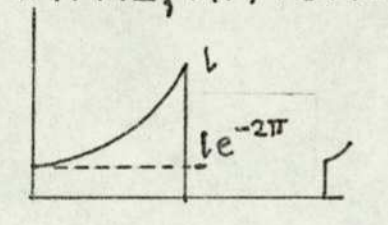
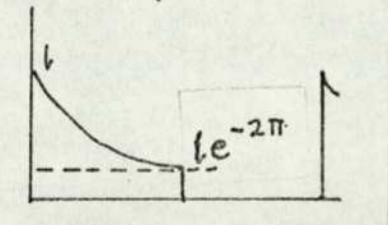
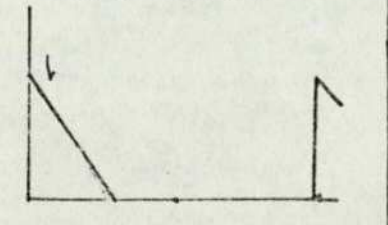
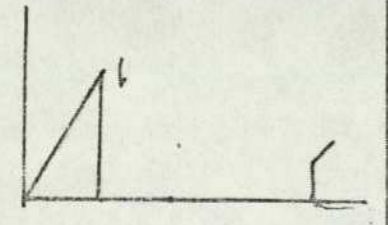
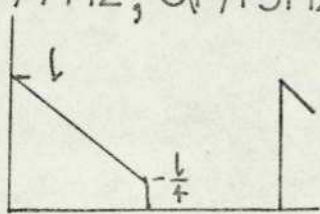
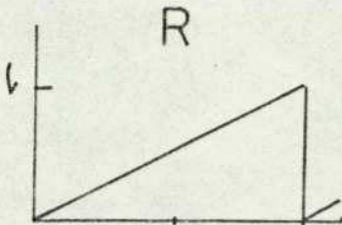
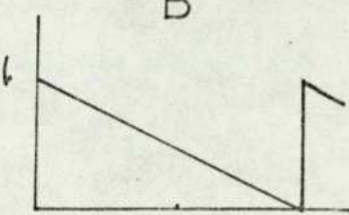
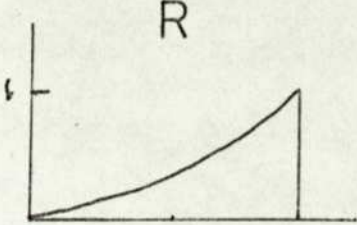
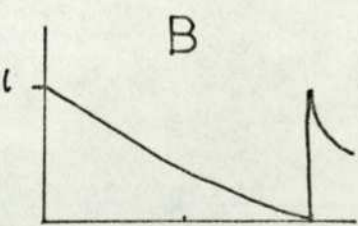
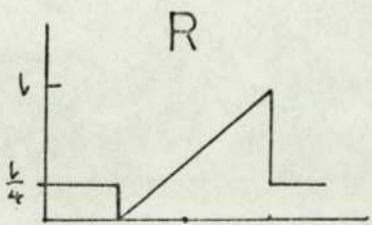
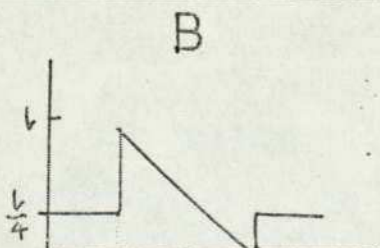
No	SIGNAL	DETAILS
1	N(F) 	SQ. WAVE, P.C.F. = $\frac{1}{2}$
2	M(F) 	RAMP, P.C.F. = $\frac{1}{2}$
3	R(F) 7Hz, Y(F) 15Hz 	$L(t) = l(\exp 2(wt - \pi))$ for first half of each cycle
4	B 	$L(t) = l(\exp(-2wt))$ for first half of each cycle
5	G(F) 15Hz 	RAMP, P.C.F. = $\frac{1}{4}$
6	Y 	RAMP, P.C.F. = $\frac{1}{4}$

Fig 49 Temporal signals used l - max luminance.

7		RAMP, P.C.F. = $\frac{1}{2}$
8		RAMP, P.C.F. = 1
9		RAMP, P.C.F. = 1
10		$L(t) = \frac{1}{5}l(4\exp(wt - 2\pi) + 1)$ over one cycle
11		$L t = \frac{1}{5}l(4\exp(-wt) + 1)$ over one cycle
12		RAMP, P.C.F. = $\frac{1}{2}$
13		RAMP, P.C.F. = $\frac{1}{2}$

For each of the two luminance levels tested, two flicker frequencies were employed viz 7Hz and 15Hz. The order of presentation of the signals was randomised and each experimental session involved data collected from all the signals for one target configuration and for one luminance level.

During initial experimental runs, both the observers (J.R.J. and C.A.P.) perceived moving blotches of colour in the stimulus field, particularly for the 4600 td stimuli. These blotches of colour appeared on an achromatic background. The matching task, following the observation of this phenomenon, was to measure these blotches of colour regardless of their spatial characteristics.

c. Results

Figure 50 (a, b) shows the data for both the observers with the rectangular bar target employed, the maximum retinal illuminance being 1200 td. All thirteen flicker waveforms were tested with observer J.R.J. and only waveforms classified as 1-7 in figure 49 were used with observer C.A.P. The (0) point refers to the colorimeter match made to the steady stimulus condition.

Each value of x and y shown in the figures represents the mean of four values calculated from the four groups of colorimeter readings (the same as in experiment 1). In fact, any value of x or y quoted, in this thesis, represents this mean value.

The standard deviations calculated for each determination of x and y are shown in figure 51 (a, b) for both observers. The data do not reveal any systematic flicker waveform-dependent subjective colour for both observers. According to KELLY (1943), the general location of all data points is in the achromatic-purple region of the chromaticity diagram i.e. the intermittent stimulus always appeared slightly purple compared with the steady condition.

Figure 52 shows the results for observer J.R.J. with the

grating target employed. All the data points are clustered around the steady condition point 0, and would be termed achromatic by Kelly. Note that there is a slight trend of the data toward the purple region of the chromaticity diagram. The standard deviation calculations are shown in figure 53b.

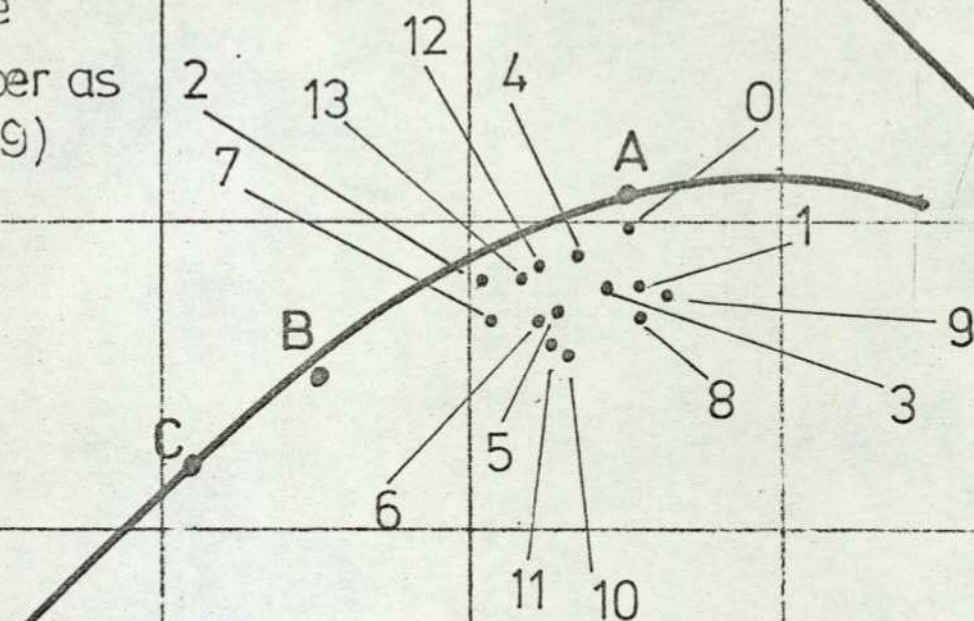
Figure 54 (a, b) shows the results for the 4600 td level, and with the bar target employed, for both observers. The flicker frequency employed for both observers was 7Hz. Data were also collected at 15Hz (observer J.R.J. only) as shown in this figure, and standard deviations are given in figure 55 (a, b) for the 7Hz condition and figure 53a for the 15Hz condition. The data for both observers show little systematic waveform effect in the subjective colours induced. The data are thus closely grouped for each observer, but the purple subjective colour induction was greater than for the 1200 td stimuli. (Note, however, that the steady condition point (0) is also shifted toward the blue-purple regions of the chromaticity diagram, due to the lamps operating at a higher colour temperature). These data (figures 50-55) are colour matches of the "purple blotches" effect noted by both observers.

The Festinger signals only, are considered in figure 56 (see again figure 18, Chapter 1). The data obtained from the Festinger et al study are shown together with the data obtained from observer J.R.J. Alongside each data point is indicated the predicted subjective colour. To see which signal a letter in figure 56 refers to, consult figure 49. The signal marked C (cyan), for example, is the signal 7 operating at 15Hz. Festinger et al presented their data on the C.I.E. (u, v) chromaticity diagram, thus to compare their data with the data obtained from experiment 2A, it was necessary to use the transform equations given below¹⁵. The Festinger et al values of x and y shown in figure 56, represent the mean values obtained from the data of the four observers used in their study. This was done since the data of each observer showed

Fig 50 Colours evoked from the temporal signals

(figures denote
stimulus number as
shown in fig 49)

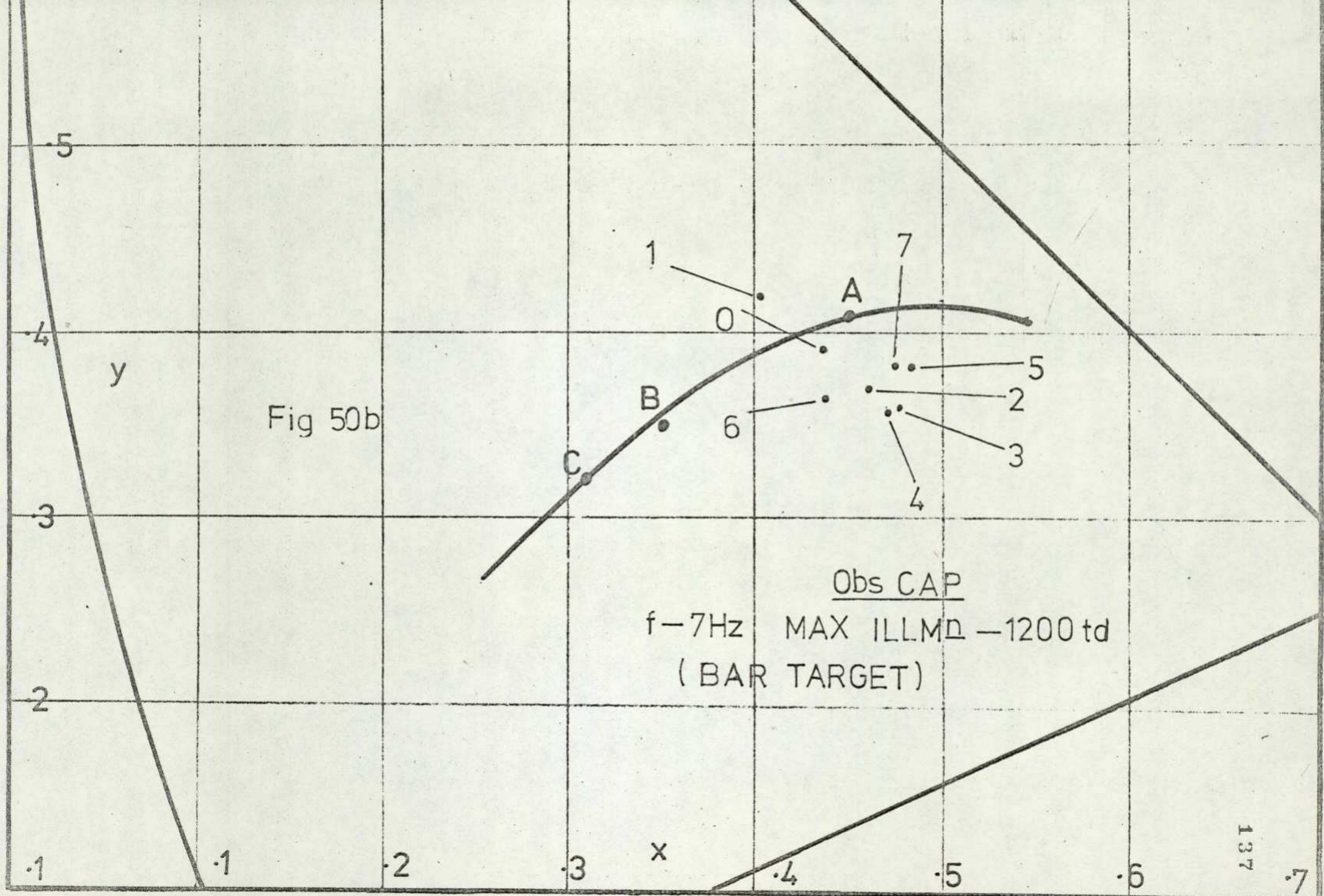
Fig 50 a



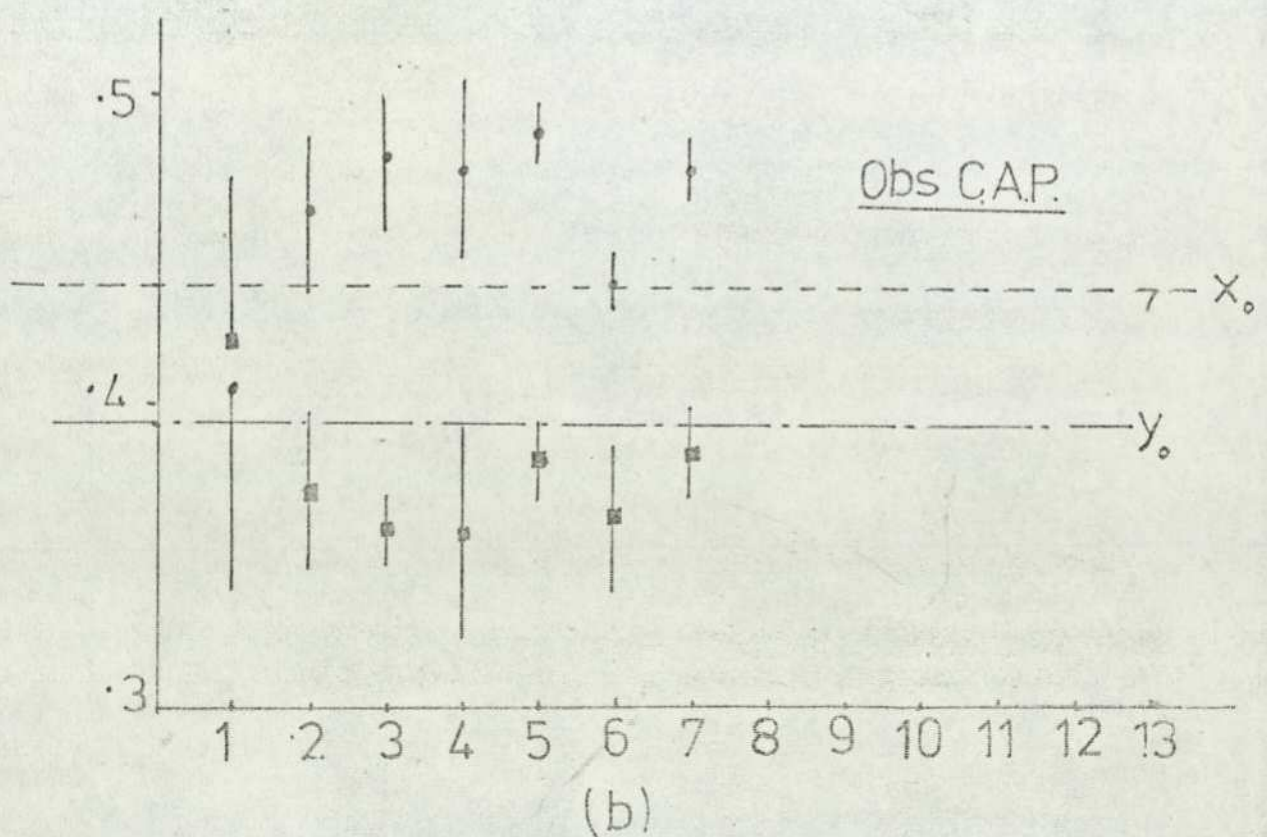
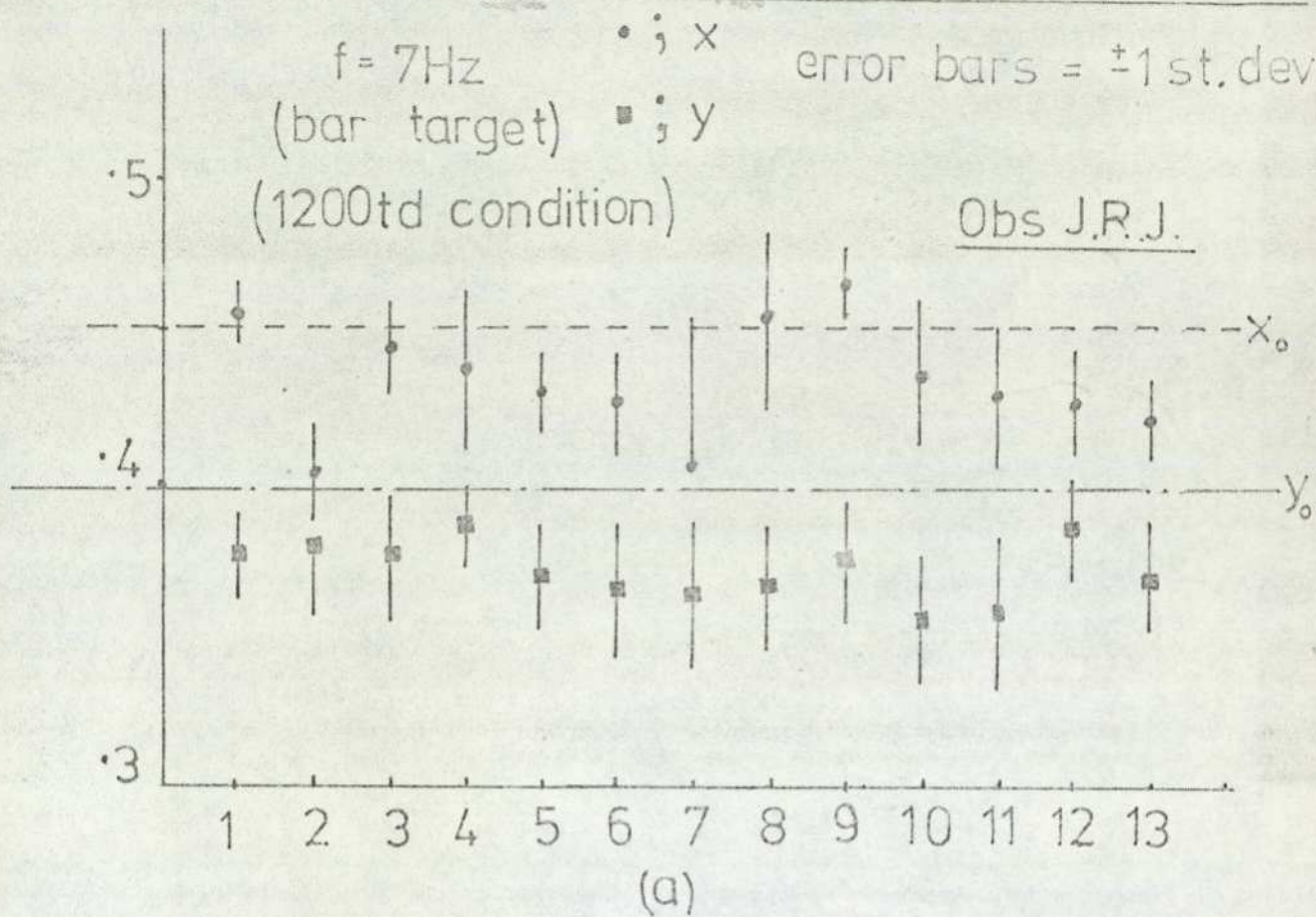
Obs JRJ

f-7Hz MAX ILLM Δ - 1200td

(BAR TARGET)



CIÉ(x,y) chromaticity coordinates vs. signal no.



x_0, y_0 refer to the 'steady condition' (0)

Fig. 52 Colours evoked from the
temporal signals

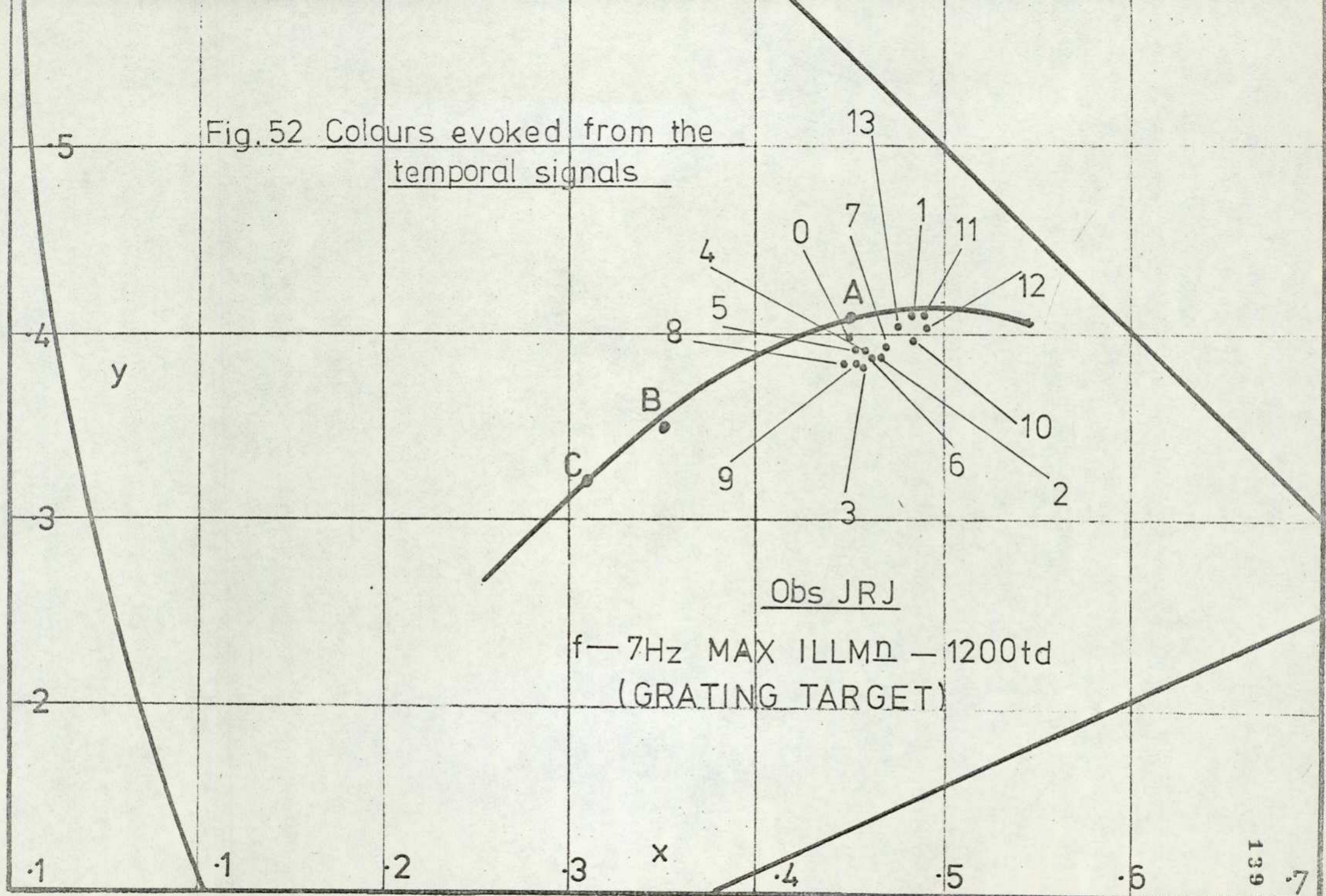


Fig. 53
CIE Chromaticity coordinates vs. signal no

•; x •; y — error bars - ± 1 st. dev.

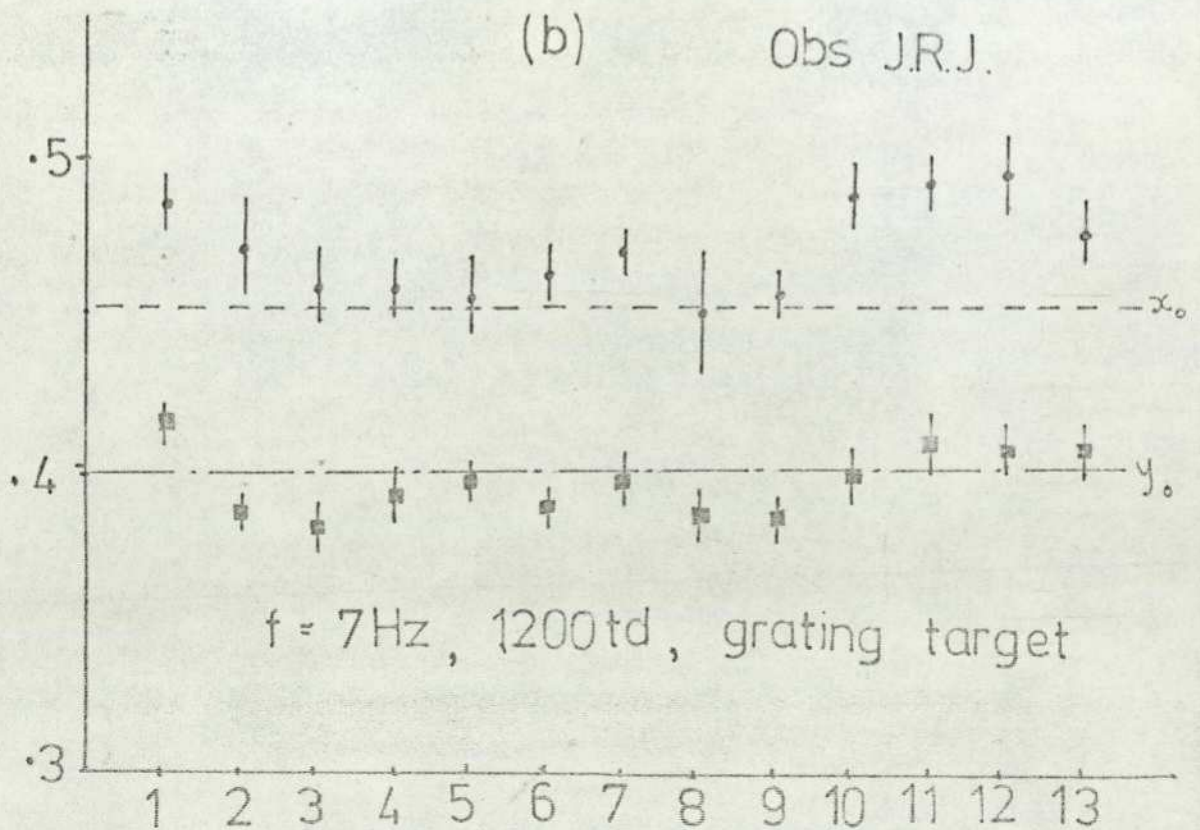
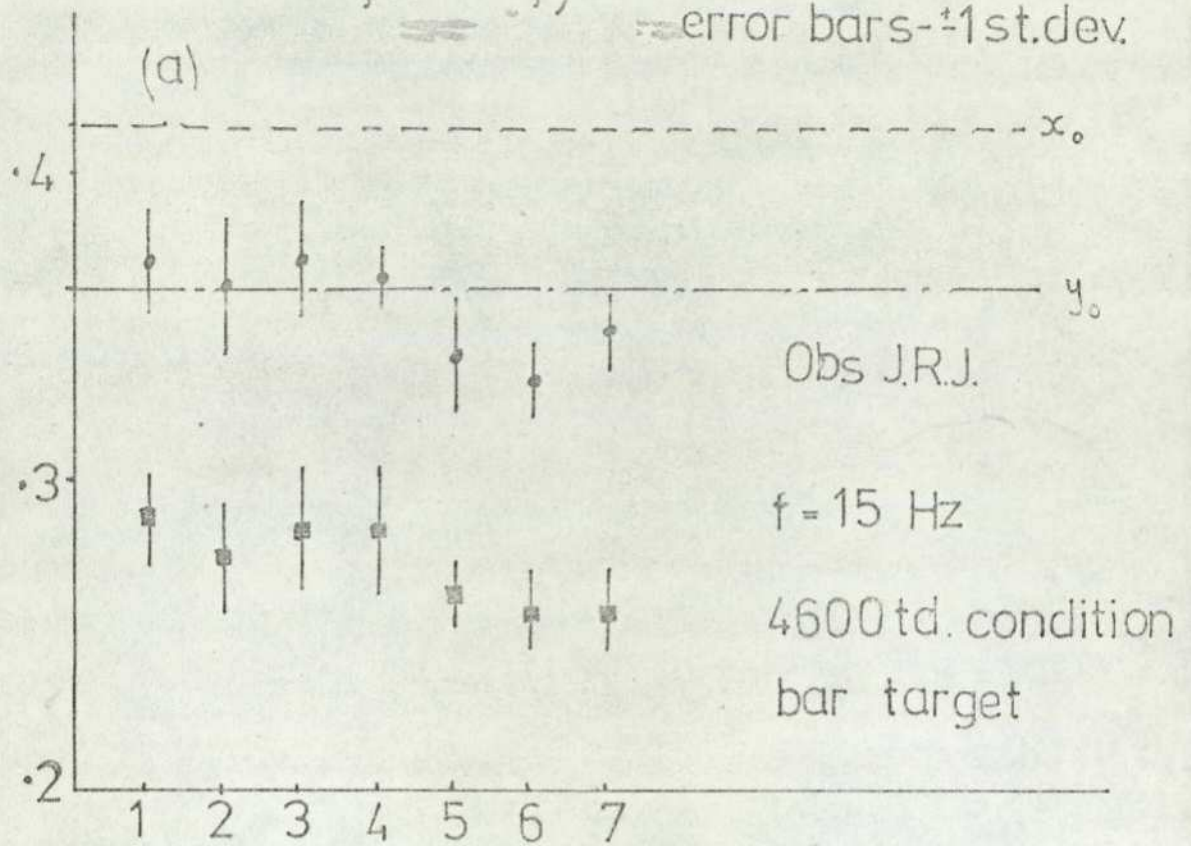


Fig. 54 Colours evoked from the temporal signals

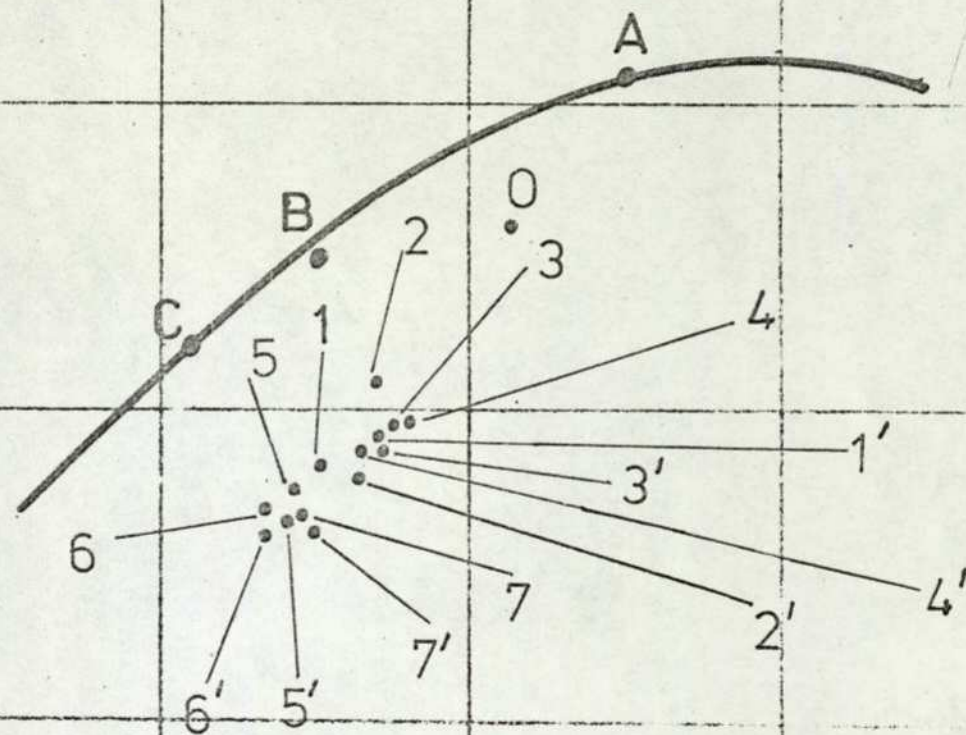
Obs JRJ

MAX ILLMD — 4600 td

7 Hz — X
15 Hz — X'

y (BAR TARGET)

Fig 54a



Obs CAP

f—7Hz MAX ILLM Δ — 4600 td
(BAR TARGET)

Fig 54b

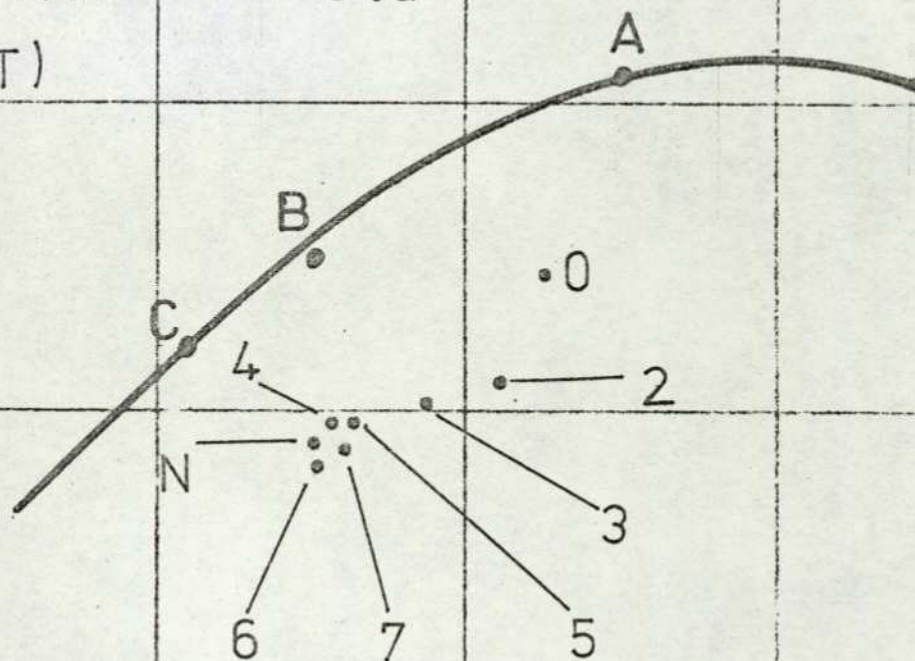


Fig 55

CIE Chromaticity coordinates vs. signal n°

•; x

■; y

f=7Hz, 4600 td condition

error bars ± 1 st. dev.

bar target

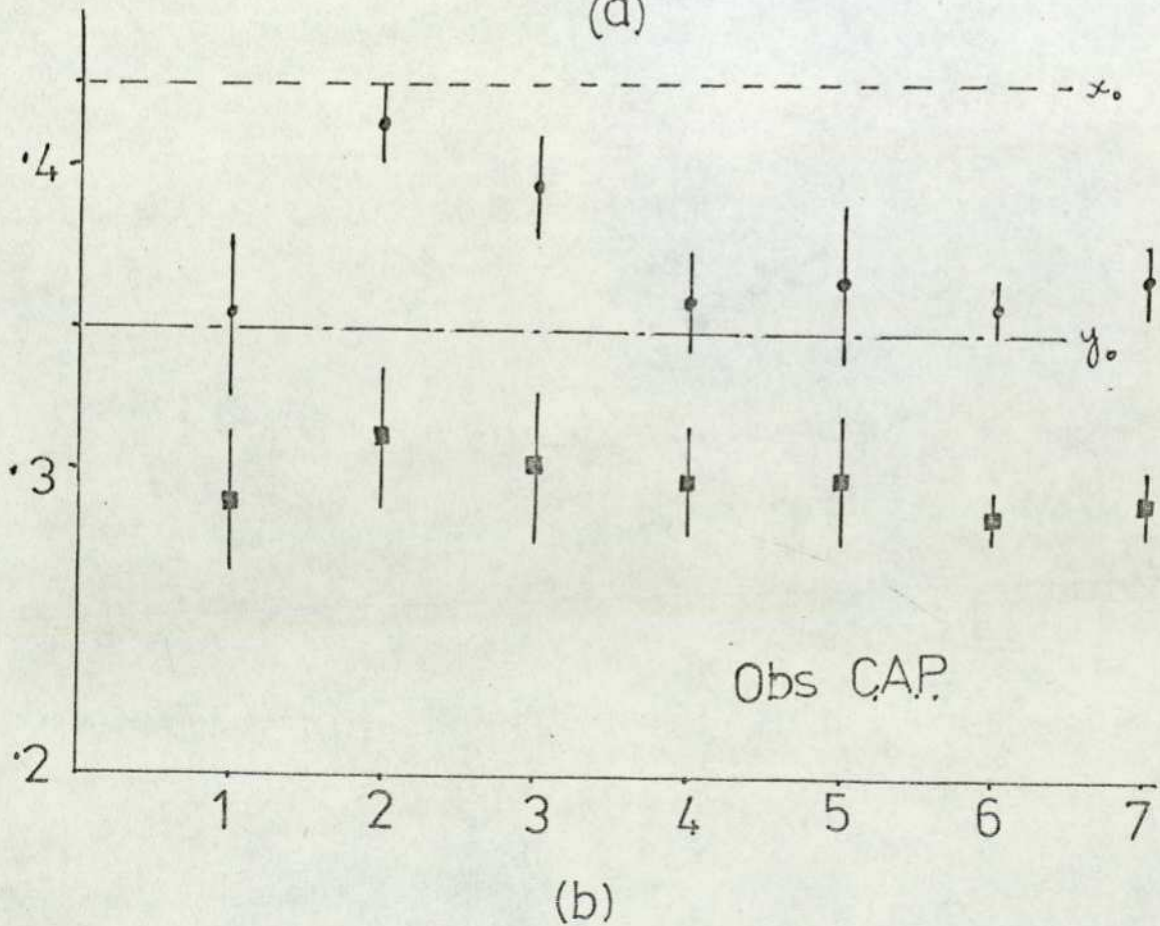
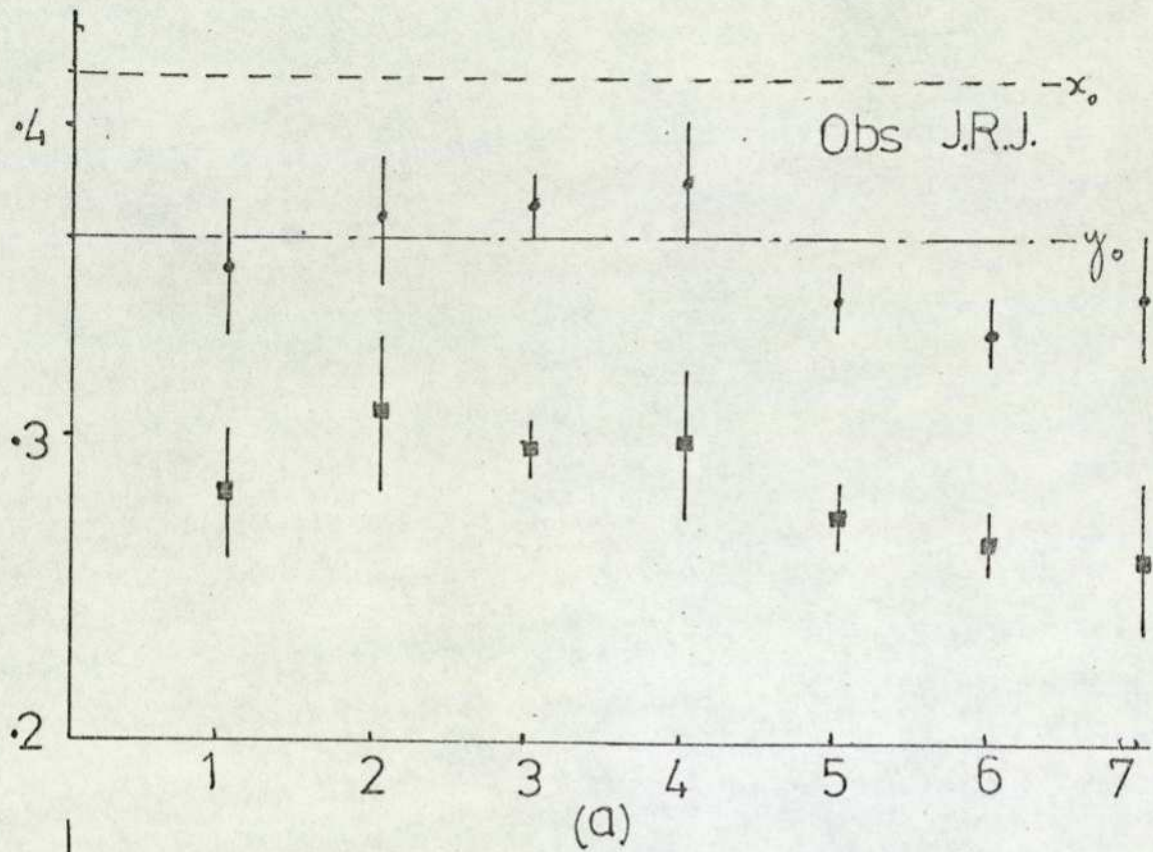
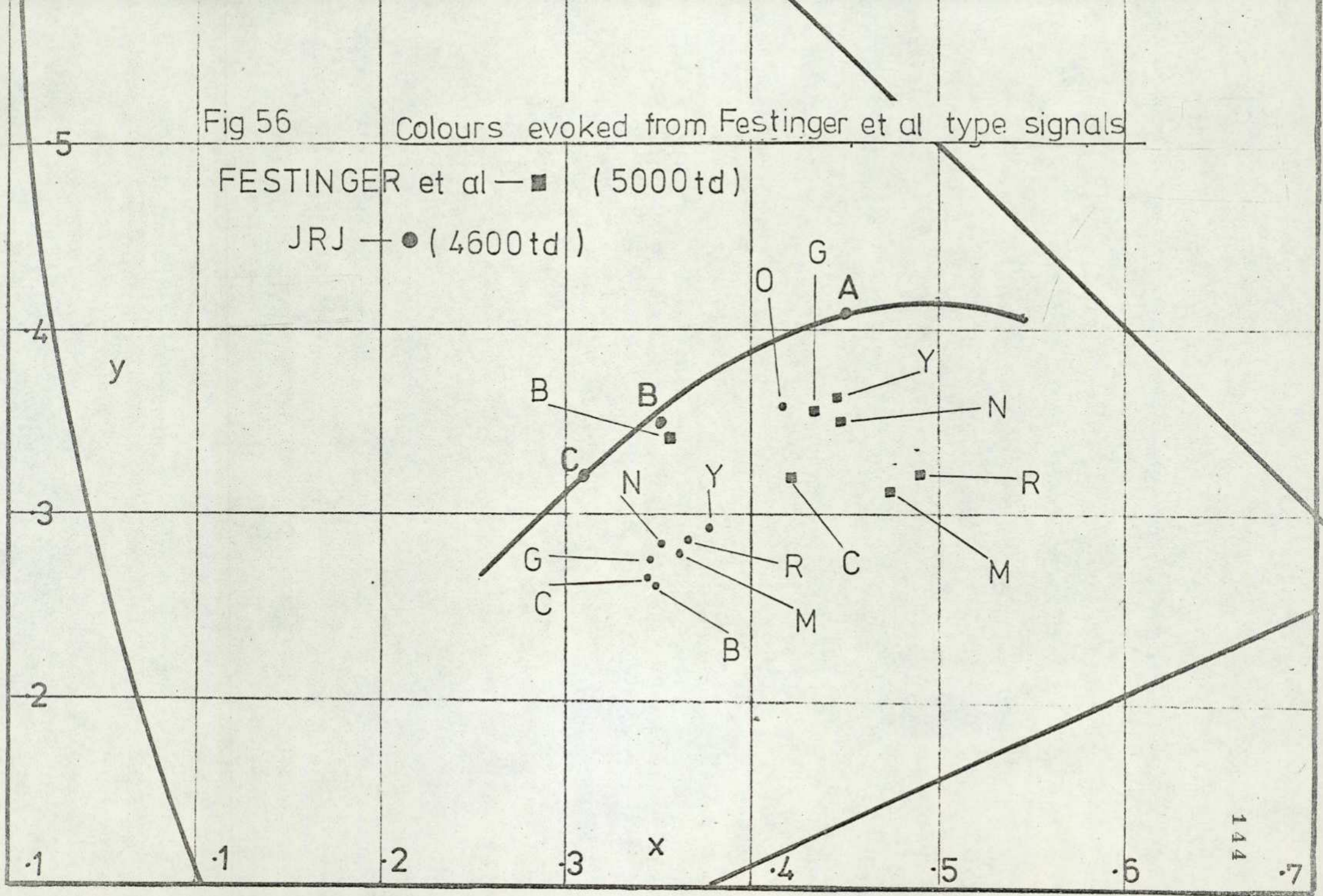


Fig 56

Colours evoked from Festinger et al type signals

FESTINGER et al —■ (5000td)

JRJ —● (4600td)



similar waveform trends in the colour matches. Note that the subjective colours claimed to have been observed in the Festinger et al study are somewhat unjustified. Also, the steady condition chromatic appearance of the stimulus was not specified by these authors. Flicker waveform-dependent subjective colours, obtained from a single intermittent achromatic light, are clearly only evident in the Festinger data.

d. Discussion

Some of the differences between data points in figures 50-55 may be explained from a consideration of the subjective colour effects which occur in a single intermittent coloured light. These effects include a hue shift (VAN DER HORST and MUIS, 1969; NILSSON and NELSON, 1971; NILSSON, 1972) and desaturation (BALL, 1964; BARTLEY and BALL, 1969) of the coloured light source. Furthermore, all these changes are influenced by both P.C.F. (BALL, 1964) and stimulus luminance (VAN DER HORST and MUIS, 1969). These facts may explain the differences in the data between signals where the P.C.F. of time averaged luminance differs. Signals, identical with respect to these two quantities (for example signals (2 and 7) and (3 and 4) in figure 50a) tend to plot close together. Apart from these small effects in the results of this experiment, there is no production of the variety of subjective colours found in experiment 1.

In general, therefore, the results cast serious doubt on the "Morse Code" theory of F-B subjective colour. They also add support to the suggestion made by JARVIS (1973) and in Chapter 1, that the glow modulator tube is unsuitable as a white light modulator. The waveform-dependent subject colours observed by Festinger et al may well be objective colour artefacts, coming from the Sylvania R1131C glow modulator tube employed.

The purple subjective colour has been observed before in an intermittent achromatic light (see, for example, PIGGINS, KINGHAM and HOLMES (1972)). This "purple effect" probably involves different visual mechanisms to those concerned with F-B subjective colour, for the following reasons;

- (i) The results of this experiment indicate that the optimum conditions for the manifestation of the purple effect involve retinal illuminances higher than those required for optimum F-B subjective colour induction. (The experimental results suggest 4600 td or above, for the former and the results of experiment 1, about 1200 td for the latter).

FOOTNOTE 15; The transform equations are;

$$u = \frac{4x}{-2x+12y+3}, \quad v = \frac{6y}{-2x+12y+3}$$

(ii) The "purple effect" appears to have a completely different spatial distribution compared with F-B subjective colour, which as discussed in Chapter 1, often appears to cling to a black-white boundary in the stimulus field, bearing a similarity to the Mach band phenomenon (see CAMPENHAUSEN, 1968a; HASEGAWA, 1971). The "purple effect" on the other hand, is confined to blotches of colour which appear to move around the central regions of the stimulus field, whilst the border regions of the field appear achromatic. The data for observer J.R.J. shown in figures 50a and 52 illustrate the fact that the effect is slightly greater in the larger bar target than in the grating target. Most of the experiments on Benham's disc have suggested that narrow grating type targets produce near optimum spatial conditions for F-B subjective colour. (contd overleaf)

The possibility that the purple effect involves a positive after-image in its manifestation is not considered. First, it is important to realize that the visual responses occur following a stimulus consisting of a bright spot or light flash. The response is the perception of a white flash, and the other is a positive after-image which is perceived at the cessation of the light flash. The luminosity and colour properties of this after-image persist and change over a considerable period of time (often up to 75 minutes, if the light flash is intense enough (PANDHAR, 1958)). For a flickering stimulus, it is conceivable that at a certain frequency is suggested, these two responses may be produced a perception similar to that resulting from a mixture of two lights, one achromatic and the other similar in colour to the initial phase of the after-image. A similar visual process, in fact, is that which occurs when the critical colour flicker frequency is approached for two separately coloured lights (see for example, de LANGE, 1952b). To explain the purple effect in this manner, would require the initial chromaticity of the positive after-image, following each flash, to be purple. PANDHAR (1958), has shown that for a positive after-image formed from very bright achromatic (standard illuminant A) light flashes, the after-image chromaticity changes

Apart from these speculations on the "purple effect", it is difficult to form any conclusions from the experimental data, concerning the visual mechanisms responsible. However, the pertinent finding with respect to this effect, is that it is most likely not a manifestation of F-B subjective colour, which is the main phenomenon of interest.

In conclusion, therefore, the data of this experiment support the suggestion made by CAMPENHAUSEN (1968a), that both an intermittent target and surround region in the stimulus field are necessary to produce the full gamut of F-B subjective colour.

2) Expt. 2B An investigation of flicker waveform in both target and surround regions of the grating stimulus

a. Introduction

The possibility that F-B subjective colour is flicker-waveform dependent within an intermittent target-surround stimulus configuration was investigated. The results given are the main findings of this exploratory experiment, which employed the stimulus shown in figure 36, viz the three bar grating target. The stimulus waveforms, from which data were collected, are shown in figure 57 (The signals R(3), G(3) and B(3) are not shown, since they have already been discussed in Chapter 3). Note that the target waveform in some cases was the same as in the investigation of subjective colour from a single intermittent light. In this experiment, the surround is flickered as well. The colour appearance of the grating bars, with a temporal frequency of 7Hz employed (for both target and surround, with the phase relationship as indicated) was measured, for each of the signals. The maximum retinal illuminance obtained from each signal was 1200 td.

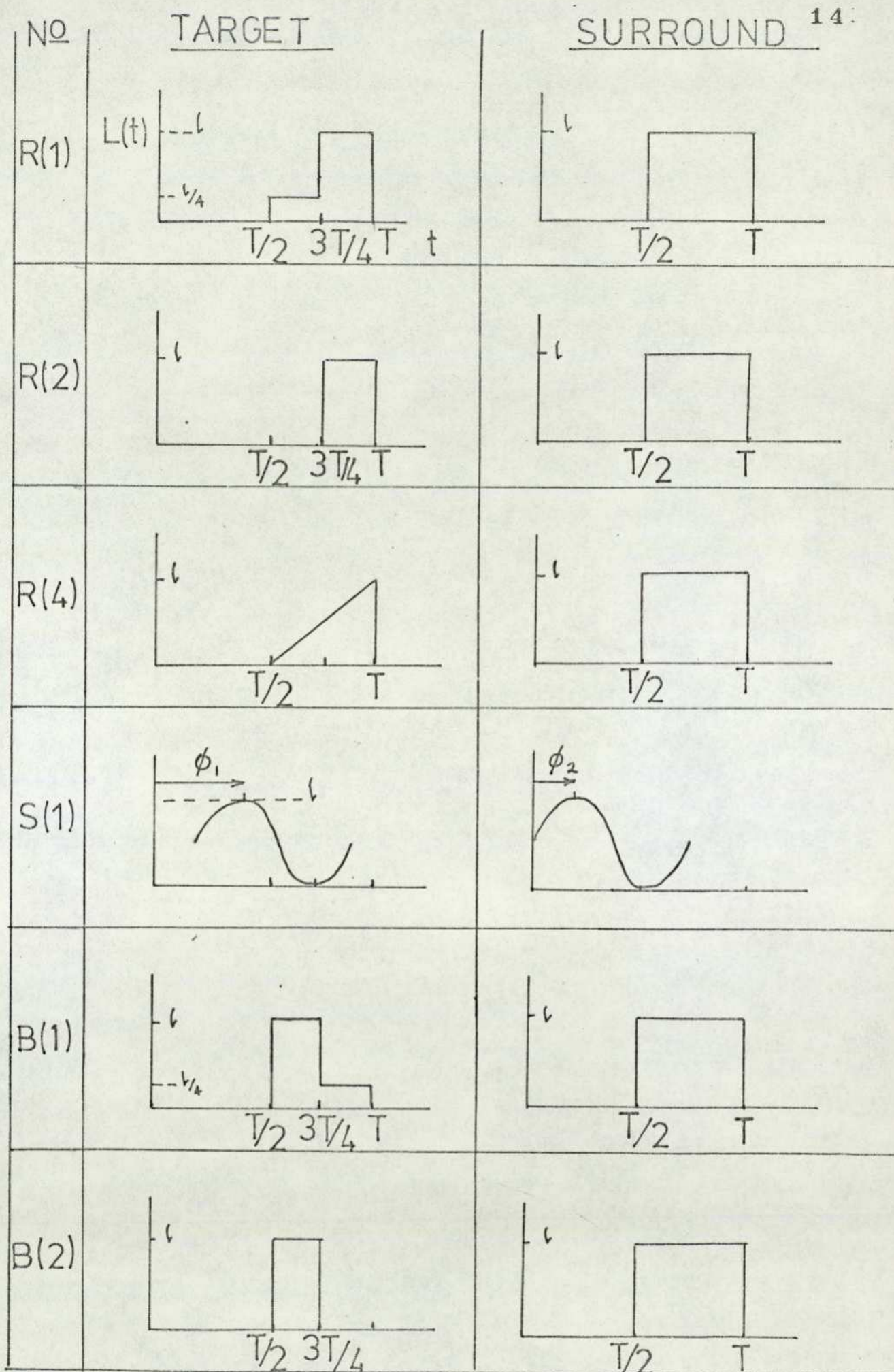
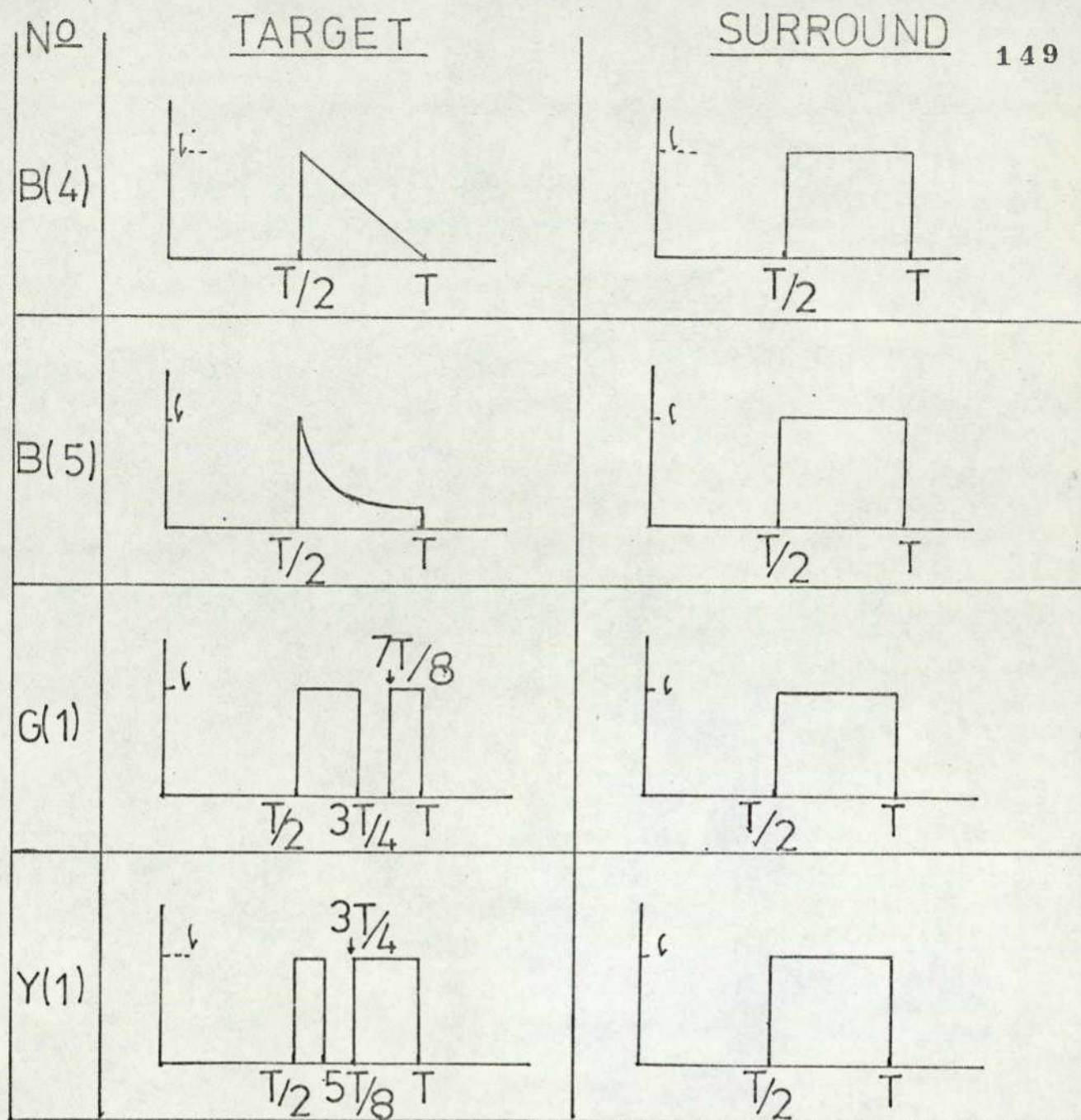


Fig 57



KEY; t - time
 T - periodic time
 l - max. luminance

Fig 57 Temporal signals used

Although a large variety of stimulus waveforms were utilized in both target (the three bars) and surround regions of the stimulus, the results for the waveforms given in figure 57 reveal the main effects, for the phase relationship employed. None of the predicted green inducing signals produced this colour in any really convincing manner. When the target and surround waveforms were changed over, the colour, as was expected, now appeared in the two gaps between the three bars of the grating.

