Keele UNIVERSITY

A PSYCHOPHYSICAL STUDY OF THE DYNAMICS OF COLOUR VISION USING WAVELENGTH - MODULATED LIGHT.

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Contents.

1.1. Introduction : Summary

The purpose of this thesis is to study the response of the human visual system[1] to chromatic stimuli by means of the dynamic techniques of systems analysis (which are summarised in section 4). Section 2 is a review of the established knowledge concerning colour vision required in this study. The previous work on temporal effects in colour perception is reviewed in section 3. In the steady-state frequency domain, two approaches have been previously utilised to study such effects;

luminance modulation for various waveforms of modulation of chromatic stimuli and alternation between two different chromatic stimuli at constant luminance by several means. The luminance modulation data can only give information on those parts of the visual system common to colour and brightness processing. Evidence relating to the structure of the visual system is reviewed in section 2.5. The colour alternation methods are difficult to apply to the whole colour-space in the absence of extension of C.I.E. description of chromaticity to the time domain. The use of the constant-luminance wavelength modulation stimulus developed in the present research allows the study of colour change without making assumptions about how that change is processed except that the two types of stimulus (chromatic and luminous) are processed independently at the site of perception. It further provides a continuously variable parameter with which the whole spectrum and a full frequency range can be studied.

A similar state of affairs to that in the steady-state investigations is apparent in studies of transient responses in colour vision.

Most work has concentrated on the use of luminance changes and increments (as described in sections 3.9 & 3.10.), and the colour of the stimulus has been used as a parameter. The results have not all been in agreement. The study of the response of the colour processing system as such is considered to require a stimulus consisting of a change in colour with luminance held constant.

In Section 5 apparatus designed to provide both steady-state and transient wavelength modulation with luminance held constant is described. The method and controls for ensuring that the apparatus produced the desired effects are described in section 6. The results obtained for luminance modulation of chromatic stimuli similar to previous work, under a variety of conditions, constitute section 7.1. Section 7.2. consists of the results obtained using steady-state wavelength modulation under various conditions of mean wavelength, retinal illuminance, waveform of modulation, etc. In sections 7.3. and 4 a dynamic wavelength discrimination task analogous to the classical type of wavelength discrimination but with time varying wavelength difference is investigated. In section 7.5. some aspects of the response to transient changes in wavelength are described.

In section 8 a number of models of the data on frequency dependence of the dynamic wavelength discrimination, and of the relationship between steady-state and transient responses, are considered.

1.2 Psychophysical Methods.

The basic object of psychophysical investigations is to obtain a quantitative measure of the effect of a certain stimulus configuration upon an organism (usually a human observer).

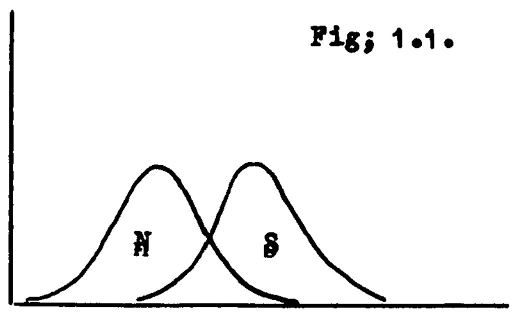
The psychological effect, as reported verbally or behaviourally, will reflect the processing of sensory signals up to the point in the processing system at which the decision to initiate a verbal or behavioural response is made. The various psychophysical methods described below may be employed to study different aspects of the response of the processing system, and the type of stimulus used may be selected in conjunction with the psychophysical method to investigate the logical structure of the stimulus processing system (as opposed to its physiological structure).

Psychophysical investigations may be considered in two classes, using respectively threshold and supra-threshold criteria. The threshold response may be of detection (or absolute threshold) of a definable aspect of the stimulus, or of discrimination threshold of the least difference between two slightly dissimilar stimuli to which the organism will respond. Supra-threshold or stimulus matching experiments ~~experiments~~ require the organism to indicate the point at which two objectively dissimilar stimuli have some feature in common. For both classes of experiment one type of stimulus may be used as a reference against which the other is judged. The reference stimulus may also be evoked from the memory of the organism rather than being physically presented to the organism, as in the case in experiments where a subject is required to name the colour of a stimulus, or assign a numerical estimate of the magnitude of the sensation produced by a stimulus.

Threshold Criteria.

Tanner and Swets (1954) have suggested that threshold experiments can be regarded as the discrimination of one signal (S) at the site of discrimination, with a certain amplitude distribution in the dimension under investigation, from another similar signal (N) with a slightly different distribution (Fig. 1.1). In the case of detection threshold experiments, the inherent "noise" of the experimental situation acts as N. In discrimination threshold experiments, on the other hand, N and S are the reference and test stimuli. The distribution of the amplitude of S and N at the site of discrimination may be physical, neural or psychological in origin. Tanner and Swets make assumptions as to the form of the distribution of each signal in order to perform statistical analysis on their

Fig; 1.1.



results. However, the basic description is applicable to any detection or discrimination experiment without limiting assumptions. The task is to discriminate signal from noise. The separation between the two distributions determines the probability with which the task will be successful. Various methodological approaches have been employed to derive a quantitive estimate of the "threshold" given the above analysis which indicates that discrimination "threshold" is a probability distribution of discrimination success. The main methods used in psychophysical studies with human observers are described below.

Supra-threshold Criteria.

Supra-threshold techniques are most often used when the experiment requires some aspect of the response to a stimulus to be measured in terms of an equivalent aspect of a different type of stimulus. In some cases, e.g. colour matching, the two stimuli will appear subjectively identical when matched, although they have different objective characteristics e.g. different spectral composition. In other cases, such as matching of the brightness of a flickering or coloured light, the quality to be matched must be abstracted from the total stimulus situation and compared with the same abstracted quality in the reference stimulus. Similar abstraction is required in the estimation of magnitude of some stimulus sensation against a remembered numerical scale of magnitude. Matching experiments may therefore be modelled in terms of the distribution of values of the test stimulus around the value of the reference stimulus, along the dimension of interest, (where the variance of this distribution contains contributions from the variance of test and reference stimuli at the site of comparison). In most matching experiments, the object is to obtain values of the test stimulus parameters which match given reference stimulus parameters. In some cases, however, the standard deviation of the distribution is used as a measure of the discriminablity (or non-discriminability) of the test stimulus from the reference. In such cases, the two stimuli will be of similar physical constitution.

Method of Constant Stimuli.

This is a threshold method which involves the presentation of the stimuli to be discriminated (a large number of times) at fixed physical stimulus levels. A number of levels are selected, such that the probability of detection or discrimination by the subject at all levels gives a measure of probability distribution or "percent frequency of seeing curve" of the test stimulus. This method is often used for measurements of absolute luminance threshold (e.g. Hecht, Shlaer and Pirenne, 1942), and in general in situations where it is of value to know the form of the probability distribution.

Method of Limits (or Just-Noticeable-Differences).

This method for obtaining thresholds requires the subject to hold a fixed criterion in terms of a level on the discrimination probability distribution. The stimulus difference is then increased or decreased along the dimension of interest until the criterion is reached, at which point the subject responds. The criterion may differ according to whether the difference between test and reference stimuli is being increased or decreased. In such cases, determinations in each direction are averaged to give a mean value. Where the two stimuli are both above threshold in the dimension under consideration, this method may be termed the Method of Just-Noticeable-Differences. The method of limits is used where a quantitative measure of the threshold is required in a short time, for example in order to compare the effects over a large number of stimulus conditions.

<u>Method of Adjustment.</u>

The adjustment may or may not involve a bracketing procedure in which the subject sets the test stimulus at a value midway between that just discriminably lower than the reference and that just discriminably higher. The matching test stimulus settings are averaged to obtain the best estimate of the values of the test stimulus parameters corresponding to a range of values of the reference stimulus parameters.

An alternative use of the method of adjustment is the measurement of the average error of adjustment for use as an index of discrimination threshold. The subject is required to match the test stimulus against a reference a large number of times. The standard deviation of the distribution of settings from the mean value is taken as a measure of degree of discrimination at each point in the dimension of interest. The method of average error of adjustment gives a direct measure of the distribution of values of the test stimulus relative to the reference, but requires many more readings than the method of limits to obtain difference threshold measurements.

Sensory Magnitude Estimation (Absolute Methods).

Sensory magnitude estimation methods are those in which the subject is presented with a single test stimulus and required to match it against an internally generated reference, rather than a physical reference. When only two responses - the matching or non-matching of a certain reference - are involved, the method becomes equivalent to the method of constant stimuli. But when a number of response categories are used, whether on a quantitative ordinal scale or a qualitative nominal scale, the absolute method permits investigation of the subjectively perceived dimensions of the sensations arising from stimuli. These do not necessarily correspond to the dimensions obtained by other psychophysical methods, which only require the subject to judge whether or not two stimuli differ in some respect. Furthermore, the absence of a physical comparison stimulus makes the accuracy of the absolute method lower than direct comparison methods.

Conclusion.

The main methods of psychophysical experiments have been outlined in this section indicating the limitations and uses of each method. The reviews of section 3 will make frequent references to these methods, and also give an indication of the type of information that can be obtained concerning, in this case, the human visual system, by means of psychophysical experiments.

2.1. Visual Response to Light

2.1.1. Introduction:

The object of this section is to describe the basic parameters of visual response to light stimuli, and to define the terms used in the following chapters.

The range of wavelengths of electromagnetic radiation to which the eye is sensitive is approximately 400-750 nm. Only radiation within this range is described as light. (Wright, 1944).

The principal aspects of a light stimulus impinging upon the retina to which the human visual system is responsive are the absolute distribution of energy across the visible wavelength spectrum, and the spatial and temporal variations in this distribution.

2.1.2. Trivariance of Vision:

Of the infinite range of variability in the energy distribution of light, the visual system is sensitive to only three independent variables of the distribution, i.e., the eye is trivariant in its response, (subject to the conditions specified below). The trivariance of vision was first established by Maxwell (1855, 1890). Later investigations by Guild (1931) and Wright (1928-9) were accepted by the C.I.E. in 1931 as defining the trivariant response to light of the standard observer. A description of this work is given in section 2.2. The conditions under which trivariance holds are the use of photopic radiant energy levels, and a field of 2^{o} subtense with a uniform surround viewed with the fovea. Trivariance has also been established for a 10^{o} field by Stiles (1955) but his subjects were instructed to ignore the central area in the colour matching procedure.

2.1.3. Use of Monochromatic Spectrum in Colour Vision

Any stimulus will emit a certain total energy per unit time (or radiant flux) which may be specified in terms of the visual sensitivity at each wavelength to light radiation i.e. in units of luminous flux. The luminous flux (F) in humans is obtained by weighting the radiant flux (P_λ) at each wavelength with the spectral sensitivity (V_λ) of the eye at each wavelength. Thus, in the limit

$$F = K \int_0^\infty V_\lambda \cdot P_\lambda \; d\lambda \qquad (1)$$

where K is a scaling constant..

In experimental situations, the light is observed via a pupil (natural or artificial) and having a certain angular subtense (W) at the source, which is often an extended source of area (a). The luminance (L) of a stimulus is defined as the luminous flux per unit area of source.

$$L = \frac{F}{W.a.} \qquad \text{Lumen } /W/m^2 \qquad (2)$$

In order to define the effect of a stimulus on the retina, correction should be made for the area of pupil through which the stimulus is viewed. The product of the luminance and pupil area in mm^2 defines the retinal illuminance in trolands.

The trivariance of vision permits the sensation resulting from a source (S), with any of the entire range of possible light energy distributions, to be matched by a source composed of a mixture of white light (S_w) of luminance (L_w) and a monochromatic light (S_λ)

of wavelength (λ_m) and luminance ($L\lambda$), (or a purple light made up of some mixture of red and blue monochromatic lights).

$$L\ (S) = L_w\ (S_w) + L\lambda\ (S\lambda) \qquad (3)$$

The three variables specifying the matching stimulus are L_w, $L\lambda$ and λm. Monochromatic and white light are opposite extremes of the possible spectral distributions. Monochromatic light has an arbitrarily narrow spectral distribution that is described by the single value of its wavelength , (λ) apart from its radiant flux.

$$P\lambda = 0, \quad \lambda \neq \lambda m \qquad (4)$$

White light is defined as having a distribution that does not deviate greatly from equal energy at each wavelength with the visible spectrum (Le Grand, 1957). For the present discussion, as for the theoretical purposes of the C.I.E. chromaticity chart, the reference white (S_w) is defined as an equal energy white.

$$P_\lambda = \text{const} \qquad (5)$$

Equation 3 may be used to define the dominant wavelength (λd) of any light (S) (except purples) as the wavelength of the monochromatic component of the mixture of white and monochromatic light which matches S. The case of purples is dealt with in section 2.2.

Thus:

$$\lambda_d = \lambda_m \qquad (6)$$

when the lights corresponding to the two halves of equation 3 are judged to match by a normal observer.

The colorimetric purity (p_c) of any light S is defined as the ratio of the luminance of monochromatic component to the luminance of the total source:

$$P_c = \frac{L_\lambda}{L_\lambda + L_w} \qquad (7)$$

2.1.4. Grassman's Laws of Colour Mixture:

Grassman (1854) formulated four laws of the relationships involved in colour mixture between the composition of the lights being mixed and the resultant visual effect. These laws form the basis for the equations of colorimetry (Section 2.2.). The first law has already been described in the form of equation (3) i.e. the sensation from any uniform light stimulus may be matched by the sensation from an appropriate mixture of white and monochromatic lights (or pure purple light). The second law states that for a continuous variation in one of the components of a colour mixture, there is a continuous variation in the appearance of the mixture. Taken in combination with the first law, this law implies that a) for every colour there is a complementray colour, such that when the two are mixed in the right proportion an achromatic light is produced, and if mixed in any other proportion a light with the dominant wavelength of one of the components is produced, depending on the proportions of the mixture.

and b) The mixture of non-complementary colours gives a colour intermediate in saturation and hue between the two colours.

The third law states that colour mixtures are transitive i.e. that any two mixtures which match a third light will match each other. Grassman's fourth law, also known as Abney's law of heterochromatic additivity, states that the luminance of the mixture is equal to the sum of the luminances of the components of the mixture. In practice, substantial deviations from additivity occur in some conditions, notably when the luminances of the lights are measured by the method of direct comparison with a standard stimulus, Dresler (1953). Clarke (1960) has shown that gross failures of additivity occur in extra foveal colour matches. However, the departures from additivity have been found to be small for 2° foveal presentation. Trezona (1953, 1954), investigating the trichromatic co-ordinates of colour mixtures, reported that definite departures from additivity did occur under the latter conditions, but that they lay within one discrimination step. Ives (1912) has shown that, for a photopic 2° field, heterochromatic brightness matching by flicker photometry conforms well to the additivity law. This result has been substantiated more recently by Dresler (1953) and Sperling (1958).

2.2. Chromaticity Coordinates

The trivariance of vision implies that any light may be matched by a suitable mixture of any three monochromatic lights. In practice one of the three may have to be subtracted from the mixture, i.e., added to the test light, since it is not possible to select three monochromatic lights to match the upper extremes of the range of purities of the whole spectrum.

$$L_s \quad (S_s) \equiv L_1 \ (S\lambda_1) \ + \ L_2 \ (S\lambda_2) + L_3 \ (S\lambda_3) \qquad (1)$$

or $$L_s \quad (S_s) \quad + L_1(S\lambda_1) = L_2 \ (S\lambda_2) \ + \ L_3 \ (S\lambda_3) \qquad (2)$$

The values of $S\lambda_1$, $S\lambda_2$ and $S\lambda_3$ are arbitrary chosen, usually as widely separated as possible to reduce the number of subtractive mixtures. The luminances of each stimulus may be expressed in different units according to whether the colour or brightness of the mixture is being considered, and the units may be different for each component stimulus. (Guild 1924-5). The luminous units (L_i) are therefore specified for each component (S_i) together with the number of units (or tristimulus values) of each component (C_i). Thus the luminance of each component required for the match is given by:

$$L_s \ C_s \quad = \ L_1 \ C_1 \ + \ L_2C_2 \ + \ L_3C_3 \qquad (3)$$

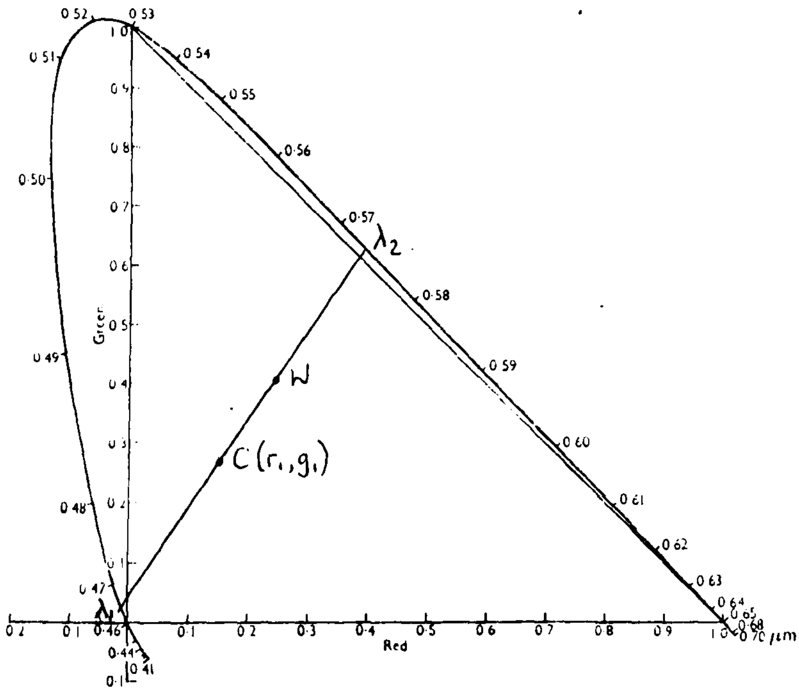
The value of L_s follows from the convention that

$$C_s \ = \ C_1 \ + \ C_2 \ + \ C_3 \qquad (4)$$

The units L_i are often defined by assuming that equal tristimulus values C_i of the units are required to make up a defined white,

$$C_1 \ = \ C_2 \ = \ C_3 \ = \ 3C_w \quad \text{when } L_1C_1 + L_2C_2 + L_3C_3 = L_wC_w \qquad (5)$$

but Wright (1928-9) in his study of colour mixture functions defined the luminous units in terms



<u>Fig. 2.1.</u> W.D.W. chromaticity diagram.

of the spectral colours of 582.5 + 494.0 nm, with the advantage that the coordinates were not sensitive to variations in macular pigmentation.

The tristimulus values for a set of primaries may be measured for any uniform field. However, it is often desirable to consider stimuli of constant brightness level and investigate only the variations in colour of the stimulus. This condition is met by considering the proportion of each tristimulus value relative to the sum of the tristimulus values. The proportional tristimulus values are called chromaticity coordinates (r,g,b), and they define the chromaticity of the stimulus. The chromaticity system described here is the W.D. Wright system (Wright, 1928-9).

$$r = \frac{C_1}{C_1 + C_2 + C_3} \quad \text{etc.} \qquad (6)$$

The sum of the three chromaticity coordinates is therefore unity,

$$r + g + b = 1, \qquad (7)$$

They define a two-dimensional chromaticity space in which the third coordinate is derived from the unit equation (7).

The aspects of visual sensitivity to light outlined in section 2.1.1. (dominant wavelength, purity, colour match, etc.) can be described in terms of this chromaticity diagram (Fig. 2.1.) The selection of three lights for the definition of the chromaticity space is arbitrary, but the monochromatic primaries 650, 530 + 460 nm used by Wright (1947) have the virtues for the present purpose of being realisable spectral lights, and of requiring very few negative values in matching the whole colour space.(Negative values represent the addition of one of the primaries to the test rather than the comparison stimulus).

The geometric relationships of the chromaticity diagram represent algebraic manipulations of the trichromatic equations. The spectrum locus runs roughly along the outside of the diagram from r to g to b. Non-spectral purples lie in the triangle between r, b and w. The complementary wavelength λ_2 (in fig. 2.1.) for any wavelength (λ_1) on the spectrum locus is defined by the intersection of the line λ_1w with the spectrum locus opposite at λ_2, where w is achromatic equal energy white at the centroid of the chromaticity triangle. Complementary colours for wavelengths between 495 and 570 nm are non-spectral purples and are made up of mixture of red and blue lights. The dominant wavelength of any colour C(r_1, g_1) is defined as the intersection of the straight line wC with the spectrum locus. For purples, where there is no intersection between wC and the spectrum locus, the complementary dominant wavelength of the intersection of wC with the spectrum locus is used to define this aspect of the stimulus.

Colour mixture is represented on the chromaticity diagram in terms of a straight line between coordinates of the two lights to be mixed. The distance of the coordinates of mixture along this line is determined by the proportion in which the two lights are mixed. Thus two complementary colours in suitable proportions will produce white (w). Clearly, the colour mixture construction implies that any colour in the chromaticity diagram can be matched by a mixture of a spectrum colour (or a pure purple) and white, as stated by Grassman's first law (section 2.1.4.) The closer the colour is to the centroid, the less saturated it will appear. However, the relationship between measures of purity and the sensation of saturation are beyond the scope of this review (see "The Science of Color" Committee on Colorimetry of Opt. Soc. Am., 1953).

A further refinement of the chromaticity diagram as so far described has been adopted by the 1931 C.I.E. Committee on Colorimetry. It involves hypothetical primaries (X,Y,Z), which are linear transformations of monochromatic primaries similar to those used by Wright, such that the whole of the spectrum locus is contained within the positive area of the diagram. Further, the coordinates are chosen such that the luminosity is specified entirely by the Y primary, the X and Z primaries having zero luminous units.

2.3. Colour Discrimination.

2.3.1. Methods.

Many methods have been employed to measure the extent to which stimuli of equal luminance but different spectral composition can be differentiated by a human observer. Of the psychophysical methods discussed in section 1.2, the main approaches that have been investigated are as follows:

Wavelength Discrimination. The smallest discriminable difference in wavelength between two equiluminant monochromatic lights has been obtained as a function of wavelength. Psychophysical methods that have been used include those of just noticeable differences (j.n.d) (Wright, 1947), and of average error of adjustment. (Konig and Dieterici, 1884).

Saturation Discrimination. The smallest discriminable difference between two equiluminant lights each consisting of some mixture of monochromatic and white light is obtained as a function of wavelength of the monochromatic component. Only the proportion of white to monochromatic radiation is varied. Studies have used either pure white light (Wright and Pitt, 1935), or pure monochromatic light (Hurvich and Jameson, 1955) as the comparison light.

Alternatively, the number of j.nd.'s between each monochromatic light and white may be measured. (E.g. Jones & Lowry, 1926).

Chromaticity Discrimination. Chromaticity discrimination is a measure of the discriminability of any two equiluminant lights specified in terms of their chromaticity co-ordinates in some chromaticity system. In practice, the two stimuli are usually made up of mixtures of monochromatic lights. The smallest discriminable difference is obtained either by the method of just-noticeable differences (Wright, 1947) or of average error of adjustment (Mac Adam, 1942). The results are plotted as steps within the chromaticity diagram, rather than in relation to the spectrum. In this way discrimination in the whole of the colour (and also brightness) space may be investigated, including, if desired, the dimensions corresponding to the wavelength and saturation discrimination tasks described above.

Various methods other than discrimination have been utilised in the study of the differential response to coloured stimuli. Colour naming has been used by Walraven (1962) and Wilson (1969) amongst others, to examine effects of wavelength at the chromatic threshold. Jameson and Hurvich (1955) used the method of chromatic valence in the cancellation of subjective colour components of the stimulus to study the operation of opponent mechanisms in the processing of colour information across the spectrum. Colour matching has been used to study the differential effect of parameters such as luminance and flicker frequency on spectral hue (see Walraven, 1962; and Van der Horst and Muis, 1969), and the chromaticity position of invariant primaries under chromatic adaptation (Scheibner, 1966).

Each of these approaches contribute valuable information to knowledge of the colour processing system. However, the present study will utilise only the wavelength discrimination approach for a variety of reasons. Studies of the influence temporal factors in colour discrimination have concentrated on chromaticity discrimination (section 2.3.5). The stimulus in wavelength discrimination is simply specified in physical terms without complex computations.

Finally, the wavelength stimulus is defined with minimal assumptions as to the colour processing systems, whereas the definition of chromaticity (subsuming saturation) is heavily dependent on empirical data not necessarily applicable to the dynamic situation (see section 3.7.1).

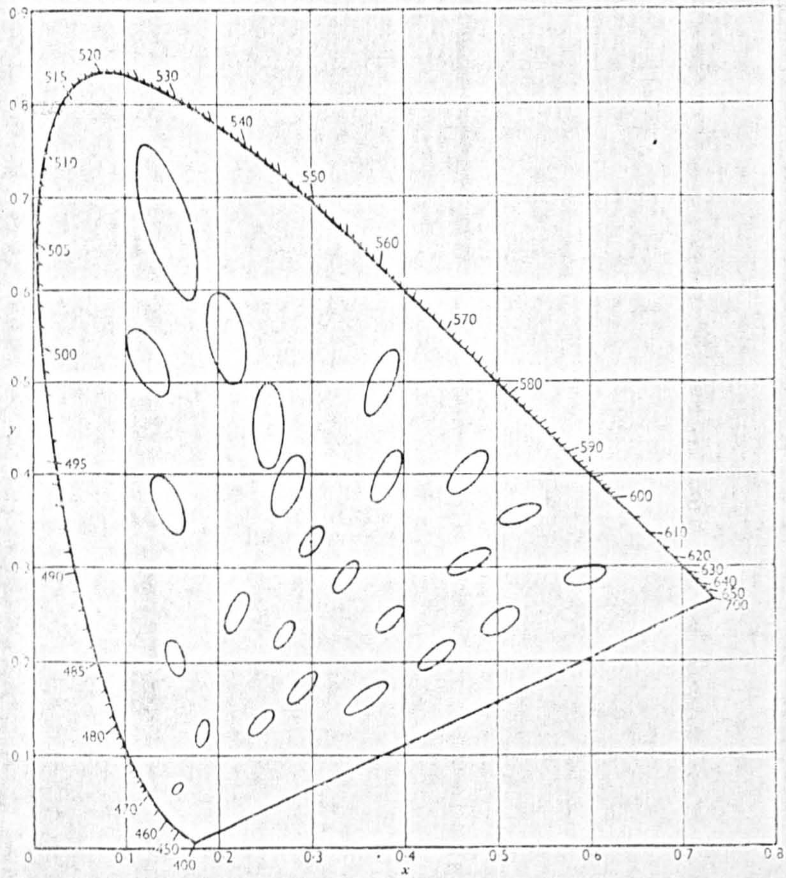


Fig. 2.2. MacAdam's (1942) ellipses of chromaticity discrimination. Standard deviation of settings of colour matches in several directions is plotted on the C.I.E. chromaticity diagram for comparison stimuli in a number of positions in the chromaticity space. The results can be described in terms of ellipses with appropriate size, axis, ratio and orientation.

2.3.2. Classical Data of Wavelength Discrimination.

Data on classical discrimination obtained by various methods with (usually) luminance equated has been collated from a number of experimenters by Judd (1932). Wright and Pitt (1934) carefully studied the foveal wavelength discrimination functions five normal observers and Siegel (1962, 1964) studied the mean and standard deviation of discrimination in 3 subjects. Although the results show variabilities with a range of about 50%, they are consistent in showing threshold minima at 580-600nm and 480-500nm, with a maximum in between at 520-540 nm i.e. nearer to the short than the long wavelength minimum. Many studies find a further minimum in the region of 430-440nm. Wright (1947) has criticised the data of Laurens and Hamilton (1923) showing yet another minimum at about 630nm. The evidence on this point is not decisive.

The studies of the effects of various parameters or wavelength discrimination described below also confirm the main features of the above description. Both Wright (1947) and MacAdam (1942) have measured sensitivity to chromaticity differences at a large number of points in the C.I.E. chromaticity space. Wright used the method of just noticeable differences between the two sides of a bipartite field, and MacAdam measured the average error of adjustment in a colour match, which he plotted as an ellipse around the coordinates of the comparison colour in the C.I.E. chromaticity diagram (Fig.2.2). The results are roughly comparable, and may described approximately in the following way. Chromaticity discrimination is best for the smallest values of X and Y coordinates, (i.e. at the blue spectral locus) and becomes progressively worse as distance from this region increases. MacAdam's ellipses of standard deviation in setting error seem to be roughly aligned so that the long axis (poor discrimination) points towards the spectral blue region.

2.3.3. Effects of Luminance.

Wright (1947) states that wavelength discrimination is not greatly affected by changes in luminance, although Stiles (1946) has suggested that Wright's data in the blue end of the spectrum is affected by the use of intensity levels reduced by a factor of 20. Bedford and Wyszecki (1958) measured wavelength discrimination between 400-660nm using a 1° field. Their data support Stiles' suggestion that discrimination thresholds are about half as high as those found by Wright below 480nm. Their results for 12' field indicate that that decreasing brightness from 500 to 25 trolands does not significantly affect wavelength discrimination, whereas for a 1.5' field discrimination was markedly impaired by the equivalent drop in luminance. Weale (1951) working at lower luminance level also found a general impairment of discrimination as luminance was decreased by 1 log unit, together with a shift in the blue minimum from 480 to 460nm. Bedford and Wyszecki do not report a shift in the blue minimum as found by Weale, but the sise of the blue minimum was found to be of the same order as the range of variability of the data, so that detailed conclusions cannot be drawn. Thompson and Trezona's (1951) data shows a shift of the blue minimum about 30nm towards the short wavelengths and of the yellow minimum about 20nm towards the long wavelengths as luminance is decreased by 2.3 log units. Overall discrimination is impaired to the order of 1.0 log nm by this luminance decrease. They do not comment on this shift in the minima, but they do note that lowering the luminance does not produce tritanomaly, as is produced by a reduction in field size (Thompson & Wright, 1947; McCree, 1960b). In this connexion, tritanomaly is used to mean a tendency of the wavelength discrimination function to approach the form of that for tritanopes (Wright, 1952); in particular, to show a relative loss of discrimination ability in the spectral region around 460nm. McCree's (1960b) study on the effect of field size includes data at two luminance levels over 2 log units apart. These show effects in accord with those found by Thompson and Trezona, in showing shifts of both minima towards the ends of the spectrum with decrease in luminance, and lack of a tritanomalous effect.

On the other hand, Brown (1951) measured chromaticity discrimination at a number of points in the chromaticity space down to luminances of the order of .05 ft. lambert, using the method of average error. He found tendency towards tritanomalous confusions along lines on the chromaticity diagram corresponding to the confusion lines of tritanopes (Wright, 1952) together with a general impairment of discrimination as luminance was decreased below 1 ft. lambert. Brown's results are not necessarily incompatible with those described above. He did not measure any points in the neighbourhood of the blue spectrum locus, and his method has been shown to enhance tritanopic effects relative to the method of just noticeable differences (Farnsworth, 1958). Walraven and Bouman (1966) have discussed Brown's data, suggesting that the tritanomalous confusions are restricted to the upper part of the C.I.E. chromaticity diagram and should therefore be described as pseudo-tritanomaly. They find that the pseudo-tritanomaly can be explained in their fluctuation theory as resulting from a change in the weighting factor (β^2) multiplying the signal from the blue cones to the chromatic system rather than a decrease in blue and yellow discrimination sensitivity, which results in tritanomaly (for a summary of the fluctuation theory, see section2.4.3).

2.3.4 Effect of field size and bandwidth.

Willmer and Wright (1945) reported that wavelength discrimination tended towards tritanopia for reduced bipartite field size of 20' (maintaining strict central fixation.) Bedford and Wyszecki (1958) found no such tendency for field size as small as 1.5', but they used a wide separation between test and comparison field, and allowed the observer to scan the stimulus. Either of these latter factors could have influenced their results. However, McCree (1960b), using a range of seven field sizes and a bipartite field which the observer scanned continuously reported a progressive tendency towards tritanopic form of the discrimination function as field size was decreased. All the above authors found that discrimination was impaired for smaller field sizes. Hilz and Cavonius (1970) varying bar width of an equiluminant chromatic grating, rather than field size, reported no evidence of shifts in the minima as grating bar width was decreased to about 1.5' but their data is not very complete at the lower bar widths. Their results confirm a progressive worsening of discrimination throughout the spectrum as bar width is decreased.

Another factor important in the design of colour discrimination experiments is that of bandwidth of the monochromatic light. Siegel (1963) reported that colour discrimination was unaffected by variations in bandwidth between 5 and 80nm. He based his conclusion on the standard deviations of hue limen settings. However, the hue limens themselves show effects which appear to the present author to be consistent for three subjects, although Siegel states that the reliability is lower for the hue limen data. In each case discrimination appears to be progressively impaired in the region of the green threshold maximum, roughly as bandwidth is reduced, while there is little effect at the long wavelength end of the spectrum. Measurements were not made below 500nm. The region of impairment of discrimination corresponds approximately with the region in which colorimetric purity is reduced by increase in bandwidth, as tabulated by Siegel.

2.3.5. Effects of Temporal Factors

The effect of time of observation on chromaticity discrimination has been collated by Farnsworth (1958) from three disparate investigations. His calculations indicate that the longer time taken per observation, the greater the reduction in blue-yellow discrimination relative to red-green. He reports some experiments in support of this observation. Yustova (1958) presents evidence that the longer durations of observation reduce the extent of the chromaticity space, due to chromatic adaptation to the discrimination field. Wright (1947) describes some complex results on the time course of recovery to chromatic adaptation by means of a colour matching technique, but he does not examine the time course of hue discrimination limens in this situation.

One approach to the problem of effects of fixation on colour discrimination is the use of image stabilisation on the retina (Ditchburn 1958). Colours were found to fade under such conditions. McCree (1960a) has studied colour discrimination over the whole spectrum with voluntary fixation. He found that under such conditions, virtually any two colours could appear to match. Colour discrimination could be restored either by instructing the observer to glance at the field, or by interrupting the stimulus every 0.5 sec for 0.05 sec. McCree concluded that the effect was not due to desaturation of the field, although this phenomenon was present to a small extent. Clarke (1960) has also found desaturation and hue shift with increases in exposure time. A bipartite field was flashed on for 0.5 sec every 2 sec., and number of flashes varied from 4 to 30.

Luria and Weissman (1965) have studied the effect of exposure duration on perception of the components of two colour mixture, which was effectively a chromaticity discrimination task around a colour near the centre of the chromaticity chart. They found that for a 1° bipartite field, viewed foveally, discrimination was impaired below 50-100 msec, differentially in different directions on the chromaticity chart, but was essentially unaffected up to times of 300 m sec.

In a similar study Siegel (1965) has the effect of exposure time on a bipartite field wavelength discrimination for a single spectral location (575 nm). He measured the standard deviations for colour matching settings for eight subjects and pooled the data. He found that discrimination ability improved continuously from 20 msec to 5 secs exposure. Siegel suggests that the improvement at longer duration may be the result of an artefact, and that this might be due to differences in fixation of the stimulus, which was an uncontrolled variable.

Thus both the preceding studies show a reduction in discrimination as exposure times are reduced. Many of the studies in this section do not investigate separately the effect of exposure time on effective stimulus luminance (Bloch's Law) but Luria and Weissman compensated for this effect. In a limited experiment, equal luminance exposures showed generally similar effects to those for equal energy exposures.

It thus appears that in both wavelength discrimination and in general chromaticity discrimination, the discrimination ability is impaired for either long or short durations of exposure, whether presentation is continuous or intermittent.

2.4. Theories of Colour Discrimination.

2.4.1 Introduction.

In general, theories of colour vision are incomplete if they do not provide an explanation for the phenomena of the whole field of colour vision. This should include, for example, predictions of the luminosity functions, colour mixture data, and the various aspects of chromaticity discrimination both for normals and for each of the main types of colour defect (deuteranopia, protanopia, tritanopia). Data on many of these aspects of colour vision are now available.

A body of data concerning temporal phenomena in colour vision is also being established (see section 3) of which future theories should take account.

The present thesis concentrates on a single aspect of colour perception, namely, the temporal factors involved in colour discrimination. Consequently this section will review only the facet of each theory dealing with colour discrimination.

Three major theoretical approaches to the data of colour discrimination are described in this section. The Helmholtz-Stiles Line Element theory bases the prediction of discrimination ability essentially on the relative excitation of the three fundamental colour systems. The Walraven-Bouman Quantum Fluctuation theory assumes that the discrimination step is limited by the quantum fluctuations in the light signal to the three response mechanisms, and makes additional assumptions concerning a bidimensional division of the colour space. The Hurvich-Jameson Opponent Process theory utilises only the bidimensional division of the perceived opponent colours.

In section 6, the data of dynamic wavelength discrimination obtained for this thesis are considered in relation to the theories of colour discrimination outlined in this section. However, in the case of the Line Element theory it was found that Stiles (1946) gave insufficient information to enable computation of the relevant values.

2.4.2 Helmholtz Stiles Line Element Theory.

The line element theory was first postulated by Helmholtz (1896), but modified by Stiles (1946) to the form described here. The perceptual difference between two light patches is assumed to be mapped by a line joining the coordinates of the two patches in three-dimensional luminance-chromaticity space. The theory postulates that the just discriminable distance is of fixed length in a Non-Euclidean space where the axes are defined as the response magnitudes of the three fundamental response mechanisms. Any light is described as a point in the space determined by its trichromatic coordinates in terms of the fundamentals. Stiles used the fundamentals determined earlier (Stiles, 1939) by an increment threshold technique as a basis for his calculations. Extra measurements of the differential sensitivity (or Fechner fraction) for each mechanism were included in the specification by Stiles. The threshold change in stimulus wavelength is predicted as the change in stimulation to produce a fixed magnitude of change of the primary amplitudes weighted by their respective sensitivities. The line element theory predicts the basic features of the hue discrimination curve, i.e. threshold minima near 590, 490 and 450 nm, but the predicted discrimination limens in the short wavelength end of the spectrum are much lower than those found by Wright and Pitt (1934), with which Stiles compares the theory. Stiles suggests that their use of lower luminance for the short wavelength may have affected their results.

Later data by Bedford and Wyszecki (1958), correspond more closely to Stiles' prediction. For the data of Thomson and Trezona (1951), Stiles' prediction is a good fit for one observer, but a poor one for the other. Since the observers used different discrimination methods, the method may be a factor limiting the applicability of the theory.

The line element colour discrimination theory can be extended to predict MacAdam's ellipses of chromaticity discrimination (described in section 2.3.2). Both the area and orientation of the major axis of the ellipses are well predicted by the theory. The theory is not extended to data on the effect of luminance or field size on wavelength discrimination, nor are the classical data of defective colour vision covered. However, assuming that the spectral sensitivities of the three colour channels are unaffected under these various conditions, the possibility of alterations in the Fechner fractions for the three mechanisms nevertheless provides two degrees of freedom in the theory by means of which these data might be explained. If, as Stiles (1949) suggests, the Fechner fraction for each mechanism varies differently as luminance is reduced, (or with changes in field size), this provides a basis for prediction of the shape of the wavelength discrimination curve under the appropriate conditions. Data indicating the effects of stimulus frequency on Fechner fraction for the cone mechanisms, and hence prediction of the effects of frequency in a suitable wavelength discrimination situation, such as is described in section 7.3, would be of value in extending the scope of the line element theory.

2.4.3 Fluctuation Theory of Colour Discrimination.

Walraven (1962) and Walraven and Bouman (1966) have approached the problem of wavelength discrimination by considering the effect of quantum fluctuations in the input, first applied to the problem of brightness discrimination by de Vries (1943) and Rose (1946) to each of the three photoreceptor types. Since the r.m.s. quantum fluctuations are proportional to the square root of the input amplitude to each photoreceptor type(see Ditchburn, 1963.), the threshold of colour discrimination is hypothesised to be proportional to the square root of the vector sum of the input amplitudes to the three receptor systems. The receptor systems are assumed to be independent, hence the quantum fluctuations are proportional to spheres of constant size in a three-dimensional square root diagram, in which the inputs to the three receptor systems are the orthogonal axes. The spectrum locus is plotted on the square root diagram in terms of the response of each receptor system to each point on the spectrum. Hence the form of the colour discrimination curve is obtained from the spectral extent of the square root fluctuation spheres at each point in the spectrum. Two points are worth noting. The basic fluctuation theory makes no physiological assumptions, but describe the behaviour of an ideal physical detector, e.g. three independent photocells, although some mechanism for combining the three inputs is required. Additionally, the theory as utilised by Walraven and Bouman predicts only the relative proportions and not the absolute magnitude of the discrimination function. A test therefore of whether the threshold magnitude is as predicted by quantum fluctuation would be of interest. This problem could be approached by the addition of extra random fluctuations to the input signals, to investigate the effect on thresholds.

In applying the fluctuation theory both to normal and to colour-defective subjects under a variety of conditions of luminance and field size, Walraven and Bouman found that modifications were required to the basic fluctuation theory. The blue receptor input was postulated as having different effectiveness for brightness and colour perception. A variable amplification factor of β^2 for the colour perception process was found to describe adequately the short wavelength discrimination for both normals and deuteranopes. The value of β^2 was varied to fit data at a range of luminance levels. The main result of increasing β^2 was to shift the threshold minimum in the blue from 470nm to 500nm, corresponding to the shift for increasing luminance by 3 log units.

They further postulated that the sensitivity to the effect of quantum fluctuations was different in different directions in the square root diagram. The two orthogonal directions suggested were along lines between red and green, and between red-plus-green (yellow) and blue. Discrimination along these lines is referred to as tritanopic and deuteranopic respectively, as the discrimination functions in the two directions resemble the discrimination of the respective colour defective eyes. Use of the two bivariant components in varying proportions permitted matching of data on the effect of field size on wavelength discrimination. Small field tritanomaly is hypothesised as a reduction in the effect of the blue-yellow discrimination component. This approach also allows prediction of MacAdam's chromaticity discrimination ellipses. The Fluctuation theory of colour discrimination as developed by Walraven and Bouman (1966) this provides two degrees of freedom beyond the basic curve obtained by the application of the assumption that threshold is proportional to the quantum fluctuations of the stimulus. By means of these extra parameters many of the classical data of colour discrimination effects can be accommodated. The application of the theory to dynamic wavelength discrimination data is considered in section 8.2.

2.4.4. Hurvich-Jameson Opponent Colour Theory.

Hurvich and Jameson (1955) base their theory of wavelength discrimination on their Opponent Process theory of visual perception. Derived from the concept of Hering (1920), the theory is based on the hypothesis that human vision is mediated by three opponent processes, viz. red-green, yellow-blue and white-black. The first two processes were originally conceived of as involving excitation of opponent red or green, and yellow or blue processes respectively. The white-black process, on the other hand, represents either excitation or de-excitation i.e. two kinds of activity of the same process. The form of three opponent process responses may be transformed from the C.I.E. tristimulus values, but it should be noted that the white and black functions have the same transformation values, but each is multiplied by a different constant. It would appear therefore that appropriate selection of constants would enable the white-black 'opponent' process to be represented by a single non-opponent process.

However, for the present purposes, the two chromatic opponent processes are the only ones of relevance. Jameson and Hurvich (1955) measured the spectral chromatic response of each process (or chromatic valence) as the relative energy of the opponent 'cancellation' stimulus for cancellation of each spectral stimulus to a neutral colour. The opponent 'cancellation' stimuli were selected on the basis of psychological uniqueness.

The chromatic valence curves may be transformed to a coefficient of the relative valence at each wavelength, or hue coefficients. Hurvich and Jameson (1955) suggest that spectral hue discrimination will be proportional to the rate of change of hue coefficients (or difference in hue information between a pair of wavelengths separated by a small amount). Wavelength discrimination will involve such hue discrimination information, but will also be affected by changes in saturation through the spectrum. As a first approximation, Hurvich and Jameson suggest that saturation and hue changes will have equivalent effects in the determination of the wavelength discrimination functions. The saturation coefficient used for this purpose was defined as the ratio of the chromatic responses to the sum of the chromatic and achromatic responses.

The predicted wavelength discrimination functions were computed from the hue and saturation coefficients at two levels of luminance. These exhibit essentially similar features to those obtained by Weale (1951), viz, minima in the regions of 580 and 480nm, and a shift of the short wavelength and general reduction in discrimination with a reduction in luminance.

These features are also similar to those found by other investigators (reviewed in section 2.3.3.).

2.5 Independence of the Colour Processing System.

Walraven (1962) has reviewed evidence that there is an independence between the processing of brightness and colour perceptions in the photopic retina, such that the channel processing stimulus luminance information, (i.e. a measure of the combined responses of the three primary receptor systems) diverges from the channel processing chromaticness information (i.e. a measure of the relative response of the three receptor systems) at some level. The alternative to such a divergent system would be a sequential system in which, for example, the visual information is first processed in the manner required for colour perception, and the luminosity information is then obtained from the output of the colour processing system. The latter type of system would require the eventual separation of luminance and chromatic information, but all the chromatic processing would occur before the separation. Since both systems include three primary receptors as the input stage for both luminance and chromaticness processing, the difference between the systems lies essentially in the level at which the two types of processing diverge. The hypothesis of independence of luminance and chromaticness channel should therefore be understood to imply that essentially no processing between primary receptor signals (e.g. lateral interactions, opponent colour interactions, etc) occurs prior to the divergence of the luminance and chromaticness channels.

It should be noted that the hypothesis of independence in the processing of luminance and chromaticness information does not imply that, for example, the chromaticness of a stimulus is unaffected by a change in the stimulus luminance (as in the Bezold-Brucke hue shift), but that the change in chromaticness is hypothesised to be due to effects within the chromaticness processing channel which are not connected with the processing for brightness perception. Similarly, differential sensitivity to luminance differences for stimuli of various wavelengths may not be accompanied by the corresponding differences in the chromaticness channel (e.g. see Walraven and Bouman, 1966).