For ~~most~~ other waveform combinations not including a square pulse sequence as one component, (e.g. Two ramp waveforms) no subjective colour effects were judged to appear and as a consequence, no colour matches were made. For the signals given in figure 57, the measurements of the colour appearance of the grating bars are shown in figure 58, for both the observers employed (J.R.J. and C.A.P.). For observer J.R.J., the results of experiment 1 for the R(3) and B(3) signals (7Hz) have been shown as well, and the subjective colour perceived with all the R signals was similar, being orange. The B signals all produced subjective colour data on the blue and purple sides of the (0) steady condition point, for this observer. The G and Y signals plot in the same general location of the chromaticity diagram, (yellowish-orange) for both observers. The R and B data for observer C.A.P. show a similar, if not as pronounced trend, to those of observer J.R.J.

The stimuli shown as S(1), in figure 57, are expressed mathematically, as;

$$L(t) = 0.51 (1 + \sin 2\pi ft) \text{ ————— } 10.$$

for the target signal,

$$\text{and} \quad L(t) = 0.51 (1 + \sin (2\pi ft + \phi)) \text{ ————— } 11.$$

for the surround signal, where $f = 7\text{Hz}$.

The chromaticity of the grating bars was measured for ϕ taking a range of values from 0° to 120° (surround leading target) and from 0° to

Fig 58 Colours evoked

• — Obs J R J Obs CAP — ■

f — 7 Hz MAX ILLUM — 1200 td

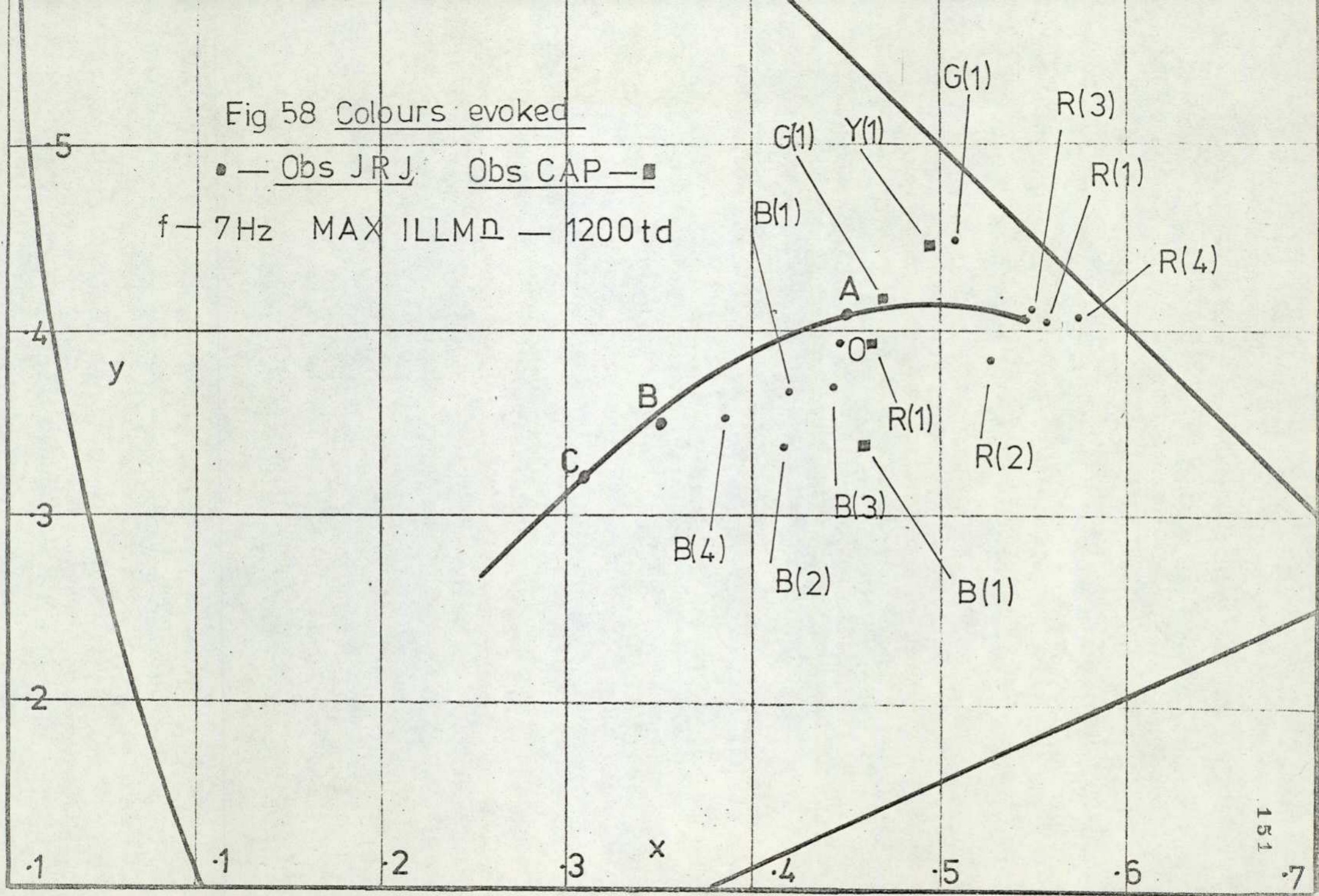


Fig 59

ADJACENT SINUSOIDS

• — Surround leads target

■ — " " lags on " "

O_s — Steady condition

Obs JRJ

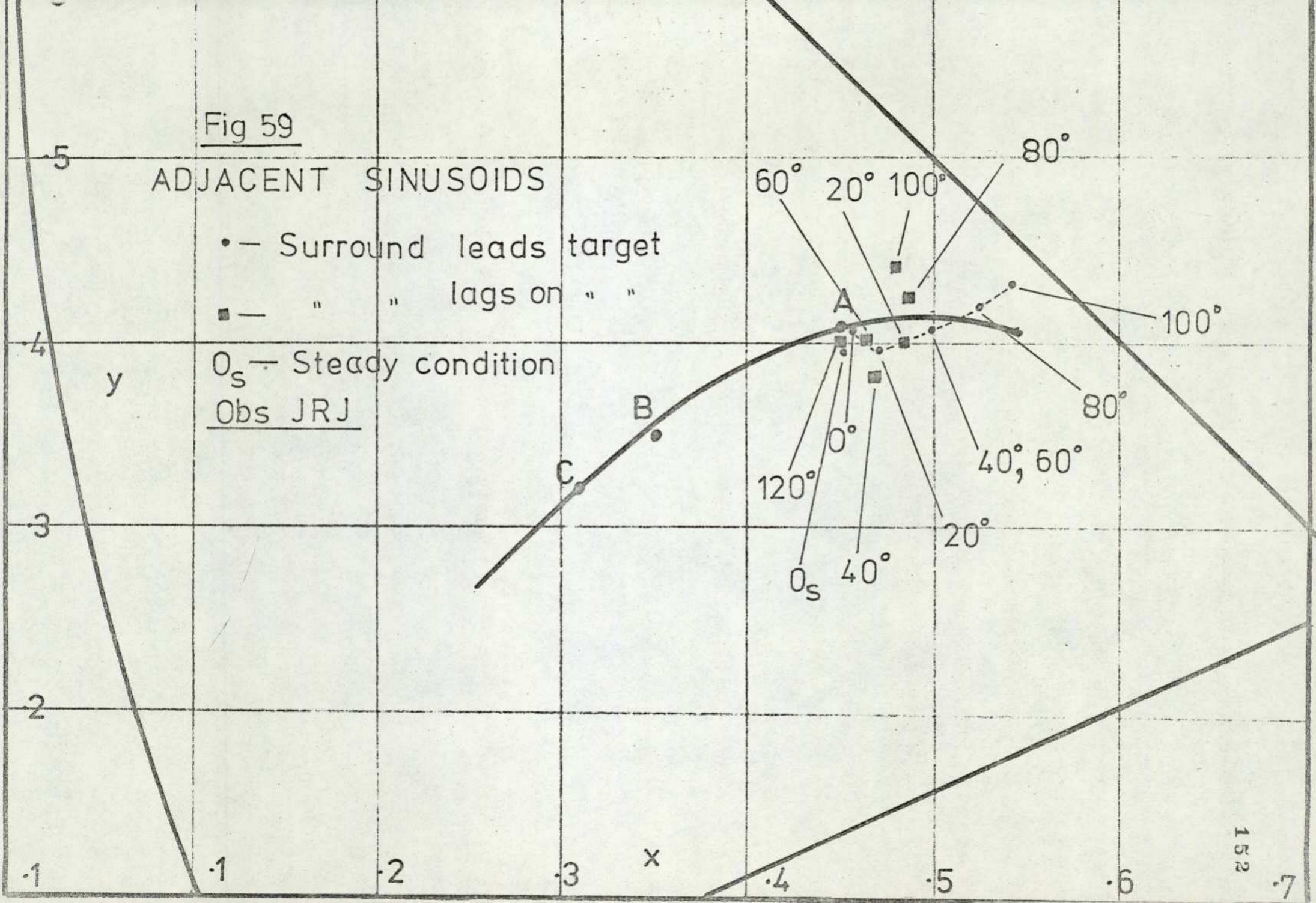
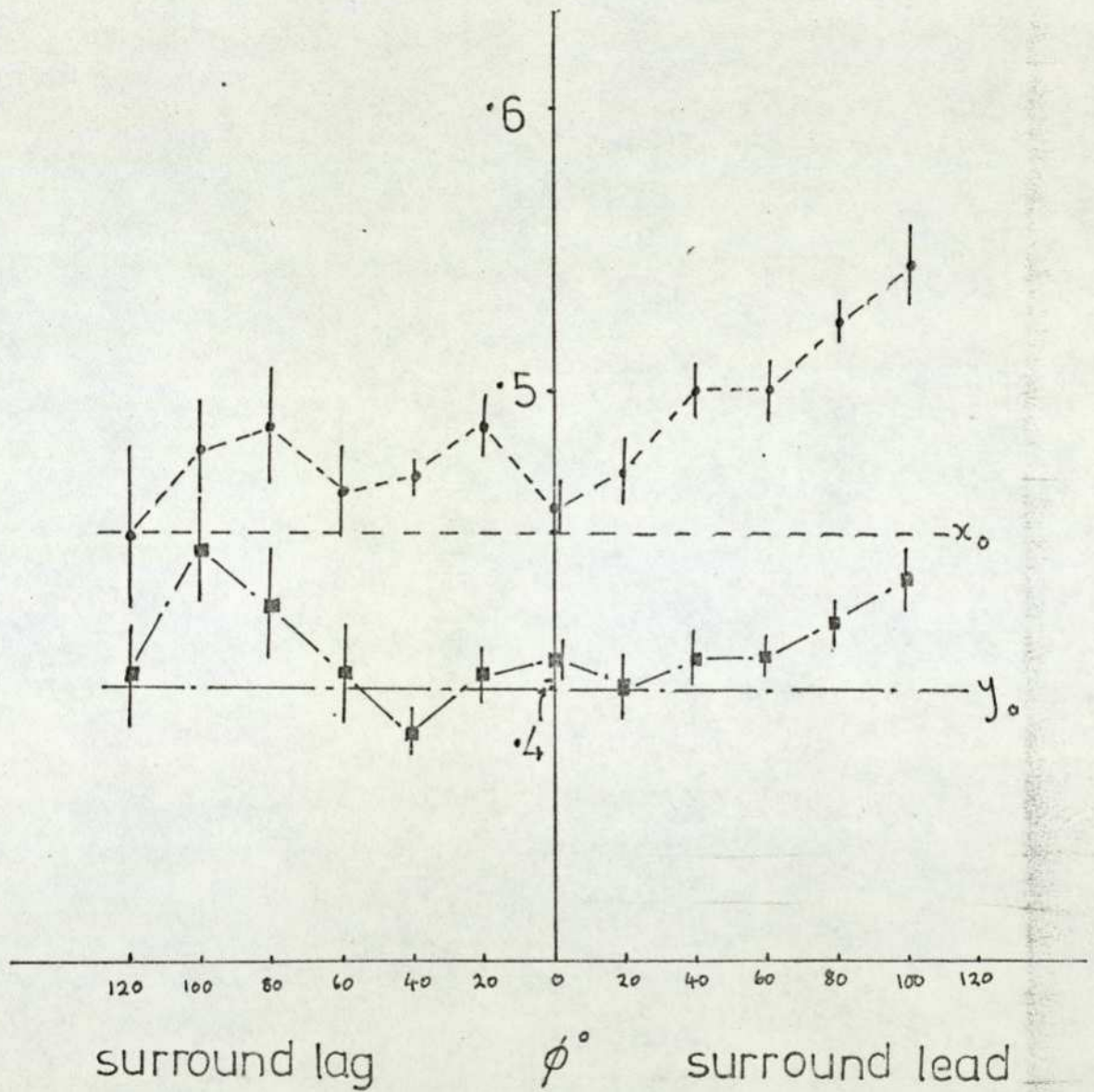


Fig. 60

CIE Chromaticity coordinates vs. phase angle
(signal S(1))

•; x ■; y

error bars ± 1 st. dev.



-120° (surround lagging on target). The results are shown in figure 59.

Measurements made outside these ranges of ϕ were unreliable and extreme difficulty was experienced in obtaining any match at values of ϕ near 180° . Order of presentation of each signal (variable ϕ) was randomised. A noticeable feature of figure 59, is the trend of the data points into the orange region of the chromaticity diagram for values of ϕ in the range 0° to 100° . Thus, for a lead of the surround on the target, for these ϕ values, it appears that F-B subjective colour was induced (in the target). Standard deviations are shown in figure 60.

c. Discussion

The data obtained from the achromatic sinusoidal waveform investigation may explain, in terms of F-B subjective colour induction, the extra hue shifts¹⁶ observed by BIJL and VERINGA (1971) in a sinusoidally flickering orange target, when a second flickering target was placed spatially adjacent, i.e. the total measured hue shift may have been produced from a manifestation of F-B subjective colour occurring as well as the subjective hue shift which is known to occur in a single intermittent coloured light. (The details of the stimuli employed by Bijl and Veringa were similar to the sinusoids employed in this experiment, in that they had the same maximum luminance, same modulation depth (100 per cent) and the flicker frequency was 12Hz). Bijl and Veringa found, in fact, that a large hue shift toward the red occurred in one of their intermittent light sources, when this had a phase lag of about 90° on the surrounding light source. This phase relationship was found to produce good subjective colour induction from the stimuli employed on observer J.R.J.

If now, a single cycle of the target and surround components of the R stimuli shown in figure 57 are studied, a common feature is revealed; the maximum luminance of the target component occurs toward the end of the cycle and coincides, in time, with the final part of the surround pulse. A similar state of affairs exists for the B signals, only now the maximum luminance in the target component coincides, in time, with the

beginning of the surround pulse.

It seems a plausible postulate, that the production of F-B subjective colour may well be determined by the interaction of the neural responses following a single target light pulse and a single adjacent surround light pulse, (both of rectangular profile) the temporal separation of these determining the subjective colour perceived. Chapter V is concerned with an investigation of this idea.

FOOTNOTE 16; The hue shifts observed by these authors were often greater than those normally associated with a single, flickering coloured light (see the previous discussion in this Chapter).

EXPERIMENT 3AN INVESTIGATION OF FECHNER-BENHAM SUBJECTIVE COLOUR FROMTWO ACHROMATIC LIGHT PULSESa) Introduction

PIERON (1957), in his development of the "Fechnerian theory" of the colours observed on a Benham's disc, suggested that the phenomenon is produced from a single achromatic light pulse. The results of experiment 2 (A, B) show both that;

i) Fechner-Benham (F-B) subjective colour cannot be produced from a single intermittent achromatic light.

ii) At least two light pulses are required, being spatially adjacent in the stimulus field.

In the discussion of experiment 2B, the idea was raised that a full gamut of subjective colours may be obtainable from a stimulus comprising a single adjacent light pulses, of simple rectangular profile, the temporal separation of these determining the colour sensation aroused i.e. for red subjective colour the target pulse onset occurs near the cessation of the surround pulse and for blue induction, the target pulse onset occurs near the onset of the surround pulse. Following this deduction, green may be produced from a target pulse occurring simultaneously with the middle part of the surround pulse. One of the main aims of this experiment is to explore these possibilities, using appropriate two-pulse stimuli.

b) Apparatus and Methods

The apparatus used was the same as in experiments 1 and 2, but in addition a small shutter placed in front of the observer's right eye was incorporated, to obtain single pulses from the flickering stimuli provided from the modulator channels. The shutter motor was operated by a microswitch, which together with its triggering mechanism are shown in figure 61. The cog shown, meshes with a smaller cog fixed to the rotating

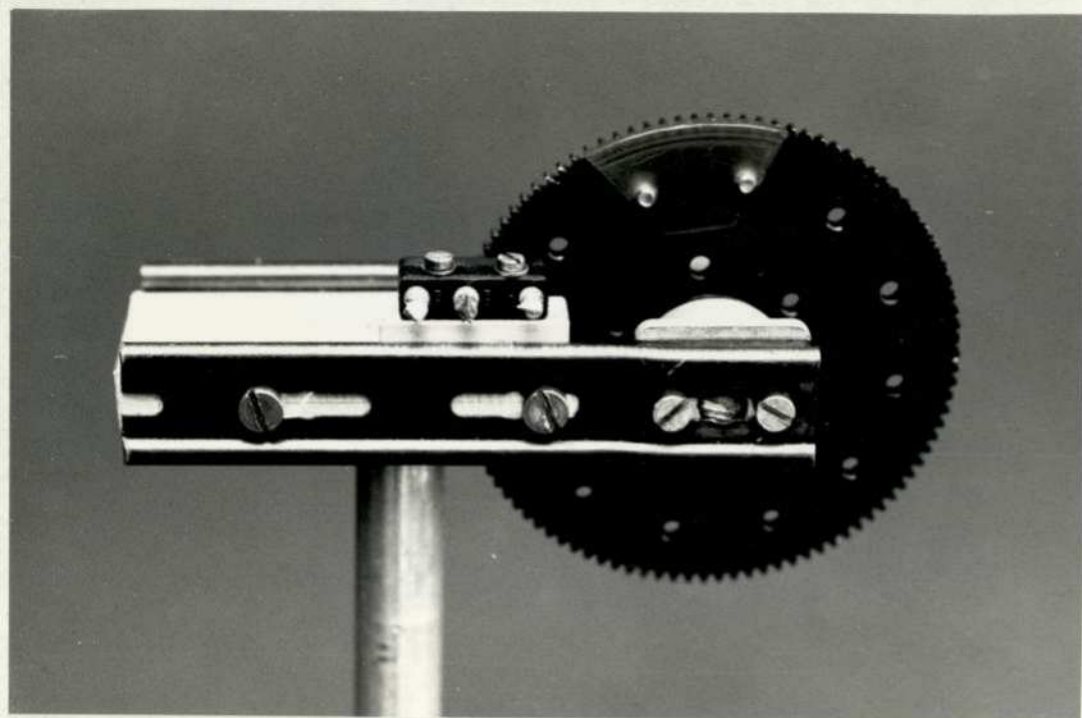


Fig 61 Trigger mechanism for the shutter

stepper motor axle. The small plastic fillet shown attached to the cog, is the microswitch trigger. This device enabled only one pulse in every five cycles in a flicker sequence to be observed. The first part of the experiment involved a comparison between data obtained from the flicker mode of presentation of the waveforms R(2), G(1), Y(1) and B(2) shown in figure 57 and data obtained from single cycles of these, using the shutter. The rotational frequency of the stepper motor was 7Hz, thus the surround pulse duration was 71msec. Each pulse produced a maximum retinal illuminance of 1200td. A re-cycling time of 700msec was employed for the pulse mode of presentation for each of the temporal signals. Initially, colour matches were made of signal R(2) with;

- i) The observer continuously viewing the stimulus, with the pulse mode of presentation.
- ii) The observer viewing a single two-pulse event (one cycle of the R(2) signal) closing his right eye for a few seconds and then making a match from memory. After this pause, a further two-pulse event was viewed and adjustments were made to the original match, if this was considered necessary. This sequence was repeated until the observer considered that the colorimeter field was of the same chromaticity and luminosity as the pulsed target (the three bars of the grating).

This second procedure was used to determine whether a re-cycling time of 700msec was sufficiently long to prevent an interaction occurring between two successive two-pulse events. Since the results with the R(2) signal showed little difference between the colour matches made with these two methods employed, matches to the other pulsed signals were made with the observer continuing to view the repeated stimulus. Data were re-collected using the flicker mode of presentation (no shutter) for all the signals. For each temporal signal, the order of presentation of the stimuli i.e. flicker or pulse, was randomised. One experimental session involved the collection of data from one temporal signal only.

For the pulse presentation of B(2), with the grating target,

the luminosity reduction of the target was so great, that an attenuating filter 'G' was placed in the colorimeter channel, as shown in figure 28, Chapter 2). This ensured that larger fractions of the colorimeter filters were exposed in making a match. Without an attenuating filter, the fractions of the colour filters exposed to light, when involved in a low luminosity colour match are extremely small, which introduces an extra source of inaccuracy since reading errors of the colorimeter scales will have a greater influence on the measurements. Initially, both Ilford and Wratten neutral density filters (1.0 N.D.) were considered as possible attenuators, but spectrophotometric measurements revealed that these filters absorbed heavily in the blue region of the spectrum.¹⁷ Finally, it was decided to use a sheet of metal wire gauze as the attenuator, which was spectrally neutral in its light transmitting properties.

c) Results and discussion

Figure 62 (a, b) shows the results for both observers (J.R.J. and C.A.P.). An 'F' placed before the signal classification denotes a flicker mode of presentation and 'P' denotes a pulse (continuous viewing) mode of presentation. The data point obtained from signal R(2) with the observer occasionally closing one eye is shown unmarked. Data are also shown with the B(2) signal using the bar target, since it had been noted in previous experiments that this seemed to enhance the blue F-B subjective colour. These data are shown with a dashed symbol in figure 62. This blue enhancement may be a manifestation of the "purple effect", which, as discussed in experiment 2A, appears to be more pronounced with larger targets. The "purple effect" is unlikely to be true F-B subjective colour for the reasons given in Chapter 4.

A t-test (two-tailed and for independent samples) was employed, to ascertain whether the differences between the pulse and flicker data for a given temporal signal are significant. Comparisons were first made

FOOTNOTE 17; Tests made on a 'Cinemoid' filter gave results comparable with the more expensive Wratten filter.

Fig 62a

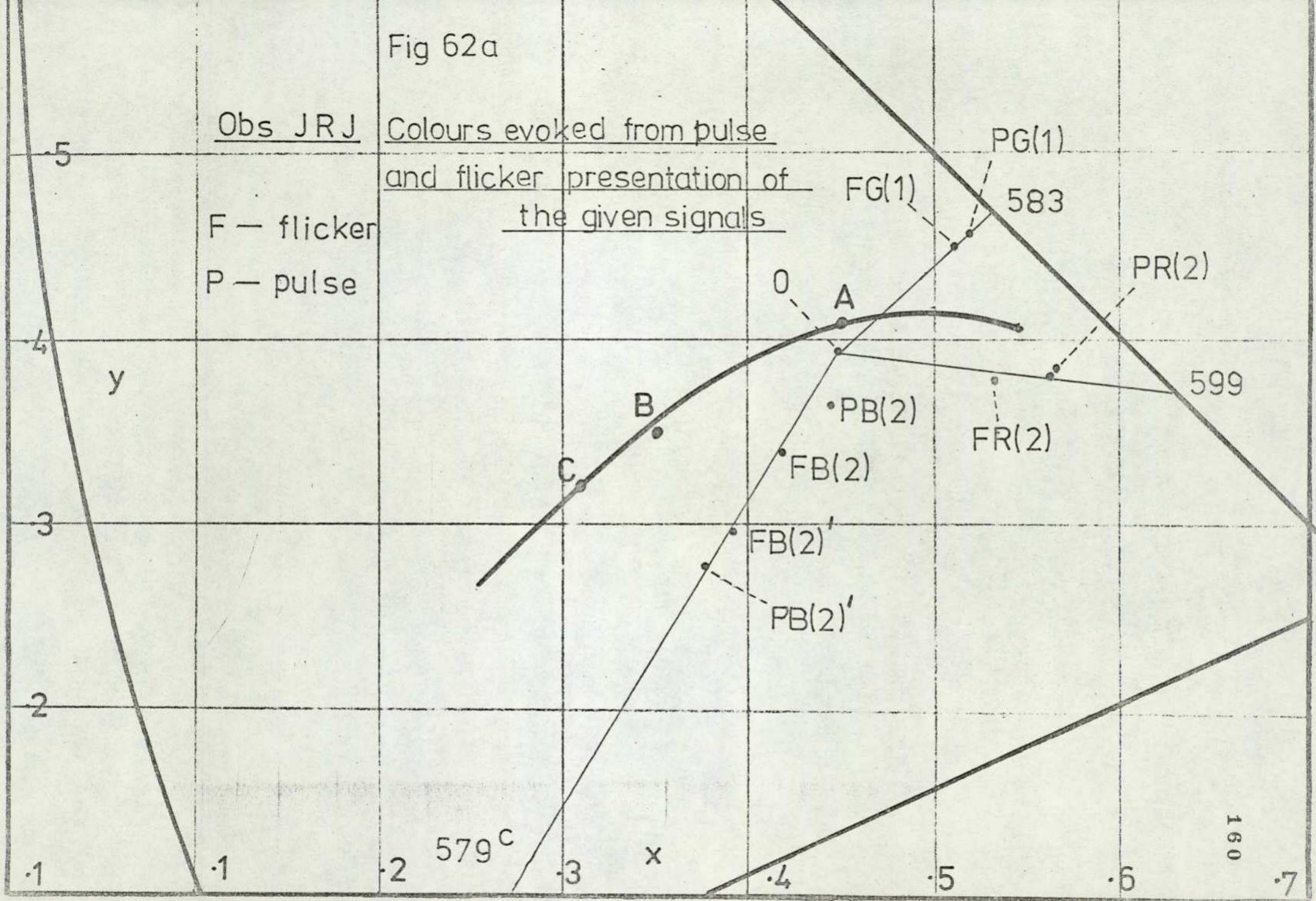
Obs JRJ

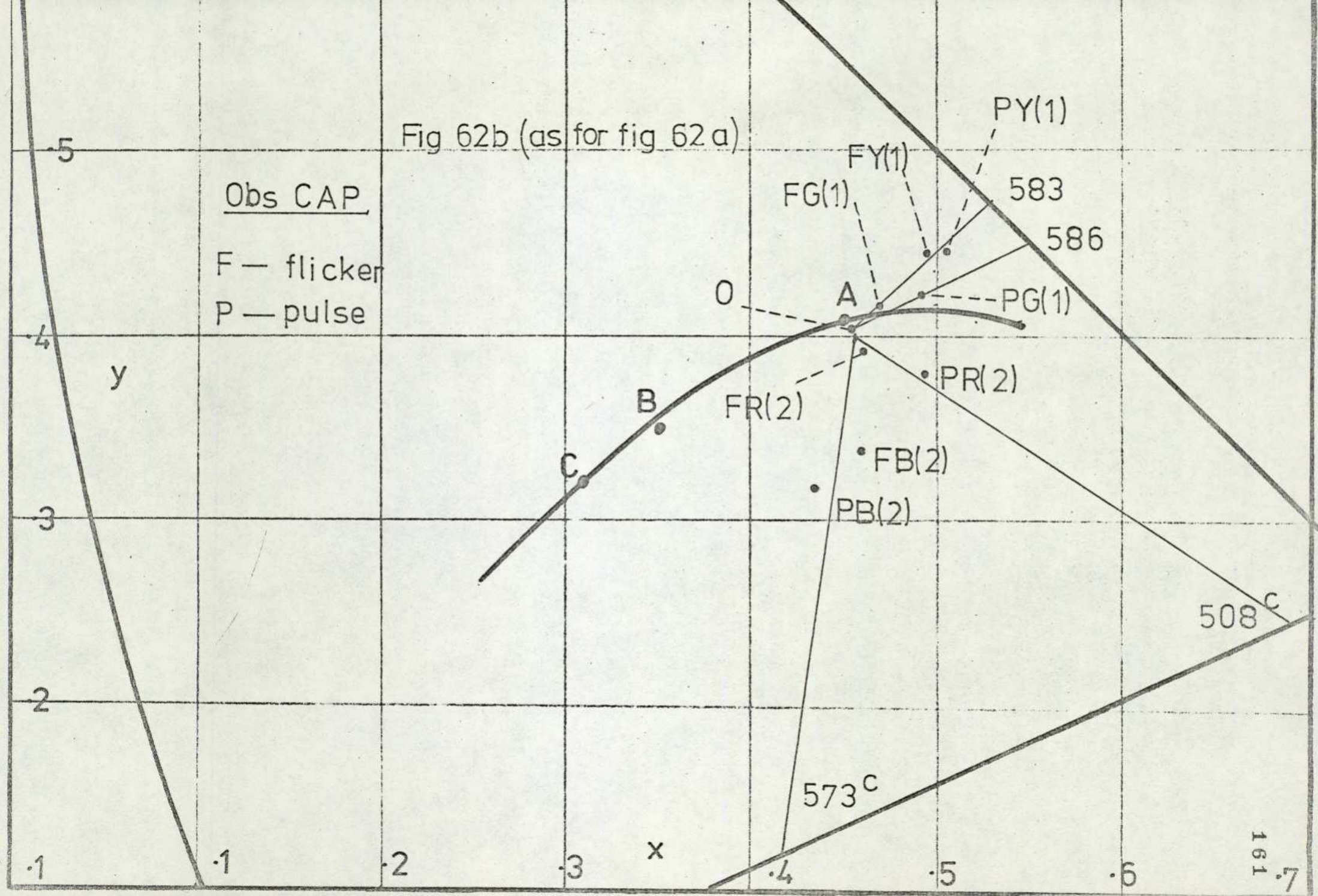
Colours evoked from pulse

and flicker presentation of
the given signals

F — flicker

P — pulse





between the x chromaticity coordinates of the target appearance for the pulse and flicker conditions, and then the y values were compared. Clearly, if a significant difference exists between either the pair of x values, or the pair of y values, then a significant difference existed between the colour appearance of the target for these two stimulus conditions. The results of the t-analysis are shown in table 3.

signal	<u>obs. J.R.J.</u>		<u>obs. C.A.P.</u>	
	level of significance		level of significance	
	x values	y values	x values	y values
R(2)	.001	.1	.01	.02
B(2)	.05	.01	.02	.02
(bar target) B(2)'	.05	.01	-	-
G(1)	A	.05	.02	B
Y(1)	-	-	.02	C

df = 7, for each test.

A, B, C; No significant difference at .2 level.

TABLE 3

Table 3 shows at what level the x and y chromaticity coordinates for the two stimulus conditions are significantly different. The x values for signal R(2) (observer J.R.J.), for example, are significantly different at the .001 level. Except for the Y(1) signal (observer C.A.P.), the t-test results confirm that the flicker mode of presentation produced significantly different subjective colour effects from the pulse mode of presentation. The data show that not only is colour manifest from single cycles of the temporal signals employed, but also the saturation is greater than for the flicker mode of presentation (except for observer J.R.J. with the B(2) signal and the grating target). The hue appears to have been only slightly affected by changing the mode of presentation from flicker to pulse. The dominant wavelengths of the data are shown in figure 62 (a, b).

These results are not in agreement with the findings of

HELMHOLTZ (1860), who claimed that F-B subjective colour is enhanced by flicker adaptation provided from continuously viewing a Benham's disc. They do, however, show that a single cycle of Benham's disc will produce the colours, as PIERON (1957) suggested. Pieron's interpretation of a Benham's disc was however, in terms of a single achromatic light pulse and not two spatially adjacent pulses, as appears to be the true interpretation.

The fact that a pulse presentation of the stimuli provides better subjective colour percepts than flicker presentation, suggests that a theoretical analysis of the phenomenon will involve a consideration of transient activity in the visual system, induced from single pulses. Furthermore, the fact that both a target and a surround light pulse are necessary to produce F-B subjective colour will require a consideration of an interaction between two transients; one a response to the target pulse and the other a response to the surround pulse. Finally, it is of interest to note that single pulses of the flicker sequences shown in figure 49, Chapter 4 (i.e. for the constant surround data) were re-examined due to the (unlikely) fact that these may produce F-B subjective colour. No colour effects were judged to occur and no data were collected.

d) An attempt to obtain a full gamut of F-B subjective colour from two light pulses

The second investigation reported here, involved the possibility of obtaining a full gamut of F-B subjective colour from two spatially adjacent rectangular light pulses, by an adjustment of the temporal separation between them. The stimulus field employed for this investigation was, as before, the three bar grating with the surround component of the temporal signal being fixed at a single 75msec light pulse. This value was adopted, since the experiments carried out had shown that near optimum subjective colours occur for surround light-pulse lengths of this order (see the purity vs. frequency graphs of experiment 1, for example). Rectangular pulses of various durations and of the same luminance as the

surround pulse were then investigated for the target component of the stimulus i.e. different T/M ¹⁸ values for the stimulus were investigated.

The method employed in this experiment, was to adjust the onset of the target pulse relative to the onset of the surround pulse, for each T/M value and then examine the target for subjective colour at each of these temporal separations (Δt). In this fashion, an attempt was made to find stimuli with a T/M value producing near optimum subjective colour. Such a value found to fulfil this requirement was, in fact, 0.2 i.e. the target pulse was 15msec. Many other values of T/M produce the subjective colours (see for example, signals R(2) and B(2)), but a value of 0.2 was judged to optimise the effect. The maximum retinal illuminance obtained from both target and surround pulses was 1200td.

Data were then collected using stimuli with $T/M = 0.2$ from two observers (J.R.J. and J.E.S.). Colour and luminosity matches were made of the target at each of several values for the temporal separation Δt , of the target and surround pulse onsets. The values of Δt were randomised. In addition, data were collected for $T/M = 1$ with both 15msec and 75msec pulses.

It is of interest to note, at this point, that the stimuli investigated in this experiment are of the type which have been employed in many of the studies of para- and metacontrast¹⁹ that have emerged, since STIGLER (1910) first reported these effects. It seems likely that the luminosity of the target, when F-B subjective colour is manifested, may be described, at least in part, by para- and metacontrast. Although these luminosity phenomena have received extensive research (see for example,

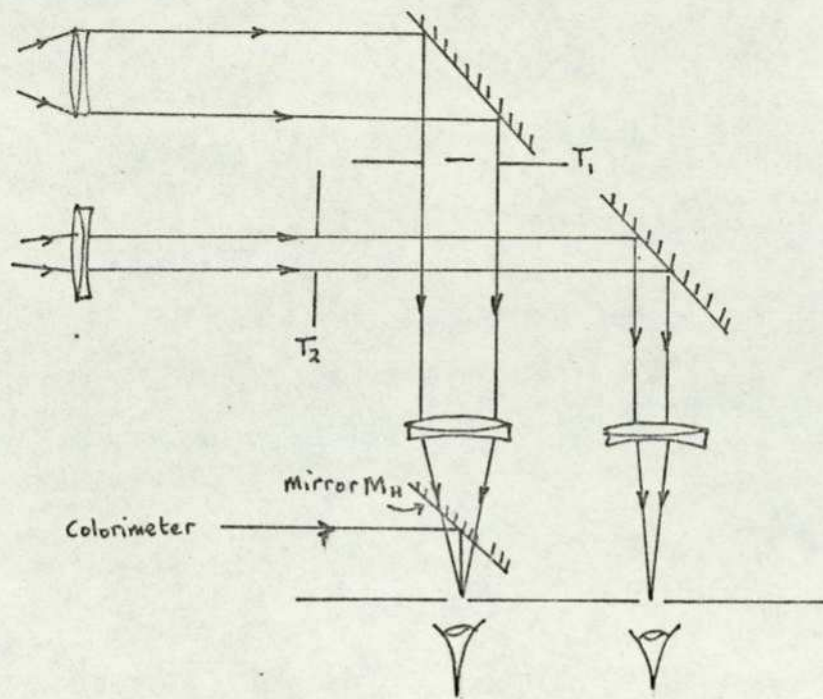
FOOTNOTE 18; T/M refers to the ratio of the target (or test) light flash energy to the surround (or mask) flash energy. This quantity has been used to describe the stimuli employed in many of the investigations of metacontrast, which are discussed in relation to the experimental findings later in this chapter.

ALPERN, 1953 and WEISSTEIN, 1972), no mention has been given to the perception of subjective colours, even though as just mentioned, a similarity exists between the design of experiment 3 and these other studies.

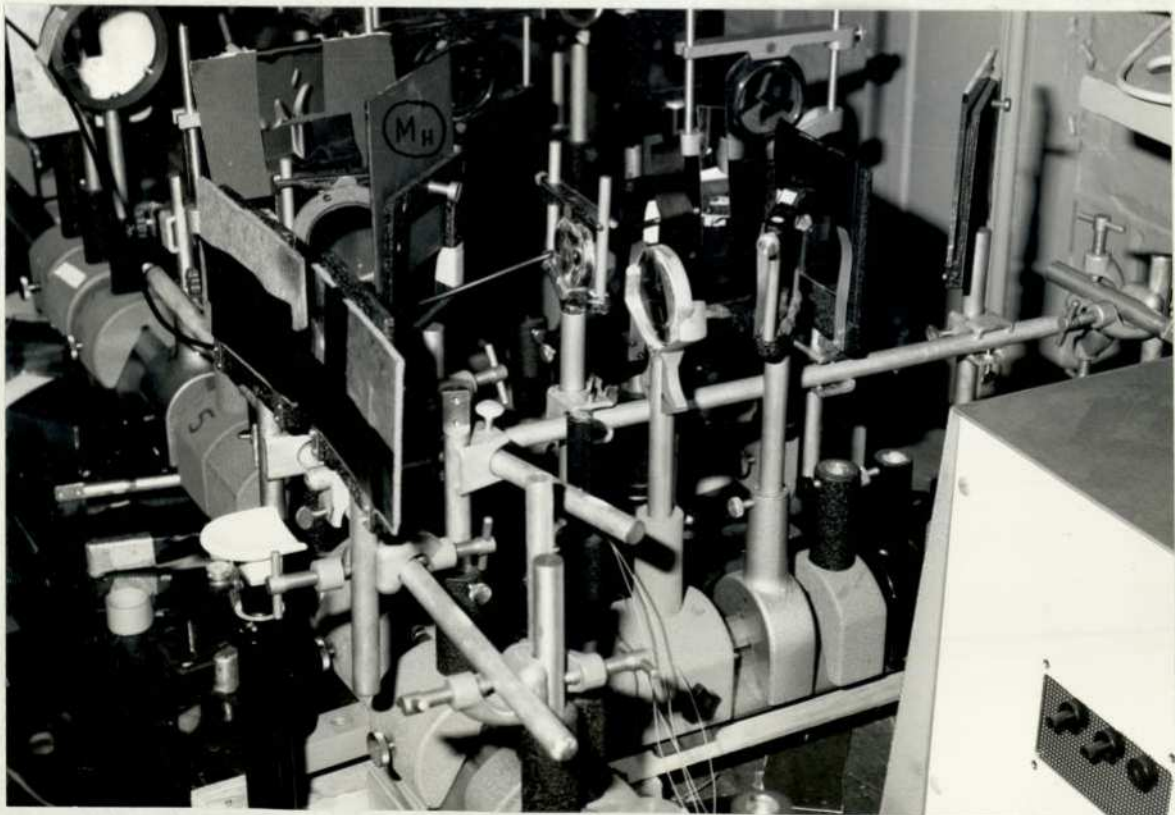
In addition to collecting data from the stimulus viewed monoptically, the apparatus was modified to enable a dichoptic viewing situation to be produced i.e. the target was viewed by the right eye and the surround viewed by the left eye. When the observer fused the two scenes, the appearance of the field was identical to that under monoptic viewing conditions. Failure to observe the subjective colours in the target under this viewing condition would be interpreted as indicating that the visual mechanisms responsible for the colours are most probably situated peripherally i.e. in the retina. Such a finding would add support to the results obtained by CAMPENHAUSEN (1968b), GREGORY (1968) and HESS (1953) who failed to produce F-B subjective colour from a dichoptic presentation of rotating black and white patterned stimuli, all of which produce the colour effects when viewed monoptically.

The modification of the apparatus necessary to establish the dichoptic situation is shown in figure 63 (a, b). The target T_2 component of the stimulus was viewed by the observer's right eye and the surround T_1 component was viewed by the observer's left eye, together with the colorimeter light patch. Figure 64 (a, b) shows the appearance of the left and right fields and figure 64c shows the fused scene (i.e.) identical to that illustrated in figure 36, Chapter 3. The mirror M_H , shown in figure 63a, FOOTNOTE 19; Metacontrast refers to the luminosity reduction (masking) of a suprathreshold test light pulse induced by a suprathreshold light pulse in the surround, whose onset occurs after the onset of the test flash. (defined with negative Δt). The luminosity reduction which occurs in the test pulse when the surround pulse onset occurs before the onset of the test (defined with positive Δt), is known as paracontrast.

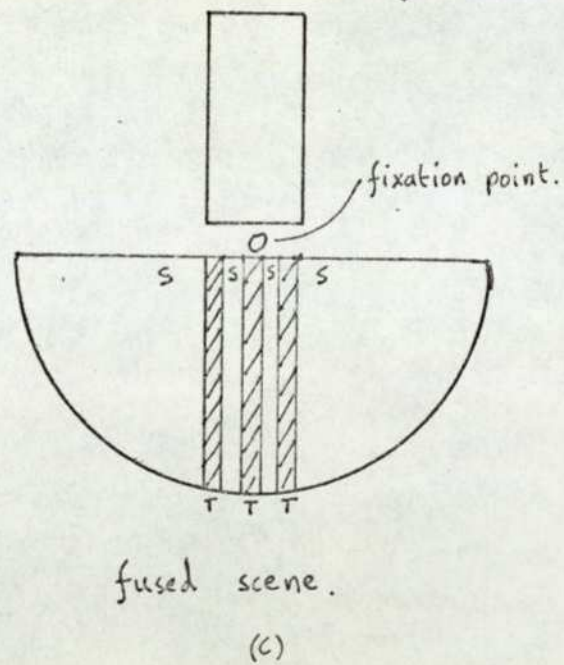
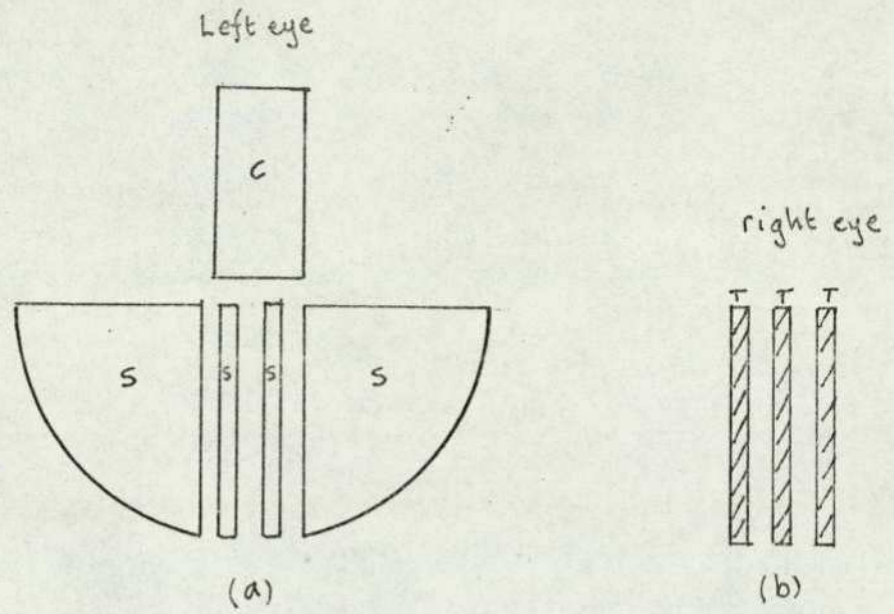
Fig. 63 Apparatus for the dichoptic expt.
(see also fig 28)



(a)



(b)



T- target
 S- surround.
 c- colorimeter light patch.

Fig 64. spatial features of the stimulus
 (dichoptic expt.)

was arranged to give the observer a clear view of the surround field (see the photograph in figure 63b). To ensure that the target and surround fields were always correctly aligned, a small fibre optic fixation light source was employed (marked O in figure 64). The observer was instructed to converge his eyes until the fixation light appeared directly beneath the bottom right-hand corner of the colorimeter light patch. When this occurred, the target and surround had the correct alignment. This extra fixation light was necessary, since without it, the observer was unable to maintain the correct visual alignment of target and surround, mainly due to the fact that these were intermittent.

The surround and colorimeter light patch were viewed by the same eye to prevent scattered light from the retinal image of the colorimeter light patch, falling on to the target retinal image. The possibility of a lateral interaction between the parts of the retina stimulated by the colorimeter light patch and target was also removed. It was considered more important to prevent such contamination effects from interfering with the response from the target rather than the surround.

During the initial experimental runs, it was ~~discovered~~ by observer J.R.J., that the luminosity of the target was affected by the observer's state of preparation as regards perceiving the target pulse.* For example, with the $T/M = 1$ stimuli, it was found that for $-50 < \Delta t < 0$ msec, the target was initially judged to possess an extremely low luminosity. If, however, the observer prepared himself to see a target pulse of extremely short duration (subjectively much shorter in duration, than without the surround pulse), a bright flash was often perceived. Colorimeter matches made under this observing condition, gave higher values of brightness gain G . It seems as if the target pulse for these values of Δt , appeared so short in duration, that unless the observer was made to concentrate hard to perceive the pulse, its luminance properties remained undetected.

The results for the stimuli with $T/M = 0.2$, and for monoptic observation are shown in figure 65 (a, b), for both observers employed

* This kind of effect is well known (see for example, MURPHY (1951)).

(J.R.J. and J.E.S.). The surround pulse had a duration of 75msec and the target pulse had a duration of 15msec. In figure 65, the numbers shown by each data point represent the time difference between surround and target pulse onsets. The interesting feature of this figure for both observers, is the manner in which the data points 'make a circuit' around the steady condition point as Δt ranges from large positive values, through zero, to large negative values. As found from the previous experiments, blue and red subjective colour effects were obtained when the target pulse onset occurred near the onset and offset, respectively, of the surround pulse. As predicted, the data points tend toward the green region of the chromaticity diagram for target pulse onsets occurring near the 'middle portion' of the surround pulse. This data circuit is most pronounced for observer J.E.S.

The values of x , y and z as functions of Δt , together with standard deviation calculations (error bars are ± 1 S.D.) are shown in figure 66 (a, b). The x and y functions show an anti-phase relationship, similar to the results obtained in experiment 1, when x , y and z obtained from the $R(3)$, $G(3)$ and $B(3)$ temporal signals were plotted as functions of flicker frequency.

The measurements made with a dichoptic presentation of the target and surround components of the stimulus show that no F-B subjective colour was perceived. The C.I.E. x and y values as a function of t are shown in figure 67 (a, b), together with standard deviation calculations. The values of x_0 and y_0 shown in figures 65 and 67 are the C.I.E. chromaticity coordinates of the colorimeter light patch, when matching the target under the steady condition. The results for the $T/M = 1$ data, (monoptic viewing only) are shown in figure 68 (a, b) and as can be seen, although evidence of F-B subjective colour induction exists, the effects are small. The brightness gain data of the target, as a function of Δt for all the stimuli employed, are shown in figure 69 a, b. The horizontal hatched lines show the values of G for target pulses without a surround. The

duration of the target pulse is shown alongside each line. For monoptic viewing, the data show the luminosity reduction effects (para- and meta-contrast) normally associated with such stimuli. The two open symbols in figure 69a show the values of brightness gain G , which were calculated from the data collected before the observer had started to examine the target carefully for the appearance of a bright and seemingly very brief light flash. As can be seen, the difference in the calculated value of G , from these two conditions, is relatively large. For the $T/M = 0.2$ stimuli, the brief target flash (as observed with the $T/M = 1$ stimuli) was not perceived and the target was always judged to possess a low luminosity for $\Delta t < 0$ msec.

In each of the curves of figure 69, the range of values of Δt for which F-B subjective colour was induced in the target are indicated by the vertical arrows. Colour was induced, for example, for $-25 < \Delta t < 75$ msec with the $T/M = 0.2$ stimuli (observer J.R.J.).

The dichoptic data for observer J.R.J., illustrate that the luminosity of the target was the same as when viewed with no surround, for all values of Δt i.e. no para- and metacontrast effects occurred. The data for observer J.E.S., however, show that a slight manifestation of para- and metacontrast occurred under the dichoptic condition. The G functions for observer J.R.J. with the $T/M = 1$ (15 msec pulses) stimuli show that for some values of $\Delta t > 50$ msec, the target was perceived with a greater luminosity than when viewed without the surround stimulus.

d) General discussion

The results clearly illustrate that a stationary target in which F-B subjective colour is induced, shows para- and metacontrast. Thus, since these masking effects play a role in the total perception of F-B subjective colour, it appears relevant to outline, in this discussion, the main facts known about para- and metacontrast. The phenomenon of paracontrast, in fact, may well explain certain disparities between the results of experiment 3 and predictions given from the theory of F-B subjective colour outlined

later.

The most noted general feature of para- and metacontrast is displayed by the brightness gain curves obtained from the $T/M = 1$ stimuli (see figure 69). This feature is the 'U' profile of these curves. ALPERN (1953), for example, in his investigation of para- and metacontrast found such 'U' functions, each being centred on about the line $\Delta t = -100\text{msec}$. This author also found that the luminosity masking of the target by the surround in his stimulus was diminished at $\Delta t = 0\text{msec}$. WEISSTEIN and GROWNEY (1970), however, have found in their investigation of para- and metacontrast that 'U'-shaped functions, similar to the Alpern type resulted from some observers, but for others, the functions were symmetrical about $\Delta t = 0\text{msec}$, as for the ($T/M = 1$) data of figure 69. In addition to the luminosity masking effects shown in figure 69, it is clear that paracontrast may sometimes act to enhance the luminosity of the target as shown in the $T/M = 1$ (15msec) data for $\Delta t > 50\text{msec}$. This effect has been noted before with paracontrast (WEISSTEIN, 1972). In general, however, paracontrast appears to involve luminosity reduction in a similar fashion to metacontrast (ALPERN, 1953). Alpern, in fact, attributed paracontrast mainly due to scattered light in the eye, since a glare source placed 25° away from the target was claimed to produce the same luminosity masking as the surround field in paracontrast situations. This scattered light explanation of paracontrast will be referred to again later in this thesis, when a possible theory of F-B subjective colour is discussed.

For observer J.R.J., the 'U' function obtained from the $T/M = 0.2$ stimuli, is slightly distorted in the paracontrast region, being elevated away from the 'U' profile. This same trend, only in a less pronounced manner, is shown in the (monoptic) data obtained from observer J.E.S. This distortion occurs at Δt values where F-B subjective colour was manifested. It appears, therefore, that this G vs. Δt function contains greater values under these conditions than would have occurred in the absence of F-B colour induction. Thus, without colour induction, it is plausible

that this curve, for $\Delta t > 0$, would then take the form shown as a hatched line, resembling in profile the curve for the $T/M = 1$ (75msec) condition (under which no subjective colour was induced). This possible elevating effect in the brightness gain data will be referred to again, later.

The finding that the observers state of preparation to perceive a target flash can effect the metacontrast function is clearly of prime importance (see again, the open data points in figure 69a). Failure to observe the brief target flash (for $\Delta t < 0$), would shift the value of Δt for maximum masking from $\Delta t = 0$ to negative values, for the $T/M = 1$ functions. These functions would then be of the type found by Alpern. It is possible, therefore, that the findings of WEISSTEIN and GROWNEY (1970), concerning individual differences in the obtained metacontrast functions, can be attributed to individual differences in the state of awareness to perceive the target pulse. SAUNDERS (1974 unpublished data), in a recent re-investigation of metacontrast has also noted that the perception of the masked target under some conditions may be affected by instructions given to the observer.

This effect is also of interest in relation to the findings of FEHRER and RAAB (1962), who showed that the decrease in luminosity of a target masked by metacontrast, was not accompanied by an increase in reaction time to the target. Also, SCHILLER and SMITH (1966) found that even for complete occlusion of the target by the surround, the observers were able to report in which portion of the target (which comprised two small annuli) the target flash had occurred. These findings are rather less remarkable, when compared with the luminosity data of figure 69a, which illustrate that seemingly intense luminosity masking can be considerably reduced by changing the matching instruction.

The fact that dichoptic presentation of the stimulus produced slight luminosity masking for observer J.E.S., suggests that some cortical processes may be involved in determining the luminosity of F-B subjective colour inducing stimuli. The effect was, however, very small, and no

evidence from either observer, was obtained showing that dichoptic presentation of the stimulus can produce greater masking effects than monoptic presentation, as was found in a study carried out by SCHILLER and SMITH (1968). There is, in fact, a vast amount of conflicting data available regarding masking obtained from dichoptic presentation of the stimulus. ALPERN (1953), on the one hand, was unable to obtain this effect (as in the case of observer J.R.J., as shown in figure 69a), whereas SCHILLER and SMITH (1968) and WEISSTEIN and GROWNEY (1969) were able to.

In the (unpublished) investigation of metacontrast made by SAUNDERS (1974), dichoptic presentation of the stimulus produced considerable metacontrast for one observer (J.E.S.). Data were also collected from three other observers, viz J.R.J., J.C. and M.N.W.²⁰ The data for observer J.C. were inconsistent, due to her failure to maintain the target and surround in correct visual alignment. The data for observers J.R.J. and M.N.W. failed to show any metacontrast effects. The stimulus used in this investigation consisted of a small (30') circular test spot and annular surround. Green light was used and the pulses produced a maximum retinal illuminance of 100 td. A T/M of .1 was employed, with test and surround pulses of 10msec and 100msec duration, respectively.

Since experiments (reported in the literature), which were designed to establish the location in the visual system of para- and meta-contrast producing mechanisms, have given conflicting data, there is no general agreement concerning the theoretical aspects of the phenomena. On the one hand ALPERN (1953) concluded that retinal lateral inhibition is responsible for metacontrast, and in support of this are the findings of RATLIFF, HARTLINE and MILLER (1963), who obtained direct electrophysiological evidence that metacontrast can be explained in this manner, at least in the limulus. WEISSTEIN (1972), on the other hand, proposed a model to explain metacontrast which includes cortical mechanisms, mainly due to the dichoptic

FOOTNOTE 20; J.C. (female, 27 years) and M.N.W. (male, 28 years) are both university lecturers.

* Long distance effects have, however, been noted at both retinal and LGN levels. McILWAIN (1964), for example, described a facilitatory influence of patterned stimuli (mostly moving black discs) from very distant regions of the retina upon ganglion cells and L.G.N. neurones

The data of experiment 3 obtained from a dichoptic presentation of the stimulus, show that no subjective colour was induced with any value of Δt for both observers. Thus, the most probable locus for the visual mechanisms responsible for the subjective colours is in the retina. Having made this statement, it must be emphasised that the possibility still exists that this mechanism consists of two components; one in the retina and the other in the cortex. If this were the case, then dichoptic presentation of the stimulus would not elicit the colours.

This two-component nature may exist, for example, in the mechanism responsible for "long range" contrast effects. In connection with this postulate, DE VALOIS and PEASE (1971) have found that although the production of "short range" border contrast effects e.g. Mach bands, can be attributed to the activity of certain L.G.N. cells, the "long range" effect of brightness and colour contrast, operating over several degrees of visual angle, cannot be attributed to the activity of any cells in the L.G.N. It appears plausible that the border responsive L.G.N. cells, when stimulated by a visual field which produces a "long range" contrast effect, develop a neural signal which triggers off a kind of "filling in process" in the cortex. This second and cortical process, thus accounts for the rest of the perceptual experience.

The de Valois and Pease experiment in fact, suggests that all contrast sensitive mechanisms in the L.G.N. operate over only small ranges. This situation probably applies to contrast sensitive mechanisms in the retina as well, since L.G.N. cells appear to possess similar properties to ganglion cells (DE VALOIS and ABRAMOV, 1966). Now, F-B subjective colour has been observed to cling to a black-white boundary in the stimulus field and possess similar spatial properties to Mach bands (CAMPENHAUSEN, 1968a; HASEGAWA, 1971). In this sense, F-B subjective colour appears to involve a "short range" contrast effect and thus the discussion above, would suggest that the mechanisms responsible for the phenomenon lay

entirely in the retina. This conclusion must, however, allow for cortical modification of the colours under some stimulus conditions. A Benham's disc, for example, with wide grey bands replacing the black arc lines produces colours which appear to extend uniformly over the whole of the band width. (No formal investigation of this effect has, however, been published). It is possible to explain this effect by an activation of the cortical "filling in process" referred to previously, which otherwise would be inactive if the Benham's disc had the usual form of narrow black lines.

Fig 65a Colours evoked from the two-pulse stimuli

Obs J R J

$t_1 = 75 \text{ msec (surround)}$
 $t_2 = 15 \text{ msec (target)}$

figures denote the
 temporal separation of
 the target and
 surround light pulses
 (Δt)

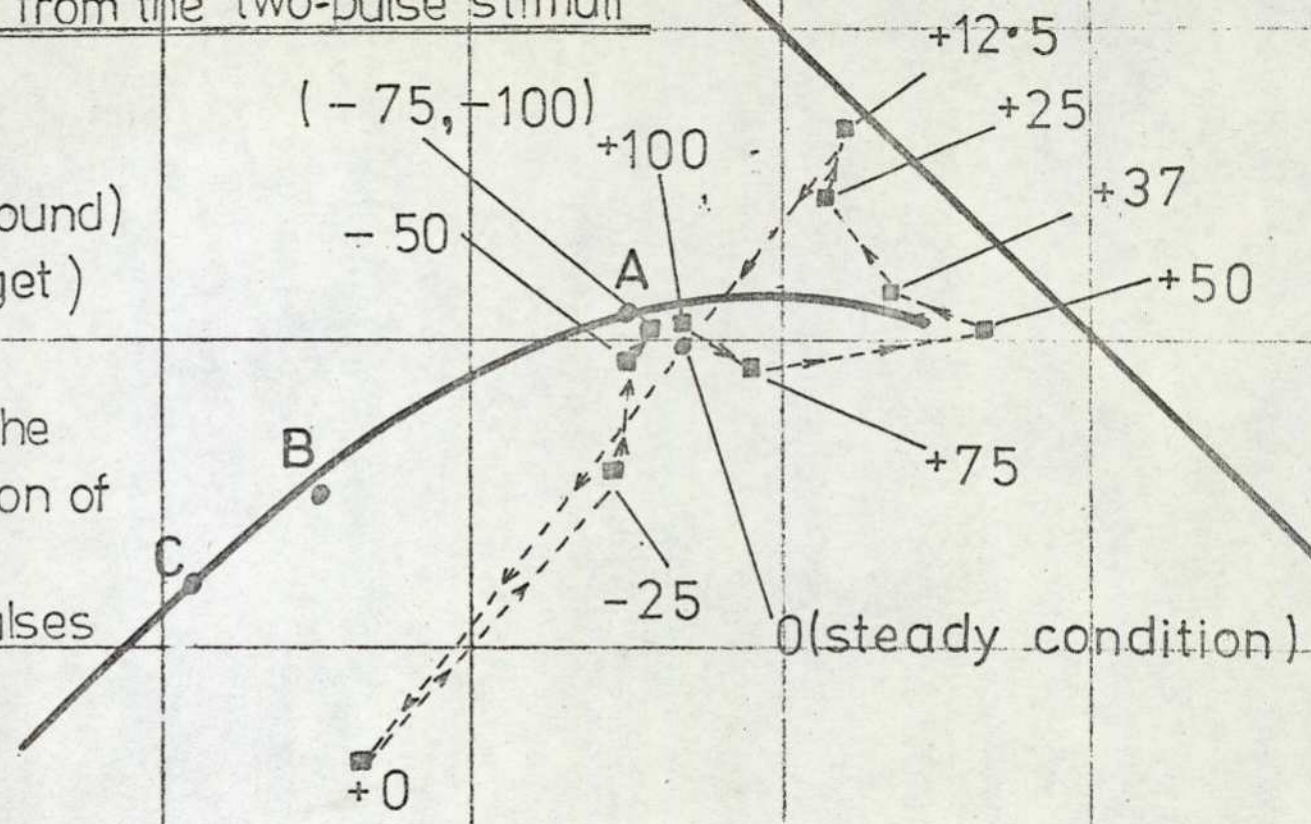


Fig 65 b (as for fig 65a)

Obs J E S

$t_1 = 75 \text{ msec}$

$t_2 = 15 \text{ msec}$

0 (steady condition)

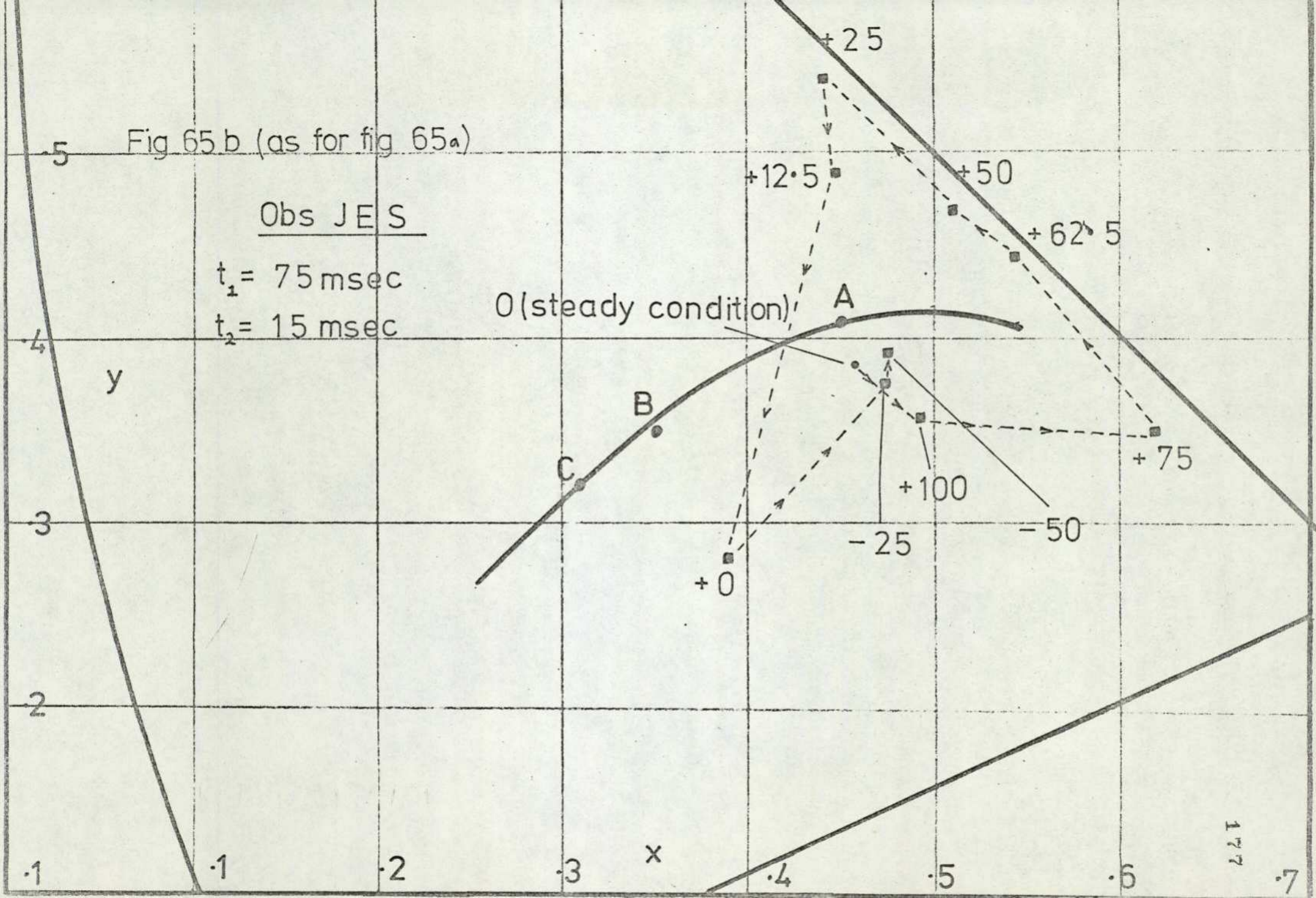


Fig 66a

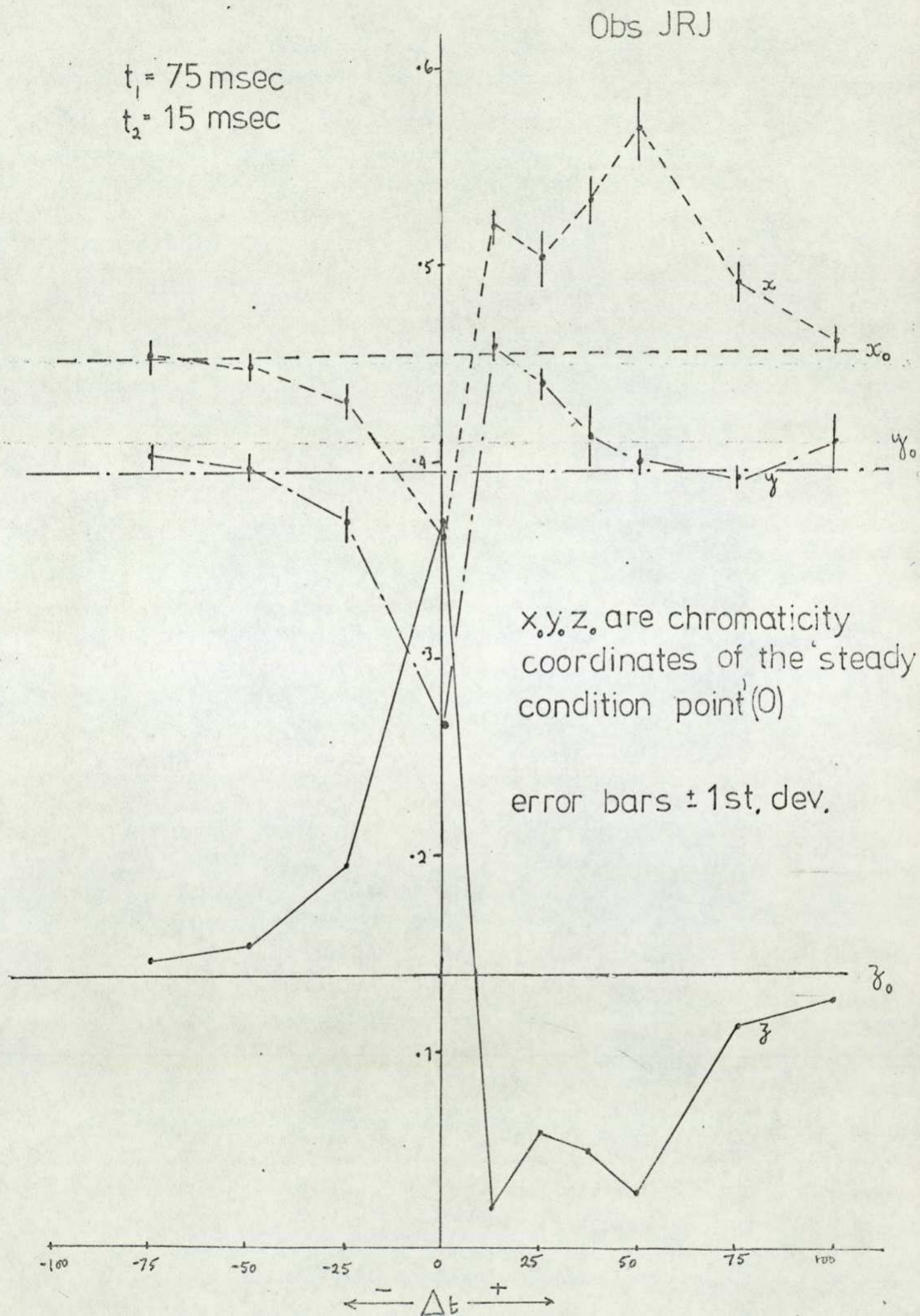
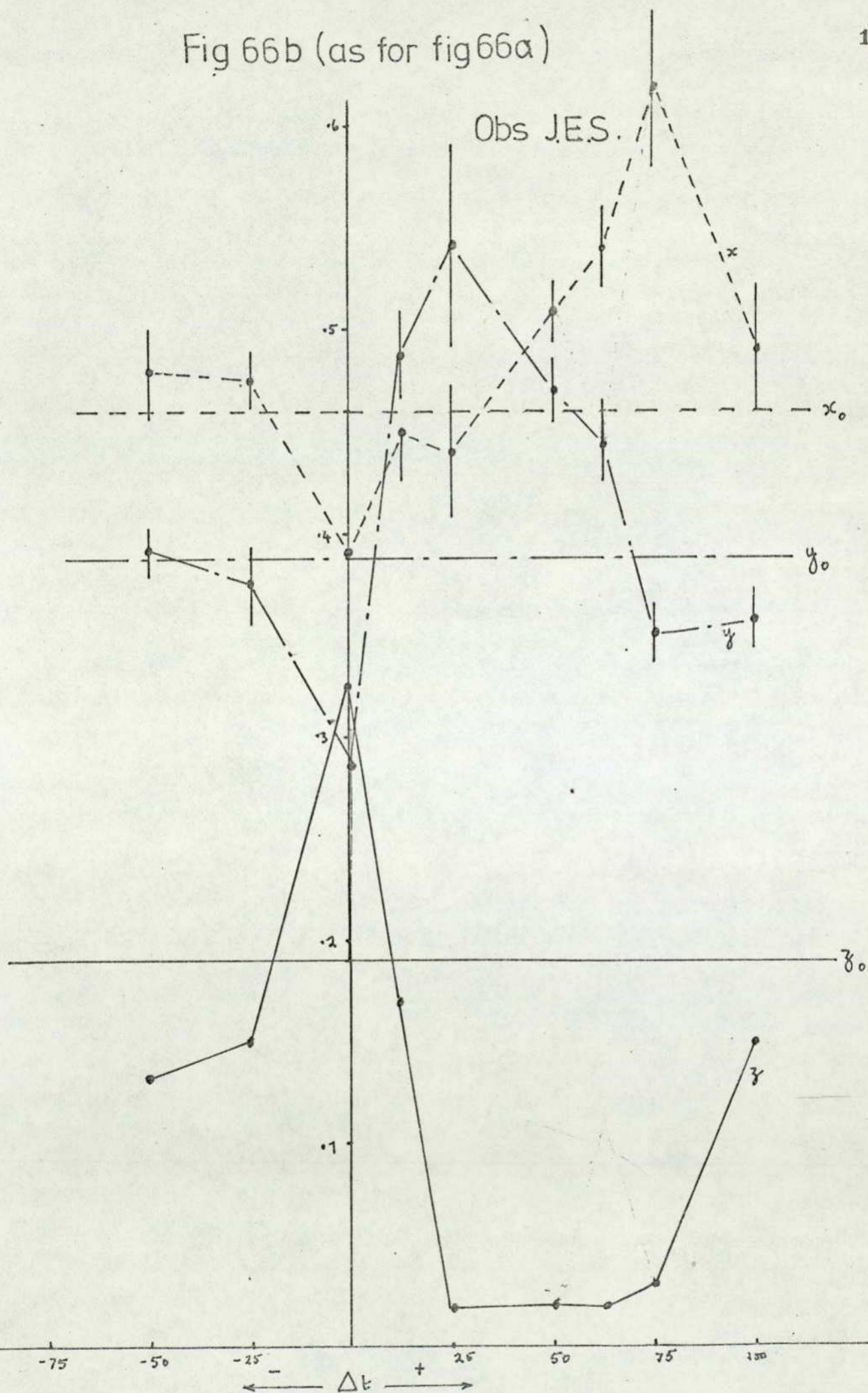
CIE Chromaticity coordinates vs Δt (see fig 65) 178

Fig 66b (as for fig 66a)



Dichoptic presentation of the stimuli

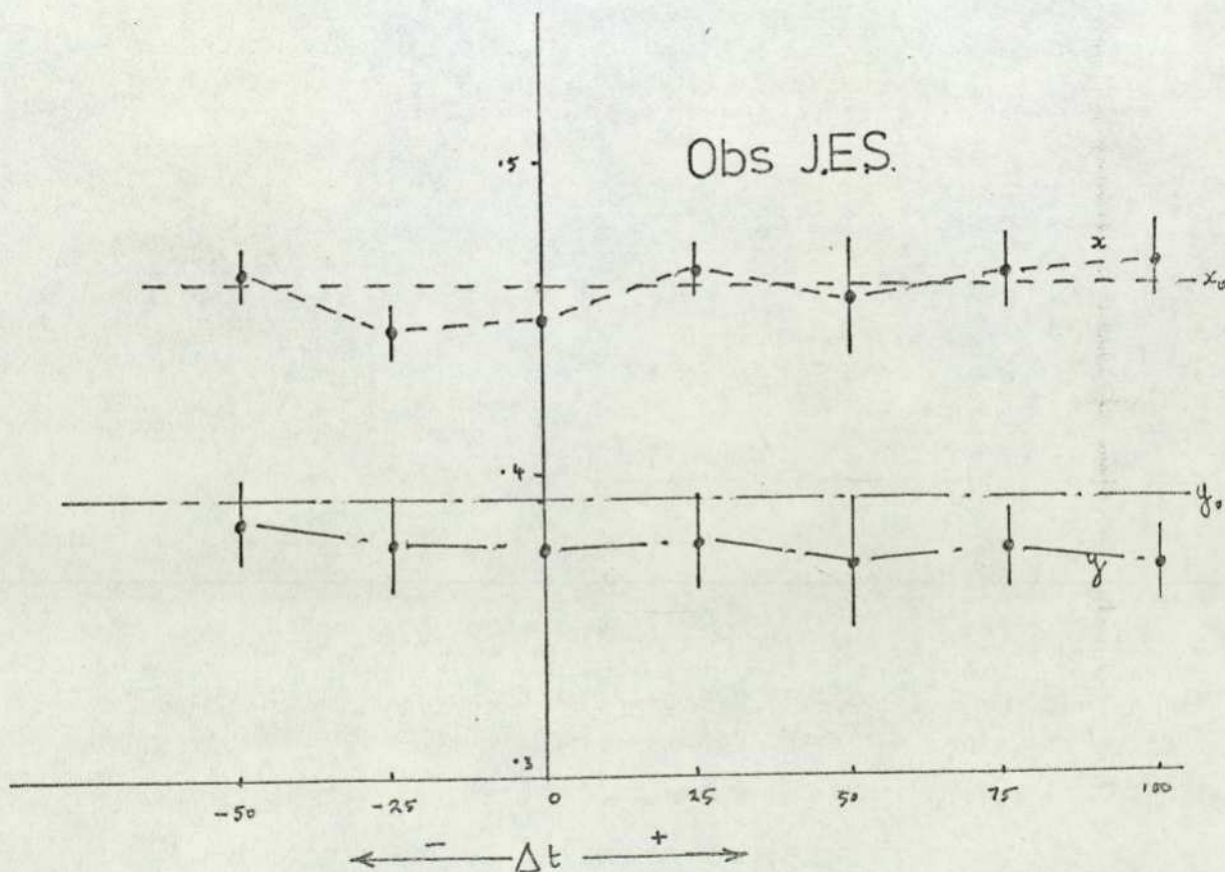
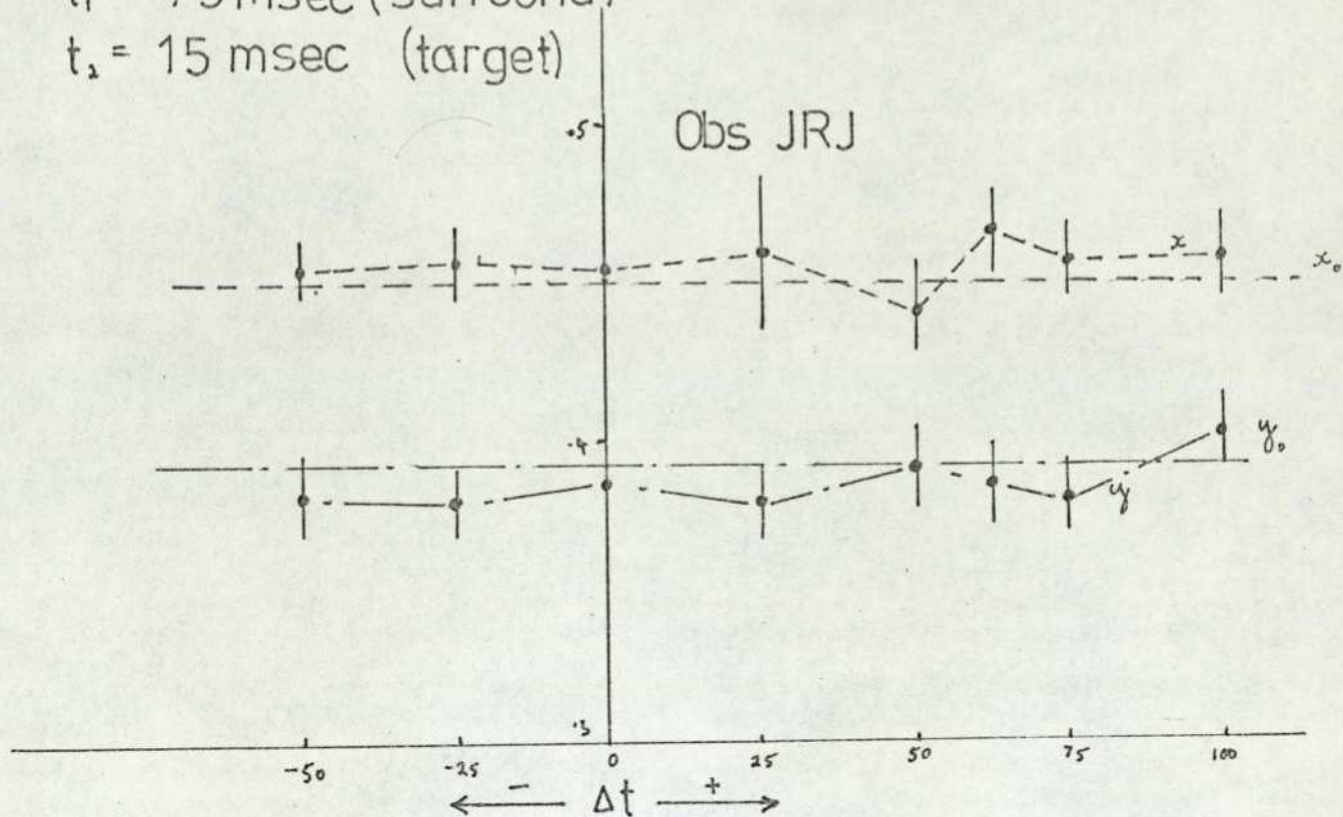
 $t_1 = 75 \text{ msec}$ (surround) $t_2 = 15 \text{ msec}$ (target)

Fig 68a Colours evoked from the two-pulse

Obs JRJ

$t_1 = 15 \text{ msec}$

$t_2 = 15 \text{ msec}$

0_s - steady condition

stimuli

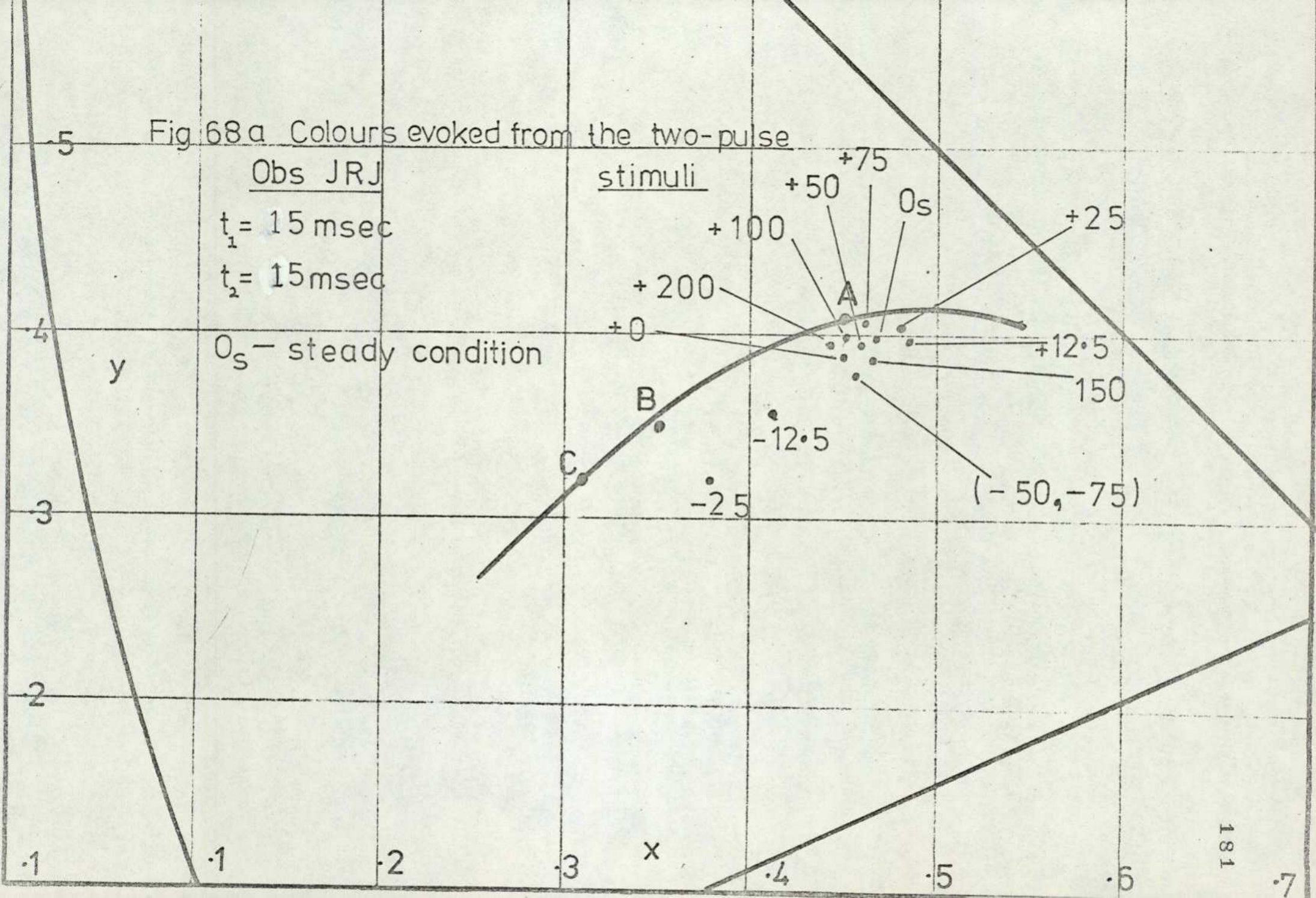


Fig 68b (as for fig 68b)

Obs JRJ

$t_1 = 75 \text{ msec}$

$t_2 = 75 \text{ msec}$

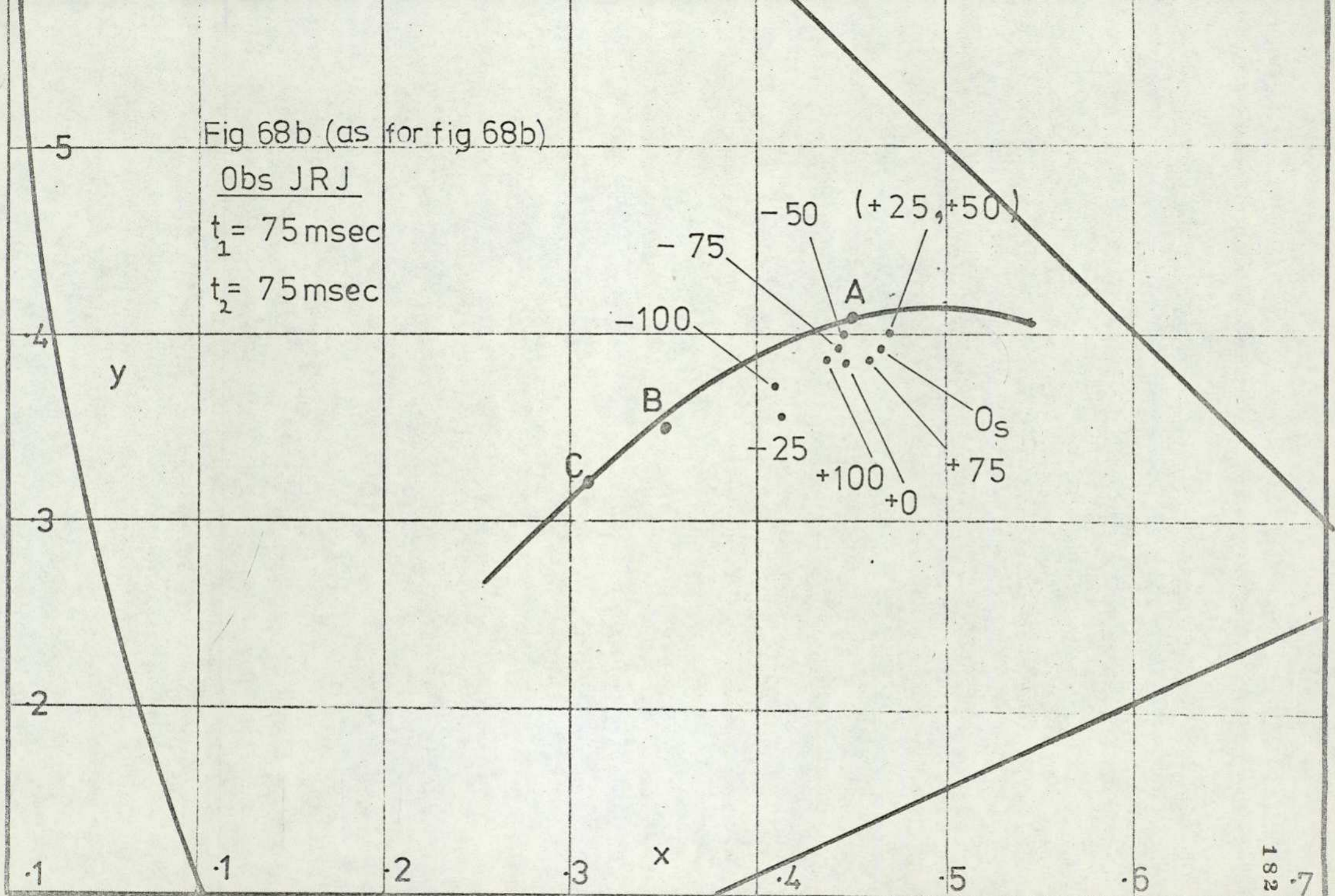


Fig. 69a Brightness gain vs. Δt Obs. J.R.J.

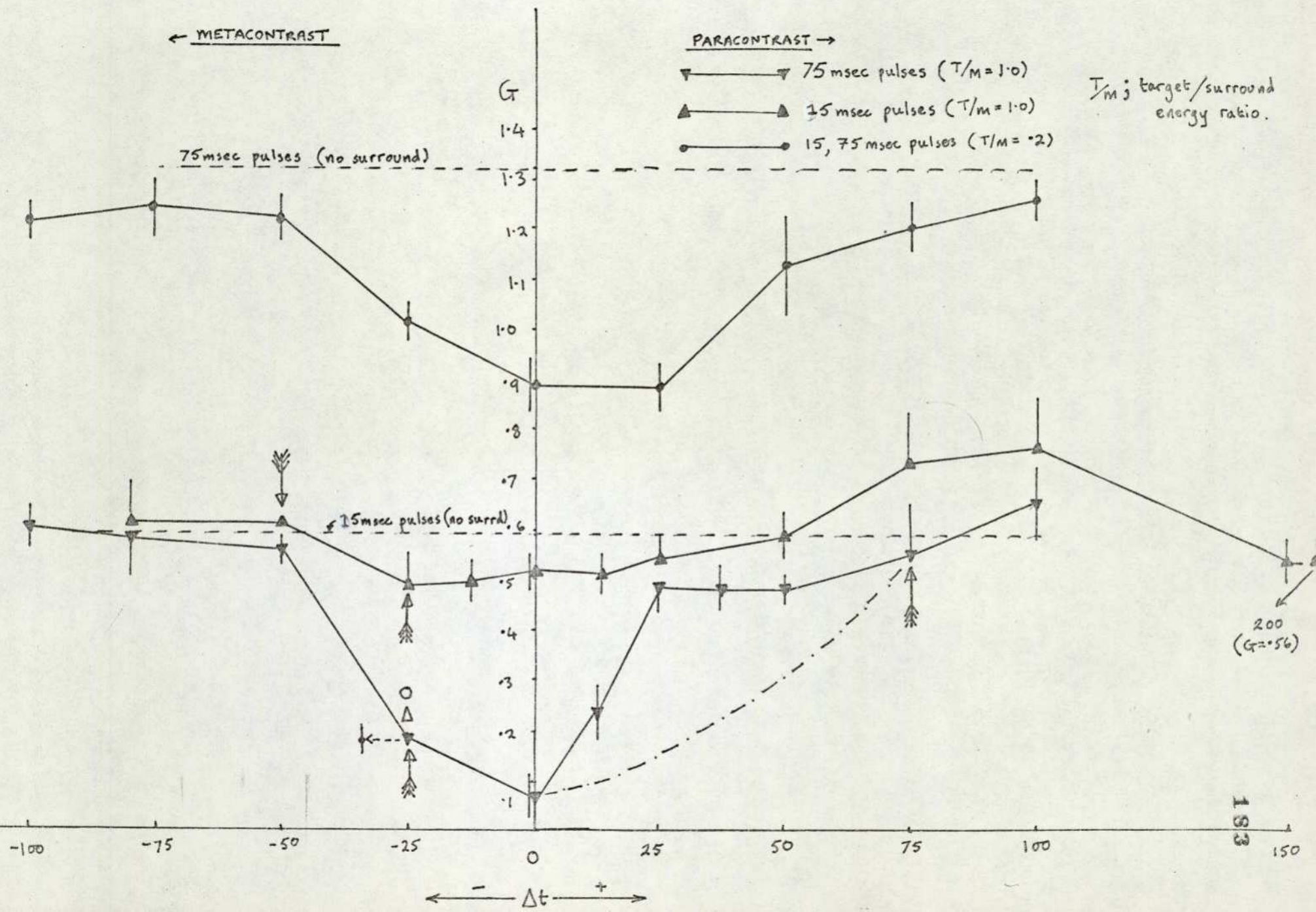


Fig 69a (contd)

Dichoptic data

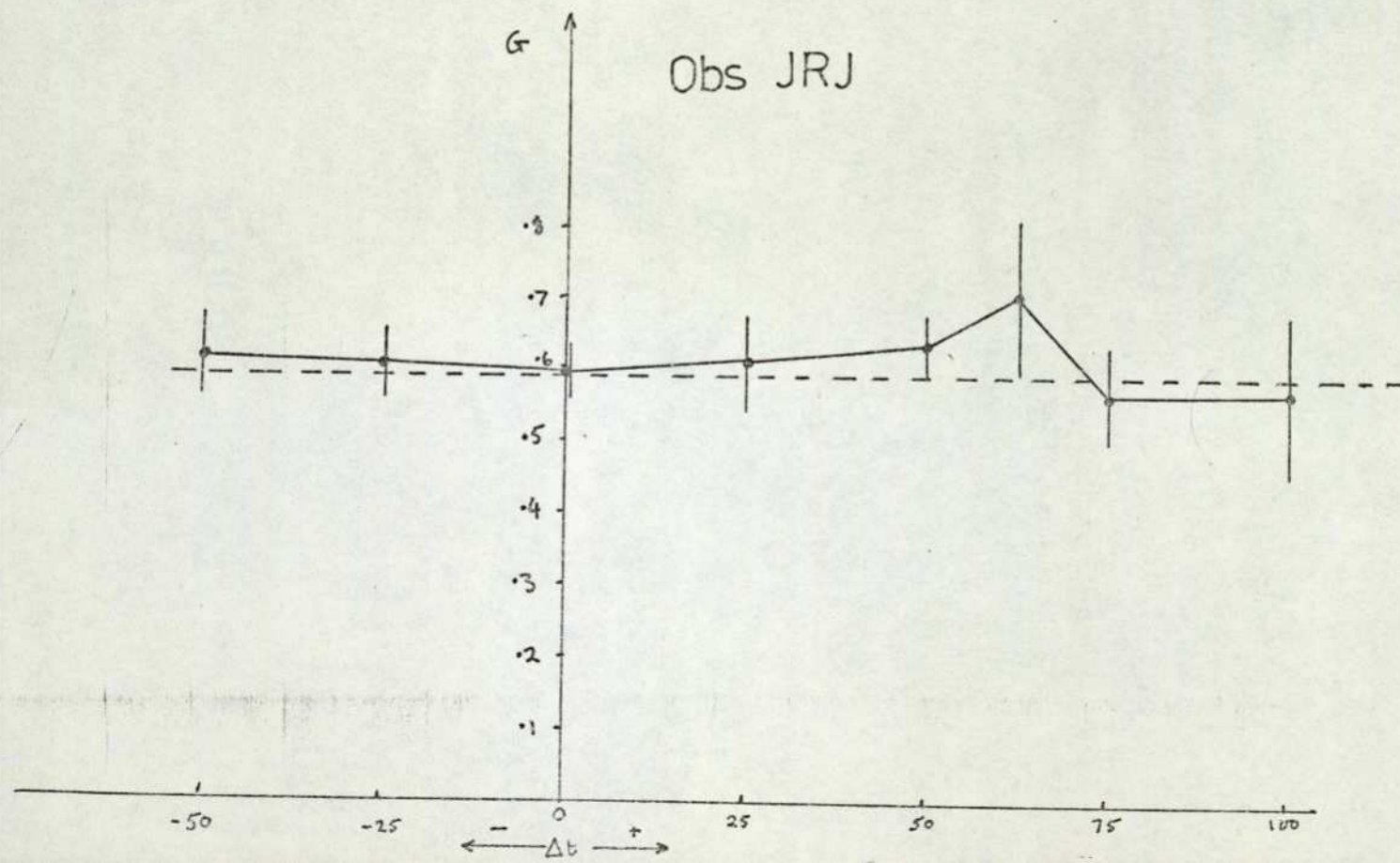
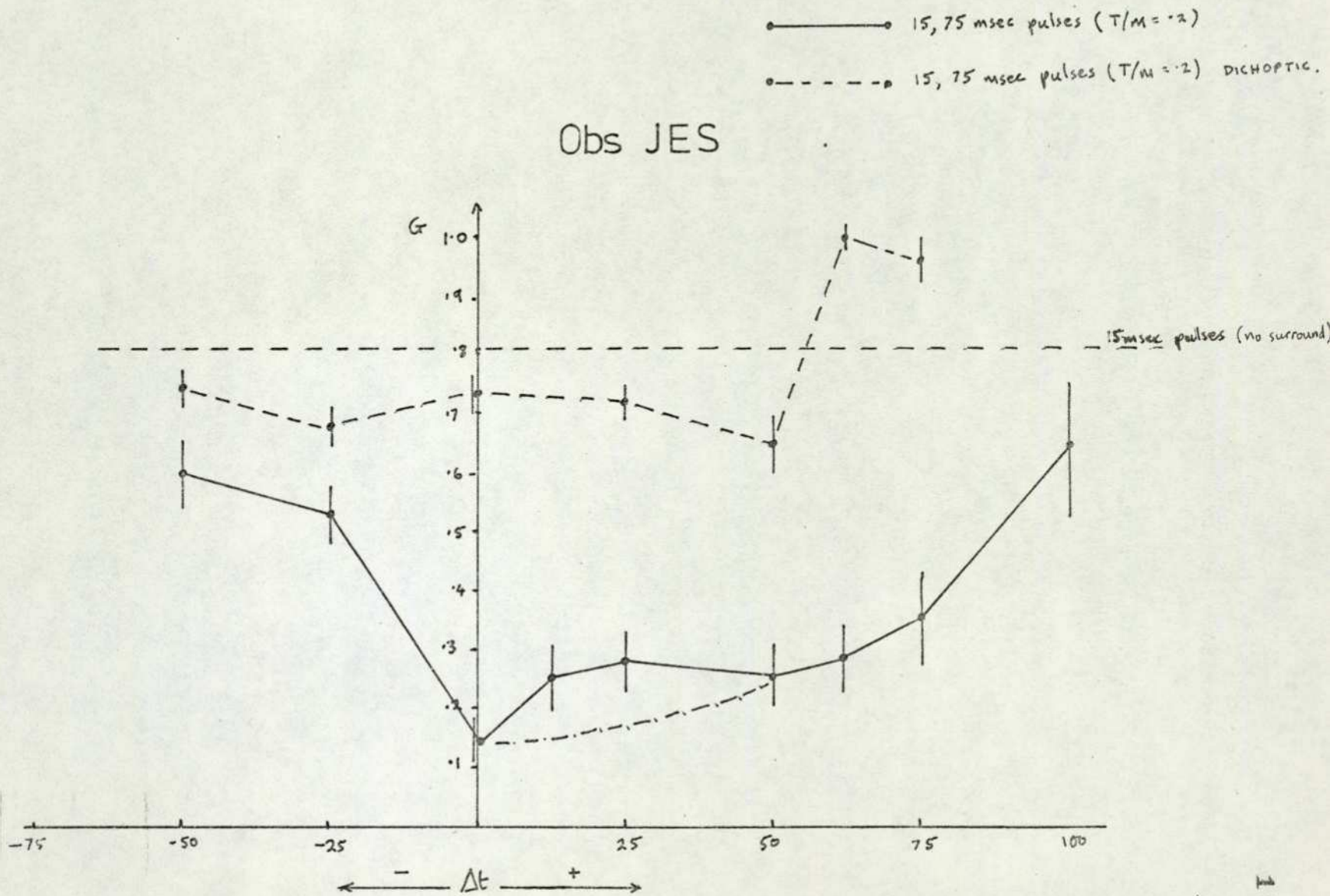


Fig 69b(as for fig 69a)



CHAPTER 6

EXPERIMENT 4 (A, B)

AN INVESTIGATION OF THE SPATIAL FEATURES OF FECHNER-BENHAMSUBJECTIVE COLOUR INDUCING STIMULIa) Introduction

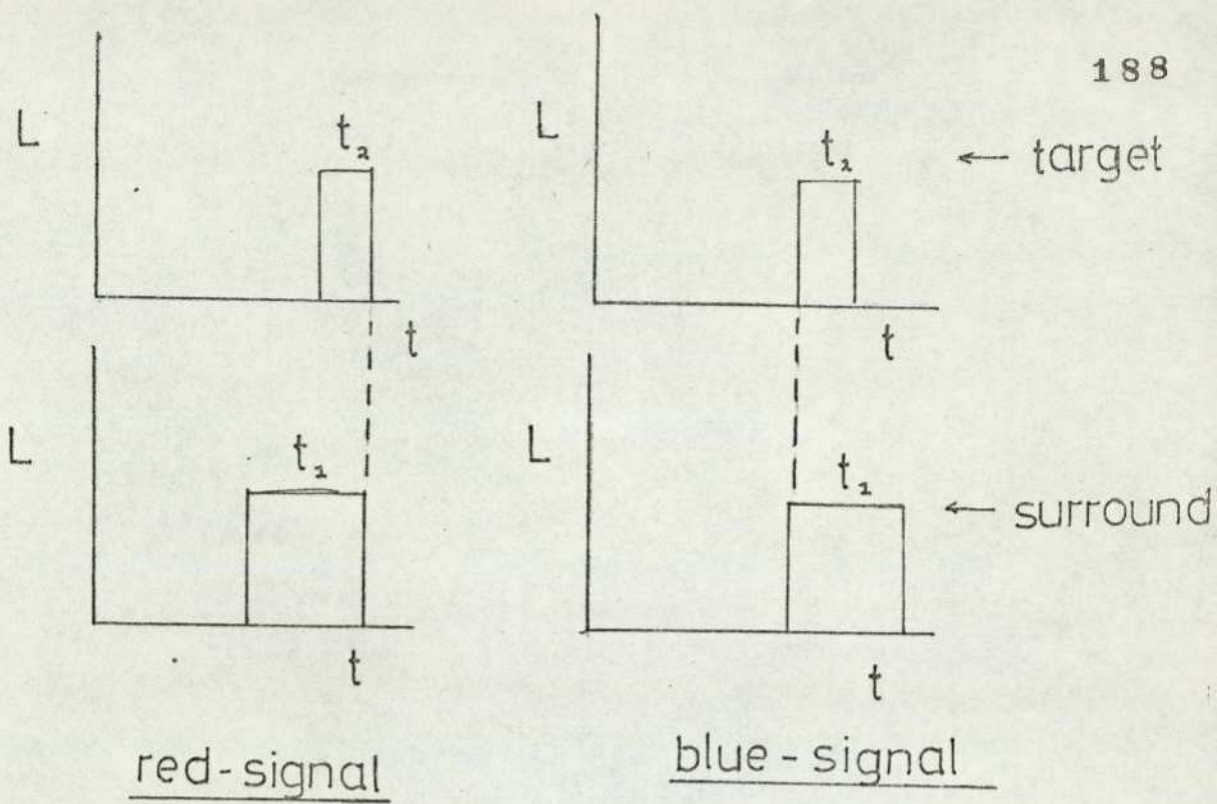
The experiments reported and discussed have led to the conclusion that to produce F-B subjective colour, two spatially adjacent²¹ light pulses are necessary in the stimulus field. Also, it was concluded that the visual mechanism responsible for the colours lies in the retina and to produce the effect, an interaction between two transients in the neural activity of the retina, arising as responses to the two light pulses, probably takes place within this mechanism. Thus, the receptive field of the retinal mechanism is assumed to consist of two components i.e. centre and surround, so that two separate neural signals can be received and processed by the mechanism. Candidates for this subjective colour producing mechanism are colour coded ganglion cells, since it is known that at least some of these in the rhesus monkey retina possess receptive fields with a circular centre and annular surround spatial arrangement (GOURAS, 1968, 1971; LEVICK, 1972). As discussed in Chapter 1, a similar situation probably exists for some ganglion cell receptive fields in the retina of man, since rhesus monkey colour vision resembles that of man (see DAW, 1973 pp 586-587 for a discussion).

If colour coded ganglion cells are the sole mechanisms responsible for F-B subjective colour, then complex spatial patterning of the stimulus as shown, for example, by the three bar grating used in the experimentation

FOOTNOTE 21; Until now, the term 'adjacent' has been used loosely. For example, it may well be that the subjective colours are still elicited when the surround light pulse is separated from the target pulse by a small black gap in the stimulus field. This was investigated and the results are reported in this Chapter.

reported so far, would be unnecessary, and the colours would be expected from a stimulus consisting of a circular target and annular surround. On the other hand, a number of authors have emphasized that spatial patterning in F-B subjective colour inducing stimuli is necessary (BUTTERFIELD, 1970, ROELOFS and ZEEMAN, 1957, 1958; CAMPENHAUSEN, 1968a, 1969, 1973). Now REGAN (1973b), has produced E.P. (evoked potential) data to indicate that the human visual system may handle colour information entirely differently when colour is linked with spatial form, compared with when the colour information is not so linked. Graphs of E.P. amplitude vs. number of colour contrast reversals occurring in his grating (and checkerboard) targets per second, show a maximum in the (6-8) Hz frequency band. The saturation of the colour produced from signal R(3) in experiment 1 was a maximum at a similar frequency location when a grating target was employed. Thus, it is possible that F-B subjective colour may be concerned with dynamic activity in Regan's postulated separate colour contrast channel. If this is so, then the ganglion cells of the retina may operate with pattern sensitive detector cells in the cortex, forming a two-component mechanism of the type outlined in the discussion of experiment 3.

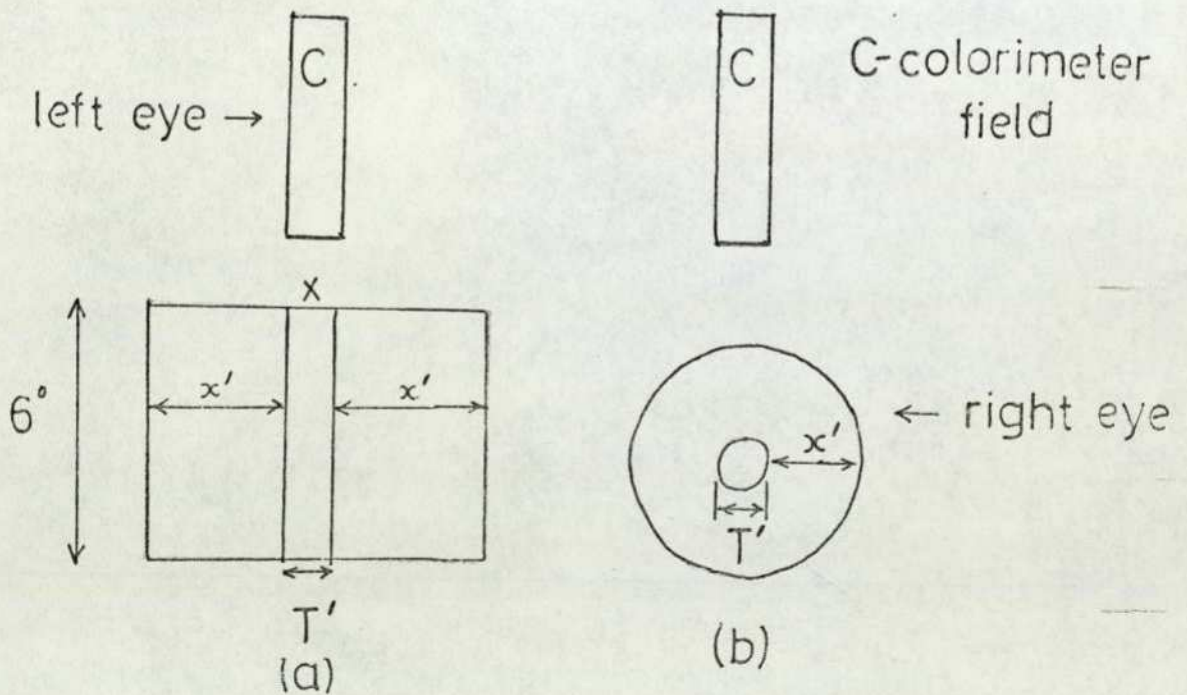
In this investigation of the spatial features of F-B subjective colour inducing stimuli, both linear targets (in the form of a single line of length 6° and variable width) and circular targets (with variable diameters) were investigated for two colour inducing signals; an 'R'- and a 'B'- signal as shown in figure 70. The linear targets were included, since initial trial experimentation suggested that the best blue subjective colour was obtained from a linear type of target. In this figure, t_1 represents the duration of the surround light pulse, and t_2 represents the duration of the target pulse. For the R-signal, the cessation of the surround and target pulses coincide and for the B-signal the onsets of the two pulses coincide. Previous experiments (see Chapter 5), have shown that near optimum red and blue F-B colour effects occur for such temporal signals with pulse lengths of 15 and 75 msec. G-signals were not chosen,



Temporal features of the stimulus

$$t_2 = 75 \text{ msec}, t = 15 \text{ msec}.$$

Fig 70



Spatial features of the stimulus

Fig 71

partly due to the fact that little subjective green has been induced throughout this study.

b) Apparatus and Methods

The shutter device described in Chapter 5 was again used in conjunction with the modulators, to provide single sequences of each of the temporal signals shown in figure 70, with a re-cycling time of 700msec. The maximum retinal illuminance provided by each light pulse was 1200td and two observers were employed (J.R.J. and J.E.S.). Each circular target had an annular surround, and each linear target had two flanking rectangular areas to form the surround. Figure 71 shows the total field of view in each case.

In figure 71, T mins arc represents the width (diameter) of the linear (circular) target employed and x mins arc denotes the width of the surround region in each case. With the linear target condition, fixation was made at the top of the target (indicated by a cross in figure 71a). For the circular target condition, the observer fixated at the centre of the target and then transferred his gaze to the centre of the colorimeter field (C) to make a (short term memory) match in terms of luminosity and chromaticity. The matching technique employed for the circular target condition was considered necessary, since the target could only be viewed adjacent to the colorimeter field by removing a portion of the annular surround.

The first experiment (expt. 4(A)) of the series, involved an investigation of the effect of varying the parameter T (target width), keeping x fixed at 360'. For each value of T, with the circular targets employed, the observer matched what he judged to be the most central portion of the target. With the linear target condition, the observer matched the central linear portion. The targets were presented with the values of T randomised (T varied from 1' to 360'). Observer J.R.J. produced data for all the experimental conditions and observer J.E.S. provided an extra source of information for the most important experimental

findings. Data collection was completed first under the linear target condition and then under the circular target condition. Matches were made of the target for each of the two temporal signals presented in turn. For each value of T , four matches were made by the observer and from their raw data, mean values of the C.I.E. (x , y) chromaticity coordinates were calculated and plotted on the chromaticity diagram (as in previous experiments). Prior to performing any experimentation, the observer dark adapted for ten minutes, followed by further periods of dark adaptation (3 minutes duration) between adjustments made to the T parameter.