The independence hypothesis was originally postulated in a stronger form by Piéron (1939) who suggested the existence of an extra "brightness cone" to account for evidence of independence of the signals for brightness and colour. Since the "brightness cone" was supposed to contain all three photosensitive substances present in the other three "chromatic cones". Piéron's model is functionally very similar to a model in which the information for brightness perception is a combination of the direct outputs of three cones diverging from the channel processing of chromaticness.

The evidence for the independence model, reviewed by Walraven (1962), is summarised below. Piéron (1939) and Troland (1922) showed that the luminosity curve is only slightly affected by moderate chromatic adaptation, whereas perceived hues are radically affected. Since the luminosity curve is assumed to be the sum of the sensitivity curves of the three receptor systems, the adaptation cannot be affecting the latter markedly, but must be acting in an independent chromaticness channel. Similar considerations apply to the strong chromatic adaptation employed by Brindley (1953). According to Walraven's analysis the three receptor systems are operative under strong chromatic adaptation, although at reduced levels, but the eye becomes monochromatic, which is suggested to result from complete fatigue of the chromaticness channel. Svaetichin and MacNicol (1958) found corresponding independence in the electrical responses under chromatic adaptation in fish retina. Finally Fincham (1953) found that the chromatic aberration reflex for accommodation in cone monochromats was unimpaired although colour vision was absent. It therefore appears that the colour information is present at an early stage but that the chromaticness channel is inoperative. Similarly Weale (1953) concluded that the spectral sensitivity of cone monochromats was not that of a single (green) receptor, and that therefore the colour defect was located in post receptor structures, i.e. presumably the chromaticness rather than luminance channel.

Walraven's theoretical interpretations of the Bezold-Brucke hue shift, colour naming experiments and colour discrimination of dichromats are based on the independence hypothesis, as is Walraven and Bouman's (1966) interpretation of the colour discrimination of trichromats for different luminances and field sizes (described in section 2.4.3).

Recently, other lines of evidence have been obtained which support the independence hypothesis. In particular, there is evidence for spatial inhibitory interactions in the luminance channel which are not present in the chromaticness channel. The evidence implies that the spatial inhibitory interactions occur either sequentially following the processing of chromaticness, or in a separate channel. Since the evidence reviewed above suggests that the luminance processing does not occur following the processing of chromaticness, the evidence presented below supports the latter hypothesis of separate channels for luminance and chromaticness (after the primary receptor stage).

Mach bands of brightness perceived in the observation of spatial brightness gradients are usually interpreted as resulting from spatial inhibitory interactions (Ratliff, 1965). Most studies report the absence of colour Mach bands for stimuli of constant-luminance chromaticity gradient, (Thouless, 1922; Koffka and Harrower, 1931; Fry, 1948; Ercoles-Guzzoni and Fiorentini, 1958; Van der Horst and Bouman, 1967), although

Daw (1964) reports the observation of colour Mach bands using step changes in dominant wavelength together with purity. A related line of evidence is the Liebmann effect (Liebmann, 1927), in which the visibility of the edges of a figure is markedly reduced when there is no luminance difference across the edge, even with large chromaticity differences. This suggests that edge enhancement effects are reduced or absent in the chromatic channel. This evidence therefore seems in favour of a lack of (or at least marked reduction of) spatial inhibitory interactions in the chromaticness channel.

A second approach to the spatial characteristics of the two systems has been made via spatial frequency response functions. Sensitivity to spatial sinusoidal luminance grating shows a band-pass form (Westheimer, 1960; De Palma and Lowry, 1962). The low frequency attenuation has been interpreted by these authors as corresponding to spatial inhibitory interactions. Schade (1958) found a similar phenomenon for spatial sinusoidal purity-modulated gratings, and the data of Van der Horst (1969b), using gratings of purity-modulation around white, show evidence of a small decrease in sensitivity at low spatial frequencies. In combination with the observation of Mach bands by Daw (1964), in a situation in which step changes in purity occurred, the above results suggest that there may be spatial inhibitory interactions operative in the processing of stimuli of varying purity. Further experimentation designed to specifically test this hypothesis is required. However, experiments using spatial chromatic modulation at high purity close to the spectrum locus have found no evidence of low frequency attenuation (Van der Horst et al., 1967; Clarke, 1967; Hilz and Cavonius, 1970). Similarly, Van der Horst and Bouman (1969) found no low frequency attenuation for travelling chromatic-modulation grating sensitivity. In summary, the evidence suggests that luminance modulated gratings produce a low frequency attenuation in the frequency response function, as is probably the case for purity modulated gratings. Dominant wavelength-modulated gratings do not appear to produce a low frequency attenuation.

Similar effects in the temporal domain are considered in terms of the independence hypothesis in section 8.6.

The evidence reviewed in this section indicates that the processing of chromaticness information and opponent colour interactions occurs in the chromaticness channel , after it diverges from the luminance channel, and the processing of lateral inhibitory interactions occurs in the luminance channel after the divergence of the chromaticness channel. The evidence is therefore in support of the hypothesis of independence of luminance and chromaticness processing in the form stated above.

3. Temporal Characteristics of Colour Vision.

3.1. Square Wave Flicker: Introduction.

A vast array of investigations have been used as a stimulus, a light source which is alternately switched on and off, giving an effectively rectangular variation in luminance (square wave flicker). The principal parameters of such a stimulus that have been investigated are the frequency of occurrence of each switching cycle and the ratio of time for which the light is on to time for which it is off. (Light-dark ratio). The inter-relation-ships of frequency and light-dark ratio will be considered in section 3.3.

The first attempt to bring order to the "chaos of knowledge" as he described it, was by Landis in 1953. He published a bibliography of flicker-fusion phenomena attempting to include all studies up to that date. The bibliography has been continued by Ginsberg (1970) up to 1968. It appears that the critical fusion frequency (CFF) which the subject judges to be his threshold for the perception of flicker, is influenced by many factors. The most important factor affecting CFF is the retinal illuminance of the flickering stimulus. The retinal illuminance function is often used as a means of examining the effects of other stimulus parameters on the CFF. Important amongst the latter are the retinal subtense, retinal locus, colour characteristics and spatial configuration of the stimulus and its surround; degree and type of adaptation of the retina, activity in the contralateral eye and a number of psychological factors.

(For a summary of these effects see Brown (1965 pg. 251-268).

3.2. Wavelength Effects in Flicker Studies.

In the photopic luminance range Hecht and Sḟhlaer (1936) found CFF to be substantially independent of wavelength of the flickering light, when the stimuli of different wavelengths were matched for brightness (heterochromatic brightness match). This result held over a large range of photopic luminances. The stimulus consisted of a sudden alternation between the light stimulus and darkness with a 1:1 light/dark ratio.

In contrast, the scotopic portion of the CFF versus log luminance curves showed large divergences for different wavelengths. The divergence of the curve for each wavelength is roughly proportional to the difference between scotopic and photopic sensitivity at that wavelength (photochromatic interval). The divergences thus reflect the inappropriateness of a photopic brightness match for the scotopic region. The separation of the CFF function into high and low luminance regions with distinct characteristics confirms the Duplicity theory of retinal function for dynamic stimuli. First proposed by Schultze (1866) the Duplicity theory holds that low and high luminance stimuli are processed by two different classes of receptor (called scotopic and photopic respectively), which have markedly different characteristics. The data of Hecht and Sḟhlaer indicate that the differences in spectral sensitivity of the two classes of receptor found under static conditions (e.g. Wald, 1945) are maintained in this dynamic situation involving square-wave temporal modulation of the light intensity. The use of square wave flicker to study the luminosity function by examining CFF of monochromatic stimuli as a function of wavelength has not been widespread, since, as Ives (1912) points out, there is only a very small variation in CFF for large changes in luminosity. The data of Hecht and Shlaer (1936) indicate that in the photopic region, except at very high brightness, CFF varies roughly in proportion to the luminance as determined by heterochromatic brightness matches. Berger et al.(1958), Collins (1961), Heath (1958) and others have used the CFF criterion in studies of colour defective luminosity function. The results present no clear picture. Ikeda and Urakubo (1968) have studied normal and colour-defective subjects using a field of alternating red and green stimuli and a red or green adapting field. They found that the ratio of the radiances of the two stimuli at subjective minimum flicker distinguished colour defectives and normals, effectively in terms of spectral sensitivity determined by means of heterochromatic contrast threshold, and also by the effects of adaptation. They do not study the colour flicker induced by their stimulus, and they have not published the data of the actual variation of the contrast threshold with wavelength.

There appear to be no other studies of luminosity function using the heterochromatic contrast threshold at a fixed frequency of flicker.

3.3 De Lange Curves.

De Lange (1952) brought a new order to the study of flicker fusion phenomena when he developed the technique of varying the modulation depth (m) of a flickering light (or contrast ratio (r_c) between the luminance of "light" (L_L) and "dark" (L_D) phases of flicker relative to mean luminance. Specifically,

$$r_c = \frac{(L_L - L_D)}{(L_L + L_D)/2}$$

For a sinusoidal waveform of modulation the expression for modulation depth (m) is:

$$m = \frac{L\ max - L\ min}{2L_0}$$

where $L = L_0\ (1 + m\sin \omega t)$

and L_0 is the time average luminance

De Lange plotted the reciprocal modulation depth ($\frac{1}{m}$) at subjective threshold as a function of modulation frequency, of sinusoidal luminance flicker to give a measure of the input-output ratio of the visual system to luminance changes when a steady-state in the flicker perception had been reached. Curves of reciprocal threshold modulation depth as a function of frequency are known as De Lange curves. De Lange used a

2^o flickering field with an equiluminant surround to maintain the adaptation level virtually constant at all frequencies. He found that the De Lange curves exhibited a sudden fall-off in sensitivity near a certain frequency at low retinal illuminance levels, but showed an increasing peak in sensitivity before the step fall-off when average luminance was increased.

Similar results were reported by Kelly (1961b) using a 65^o field with a blurred edge. Kelly plotted his results in terms of absolute modulation sensitivity, rather than sensitivity relative to the time-average luminance. He found that the high frequency slopes, over a range of retinal illuminance spanning more than five log units, conformed to a single curve. De Lange's data show a similar effect when replotted in this way (Levinson and Harman, 1961). This indicates that for the high frequency slope, sensitivity to flicker is dependent solely on the absolute modulation amplitude and independent of adapting luminance.

A different approach to flicker sensitivity has been developed by Bartley and his co-workers, (see Bartley, 1961) based on the enhancement of perceived brightness of a flickering light relative to that of a steady light of the same time-average luminance, first reported by Brücke (1864). The details of the brightness enhancement effect of flicker are not relevant for the present purposes, but it should be pointed out that it involves a different phenomena from those relating to threshold De Lange curves.

a) The brightness enhancement effect only occurs with supra-threshold flicker. When the flicker is at CFF no brightness enhancement is observable. De Lange's measurements are by definition made at CFF for the prevailing conditions, so that the conditions of observation for the two types of experiment are different.

b) The above distinction raises the question whether brightness enhancement could be due to the same processes which determine the De Lange characteristics. De Lange (1957, pg. 59) points out that the form of his "attenuation" functions at high luminance is such as to suggest that, if the visual system behaves in a linear manner, an overshoot should occur in the response to square-wave modulation. However, such an overshoot would not produce a brightness enhancement effect (only a flicker enhancement) unless the visual system behaved in a non-linear manner. It therefore appears that the phenomenon of brightness enhancement implies a non-linearity of the visual system which is not recognisable (as analysed by De Lange) in the De Lange curves.

c) There is evidence (Onley and Sternheim, 1967) that brightness and luminance processing may be dissociated by adaptation condition. Similarly, Harvey (1970) has shown that flicker threshold is dependent on the stimulus luminance under conditions where the perceived brightness of the flickering stimulus is manipulated. I have not been able to discover any studies designed to investigate such a dissociation between brightness enhancement and flicker threshold, but the above experiments suggest that the processes involved in the two types of approach may be independent.

Section 3.4 Perception of Steady-State Stimuli

De Lange regarded his De Lange curves as depicting the attenuation characteristics of the visual system for luminance stimuli, by analogy with the attenuation characteristics of electrical networks (Bode, 1945). However, his investigations on two subjects revealed a number of limitations to this useful description. The assumption is involved that the threshold criterion is independent of frequency. However, the subjective impression of flicker is different for different frequencies and this might make it difficult to hold a constant criterion. De Lange found that the visual sytem is not linear in its response to sinusoidal modulation with respect to retinal illuminance (except possibly at very high values) for a 2° flickering field with an equiluminant surround. The sensitivity curve changes in shape from having the form of a simple cut-off at low retinal illuminance to having a pseudo-resonant peak near 10 Hz at high retinal illuminance. As a result of this change in form the low frequency flicker sensitivity hardly varies between about 4 and 10,000 trolands, but the high frequency slope shifts continously towards higher frequencies as retinal illuminance is increased (see section 7.1.).

The visual sensitivity is thus non-linear with respect to mean stimulus amplitude. However, experiments on the perception of supra-threshold flicker by Veringa (1958) indicate that, using a criterion of constant apparent flicker, curves of similar shape may be obtained for roughly a 5:1 range of modulation amplitudes.

However, Veringa's results apply only to frequencies above about 10 Hz i.e., to the high frequency slope of the De Lange curve. Recently Marks (1970) has extended such observations down to about 3 Hz, using trapezoidal modulation approximating a sinusoidal waveform, and a 2° field. He found that the form of the constant apparent modulation depth curves were similar to that of De Lange curves with a peak near 10Hz. The form of the curves was not greatly affected by an increase in modulation depth of about a log unit (or somewhat less at lower retinal illuminances) from the threshold (De Lange) condition. It therefore appears that the visual system response is approximately linear with respect to modulation amplitude over a range of up to 1 log unit. Beyond this limit, however, the form of the apparent modulation depth curves changes considerably, i.e. the non-linearity is no longer negligible. De Lange notes that both the height and width of the high retinal illuminance peak is somewhat variable both between observers and on different occasions in the same observer. Within these limitations, De Lange was able to construct an electrical analogue of the visual response to the steady-state sinusoidal stimulation which gave acceptable predictions of the response to square-wave and "90° impulse shaped" modulation. His earlier (De Lange, 1952) experiments on the high freqency slope had confirmed Ives' (1922) conclusion that the visual threshold was determined by the fundamental Fourier component of complex waveforms. Kelly (1961) and Gibbins & Howarth (1961) have shown that it is possible to explain much previous work on variation of CFF with light-dark ratio on the basis that the amplitude of the fundamental Fourier component of each waveform determined subjective threshold.

This idea has received further support in the work of Levinson (1959) and Brown (1962), which indicated that the threshold for a complex waveform is determined by the threshold for the largest Fourier component of the waveform. However, Levinson (1960), investigated the perception of waveforms composed of fundamental and second harmomic modulation of amplitudes in proportion to their individual thresholds, i.e. of equivalent subjective effect. In this situation, the threshold for the complex waveform was much lower than for the individual components, and was dependent on the phase relationship of the components. The threshold varied by ± 15% and was minimal at a lag of the second harmonic relative to the fundamental of about 220° (of the second harmonic cycle). No method of obtaining phase relation or waveform at the site of the non-linearity was investigated. It therefore appears that these results may be described as follows. The attenuation of the Fourier components of a complex waveform is the same as for each component alone. On the other hand the response of the flicker perception mechanism is not just proportional to the sum of the amplitudes of the Fourier components, but is also influenced by the phase-dependent waveform of a complex stimulus in the manner just described.

A further example of a situation in which flicker perception behaves linearly was pointed out by Kelly (1961b). The De Lange curves may be plotted in terms of absolute modulation depth without regard to the adapting illuminance level. Recently Kelly (1969a) has shown that this high frequency slope lies about midway between that predicted by a cascaded integrator model, such as De Lange's, and the Ferry-Porter law of a linear relationship between CFF and log luminance (or, if luminance is unimportant, between flicker fusion and log modulation amplitude.) He has suggested a solution of a diffusion equation which accurately describes the data.

However, the behaviour of the flicker threshold at points not on the high frequency slope is non-linear and is not described by Kelly's (1969a) model.

The experiments described in this section indicate the value of the systems analysis approach in integrating and explaining the experimental findings concerning time-varying stimuli. However, techniques for dealing with non-linear systems are much more limited than those for linear systems (see section 4). Since the visual system behaves non-linearly in many respects, as discussed above, the more detailed mathematical and formal modelling of the system is limited in its applicability. A model derived from the response under one set of conditions is not predictive of the response under different conditions e.g. at different levels of mean luminance. The model is reduced to having a largely descriptive value, i.e. condensing the experimental information into a compact form rather than being of use in predicting further types of experimental result.

3.5 Effects of Colour on De Lange Curves.

De Lange (1957) was the first to study the effect of stimulus wavelength on the De Lange curve of a flickering monochromatic light. The stimulus consisted of a 2° monochromatic field with a white equiluminance surround. He found small differences in sensitivity between the curves for several wavelengths holding over a luminance range of nearly 2 log units. The differences were mainly in the low frequency region below 10 Hz. Differences in both overall sensitivity between 1 and 10 Hz. and in the slope of the increase in sensitivity to about 10 Hz. were evident. The slope differences occurred largely in the long wavelength region of the spectrum.

Before comparing De Lange's results with those reported in section 7.1.3., there are two points which should be made concerning De Lange's methodology. He used a white equiluminant surround in the experiments on coloured light. Luria and Sperling (1959) have found that the colour of the surround field effects the CFF of a test field. Since a small effect on CFF may correspond to a large difference in modulation depth of the flat, low frequency portion of the De Lange curve, small differences in the number of chromaticity discrimination steps (Wright, 1947) between white and each of the colours used may have affected the threshold of the test field differently for different colours. In a literature search I failed to locate any studies on the effect of a white surround on the modulation threshold for coloured light.

The second point is the apparent contradiction between the results presented in figures 25 and 26 (De Lange, 1957 pg. 71-2). These figures contain some examples of data obtained under the same conditions on two different occasions. In particular his curves for the 512 and 465 nm conditions coincide on the first occasion, but are different in the low frequency region by almost the full range of variability which he attributes to wavelength effects on the second occasion. In other words, De Lange's experimental error is apparently of the same order as the wavelength effects he describes. However, the differences in shape between the curves, particularly noticeable at 641nm, seem to be similar on the two occasions.

In sum, De Lange's data concerning the effect of colour on modulation sensitivity do not demonstrate unequivocally that there is an effect, except in the wavelength region above 600nm. Kelly (1962b) has measured dynamic spectral sensitivities at three modulation frequencies using a 65° blurred-edge white field to which was added a threshold luminance of a 100% sinusoidally modulated monochromatic beam, of which the wavelength was varied. Kelly found that between 5 and 12 Hz. sensitivity increased in the green region compared to the ends of the spectrum, and between 12 and 25 Hz. sensitivity decreased in the extreme blue relative to the rest of the spectrum. These results do not correspond at all closely to those obtained by De Lange. This is not surprising since Kelly's large field has given results consistently differing in detail from De Lange's. Further, the stimulus Kelly used in measuring dynamic spectral sensitivity was not perceptibly different from white at threshold, whereas De Lange's test field was monochromatic with a white surround.

Kelly (1961a) obtained De Lange curves for two monochromatic colours. The curves showed features similar to those obtained for monochromatic fields with a threshold amount of added flickering white light (Kelly, 1961b). The difference between the change in threshold from 1 to 20 Hz. for 538nm and 670nm fields was of the order of a factor of 4 (the largest change obtained by Kelly). De Lange's largest differences are about a factor of 1.5. Clearly the flicker sensitivity is affected much more by wavelength when Kelly's stimulus is used. Kelly (1962b) described the effects he found in terms of subpeaks in the De Lange curves (for 4 out of 8 subjects) sensitive to adaptation by the colour of the adapting field. Peaks near 6, 12 and 24 Hz. are sensitive to blue, green and red adaptation respectively. Kelly explained the occurrence of the subpeaks and their sensitivity to chromatic adaptation as resulting from three fundamental colour channels each with different temporal characteristics. He suggests that the red, green and blue channels appear to have progressively lower frequency characteristics. Kelly comments that the shape of his De Lange curves "depends almost entirely on the colours of the adaptation and flicker beams, while its [their] height is practically constant". (1962b pg. 945).

Only the blue and green peaks were observable when a 4° field with a dark surround was used. Kelly attributed this low frequency enhancement to the presence of edges in the field. Green (1969) performed experiments involving colour adaptation of flicker, with a stimulus rather different from Kelly's. The stimulus consisted of a 2° test field of variable modulation depth superimposed on a large background of a different colour, several log units higher in retinal illuminance than the test field. Under these conditions, with suitably chosen test and background colours, there is evidence that the three cone mechanisms were obtained. The green mechanism shows a large pseudo-resonant peak around 10 Hz., whereas those for red and blue are nearly flat to 10 Hz. On the other hand, the overall sensitivity of the blue mechanism is about 1 log unit lower than that for the red and green mechanism, thus accounting for Brindley et al's (1966) finding that the blue mechanism has a lower CFF than the red and green mechanisms. The high frequency cut-off seems to occur at similar frequencies for each mechanism. Green has not found it possible to relate his results to those obtained by Kelly (1962b) with similar test and adapting colours. Kelly's results do not show effects corresponding to those found by Green.

In conclusion, it is apparent that the effects of colour on the frequency response characteristics of the retina depend on the spatial configuration of the stimulus on the retina as well as its chromatic structure. It is clearly of importance that future studies of the effects of colour in the frequency domain should be related to the classical data of colour vision, in particular to the C.I.E. chromaticity description and to wavelength discrimination.

3.6 CCFF as a Function of Colour.

The effects described in the above sections involve the luminance of the stimulus as the dependent variable. It is also possible to modulate some aspect of the colour of the stimulus in time in such a way that the luminance remains constant. Such a stimulus will be called chromatic modulation.

The applicability of the C.I.E. chromaticity coordinates to a dynamic situation have not yet been established.

The term "chromatic flicker" will therefore be used to imply continuous temporal variations in a spatially uniform stimulus field in which the luminance remains constant, but the spectral distribution of the luminous flux changes. Such changes in the spectral distribution are not necessarily describable in terms of the established C.I.E. chromaticity coordinates (i.e. as "chromaticity flicker"), whose applicability to temporal variations of spectral distribution is discussed in section (3.7).

The earliest studies in which a stimulus involving time variation of stimulus colour is used are derived from heterochromatic flicker photometry (HFP), which is a technique for equating the subjective brightness of two stimuli differing in colour by presenting each stimulus alternately with the other. When the brightnesses of two alternated stimuli are equated subjectively, the stimulus consists of a square wave chromatic modulation. Ives (1912) investigated a particular example of such a stimulus, in which the rotation of a sector disc alternated a reference white stimulus and a range of spectral coloured stimuli. The relative intensities of the two stimuli were varied until a point of minimum perceptual flicker was obtained. At this point he took the brightnesses to be equal under the experimental conditions described. The residual flicker is caused by interactions within the chromatic channels. The flicker rate or frequency was varied until at the perceptual minimum the flicker was imperceptible, or just below threshold. Ives found that the chromatic critical flicker frequency, (CCFF) which was the variable thus measured, varied according to the dominant wavelength of the light alternated with white. Specifically, CCFF increase in frequency as dominant wavelength moves from about 570nm towards either end of the spectrum. However, as dominant wavelength changes, there are also variations in the chromaticity difference (i.e. saturation difference) between the two stimuli. Within the range studied by Ives, it appears that the increases in CCFF were roughly correlated with increases in the chromaticity distance between the two stimuli alternated. Troland (1916) reported similar results. A study by Galifret and Piéron (1949) also showed variations of CFF for different colours of stimuli alternated with an equiluminant white. Galifret and Piéron (1948) gave evidence that the fusion frequency was independent of saturation degree (purity) of the coloured stimulus from 10-100%. This finding has been criticised by De Lange (1958b), who suggests that the transition between the two stimuli involved was insufficiently smooth and the resultant luminance transients determined the threshold. Furthermore, experiments by Walraven et al (1958) described in the next section indicate that purity is an important factor in the fusion threshold.

A stimulus alternation technique for colour matching was used by Bongard et al.(1958) in their investigation of the colour vision of the peripheral retina. They used only one low frequency and do not report the comparative effect of alternation versus simultaneous presentation on colour matches. But it is of interest that the alternation technique is applicable to colour matching procedures. A full examination of the effect of frequency in this type of experiment would provide some basic data for the extension of the C.I.E. chromaticity chart to time varying stimuli.

3.7 Sensitivity to Chromatic Flicker as a Function of Frequency.

Truss (1957) has studied the relation between CCFF and chromatic separation of alternated stimuli. He showed that for alternation between 15 pairs of spectral stimuli (white was not used), the persistence (or reciprocal of CCFF) was proportional to log chromatic separation of the two stimuli used in each case. The chromatic separation was defined as the distance in mean j.n.d. steps (Wright, 1943) between the C.I.E. co-ordinates of each pair of colours.

Truss' results show threshold chromatic separation is correlated with CCFF close to the spectral locus as well as along lines of constant dominant wavelength, as described in the previous section.

Recomputation of Truss' data in terms of the equivalent wavelength swing for constant CCFF as a function of the mean of the wavelengths of the two alternated stimuli, might be expected to produce a curve corresponding to a dynamic equivalent of the wavelength discrimination function at the frequency he used (10.4 Hz.). In fact the data appear to be subject to great variability as a result of which no sound conclusions can be drawn.

De Lange (1957, 1958b) suggested a method whereby the chromatic variation around a fixed mean colour may be continuously controlled, thus permitting the study of flicker threshold over a range of frequencies for a single combination of stimuli.

In his experiments, a red stimulus was alternated sinusoidally with an equiluminant green stimulus. A variable amount of steady orange could be added to the alternating stimulus, with luminance as determined by flicker photometry held constant. The implications of this method of luminance measurement are discussed in section 7.1.4.

The phase difference between the two alternating stimuli was adjusted so that brightness flicker was minimised for 100% modulation. It was assumed that to phase differences at low frequencies were so much reduced by the low modulation depths at these frequencies that no further phase correction was required.

The amount of orange added was set so that flicker was at perceptual threshold for a range of alternation frequencies. De Lange found that the sensitivity to colour flicker thus measured fell continuously as frequency increased, but exhibited a small peak at 8Hz, the same frequency at which the large peak occurred the luminance modulation curve for the same mean chromaticness. He attempted to describe the difference between the shapes of colour and luminance modulation curves in terms of a small number of sequential first order stages of attenuation the number of stages varying with the mean retinal illuminance. A single stage was required at 285 trolands retinal illuminance, and three stages on a retinal illuminance reduced by two log units. He did not test this interpretation at any other mean wavelengths.

A study in which frequency sensitivity to chromatic flicker was measured for a number of different wavelengths was performed by Walraven, Leebaek and Bouman (1958). They alternated a mixture of white and spectral stimuli with a white stimulus, using a sector disc, and thus producing a stimulus modulated in purity.

Although they did not find it possible to measure thresholds below about 5 Hz, they were able to study the high frequency slopes for 12 dominant wavelengths. They found that the high frequency slopes decreased from red to yellow, then increased towards blue. They attributed the change in slope to variations in the residual brightness flicker caused by variations in the phase relationship between the white and the coloured periods of the stimulus. They therefore imply that the thresholds measured were determined not by the changes in purity per se but by concomitant brightness flicker. However, their results do not follow the high frequency slope to be expected if brightness flicker were the determining factor in the psychophysical threshold. It appears to the present author that Walraven et al. have left out of consideration the reduction in the residual brightness flicker modulation due to phase with reduction in purity of the alternated coloured light. Since the phase shift is entirely attributable to the spectral component of the impure mixture alternated with white, the effect of a phase shift in producing residual brightness flicker will be reduced in proportion to the reduction in purity of the mixture. They also appear to have over-estimated the modulation depth due to a hypothetical phase shift. Recalculation of the expression for the estimated modulation depth suggests that the latter is small enough to be below threshold at virtually any frequency except possibly close to 100% purity. These considerations lead to the conclusion that Walraven et al.'s results do represent frequency sensitivity to purity modulation, contrary to their own conclusions.

In a recent study, Van der Horst (1969a) has extended De Lange's experiments or chromatic flicker frequency characteristics to a wider range of luminance levels. The luminances of two superposed coloured fields (red and green) were modulated in antiphase. No phase correction was applied. He made the assumption a) that the sensitivity to change (ΔC) in the C.I.E. chromaticity description of the modulated light was linear with respect of the modulated light was linear with respect to the modulation depth (m) of each beam ($\Delta C = 0.041\ m$).

b) that the chromaticity coordinates determined for each beam remained independent of the frequency of modulation.

Neither assumption was subjected to test, nor have they been previously investigated. Although these considerations limit the generality of Van der Horst's results until the assumptions have been established, they do not invalidate his main conclusiens. He found that the chromatic flicker frequency characteristics remained similar in form over a range of about 2 log units of retinal illuminance, and approximate adherence of the CCFF to the Ferry-Porter Law (CCFF = a. log I + b, where I = retinal illuminance; a, b are constant). The quantum fluctuation theory prediction of the square root relationship between threshold chromaticity modulation and retinal illuminance was confirmed. The thresholds for various modulation waveforms were found to be close to the values predicted if the thresholds had been determined by the fundamental Fourier component of the waveform at all frequencies.

However, the form of the sinusoidal chromatic frequency characteristics differed somewhat from those found by De Lange under similar conditions. Van der Horst's curves were characterised by a flat low frequency portion and a linear slope high frequency portion at all luminances. De Lange's high luminance curve showed a shallow and a steep sloping portion with a small pseudo-resonant peak. The low luminance curve was similar to Van der Horst's curves. However, this difference may be due to the use of different field sizes and different colour surrounds by the two investigators.

As mentioned above, it is a general problem in studies of temporal effects in colour perception that the effect of stimulus frequency on the chromaticity coordinates of a stimulus is not known. De Lange did not take account of possible deviations from Grassman's laws of colour mixture as a function of frequency, or their relation to colour discrimination in his experiments on chromatic flicker, and Van der Horst explicitly assumed the applicability of the C.I.E. chromaticity coordinates. However, Van der Horst and Mius (1969) have discovered a large shift in apparent hue of a monochromatic light flickering in luminance. The effect is different for different wavelengths and indicates that the chromaticity coordinates of a strongly flickering light obtained by matching against a steady light would be altered. The C.I.E. chromaticity specification of a set of stimuli would thereby be distorted in a manner dependent on the stimulus frequency. It is not known, however, to whether a similar effect might operate with chromatic flicker.

It is important therefore to establish the relationship between the C.I.E. chromaticity diagram for static stimuli and the matching coordinates for time varying and steady-state flickering stimuli. Some work which has been done on the effects of time of observation on the chromaticity of stimuli and on discrimination ability is reviewed in section 2.3.5.

3.8. Phase Shifts and Colour

A few authors have studied phase relationships in flicker perception as a function of stimulus colour, but none have extended the work to chromatic flicker. These studies are therefore relevant to the way in which signals from the separate colour mechanisms are combined into a luminance signal, but not to the colour encoding or opponent colour signals.

The initial study of the phase shifts between sinusoidal stimuli of different colours was performed by De Lange (1957). His stimuli consisted of two monochromatic beams modulated sinusoidally in luminance and combined to form a singe field. He found that the phase difference between the two beams, for complete cancellation of perceived luminance flicker in the field, deviated by small amounts from antiphase (i.e. from the phase relationship which would produce a steady output for a univariant receptor such as a photocell). He interpreted this phase deviation from antiphase as corresponding to a difference in phase shifts produced by the colour mechanisms mediating the input. The phase deviation for constant luminance was found to vary both as function of modulation frequency and of the wavelength difference between the monochromatic beams. Specifically, the phase deviation as a function of frequency was maximal (1.5°) at 5Hz for 641 nm versus 689 nm. With respect to wavelength difference between the two beams the phase deviation for a range of wavelengths relative to 689 nm was maximal at 570 nm for both 6 and 14 Hz. It reached 9° lead in the case of 6Hz. De Lange attempted to correlate the phase deviations he found with the minimum phase predictions from the amplitude characteristics for monochromatic light. He states that the method was too inaccurate to describe his results, but in view of the inconsistencies in his result (section 3.5) his lack of success may be due to inaccuracies in the data.

Walraven and Leebeek (1964), using De Lange's apparatus, measured phase deviations under a wider range of conditions for a different observer. They built up the phase deviation as a function of wavelength by adding together the deviation produced with up to 9 successive pairs of wavelengths across the spectrum. They checked the validity of the phase additivity assumption in various regions of the spectrum. In the example given, deviations from additivity of up to 5° are present over a total wavelength difference of 40 nm. Their results differ from De Lange's, particularly for the phase deviation as a function of wavelength. The wavelength used as a reference was close to that used by De Lange (675 nm rather than 689 nm), but Walraven and Leebeek found total phase deviations of up to 30° lag (3Hz) and 20° lead (9Hz) in the region of 500-530 nm, where the phase deviations were maximal. The maximum phase deviation found by De Lange was only 9° lead at 6 Hz. The position of the maximum phase shift on the wavelength axis was 500 nm for the phase lead and 530 nm for the lag in Walraven and Leebeeks's data, which is a great discrepancy from De Lange's maximum (for phase lead) at 570 nm.

However, these differences may be due to the use of different subjects. Walraven and Leebeek point out that their assumption of additivity of phase deviations implies that the system behaves linearly, whereas their data indicates the presence of non-linearities which would affect the phase additivity. It is therefore important to repeat the phase deviation experiment using direct rather than summed measures of phase deviations across the spectrum, before a reliable picture can be obtained.

3.9 Transient Visual Responses in the Colour System

Introduction

Two main methods have been used in studying the responses of the visual system to transient imputs. The maximum amplitude of the response has been studied either by reducing the stimulus to subjective threshold, or by matching the response amplitude against the amplitude of a steady stimulus. The temporal form of the response has been studied by the increment threshold technique of adding a brief pulse to the main stimulus and determining its threshold as a function of delay relative to the main stimulus. The results of these experiments have been varied and in some cases contradictory.

Reciprocity

Bloch (1885) formulated the law that for variable duration luminance pulses below a certain stimulus duration, the stimulus luminous energy (E_l) required to reach threshold would remain constant as stimulus duration (t) varied.

$$E_l = dL.t. = \text{constant} \quad 2 \qquad \text{where } L \text{ is stimulus luminance}$$

This law involves reciprocity between pulse duration and change in luminance (dL). Above the limiting stimulus duration, the threshold luminance change is independent of time. Reciprocity has been found to hold down to 2 m sec over a 5 log unit range of adapting luminance by Graham & Kemp (1938), and Brindley (1952) has verifed the law down to duration of 400 nanoseconds.

Critical Duration

The point at which the extrapolated reciprocity and time independence lines meet is called the critical duration (t_c). The critical duration was a linear function of the log adapting luminance (Graham & Kemp 1938), increasing from 30 to 100 m sec as adapting luminance was reduced. Several authors have studied the intensity-time relationship for a range of stimulus wavelengths at absolute threshold. Rouse (1952) has found that critical duration is independent of stimulus wavelength for a small field size of the order of 1'. Sperling and Jolliffe (1965) have confirmed that critical duration is independent of wavelength for a 4.5' field, but found a difference in the form of the intensity time function at different wavelengths for a 45' field, under conditions of light-adaptation which controlled for rod intrusion. If critical durations are computed from their data on the best fitting asymptotes (which they did not attempt since full convergence to the asymptote i.e./absence of temporal summation, was not completely attained in the case of the blue stimulus) a difference in computed critical duration of about 60% over 200 nm wavelength separation. Connors (1970) results confirm the wavelength independence of critical duration for small (2.5') diameter stimuli, but she found no evidence to support Sperling & Jolliffe's finding of a wavelength effect with a 65' stimulus. Sperling & Jolliffe interpreted the discrepancy between large and small field data as reflecting the difference in receptive field sizes for different types of cone. The small field is below the minimum size of receptive field, so does not show any effect of wavelength. It would therefore appear that even on the basis of Sperling & Jolliffe's data the temporal effects revealed by the luminance pulse method are a reflection of spatial organisation of luminance channels with different spectral sensitivities rather than an essential difference in the temporal characteristics of the colour channels. It may be concluded that the existing studies of the visual system have revealed no information concerning the temporal characteristics of the independent colour processing system as described in section 2.5.

3. 10. Transient Waveform

The level reached by the visual response to an input step stimulus of, say, luminance may be measured at a set of intervals after onset by comparison with the level of a steady stimulus. Using this method, Broca & Sulzer (1902) found that there was an initial overshoot before the steady level was reached, whose amplitude was proportional to stimulus luminance, (Broca-Sulzer Effect). The existence of this overshoot and its relation to luminance was confirmed by a different technique by Crawford (1947), who obtained the increment threshold of a 10 m sec test flash on a longer conditioning pulse.

The Broca & Sulzer Effect has been related to the Bartley-Brucke brightness enhancement effect, (Bartley, 1961), since the overshoot is only apparent at stimulus onset and not at offset. Consequently, the apparent brightness of a train of pulses in supra-threshold conditions will have a higher mean level than the brightness of a steady light of the same average luminance as the pulse train. Similarly, for threshold sinusoidal modulation De Lange (1957) has interpreted the form of the frequency response curve as predicting an overshoot similar to that of Broca & Sulzer in the transient response.

Using a similar method from that of Broca & Sulzer, Kleitman & Pieron (1925) studied the duration of stimulus required for various levels of comparison luminance to be reached. Their results indicate that scotopic (peripheral) levels are reached in approximately half the time taken by photic (foveal) response to the same level. In the wavelength dimension shorter wavelengths appear to have longer rise times, a blue stimulus taking about twice as long to reach a given luminance level as a red stimulus. On the other hand, Ferree and Rand, [in Farnsworth (1958)], using a method of just noticeable luminance differences between stimuli of slightly different durations found that the rate of rise as a function of wavelength vaired in the opposite direction, red stimuli reaching a given number of j.n.d.'s in about twice the time for blue stimuli.

The most exhaustive study of the effect of wavelength on perception of pulse stimuli has been carried out by Wasserman (1966). Using the method similar to that of Broca & Sulzer, he measured the apparent luminance of luminance pulses from 50 to 320 m sec duration for 25 stimulus wavelengths. He found that the apparent luminance showed overshoot characteristics (brightness enhancement) peaking at about 100 m sec for 470, 500 & 575 nm wavelengths, but a lack of overshoot in the rest of the spectrum. He related the brightness enhancement wavelengths to the invariant hues[3] of opponent colour investigations (Hurvich & Jameson, 1951) and of the Bezold-Brucke phenomenon, but presented no clear picture of the mechanisms that might be involved. In the chromaticity domain results were obtained in experiments studying the rate of rise of chromatic saturation (Piéron, 1932). A monochromatic light (or mixture of monochromatic and white light), was substituted for an equiluminant white light, and rise times to maximum chromatic purity were found to be longest for the blue and shortest for the red, although the range of variation was only 30%

Piéron states that the rise time was independent of the purity of the mixed light. As in the case of step luminance stimuli, the response to the chromatic step showed an overshoot to a saturation level greater than that of the steady comparison stimulus. The saturation is then reduced slowly to the steady level. This latter phase is attributed by Pieron to chromatic adaptation, as distinct from his description of the overshoot to a luminance step as oscillatory rebound type of phenomenon.
(Kleitman & Pieron, 1925).

4. Systems Analysis

4.1 Introduction

The aim of human experimental psychology is the analysis of the activities of the human organism. Virtually any method of analysing a system or organism of which the parts are not completely accessible will necessarily involve arranging a set of environmental (input) conditions for that system and observing the subsequent effects of this input in terms of some output parameter. The important feature of analysis is consequently the input/output relationship. In many situations, it is possible to quantify the input and output parameters in terms of specified dimensions of variations.

For the purpose of the present thesis, the dimensions of interest are principally luminance and wavelength of a monochromatic light stimulus. The dimension through which these quantities are varied is time. Temporal variations of input parameters may be conveniently separated into three classes, although these inevitably shade into one another.

<u>Transient input</u> - brief change in the values of the input parameter effectively separated from other changes by a steady state of the parameter before and after the change.

<u>Continuous input</u> - continuous or repetitive changes in the values of the input parameter. Response is usually measured when steady state condition is reached in the system.

<u>Stochastic input</u> - a random variation in the values of the

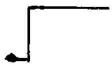
input parameter within a specified range of constraint. This type of input has not been used in the present thesis, so will not be further discussed.

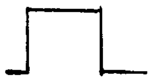
4.2. Forms of Input

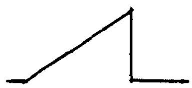
Transient Inputs

A waveform of virtually any shape may make up a unit input. However, the simplest to deal with and most often used are:-

Impulse 

Step 

Rectangular Pulse 

Ramp 

In the use of such waveforms, the emphasis is on the effect of a single stimulus, though responses to a number may be averaged together for greater accuracy. The output is known as a transient response. In most physical systems the output is of a different shape from the input, and both shape and size considerations are necessary in analysis.

Continuous Inputs

When a set of single waves running consecutively constitute the stimulus, it may be called a continuous input. Any of the above waveforms may be used to make up such a stimulus, but the output variations with changes in input frequency, amplitude etc., are complex and difficult to describe. On the other hand, a comprehensive technique for describing continuous inputs in terms of sinusiodal components is available, known as linear systems analysis. This is based on the Fourier Theorem that all repetitive waveforms can be analysed into a set of sine waves of appropriate amplitude and phase. It is also applicable to many non-linear systems (see 4.3.). In a linear system, by definition, the output to a sinusoidal input is a sinusoid of the same frequency, but altered amplitude and phase. In many non-linear systems (see 4.4.) the output can also be approximately described in terms of its fundamental Fourier component.

4.3. Types of System

Introduction

The systems under discussion may be considered, as indicated above, in two broad categories - linear and non-linear. A linear system is one which can in principal be described by a linear differential equation. This in turn implies that the input/Output ratio remains constant for any amplitude of input and that the effect of the sum of two inputs on an output parameter is equal to the sum of their individual effects (principle of Superposition). Thus all properties of the system are independent of input amplitude.

A system that does not fulfil these requirements is non-linear in some respect.

A convenient classification of linear systems is in terms of the order of the highest derivative of the differential equation.

Zero order System

The equation of a zero-order system is of the form: $y = ax + b$

This equation contains no derivatives of x and output is directly proportional to input regardless of frequency, etc.

First order system

The first order system has an equation of the form: $y = a\dot{x} + bx + c$

The first derivative of x occurs in the differential equation, hence the system characteristics are affected by rate of change of the input as well as the amplitude. As a result the system is frequency sensitive and representations of amplitude and phase variations for sinusiodal continuous inputs become necessary. First order systems may contain various combinations of differentiation and integration (in terms of sinusoidal inputs, a 90° lag and lead respectively) in defined regions on the frequency axis.

2nd order systems

In second order systems, the sinusoidal response amplitude (y) depends on second derivative of input (x) as well as the first, the frequency response characteristic depends on the damping in the system:

Equ. $$y = w_0^2 x + 2 w_0 \xi \dot{x} + \ddot{x}$$

ξ = damping ratio

w_0 = constant

Damping is determined by the ratio of resistance to velocity to resistance to acceleration of the system output, i.e. ratio of friction to inertia in a mechanical system. The damping ratio, is related to both the frequency response characteristic and impulse response.

A basic second order system has a resonant peak in the frequency response characteristic, the height and sharpness of which depends on the damping ratio, (ξ). Considering the impulse response the rate of decay of the transient response to an impulse is complementarily related to the damping ratio (ξ) by the relation

$$\alpha = \xi . w_0$$ α = time constant

For systems of order higher than second order the mathematical analysis rapidly becomes very complicated. Second order characteristics are the highest order considered in the present thesis.

4.4. Non-Linear Systems.

A non-linear system is defined as a system whose behaviour is not described by a linear differential equation with constant or variable coefficients. Non-linearities may be described in two classes, analytic and discontinuous. Analytic non-linearities are continuous and therefore differentiable in the region of interest, whereas non-analytic non-linearities are not differentiable. For both analytic and non-analytic non-linearities the form of the output is not independent of the input amplitude. For such systems therefore, the principle of superposition does not apply, that is, the output to the sum of a number of inputs is not necessarily the same as the sum of the outputs to each of the inputs separately.

A major consequence of the invalidition of the superposition principle is the Fourier integral is no longer applicable. There is no formal relationship between the time and frequency responses of the system, and it is therefore no longer possible to compute one from the other.

In general, the approach to non-linear systems is descriptive, in that knowledge of the response to one type of input does not allow prediction of the response to another type, or even to a larger or smaller version of the same input. However, it has sometimes been possible to completely analyse specific non-linear systems. Knowledge of a non-linear system is therefore usually limited to the specific input conditions under which it has been analysed.

Analysis of Non-linear Systems

The methods available for analysis of non-linear systems are limited and applicable only to specific aspects of a given system response. Only the method used in the present thesis will be described here.

An important method of treating non-linear system responses is to limit the range of inputs such that within that range the system does not deviate significantly from linear behaviour. This is known as the method of linear approximation. In practice, all physical systems become non-linear at some point, so that the practical application of linear analysis will always involve some degree of linear approximation. For a given system, it is therefore of value to discover to what extent it acts in a linear manner, and may be described analytically, and to what extent its non-linearity requires a descriptive treatment of the output for each separate type of input. In section 8.5 a linear analysis of the luminance and colour processing systems is applied in order to ascertain the extent of its non-linearity.