Initially, each observer made colorimetric matches to one linear target ($T = 6'$) and one circular target ($T = 5'$), with the surround field dark and the target luminance held constant with time. These measurements provided the appropriate white light reference points on the chromaticity diagram (i.e.) two 'steady condition' points; one for the linear target condition and the other for the circular target condition. Matches were also made for several values of T (for both linear and circular targets), when the target was providing pulses of 15msec duration and the surround was completely dark. Thus, an investigation was made of how changing the size of a pulsed, isolated, achromatic light effected the chromaticity and luminosity.

c) Results of Experiment 4(A)

The chromaticity of the pulsed circular target with no surround employed, is shown in figure 72 (a, b) for each value of T investigated (both observers). Figure 73 (a, b) shows the equivalent data for the linear target situation. Both figures show that little variation in the colour appearance of the target occurred as T varied for either the circular or linear target condition. The general shift of the data away from the steady condition (O) points is toward the purple-blue regions of the chromaticity diagram (as was expected due to a manifestation of the 'purple effect' (see Chapter 4)). This shift away from the steady condition point was, however, small for both the linear and circular target conditions.

Thus for each target condition i.e. either circular or linear, the means of the x and y values were calculated, and these defined the point taken to represent the chromatic appearance of a single pulsed achromatic (standard illuminant A) light source. The brightness gain data also shows little variation as target size is varied (for both the circular and linear target condition) and again, mean values were calculated; one for the circular target condition and the other for the linear target condition. These are shown in figures 78 (a, b) by horizontal arrows. The values of brightness gain G for each value of target width T are shown in figure 79 for the linear target condition (observer J.R.J.). This serves to illustrate the fact that variation in brightness gain as target size was changed, was indeed small.

The colour appearance of the linear target for each value of T, and with the subjective colour inducing signals employed, is shown in figure 74a (observer J.R.J.) and figure 74b (observer J.E.S.). Figures 75a and 75b show the data for the circular target condition. With the R-signal employed, it is clear that F-B subjective colour was induced using both circular and linear targets. The majority of the data points are confined to the (590-610) nm dominant wavelength band, and peak colour induction occurred for $T \approx 5'$. (for both observers, and for both the linear and circular target conditions).

For the B-signal, with linear targets employed, the colour induction was relatively small and as found in previous experiments, such a signal produced data points in the achromatic zone of the chromaticity diagram, on the 'blue-purple' side of the steady condition point. The B-signal employed under the circular target condition displayed even less subjective colour compared with the linear target condition, and reliable colour matches could only be made for target sizes greater than about 60' in diameter. Targets having a smaller diameter were generally perceived as black spots and the nearest colorimeter match involved all three colorimeter filters being completely occluded. A similar difficulty

was experienced with the B-signal presented with the narrowest of the linear targets. The target, in fact, always possessed an extremely low luminosity when the B-signal was employed, and the gauze attenuator used in experiment 3 was incorporated in the colorimeter. From the data of figures 74 (a, b) and 75 (a, b), the excitation purity of each data point, relative to the appropriate steady condition point (i.e. linear or circular target condition) was calculated. The results are shown in figures 76 (a, b) and 77. Since for each temporal signal, the variation in dominant wavelengths of the data are confined to a fairly narrow wave-band, as T is varied (see again figures 74 (a, b) and 75 (a, b)), excitation purity gives an indication of how the saturation of the subjective colour changed, in the central region of the target as T was varied (see experiment 1, Chapter 3, for a discussion). Furthermore, if the apparently small variation in dominant wavelength is assumed to be negligible, then the degree of colour induction produced by the temporal signals employed, is measured by one variable viz, excitation purity. For observer J.R.J., similar shaped functions are obtained in the plots of excitation purity (P_e) vs. T, with both the circular and linear targets employed. For the R-signal, a peak occurs near $T=5'$ in both functions, showing that maximum saturation occurred near this value. As T increases beyond about $5'$, the function decreases until it reaches values similar to the excitation purity displayed by the pulsed target in the absence of any surround. This occurs at about $T = (40-100)'$ for both the linear and circular target conditions. For observer J.E.S., (the R signal was employed only under the circular target condition for this observer) the data show a similar trend. Also, the graphs for both observers show that as T is decreased below about $5'$, excitation purity decreases.²²

FOOTNOTE 22; The data for $T=1'$ may not reflect the true saturation of the subjective colour, under the circular target condition, since it was never possible to align the two transparencies forming the target and surround fields (see figure 28, Chapter 3) with entire satisfaction.

With the B-signal employed under the linear target condition, the calculated excitation purity vs. T functions are similar in profile for both observers. Furthermore, the functions are similar in profile to those obtained from the R-signal. The peak in the B-signal excitation purity function occurs at about $T = 15'$ for both observers. The data obtained from the B-signal under the circular target condition are rather inconclusive, but a little subjective colour was obtained (see again figures 74 (a, b) and 75 (a, b)).

An interesting feature of this experiment is that with the R-signal employed, both observers reported that not all of the target pulses appeared coloured for any given small ($\leq 5'$) circular target. For example, observer J.E.S. estimated that when the $5'$ circular target was viewed, one in every five target pulses appeared coloured. Also, the observers examined each of the larger targets to see how the subjective colour was arranged spatially (this was performed after the data had been collected and as mentioned previously, the colour and luminosity properties of the central portion of each target only, were actually measured). However, these extra qualitative observations indicated that the colours were most saturated toward the edges of the target.

Figures 78 (a, b) and 79 show plots of brightness gain G vs. T for both the linear and circular target conditions. For the linear targets, each brightness gain function increases as T is increased, and for the R-signal, the tendency of the function is toward an asymptote corresponding to the brightness gain of the pulsed target in the absence of colour induction i.e. no surround condition. This asymptote is reached at about $T = 30'$, for observer J.R.J. The brightness gain functions obtained from both the linear and circular target conditions, with the B-signal employed, never attain values near that associated with the pulsed target (no surround condition). Severe luminosity masking was always evident with the B-signal irrespective of target shape or size. For the circular target condition and with the R-signal employed, the

brightness gain function again increases with an increase in T for both observers. Again, apart from the 1' target condition, brightness gain values remain substantially lower than the value associated with the pulsed target (no surround condition). The error bars shown (± 1 standard deviation) have the same order of magnitude as for the pulsed data of experiment 3.

d) Discussion

All the excitation purity vs. T (target size) curves illustrate the fact that the saturation of the subjective colour in the central region of the target changed considerably as target size was altered. FESTINGER, ALLYN and WHITE (1971), could find no variation in the reported subjective colour effects as a function of target size, in their target-surround stimulus configuration. This might be expected, however, if the colour effects obtained by these authors were colour artefacts from the apparatus employed, which may have been the case as discussed in Chapter 4. The qualitative reports made by both observers in connection with the spatial orientation of the subjective colours within the larger targets, adds further support to the idea that the 'purple effect' reported previously, is not F-B subjective colour. Although the subjective colour induced from the B-signal often resembles in chromaticity the 'purple effect', the former appears to be more saturated toward the edge of the target, whereas the latter appears to be confined to the central regions of the target in moving blotches of colour and the edges of the target appear achromatic. To obtain quantitative measures, rather than qualitative reports of the spread of F-B subjective colour across the target field is, however, necessary to enable further comment to be made on this point. The fact that a circular target with an annular surround provides F-B subjective colour with at least the same degree of saturation as more spatially complex targets is in keeping with the postulate that the visual mechanisms responsible for the phenomenon are single ganglion cells.

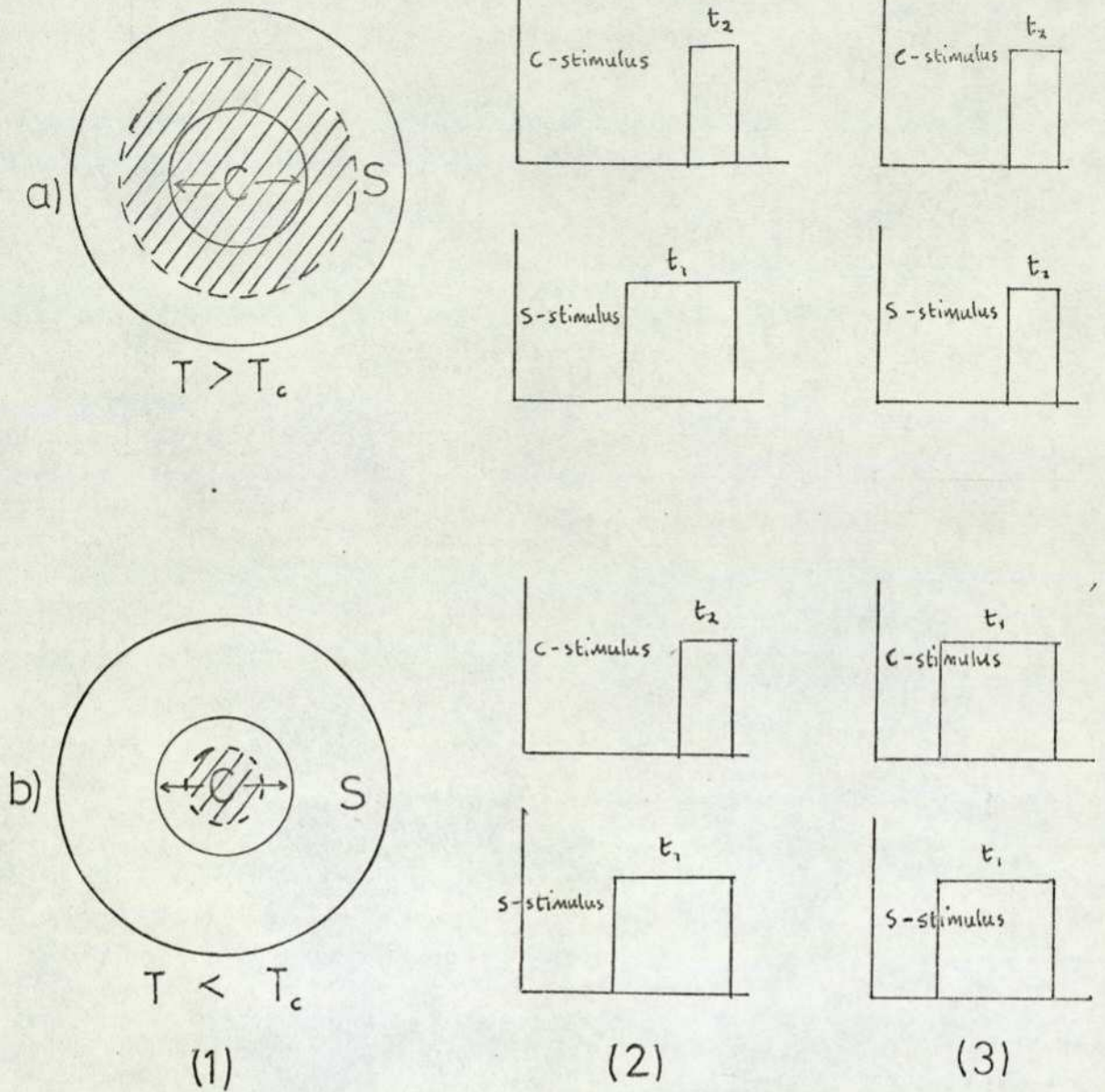
To explain the basic profile of the excitation purity curves,

several assumptions are made. The first of these is that separate centre-surround subjective colour inducing mechanisms exist; one accounting for the red subjective colour effects and the other accounting for the blue colour induction. The second assumption is that the receptive field of each of these mechanisms has a circular centre and annular surround (which of course would be the case if the mechanisms are ganglion cells). It is also assumed that to produce a subjective colour signal as its output, each of the mechanisms must receive two signals; one from the centre of its receptive field derived from the target light pulse and the other from the surround of the receptive field, this signal being derived from the light pulse produced in the surround regions of the stimulus field.

Consider now, the R-signal used in the experiment reported in this chapter, presented in a circular target with annular surround stimulus field. Consider further, a circular target which gives rise to a retinal image that just completely covers the centre of the receptive field of a red subjective colour inducing mechanism (R-mechanism). Let this particular value of target diameter be denoted by T_C . Under this stimulus condition, the red peaks shown in figures 76 (a, b) would be expected. For values of T greater or less than T_C , reduced saturation of the subjective colour would also be expected. To explain this, consider figure 80.

Text of figure 80; Column 1) shows the receptive field of an R-mechanism. Column 2) shows the R-signal which only partly stimulates the mechanism. Column 3) shows the other temporal component of the stimulus for each of the two conditions $T > T_C$, $T < T_C$ (see text for further details). $t_1 = 75\text{msec}$, $t_2 = 15\text{msec}$.

In figure 80, column 1) shows for both rows a) and b), the receptive field of an R-mechanism; C denotes the centre zone of the receptive field and S the surround zone. The hatched circle shows the edge of the retinal image of the circular target; row a) refers to the case when $T > T_C$, and row b) refers to the case when $T < T_C$. Columns 2) and



C = centre - zone of a 'red' (R)-mechanism receptive field
 S = surround-zone " " " " " "

Column 1 shows the receptive field of an R-mechanism.
 Column 2 shows the R-signal which only partly stimulates the mechanism. Column 3 shows the other temporal component of the stimulus for each of the two conditions; $T > T_c$ & $T < T_c$ (see text for further details.)

T - target size. (shaded regions indicate target retinal image)
 T_c - target size corresponding to size of C-zone.

Fig 80

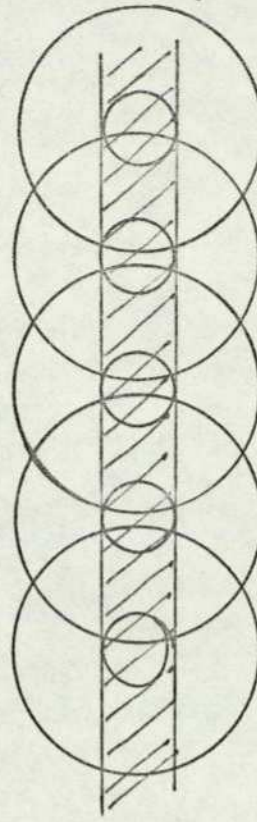


Fig. 81 Overlap of B-mechanism receptive fields.

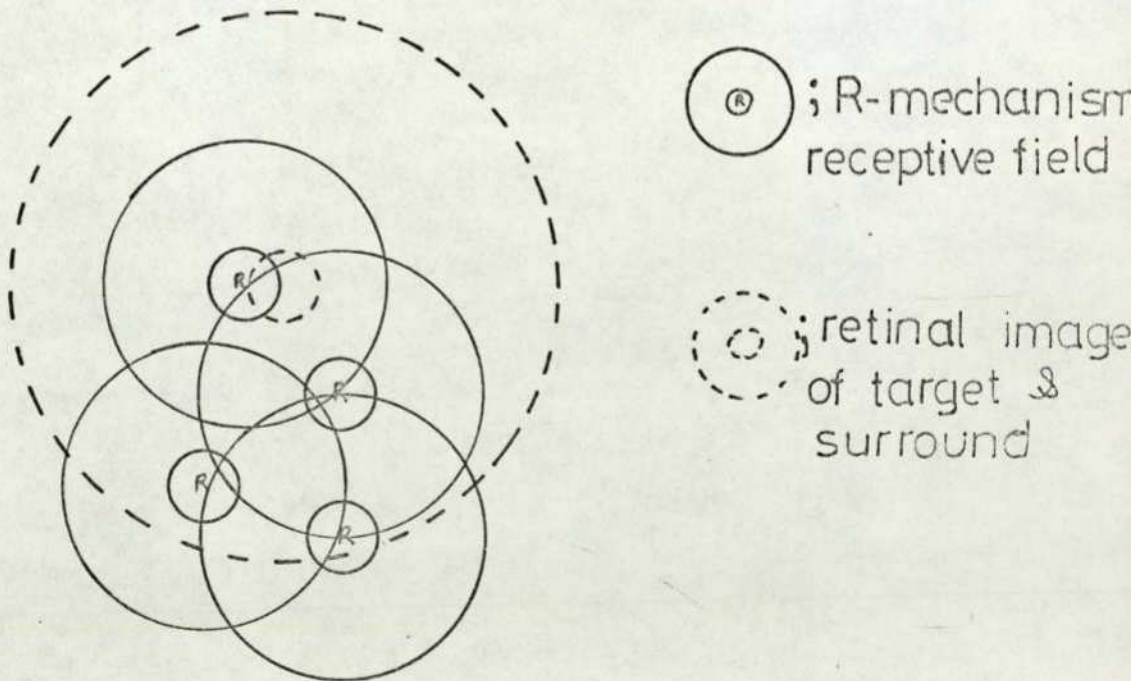


Fig.82 Stimulus retinal image in relation to some R-mechanism receptive fields

3) show the temporal features of the stimulus in both cases. Now, to produce the red subjective colour measured in this experiment, the R-mechanism requires an R-signal consisting of a 15msec light pulse delivered to the centre of the receptive field and a 75msec pulse delivered to the surround of the receptive field. For values of $T > T_c$, not all of the surround zone of the receptive field receives the required 75msec pulse, i.e. only the unshaded region in figure 80 (row a), column 1). Thus, the subjective colour producing input signal to the mechanism, from the surround zone is reduced, and as a consequence, a reduction of the subjective colour would be expected. The alteration of the temporal features (occurring since $T > T_c$) of the stimulus must also be considered. In fact, the temporal features may be regarded as two distinct components; the first is the R-signal (column 2), row a)) which the R-mechanism only partly receives, with $T > T_c$. The other component consists of two 15msec pulses (column 3), row a)), delivered to the shaded regions of the centre and surround zones of the receptive field. This last stimulus component is, in effect, a neutral signal which does not induce F-B subjective colour and this acts to only dilute the F-B colour.

For values of $T < T_c$, not all of the centre zone of the R-mechanism receptive field receives the required 15msec pulse i.e. only the shaded region in column 1, row b). Thus, the subjective colour producing input signal to the R-mechanism is reduced by similar spatial and temporal effects as described above. (The two temporal components of the stimulus, in this case, are shown in row b of figure 80).

When the retinal image of the target completely covers the receptive field, then the R-mechanism does not receive any of the R-signal and no F-B subjective colour would be expected. Thus, excitation purity functions shown in figure 76 (a, b) for both observers, suggest, if the above analysis is correct, that the centre of the R-mechanism receptive field is about 5' arc in size and the total extent of the receptive field is about (40-100)' arc. The results for the B-signal,

if the above analysis is applied to the postulated blue subjective colour inducing mechanism (B-mechanism), suggest that the centre of the receptive field is about $15'$ arc in size and the total extent of the receptive field is about $(40-100')$ arc. These figures for the B-mechanism are derived from the data obtained from the linear target condition, and the extra assumption is that to produce the colour effect throughout the whole length of the line target, the B-mechanism receptive fields overlap as shown in figure 81.

The shaded region in this figure shows the retinal image of a target which just covers the centre zone of each receptive field. By applying the same analysis as illustrated in figure 80, maximum saturation would be expected of the blue subjective colour for such a linear target.

The data have shown that little blue subjective colour was obtained with the foveally observed circular target stimulus condition. This may be due to the fact that blue receptors are sparse in the retina (see for example, WALRAVEN, 1973). The linear targets, stimulating more of the retina would lead to stimulation of more blue receptors.

It is important to mention that the decrease in saturation reflected in figure 76 (a, b) for values of $T < 5'$ may be partly if not wholly due to light spread from retinal regions adjoining the image of the target and not due to the reasons given previously. Spread of light from the surround 75msec light pulse onto the centre of either the B- or R-mechanism receptive field would add a neutral temporal signal to the stimulus i.e. two 75msec pulses; one stimulating the centre and the other the surround of the receptive field. The introduction of such a signal may well lead to a saturation reduction of the subjective colour. Evidence for the type of light spread required to produce this effect comes from WESTHEIMER and CAMPBELL (1962) and KRAUSKOPF (1962), who have shown that the retinal illuminance of a point $2'$ from a spatial rectangular illuminance variation is about 20 per cent of the maximum. If this light spreading hypothesis is correct, then the size of the centre

* A 'veiling light' effect operating on the target due to the surround, may also exist to reduce the subjective colour signal. (see, for example, STILES & CRAWFORD (1932)).

zone of both the B- and R-mechanisms may be less than indicated from the data.

The observation that not all of the light pulses appeared coloured for circular targets of 5' arc in diameter and with the R-signal employed, would be expected from the above discussion concerning the spatial shape and layout of the R-mechanism receptive field i.e. if the target produced a retinal image about the same size as the R-mechanism receptive field centre, then small involuntary eye movements would ensure that not every target pulse stimulated the receptive field centre to the required extent. To understand this more fully consider figure 82. In this figure, it is assumed that the receptive fields of the subjective colour inducing R-mechanisms overlap as shown. This is likely to be the case if the subjective colour inducing mechanisms are ganglion cells. Four receptive fields are given, and the retinal image of a target and annular surround in which red subjective colour is induced is shown by the hatched circles. Since the target retinal image is the same size as the receptive field centre, small eye movements would easily displace the image (as shown) so that little or none of an R-mechanism receptive field centre is stimulated. This behaviour would certainly be expected if colour coded ganglion cells are the subjective colour inducing mechanisms. GOURAS (1968, 1971), for example, has found that if the small light spot used to stimulate the receptive field centres of each of the colour coded (tonic) ganglion cells under study, was even slightly displaced, no discharge at all was obtained from the cell.*

The luminosity effects illustrated by the brightness gain curves are rather difficult to interpret. The main feature illustrated by the B-signal curves is that the luminosity of the target remained considerably reduced even for $T = 360'$. Thus, a surround inhibiting effect on the luminosity of the target takes place, and which operates over larger retinal distances than is likely for the surround effects responsible for the subjective colours. Such large range luminosity

* An alternative explanation may be in terms of the fluctuation theory of colour discrimination (see WALRAVEN and BOUMAN, 1966).

masking may well involve cortical mechanisms (DE VALOIS, 1971; and DE VALOIS and PEASE, 1971) as discussed in Chapter 5.

e) Experiment 4 (B)

For each subjective colour inducing mechanism, the extent of the receptive field surround can be measured more directly than in experiment 4 (A), by varying the extent of the stimulus surround. Graphs of excitation purity P_e vs. x mins arc (surround extent as shown in figure 71), should include a turning point $x = x_L$ say, where this value of x corresponds to the limit of the surround zone of the receptive field. For $x > x_L$, excitation purity should remain constant. For $x < x_L$, the shape of the curve will depend on the type of function relating the strength of the subjective colour effect to the area of stimulation within the receptive field. Now, if excitation purity is constant for $x > x_L$, this could reflect a non-linearity i.e. saturation, in the summation effects within the receptive field surround, rather than the actual limit of the field. To test this a black annulus (for the circular target condition) or black rectangles (for the linear target condition) could be introduced between target and surround. If the hypothesis that the turning point in the excitation purity vs. x function reflects the total extent of the receptive field, is correct, then the excitation purity vs. y mins arc (extent of the black surround as shown in figure 83) function should include a turning point at $y = y_L$, where $y_L = x_L$. For $y > y_L$, the excitation purity should remain constant and be the same as for the pulsed target (no surround) condition. Figure 83 shows the stimulus field for both the circular and linear target conditions, with the black rectangles or annulus introduced within a large surround of 14° total extent, as shown.

The first stage of experiment 4 (B) involved a determination of the excitation purity vs. x functions for both the circular and linear target conditions, using values of target size T mins arc, giving near optimum colour effects in experiment 4 (A) i.e. $5'$ arc for the red induction and $15'$ for the blue induction. The order of presentation of

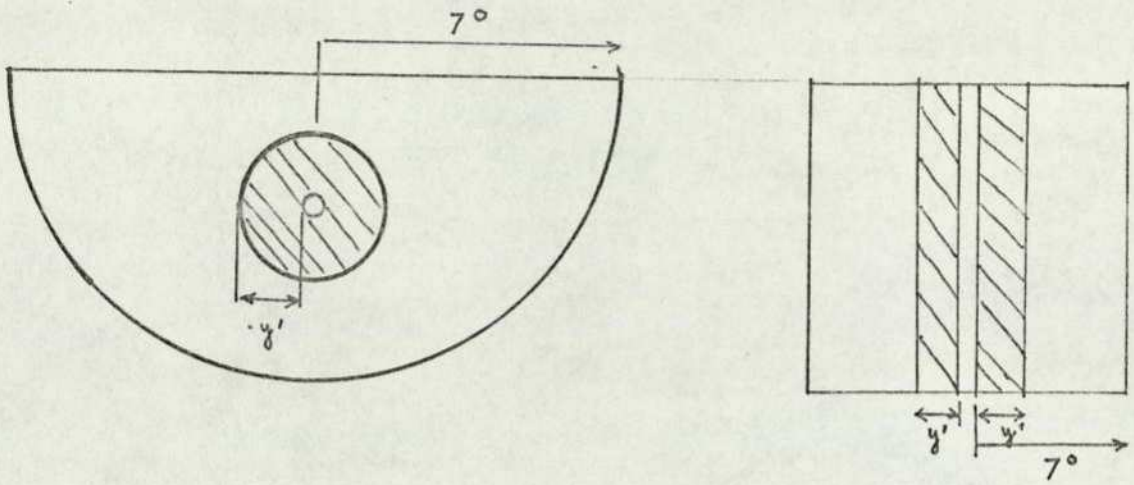


Fig. 83 Spatial arrangement of the stimulus field after the insertion of either a dark annulus or dark rectangles. (shaded region)

each surround in the stimulus field was randomised and the experimental procedure was similar to that described for experiment 4 (A). The R- and B-signals employed in experiment 4 (A) were again used.

f) Results

Figure 84 (a, b) shows the locations on the chromaticity diagram for colour matches made, as x was varied, with the circular target in use ($T = 5'$ arc). Data for both observers are given. The equivalent results under the linear target condition are shown in figure 85 (a, b). ($T = 5'$ for the red colour induction and $15'$ for the blue induction). From these data, excitation purity P_e vs. x curves were derived and these are shown in figure 86 (a, b) for the circular target condition and figures 86b and 87 for the linear target condition. Each of the purity curves contains the predicted turning point ($x = x_L$). With the R-signal, the value of x_L is about $30'$ for the circular target condition and for both observers. For the linear target condition, x_L is about $20'$ for the data obtained from observer J.R.J. with ^{both} the temporal signals employed. The x_L value for the data obtained from observer J.E.S. with the B-signal employed is about $30'$. It appears from the data, that the total diameter of the receptive field of both subjective colour inducing mechanisms is about 1° .

The brightness gain functions (figure 88 (a, b) for the circular target condition; figures 88b and 89 for the linear target condition) show similar turning points as in the purity data. The values of x_L for the data obtained from the circular target condition with the R-signal employed are $77'$ for observer J.R.J. and $30'$ for observer J.E.S. For the linear target condition, the values are $30'$ (observer J.R.J. with the R-signal employed), $22'$ (observer J.R.J. with the B-signal employed) and the data for observer J.E.S. are inconclusive. Extra data were collected for the B-signal employed in a stimulus where $T = 5'$ (observer J.R.J. only). The value of x_L in this case is about $30'$ arc (see figure 89). Thus the data reveal a mechanism concerned with the luminosity of

the target, which appears to have a receptive field of about the same size as each colour inducing mechanism receptive field.

To ascertain whether or not the x_L values obtained from each graph (purity and brightness gain data) reflect the size of the receptive field for each colour inducing mechanism (and the luminosity mechanism discovered), black rectangular areas or a black annulus were introduced in the stimulus field as discussed previously. The total stimulus field for each condition (rectangular or circular) is shown in figure 83. For the linear target, the black rectangles were introduced as shown, within a large rectangular surround subtending 14° . For the circular target, the black annulus was introduced within a large semi-circular surround subtending 14° in diameter. The data obtained for various intervening black annuli and rectangles are shown in figure 90 (a, b) for the linear target condition and figure 91 (a, b) for the circular target condition. The excitation purity values calculated from these data are shown in figure 92 (a, b) for the circular target condition and figures 93 and 92b for the linear target condition. For each purity curve, turning points ($y = y_L$) are found and furthermore, for $y > y_L$, the purity remains constant, and approximately the same value as for the pulsed target (no surround) condition. The values of y_L for the circular target data and with the R-signal employed are about $30'$ for both observers. This result indicates that the x_L and y_L values both being the same, reflect the limit of the surround zone of the R-mechanism receptive field. This conclusion is confirmed by the data obtained from the linear target condition with the R-signal employed, where the y_L value for observer J.R.J. is about $22'$ (x_L). The values of y_L for the B-signal are $22'$ for observer J.R.J. and between $20'$ - $30'$ for observer J.E.S. Thus, the general conclusion from all the x' and y' data is that since x_L is the same as or very similar to y_L for the purity data of each observer, when the appropriate two functions are compared, estimates of the receptive field size for each colour inducing mechanism have been obtained. It appears,

furthermore, that the total extent of both the R- and B-mechanism receptive fields is about 1° .

The brightness gain functions are shown in figure 94 (a, b) for the circular target condition and figures 94b and 95 for the linear target condition. For the circular target data y_L is about $30'$ for both observers. For the linear target data, y_L is about $30'$, obtained from the R-signal condition (observer J.R.J.), whereas the value is about $55'$ obtained from the B-signal condition (observer J.R.J.). The corresponding figure for observer J.E.S. is $30'$. The extra data obtained using the B-signal employed, in the small ($5'$) linear target shows y_L to be about $30'$.

When appropriate x_L and y_L values are compared, the similarity between them is not as great as for the purity data e.g. $x_L = 77'$ whereas $y_L = 30'$ for data obtained from the R-signal presented under the circular target condition (observer J.R.J.). Nevertheless, the general impression obtained from the results is that a luminosity influencing mechanism (for the subjective colours) has been discovered and its receptive field size appears to be the same or slightly larger in total extent, as each colour mechanism receptive field. A summary of the x_L and y_L values obtained from all the data (purity and brightness gain) is given in table 4. The turning points for the brightness gain curves have a small 'B' index to avoid confusion with the purity turning points.

obs.	signal	(T = 5')				(T=5', or 15')				(T = 5')	
		circular target				linear target				linear target	
		x_L	y_L	x_L^B	y_L^B	x_L	y_L	x_L^B	y_L^B	x_L^B	y_L^B
J.R.J.	R	30	30	77	30	20	22	30	30	/	/
	B	/	/	/	/	20	22	22	55	30	30
J.E.S.	R	30	30	30	30	/	/	/	/	/	/
	B	/	/	/	/	30	20-30	?	30	/	/

Table 4

The standard deviation calculations obtained from the brightness gain data in both this experiment (4B) and experiment 4A have a similar order of magnitude, being that found from the brightness gain data of experiment 3. For the C.I.E. x, y chromaticity coordinate determinations, the standard deviation calculations were also of the same order of magnitude as found in experiment 3. No systematic variation was found to occur as target width was varied, nor did changing the matching procedure (circular or linear target matching condition) effect the accuracy of the subjective colour determinations.

g) General discussion and conclusions

For the hypothesized red subjective colour-inducing mechanism (whose retinal receptive field is assumed to possess a centre-surround spatial configuration), the following points have emerged from experiment 4 (A, B). Firstly, the receptive field possesses a very small centre, less than or equal to 5' arc. Due to the possible effects of light spread in the retinal image of each stimulus employed, it was argued that an exact determination of the size of this centre process was perhaps, not possible. Secondly, the total extent of the receptive field appears to be in the order of 1° . These dimensions refer to red colour inducing mechanisms located in the fovea. Estimates of the total extent of the receptive field using linear targets, which stimulated both foveal and extra-foveal retinal regions (and involved a slightly different matching technique), are in general agreement with this figure. Thirdly, the introduction of a small black area between the target and surround components of the stimulus field does not prevent the colours from being manifested although the saturation of the subjective^{colour} is always extremely small.* A further point obtained from the red subjective colour data is that since foveally viewed stimuli of a small total extent still elicit the subjective colour, it can be concluded that rod activity does not play a role in the R-mechanism.* (Thus, target and surround do not have to be absolutely adjacent in the stimulus field.) Whether or not sharply

defined edges are necessary in the stimulus field has yet to be investigated. An experiment designed to test this could be carried out, by introducing various degrees of blur in the retinal image of the stimulus and re-measuring the subjective colours. The drug (cyclopentolate-hydrochloride) could be inserted in the observer's right eye to fix his accommodation and a variety of blurred conditions, introduced by placing positive lenses in front of the treated eye.²² For the hypothesised blue subjective colour inducing mechanisms (whose retinal receptive field is assumed to have the same centre-surround type of configuration as the red mechanism's receptive field), the following points have emerged. Firstly, the retinal receptive field of this mechanism possesses a larger centre than the red-inducing mechanism's receptive field, being estimated at about 15 mins arc. Secondly, the total extent of the receptive field seems to be similar to that for the red mechanism. Thirdly, the introduction of a black area between target and surround produced similar effects on excitation purity values as in the red mechanism case.

Applying the rationale used to interpret the excitation purity vs. x, y curves, to the brightness gain vs. x, y data, the conclusion is drawn that a mechanism responsible for the luminosity of each target in which F-B subjective colour was induced, exists and has a receptive field of about 1° total extent. The brightness gain data vs. T (target size) curves clearly show that the luminosity of the central region of targets as large as 6° is considerably reduced when F-B subjective colour inducing signals are observed. This "long range" luminosity reducing effect cannot be accounted for by a single mechanism having a receptive field of about 1° . A plausible explanation of the

FOOTNOTE 22; By removing the optical correction to his right eye (-2.75D), observer J.R.J. was able to view the stimulus with a degree of blurring imposed. The colour effects were found to be still clearly visible although no data were collected.

luminosity effects is the existence of a two-component mechanism as discussed in Chapter 5. One component, possibly retinal, having a 1° receptive field and the other, possibly cortical, acting as a "filling in" process. A "long range" colour inducing effect operating over distances of the order of 6° was not found in this experiment.

The two measuring techniques employed in experiment 4 (A, B) have produced similar estimates for the red subjective colour induced in the circular and linear targets. It will be recalled that one technique involved the observer fixating at a spot between the colorimeter field and the stimulus field whereas the other technique involved the observer transferring his gaze from the stimulus to the colorimeter light patch to make a match. Both these techniques have been employed before in the measurement of hue shifts associated with an intermittent coloured light source. The first method mentioned above has been employed to measure the hue shifts in a small rectangular target (NILSSON and NELSON, 1971) and the second method by BIJL and VERINGA (1971). The results of experiment 4 (A, B) have shown both methods equally effective in measuring temporally-based subjective colour.

Finally, the suggestion made previously in this chapter, that colour coded ganglion cells may be the F-B subjective colour mechanisms, will now be discussed. Now, the electrophysiological information available on the activity of ganglion cells in the rhesus monkey (whose colour vision resembles that of man) suggests (as discussed briefly in Chapter 1) that some higher primate ganglion cells can be divided into two types (GOURAS 1968, 1971). Both types have receptive fields with a centre-surround spatial arrangement (similar to the receptive field organisation of the postulated colour inducing mechanisms). One kind of ganglion cell found, was termed "phasic" since it responds

FOOTNOTE 23; Both on and off-centre ganglion cells were found by Gouras. The results for only on-centre cells were given by this author since off-centre cells appear to be far less common in number.

only transiently to maintained stimuli. This cell type receives signals from both red and green cone mechanisms, both of which excite in the centre and inhibit in the periphery of the cell's receptive field. An input from the blue sensitive cone mechanism to this cell type is absent (or too weak to be detected). The second type of cell examined was termed "tonic" by Gouras, since it responds continuously to maintained stimuli. Cells of this type receive excitatory signals from only one cone mechanism, either blue, red or green in the centre and inhibition from another cone mechanism in the periphery of its receptive field. Surround antagonism from the same cone mechanism which controls the centre of the receptive field of a tonic cell was not found. It appears from the findings of Gouras that phasic cells are contained within the luminosity information channel and tonic cells are concerned with the transport of information within the colour channels of the rhesus monkey visual system. Tonic cells receiving excitatory signals from either red or green sensitive cone mechanisms have smaller receptive field centres than those receiving excitation from the blue sensitive mechanism. Furthermore, the receptive field centres for the former cell types are extremely small (of the order of a few minutes of arc). The same state of affairs seems to exist for the red and blue subjective colour mechanism receptive field centres.

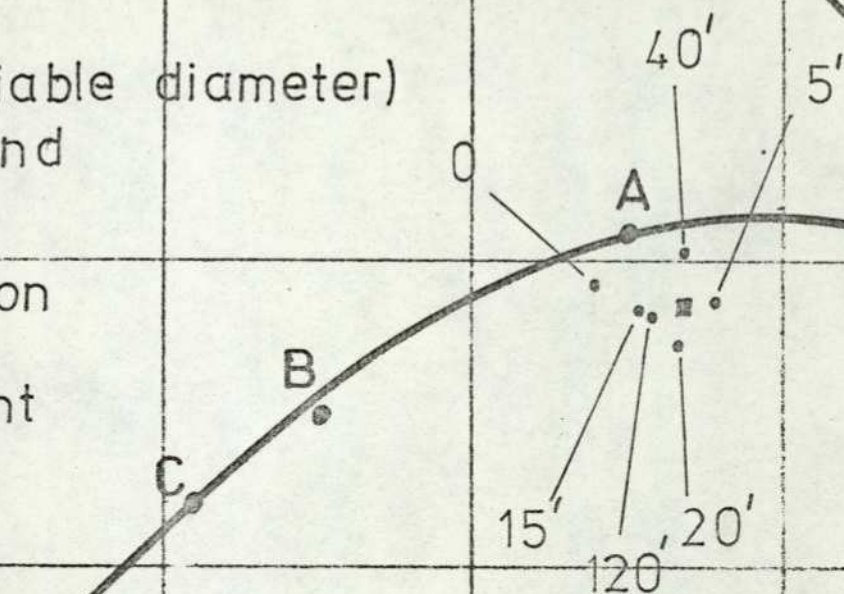
Thus, the results of experiment 4 (A, B), together with the failure to elicit the subjective colours with dichoptic presentation of the stimulus (experiment 3), suggests the hypothesis that the subjective colour inducing mechanisms in the visual system, are tonic ganglion cells, is plausible. The receptive fields of phasic cells appear to have a slightly greater size than the tonic cell receptive fields. Thus, the luminosity mechanism discovered in experiment 4B may well be the phasic ganglion cell.

Fig 72(a) Obs JRJ

Circular target (variable diameter)
no surround

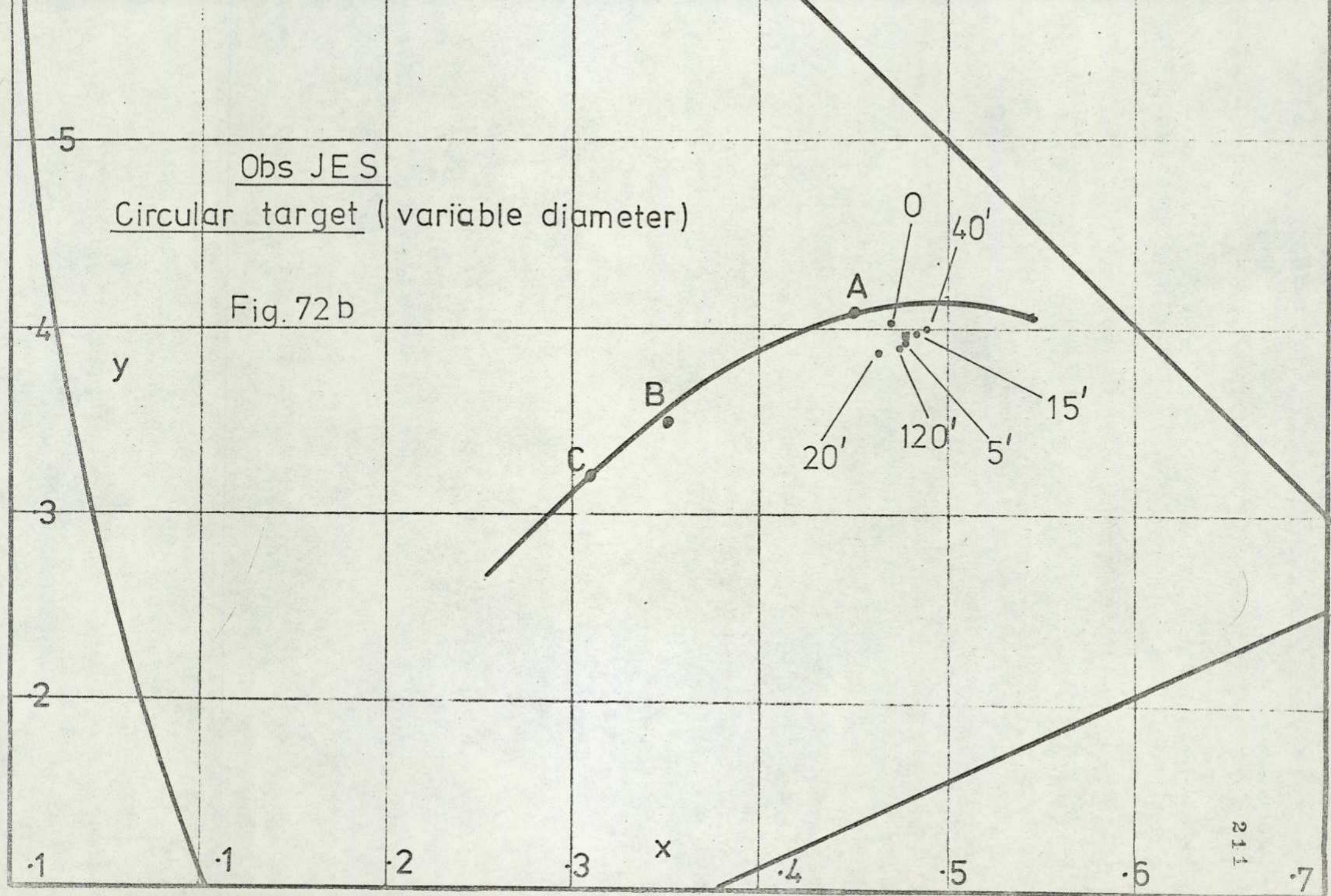
y 0 — steady condition

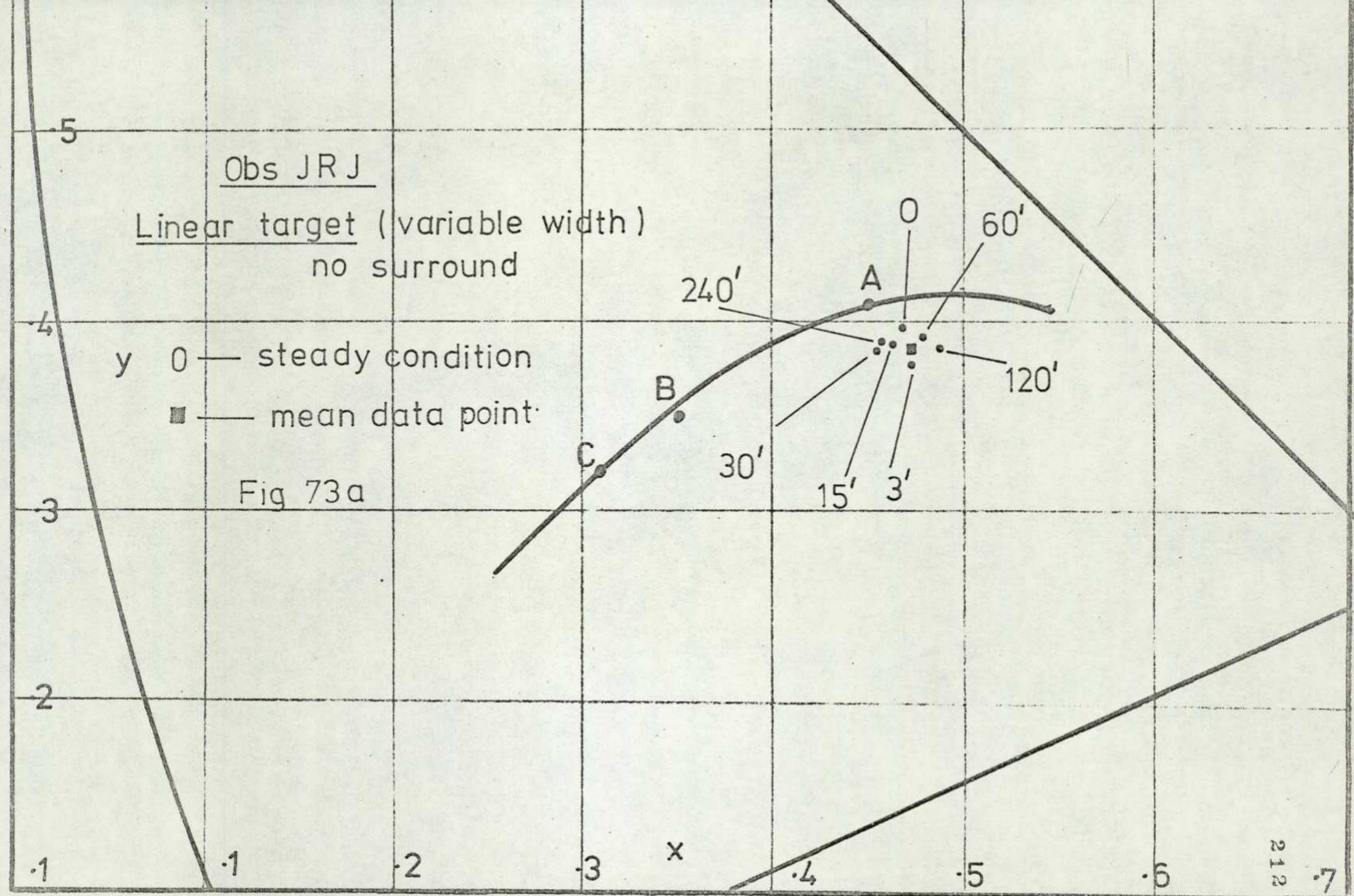
■ — mean data point

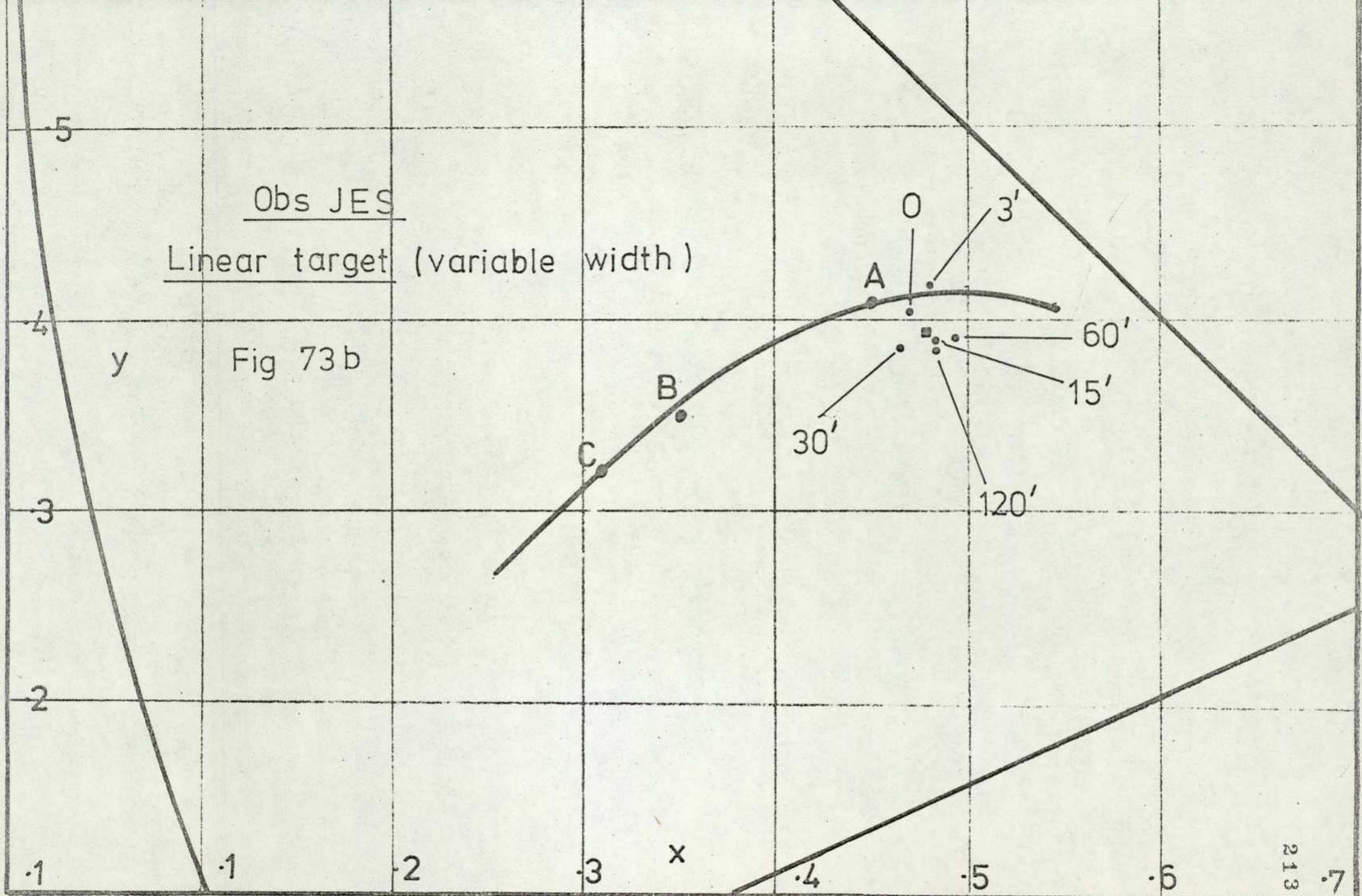


Figs 72-73 Colour appearance of pulsed targets of various sizes

figures denote target size (mins. arc)







5

Fig 74a Obs JRJ

Linear target (variable width)

'R'-signal ; ●

y 'B'-signal ; ■

($x' = 360'$)

4

3

2

1

480

Figs 74-75

Colour of targets of various sizes with the red and blue inducing signals employed

x

214

7

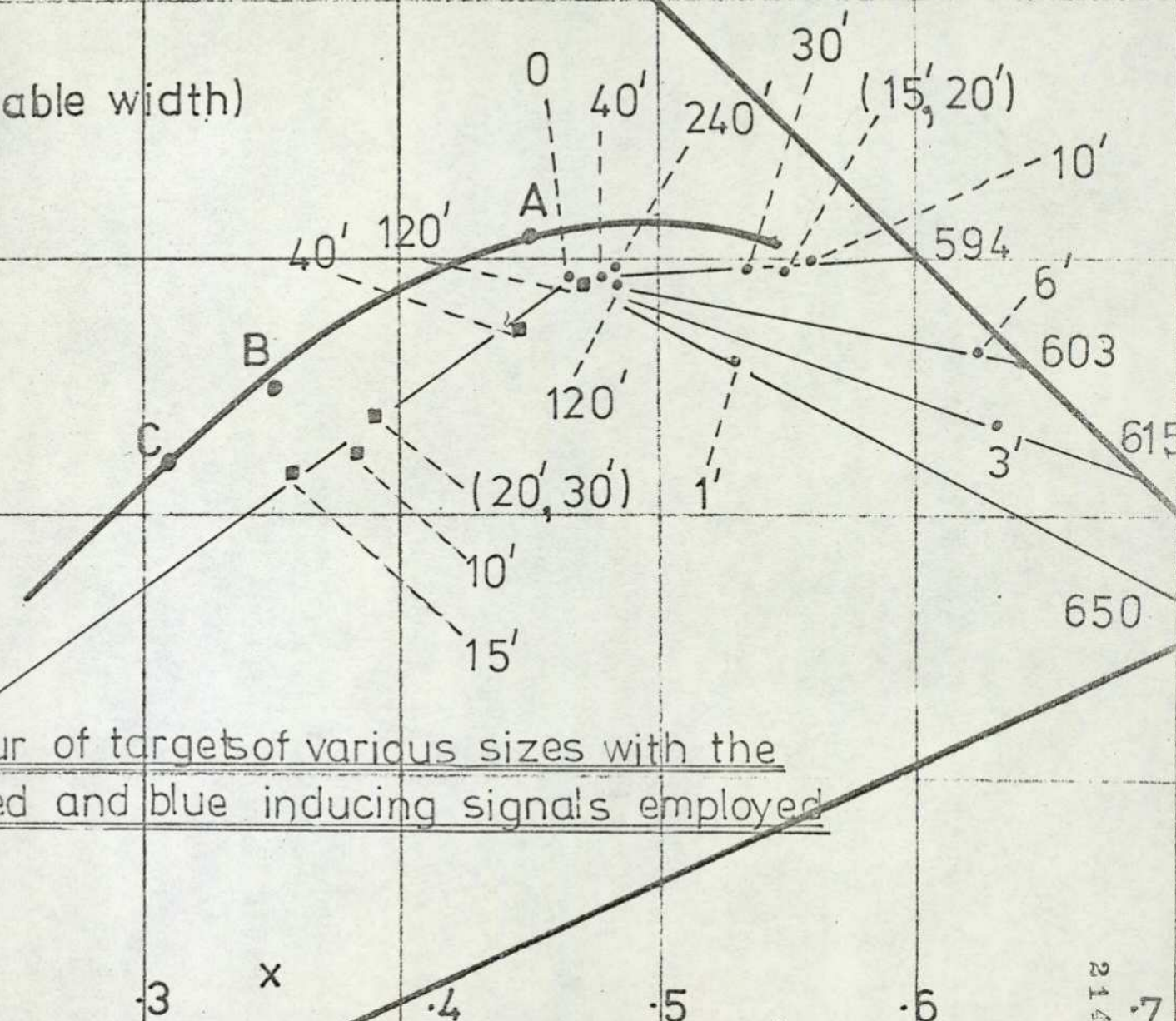


Fig 74b Obs JES

Linear target (variable width)
'B' — signal

y (x = 360')

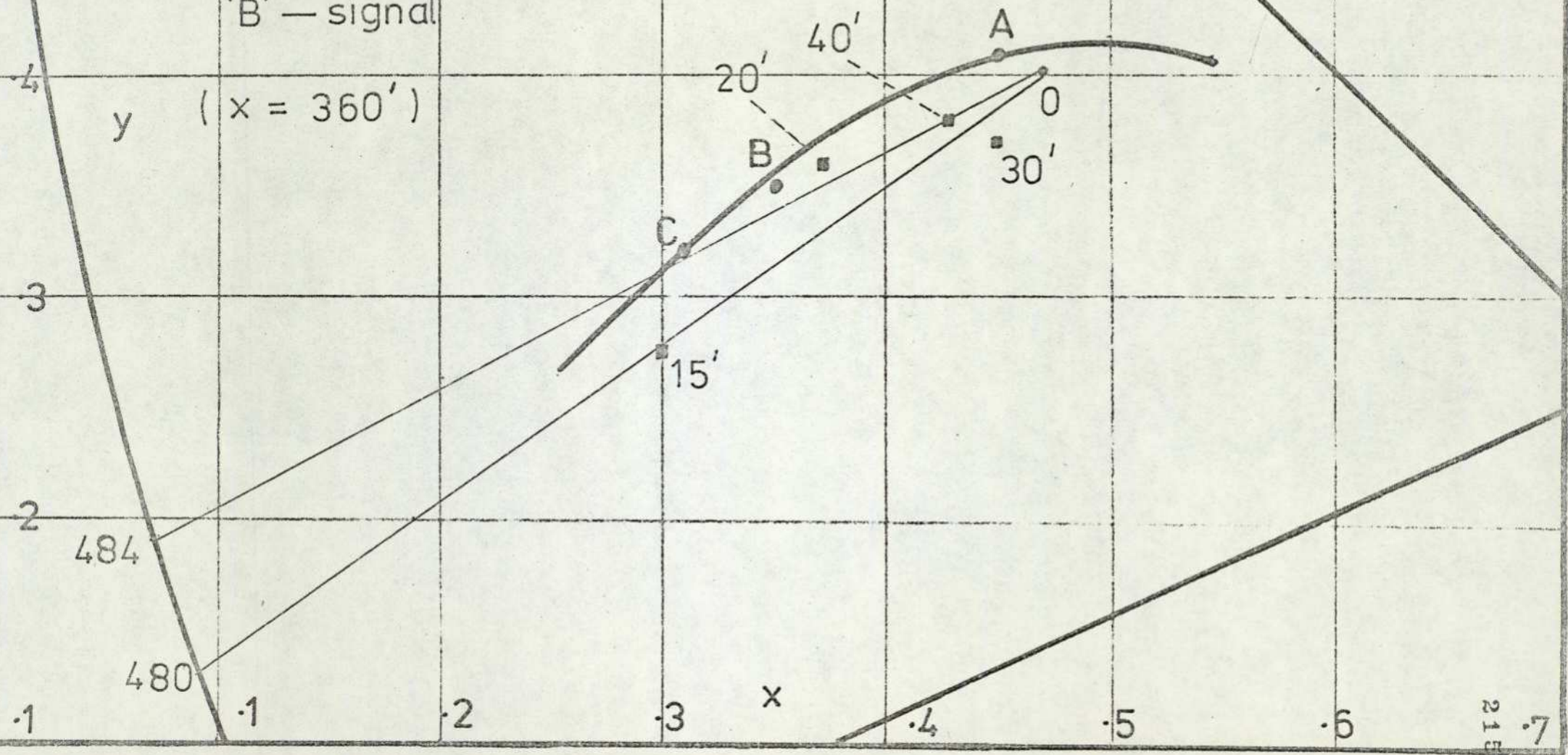


Fig 75a Obs JRJ

Circular target (variable dia.)

'R'— signal ; ●

'B'— signal ; ■

(x = 360')

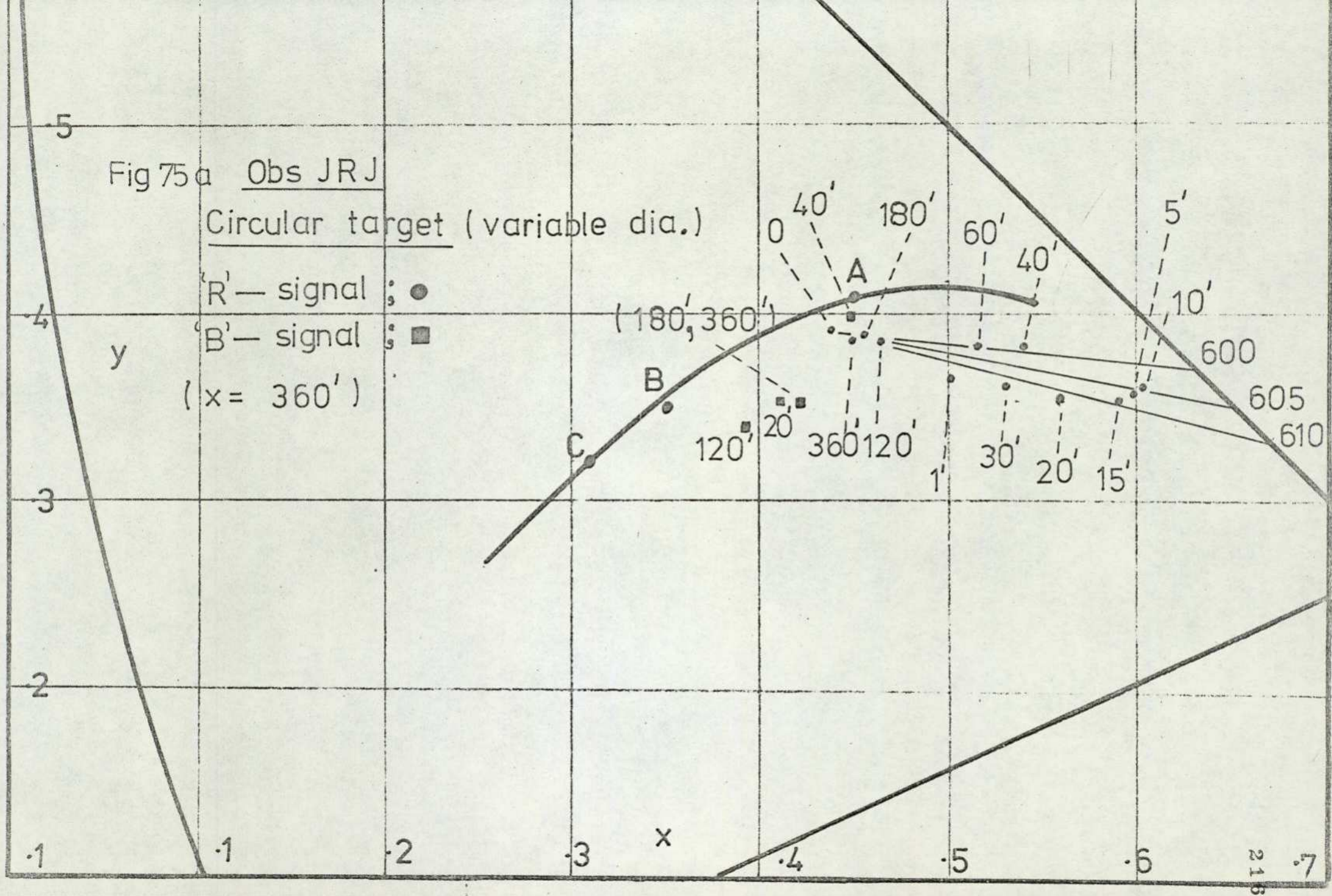


Fig 75 b

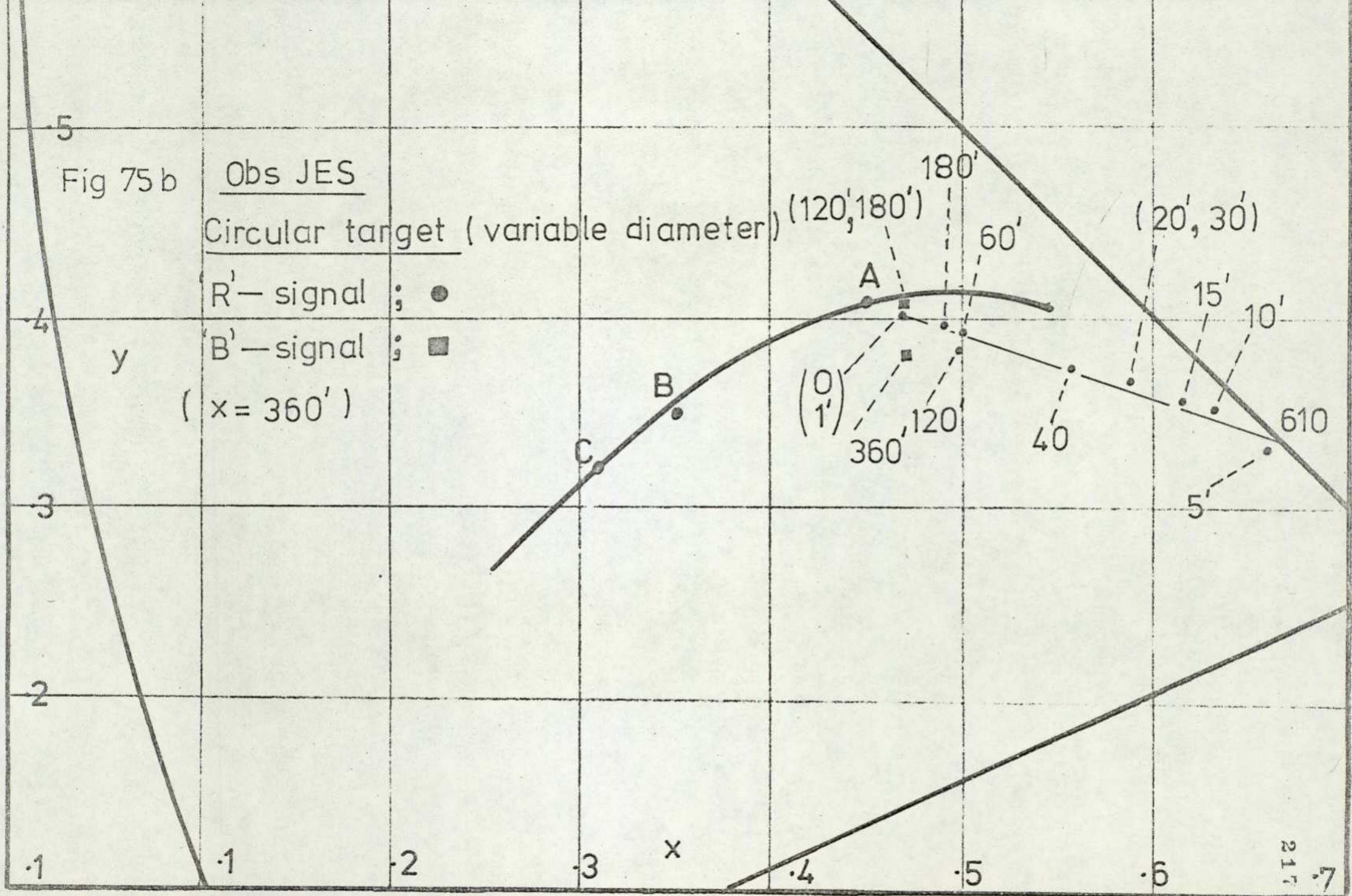
Obs JES

Circular target (variable diameter)

R'—signal ; ●

B'—signal ; ■

(x = 360')



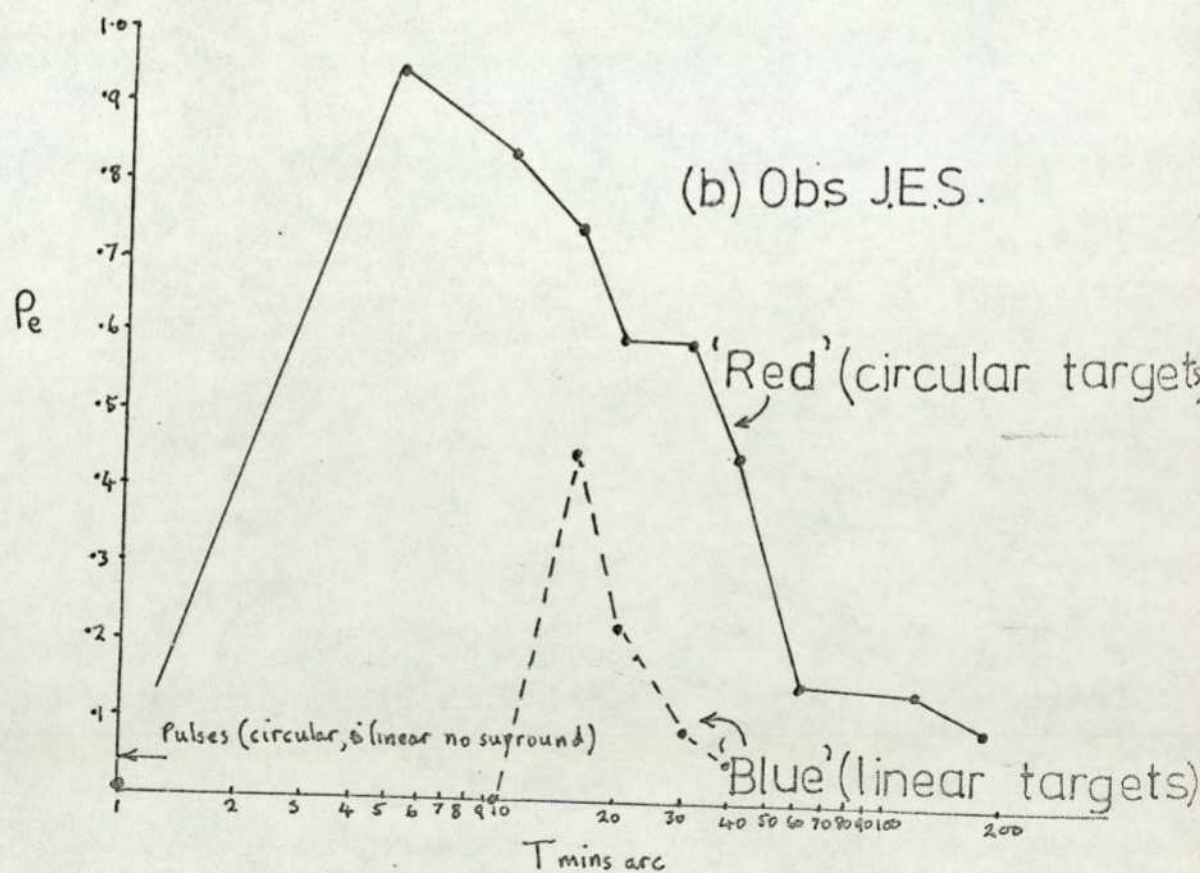
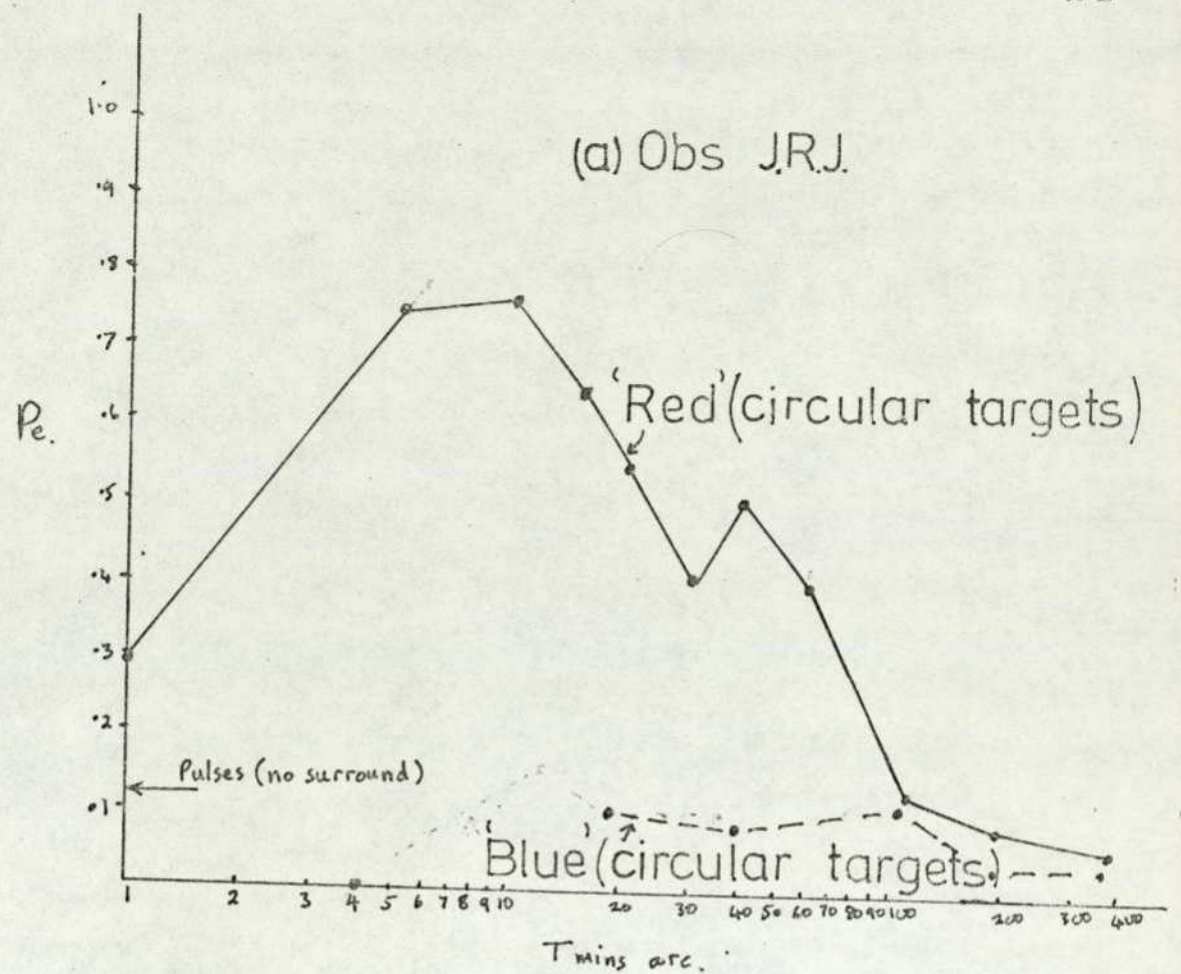


Fig. 76. Purity vs. target size

Fig 77 Purity vs. target size

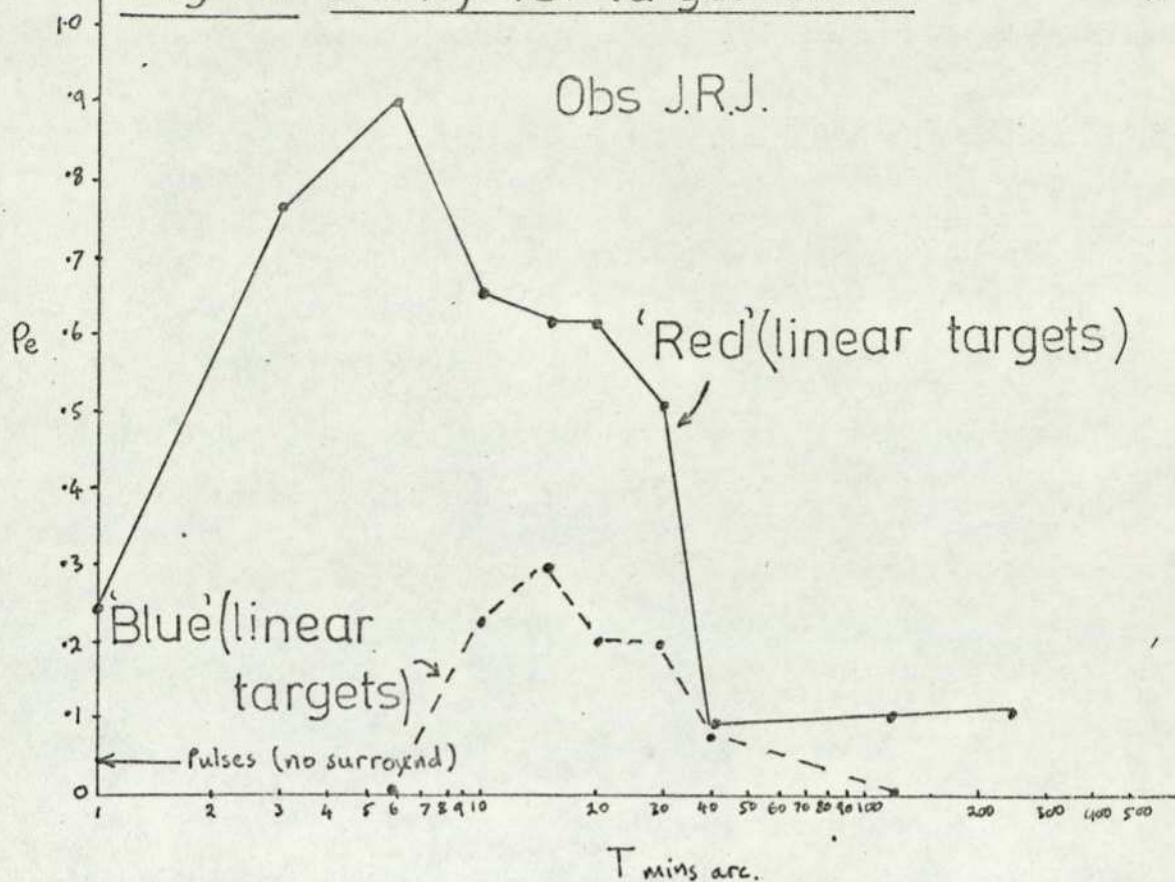
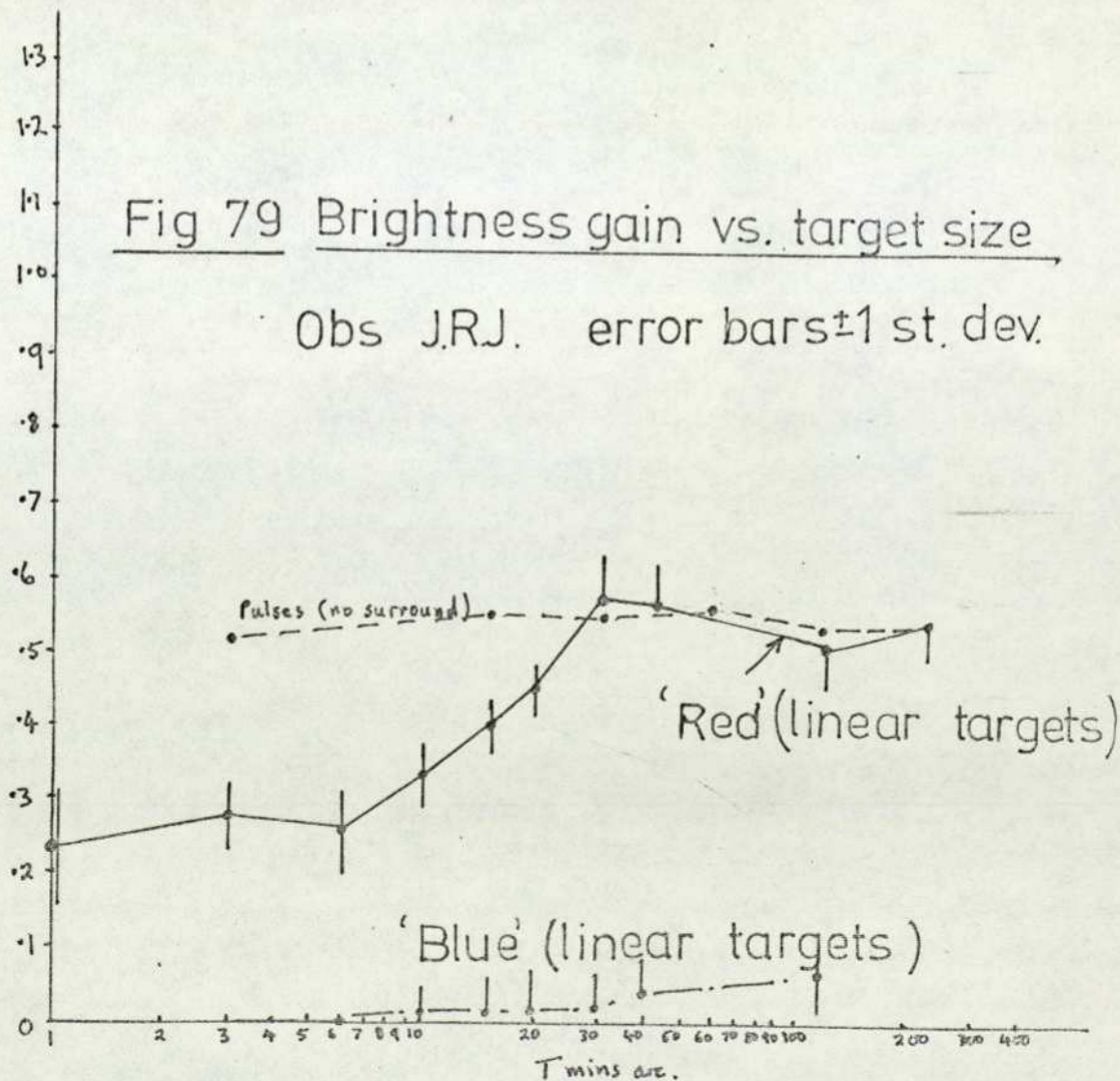


Fig 79 Brightness gain vs. target size

Obs J.R.J. error bars ± 1 st. dev.



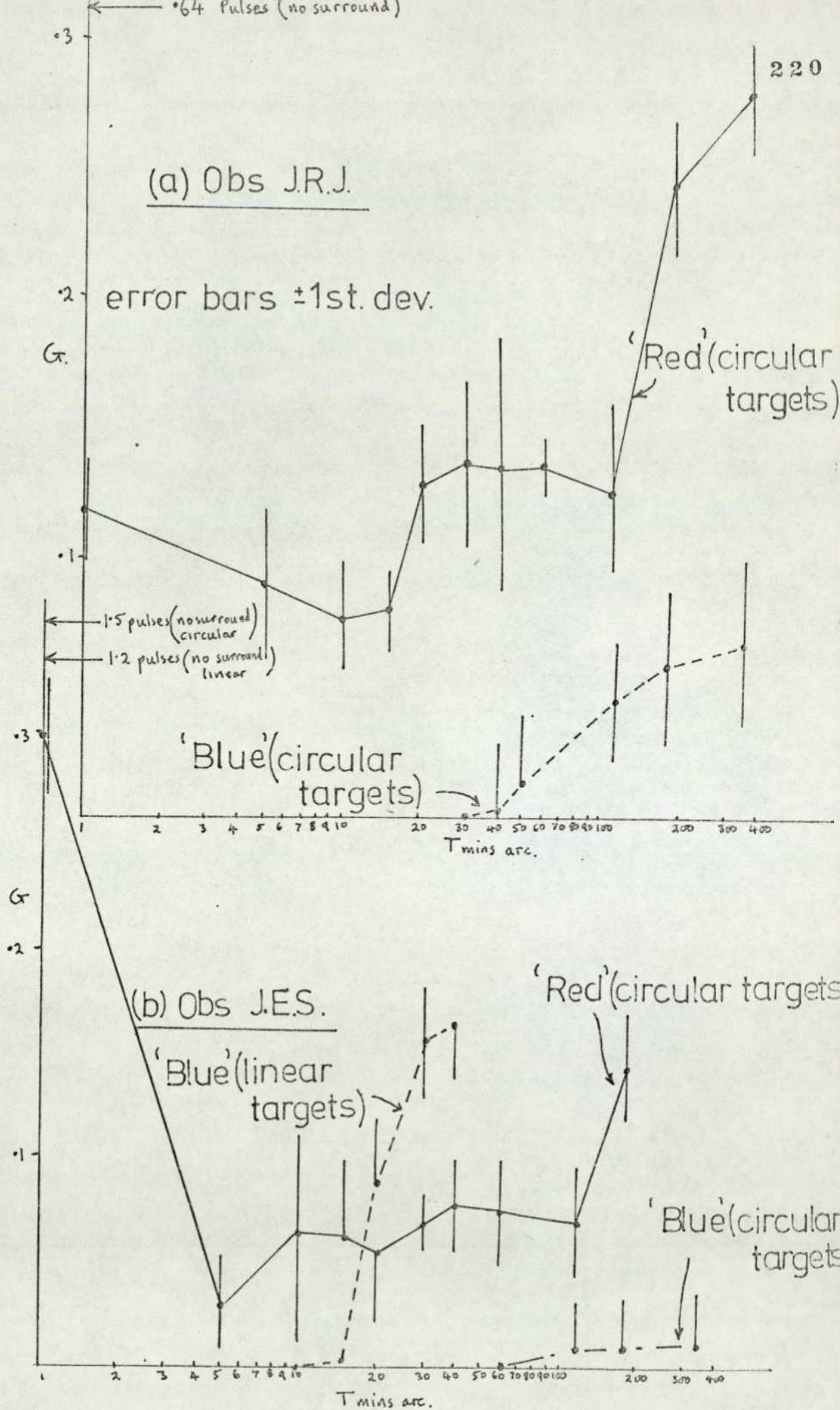


Fig 78 Brightness gain vs. target size

Fig 84a Obs JRJ

Linear target (variable surround)

x'

y

●; 'R' — signal

■; 'B' — signal

$\left[\begin{array}{l} T = 5' (R) \\ T = 15' (B) \end{array} \right]$

5

4

3

2

1

1

2

3

x

4

5

6

7

Figs 84 -85 Colour appearance of pulsed targets with various surrounds

R and B signals employed, figures denote surround size (see fig 71)

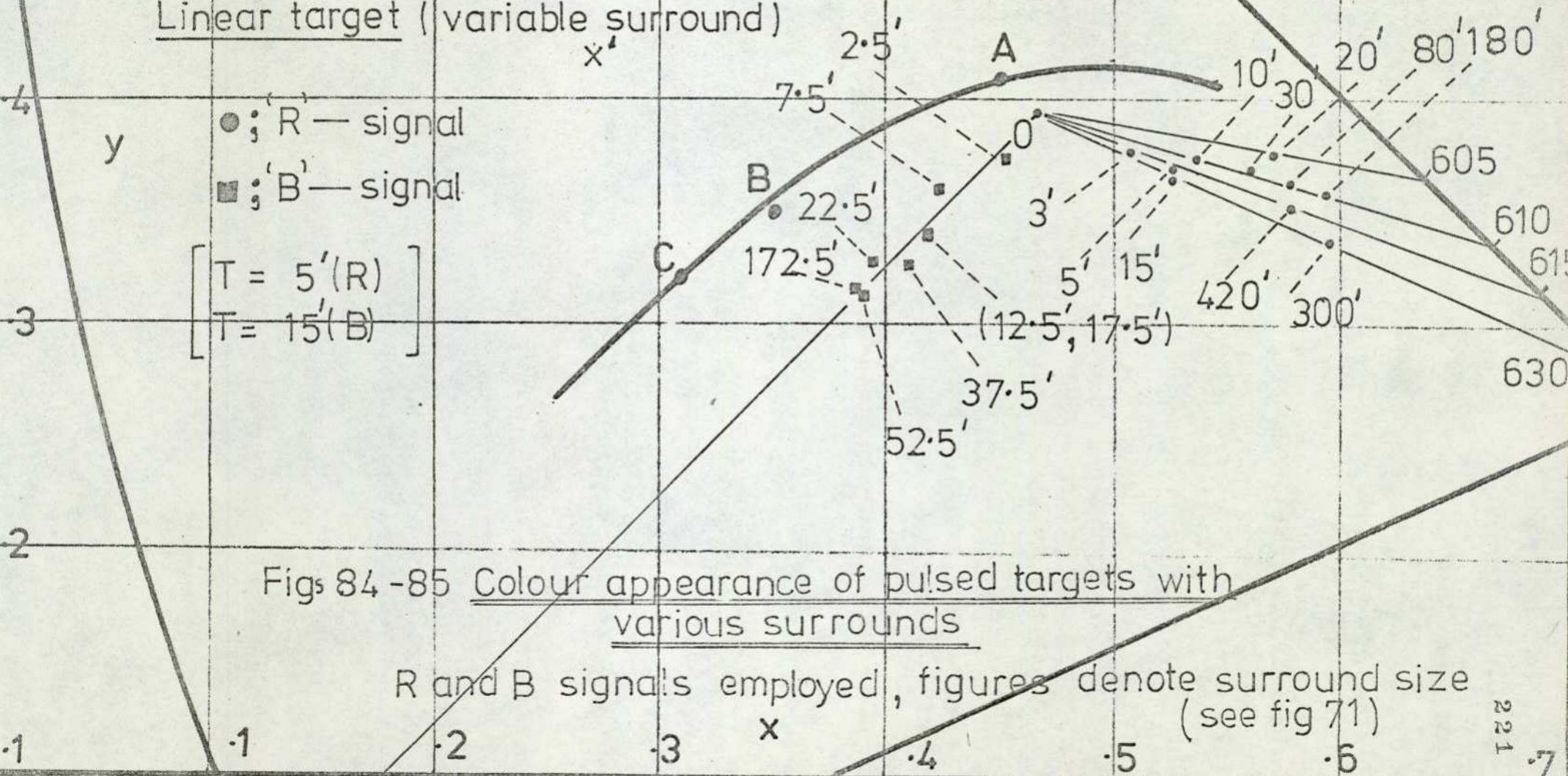


Fig 84b Obs JES

Linear target (variable surround)
'B'-signal

(T = 15')

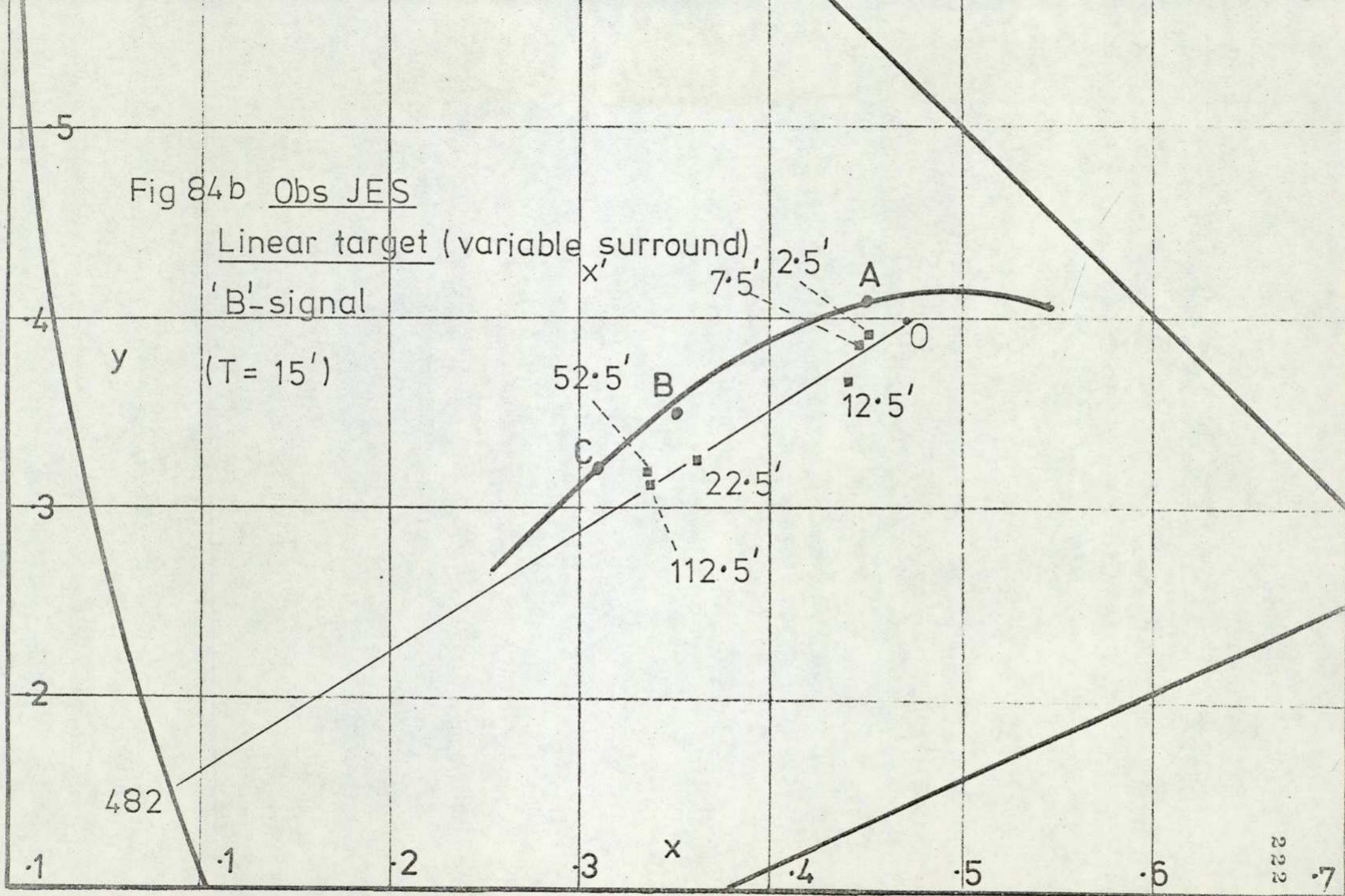


Fig 85a. Obs JRJ

Circular target (variable surround)

y 'R'-signal
($T=5'$)

x'

x

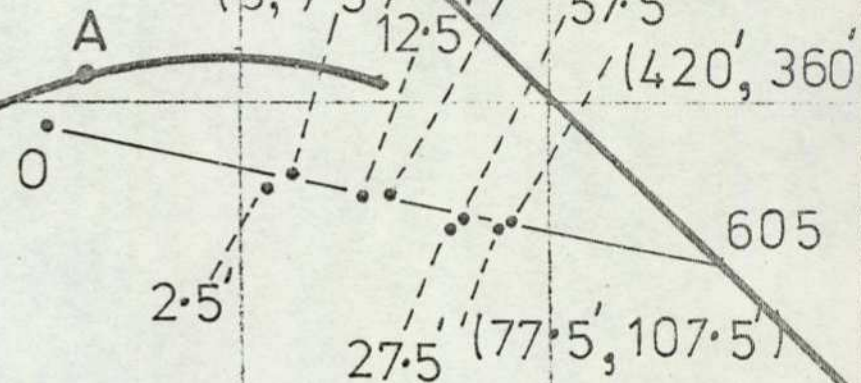
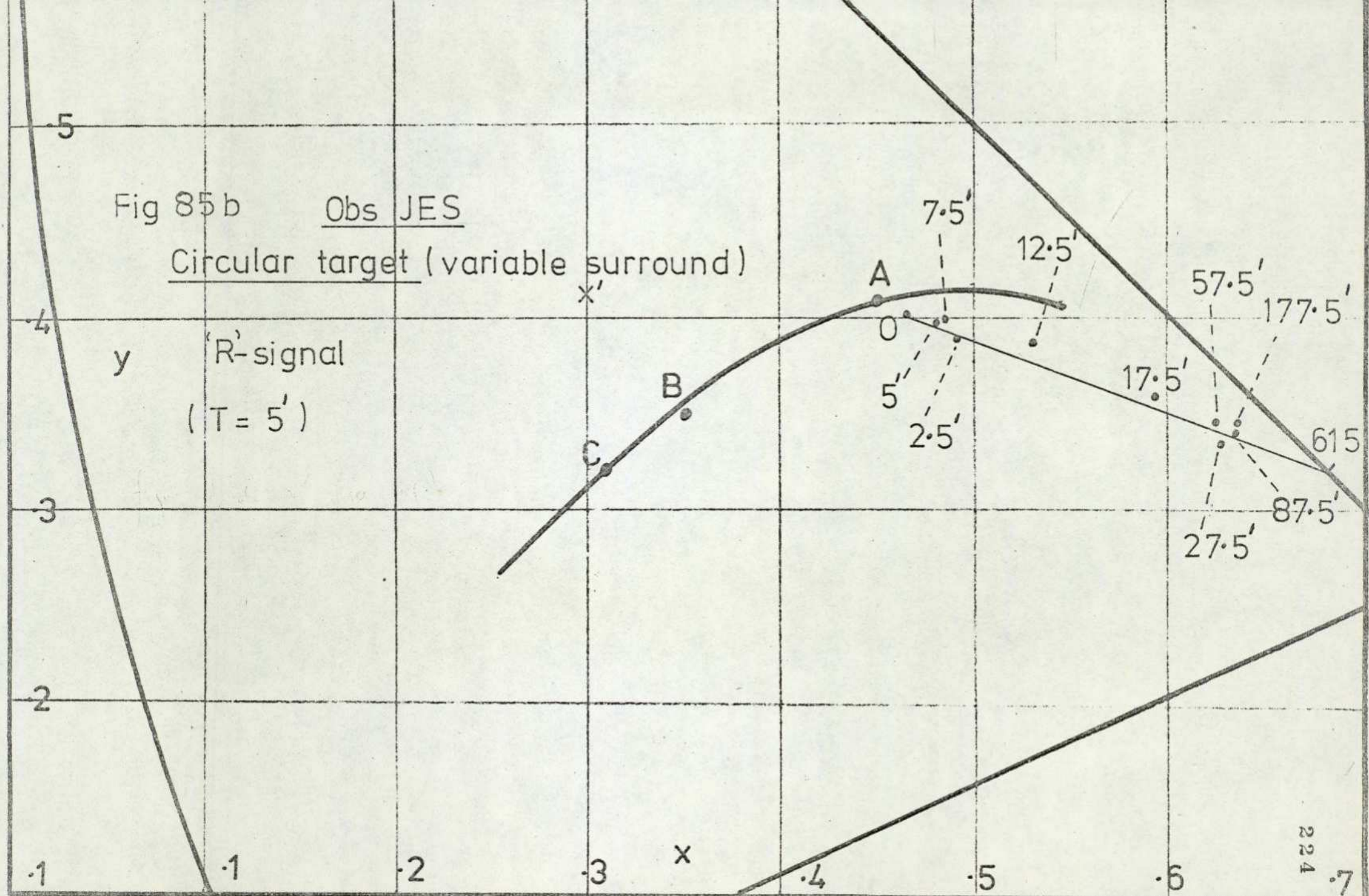


Fig 85 b Obs JES

Circular target (variable surround)



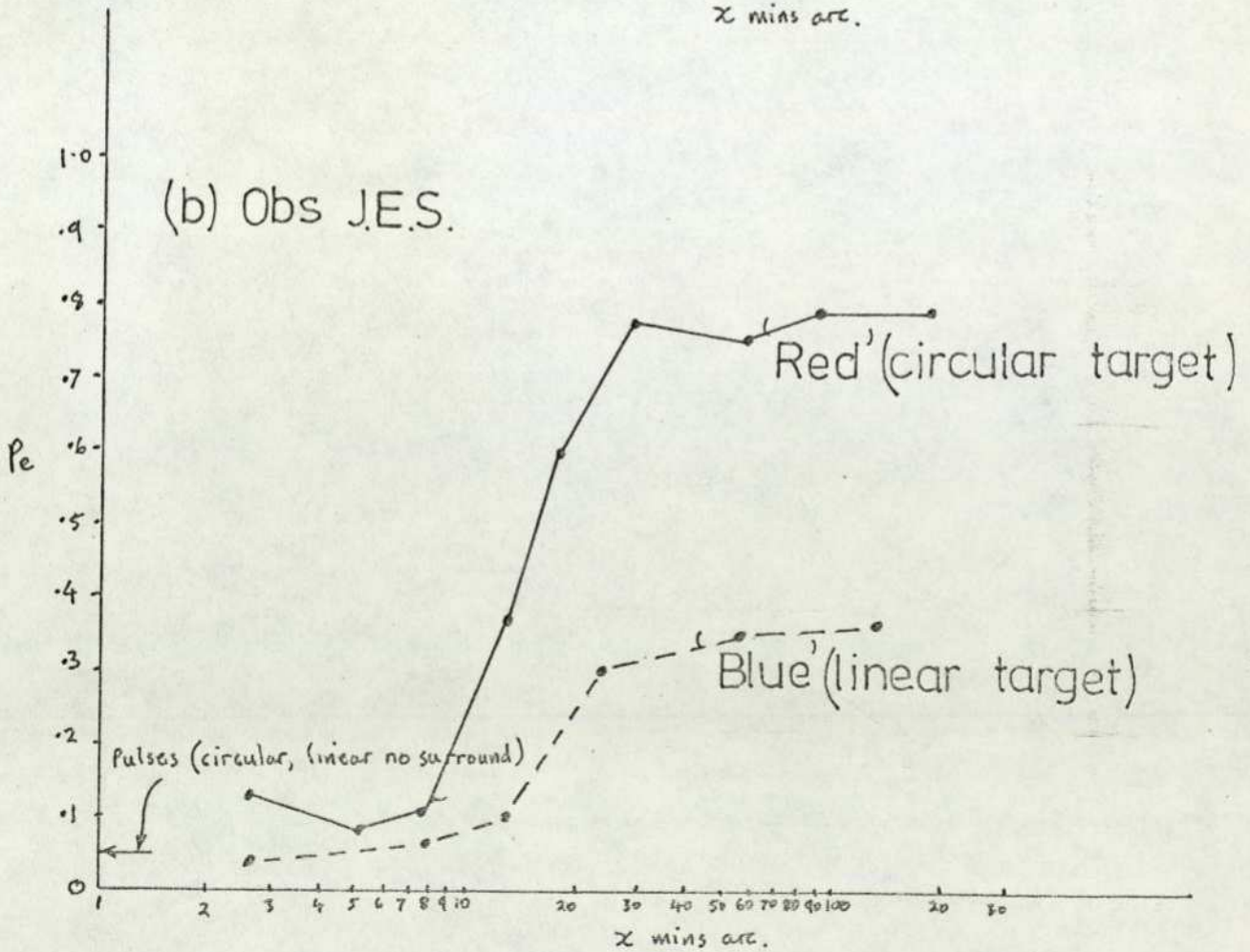
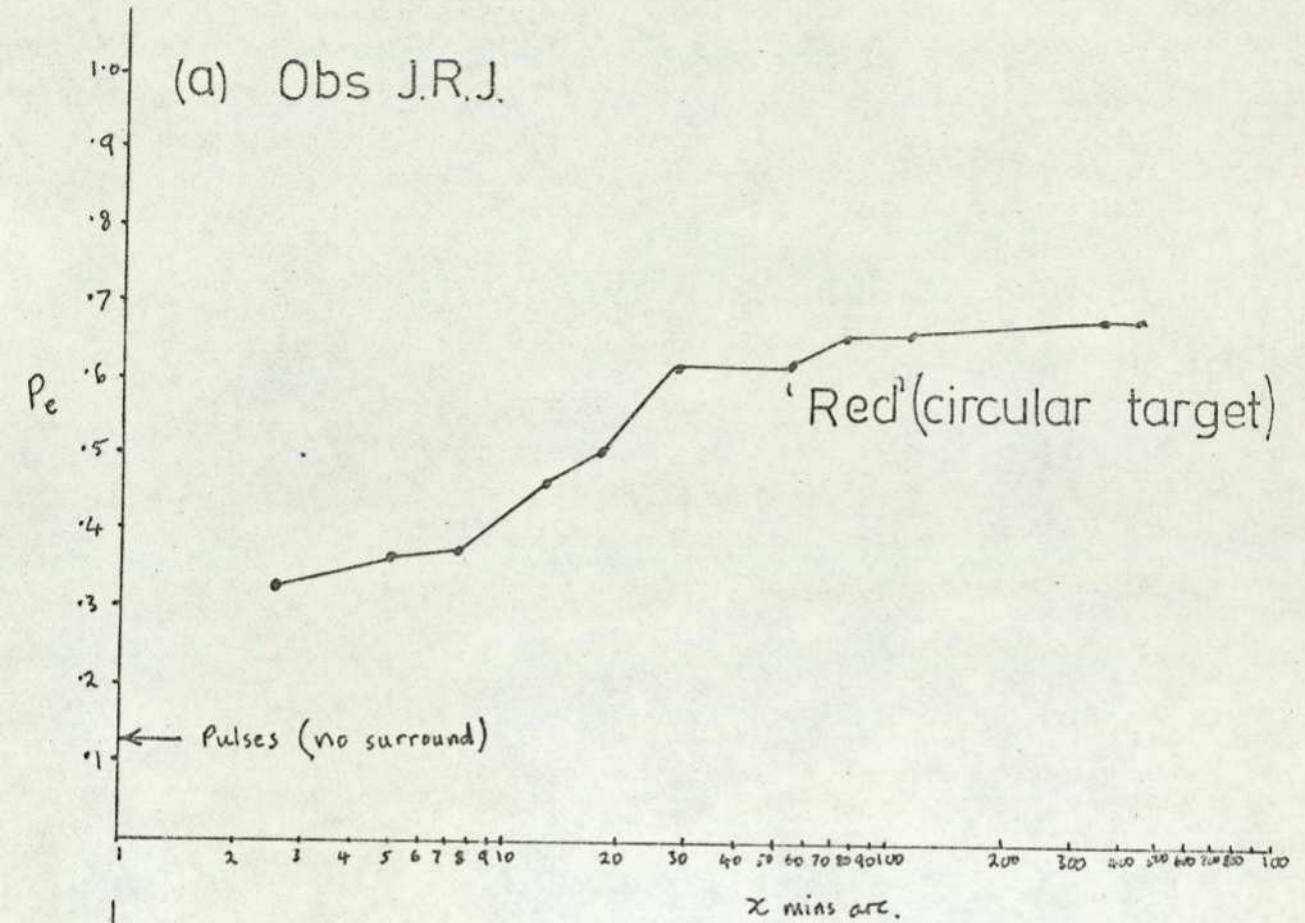


Fig 86 Purity vs. surround extent

Fig 87 Purity vs. surround extent

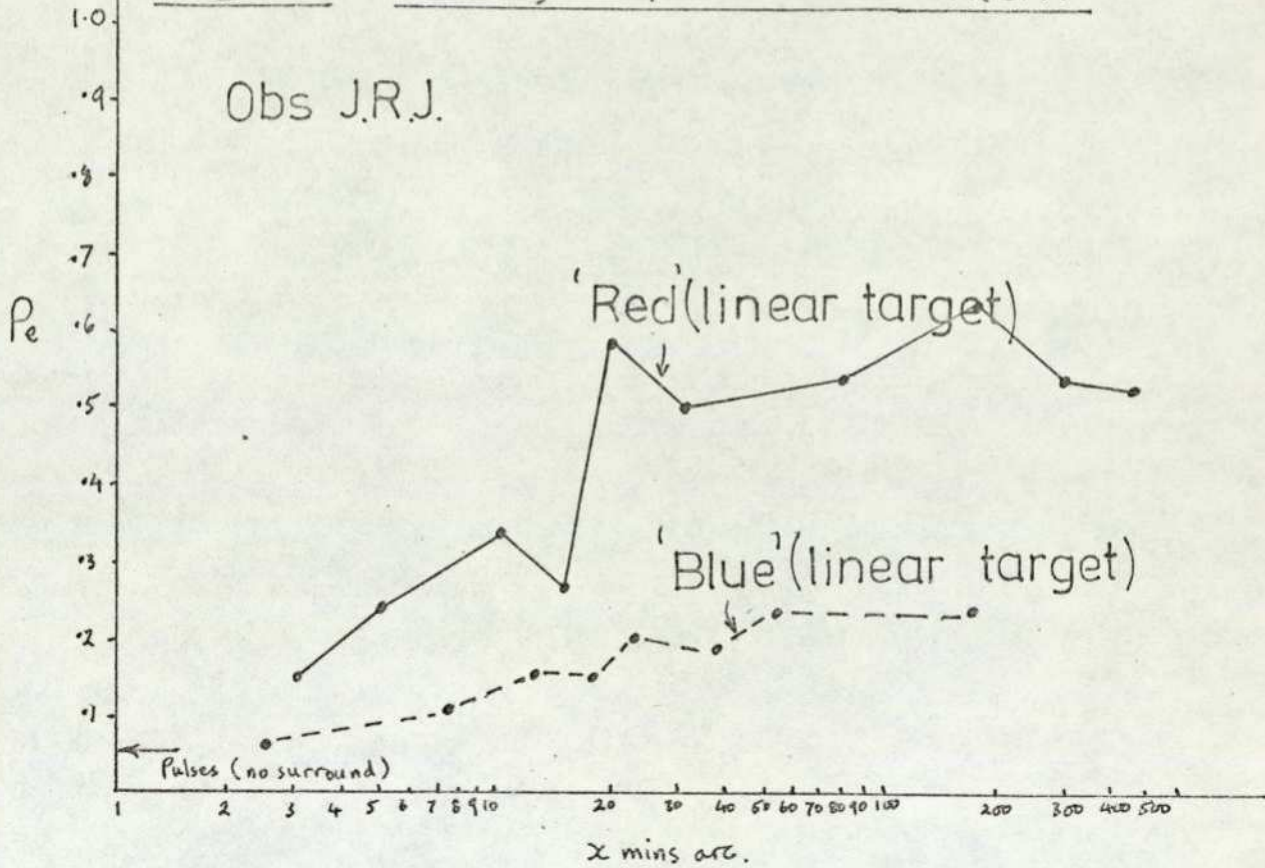
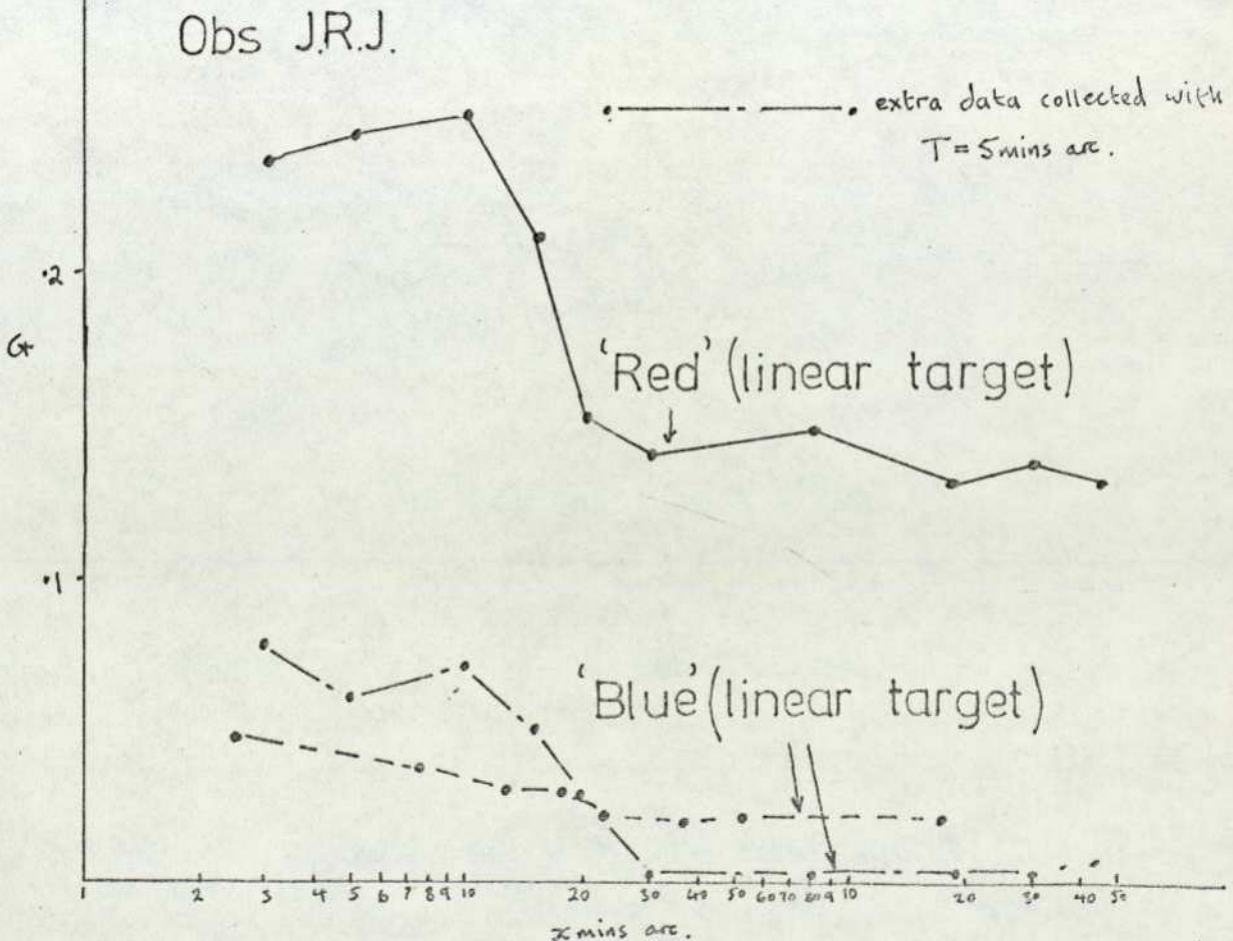
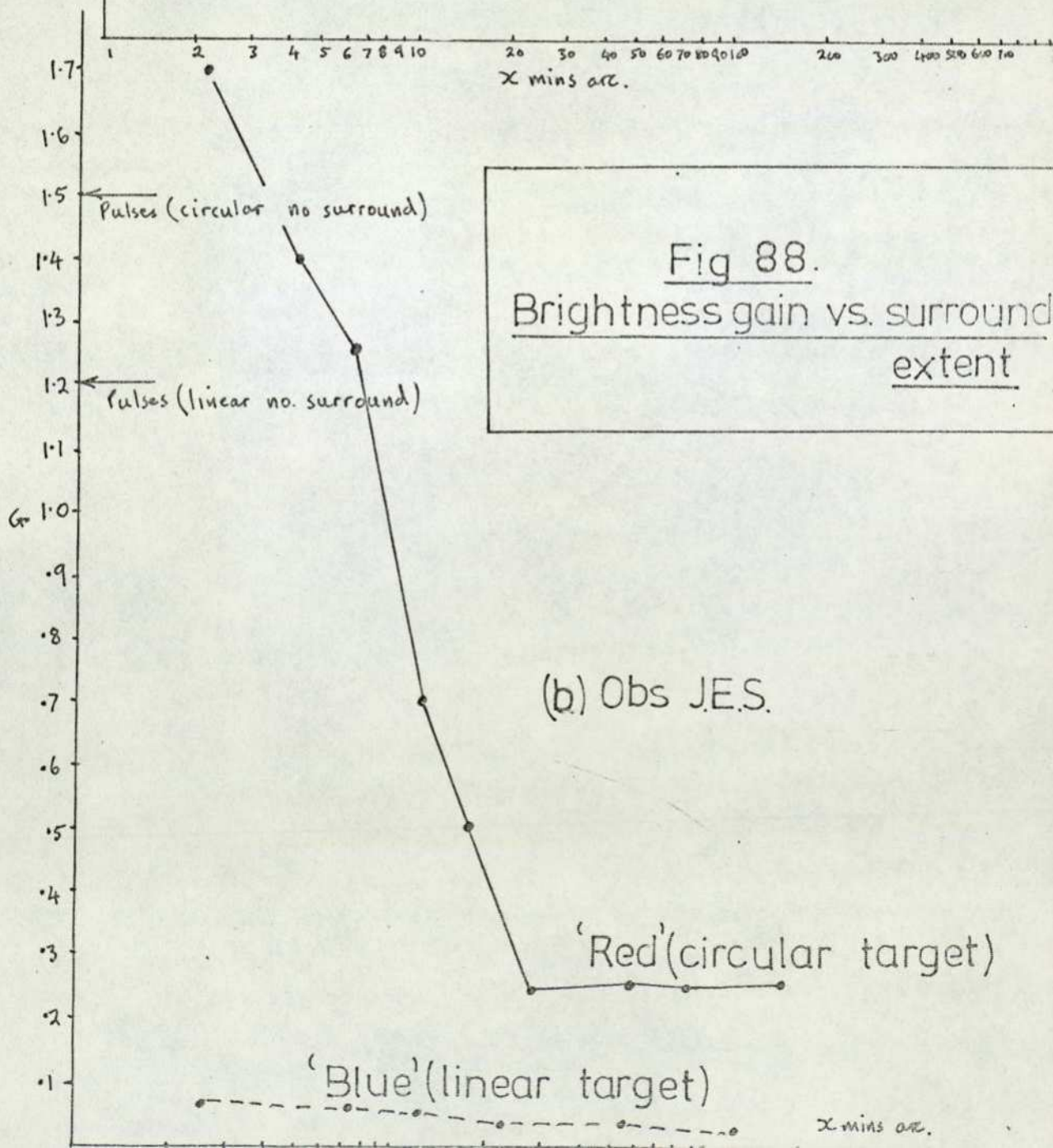
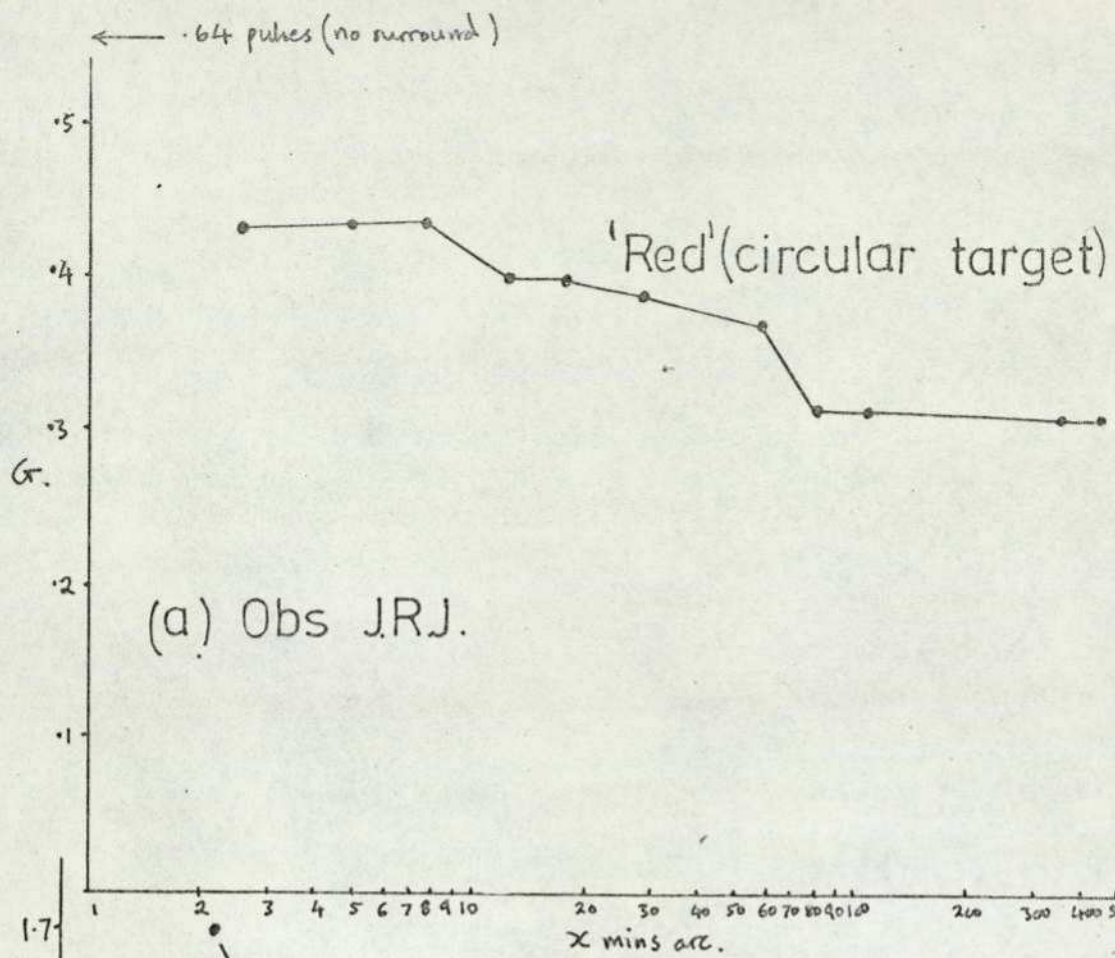