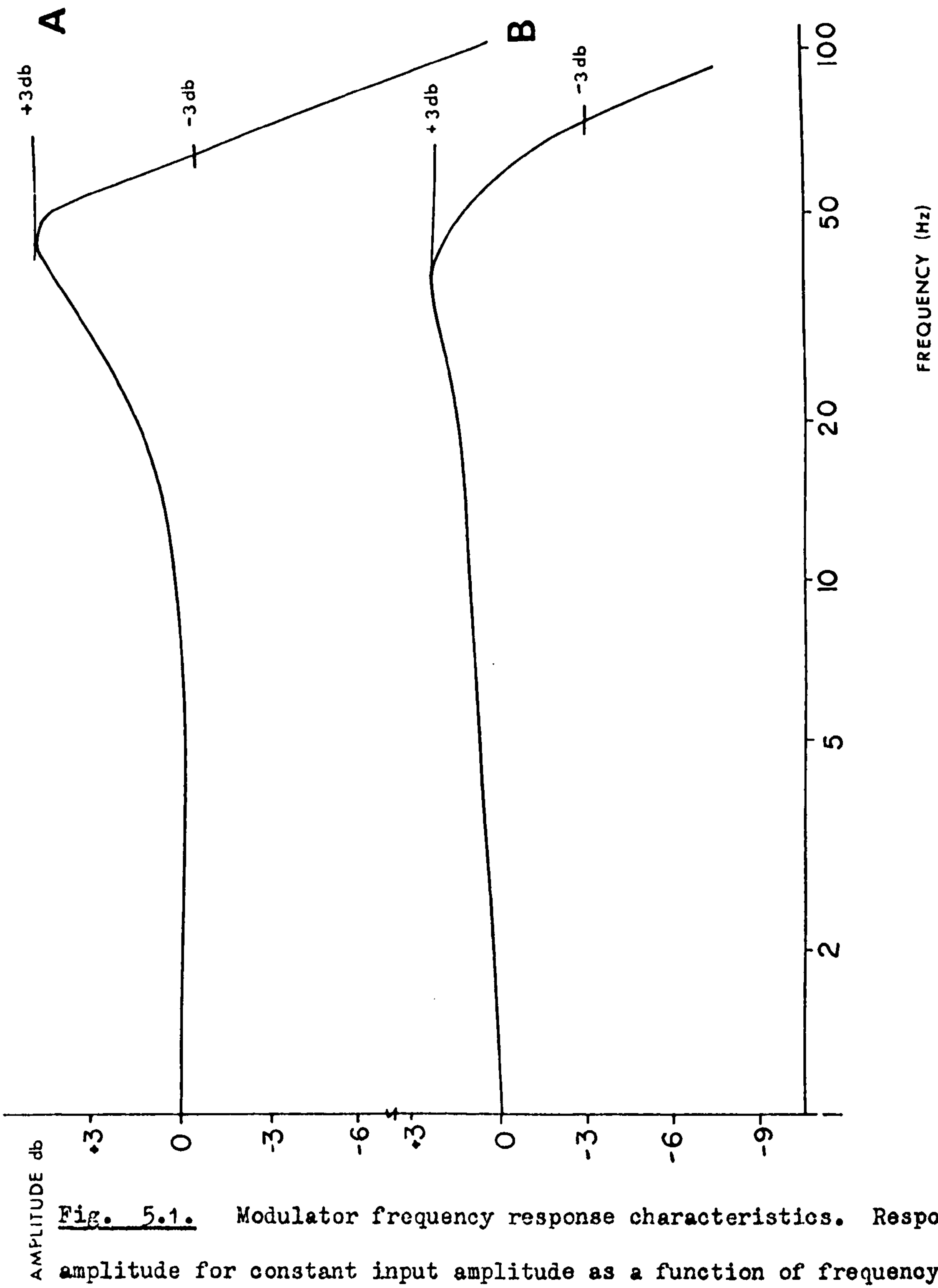


Fig. 5.1. Modulator frequency response characteristics. Response amplitude for constant input amplitude as a function of frequency. A. Wavelength modulator frequency response. Response is flat (± 3db) to 65 Hz. B. Luminance modulator frequency response. Response is flat (± 3db) to 70 Hz.

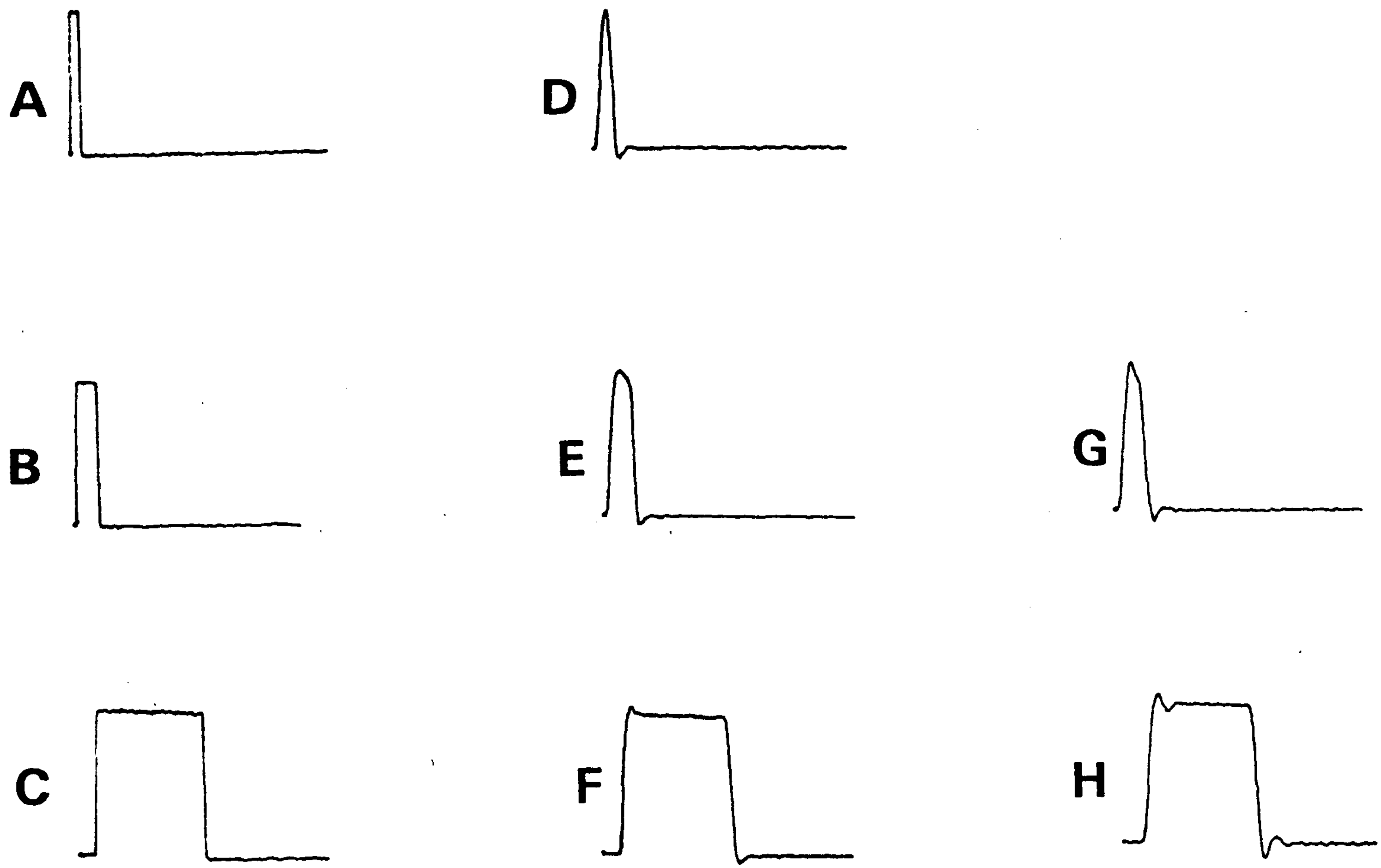
5. Apparatus

5.1. Luminance Modulator

The light source was a 48 W automobile headlamp bulb overrun from a stabilised d.c. supply. Its light was collimated by an f/2.6. aircraft camera lens. Infra-red components were filtered from the beam with a piece of Chance HA3 glass, in order to avoid damaging the polaroid sheets of the modulator described below.

The luminance modulator consisted of a pair of crossed polaroids, one fixed and one rotable. The movable polaroid was rotated by means of a Devices pen motor, which had a maximum angle of swing of ± 18°. This permitted light modulation up to 60%, linear within ± 5% to input voltage (a 200 Hz dither signal was added to improve low amplitude linearity). The frequency response was 70Hz (± 3db) (fig 5.1.). The use of a polaroid modulator ensured that the spectral distribution of the light was constant and the light weight of the polaroid enabled a good frequency response to be acheived.

In sections 7.3., 4. and 5. some experiments are described in which the luminance modulator is used with square-wave and pulse inputs. For such stimuli, the rise time to maximum amplitude of the basic modulator was 13 m sec with 5% overshoot. Introduction of low pass filter with a time constant of 0.017 secs in the modulator input reduced the overshoot to the mean pulse level. Fig 5.2. shows the average of 20 responses of the modulator as seen by an STC silicon photovoltaic diode (PV10AF) at the exit pupil of the maxwellian view system for three pulse durations of 10, 20 & 100 msec. (Fig. 5.2. D.E.F.) The averaged input pulses are also shown for comparison



<u>Fig. 5.2.</u> Modulator pulse responses (see text for method). A, B, C - averaged voltage input to modulators for 10, 20 and 100 msec. pulses respectively. D, E, F - averaged photocell output for response of luminance modulator for 10, 20, and 100 msec. pulses respectively. G, H - averaged photocell output for response of wavelength modulator for 20 and 100 msec. pulses respectively. Modulator response waveforms are adequate under all conditions.

(Figs. 5.2. A,B,C.). Even at pulse durations as brief as 10 msec., the modulator gives a pulse of adequate waveform.

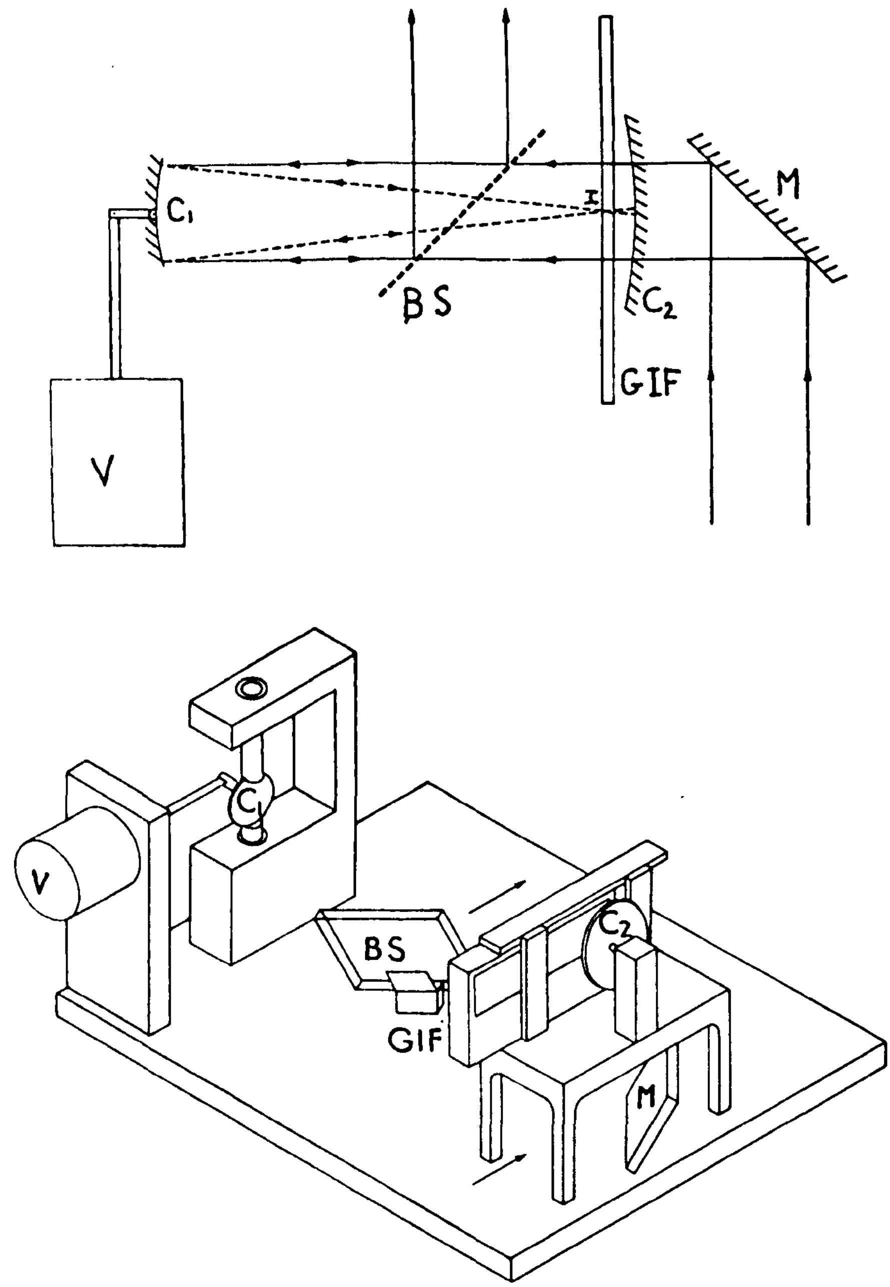


Fig. 5.3. Optical arrangement of wavelength modulator.

Upper figure - isometric sketch. Lower figure - ray diagram.

BS - Beam-splitter; C_1, C_2 - concave mirrors ; GIF - graded interference filter; I - image of filament; M - plane mirror; V - vibrator.

5.2. Wavelength Modulator

The wavelength modulator was designed by Dr. D. Regan. The description of its construction and calibration is largely taken from Regan & Tyler (1970).

A parallel beam from the light source was deflected by a front-aluminised plane mirror M (Fig. 5.3.) so as to fall on a pivoted front- aluminised concave mirror C_1 (Fig.5.3.), of 20 cm radius of curvature. Mirror C_1 focussed a 2 mm wide slit image I (Fig. 5.3.) of the source onto the surface of a second, fixed front-aluminised concave morror C_2 (Fig. 5.3.) of 10 cm. radius of curvature. Immediately in front of C_2 was a graded interference filter GIF. The halfwidth for a single passage of light was 200 A° for a 2 mm slit. The radius of curvture of C_2 was equal to the distance from C_1 and C_2, so that to a first approximation all rays from C_1 were incident normally onto C_2. When mirror C_1 was oscillated through small angles (less than ± 6°) the light incident onto mirror C_2 was therefore at all times reflected back along its own path; of this returning beam, 50% was deflected out of the modulator by a beamsplitter BS.

The essential feature of the optical arrangement just described was that when mirror C_1 was deflected as as to sweep the slit image of the light source to and fro along the graded interference filter, the beam of light leaving the system did not oscillate in position, but merely varied in wavelength. The purpose of this design was to ensure that the subject had no visual clues other than brightness

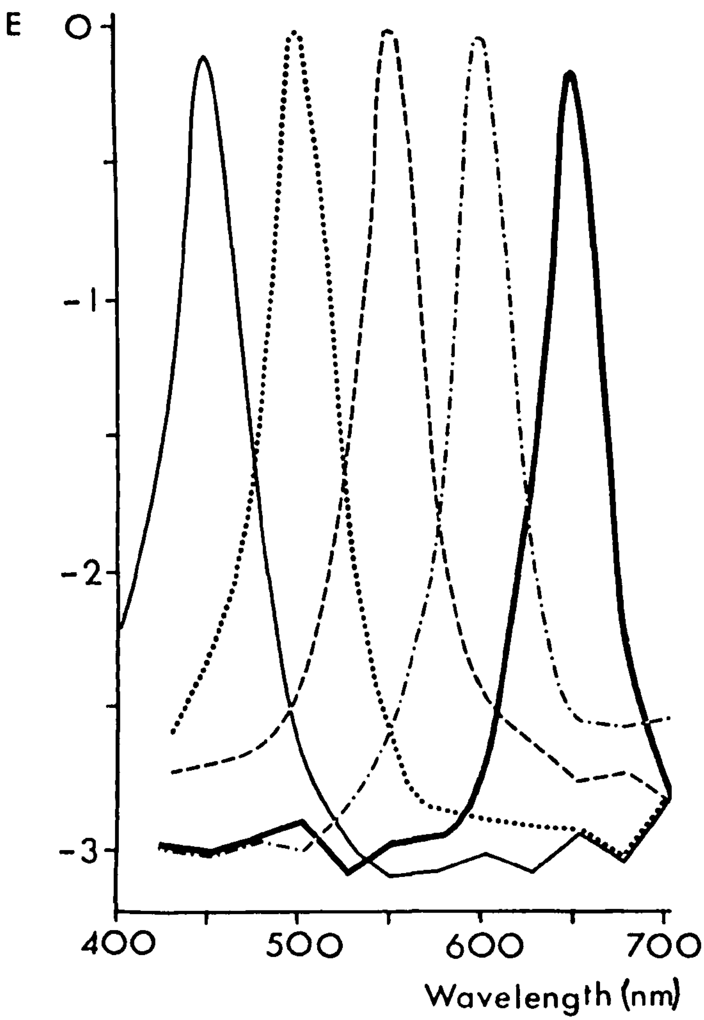


Fig. 5.4. Performance of wavelength modulator as monochromator. A grating monochromator followed by a photomultiplier was placed at exit pupil and read for five settings of the modulator wavelength. The photomultiplier was calibrated against a Hilger-Schwartz vacuum thermopile, giving values of relative energy (E).

or colour changes of the field as-a-whole, and specifically to ensure that there were no periodic changes in the spatial distribution of stimulus light when the wavelength of the stimulus was modulated.

The performance of the device as a simple form of wide-band pass double monochromator is illustrated in Fig. 5.4. which shows that, as is essential for the present application, the instrument let through very little light outside the pass band and that secondary peaks were negligible.

The wavelength of the stimulus beam was modulated in the following way. Mirror C_1 was mounted in the axis of rotation of a freely pivoted rod. The rod was oscillated by a Pye-Ling Vibration generator V (Fig. 5.3.) so that the focussed image of the source oscillated across the graded interference filter. The result was that for small angles the wavelength of the stimulus beam varied proportionally to the driving signal applied to this vibrator V (Fig.5.3.) The frequency response of the device was d.c. to 30 Hz (within ±1db); the wavelength swing was continuously variable from zero to the maximum swing used ($\pm 6^{\circ}$). In order to improve linearity, a low amplitude 200 Hz "dither" signal was added to the input to the vibrator. This "dither" signal was intended to minimise any of the jerkiness of movement which can result from static friction, particularly at low modulation amplitudes.

Within the limitation set by the d.c. to 30 Hz frequency response, a variety of modulation waveforms could be used. For the square-wave and pulse waveform experiments, the transient response of the wavelength modulator was checked. Its rise time to maximum amplitude was 15 msec with an overshoot of 10%. The inclusion of a 0.066 sec time constant low pass filter in the input to the modulator was sufficient to reduce the overshoot to approximately the mean pulse level. Fig. 5.2. (F.G.) shows the average of 20 responses of the modulator as seen by an S&C silicon photovoltaic diode (PV10AF) at the exit pupil for two pulse durations of 20 and 100 m sec. The height and waveform of the pulse are adequate at the 20 msec duration, and since the pulse experiments indicate that the critical duration for wavelength pulses is longer than that for luminance pulses, the slightly impaired performance of the wavelength modulator is acceptable.

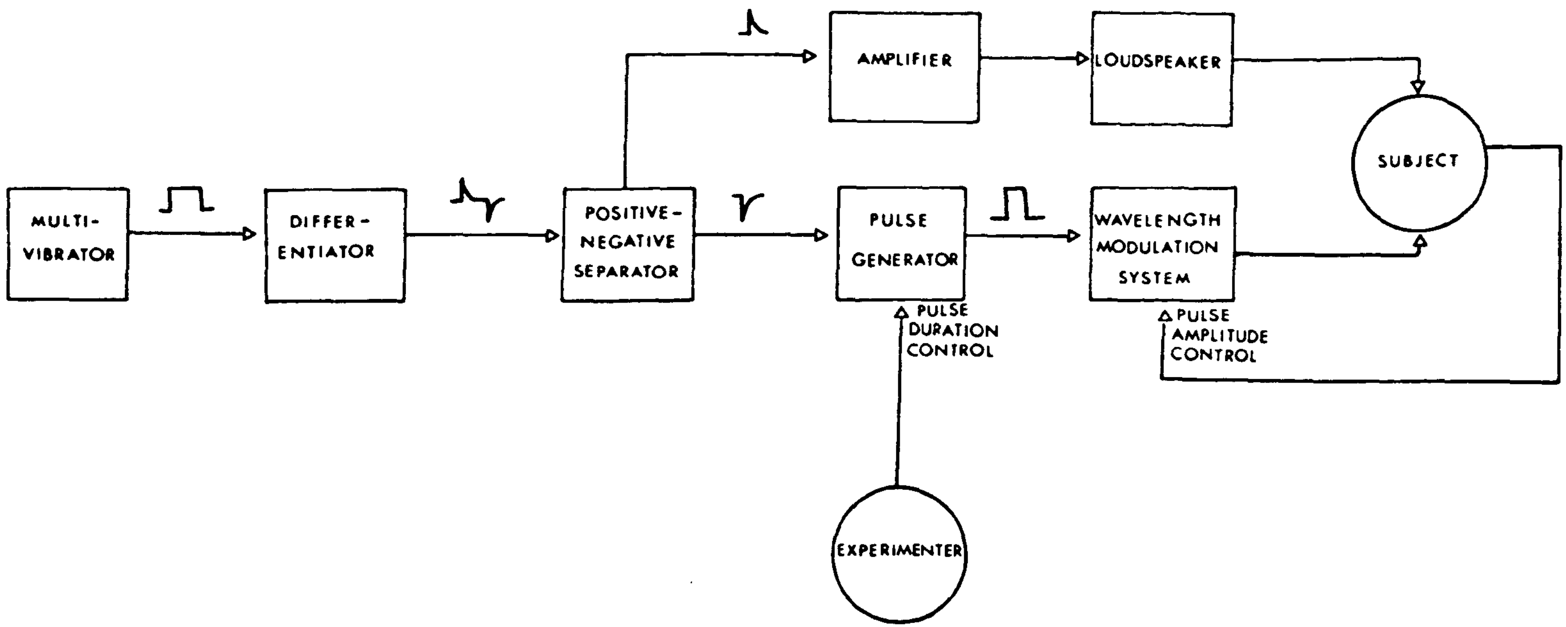


__Fig. 5.5.__ Block diagram of pulse generation equipment.

5.3. Ancillary Equipment.

The basic organisation of the wavelength-modulation equipment is shown in Fig. 6.2 and its operation described in section 6.2. The two phase oscillator was an Advance Variable Phase Oscillator, and the syncronising oscillator was a Levell Transistor R.C. Oscillator.