Fig 89 Brightness gain vs. surround extent





5

Fig 90a Obs JRJ

Linear target (variable black surround)

● 'R'-signal

■ 'B'-signal

$[T = 5'(R)]$
 $[T = 15'(B)]$

4

3

2

1

Figs.90-91

Colour appearance of pulsed targets with dark gaps introduced (between target and surround)

figures denote gaps.(mins.arc)

2 462

3

x

4

5

6

228

7

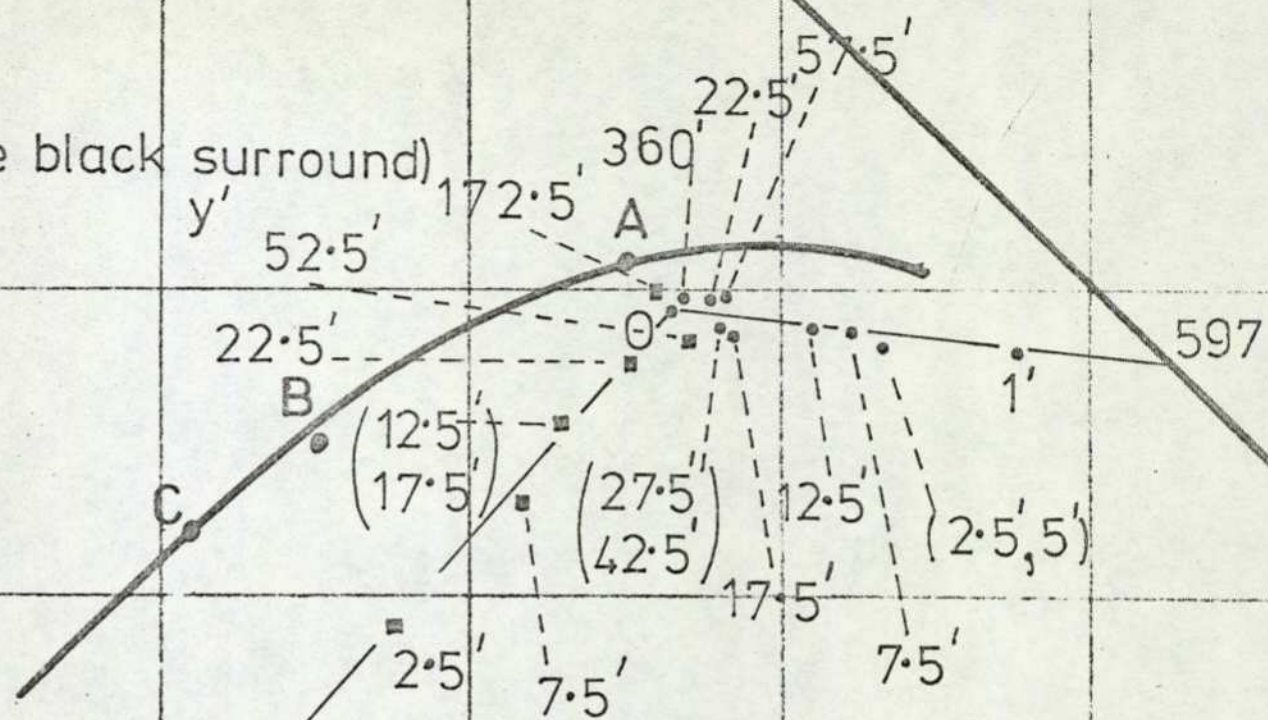


Fig 90b Obs JES

Linear target (variable black surround)

'B'-signal

($T = 15'$)

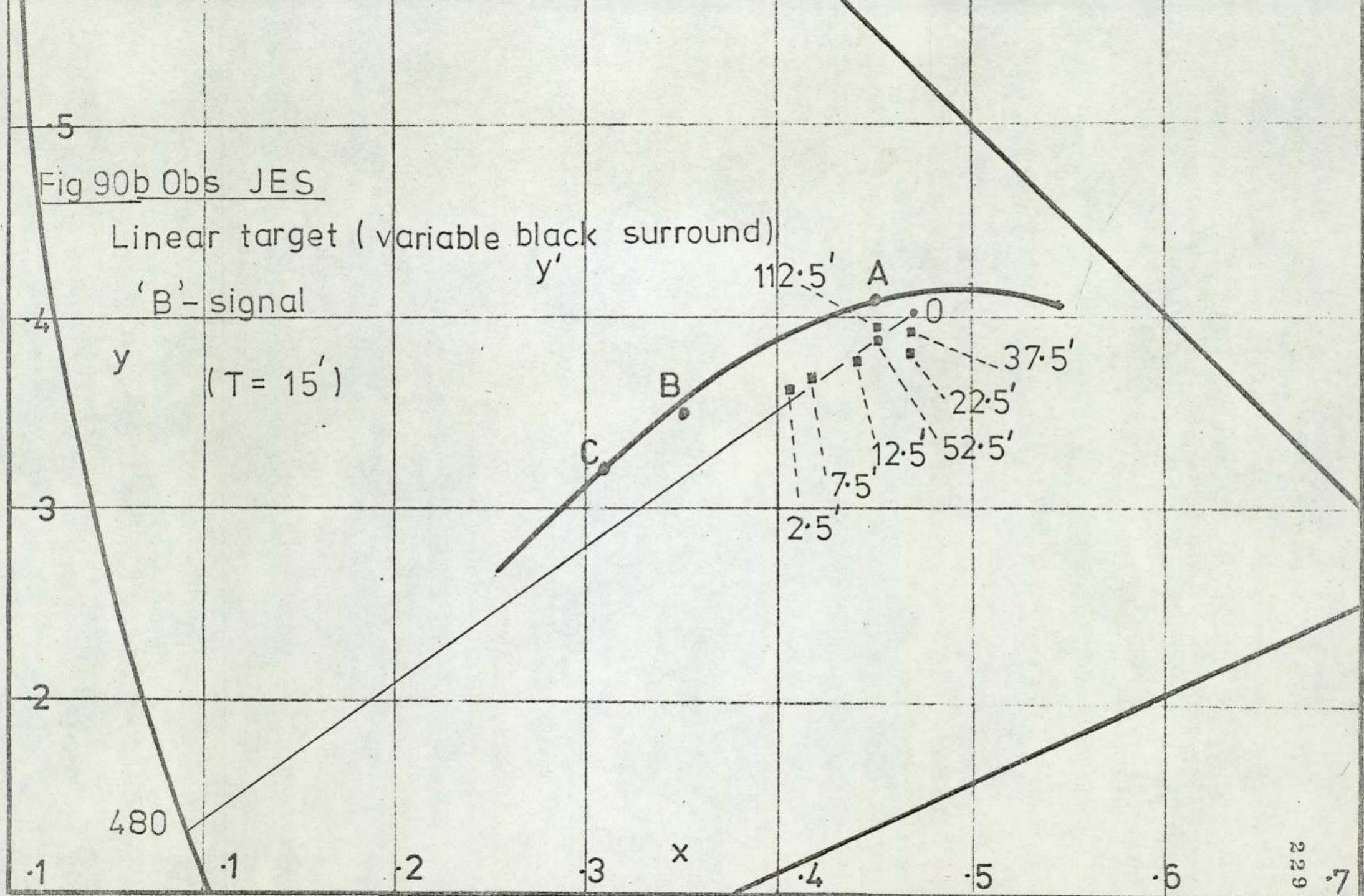


Fig 91a Obs JRJ

Circular target (variable black surround)

'R'- signal

(T = 5')

y

x

.1

.1

.2

.3

.4

.5

.6

.7
230

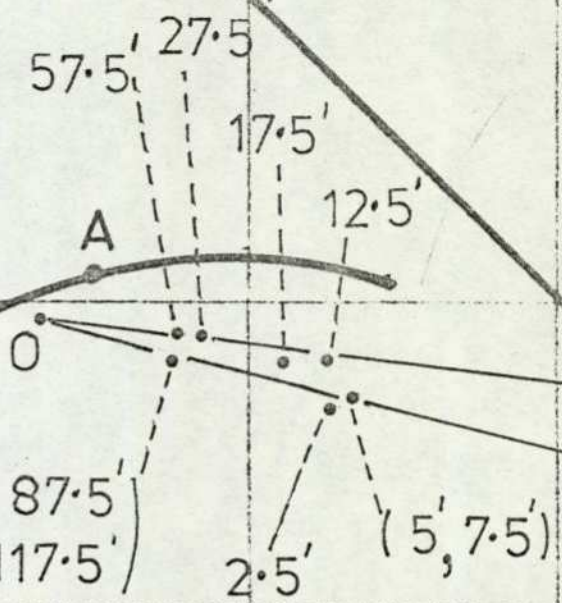


Fig 91b

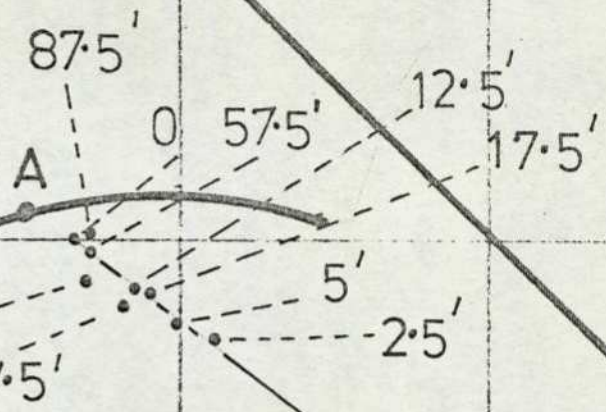
Obs JES

Circular target (variable black surround)

'R'-signal

y (T = 5')

x



509^c

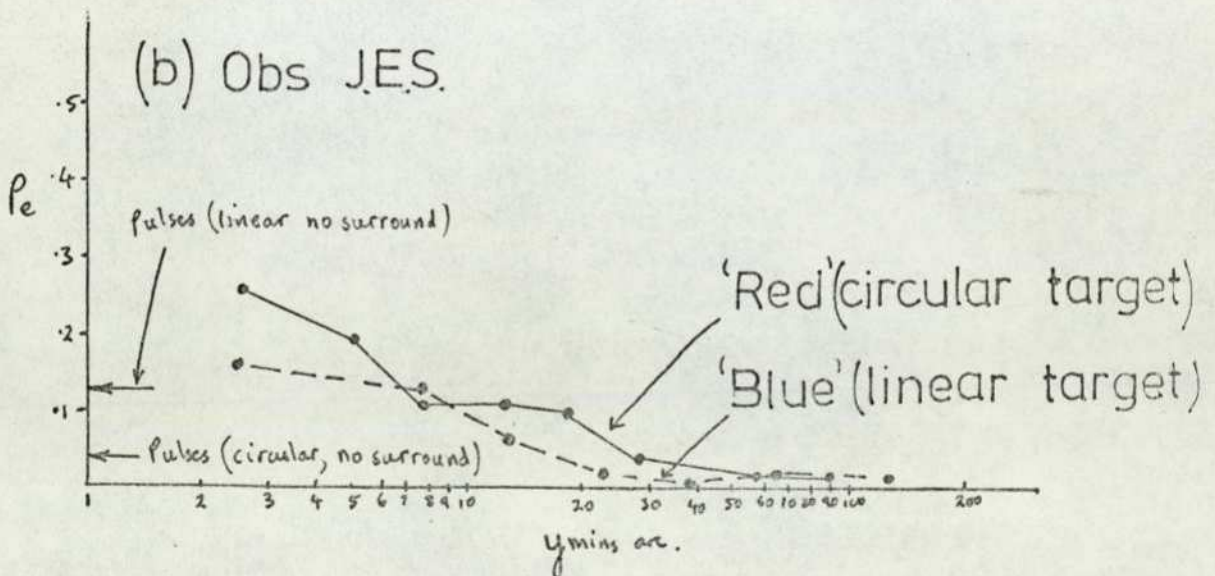
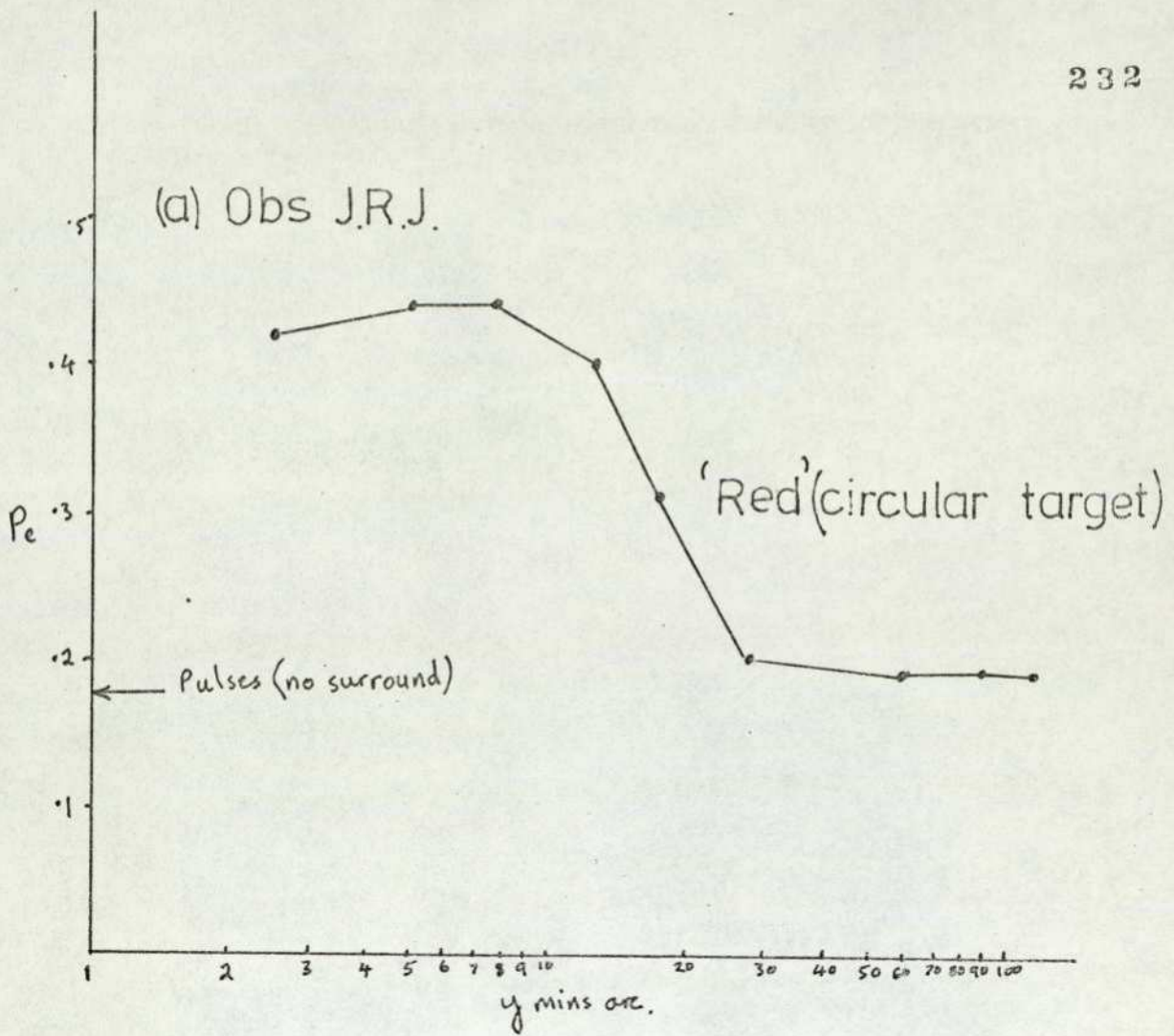


Fig. 92. Purity vs. dark gap size

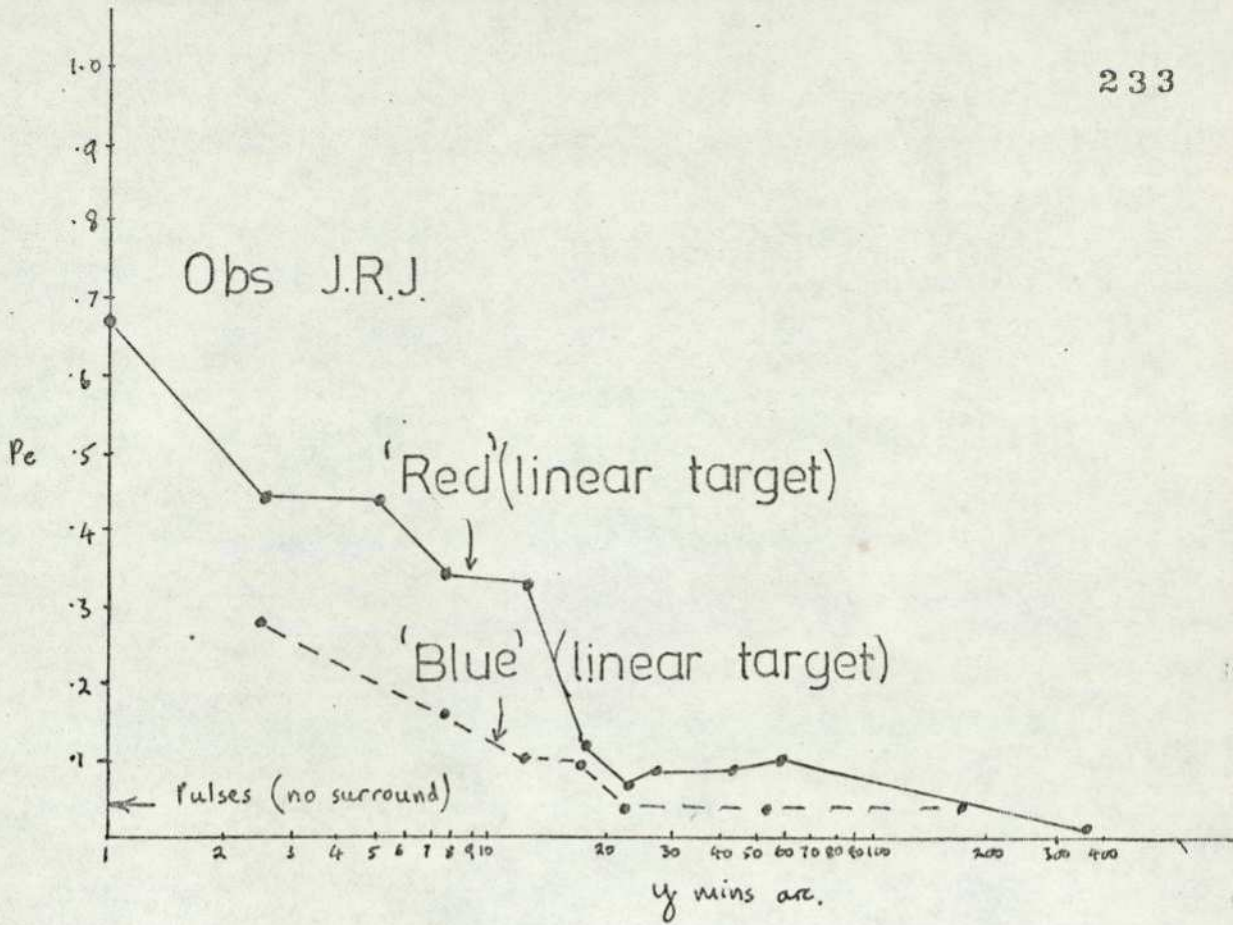
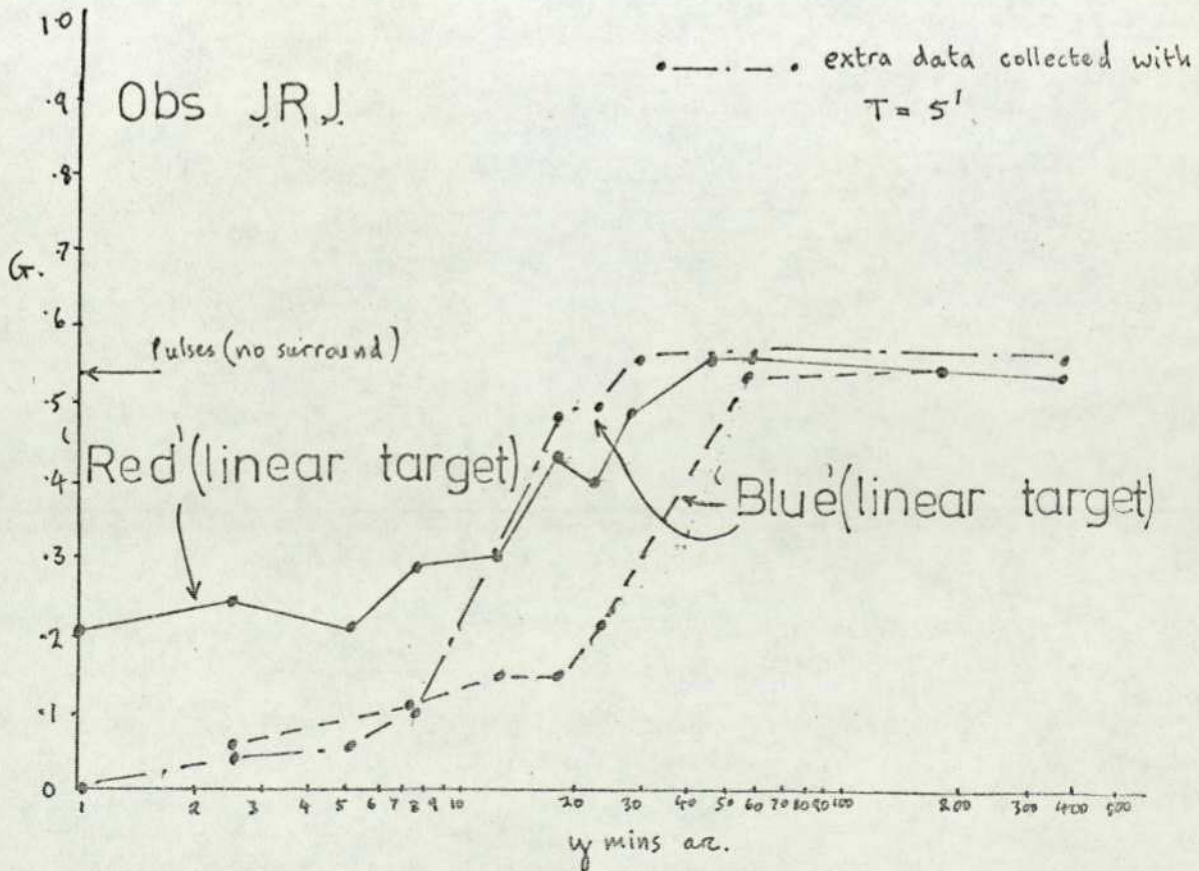
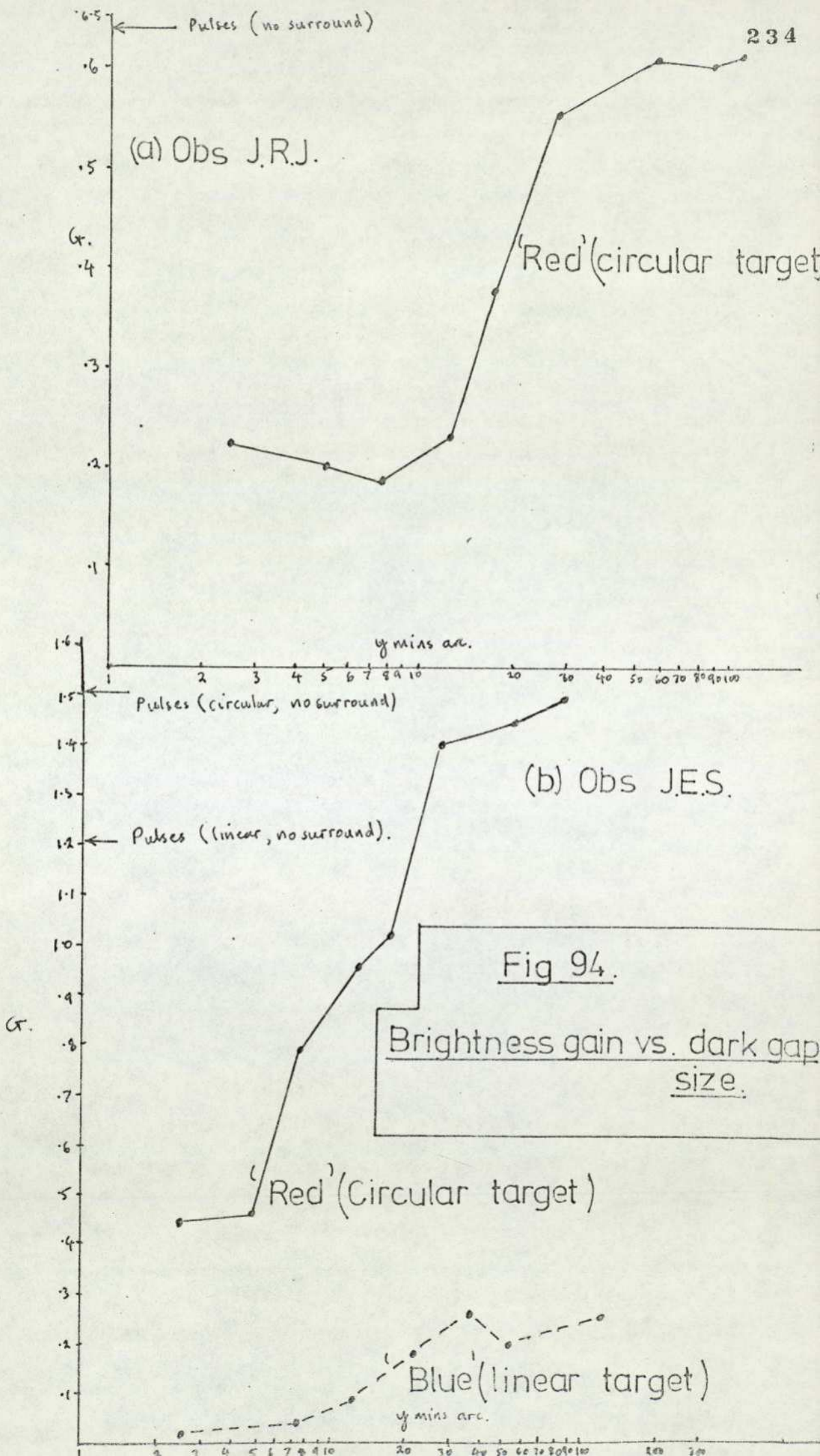


Fig 93 Purity vs. dark gap size

Fig 95 Brightness gain vs. dark gap size





A THEORETICAL INTERPRETATION OF FECHNER-BENHAM SUBJECTIVE COLOURa) Introduction

The theory of F-B subjective colour outlined in this chapter is based on the following experimental findings and speculations;

- i) The subjective colours cannot be obtained from a single pulsed achromatic light by manipulating the flicker frequency, flicker waveform, P.C.F. (pulse to cycle fraction) or luminance. This casts serious doubt on the "Morse Code theory" which is considered untenable (see the results of experiment 2).
- ii) A necessary condition to obtain F-B subjective colour is that the stimulus should have two components; a target and a surround. The subjective colours are then obtained from two achromatic light pulses, one in the target and the other close by in the surround. By adjusting the temporal separation of these pulses, a full spectrum of subjective colour, blue through yellow-green to red can be obtained in the target. Near optimum conditions appear to be for a target pulse to surround pulse energy ratio of about 0.2, where the maximum retinal illuminance provided by each (rectangular) pulse is about 1200 td. (see the results of experiments 1, 2 and 3). That two pulses are necessary in this manner to produce the subjective colours, indicates that a point must exist somewhere in the visual system where the transient neural signals stemming from these two pulses can interact. In this way, the mechanism responsible for the interaction process can be considered to have a two-component receptive field (i.e. centre-surround kind of arrangement).
- iii) Meta- and paracontrast is manifested in the target when F-B subjective colour is observed. (see the results of experiment 3).
- iv) The subjective colour-producing mechanism is most probably located in the retina, since dichoptic presentation of target and surround fails to elicit the colours (see experiment 3). Furthermore, it appears that no rod contribution to the subjective colour mechanism involved in the induction of

the red colour occurs, since small foveally viewed circular target-annulus stimulus configurations (of $<1^\circ$ total extent) produce the colour, with optimum or near optimum saturation (experiment 4). The results of experiment 4 (A, B) have in fact suggested that more than one variation of the subjective colour inducing mechanism exists in the retina i.e. an R-mechanism responsible for the red colour effects and a B-mechanism responsible for the blue colour effects. The possibility also exists that another mechanism accounting for the green subjective colour may be found, but this was not investigated experimentally. In the report of experiment 4, the plausibility that the subjective colour inducing mechanisms are tonic ganglion cells was discussed in relation to the findings of GOURAS (1968, 1971) who examined such cells in the rhesus monkey retina. The general conclusion was that such cells could indeed be these mechanisms and that phasic cell activity may account for some of the luminosity effects revealed by the brightness gain data of experiment 4B. If tonic and phasic ganglion cells are involved in this manner, then the lateral interaction process between centre and surround zones of the subjective colour mechanisms is one of lateral inhibition as suggested by BRIGNER (1971) and CAMPENHAUSEN (1968 a, b, 1971). The results of experiment 1, in which the red subjective colour purity vs. flicker frequency curves were found to possess low values for frequencies greater than about 15Hz, are also in agreement with the postulate of lateral inhibition. Both KELLY (1969) and FIORENTINI and MAFFEI (1970), while investigating the dynamic properties of retinal lateral inhibition, have found such mechanisms are insensitive to flicker frequencies of about this value and above.

Psychophysical investigations of lateral inhibition within the colour channels have led to some confusing results. On the one hand, failure to find Mach band type phenomena in sharp boundaries between two equi-luminous colours has been interpreted as showing that such interactions

cannot occur (VAN DER HORST and BOUMAN, 1967; WALRAVEN 1972). On the other hand, such interactions are used to explain simultaneous colour contrast effects (CORNSEWET, 1968).²⁴ Investigations of lateral inhibition between Π -mechanisms, using steady state target-surround type stimuli (threshold signals) have shown that such interactions are conveyed within only a single colour mechanism and not between mechanisms (McKEE and WESTHEIMER, 1971; BENDER, 1973). There is also some evidence to suggest that steady-state disc-annulus interactions occur in the retina (FIORENTINI, BAYLY and MAFFEI, 1972), since dichoptic presentation of the stimulus fails to reveal any interaction. If such inhibitory effects concern a centre-surround interaction within the receptive fields of ganglion cells, then according to the findings of Gouras, phasic cells are likely to be responsible, since lateral inhibition between like colour mechanisms is not reflected by tonic (colour coded) cell activity. If this is the case, then the findings of McKee and Westheimer and Bender appear to be related to colour mechanism interactions within the luminosity information channel, rather than the colour channels. This is not unreasonable, since in the fastest routes to the cortex appear to be contained within the luminosity channel (de LANGE 1958b, GOURAS, 1969). It seems plausible that threshold detection is mediated through the luminosity channel rather than the colour channels, since the first information reaching the brain, and presumably the information to which the organism first reacts, will be that concerning luminosity.

Thus, having compared the psychophysical findings concerning lateral inhibition between colour mechanisms within the retina, with the electrophysiological findings outlined in terms of tonic and phasic ganglion cell activity in the discussion of experiment 4, the seemingly

FOOTNOTE 24; This author explains simultaneous colour contrast in terms of retinal lateral inhibition. The findings of DE VALOIS and PEASE (1971) suggest the mechanisms are cortical as discussed in Chapter 5.

conflicting nature of these two sources of information can be reconciled.

A further relevant point is that although psychophysical investigations of the type of interaction described above have shown these to occur within the retina, dichoptic presentation of disc-annulus stimuli designed to investigate transient interactions within the retina (e.g. flicker threshold interactions), has produced results to suggest that these occur at a more central stage in the visual system. This cannot be considered to apply generally to all transient lateral interactions, since the results of the experiments reported in this thesis have shown that the transient lateral interactions which must occur to obtain F-B subjective colour, most probably arise in the retina.

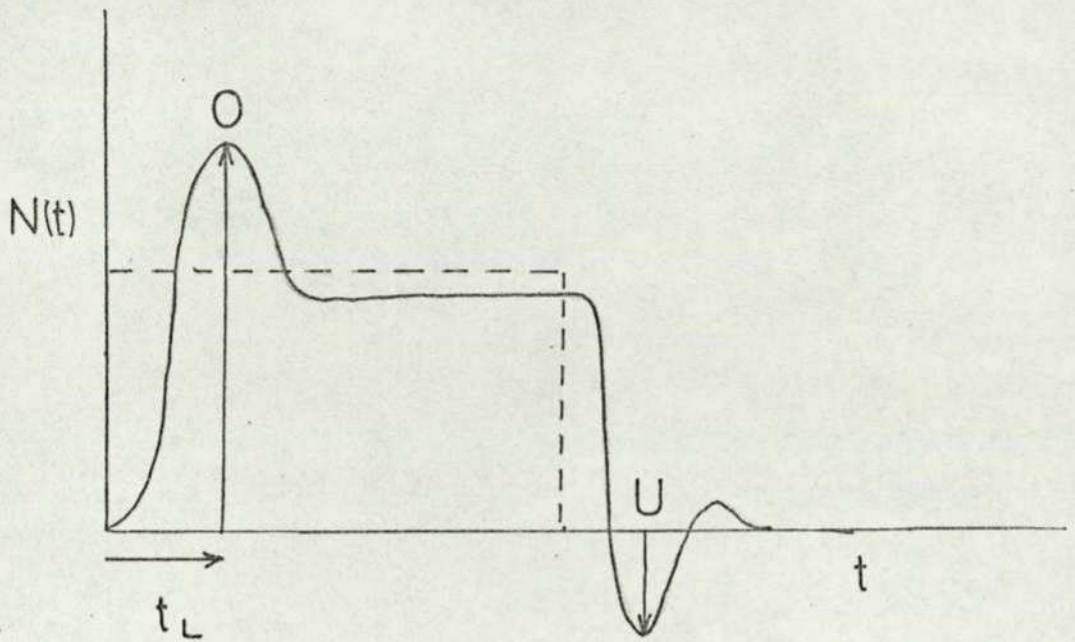
b) The Theory

The proposition that tonic and phasic ganglion cells in the retina may represent the subjective colour inducing mechanisms, will be assumed to be true in the theory outlined. This section is an attempt to suggest possible ways in which the dynamic behaviour of such cells can account for the phenomenon of F-B subjective colour.

To explain the way in which a tonic cell may function to produce a subjective colour signal as its output, consider first a +R -G cell. As mentioned previously such an on-centre ganglion cell receives an excitatory input from the red cone mechanism (Π_5) in the centre and an inhibitory input from the green (Π_4) cone mechanism²⁵ in the surround (periphery) of its receptive field. It will be further assumed that the necessary centre signal to produce the subjective colour is derived from the light pulse delivered by the target component of the stimulus and the necessary surround signal is derived from the light pulse delivered by the surround component of the stimulus field (see the ~~discussions~~ of experiment 4, which suggested that this might be the case). Consider the point where the centre and surround neural signals interact and let this point be denoted by P. It is the interaction process, at P, which is assumed to determine whether or not a subjective colour signal is delivered

from the cell and onto the cortex. The question now raised concerns how the neural activity of both ~~centre~~ and surround processes of the receptive field may be represented on the time scale, at this interaction point. In the visual system, neurons peripheral to the ganglion cells produce a continuous graded D.C. type electrical response to light stimuli (see for example, DOWLING and WERBLIN, 1971; and the notes on retinal physiology given by SHEPPARD, 1968). Ganglion cells on the other hand, respond with identical spike-type nerve impulses and the only way information can be conveyed from these cells is by a frequency coding. Some amacrine²⁶ cells also show such nerve impulses (see for example, TOYODA, HASHIMOTO and OHTSU, 1973). Since the interaction point P is presumably peripheral to the first stage in the visual system where nerve impulses are generated, the neural activity vs. time functions of interest at the point P are likely to consist of graded D.C. activity. Now, consider figure 96, which is a possible representation of a single rectangular light flash delivered to the centre of the tonic cell receptive field, in terms of neural activity in the receptive field centre process, at the input to the interaction point P. Shown as a hatched line is the luminance vs. time function representing the light pulse. The neural activity function shown in figure 96, is characterised by two transient peaks; an overshoot or on-transient (O) and an undershoot or off-transient (U). After the on-transient (the peak of which occurs at a time t_L , where stimulus onset occurs at $t = 0$), the neural activity settles to a steady level for the remainder of the stimulus. At the cessation of the stimulus, the off-transient peak occurs after a further short delay. Sensation vs. time functions having such a profile are well known. For example, BIDWELL (1899) described the sensation aroused by a light flash presented in a totally dark field in such terms and the off-transient was described as a period of "abnormal darkness" which followed

FOOTNOTE 25; Gouras (1968) found that the spectral sensitivities of the red, green and blue cone mechanisms discovered as inputs to the tonic and phasic cells, correspond to Stiles' Π_5 , - Π_4 - and Π_1 - mechanisms respectively.



$N(t)$; neural activity

t ; time

O ; on-transient

U ; off-transient

Hypothesised neural activity, following a light pulse

Fig 96

the light stimulus, i.e. the region occupied by the light flash appeared to Bidwell, darker than the dark surround at cessation of the stimulus.

From animal studies, the following evidence is available in support of suggestions described in figure 96. RATLIFF, HARTLINE and MILLER (1963) investigated the change in discharge frequency of single limulus optic nerve preparations, stimulated by single light flashes. Both on- and off-transients of approximately equal amplitude were found. Similar results have been obtained from optic nerve fibre investigations in the spicula (KENNEDY, 1963) and in the experiments performed by IKEDA and WRIGHT (1972) on sustained ²⁷ ganglion cells in the cat retina. More pertinent evidence to support the postulate that such transients can occur at locations peripheral to the ganglion cell level (as is suggested in figure 96) are the findings of WHITTEN and BROWN (1973) who found that such on- and off-transients were displayed by rhesus monkey cone late receptor potentials (L.R.P.'s), when 400msec light flashes were used as stimuli. Also, such behaviour has been found to occur in bipolar cell responses in the carp (TOYODA, 1973), in the graded D.C. activity of some amacrine cells (TOYODA, HASHIMOTO and OHTSU, 1973) and in horizontal cell responses of this fish (MACNICHOL and SVAETICHIN, 1958).

Psychophysical studies have also produced some information on the existence of on- and off-transient activity in the human visual system. KELLY (1961), for example, proposed a single-channel model of the human photopic visual system to explain his data on amplitude sensitivity to sinusoidally flickering achromatic light. It consisted of a linear photo-reactive stage whose output was continuous (graded D.C.). The second stage

FOOTNOTE 26; It appears that some amacrine cells display spike activity, whereas others display just a graded D.C. response.

FOOTNOTE 27; These ganglion cells are similar to the tonic cells in the rhesus monkey retina in that they give a continuous response to a maintained light stimulus.

in the model was a non-linear pulse encoder occurring at the first location in the visual system where spike discharges are generated. Kelly's model was capable of predicting the output of the first linear photoreactive stage in response to suprathreshold light pulses. The output functions were similar in profile to that shown in figure 9b (Kelly's data were, however, collected from large stimulus fields and not small spot or annulus stimuli).

Whatever the cause of these on- and off-transients, the evidence outlined above suggests that their existence in the neural activity function described in figure 9b is plausible. The function shown in figure 9b is also considered applicable to the signal which forms an input to the interaction point P, from the surround process of the receptive field, when this is stimulated by a light pulse. The surround process is one of inhibition, however, (GOURAS, 1968) and the possible mode of operation governing the interaction of two such signals (centre and surround) needs further investigation. Again, animal studies provide some useful ideas on the laws which govern such interactions. For example, SPEKREIJSE and VAN DEN BERG (1971) have found that for goldfish ganglion cells an interaction between centre and surround receptive field signals occurs before the non-linear rectifier element discovered in this fish by SPEKREIJSE (1969). Furthermore, the interaction process was found to involve an algebraic mode of operation. BARLOW (1953) in threshold experiments has shown that a linear addition of signals from the centre and surround of ganglion cell receptive fields in the frog takes place. MAFFEI and CERVETTO (1968) have found, working on cat ganglion cells and using 100 per cent modulated sinusoidal signals, that provided the mean illuminance level remained the same for centre and surround zones of the receptive field, the interaction between centre and surround signals approximated closely a linear operation. A similar conclusion was obtained by IKEDA and WRIGHT (1972), working on sustained ganglion cells in the cat.

From psychophysical experiments performed with human observers, KELLY (1969) proposed a model to account for lateral inhibition within the human retina. The interaction process between the excitatory and inhibitory channels of his model was assumed to obey the laws of algebra.

Using the above evidence in support, it is assumed in the subjective colour theory that the interaction at the point P between surround and centre signals is also governed by the laws of algebra i.e. a linear operation.

For the subjective colour producing tonic cell under consideration (+R-G), to simplify the mathematical analysis of the interaction process occurring at the point P between the two neural signals, the waveform of each signal is considered without the plateau component given in figure 96. Both centre and surround signals are assumed to be represented by the function shown in figure 97a i.e. just the on- and off-transients are considered. Whether such a function exists for each signal at the point P, or whether one or both signals resemble the waveform given in figure 96 is not considered important. The main feature is that two transients must exist as shown by the arrows in both figures. Nor is the fact that it is highly unlikely that the neural activity finishes abruptly as shown in figure 97a, considered important. This function is regarded only as a mathematical convenience in demonstrating the type of interaction process which may well account for the subjective colours. Thus, the main essence of the theory is an examination of the interaction between on- and off-transients in two neural signals; one excitatory (centre signal) the other inhibitory (surround signal).

Before examining the interaction process at the point P more fully, for the +R-G tonic cell under consideration, a short review of the general information available on the dynamic features of centre-surround ganglion cell receptive field interactions is given. Also relevant are the points made in Chapter 1 and to be recapitulated here, about possible latency differences between the colour mechanisms. Firstly, there is some

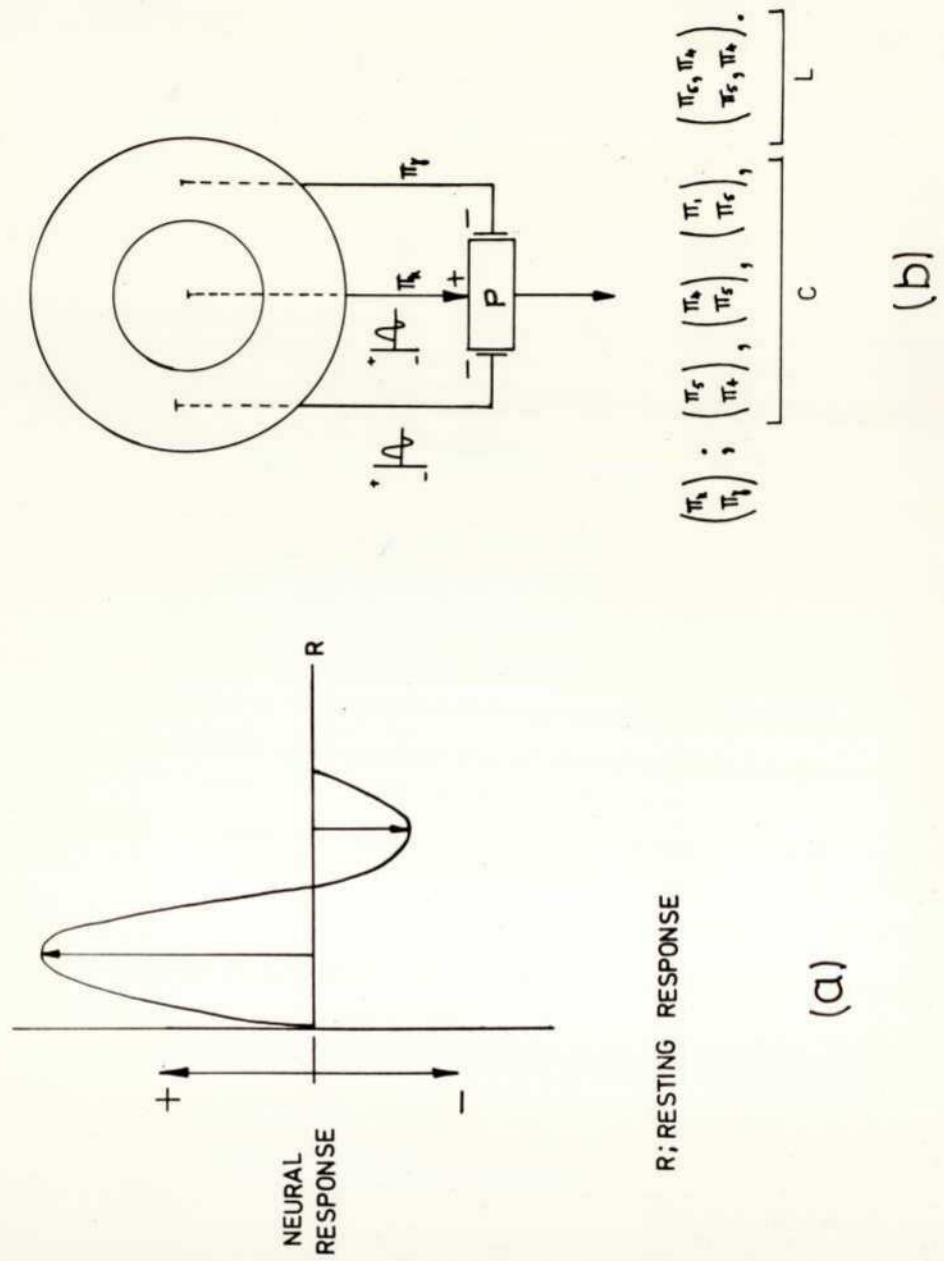


Fig 97 Neural activity (a) occurring at the interaction point P. (b)

evidence that receptive field surrounds (of retinal neurons) influence the firing rate of a cell with a latency longer than that required for the influence of light in the receptive field centre. In limulus, RATLIFF, HARTLINE and MILLER (1963) have shown that the delay between the generation of a nerve impulse in an ommatidium and the production of its inhibitory effect on a neighbouring ommatidium can be as large as 150msec. The existence of such a delay was used by RATLIFF, KNIGHT, TOYODA and HARTLINE (1967) to explain the 3Hz peak in de Lange curves obtained from the limulus. A similar explanation was suggested to hold for the 10Hz peak occurring in human de Lange curves by these authors. In vertebrate retinas, surround processes having latencies of 30 to 60msec longer than centre processes have been found in bipolar cells in necturus (WERBLIN and DOWLING, 1969), in ganglion cells in the cat (RODIECK and STONE, 1965; MAFFEI, CERVETTO and FIORENTINI, 1970) and in the rabbit (BARLOW, HILL and LEVICK, 1964).

The possible effect that the total energy contained within the stimulus light pulse may have on the latency of the initial on-transient peak at the point P must be considered. Also of interest is the fact that if the pulse is sufficiently short, then as suggested previously, the plateau component in the function may be missing with only the two transients remaining (see figure 97a). Such functions were obtained as the output of the photoreactive stage in the KELLY (1961) model when very short (impulse) light pulses were considered. Thus, the waveform shown in figure 97a has some support from Kelly's model. Now, the latency time t_L is likely to be shortened as light pulse energy is raised and presumably this is true up to a certain pulse duration, after which Δt remains constant as duration is increased. That this is the case is suggested by the work of MANSFIELD (1973) who found that reaction times for his brief achromatic and coloured light flashes varied inversely with stimulus energy up to about 10msec and then remained essentially constant. MOLLON and KRAUSKOPF (1973) found that by raising the energy of slightly suprathreshold

coloured flashes (each of which were detected by a single colour mechanism), reaction times to these decreased. In their discussion, Mollon and Krauskopf concluded that the mechanism responsible for this effect lay in the retina. Increasing the light pulse energy was also found to decrease the latency of the initial on-transient peak in both rhesus monkey rod and cone L.R.P.'s (WHITTEN and BROWN, 1973). The possibility that such a decrease in the latency t_L occurs in the surround neural signal under F-B subjective colour inducing conditions, compared with the centre neural signal (since the former has a greater total energy), will be referred to later.

The main facts outlined in Chapter 1 suggesting that the colour mechanisms of the eye respond with different latencies, are outlined again here. Firstly, reaction time experiments have suggested that the blue colour mechanism may have a longer latency than the red mechanism (PIERON, 1932a, b) and that this difference may be as large as 50msec (MOLLON and KRAUSKOPF, 1973). Clear evidence that the blue cones respond more slowly than the red or green cones comes from WHITTEN and BROWN (1973), who showed that the difference between the blue cone and red or green cone L.R.P.'s certainly can be as large as 50msec. Longer latencies in human and rhesus monkey E.R.G. recordings obtained from stimulating blue cones compared with recordings obtained from red or green cones have been observed (NORREN and PADMOS, 1973). That the blue cones have a longer latency in their response to light than either the red or green cones thus seems to be well established. Latency differences between the red and green colour mechanisms of the eye are suggested by some psychophysical experiments. The investigations of possible phase shift differences between the red and green colour systems (WALRAVEN and LEEBEEK, 1964; de LANGE, 1958b) have been discussed fully in Chapter 1 and the results suggest a constant latency time difference of about 30msec between the red and green systems.²⁸ Furthermore it was argued that this latency difference is likely to be formed at or by the point D (the beginning of

the separate luminosity channel in the Walraven zone model (see figure 10, Chapter 1)). Thus, since the formation of this separate luminosity channel appears to occur at or before the ganglion cell level (GOURAS, 1968), this postulated latency difference is likely to occur at or before this level in the visual system. A figure of 30msec for the latency difference between red and green colour signals was also suggested by the electrophysiological findings of SPEKREIJSE and VAN DEN BERG (1971), working on the goldfish. VAN DER HORST and MUIS (1969) in their theoretical analysis of the hue shifts occurring in a single intermittent coloured light suggest a latency difference between the red and green colour mechanisms of this order of magnitude.

Latency time differences between the colour mechanisms are likely to be affected by changes in the level of light adaptation. For example, investigations of reaction time and critical duration for coloured light flashes (Stiles technique employed) have indicated that the time constants of each colour mechanism appear to be affected only by its own state of adaptation and not on the state of adaptation of the retina as a whole (MOLLON and KRAUSKOPF, 1973; KRAUSKOPF and MOLLON, 1971). Furthermore, these time constants appear to be inversely related to the level of adaptation (see the discussion of MOLLON and KRAUSKOPF, 1973).

From these notes on the dynamic features of the colour mediating mechanisms of the eye and on ganglion cell receptive field interactions, it is possible to now outline more fully the possible interaction process for the +R-G tonic cell under consideration. Firstly, it is assumed, using the above experimental findings as support, that under the subjective colour inducing conditions in which the target to surround pulse energy ratio (T/M) is 0.2 (as in experiment 3), a latency

FOOTNOTE 28; Non-linear rectifier elements can also produce phase shifting as discussed in Chapter 1.

difference of about 20msec has been manifested between the initial on-transient peaks in the red and green colour mechanism neural signals, by the interaction point P. It is assumed, in fact, that the possible extra delay imposed on the surround signal (due to the fact that surround effects may act after a relatively long latency) is exactly compensated for by a decrease in the latency of the initial green cone derived signal in the surround, due to the fact that the surround light pulse has a larger energy content than the target pulse. Thus, if the centre red signal initial on-transient peak occurs at a time x msec after the target pulse onset, then the surround green on-transient peak occurs at a time $(x + 20)$ msec after the surround pulse onset. This extra 20msec assumed to be due solely to the fact that the green colour mechanism responds more slowly (slower by 20msec) than the red mechanism.

As mentioned previously, figure 97a shows the form of both the ganglion cell receptive field centre and surround neural signals at their interaction point P. The positive direction indicated in this figure shows the on-transient activity and the negative direction, the off-transient activity. R corresponds to the resting level for the neural response of each cell (for both centre and surround activities), which precedes the interaction point P. Figure 97b shows the situation for three on-centre tonic (marked C) and all on-centre phasic (marked L) ganglion cells. Π_k refers to the colour mechanism which excites the cell and Π_j the colour mechanism which inhibits. Thus, the +R-G cell is represented by the matrix; $\begin{pmatrix} \Pi_5 \\ \Pi_4 \end{pmatrix}$. The two circles in this diagram indicate the centre and surround of the ganglion cell receptive field. Also marked are the centre and surround signals which are inputs to the interaction point P represented by the small box. Figure 98, row A column 1 shows the centre and surround input functions (marked I) to the interaction point P for the +R-G tonic cell, when a temporal separation Δt of 0msec exists between target and surround light pulses as shown at the bottom of the diagram. As the interaction process between centre and

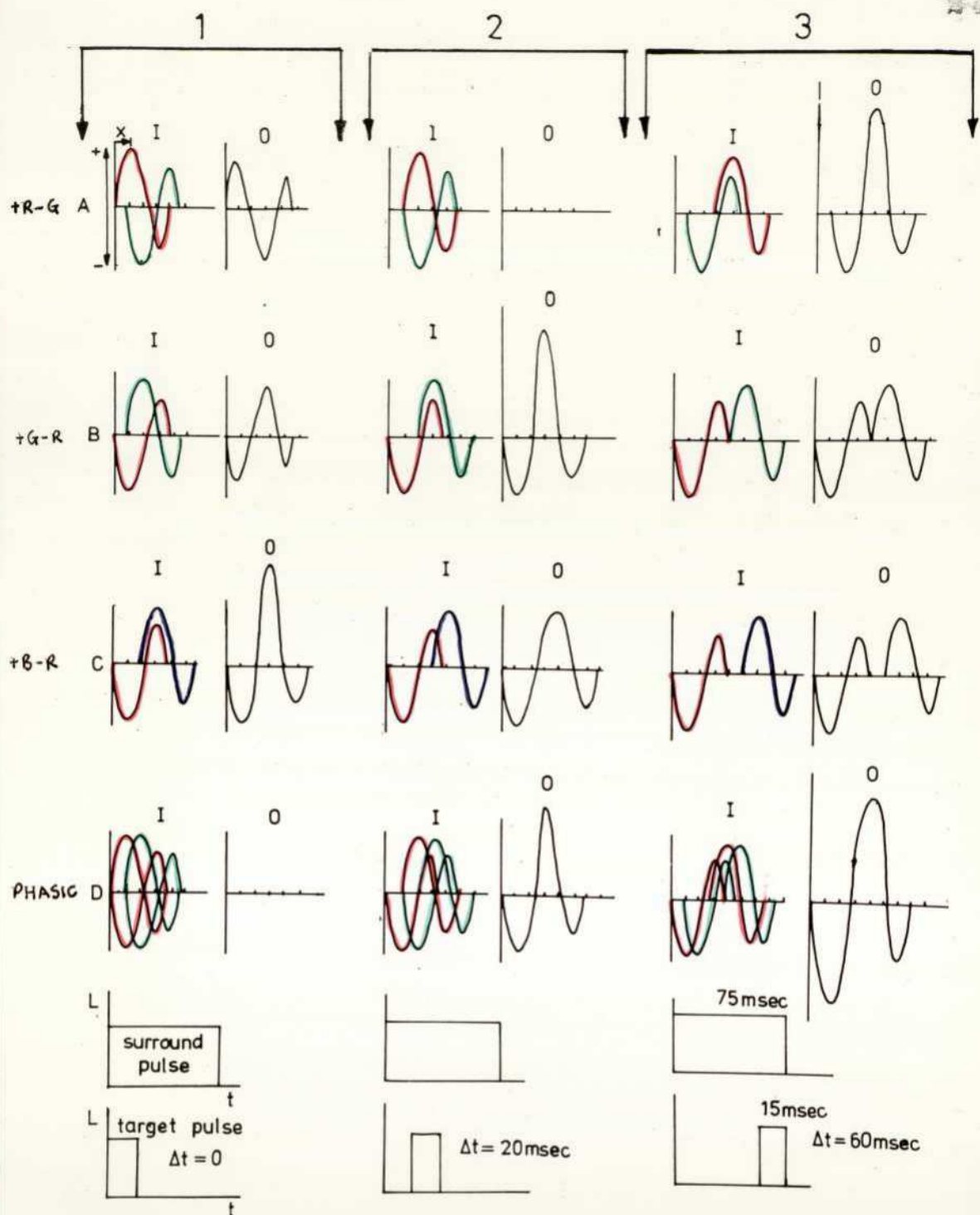


Fig 98 This figure illustrates how four types of ganglion cell may operate to produce subjective colour signals
 I = input O = output
 (see text for further details)

surround neural signals is assumed to involve an algebraic operation, the output signal (marked O) from the interaction point is obtained from a simple addition of the two input signals. Note that since the surround signal (shown green) is considered to act in an inhibitory fashion, the surround signal input is inverted on the time axis. Tick marks on the time axis of each graph represent 20msec. It is also assumed, mainly for convenience, that the centre signal on-transient peak latency x is 20msec as shown in the diagram, but the analysis is applicable for any value of x . Row B, column 1 shows the equivalent situation at the point P for a +G-R tonic cell (+G centre, -R surround), with the same stimulus applied. Row C, column 1 shows the situation for a +B-R tonic cell (+B centre, -R surround). A further assumption that at the interaction point for this cell, the blue colour mechanism (Π_1) has a latency of about $(x + 40)$ msec is now imposed. (see the previous discussion of the experimental evidence suggesting that this might be the case). Notice that now the output (marked O) from the interaction point P for the +B-R cell, contains a relatively large on-transient and the outputs from the (R, G) tonic cells do not. It is known that this stimulus ($\Delta t = 0$) favours the induction of blue subjective colour (see experiment 3).

Now, the response of such a +B-R tonic cell to a single pulse of blue light is likely to include a large on-transient, since the blue colour mechanism is more strongly activated than either the red or green mechanisms. Thus, the +B-R cell will have a strong excitatory input from Π_1 following a small blue light pulse incident in its receptive field and the output of the cell will contain a strong burst of nerve impulses. The (R, G) cells, in comparison, will be less active. That an increased blue content in a stimulus light pulse would be indicated in this manner, is certainly true for blue sensitive L.G.N. cells in the macaque monkey (de VALOIS, 1971). Thus, for the stimulus condition $\Delta t = 0$, as shown in figure 98, the achromatic target and surround light pulses are considered to have artificially created a blue response from +B-R tonic cells in the

manner described above.

By assuming that similar time constants are associated with the colour mechanism inputs to the phasic (luminosity) ganglion cell, the analysis predicts little or no output from the corresponding interaction point P. In this manner, the ganglion cell displays little departure in its activity away from the spontaneous level. The total information conveyed by all four cells analysed (shown in rows A-D, column 1 of figure 96), would appear to be that corresponding to a small low luminosity bluish light pulse. This finding agrees with the experimental findings. Column 2, in figure 98 shows the activity in all four cells when the target and surround light pulse onsets are separated in time by an amount $\Delta t = 20\text{msec}$ as shown. In the analysis, the centre neural signals at the interaction point P of each cell must now be moved along the time axis by an amount 20msec as shown. The output functions indicate that it is the +G-R cell which now displays a large on-transient. The phasic cell also shows some activity. Thus, the information conveyed by all the cells appears to correspond to that which would be produced from a small greenish light pulse of moderate luminosity. Again, this agrees fairly well with the experimental findings. Column 3 shows the analysis applied when $\Delta t = 60\text{msec}$. The predicted information from the cells now corresponds to that likely to be obtained from a small red light pulse having a relative large luminosity. (Large on-transients occur in both the +R-G and phasic cells). The predicted colour agrees well with the experimental data, but the predicted luminosity is greater than for a single achromatic light pulse. The experimental findings have shown that the luminosity of the target in which F-B subjective colour is induced **never** exceeds the luminosity associated with a single isolated target light pulse. This fact is clearly shown in figure 69 (a, b) in Chapter 5. From the data of experiment 3, it appears that the brightness gain function associated with the subjective colour inducing stimuli is elevated away from the U-profile normally associated with such two-pulse para- and

metacontrast producing stimuli (WEISSTEIN, 1972). With the stimuli employed in experiment 3, where $T/M = .2$, F-B subjective colour is manifested together with para- and metacontrast. Now for such stimuli, when $\Delta t > 0$ it is possible that scattered light²⁹ acts to severely depress the luminosity of the target as ALPERN (1953) suggested in his explanation of paracontrast (see the discussion of experiment 3), and the phasic ganglion cell activity acts to raise the luminosity as shown in figure 98. The resultant effect would then be the production of a brightness gain function raised away from the characteristic U-profile (for $\Delta t > 0$) but not perhaps sufficiently enough to elevate it above the level normally associated with an isolated pulsed target.

c. Discussion

The theory is thus concerned with the activity of four types of ganglion cell and how such cells may modify an otherwise neutral (achromatic) signal into one normally associated with a coloured light. Implicit in the theory is the postulate that tonic (sustained) ganglion cells display transient activity to pulsed light stimuli. That this is the case has recently been confirmed (GOURAS, 1971). It must be emphasized that the cells described in figure 98 are likely to constitute just a sample of many different types of cell. There is evidence, for example, that some colour coded cells in the rhesus monkey L.G.N. (and possibly also the retina) do not show a centre-surround arrangement in their receptive field (type II cells) (WIESEL and HUBEL, 1966). Off-centre tonic cells are also evident in the rhesus monkey retina (GOURAS, 1968). The possible role of these and other ganglion or L.G.N. cells is not considered in the theory. Thus, the information conveyed by the four ganglion cell types associated with the theory conveys only a fraction of

FOOTNOTE 29; That scattered light can actually depress the luminosity of a light source appears to defeat logic. However, the effect has been demonstrated by SCHOUTEN and ORNSTEIN (1939).

the total information used by cortical neurons in forming a final percept. It is reasonable, however, to assume that only a slight bias towards a colour signal shown by a few ganglion cells is required to produce a subjective colour sensation. The theory also predicts activity in colour coded ganglion cells when a single achromatic light pulse is applied to the receptive field i.e. just one neural signal of the type illustrated in figure 97a is considered to form an input to the interaction point P which in turn produces some activity in the output of the ganglion cell. Although WIESEL and HUBEL (1966) were unable to find any activity in colour coded L.G.N. cells in response to achromatic light stimuli, DE VALOIS (1971) has shown that all the L.G.N. cells tested i.e. both colour coded and non-opponent cells responded to achromatic light pulses.

With regard to the phasic cell shown in row D, column 1 of figure 98, i.e. for the case when $\Delta t = 0$ and for the stimuli shown, there is evidence obtained from limulus studies, that the small output signal shown can indeed be obtained using such stimuli and is readily obtained by an excitatory-inhibitory interaction of the type shown (RATLIFF, HARTLINE and MILLER, 1963).

It is of interest to note that one of the main assumptions in the theory, namely that the colour mediating mechanisms of the eye respond with different latencies is the main postulate of the Fechnerian theory as developed by PIERON (1922, 1957). Whilst Pieron believed that the subjective colours are the result of a single achromatic light pulse, the results of the experiments outlined have shown that two pulses are required. The lateral interaction postulated by Pieron in his theory was also one of excitation (see the notes in Chapter 1) and not inhibition.

On the question of neuron activity within the ganglion cell receptive field, the neurons which transmit the lateral (surround) signal to the interaction point P are, likely to be, either horizontal cells or amacrine cells. Horizontal cells are tightly linked with each other so that information can be conveyed laterally across the retina over considerable

distances. The same applies to amacrine cells (see, for example, DOWLING and BOYCOTT, 1966; LEVICK, 1972; MACNICHOL, FEINBERG and HAROSI, 1972; and figure 8, Chapter 1). The general conclusion from most anatomical and physiological studies of ganglion cells and their receptive fields is that both horizontal and amacrine cells are likely to be involved in centre-surround interactions (LEVICK, 1972). In some species, it appears that although steady state surround effects are conveyed via horizontal cells, dynamic surround interactions (of the type which F-B subjective colour inducing stimuli may be considered to produce), are conveyed only by the amacrine cells. This is certainly true in necturus (WERBLIN, 1973). If the same applies in the human visual system, then the interaction point P will be at the junction of the bipolar, ganglion and amacrine cells. On the other hand if the horizontal cells are the purveyors of the surround signal, then the first subjective colour signals may be bipolar cell outputs, not ganglion cell outputs.

Finally, it must be again stressed that the input and output functions shown in figure 9~~8~~ are only designed to indicate the type of interactions postulated. The discontinuities in the output functions obtained in some instances would clearly not have a physiological correlate. Again, the suggested interaction processes and the latency assumptions outlined may be entirely false. What appears fairly conclusive is that F-B subjective colour signals are produced from an interaction in the retina of two transients. A similar analysis to the one outlined in this chapter may be applicable to the hue shifts measured in a single intermittent coloured light (e.g. VAN DER HORST and MUIS, 1969; NILSSON and NELSON, 1971). Van der Horst and Muis suggested that a latency difference between the red and green colour mediating mechanisms is responsible for these shifts. Since the effect is obtained from a single light (which does not imply a centre-surround interaction process), possible candidates for the visual mechanisms responsible are the type II L.G.N. cells, investigated by WIESEL and HUBEL (1966) in the rhesus monkey. Such cells

do not have a centre-surround arrangement to their receptive field but do reveal spectral antagonism.

a) Apparatus and stimulus details

In the experiment reported here, "the black areas on a white background" component of the stimulus sequence was a checkerboard (check size; 18 mins arc x 18 mins arc, size of checkerboard; 4.2°). The manner in which the stimuli were produced is illustrated in figure 99 (a, b). Two slide projectors provided the necessary white light; one (P_1) projected an image of the checkerboard onto a ground glass screen viewed by the observer who was contained within a Faraday cage. The other projector (P_2), provided the homogeneous white field. To provide the temporal features of the stimulus, a large opaque rotating disc D, driven by a 4-phase stepper motor, (supplied by Impex Electrical Ltd.) was positioned as shown. This disc had two segments S_1 and S_2 removed (figure 99b) and

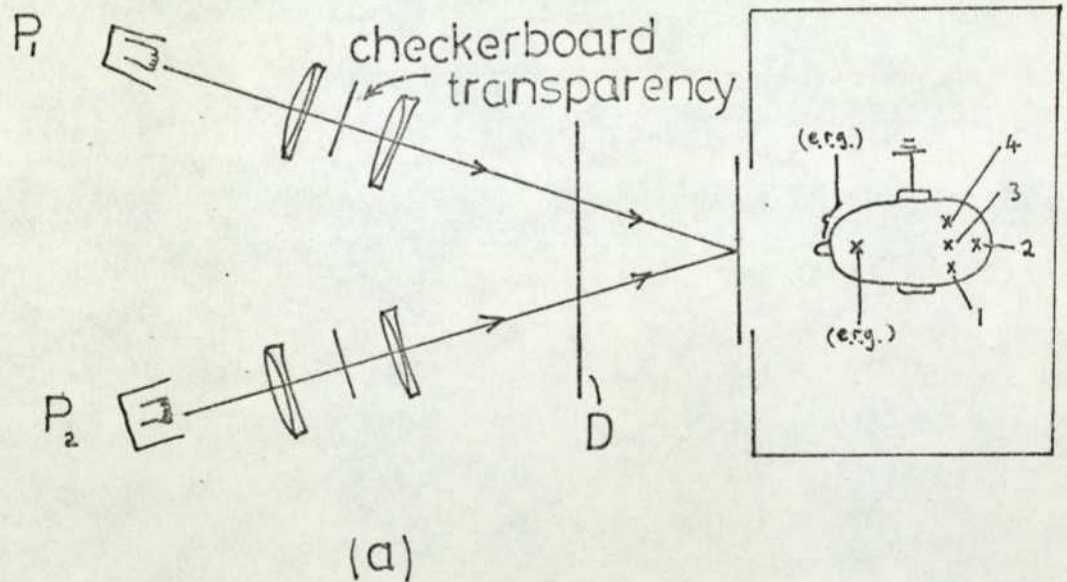
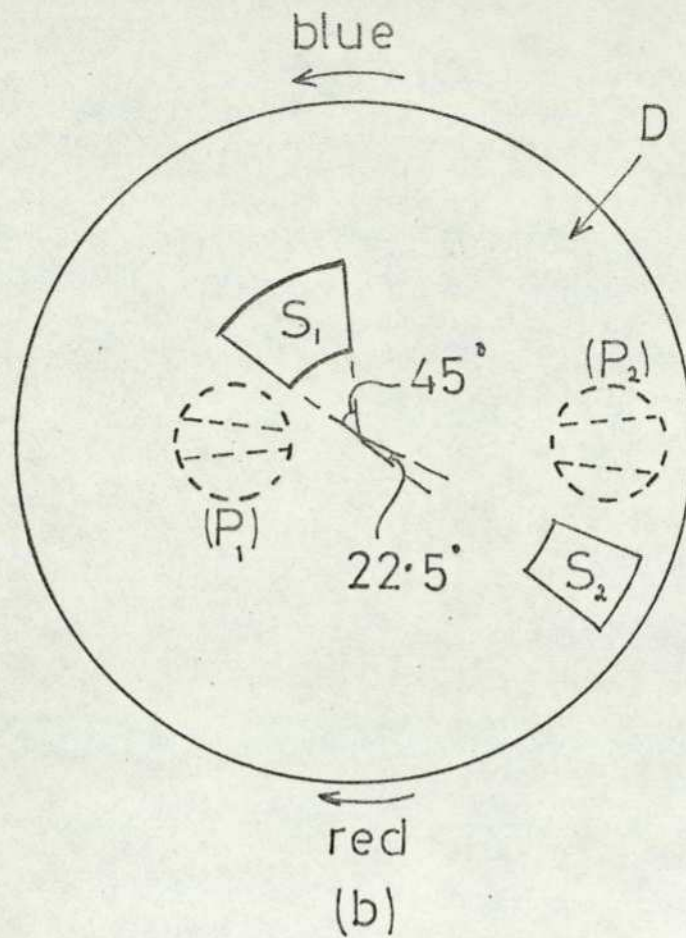


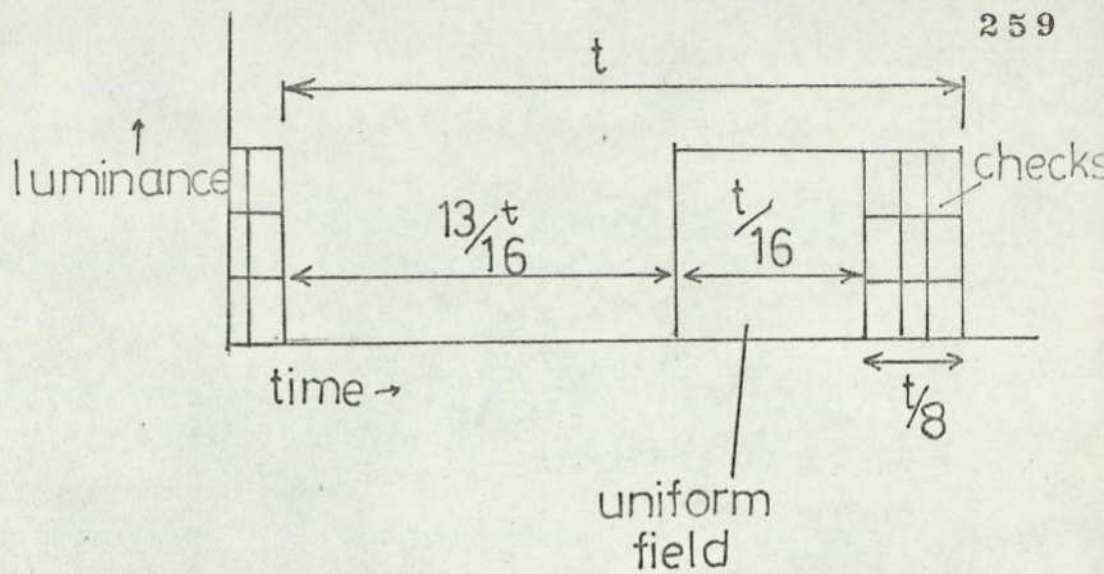
Fig 99 a) The arrangement of the projectors (P) and rotating disc D . b) The rotating disc D with small open segments S

each of these openings allowed light to pass from one projector as shown. The segments subtended 45° (S_1) and 22.5° (S_2) at the centre of the disc. Now in figure 99b, the front of the disc nearest the projectors is illustrated, together with the direction of rotation necessary to induce either red or blue subjective colour in the stimulus. If, for example, the disc is rotated in the direction shown as inducing blue, the sequence of events viewed by the observer is; 1) darkness, 2) a uniform stimulus field, followed by 3) the checkerboard and then a further period of darkness. Figure 100 shows a pictorial description of this sequence, together with the time of duration of each component of the stimulus expressed as a fraction of the periodic time t , of the disc D . To ensure a fairly sharp changeover from one projector to the other, narrow sector slits were positioned in the light paths behind each segment in the rotating disc. These slits are shown as hatched lines in figure 99b. Rise and fall times of each stimulus component were each approximately 3 per cent of the periodic time.

For the E.R.G. study, the active electrode was contained in a haptic ³¹ contact lens fitted to the observer's right eye. An indifferent electrode (Ag-Ag Cl) was placed on the forehead and approximately 4cm above the haptic lens and the right ear was earthed. For the E.P. analysis, Ag-Ag Cl electrodes were placed on the right ear (earth), on the inion (electrode 2), 5cm above the inion on the midline (electrode 3), 3cm on the left of electrode 3 (electrode 1) and 3cm on the right of electrode 3 (electrode 4). Bipolar recordings were made between electrodes 3 and 2, between electrodes 4 and 2, and between electrodes 1 and 2. The position of each electrode is shown in figure 99a. The E.R.G. and E.P. experiments were completed on separate occasions. The apparatus also included three Medlec A9 differential amplifiers and a Datalab (2 channel) averager. Both E.E.G. and E.R.G. responses were stored on a Fenlow F.M. tape recorder

FOOTNOTE 31; This lens was made from an impression prepared by

■■■■■.



A description of the blue inducing signal. t denotes the periodic time. The red signal is a time reversal of this i.e. the uniform field immediately follows the checks.

Fig100

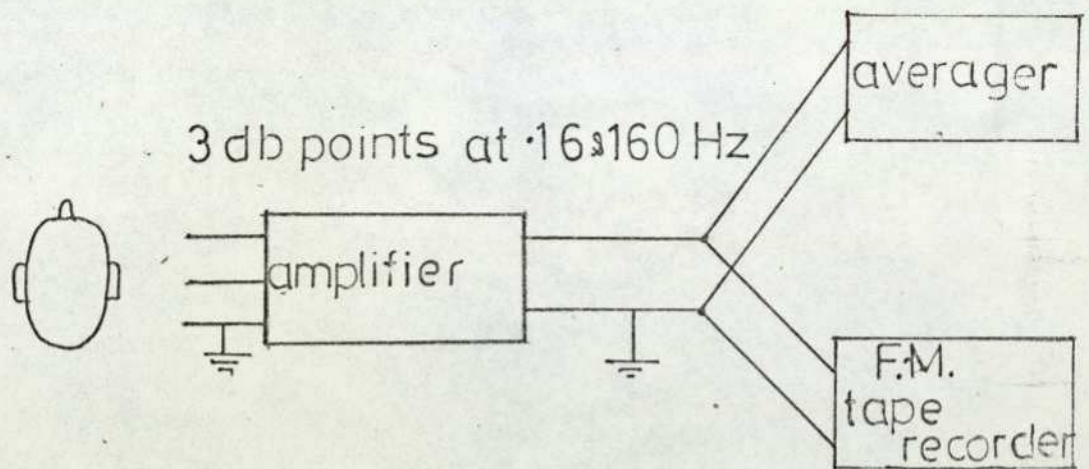


Fig101 The main electronic components

(4 channel). Figure 99 shows the main features of the electronic hardware used.

One observer was employed (J.R.J.) and data were collected for the red and blue inducing signals with disc periodic times (t) of 900, 400, 300, 225 and 140msec. Red subjective colour was judged to appear for values of t equal to 400, 300 and 225msec, with the maximum saturation at the 300msec setting. For the blue signal (obtained by rotating the disc D in the direction indicated in figure 99), little subjective colour was judged to have been manifested, but this mode of presentation appeared to give rise to a checkerboard with black and white checks of very high subjective contrast. With the red mode of presentation, the contrast between the white and black checks was considerably reduced, as well as colour being seen. This difference in the appearance of the checkerboard pattern for the two modes of presentation, with the three intermediate values of t given above was, in fact, quite marked.

In addition to the red and blue inducing stimuli, data were collected for the 'red' sequence, but with the uniform field provided by projector P_2 , replaced by a checkerboard of identical dimensions to the one provided by projector P_1 . (When viewed simultaneously, the black checks of each pattern coincided in space). The luminance of the white checks of this second pattern (projector P_2) was *twice* the luminance of the homogeneous white field which it replaced. Now, for any part of the stimulus period, the spatially averaged luminance provided by this 'double-check' signal was identical to that provided by the red inducing signal. The appearance of the stimulus however, at each of the disc rotation speeds was similar to the blue stimulus. Thus, if differences in the E.R.G. (or E.P.) data for the red and blue signals are due solely to the fact that the spatially averaged luminance at any instant in the stimulus cycle (excluding the totally dark periods) is different, then the results obtained from the red signal and the double-check signal should be the same.

Two experimental runs were performed in the E.R.G. investigation and in each run, all three temporal signals were presented in turn; red, blue, double-check (dCh). For the E.P. investigation, one experimental run was performed.

b) Results

The E.R.G. results are shown in figure 102. The curves obtained from each experimental run are superimposed for each stimulus condition and as can be seen, consistent results are generally obtained from both runs. The vertical arrows indicate the stimulus onset. Each row shows the results for the given disc period (msec) and each curve represents the averaged result taken over 500msec for 128 repetitions of the stimulus. For each data row, the results are qualitatively the same. Thus, although the results show consistent and low noise to signal ratios, the perceptual differences between each stimulus (for a given temporal frequency) are not indicated on the E.R.G. This result is rather inconclusive. Since, however, the E.R.G. is an indicator of the activity of many cells in the retina, it may well be too gross a recording to show the functioning of single subjective colour inducing mechanisms in the retina.

The E.P. data are shown in figure 103a for the blue signal, figure 103b for the red signal and figure 103c for the double-check signal. In each of these figures, rows 1-5 correspond to disc periodic times of 900-140msec. In each row, the data obtained from the three electrodes, 1, 3 and 4 are grouped together. The double headed arrows indicate the vertical distance in each trace corresponding to 5 v. For electrodes 4, 3 and 1 this distance is 10.5, 17.7 and 17mm respectively. These figures apply for each data group in all three figures 103 (a, b, c). The vertical arrows (single heads) indicate the onset of the stimulus. For each curve, 5cm on the time axis corresponds to 500msec. The data were taken from one observer (J.R.J.) as in the E.R.G. experiment, and the results from only a single run are shown.

Figure 102 shows plots of the difference Δv (expressed in μv) between the maximum peak and minimum trough vs. periodic time of the disc for each E.P. trace. For electrode 3, the difference Δv is slightly reduced for $t = 225$ and 300 msec in the red curve compared with either the blue or double check curves which are similar. It will be recalled that for these values of the disc periodic time, the perceptual difference between either the blue or double-check stimulus compared with the red stimulus was the greatest; the red stimulus appeared as low contrast reddish and white checkerboard, whereas the other two stimuli appeared as high contrast black and white checkerboards. The curves obtained from electrodes 1 and 4 are rather more inconclusive.³²

c) Discussion

The attempt to identify reflections in the E.P. and E.R.G. data of the action of F-B subjective colour mechanisms has produced, on the whole, rather inconclusive results. The E.P. data shown in figure 103, with electrode 3 employed, however, can be tentatively interpreted as indicating the perceptual difference obtained between the red and blue stimuli when the red induction was most pronounced. This trend in the data cannot be due to the fact that the blue and red signals have a different averaged spatial luminance at any instant during the stimulus event, since the blue and double-check data are, on the whole, similar.

The mode of presenting the stimuli was flicker and this must be criticised for the following reason; it has been shown that for stimuli of the type used in this experiment, a single pulsed presentation produces FOOTNOTE 32; In addition, the data obtained from electrode 3 were re-averaged with a sample time corresponding to the periodic time of the rotating disc. It was hoped that these curves, which possessed much lower noise to signal ratios than the other E.P. curves might reveal more pronounced differences than the curves shown in figure 103. Unfortunately this did not occur, and these extra data are not reproduced here.

colours of a greater saturation than for the flicker mode of presentation (see experiment 3). Thus, by using the flicker mode, a certain amount of interaction between successive stimulus events may act only to obscure the subjective colour effects in the E.P. traces. By using single pulse events as the stimuli, a greater degree of success in this experiment is predicted.

Figure Captions

Fig. 102. E.R.G. results. The data obtained from two experimental runs are shown superimposed. The vertical arrows denote stimulus onset, and each row contains data obtained with the given periodic time of the disc.

Fig. 103. E.P. results. Each row contains data obtained from the three electrodes 1, 3 and 4. The disc periodic times are the same as indicated in fig. 102. Vertical arrows (single heads) denote stimulus onset.

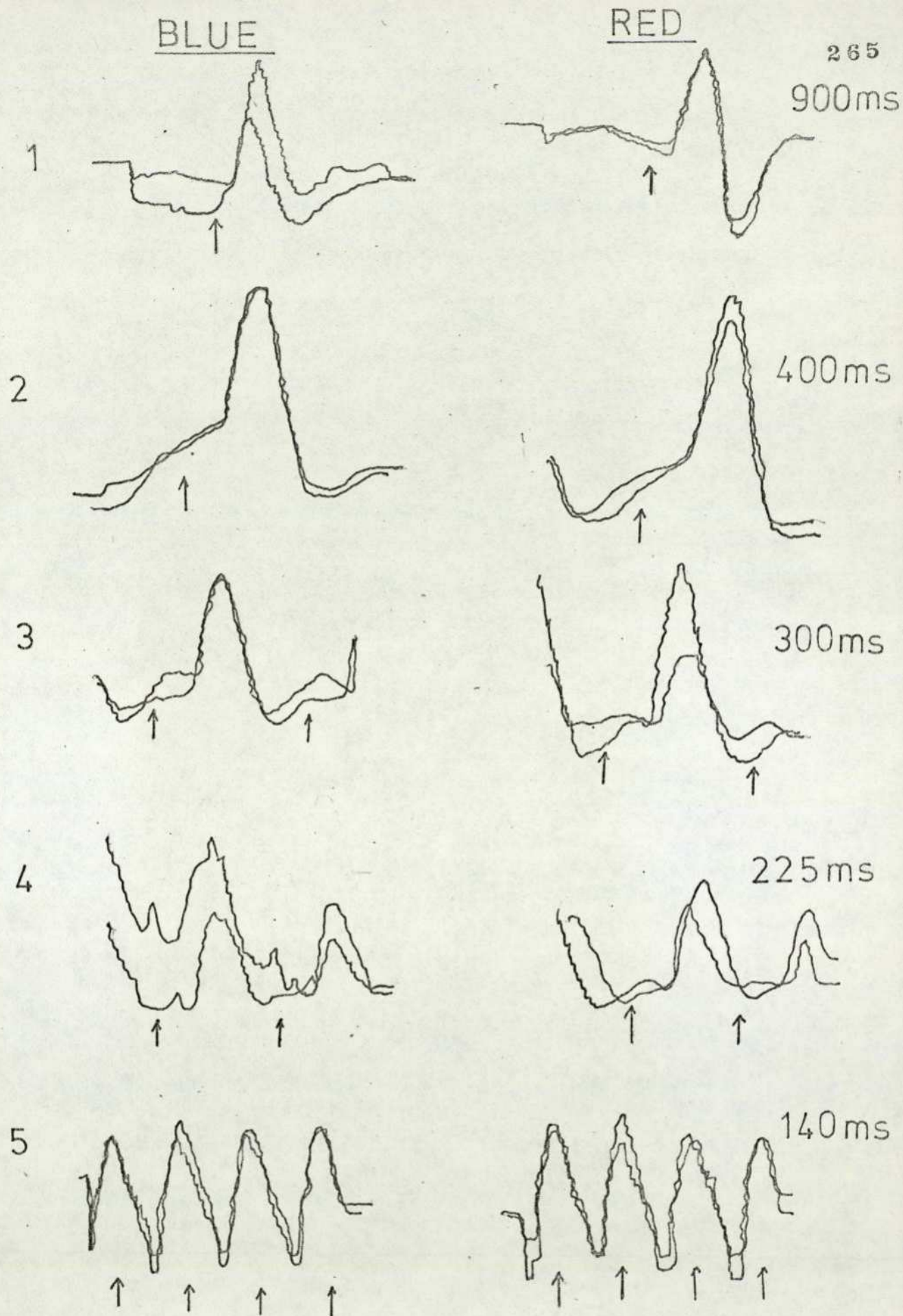
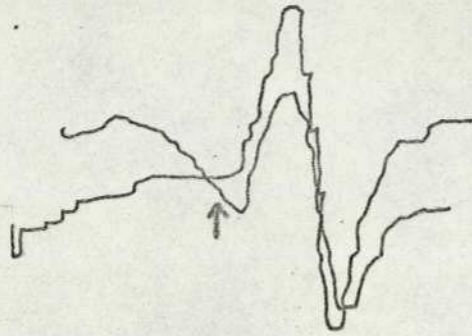


Fig 102 ERG Recordings

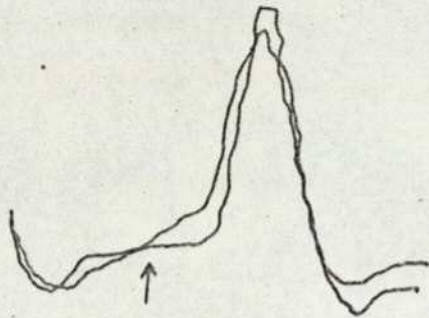
For rows 1-4 : 1cm - $16\mu\text{V}$
 " " 5 : " - $8\mu\text{V}$

500ms

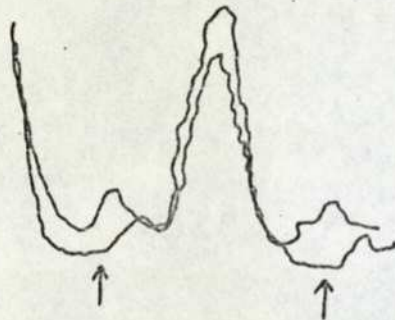
1



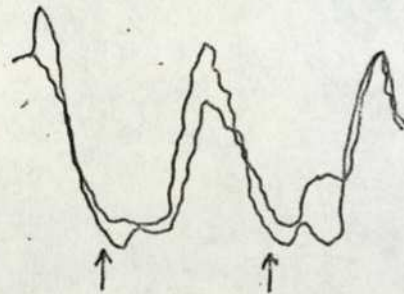
2



3



4



5

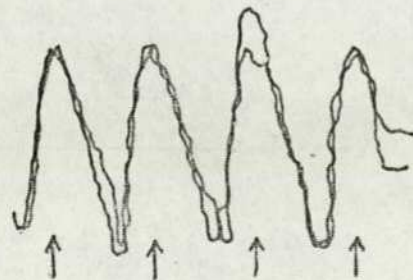


Fig102(contd) ERG Recordings (contd)

BLUE

267

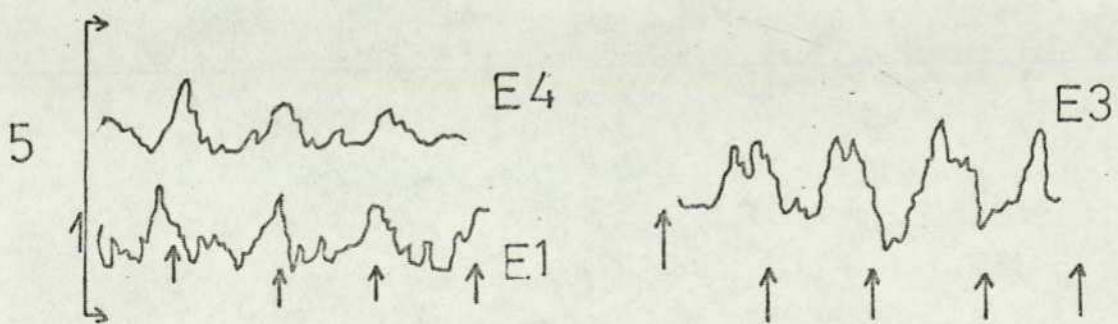
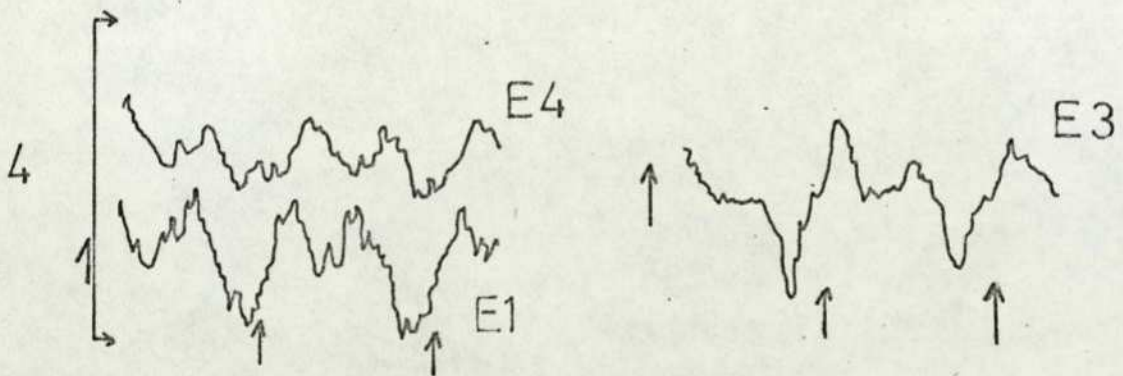
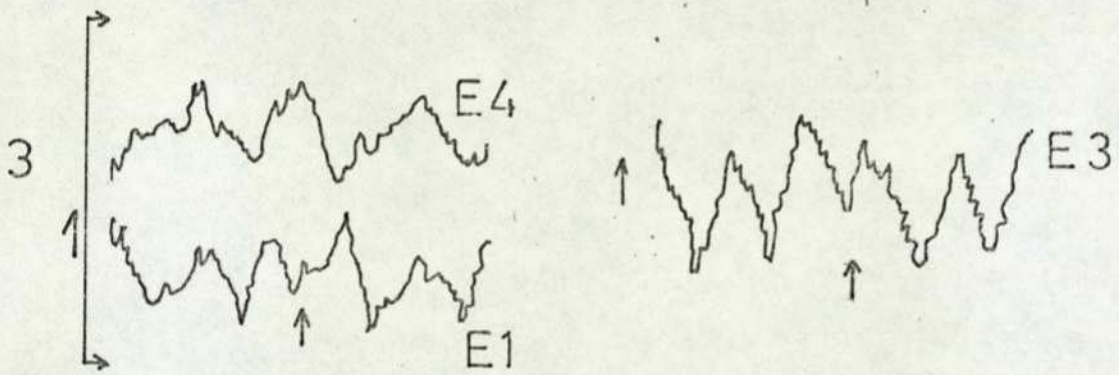
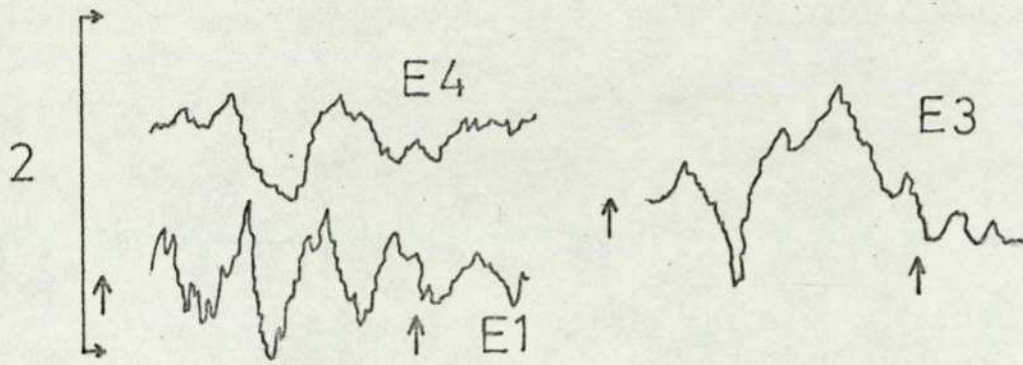
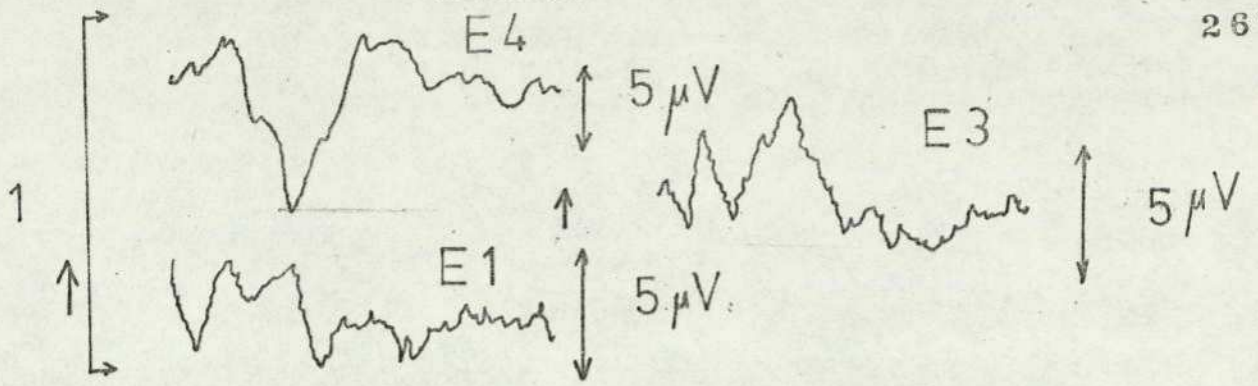


Fig 103a EP Results

500msec

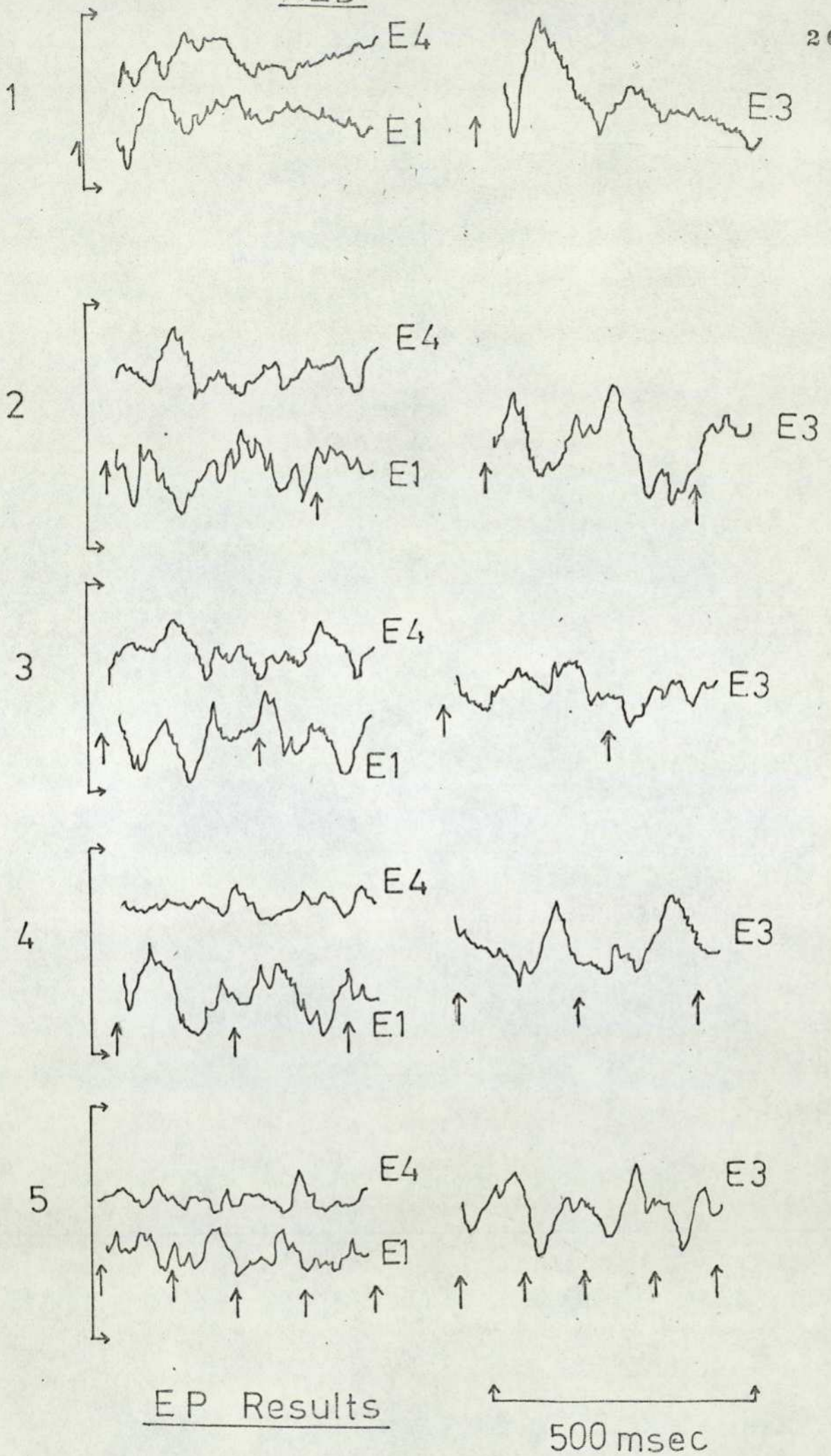


Fig103b

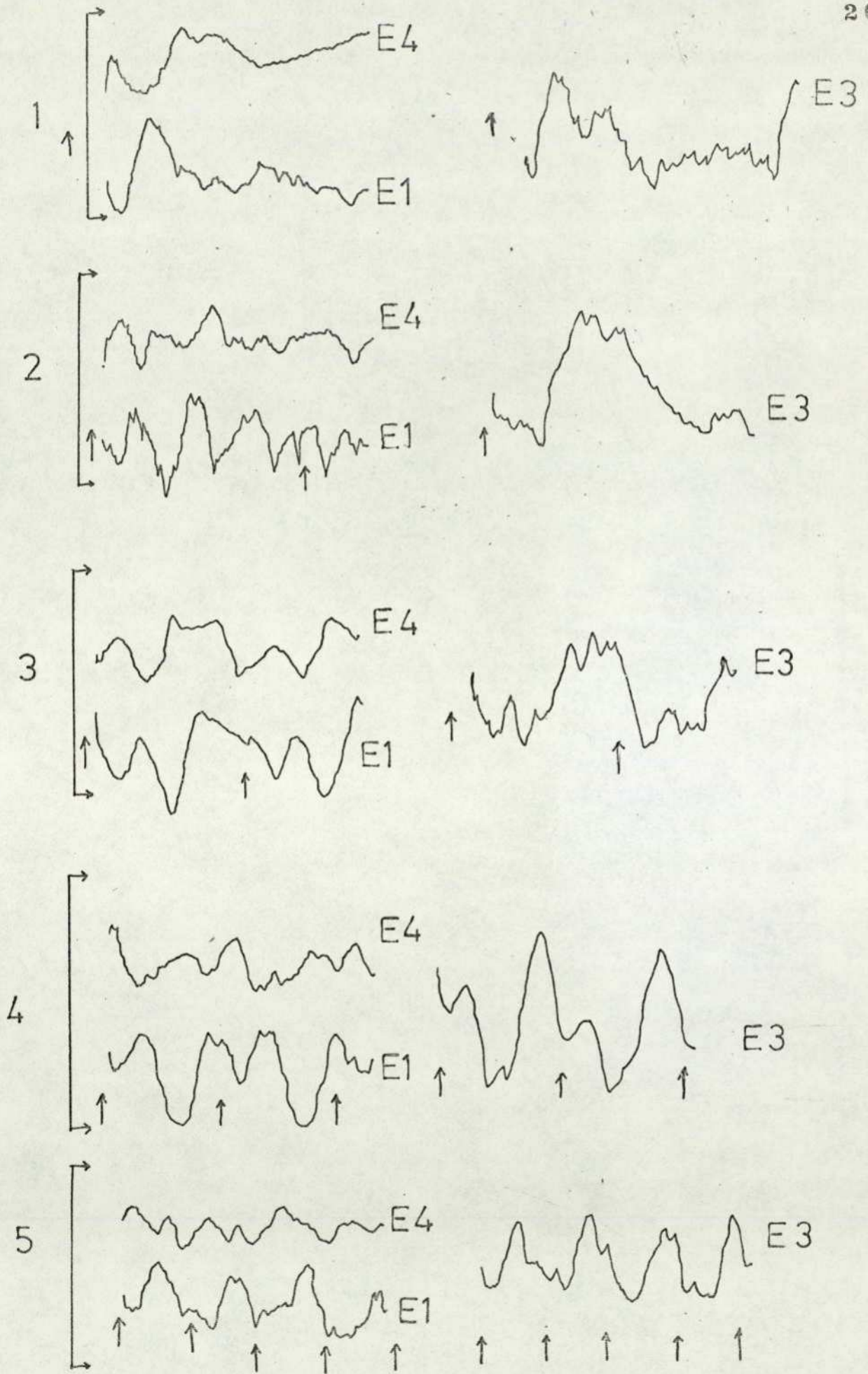
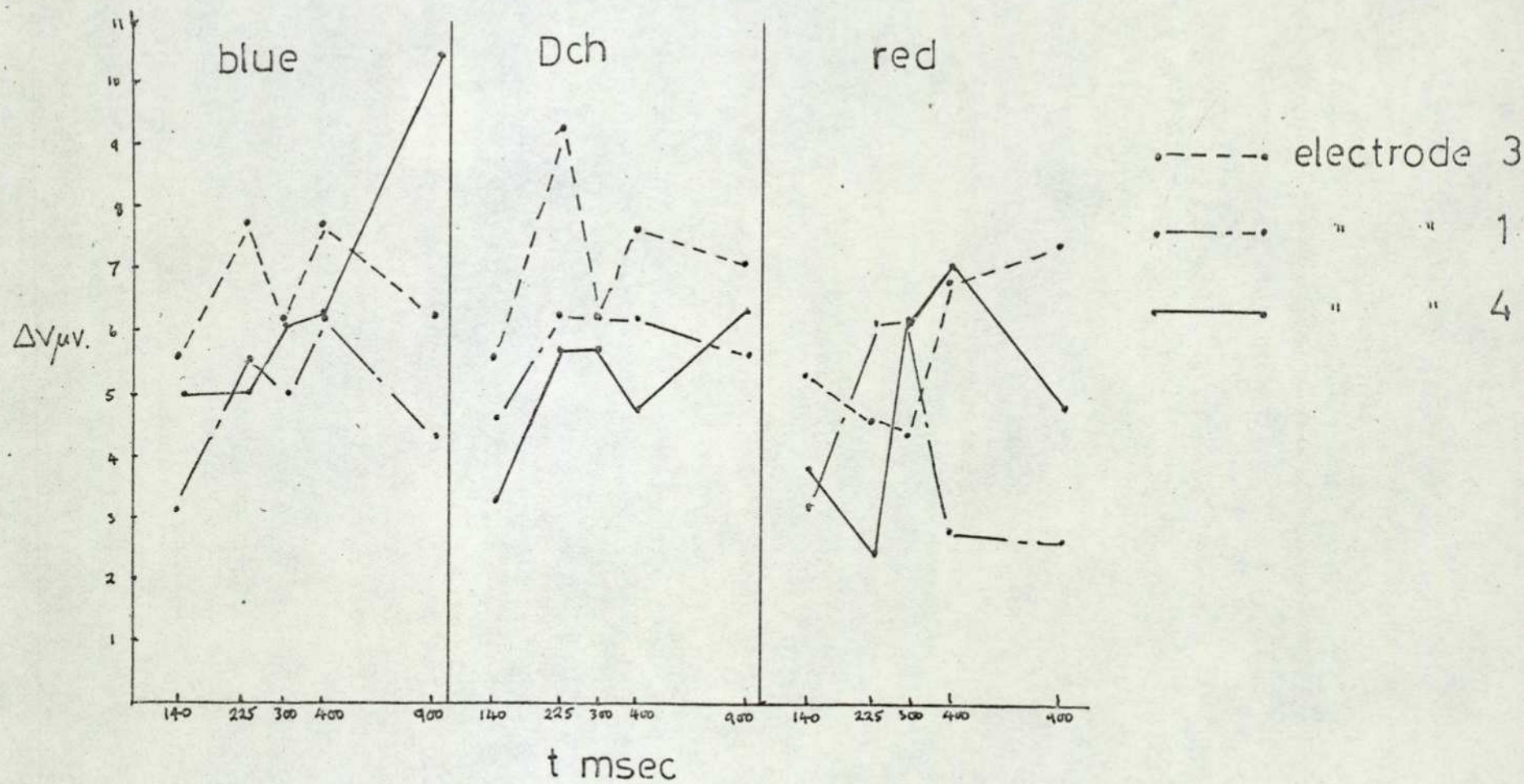


Fig 103c

EP Results

500msec



$\Delta V_{\mu v}$ (max voltage change in E.P. data) vs. t msec (disc period)

Fig 104

The phenomenon of subjective colour, induced in an intermittent achromatic stimulus has received the attention of many investigators over the last century and a half. Although a large number of experiments have been performed, (the main findings of which are discussed in Chapter 1), no really satisfactory quantitative measures of such temporally based subjective colour effects have previously been obtained.