For the pulse stimulus experiments, pulses of variable duration and amplitude was produced at a fixed repetition rate with a auditory warning pip, as in the block diagram, Fig. 5.5. A multivibrator produced a 1 sec pulse every 10 seconds. Differentiation produced positive and negative pulses which were separated by selective diodes. The earlier pulse was amplified and transmitted via a loudspeaker to act as an auditory warning signal. The later pulse acted as a trigger for a pulse generator (a Wavetek Triggered VCG), the output of which was fed into the wavelength or luminance modulation apparatus (Fig. 6.2 pg 112). The experimenter set the pulse duration for any given trial, and the subject, having set the appropriate luminance compensation in the case of wavelength modulation, reduced the pulse amplitude until subjective threshold was reached.

In several experimental conditions a secondary light source was required. It was used to provide an equiluminant surround field in section 7.4, and for the comparison half of the bipartite field in section 7.3. It was also required for the adaptation field described in section 8.2. The arrangement of the secondary source was simple, consisting of a 12V lamp filament bulb preceding a pair of condensing lenses which focussed the filament image on to a slit. Close to the slit was a wedge interference filter (bandwidth 180nm) followed by a 1 log unit wedge neutral density filter. Both filters were movable by experimenter or subject, permitting control of the luminance and wavelength of the monochromated light. The source and filters were similar to those used for the equipment previously described (sections 5.1-2). Finally the beam was collimated and provision for extra filters made. The two light paths were superimposed (in Maxwellian view) by means of a plane glass reflector, with a transmission of 90% for the primary source beam and a reflection of 10% for the secondary source beam.

6. Methods and Controls.

6.1 Introduction.

Previous work using chromatic modulation (originating with De Lange (1957)) is described in sections 3.6. and 3.7. No previous authors have utilised a wavelength modulation technique corresponding to that described in the present section, on which this thesis is based. The advantages of the use of wavelength modulation of a monochromatic light stimulus, as described in section 5, are as follows:

a) The stimulus is clearly specified in physical terms. This enables comparison with experiments in non-human organisms, with electrophysiological experiments, and other work using physical specification of stimuli.

b) Wavelength modulation permits the study of temporal responses in the colour domain without assuming the applicability of the C.I.E. chromaticity coordinates in the temporal situation. (For discussion of this point see section 3.7.).

c) The subject compensation method of luminance cancellation (with the advantages listed in section 6.2) is most easily applied in the case of wavelength modulation.

d) The wavelength modulation stimulus is very flexible, permitting a continuous range of both modulation amplitudes and centre wavelengths to be employed.

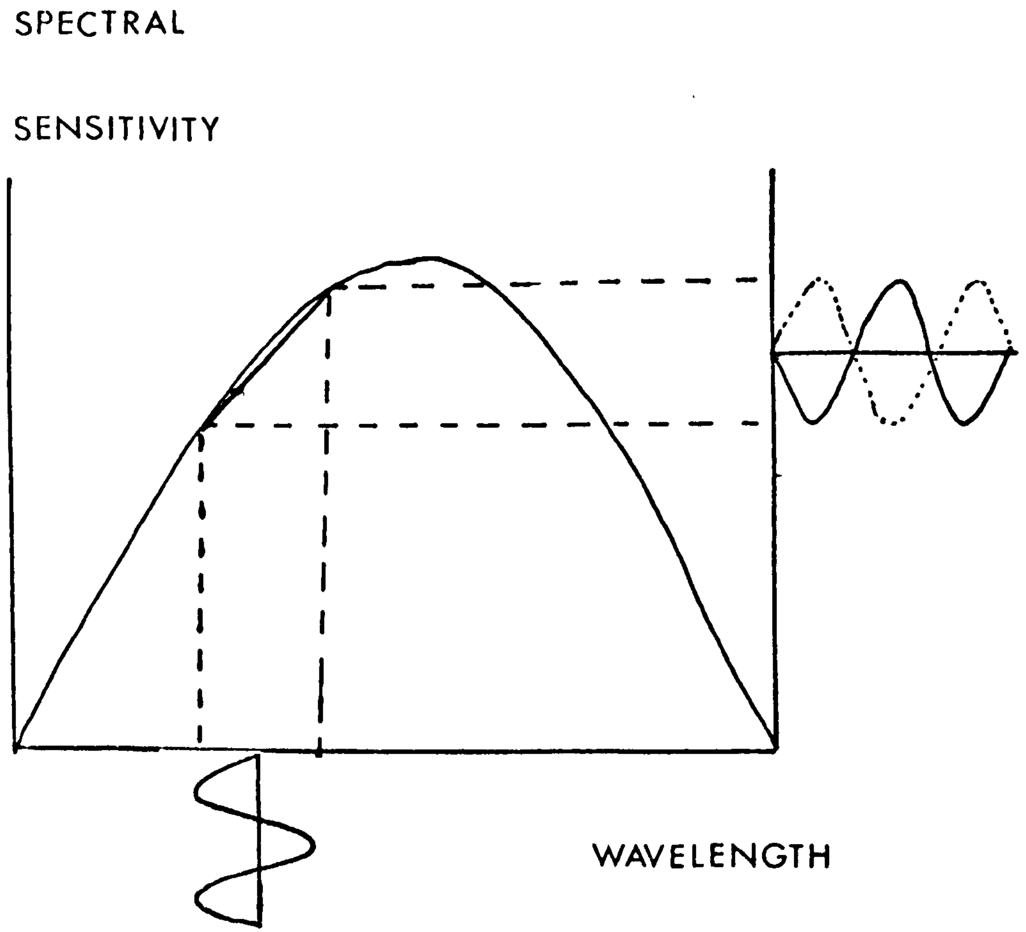


Fig. 6.0. Wavelength modulation. Spectral sensitivity is shown as a function of wavelength. A sinusoidal modulation of the stimulus wavelength produces an approximately sinusoidal modulation of luminance due to the form of the spectral sensitivity. This luminance modulation may be compensated by luminance modulation in antiphase (dotted line) of the appropriate amplitude.

The wavelength modulator of section 5.2 provided the means to vary the mean wavelengths of the stimulus in time. The luminance modulator of section 5.1 enabled control of the luminance as a function of time. In order to achieve a chromatic modulation stimulus the problem was to reduce the luminance variations to such a level that the chromatic changes alone determined subjective threshold. (see Fig. 6.0.) The first approach that was attempted (feedback compensation method) was to monitor the output of the wavelength modulator with a Megatron photocell, which has a spectral sensitivity close to that of the C.I.E. standard observer. The photocell signal proportional to luminance variations formed a negative feedback loop to the luminance modulator, whereby all variations in luminance should be cancelled.

One problem with the feedback compensation method was that the spectral sensitivity of the Megatron photocell is only accurate to within about ± 20% over the whole range of the spectrum used, although it is better than ± 10% over much of the spectrum. Moreover, there were few regions of the spectrum in which a wavelength change of, say, 10nm would produce a luminance change of less than 10%. In contrast, De Lange's (1957) data indicate that in the lower frequency regions for at photopic luminances the observer is sensitive to luminance variations of the order of 1-2%. Clearly the feedback method would only be usable under a very limited range of conditions. A further difficulty was that the signal to noise ratio in the feedback loop was small, even in the frequency band to be utilised for modulation (1-20 Hz.).

The second method investigated (photographic compensation method) involved the production of a photographic neutral density filter placed against the spectral interference filter and varying in density in proportion to the spectral sensitivity of the eye as a function of spectral location. It was expected that the film density produced by exposing it through the spectral interference filter would be sufficiently close to the spectral sensitivity of each observer to enable correction by the insertion of appropriate low purity liquid filters in the light path. This did not prove to be the case.

The third method investigated was that of subject compensation. In this method the luminance variation produced by the wavelength modulator is assumed to be linear for small amplitudes of wavelength swing (Fig. 6.0). The subject set the equivalent luminance modulation produced by the luminance modulator (either in phase or anti-phase as appropriate) to the amplitude for which there is minimum subjective flicker (Fig. 6.0). Tests of the assumptions of linear cancellation, lack of phase shift between intensity and wavelength produced luminance changes, etc. are reported in sections 6.3 and 6.4.

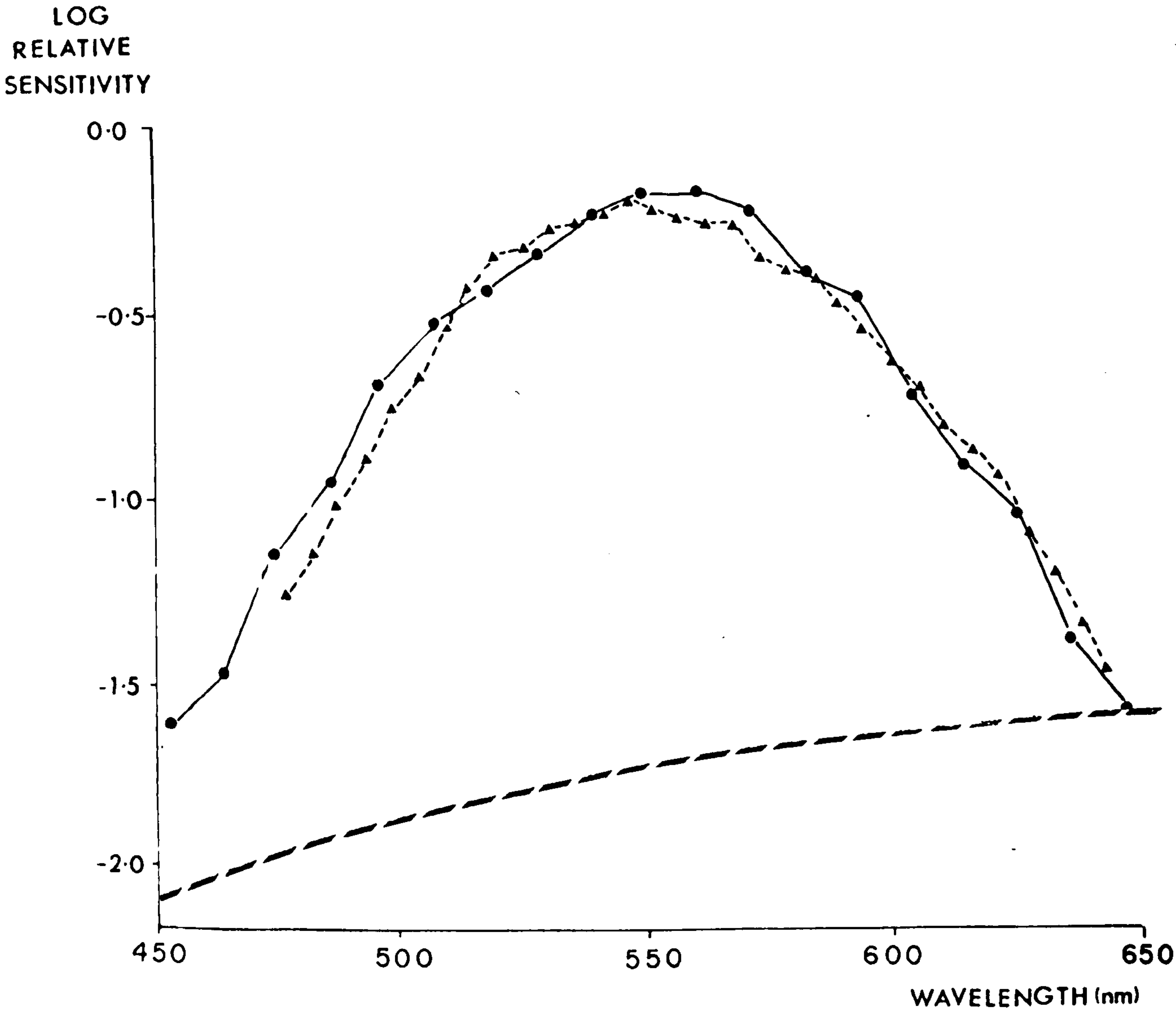


Fig. 6.1. Spectral sensitivities of subjects C.W.T. (dotted curve) and L.K.T. (full curve), by H.F.P., showing the actual brightness variations which had to be compensated. The correction which should be applied for equal-energy spectral sensitivity is shown as the dotted curve.

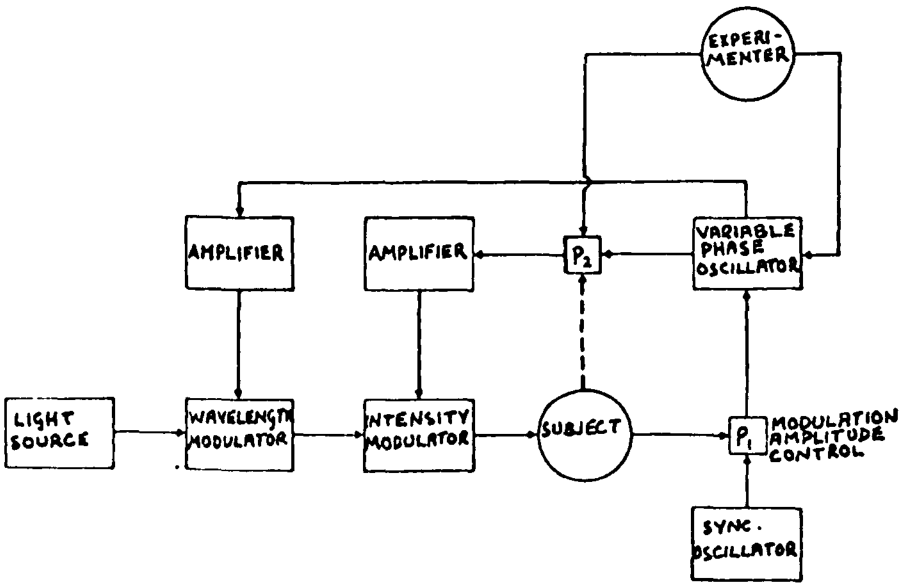


Fig. 6.2. Block diagram of wavelength modulation system.

6.2 Subject Compensation Method.

The stimulus modulation frequency was set by a low frequency oscillator (Fig. 6.2 sync.osc.). This drove a phase-locked oscillator at the frequency F (Fig. 6.2 "Variable phase oscillator") via a potentiometer P1. The phase-locked oscillator generated two signals at frequency F whose relative phases could be varied through 360°, and whose amplitudes could be varied together by potentiometer P1. One of the signals from this variable phase oscillator went directly to the wavelength modulator, and the other drove the intensity modulator via a second potentiometer P2. By means of the P2 either the experimenter or the subject could add variable amounts of intensity modulation to the wavelength-modulated stimulus light. Subsequently the modulation amplitude of this combined intensity modulated and wavelength-modulated signal could be progressively reduced to the threshold of perception by turning P1. This procedure was designed to allow any brightness modulation caused by the wavelength modulator to be cancelled so as to give threshold settings of P1 which were determined by chromatic modulation alone.

The advantages of the subject compensation method are as follows:

a) It permits a direct test of the assumption that luminance changes produced by intensity and wavelength modulation are produced at the same retinal locus and can thus be arranged to cancel simply.

b) The method ensures that cancellation of luminance changes is optimal under all conditions. Section 7.1.4 reviews the evidence that the spectral sensitivity function is frequency dependent under the stimulus conditions used by De Lange (1957) and Kelly (1962b). Since the effect of the stimulus conditions used in the present study is not known it is important that the cancellation method should not involve the assumption of frequency-independence of the spectral sensitivity function. In the subject compensation method, the luminance compensation is set individually for each reading at a modulation amplitude close to that holding at the threshold setting. Thus any variations in the luminance modulation (produced by the wavelength-modulation stimulus) resulting from frequency-dependence effects such as are manifest in the spectral sensitivity functions mentioned above, will be matched at each frequency in the subject compensation procedure.

c) The subject compensation method also compensates for changes in the spectral sensitivity function from any other cause. Hsia and Graham,(1952). inter alia show that different observers differ in the detailed form of their spectral sensitivities. see also Fig. 6.1. Sperling (1965) demonstrates that the spectral sensitivity of a single observer may vary at different luminance levels. Other factors such as field configuration or temporal waveform of the stimulus, which are examined in this thesis, may also exert an effect. The method allows compensation for any such effects, and also any minor non-linearities which may be present in the modulation equipment (see section 5).

d) The method is equivalent to that used by Wright (1947) for his classical, bipartite field studies of wavelength discrimination. It involves the setting of brightness differences to below threshold, followed by adjustment to chromatic threshold. The method used in the present experiments (see section 6.1) involves the extra control of a link between the wavelength and luminance modulators to maintain the brightness variations below threshold whereas Wright used a step-by-step procedure of sequential readjustment of each parameter until the chromaticity difference was at threshold and the brightness difference well below threshold.

6.3 Controls.

The first essential was to ensure that the psychophysical thresholds measured was determined by chromatic changes and not by accompanying brightness changes caused by the effects of the wavelength modulator combined with the curvature of the relative luminosity curve of the eye. The procedure adopted to ensure that this was the case is described below.

(a) Photocell control.

This control experiment was designed to mimic the situation which would have obtained with a subject who had no colour discrimination at all and consequently could percieve brightness changes only. A Megatron photocell which had approximately the CIE spectral sensitivity was placed in the position normally occupied by the subject's eye. The photocell's output was a measure of luminous intensity changes only. The phase difference between the electrical signal to the intensity modulator and the signal to the wavelength modulator was set to be either 0° or 180°, according to which of these phase dufferences ensured that the changes of luminous intensity could cancel at the photocell (or in (b) and (c) below, at the eye).

Potentiometer P2 (Fig. 6.2) was set to give zero input to the intensity modulator, and P1 was then adjusted so that the photocell gave a criterion output of some convenient amplitude. In general both wavelength modulation and luminance modulation were present at this stage, although the photocell

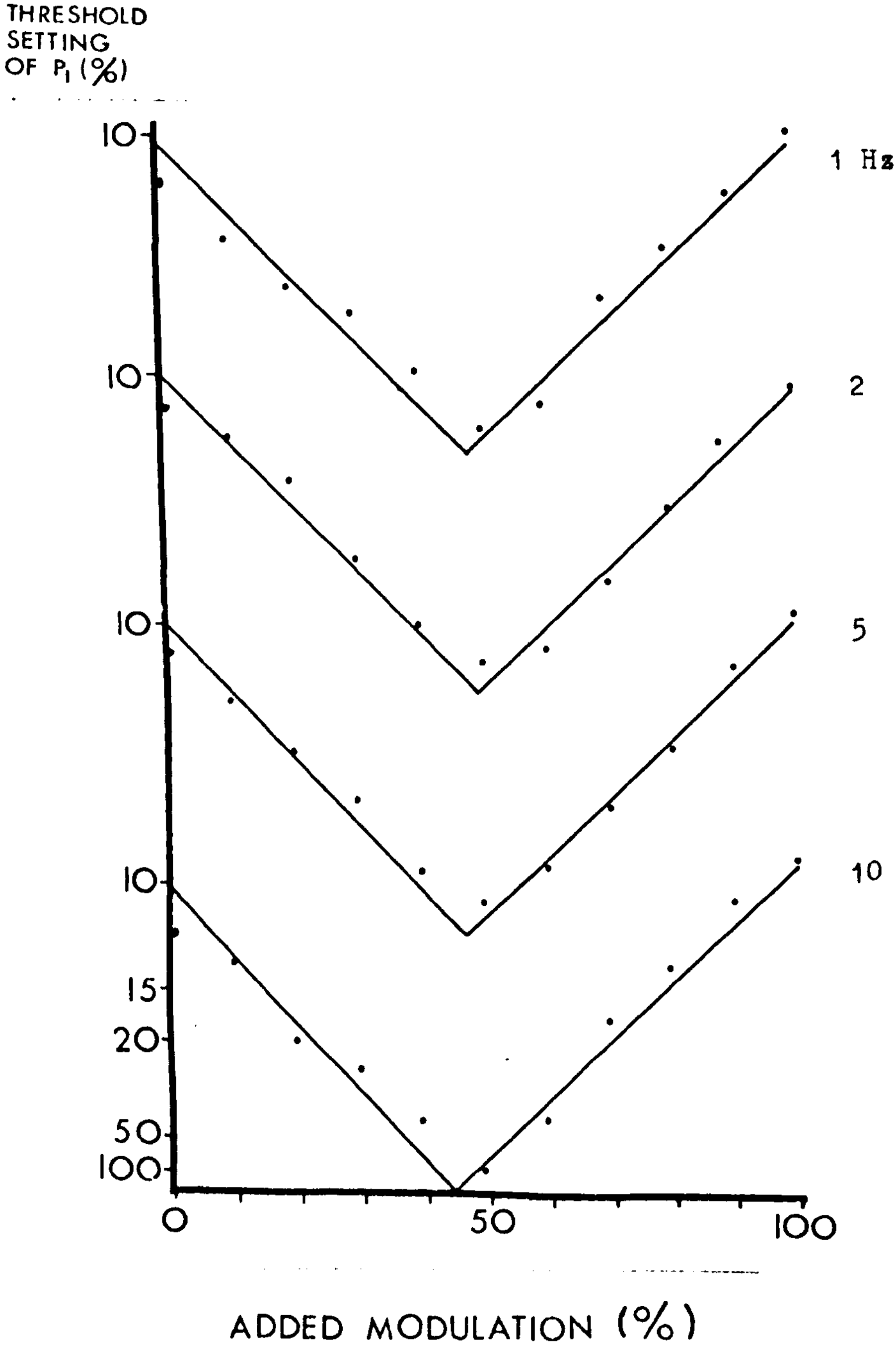


Fig. 6.3. Luminance compensation. Threshold setting of potentiometer P_1 for constant photocell output as a function of added luminance modulator amplitude (in antiphase with wavelength modulator).

could only "see" modulation of luminous intensity. Potentiometer P2 was then adjusted so that the luminance modulator generated a small modulation depth. The signals to both the luminance modulator and the wavelength modulators were then changed together by turning P1 until the photocell once more gave the same criterion output. This procedure was then repeated with the luminance modulator set to give successively greater modulation depths. The readings of P1 which gave the criterion output from the photocell were then plotted versus the modulation depths of luminance added by the luminance modulator. The resulting family of curves for four different modulation frequencies are shown in Fig. 6.3. It can be seen that all the curves had a sharp minimum. At the minimum point, the changes of luminous intensity detected by the photocell which were due to the wavelength modulator were cancelled by the added intensity modulation due to the luminance modulator. This setting for cancellation of intensity changes can be seen to vary little with frequency (Fig. 6.3).

(b) Psychophysical control:luminance changes only.