The initial stage in the project was an attempt to provide such quantitative data, where the colours were produced in a static stimulus display, rather than from rotating patterned discs, which have been employed in most of the experimental investigations reported in the literature. From the results, it was concluded that two forms of subjective colour could be manifested from the achromatic stimulus used; The first, termed 'Fechner-Benham' (F-B) subjective colour, which was the main concern of this research programme, is the effect normally associated with rotating patterned discs. The second termed the 'purple effect', appears to favour higher stimulus luminances than F-B colour for its production and has a different spatial form in the stimulus field.

One of the aims of the research was to investigate the theoretical postulates concerning the origin of F-B subjective colour which have appeared in the literature and if necessary to replace these by a new and more satisfactory theory. To enable an investigation of one particular theory (the Morse Code theory), to be undertaken, a modulator capable of providing a large variety of flicker waveforms, without producing a change in the spectral composition of the light had to be developed. Such an apparatus was produced and tested, and it was suggested that such a device would find many applications in flicker experiments. The experimental work performed with this modulator suggested that not only is the Morse Code theory untenable, but the Fechnerian theory (another commonly held theory) is also unsatisfactory,

in that it predicts F-B subjective colour from a single achromatic light pulse. Two achromatic light pulses are in fact necessary, being spatially adjacent in the stimulus field, and the temporal separation of these determining the subjective colours perceived. It was also discovered, that the meta- and paracontrast luminosity masking phenomena play a role in determining the F-B colour sensations aroused.

One of the main conclusions from the experimental work is that the F-B subjective colour inducing visual mechanisms are not only situated in the retina, but each appears to possess a receptive field with a centre-surround^{spatial} arrangement, to its receptive field. It was further agreed that colour coded (tonic) ganglion cells are the most likely candidates for the subjective colour producing mechanisms, and that the colours are obtained from an interaction between centre and surround signals in the receptive fields of such cells. If this is true, then the results obtained from one of the experiments carried out (experiment 4) provide the first estimates of the receptive field sizes of colour coded (tonic) ganglion cells in the human retina. In connection with this idea, some speculations, supported by other experimental work, concerning the dynamic properties of both tonic and phasic ganglion cells, appear to explain the formation of F-B subjective colour quite satisfactorily.

Finally, a pilot electrophysiological study was performed in an attempt to find reflections in human E.R.G. and E.P. data of the action of F-B colour inducing mechanisms. The results of this experiment were rather disappointing, although it was suggested that a more positive result may be obtained, using single pulses to produce the subjective colour, rather than a flickering stimulus.

From the viewpoint of further experimental work, quantitative measures of the spatial orientation of F-B subjective colour across the area in which it is produced, appears to be a worthwhile project, together with an investigation of the effect of blurring any sharp contours present

in the stimulus. (It will be recalled that certain authors suggested that such contours are necessary in order to produce F-B subjective colour).

The failure to perceive saturated green subjective colour also needs further investigation. It may be, for example, that predicted green inducing signals presented in target and surround fields, stimulating non-foveal locations of the retina, may produce a saturated green.

REFERENCES

- ABNEY, W. DE. (1895) An artificial spectrum top.
Nature (Lond) 51, 292.
- ABRAMOV, I. (1972) Retinal Mechanisms of Colour Vision.
Handbook of Sensory Physiology Vol. VII/2
Ed. FUORTES M.G.F., SPRINGER-VERLAG
- ALPERN, M. (1953) Metaccontrast.
J.Opt.Soc.Am. 43, 648-657.
- BAGLEY, W. B. (1902) An Investigation of Fechner's Colors.
Am. J. Psychol., 13, 488-525.
- BALL, R. J. (1964) An Investigation of brightness enhancement
tendencies.
Am. J. Optom., 41, 333-361.
- BALL, R. J. and BARTLEY, S. H. (1966) Changes in brightness-index,
saturation and hue produced by luminance-
wavelength-temporal interactions.
J. Opt. Soc. Am., 56, 695-699.
- BARLOW, H. B. (1953) Summation and inhibition in the frog retina.
J. Physiol., 119, 69-88.
- BARLOW, H. B., HILL, R. M. and LEVICK, W. R. (1964) Retinal ganglion
cells responding selectively to direction and
speed of image motion in the rabbit.
J. Physiol., 173, 377-407.
- BARTLEY, S. H. and BALL, R. J. (1969) Effects of intermittent photic
input on brightness, hue, saturation, visual
acuity, and stereopsis.
Am. J. Optom., 46, 315-318.
- BENDER, B. G. (1973) Spatial interactions between the red- and green-
sensitive colour mechanisms of the human visual
system.
Vision Res., 13, 2205-2218.

- BENHAM, C. E. (1894) The artificial spectrum top.
Nature (Lond), 51, 200.
- BIDWELL, S. (1899) Curiosities of light and sound.
(Swann Sonnenschein and Company, London).
- BIJL, G. K. and VERINGA, F. T. (1972) Hue shifts accompany phase induced modulation enhancement of sinusoidally flickering lights.
Vision Res. 12, 1431-1434.
- BRIGNER, W. (1971) Role of lateral inhibitory interaction in colour coding.
Perceptual and Motor Skills, 32, 451-468.
- BROWN, P. K. and WALD, G. (1964) Visual pigments in single rods and cones of the human retina.
Science, 144, 145-151.
- BUCKMAN-OLSEN, B. and ROSENFALCK, A. M. (1957) Spectral energy calibration of a light flash source used in physiological experiments.
J. Opt. Soc. Am., 45, 30-34.
- BURNHAM, R. W. (1952) A colorimeter for research in colour perception.
Am. J. Psychol., 65, 603-608.
- BURNHAM, R. W. (1964) Binocular subjective colors and the visual mechanism.
Am. J. Psychol., 67, 492-499.
- BUTTERFIELD, J. F. (1967) Subjective Color System.
U.S. Patent No. 3, 311, 699.
- BUTTERFIELD, J. F. (1970) Subjective Color created by black and white animation.
J. Soc. Mot. Pict. Tel. Eng., 79, 523-526.
- CAMPENHAUSEN, C. v. (1968a) Über die Farben der Benhamschen Scheibe.
Z. vergl. Physiol., 60, 351-374.

- CAMPENHAUSEN, C. v. (1968b) Über den Ursprungsort von musterinduzierten
Flickerfarben im visuellen System des Menschen.
Z. vergl. Physiol., 61, 355-360.
- CAMPENHAUSEN, C. v. (1969) The colors of Benham's top under metameric
illuminations.
Vision Res., 9, 677-682.
- CAMPENHAUSEN, C. v. (1971) Musterinduzierte Flickerfarben Untersuchungen
zur Psychophysik des Farbensehens.
Verh. dt. Zool. Ges., 64, 227-234.
- CAMPENHAUSEN, C. v. (1973) Detection of short time delays between photic
stimuli by means of pattern induced flicker
colors (P.I.F.C.s).
Vision Res., 13, 2261-2272.
- COHEN, J. and GORDON, D. A. (1949) The Prevost-Fechner-Benham
subjective colors.
Psychol. Bull., 46, 97-136.
- COLENBRANDER, M.C. (1933) Über subjektive Farbenerscheinungen.
Acta ophthal. Kbh., 11, 437-460.
- COLGAN, C. M. (1965) The effect of observational technique on
brightness enhancement.
Amer. J. Psychol., 78, 471-475.
- CORNSWEET, T. N. (1968) Visual Perception.
Academic Press, N.Y.
- CRAIG, E. A. (1973) Visual effects of subfusional rates of high-
intensity intermittent photic stimulation.
Am. J. Optom., 50, 387-394.
- DAW, N. W. (1973) Neurophysiology of Color Vision.
Physiological Reviews, 53, 571-611.
- DE VALOIS, R. L. (1971) Contribution of different lateral geniculate
cell types to visual behaviour.
Vision Res. Suppl. 3. 383-396.

- DE LANGE, H. (1958a) Research into the dynamic nature of the human fovea-cortex systems with intermittent and modulated light.
I. Attenuation characteristics with white and coloured light.
J. Opt. Soc. Am., 48, 777-784.
- DE LANGE, H. (1958b) Research into the dynamic nature of the human fovea-cortex systems with intermittent and modulated light. II. Phase shift in brightness and delay in color perception.
J. Opt. Soc. Am., 48, 784-789.
- DE VALOIS, R. L., ABRAMOV, I. and JACOBS, G. H. (1966) Analysis of response patterns of LGN cells.
J. Opt. Soc. Am., 56, 966-977.
- DE VALOIS, R. L. and JACOBS, G. H. (1968) Primate Color vision.
Science N.Y., 162, 533-540.
- DE VALOIS, R. L. and PEASE, P. L. (1971) Contours and contrast: Responses of monkey lateral geniculate nucleus cells to luminance and color figures.
Science, N.Y., 171, 694-696.
- DOWLING, J. E. and BOYCOTT, B. B. (1966). Organization of the primate retina: electronmicroscopy.
Proc. Roy. Soc. B., 166, 80-111.
- DOWLING, J. E. and WERBLIN, F. S. (1971). Synaptic organization of the vertebrate retina.
Vision Res., Suppl. 3., 1-15.
- FECHNER, G. T. (1838) Ueber eine Scheibe zur Erzeugung subjectiver Farben.
Pogg. Ann. Physik. u. Chemie., 45 (121), 227-232.

- FEHRER, E. and RAAB, D. (1962) Reaction time to stimuli masked by metacontrast.
J. exp. Psychol., 63, 143-147.
- FESTINGER, L., ALLYN, M. R. and WHITE, C. W. (1971). The perception of color with achromatic stimulation.
Vision Res., 11, 591-612.
- FIORENTINI, A. (1972) 'Mach Bands'.
Handbook of Sensory Physiology Vol. V11/4
Ed. HURVICH, L. and JAMESON, D. SPRINGER-VERLAG.
- FIORENTINI, A., BAYLY, E. J. and MAFFEI, L. (1972). Peripheral and central contributions to psychophysical spatial interactions.
Vision Res., 12, 253-259.
- FIORENTINI, A. and MAFFEI, L. (1970) Transfer characteristics of excitation and inhibition in the human visual system.
J. Neurophysiol., 33, 285-292.
- FRY, G. A. (1933a) Modulation of the optic nerve current as a basis of colour vision.
Am. J. Psychol., 45, 488-492.
- FRY, G. A. (1933b) Color phenomena from adjacent retinal areas for different temporal patterns of intermittent white light.
Am. J. Psychol., 45, 714-721.
- FRY, G. A. (1945) A photoreceptor mechanism for the modulation theory of color vision.
J. Opt. Soc. Am., 35, 114-135.
- FRY, G. A. (1965) Mechanisms subserving colour vision.
Am. J. Optom., 42, 271-287.

- GOURAS, P. (1968) Identification of cone mechanisms in monkey ganglion cells.
J. Physiol., 199, 533-547.
- GOURAS, P. (1969) Antidromic responses of orthodromically identified ganglion cells in monkey retina.
J. Physiol., 204, 407-419.
- GOURAS, P. (1971) The function of the midget cell system in primate color vision.
Vision Res., Suppl. 3, 397-410.
- GOURAS, P. (1972) S-potentials.
Handbook of sensory Physiology Vol. V11/2.
Ed. FUORTES, M.G.F., SPRINGER-VERLAG.
- GREGORY, A. H. (1968) Interaction of visual stimuli.
Nature, 219, No. 5155, 734, 735.
- GUTH, S. L. (1964) The effect of wavelength on visual perceptual latency.
Vision Res., 4, 567-578.
- HANSEL, C. E. M. (1957) Subjective color for television.
Wireless World. (October) 508.
- HASEGAWA, T. (1971) Effects of spatio-temporal interaction on Fechner color.
Acta Chromatica, 2, 49-57.
- HELMHOLTZ, H. v. (1860) In 'Treatise on physiological optics'.
(Vol. II) Ed. SOUTHALL J. P. C.
G. BANTA (publisher) 1924.
- HERING, (1872) Grundzuge einer theorie des Farbensinnes.
Sitzungber. Akad. der Wiss., Wien,
Math-Naturv. Kl, 70, 169.

- HESS, E. H. (1952) Subjective color: retinal vers. central origin.
Am. J. Psychol., 65, 278-280.
- IKEDA, H. and WRIGHT, M. J. (1972) Receptive field organization of 'sustained' and 'transient' retinal ganglion cells which subserve different functional roles.
J. Physiol., 227, 769-800.
- IWAGAKI, (1968) A new method of detecting colour anomalies.
Rinsho Ganka, 22, 515.
- JAMESON, D. (1972) 'Theoretical issues of Colour vision'
Handbook of Sensory physiology, Vol. V11/4
Ed. HURVICH, L. and JAMESON, D. SPRINGER-VERLAG.
- JARVIS, J. R. (1973) A method of changing the time pattern of a light stimulus without a temporal change in spectral composition.
Vision Res., 13, 2575-2580.
- KELLY, D. H. (1961) Visual responses to time dependent stimuli.
II Single channel model of the photopic visual system.
J. Opt. Soc. Am., 51, 747-754.
- KELLY, D.H. (1969) Flickering patterns and lateral inhibition.
J. Opt. Soc. Am., 59, 1361-1370.
- KELLY, K. L. (1943) Color designation for lights.
J. Opt. Soc. Am., 33, 627,
- KENNEDY, D. (1963) Inhibition in visual systems.
Scientific American. (JULY)
- KINNEY, J. (1965a) Effect of exposure time on induced colour.
J. Opt. Soc. Am., 55, 731-736.
- KNEHR, C.A. (1953) Individual differences in subjective color.
J. Psychol., 36, 289-294.

KNEHR, C. A. and LORENZ, R. J. (1964) Subjective color and C.F.F.

Perceptual and Motor Skills, 19, 462.

KOZAK, W. M. and REITBOECK, H. J. (1973) Color-specific temporal spike sequences in single optic-tract fibers of the cat.

J. Opt. Soc. Am., 63, 1278.

KRAUSKOPF, J. (1962) Light distribution in human retinal images.

J. Opt. Soc. Am., 52, 1046-1050.

KRAUSKOPF, J. (1973) Contributions of the primary chromatic mechanisms to the generation of visual evoked potentials.

Vision Res., 13, 2289-2298.

KRAUSKOPF, J. and MOLLON, J. D. (1971) The independence of the temporal integration properties of individual chromatic mechanisms in the human eye.

J. Physiol., 219, 611-623.

*

LIT, A., YOUNG, R. H. and SHAFFER, M. (1971) Simple reaction time as a function of luminance for various wavelengths. Percept. and Psychophys., 10, 397-399.

MACNICHOL, E. F., FEINBERG, R. and HAROSI, F. I. (1973) Colour discrimination processes in the retina.

Colour 73. Adam Hilger London, 1973.

MACNICHOL, E. F. and SVAETICHIN, G. (1958) Symposium on electrophysiology of the visual system. Natl. Ints. Health, Bethesda, Md. Am. J. Ophthal., 46, 385-404.

MAFFEI, L. and CERVETTO, L. (1968) Dynamic interactions in retinal receptive fields.

Vision Res., 8, 1299-1303.

* LEVICK, W. R. (1972) Receptive fields of retinal ganglion cells. Handbook of sensory physiology Vol VII/2 Ed FUORTES, M. G. F., SPRINGER-VERLAG

(+) McILWAIN, J.T. (1964)

Receptive fields of optic tract axons and lateral geniculate cells: peripheral extent and barbiturate sensitivity.

J. Neurophysiol. 27 1154-1173.

teristics of excitation and inhibition in
cat retinal ganglion cells.

J. Neurophysiol., 33, 276-285.

MANSFIELD, R. J. W. (1973) Latency functions in human vision.

Vision Res., 13, 2219-2234.

MARKS, W. B., DOBELLE, W.H., and MACNICHOL, E. F. (1964) Visual
pigments of single primate cones.

Science, 143, 1181-1183.

(*)

MCKEE, S.P. and WESTHEIMER, G. (1970) Specificity of cone mechanisms
in lateral interaction.

J. Physiol., 206, 117-128.

MOLLON, J. D. and KRAUSKOPF, J. (1973) Reaction time as a measure of
the temporal response properties of individual
colour mechanisms.

Vision Res., 13, 27-40.

*

NELSON, T. M. (1971) Stimulus intermittency and color studies in
review.

J. Gen. Psychol., 48, 17-28.

NILSSON, T. H. (1972) Effects of pulse duration and pulse rate on
hue of monochromatic stimuli.

Vision Res., 12, 1907-1921.

NILSSON, T. H. and NELSON, T. M. (1971) Hue shifts produced by
intermittent stimulation.

Vision Res., 11, 697-712.

NORREN, D. V. and PADMOS, P. (1973) Human and macaque blue cones
studies with electroretinography.

Vision Res., 13, 1241-1254.

OSTERBERG, G. (1935) Topography of the layer of rods and cones
in the human retina.

Acta Ophthal., suppl. 6.

* MURPHY, G. (1951).

An introduction to psychology.

Ed pub. HARPER & BROTHERS, NEW YORK, 1951

- PADGHAM, C. A. (1953) Quantitative study of visual after-images.
Br. J. Ophthal., 37, 165-170.
- PADGHAM, C. A. (1968) Measurements of the colour sequences in
positive visual after-images.
Vision Res., 8, 939-949.
- PIERON, H. (1922a) Le mecanisme d'apparition des couleurs
subjectives de Fechner-Benham.
Annee Psychol., 23, 1-49.
- PIERON, H. (1922b) Des lois du desequilibre chromatique initial
et de la preponderance de la diffusion
chromatique dans l'excitation lumineuse de
la retine (Mecanisme de production des
couleurs subjectives de Fechner-Benham).
C. R. Soc. Biol. Paris, 86, 922-925.
- PIERON, H. (1928) Influence de la composition de la luminiere
sur la nature des couleurs subjectives de
Fechner-Benham Donnees complementaires.
Annee Psychol., 29, 229-233.
- PIERON, H. (1932a) Les lois du temps du chroma. Report of a
joint discussion on vision pp. 277-280. The
Physical Society, London.
- PIERON, H. (1932b) La sensation chromatique. Donnees sur la
latence propre et l'etablissement des
sensations de couleur.
Annee Psychol., 32, 1-29.
- PIERON, H. (1939) La dissociation de l'adaptation lumineux et
de l'adaptation chromatique.
Ann. psychol, 40, 1-29.

- PIERON, H. (1957) The Sensations. Their functions, processes, and mechanisms.
Frederick and Muller Ltd.
- PIGGINS, D. J., KINGHAM, J. R., HOLMES, S. M. (1972) Colour, colour saturation, and pattern induced by intermittent illumination: an initial study.
Br. J. Phys. Opt., 27, 120-125.
- POLYAK, S. (1957) The vertebrate visual system.
Chicago: Univ. Press.
- PREVOST, B. (1826) Sur une apparence de decomposition de la lumiere blanche par le mouvement du corps qui la reflechit. Memoires de la Societe de Physique et d'Histoire naturelle de Geneva, 3, 121.
- PUGSLEY, P. (1972) Personal communication.
Chief engineer (Graphic Equipment Division)
Crosfield Electronics Ltd., London.
- RATLIFF, F., HARTLINE, H. K. and MILLER, W. H. (1963) Spatial and temporal aspects of retinal inhibitory interaction.
J. Opt. Soc. Am., 53, 110-120.
- RATLIFF, F., KNIGHT, B. W., TOYODA, J. and HARTLINE, H. K. (1967) Enhancement of flicker by lateral inhibition.
Science, 158, 392-393.
- REGAN, D. (1970) Evoked potential and psychophysical correlates of changes in stimulus colour and intensity.
Vision Res., 10, 163-177.
- REGAN, D. (1973a) An evoked potential correlate of colour: evoked potential findings and single-cell speculations.
Vision Res., 13, 1933-1941.

- REGAN, D. (1973b) Evoked potentials specific to spatial patterns of luminance and colour. *Vision Res.*, 13, 2381-2402.
- REMOLE, A. (1971) Luminance thresholds for subjective patterns in a flickering field: Effect of wavelengths. *J. Opt. Soc. Am.*, 61, 1164-1168.
- REMOLE, A. (1973a) Subjective patterns in a flickering field: Binocular vs. monocular observation. *J. Opt. Soc. Am.*, 63, 745-748.
- REMOLE, A. (1973b) Extended border enhancement during intermittent illumination: Binocular effects. *Vision Res.*, 13, 1289-1295.
- ROELOFS, C. O. and ZEEMAN, W. P. C. (1957) Colour phenomena associated with increases and decreases in physical brightness. *Acta Psychologica.*, 13, 173-196.
- ROELOFS, C. O. and ZEEMAN, W. P. C. (1958) Benham's top and the color phenomena resulting from interaction with intermittent light stimuli. *Acta Psychologica.*, 13, 334-356.
- RODIECK, R. W. and STONE, J. (1965) Analysis of receptive fields of cat retinal ganglion cells. *J. Neurophysiol.*, 28, 833-849.
- SAUNDERS, J. E. (1974) Personal communication.
- SCHOUTEN, J. F. and ORNSTEIN, L. S. (1939) Cited in ALPERN (1953). *J. Opt. Soc. Am.*, 29, 168-182.
- SCHILLER, P. H. and SMITH, M. (1966) Detection in metacontrast. *J. Exp. Psychol.*, 71, 32-39.
- SCHILLER, P. H. and SMITH, M. (1968) Monoptic and dichoptic metacontrast. *Perc. and Psychophysics*, 3, 237-239.

- SHEPPARD, J. J. (1968) Human Color Perception
Elsevier, New York.
- SILVESTRI, A. M. (1965) Chromatic induction from pulsating black and white stimuli.
J. Opt. Soc. Am., 55, 1182-1183.
- SPEKREIJSE, H. (1969) Rectification in the goldfish retina: analysis by sinusoidal and auxiliary stimulation.
Vision Res., 9, 1461-1472.
- SPEKREIJSE, H. and VAN DEN BERG, T. J. T. P. (1971). Interaction between colour and spatial coded processes converging to retinal ganglion cells in goldfish.
J. Physiol., 215, 679-692.
- STIGLER, R. (1910) Chronophotische studien uber den umgebungskontrast.
pflug. Arch. ges. Physiol., 134, 365-435.
- STILES, W. S. (1939) The directional sensitivity of the retina and the spectral sensitivities of the rods and cones.
Proc. R. Soc. B., 127, 64-105.
- STILES, W. S. (1953) Further studies of visual mechanisms by the two-colour threshold technique. In Coloquio sobre problemas opticos de la vision. pp. 65-103. Union Internationale de Physique Pure et Appliquee, Madrid.
- STILES, W. S. (1959) Colour vision: the approach through increment-threshold sensitivity.
Proc. natn. Acad. Sci., U.S.A., 45, 100-114.
- * TOYODA, J. (1973) Membrane resistance changes underlying the bipolar cell response in the carp retina.
Vision Res., 13, 283-294.

* STILES, W.S. and CRAWFORD, B.H. (1932). Equivalent adaptation levels in localized retinal areas. In: Report of a Joint discussion on vision. pp 194-211. Physical Soc. London, Cambridge Univ press (1932).

- TOYODA, J., HASHIMOTO, H. and OHTSU, K. (1973) Bipolar-amacrine transmission in the carp retina.
Vision Res., 13, 295-307.
- TREZONA, P. W. (1970) Rod participation in the 'blue' mechanism and its effect on colour matching.
Vision Res., 10, 317-332.
- TRINCKER, D. (1968) Personal communication to Campenhausen.
(CAMPENHAUSEN 1968a).
- TROLAND, L. T. (1921) The enigma of color vision.
Am. J. Physiol. Opt., 2, 23-48.
- VAN DER HORST, G. J. C. and BOUMAN, M. A. (1967) On searching for 'Mach band type' phenomena in colour vision.
Vision Res., 7, 1027-1029.
- VAN DER HORST, G.J. C. and MUIS, W. (1969) Hue shift and brightness enhancement of flickering light.
Vision Res., 9, 953-963.
- VERRIEST, G. and SEKI, R. (1964) Les chromaticites des couleurs subjectives suscitées par la rotation du disque de Fechner-Benham.
Revue D'Optique., 43, 53-63.
- WALRAVEN, J. (1973) Spatial characteristics of chromatic induction: the segregation of lateral effects from straylight artefacts. Vision Res., 13, 1739-1753.
- WALRAVEN, P. L. (1962) On the mechanisms of colour vision.
Thesis, Utrecht.
- WALRAVEN, P. L. (1972) Color Vision.
Annual Review of Psychology, 23, 347-374.
- WALRAVEN, P. L. (1973) Theoretical models of the colour vision network.
Colour 73. Adam Hilger London, 1973.
- WALRAVEN, P.L. and BOUMAN, M.A. (1966) Fluctuation theory of colour discrimination of normal trichromats.
Vision Res., 6, 567-586.

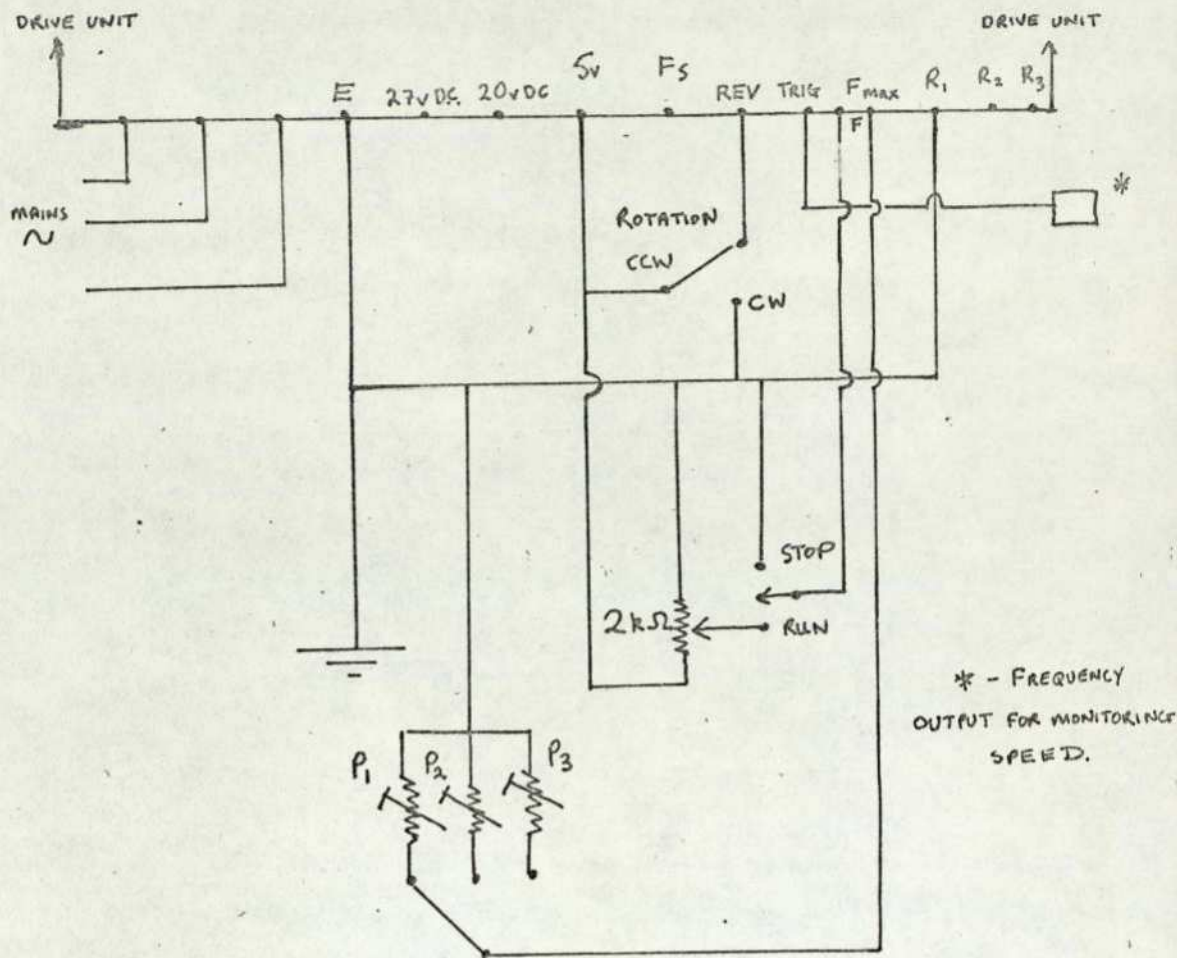
- WALRAVEN, P. L. and LEEBEEK, H. J. (1964) Phase shift of sinusoidally alternating colored stimuli.
J. Opt. Soc. Am., 54, 78-82.
- WEALE, R. (1953) Cone-monochromatism.
J. Physiol., 121, 548-569.
- WEISSTEIN, N. (1972) Metacontrast.
"Handbook of Sensory Physiology" Vol. V11/4
Ed. HURVICH, L. and JAMESON, D. SPRINGER-VERLAG.
- WEISSTEIN, N. and GROWNEY, R. L. (1969) Apparent movement and metacontrast: A note on Kahneman's formulation.
Perc. Psychophysics, 5, 321-328.
- WEISSTEIN, N. and GROWNEY, R. L. (1970) Metacontrast and some spatial characteristics of human visual receptive fields.
Paper delivered at meeting of Midwestern Psychological Association.
- WERBLIN, F. S. (1973) The control of sensitivity in the retina.
Scientific American. JAN. 1973.
- WERBLIN, F. S. and DOWLING, J. E. (1969) Organization of retina of the mudpuppy, *Necturus maculosus*. J. Neurophysiol. 32, 339-355.
- WESTHEIMER, G. and CAMPBELL, F. (1962) Light distribution in the image formed by the living human eye.
J. Opt. Soc. Am., 42, 1040-1045.
- WHITTEN, D. N. and BROWN, K. T. (1973) The time courses of late receptor potentials from monkey cones and rods.
Vision Res., 13, 107-135.
- WIESEL, T. N. and HUBEL, D. H. (1966) Spatial and chromatic interactions in the lateral geniculate body of the rhesus monkey. J. Neurophysiol., 29, 1115-1156.
- WRIGHT, W. D. (1946) Researches on normal and defective colour vision.
HENRY KIMPTON, LONDON.

Details of a) The P.D.20 stepper motor drive unit

b) The battery decay experiment

Figure 105 gives the circuit diagram for the stepper motor drive unit. To obtain greatest stability from the motor throughout the frequency ranges (60-40) Hz, (40-10) Hz and (10-0) Hz, the pre-set potentiometers P_1 , P_2 and P_3 respectively are adjusted.

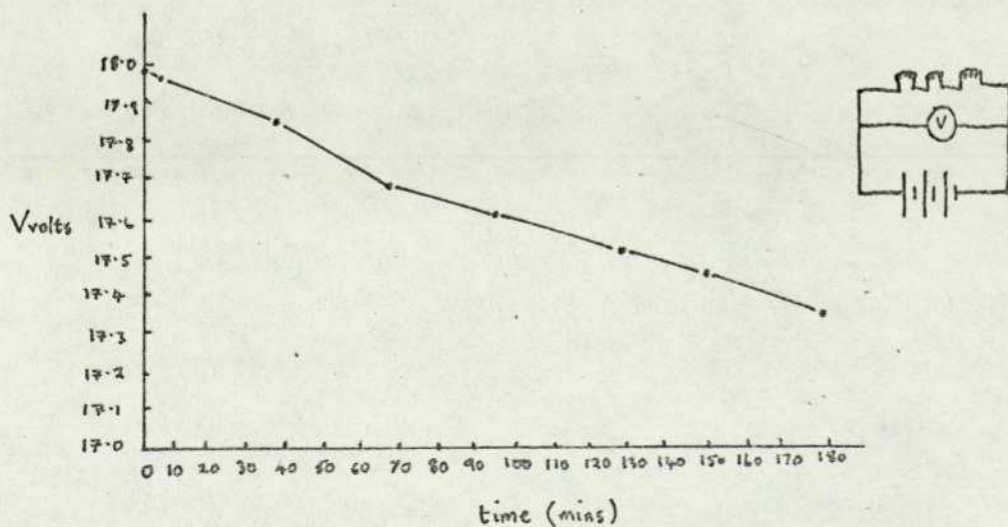
Figure 106 shows the results of the battery decay experiment referred to in Chapter 2. The circuit employed is shown in this figure and the experiment consisted of measuring the voltage across all three tungsten ribbon filament lamps at approximately half-hour intervals.



POTENTIOMETERS ; $P_1 = 5k\Omega$, $P_2 = 10k\Omega$, $P_3 = 20k\Omega$.

Fig 105 P.D.20. Stepper motor drive system

Fig 106 Battery decay expt. Results



APPENDIX 2

Details of Computer Programmes

Many of the flicker waveforms used in experiment 2 (A, B) were obtained from modulator rotating discs produced by a computer. Table 5 gives each flicker signal (shown by its classification number as described in figures 49 and 57, Chapter 4) and the appropriate programme which was employed to obtain the modulator disc.

<u>SIGNAL CLASSIFICATION</u>	<u>PROGRAM NUMBER</u>	<u>SIGNAL CLASSIFICATION</u>	<u>PROGRAM NUMBER</u>
2	3	R(4)	6
3	1	S(1)	5
4	1	B(4)	6
5	6	B(5)	1
6	6		
7	3		
8	6		
9	6		
10	2		
11	2		
12	6		
13	6		

Programs used to obtain the given flicker signal.

TABLE 5

Programme 5 was also used to obtain the flicker waveforms shown in figure 27 (Chapter 2). It will be recalled that each of these waveforms represents a synthesis of a number of terms of the Fourier expansion of the square wave shown.

Programme 4 was used to provide a rotating disc employed in a determination of the accuracy of the light modulator as described in Chapter 2.

Figure 107 shows the profile of a modulator disc provided

from the computer graph plotter. Alongside is shown the luminance vs. time function which the disc will produce in the modulator. This function in fact represents a synthesis of the first three harmonics of the square wave shown in figure 27a.

PROGRAM 1

```

MASTER DISK
INITIALISE PLOTTING
CALL HGPSTART(14HJ JARVIS SWEEP,14)
DIMENSION X(361),Y(361)
PI=3.1415927
DO 150 I=1,5
DO 130 J=1,361
DJ=J
D=J-1.0
R=(D*PI)/180.0
F=EXP((1*R)-(2.*PI))
G=1.0-F
I= (G) 101,101,10
100 SWEE=SQRT(94.0*F+47.6)
X(J)=SWEE*COS(R)+12.0
Y(J)=SWEE*SIN(R)+12.0
GO TO 130
101 X(J)=11.9*COS(R)+12.0
Y(J)=11.9*SIN(R)+12.0
130 CONTINUE
C POSITION ORIGIN FOR EACH I VALUE AND DRAW AXES
CALL HGPORIGIN(45.0,0.0)
CALL HGPAXIS(0.0,0.0,10,THE X AXIS,-10,25.0,0.0,-12.0,1.0)
CALL HGPAXIS(0.0,0.0,10,THE Y AXIS, 10,25.0,90.0,-12.0,1.0)
CALL HGPCURVE(X,Y,361,0.0,0.0,0.0)
C LOCATE INNER AND OUTER ALIGNMENT CIRCLES
CALL HGPCIRCLE(18.9,12.0,0.0,360,0.6,9.6,9.0,0.0)
CALL HGPCIRCLE(24.0,12.0,0.0,360,0.12,0.12,0.0,0.0)
CALL HGPlot(11.9,12.0,3,0)
CALL HGPlot(13.0,12.0,2,0)
CALL HGPlot(12.0,13.0,3,0)
CALL HGPlot(12.0,11.0,2,0)
150 CONTINUE
CALL HGPFINISH
STOP
END

```

END OF SEGMENT, LENGTH 144, NAME DISK

PROGRAM 2

```

MASTER DISK
C INITIALISE PLOTTING
CALL HGPSTART(14HJ JARVIS SWEEP,14)
DIMENSION X(361),Y(361)
PI=3.1415927
DO 150 I=1,5
DO 130 J=1,361
DJ=J
D=J-1.0
R=(D*PI)/180.0
F=((1-1.0)/1)*(EXP((R-PI)-PI))+1.0/1
G=1.0-F
IF (G) 101,101,130
100 SWEE=SQRT(94.0*F+47.5)
X(J)=SWEE*COS(R)+12.0
Y(J)=SWEE*SIN(R)+12.0
GO TO 130
101 X(J)=11.9*COS(R)+12.0
Y(J)=11.9*SIN(R)+12.0
130 CONTINUE
C POSITION ORIGIN FOR EACH I VALUE AND DRAW AXES
CALL HGPDRIGIN(45.0,0.0)
CALL HGPAXIS(0.0,0.0,10HTHE X AXIS,-10,25.0,0.0,-12.0,1.0)
CALL HGPAXIS(0.0,0.0,10HTHE Y AXIS, 10,25.0,90.0,-12.0,1.0)
CALL HGPSCURVE(X,Y,361,0.0,0.0,0.0)
C LOCATE INNER AND OUTER ALIGNMENT CIRCLES
CALL HGPCIRCLE(18.7,12.0,0.0,0.0,360.0,6.9,6.9,0.0)
CALL HGPCIRCLE(24.0,12.0,0.0,0.0,360.0,12.0,12.0,0.0)
CALL HGPlot(11.0,12.0,3,0)
CALL HGPlot(13.0,12.0,2,0)
CALL HGPlot(12.0,13.0,3,0)
CALL HGPlot(12.0,11.0,2,0)
150 CONTINUE
CALL HGPFINISH
STOP
END

```

END OF SEGMENT, LENGTH 253, NAME DISK

PROGRAM 3

```

MASTER DISK
C INITIALISE PLOTTING
CALL HGPSTART(14HJ JARVIS SWEEP,14)
DIMENSION X(361),Y(361)
PI=3.1415927
DO 150 I=1,5
DO 130 J=1,361
DJ=J
D=J-1.0
R=(D*PI)/180.0
F=((I-1.0)/I)*(R/PI)*(1.0/I)
G=1.0-F
IF (G) 101,101,100
100 SWEE=SQRT(94.0*F+47.6)
X(J)=SWEE*COS(R)+12.0
Y(J)=SWEE*SIN(R)+12.0
GO TO 130
101 X(J)=11.9*COS(R)+12.0
Y(J)=11.9*SIN(R)+12.0
130 CONTINUE
C POSITION ORIGIN FOR EACH I VALUE AND DRAW AXES
CALL HGPORIGIN(45.0,0.0)
CALL HGPAXIS(0.0,0.0,10*THE X AXIS,-10,25.0,0.0,-12.0,1.0)
CALL HGPAXIS(0.0,0.0,10*THE Y AXIS, 10,25.0,90.0,-12.0,1.0)
CALL HGPSCURVE(X,Y,361,0,0.0,0.0)
C LOCATE INNER AND OUTER ALIGNMENT CIRCLES
CALL HGPCIRCLE(18.9,12.0,1.0,360,0,6.9,6.9,0.0)
CALL HGPCIRCLE(24.0,12.0,0.0,360,0,12.0,12.0,0.0)
CALL HGPLOT(11.0,12.0,3,0)
CALL HGPLOT(13.0,12.0,2,0)
CALL HGPLOT(12.0,13.0,3,0)
CALL HGPLOT(12.0,11.0,2,0)
150 CONTINUE
CALL HGPFINISH
STOP
END

```

END OF SEGMENT, LENGTH 249, NAME DISK

PROGRAM 4

```

MASTER DISK
DIMENSION X(361),Y(361)
CALL HGPSTART(30HJ JARVIS SWEEP FOR SIMPLE SINE,30)
PI=3.1415927
WRITE (2,100)
100  FORMAT (1H1,10X,1HA,15X,1HX,15X,1HY)
DO 130 I=1,361
  AI=I
  A=I-181.0
  R=(I-181.0)*PI/180.0
  F=0.5+0.5*SIN(10.0*R)
  SWEE=SQRT(94.0*F+47.6)
  X(I)=SWEE*COS(R)+12.0
  Y(I)=SWEE*SIN(R)+12.0
130  CONTINUE
CALL HGPAXIS(0.0,0.0,10HTHE X AXIS,-10,25.0,0.0,-12.0,1.0)
CALL HGPAXIS(0.0,0.0,10HTHE Y AXIS, 10,25.0,90.0,-12.0,1.0)
CALL HGPSCURVE(X,Y,361,0.0,0.0,0.0)
CALL HGPCIRCLE(18.9,12.0,0.0,360.0,6.9,6.9,0.0)
CALL HGPCIRCLE(24.0,12.0,0.0,360.0,12.0,12.0,0.0)
CALL HGPCIRCLE(23.9,12.0,0.0,360.0,11.9,11.9,0.0)
CALL HGPlot(11.0,12.0,3,0)
CALL HGPlot(13.0,12.0,2,0)
CALL HGPlot(12.0,13.0,3,0)
CALL HGPlot(12.0,11.0,2,0)
CALL HGPFINISH
STOP
END

```

END OF SEGMENT, LENGTH 202, NAME DISK

PROGRAM 5

```

MASTER DISK
C INITIALISE PLOTTING
CALL HGPSTART(14HJ JARVIS SWEEP,14)
DIMENSION A(8),P(7),X(361),Y(361),W(361),Z(361)
READ(1,100)A
100 FORMAT(8F6.4)
R=AO(1,101)P
101 FORMAT(7F6.4)
PI=3.1415927
DO 150 I=1,7
WRITE (2,105)I
105 FORMAT (1H1,I2)
WRITE (2,106)
106 FORMAT(1H0,10X,1HD,15X,1HX,15X,1HY,15X,1HW,15X,1HZ)
IF (I.EQ.1) GO TO 110
N=10-I
A(N)=0.0
110 DO 130 J=1,361
DJ=J
D=J-181.0
R=(J-181.0)*PI/180.0
F=A(1)
DO 120 K=1,7
F=F+A(K+1)*SIN(K*R+P(K))
120 CONTINUE
SWEE=SQRT(94.0*F+47.6)
X(J)=SWEE*COS(R)+12.0
Y(J)=SWEE*SIN(R)+12.0
W(J)=(6.0*((R/PI)+1.0))+27.0
Z(J)=(10.0*F)+5.0
C PRINT OUT DATA VALUES D(ANGLE) X Y W Z FOR EACH I VALUE
WRITE(2,125)D,X(J),Y(J),W(J),Z(J)
125 FORMAT(1H ,5(5X,F10.3))
130 CONTINUE
C POSITION ORIGIN FOR EACH I VALUE AND DRAW AXES
CALL HGPORIGIN(45.0,0.0)
CALL HGPAXIS(0.0,0.0,10HTHE X AXIS,-10,25.0,0.0,-12.0,1.0)
CALL HGPAXIS(0.0,0.0,10HTHE Y AXIS, 10,25.0,90.0,-12.0,1.0)
C PLOT CURVE FOR EACH I VALUE
CALL HGPSCURVE(X,Y,361,0,0.0,0.0)
CALL HGPSCURVE(W,Z,361,0,0.0,0.0)
C LOCATE INNER AND OUTER ALIGNMENT CIRCLES
CALL HGPCIRCLE(23.9,12.0,0.0,360.0,11.9,11.9,0.0)
CALL HGPCIRCLE(24.0,12.0,0.0,360.0,12.0,12.0,0.0)
CALL HGPCIRCLE(13.9,12.0,0.0,360.0,6.9,6.9,0.0)
C LOCATE SWEEP CENTRE
CALL HGPlot(11.0,12.0,3,0)
CALL HGPlot(13.0,12.0,2,0)
CALL HGPlot(12.0,13.0,3,0)
CALL HGPlot(12.0,11.0,2,0)
150 CONTINUE
CALL HGPFINISH
STOP
END

```

END OF SEGMENT, LENGTH 361, NAME DISK

PROGRAM 6

MASTER DISK

C

INITIALISE PLOTTING

CALL HGPSTART(14HJ JARVIS SWEEP,14)

DIMENSION X(361),Y(361)

PI=3.1415927

DO 150 I=1,5

DO 130 J=1,361

DJ=J

D=J-1.0

R=(D*PI)/180.0

F=(1.0*R)/(2.0*PI)

G=1.0-F

I= (G) 101,101,100

100

SWEEP=SQRT(94.0*F+47.6)

X(J)=SWEEP*COS(R)+12.0

Y(J)=SWEEP*SIN(R)+12.0

GO TO 130

101

X(J)=11.9*COS(R)+12.0

Y(J)=11.9*SIN(R)+12.0

130

CONTINUE

C

POSITION ORIGIN FOR EACH I VALUE AND DRAW AXES

CALL HGPORIGIN(45.0,0.0)

CALL HGPAXIS(0.0,0.0,10H THE X AXIS, -10,25.0,0.0,-12.0,1.0)

CALL HGPAXIS(0.0,0.0,10H THE Y AXIS, 10,25.0,90.0,-12.0,1.0)

CALL HGPCURVE(X,Y,361,0.0,0.0,0.0)

C

LOCATE INNER AND OUTER ALIGNMENT CIRCLES

CALL HGPCIRCLE(18.9,12.0,0.0,0.360,0.6,9.6,9.0.0)

CALL HGPCIRCLE(24.0,12.0,0.0,0.360,0.12.0,12.0,0.0)

CALL HGPLOT(11.0,12.0,3,0)

CALL HGPLOT(13.0,12.0,2,0)

CALL HGPLOT(12.0,13.0,3,0)

CALL HGPLOT(12.0,11.0,2,0)

150

CONTINUE

CALL HGPFINISH

STOP

END

END OF SEGMENT, LENGTH 241, NAME DISK

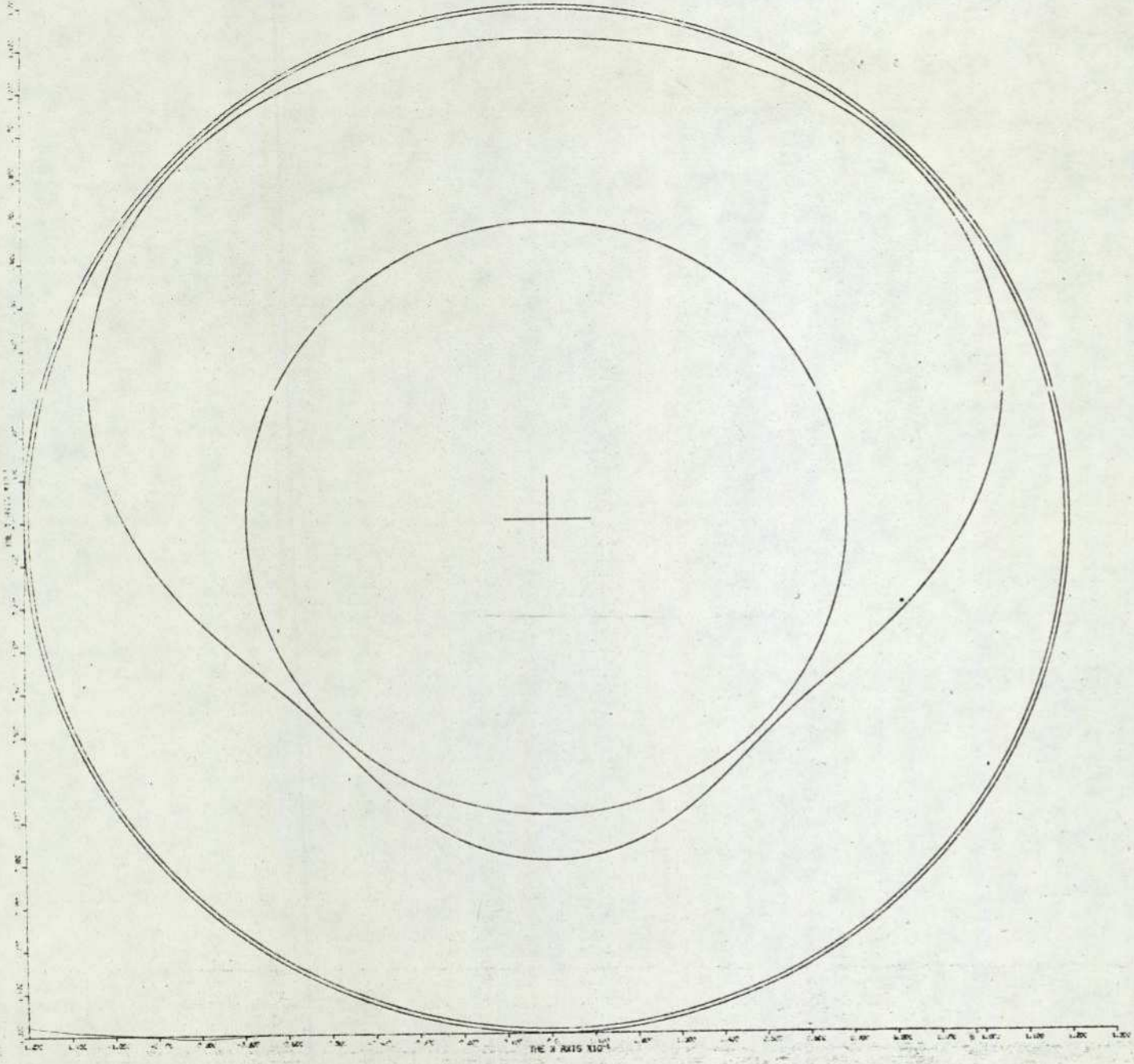
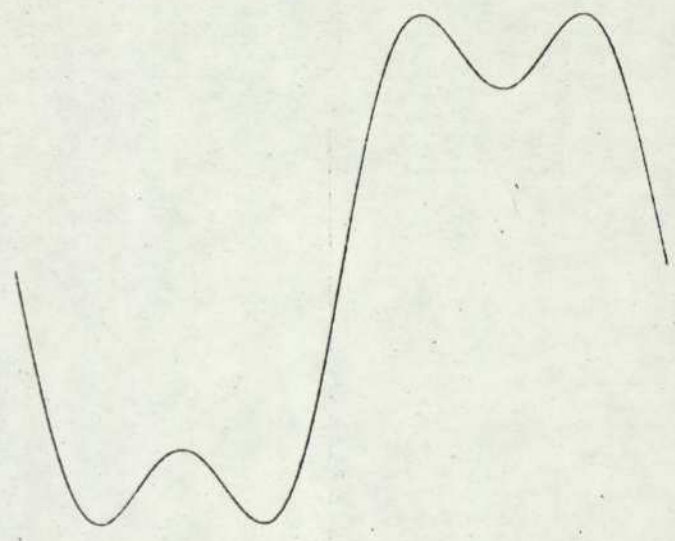


Fig 107



Example of data; obs JES, R(3) signal of expt I.

APPENDIX 3

f	l_1	l_2	l_3	Y	G	$G \pm \delta G$	x	y	$x \pm \delta x$	$y \pm \delta y$
0	1.8	5.5	5.8	1.022			.432	.405		
	1.6	4.6	4.4	.875	1.000	1.000	.438	.402	.440	.403
	1.8	5.4	4.2	1.006	$(\bar{y} = .953 \pm .06)$		.440	.410	$\pm .006$	$\pm .005$
	1.8	4.6	5.1	1.909			.449	.395		
1	2.0	5.3	5.4	1.035	1.086		.444	.409		
	2.0	5.6	5.5	1.1	1.154	1.054	.439	.414	.445	.412
	1.9	5.4	4.4	1.026	1.076	$\pm .094$	.447	.424	$\pm .004$	$\pm .01$
	1.8	4.2	4.9	.858	.900		.451	.396		
2	1.8	4.1	6.0	1.147	1.2		.440	.382		
	1.5	4.0	5.6	.792	.831	.884	.428	.387	.431	.385
	1.5	3.9	5.6	.780	.818	$\pm .2$	.428	.387	$\pm .005$	$\pm .002$
	1.3	3.2	4.8	.654	.686		.430	.383		
3	1.1	2.5	1.8	.515	.540		.477	.418		
	1.2	2.7	2.6	.562	.590	.538	.465	.405	.473	.412
	1.1	2.5	1.9	.515	.540	$\pm .038$	.475	.415	$\pm .005$	$\pm .005$
	1.0	2.2	1.8	.460	.483		.475	.411		
4	1.0	2.4	2.6	.490	.487		.452	.402		
	.8	2.1	.9	.405	.425	.488	.478	.445	.482	.427
	1.0	2.2	.9	.455	.477	$\pm .051$	.498	.433	$\pm .02$	$\pm .015$
	1.2	2.6	1.1	.541	.568		.499	.431		
5	1.2	2.7	1.2	.554	.581		.494	.432		
	1.0	2.0	1.2	.433	.454	.447	.497	.417	.497	.429
	.9	2.0	.6	.410	.430	$\pm .06$	.503	.440	$\pm .003$	$\pm .008$
	1.1	2.4	1.2	.499	.523		.494	.427		
6	1.2	2.4	1.3	.519	.544		.500	.419		
	1.3	2.5	1.5	.550	.577	.564	.501	.414	.491	.414
	1.1	2.5	1.5	.513	.538	$\pm .024$	.483	.424	$\pm .01$	$\pm .01$
	1.3	2.6	2.4	.568	.596		.480	.401		
7	1.6	2.8	2.6	.649	.691		.495	.395		
	1.2	2.3	2.6	.515	.540	.593	.475	.389	.477	.392
	1.2	2.5	2.8	.540	.566	$\pm .053$	.466	.394	$\pm .01$	$\pm .002$
	1.3	2.5	2.8	.559	.586		.475	.391		
8	1.4	2.6	2.3	.586	.615		.490	.399		
	1.3	2.6	2.4	.568	.596	.601	.480	.401	.480	.399
	1.3	2.6	2.6	.569	.597	$\pm .008$	.477	.398	$\pm .005$	$\pm .001$
	1.3	2.6	2.6	.569	.597		.477	.399		
9	1.2	2.4	2.3	.525	.551		.479	.399		
	1.0	2.1	2.3	.452	.474	.507	.467	.395	.489	.410
	1.0	2.1	2.2	.452	.474	$\pm .034$	.500	.425	$\pm .017$	$\pm .013$
	1.2	2.3	1.0	.505	.530		.511	.422		

f	l_1	l_2	l_3	Y	G	$G \pm \delta G$	x	y	$x \pm \delta x$	$y \pm \delta y$
10	1.0	2.0	1.3	.433	.454		.494	.414		
	1.2	2.0	1.5	.472	.492	.480	.504	.400	.500	.410
	1.2	2.2	1.4	.495	.519	$\pm .028$	.505	.410	$\pm .006$	$\pm .006$
	1.0	2.0	1.2	.433	.454		.497	.417		
12	.9	1.8	1.2	.390	.409		.494	.413		
	.7	1.6	1.2	.330	.346	.389	.474	.416	.481	.414
	.8	1.8	1.4	.373	.391	$\pm .025$	.475	.414	$\pm .01$	$\pm .001$
	.9	1.8	1.1	.390	.409		.500	.412		
16	.8	1.7	1.6	.362	.381		.473	.403		
	.8	1.7	2.2	.366	.384	.377	.450	.387	.460	.397 $\pm .007$
	.7	1.7	1.8	.345	.362	$\pm .004$	.452	.403	$\pm .01$	
	.8	1.7	2.1	.365	.383		.465	.381		
24	.8	1.7	2.1	.365	.383		.459	.389		
	.8	1.8	1.9	.376	.394	.386	.458	.402	.461	.396
	.8	1.7	1.8	.363	.381	$\pm .005$	.467	.397	$\pm .004$	$\pm .005$
	.9	1.7	2.0	.370	.388		.480	.380		

l_1, l_2, l_3 ; colorimeter scale readings.

Y ; Tristimulus value

G ; Brightness gain.

x, y ; C.I.E. Chromaticity coordinates.

f ; frequency (Hz).

$\pm \delta$; ± 1 std. deviation.

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Jarvis, J.R. (1973) 'A method of changing the time pattern of a light stimulus without a temporal change in spectral composition', *Vision Research*, 13(12), pp. 2575–2580.