The photocell was removed and the spectral filter in the wavelength modulator was then replaced by a neutral-density wedge. The wavelength modulator now generated pure luminance modulation of monochromatic light of wavelength 527nm with no accompanying changes in colour. The psycho-physical analogue of the "photocell control" procedure

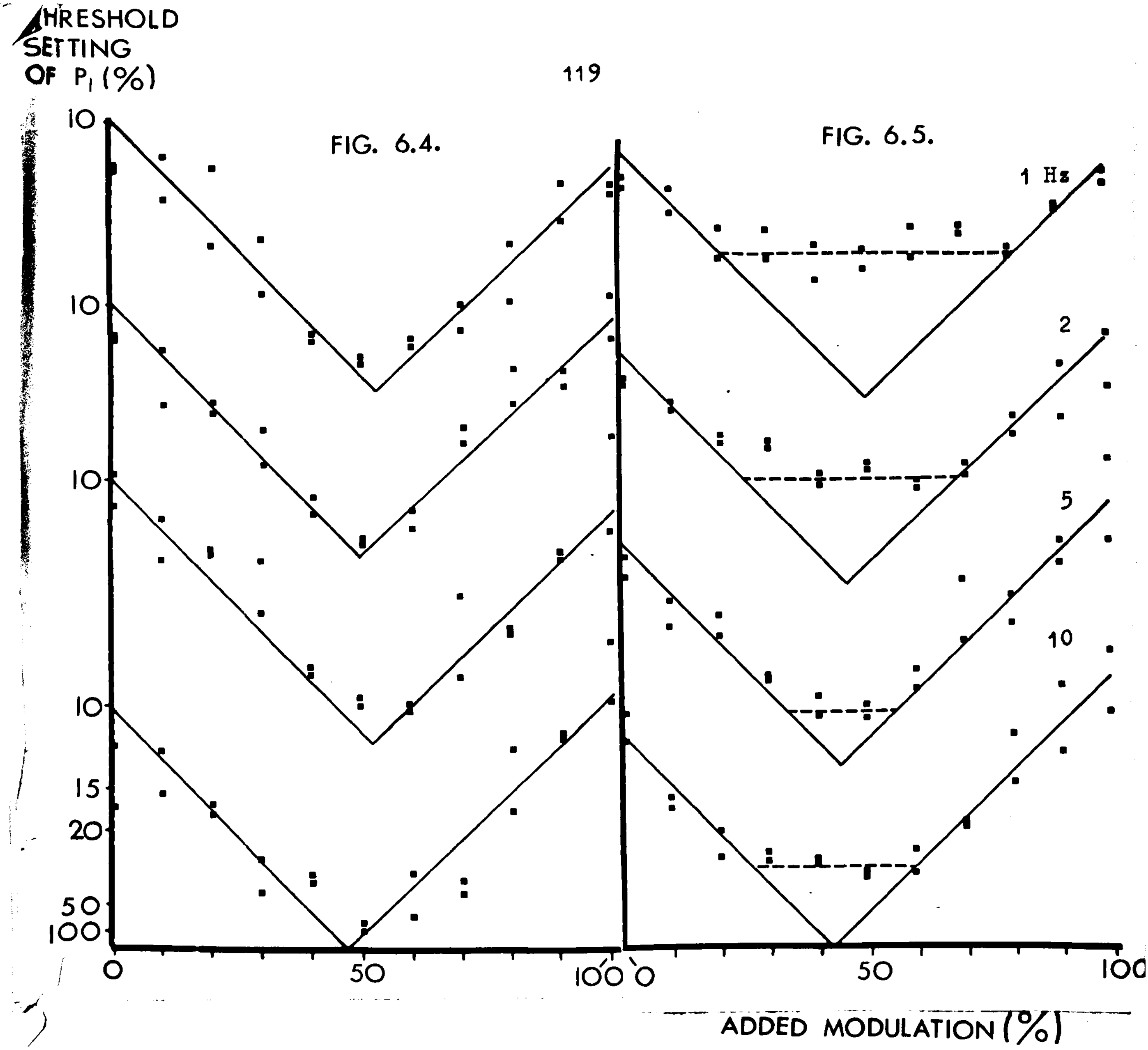


Fig. 6.4. Luminance compensation. Threshold setting of potentiometer P_1 (reciprocal scale, increasing downwards) for subjective threshold, as a function of added luminance modulation amplitude. Spectral filter of wavelength modulator replaced by a neutral density wedge, so only luminance modulation is present. Subject C.W.T. Wavelength 527nm. Mean retinal illuminance 110tr. Curves for four different frequencies (as indicated) displaced arbitrarily on ordinate. 2° field with dark surround.

Fig. 6.5. Luminance compensation. Details as for Fig. 6.4., but with spectral filter in place, so that the stimulus was mixed wavelength and luminance modulation.

described above was then carried out. Potentiometer P2 (Fig. 6.2) was set so that the luminance modulator was inoperative. Potentiometer P1 was then adjusted by the subject until he could just not perceive flicker and the reading was noted. P2 was then set so that the luminance modulator generated a small depth of modulation, and the subject once again adjusted P1 until he could just not perceive flicker, and the setting noted. This procedure was repeated as in the "photocell control" above, and a family of curves of the settings of P1 at psychophysical threshold for subject C.W.T. versus the modulation depths of luminous intensity added by the luminance modulator plotted for four values of modulation frequency (Fig. 6.4). It can be seen that in these conditions, when only luminance modulation was present, the psychophysical curves for subject C.W.T. had a sharp minimum and were similar in shape to those obtained when a photocell replaced the eye (compare Fig. 6.3 and 4). Similar results were obtained for subject L.K.T. (Fig. 6.6.A).

(c) Measurements of the psychophysical threshold which is determined by wavelength modulation alone.

The control experiments (a) and (b) above showed that, when luminance changes only were present, the psychophysical data for both subjects closely resembled the data obtained with a photocell (which could only "see" changes in luminous intensity under conditions when both luminance and wavelength

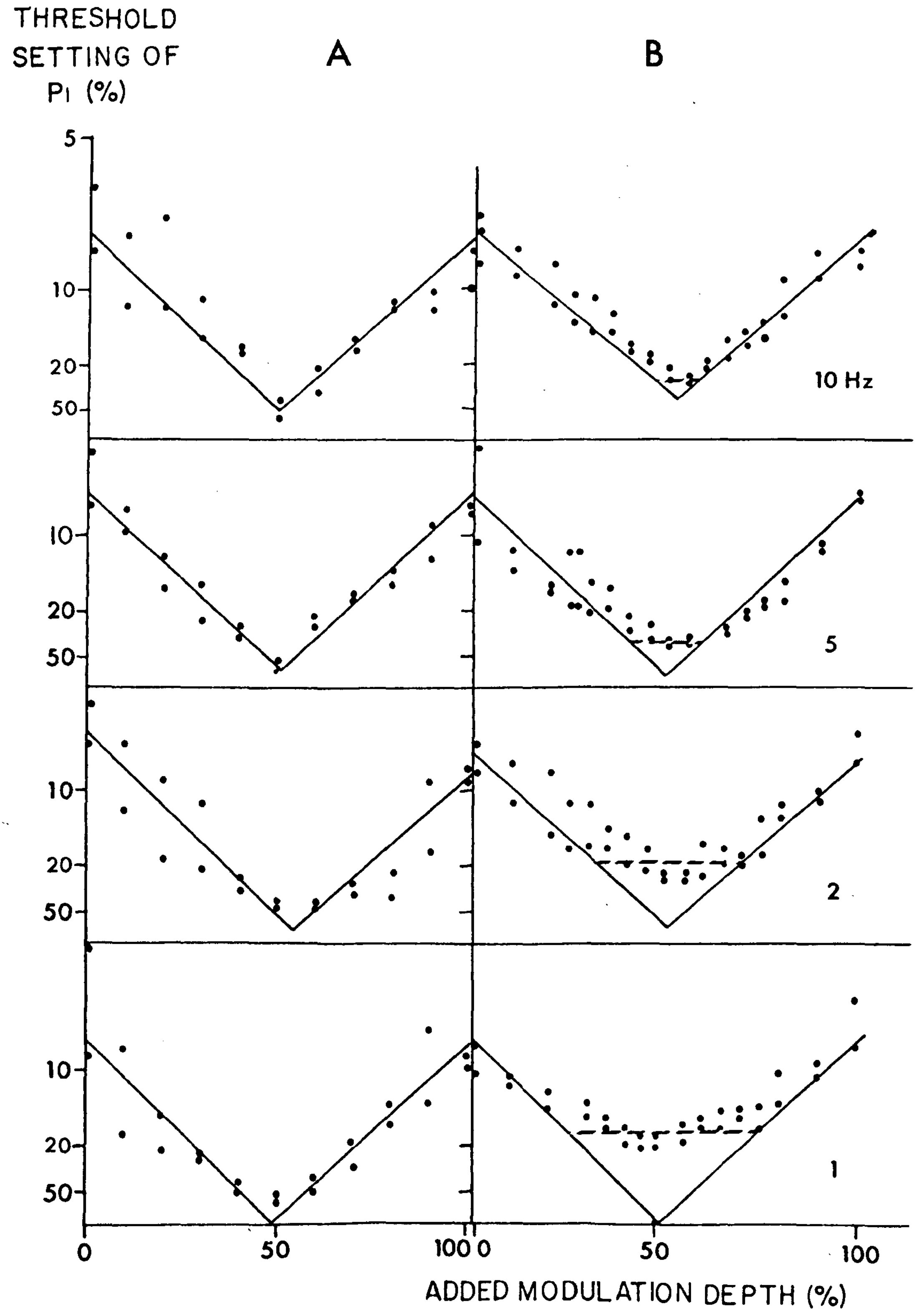
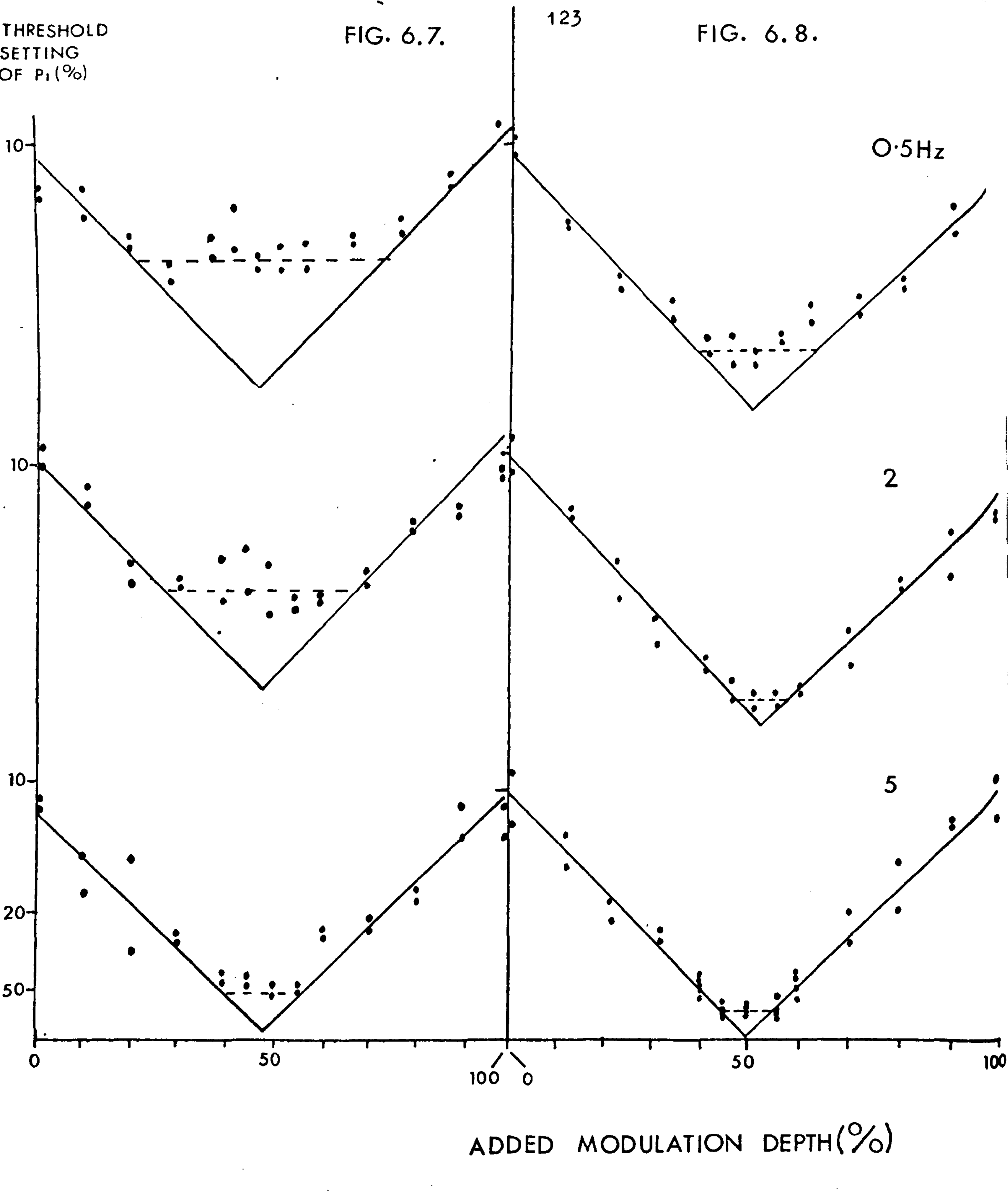


Fig. 6.6. Luminance compensation. Conditions as for Fig. 6.4., except with subject L.K.T. Left-hand figure-luminance compensation alone. Right-hand figure-luminance compensation with wavelength modulation.

change occurred. In the present procedure (c), psychophysical measurements were taken in this latter condition, with both luminance and wavelength changes present, in order to distinguish between the effects on the psychophysical threshold of chromatic-modulation and luminance-modulation.

The neutral density wedge was removed and the spectral filter replaced in the wavelength modulator. With the subject viewing the light, the procedure (b) above was repeated with the difference that now as well as luminance changes, wavelength changes also occurred. This procedure was carried out at the same mean wavelength as the control (527nm) for four values of modulation frequency.

Fig. 6.5 (subject C.W.T.) shows that for psychophysical judgements, the minimum was now much flatter than in the case when only luminance changes were present, or when the photocell was used with the spectral filter (compare Fig. 6.2., 3, and 4). The flattening of the minimum meant that in this region (but not outside this region) the depth of luminance modulation added by the luminance modulator had little influence on the setting of P1 (Fig. 6.2) which gave just-imperceptible flicker. A similar result is evident for subject L.K.T. (Fig. 6.6. A and B, compare). This suggests that, within the flattened minima of Fig. 6.5 and 6.6 B, the brightness flicker (caused by the wavelength modulator as a result of the curvature of the eye's relative luminosity

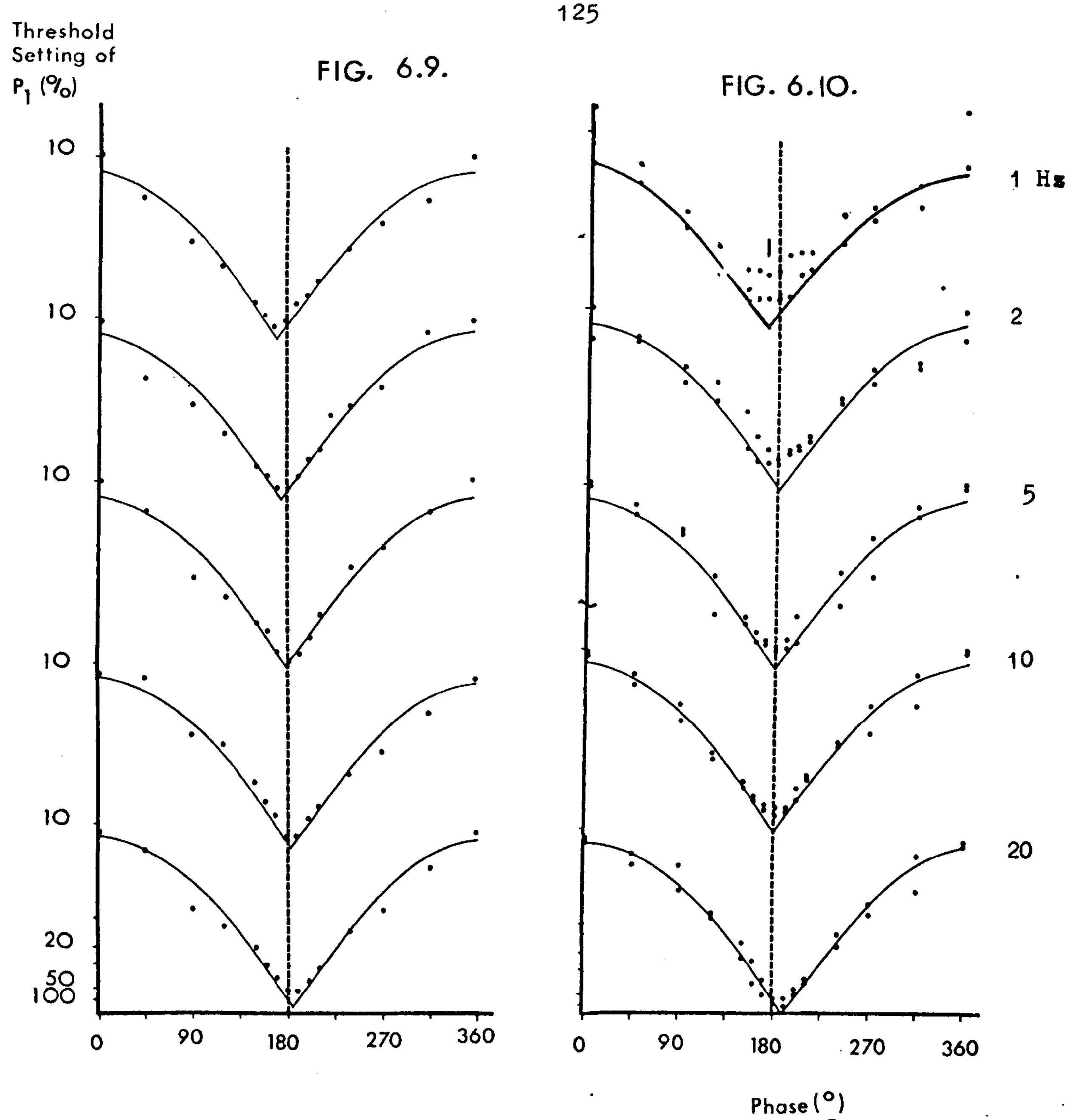


<u>Fig. 6.7.</u> Luminance compensation with wavelength modulation. Conditions as for Fig. 6.4., but with mean wavelength 622nm.

<u>Fig. 6.8.</u> As for Fig. 6.7., but with mean wavelength 498nm.

curve, Fig. 6.0.) had been cancelled to a sufficient extent for both subjects to allow the subjective threshold to be determined by <u>chromatic</u> flicker. This result is replicated for two more extreme values of spectral location (subject C.W.T.). Fig. 6.7. shows the effect of the luminance compensation procedure at 622 nm, and Fig. 6.7. at 498 nm. It should be noted that the relative sensitivity to wavelength and luminance modulation differs as a function of mean wavelength (in a manner comparable with the dynamic wavelength discrimination functions of Fig. 7.3.1., section 7.3.). (Note that the frequency parameter is plotted downwards on Figs. 6.5., 7, and 8, but upwards in Fig. 6.6.)

In these regions, therefore, chromatic changes determined the threshold for this wavelength-modulated light stimulus; the wavelength swing at threshold fell between ± 2 nm and ± 15 nm for the range of stimulus colours, intensities and modulation frequencies used (Fig. 6.5., 6.6. B, 6.7, and 6.8.). Outside the region of the flattened minima, subjective thresholds were principally determined by brightness flicker for both subjects.



<u>Fig. 6.9.</u> Phase relationships in luminance compensation. Threshold setting of potentiometer P_1 (plotted increasing downwards on a reciprocal scale) for constant photocell output as a function of phase difference (φ) between input to modulators. Points fitted by curve of: $y = A \sin wt + B \sin (wt + \varphi)$. Five modulation frequencies were used (as indicated).

<u>Fig. 6.10</u>. As for Fig. 6.9., but photocell replaced by subject C.W.T. Results are similar to those with photocell (Fig. 6.9.)
Mean wavelength 527nm. Mean retinal illuminance 25tr. 2° field with dark surround.

6.4. Psychophysical and instrumental controls for phase shifts

By repeating the procedures (a) and (c) above for a series of different phase relations between the signals to the intensity modulator and to the wavelength modulator it was possible to check that cancellation of brightness flicker took place when the two light modulations were in antiphase. Psychophysical checks were made by recording the threshold setting of P1 in the region of the flattened minimum (where, the threshold was determined by chromatic changes) and then re-setting P1 (Fig. 6.2.) to threshold for a range of values of the relative phases of the signals to the modulators. Fig. 6.9 shows the settings of P_1, for constant output of the photocell at the exit pupil. The data points are fitted by the theoretical curve of

$$y = A \sin wt + B \sin (wt + \varphi),$$

(where φ is the phase difference between the two signals) indicating that cancellation is most effective when the two signals are approximately in antiphase.

The results for subject C.W.T. show that essentially similar to those for the photocell. At 527 nm (Fig. 6.10) cancellation of brightness flicker occurs approximately in antiphase, over the range 1.0 Hz to 20 Hz (maximum departure 5°). This confirmed that only a negligible contribution to flattening of the minima shown in Fig. 6.5. & 6.6.B could be due to phase shifts between intensity signals. For example, the maximum phase shifts of 5° occurred at 1.0 Hz where a phase shift of 30° would be required to account for the observed flattening.

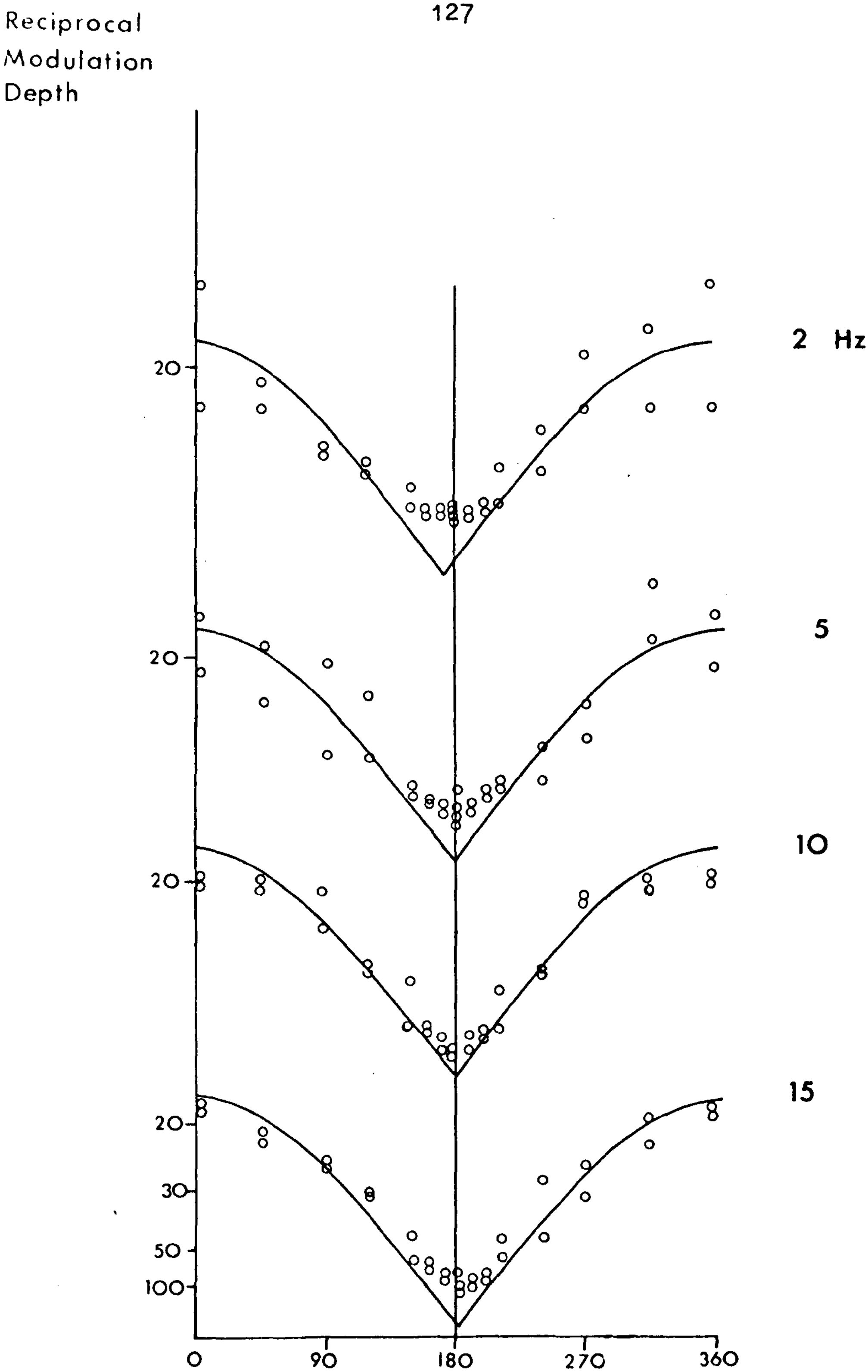
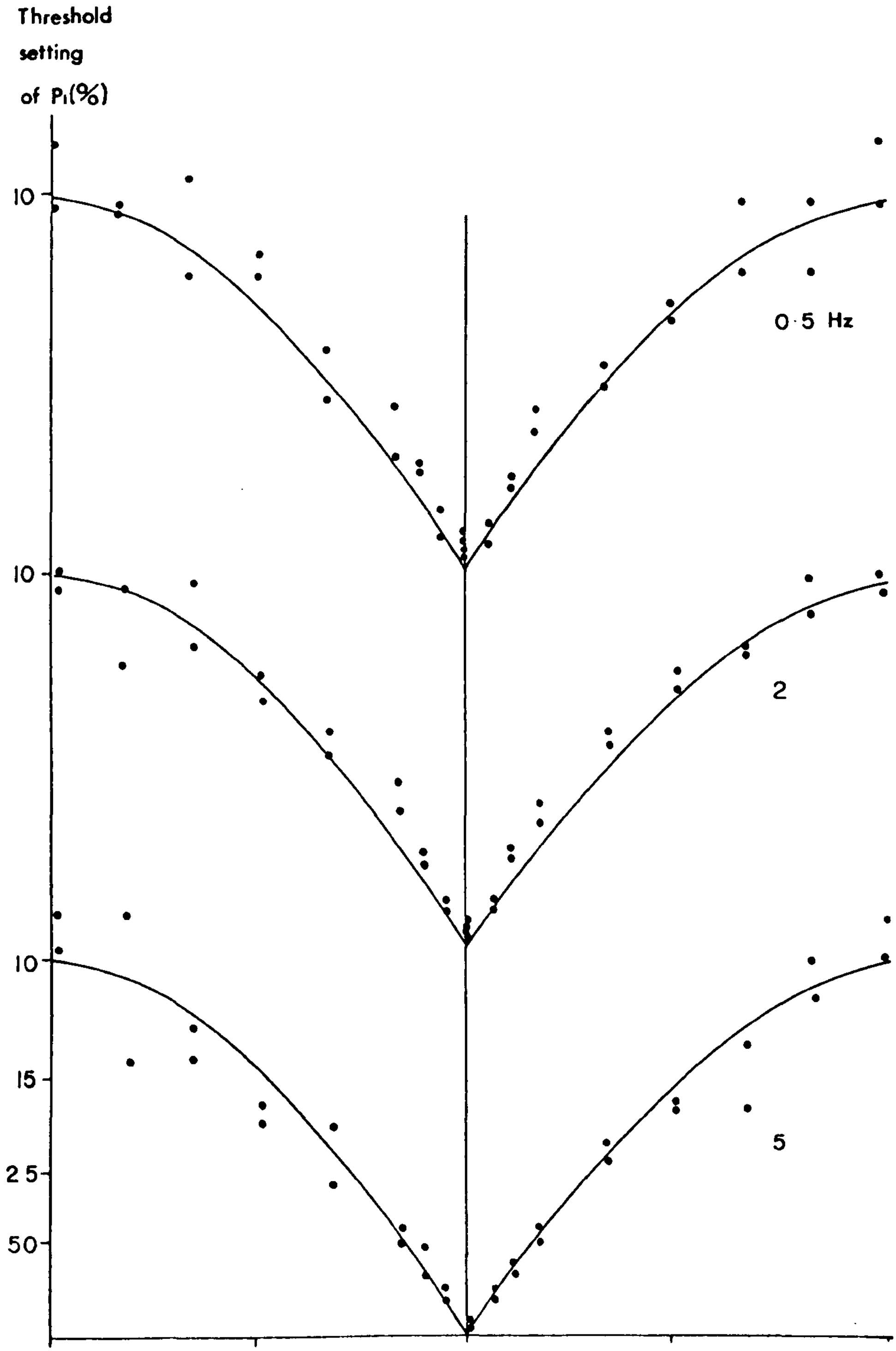


Fig. 6.11. Phase relationships in luminance compensation for three modulation frequencies (as indicated). Conditions as for Fig. 6.10., but subject was L.K.T.



<u>Fig. 6.12.</u> Phase relationships in luminance compensation. Conditions as for Fig. 6.10., but with mean wavelength of 600nm.

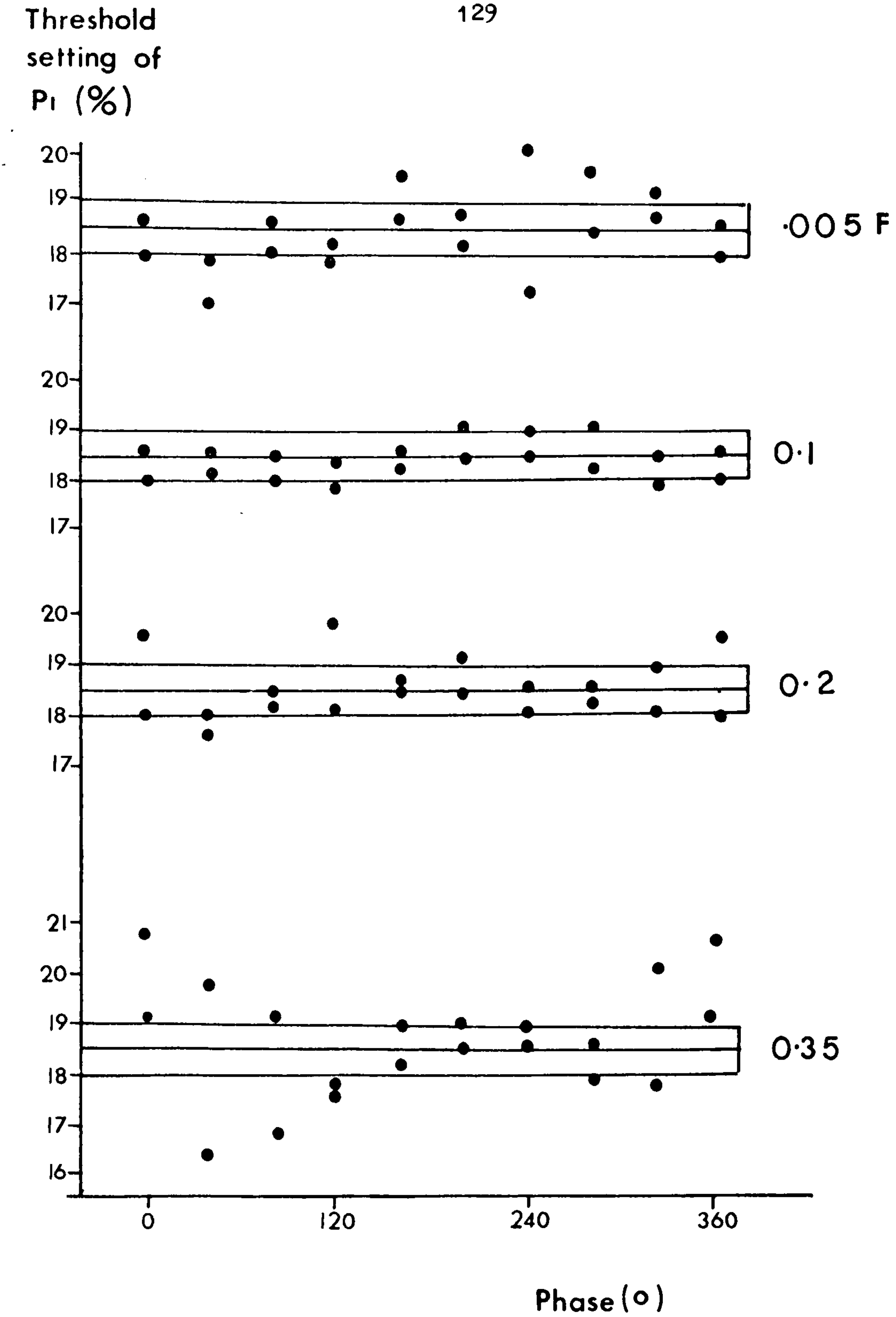


Fig. 6.13. Effect of adding a small proportion of second harmonic (F_2) to threshold setting of P_1 for fundamental (F) as a function of relative phase in degrees of F_2. Four values of F_2 (0.05F, 0.1F, 0.2F and 0.35F). Lines indicate mean and ± standard deviation.

Similarly results were obtained for subject L.K.T. at 527 nm (Fig 6.11) and at another spectral location (600 nm, subject C.W.T.) as shown in Fig. 6.12.

The curvature of the subjects relative luminosity curve might be expected to introduce non-sinusoidal changes (harmonic distortions) into the perceived brightness of the signal from the wavelength modulator (see Fig. 6.0). Control experiments were therefore carried out in which the cancelling luminance signal was made up of both fundamental and second harmonic components. With a wavelength of 527 nm, mean retinal illuminance of 110 tr and fundamental modulation frequency of 5Hz, thresholds were obtained for a set of phase relationships between fundamental (F) and second harmonic (F_2) components. (Fig. 6.13) The fundamental was previously set so as to optimally compensate the luminance variations due to wavelength modulation. Four values of relative amplitude of F_2 were used, the largest corresponding to a marked curvature of the spectral sensitivity curve. It is evident that, within the experimental error, no variation in threshold occurs with addition of F_2 in any phase, implying that negligible second harmonic distortion is present in the waveform under these conditions. At 527 nm, the curvature of the spectral sensitivity functions is approximately the greatest of anywhere in the spectrum (see Fig 6.1.). Dynamic wavelength discrimination at 527nm and 5Hz is poorer than anywhere apart from the spectral extremes. (See Figs. 7.3.1.-3.). requiring relatively greater wavelength and therefore luminance modulation for threshold. The conclusion that second harmonic distortion is negligible may therefore reasonably be extended to the rest of the spectrum examined in this thesis.

6.5 Field Configuration.

The apparatus for the production of test and surround fields is described in section 5.3. The test field used in the experiments described in this thesis was always 2° in diameter, either with or without a 10° matching surround. Such a test field was chosen, although it has not been widely used in flicker modulation studies for several reasons. (a) A 2° field with a dark surround is comparable in size with the bipartite stimulus (Wright, 1928-9) and the high frequency temporal colour mixture stimulus of Guild (1931) used in the colour-matching studies accepted by the C.I.E. in 1931 as defining the standard observer. Later data of Stiles (1955) refined the colour mixture data with a 2° bipartite field and also investigated colour mixture with a 10° field. In the latter case, subjects had to be instructed to ignore the central area (approximately 2°) since the field appeared inhomogeneous due to macular pigmentation. This difficulty is avoided by the use of a 2° field. Furthermore, the 1924 C.I.E. spectral sensitivity function (V_λ) was established for a 2° central field.

Finally, a 2° field centrally fixated stimulates almost exclusively cones, as shown for example by the threshold data of Crozier and Holway (1939) and the flicker data of Brooke (1951). The problem of rod intrusion in the colour discrimination tasks, which might be significant at the mesopic retinal illuminance levels of 25 tr used, are avoided.

The results of the C.I.E. colour matching data demonstrate that under 2^{o} field conditions and at photopic luminance levels, human vision is trivariant, as discussed in section 2.1., with respect to static, bipartite matches. The use of a 2^{o} field for the dynamic investigations described herein may consequently be compared with a body of well-established data on the colour sensitivity of this type of stimulus.

(b) Classical data on colour discrimination (e.g. Wright and Pitt, 1934) has been obtained with the same field configuration as the colour matching data. Use of the same stimulus for the "dynamic wavelength discrimination" studies (see section 7.3) enables direct comparison between the classical and dynamic wavelength discrimination data.

(c) Previous flicker studies have made use of a 2^{o} field. Hecht and Smith (1936) found that for field sizes of 2^{o} and below with central fixation, the curve of CFF as a function of retinal illuminance of the stimulus does not show any evidence of a branch corresponding to scotopic sensitivity as is the case with large field sizes. Similarly, Hecht and Verrijp (1933) found that the scotopic branch present in CFF versus illuminance curves for a 2^{o} field in peripheral locations is absent for foveal viewing. The earlier work of Ives (1912) had established that for a 2^{o} field Abney's law of additivity of the luminances of heterochromatic stimuli

stimuli was approximately valid if the brightnesses were matched by flicker photometry or the step-by-step method. This result was later confirmed by Dresler (1953), Stiles and Burch (1959) and Sperling (1958). It therefore appears that photopic response and luminance additivity can be obtained with a 2° field,

(d) The bright surround stimulus configuration appears to be analysed differently by the visual system in different frequency regions. Kelly (1969 b) has demonstrated that below 10 Hz. the flicker sensitivity increases with the number and sharpness of edges in the stimulus, while above 10 Hz. sensitivity is unaffected by these factors. Use of a dark surround, which produces a similar frequency sensitivity to the "edgeless" field at low frequencies, should minimise the changes in criterion implied by the effect of edges in the field.

(e) De Lange (1957) describes (pg. 40) the effect of a dark surround at low frequencies. i.e. the De Lange curve would have a "falling trend" as frequency was reduced. The use of a dark surround stimulus permits a direct test of his description, which is set out in section 7.4. As De Lange points out, the use of a large equiluminance surround holds the adaptation level constant at low frequencies, so that it is not possible to examine the dynamics of the adaptation at low frequencies with De Lange's stimulus.

7. Results and Discussion.

7.0 Introduction.

The results to be presented have been obtained with a 2^{o} diameter stimulus field and, in most cases a dark surround. This stimulus configuration was selected for a number of reasons, discussed in section 6.5. The effects of two principal independent variables are presented:-frequency of modulation, and mean wavelength of the light. The dependent variable is the threshold modulation depth of either luminance or wavelength modulation (see section 6.2 for controls). In the experiments using frequency as the independent variable, the assumption is made, following De Lange (1952), that the reciprocal stimulus modulation depth for constant perceptual effect (threshold) is a measure of the sensitivity for a constant stimulus modulation depth. This point is discussed further in section 3.4. The data is therefore plotted on a double logarithmic plot as used by De Lange so that log sensitivity increases upwards on the ordinate.

In experiments in which mean wavelength is the independent variable the threshold modulation amplitude is plotted directly as a function of mean wavelength, in order that the results may be easily compared with classical wavelength discrimination studies.

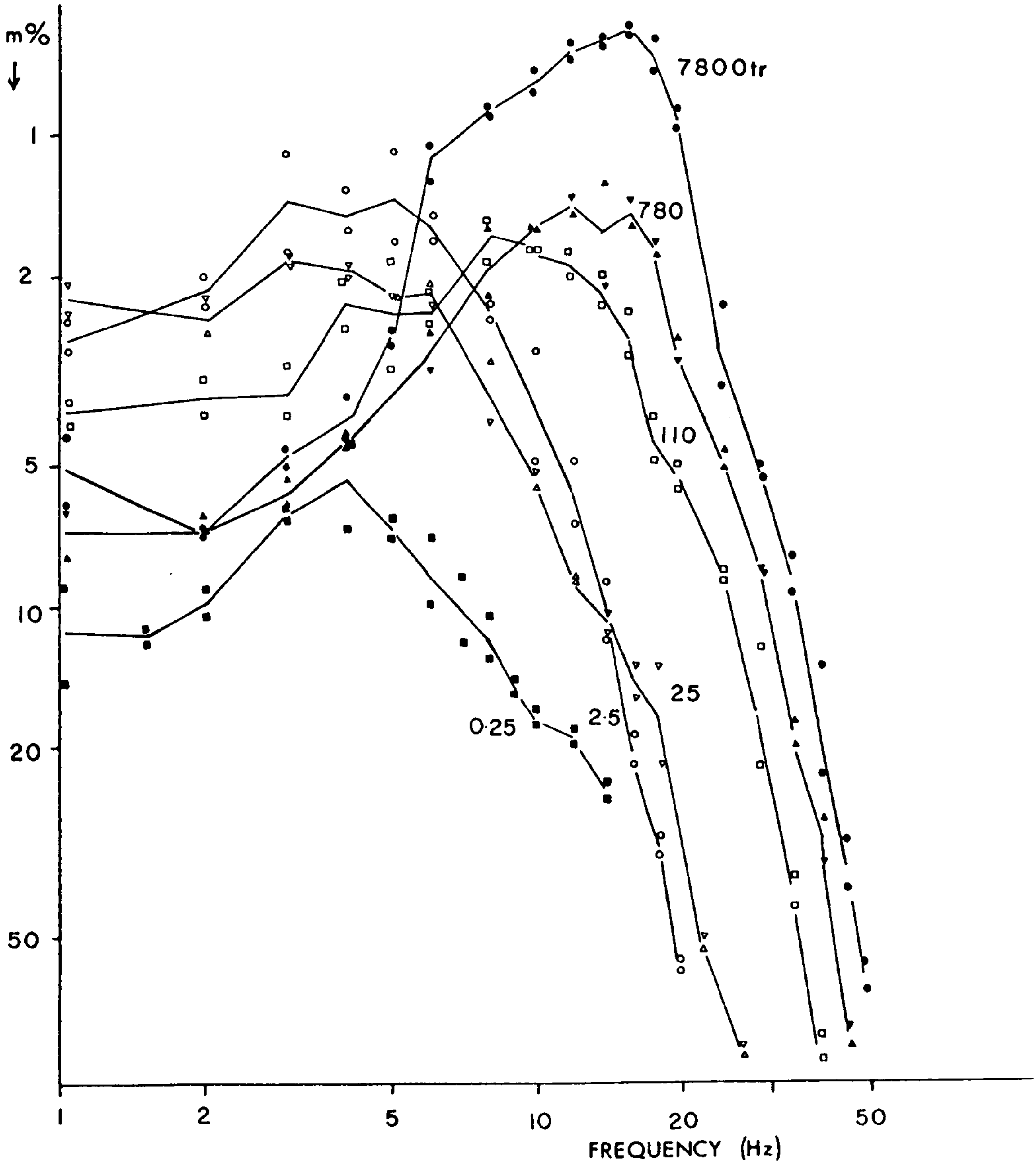
The effect of varying the parameters of time-average luminance and waveform of the modulation were also studied for some conditions.

7.1 Luminance Modulation.

7.1.1 White Light.

A set of curves of threshold sensitivity versus modulation frequency was obtained for a 2° field stimulus with a dark surround for six luminance levels spanning 4½ log units of luminance (0.25, 2.5, 25, 110, 780 and 7,800 tr). (Fig. 7.1.1). The luminance was altered by the insertion of neutral density filters into the light path. The hue of the light appeared to change negligibly with alteration of luminance level, indicating that the spectral composition of the light was effectively constant, except that a slight hue shift towards blueness was noted for very low luminances, corresponding to the Purkinje shift.

At high luminance (780 and 7,800 tr), Fig. 7.1.1 shows that the difference between the threshold sensitivity at 1 Hz. and at the maximum sensitivity reached (at about 16 Hz.) using a dark surround is greater than the difference found by De Lange using an equiluminant surround. The sensitivity difference is approximately 1 log unit for the dark surround, but about 0.5 - 0.6 log units for the equiluminant surround. This discrepancy is mainly due to a reduction in sensitivity in the low frequency region at high luminance in the dark surround case relative to the bright surround case. A similar result is described by Kelly (1959), using a 4° field with a dark surround.



<u>Fig. 7.1.1.</u> De Lange curves for white light. Reciprocal of threshold modulation amplitude ($^1/_m$) for sinusoidal modulation as a function of frequency, plotted on log-log coordinates, for 6 values of time-average retinal illuminance (as indicated). 2^o field with dark surround. Subject C.W.T.

At low luminance an unexpected result is apparent. The sensitivity in the low frequency region increases as time-average luminance is reduced. The increase is about 0.5 log units or a factor of 3 overall, and occurs over a luminance range of about 2 log units. A close examination of De Lange's data reveals that in the same frequency region both observers tend to show a slight decrease in sensitivity for stimuli of the highest luminance. This decrease may be a reflection of the effect occurring with a dark surround.

With regard to the shapes of the dark surround curves, they seem to fall midway between the peaky curves described by Kelly for some observers using a 65° field in his 1959 paper (though not so much in evidence in some later papers) amd the smooth curves of De Lange (1957). Marked changes in slope (which will be called sub-peaks) are apparent centred about frequencies which seem to remain constant across the luminance range. Subpeaks are identifiable, at 6 and 15 Hz. These subpeaks may correspond to the 4-7 and 10-15 Hz. regions respectively described by Kelly, and there is possibly an indication of his 20-30 Hz. peak in the high luminance curves in Fig. 7.1.1. (Kelly (1962b) notes that the 4° dark surround field configuration greatly suppressed the 20-30 Hz. peak relative to the 65° field in the same observer.) In addition the low luminance curves exhibit a further subpeak at around 4 Hz. This subpeak contrasts with De Lange's bright surround data in which there is no evidence of a corresponding change in slope at equivalent luminances. The luminance of the 0.25 tr curve is close to the photopic threshold, so that it is unlikely that 10% modulation of this luminance is detected by the photopic mechanisms of the retina. It is therefore probable that the 0.25 tr curve represents largely scotopic activity. This point will be considered further in section 7.1.2.

7.1.2 Flicker Data Considered as anIncrement Threshold Function.

Stiles (1949) study on increment thresholds utilised a large (10^{o}) field on which was briefly superimposed a 1^{o} test patch, the luminance of which was adjusted to threshold. De Lange's (1957) stimulus may be considered as similar to Stiles' since the time average luminance of the test area is the same as that of the surround. The differences are that decrement as well as increment was involved, and the principle parameter used was the time course of the stimulus rather than the wavelength of test and background fields.

Stiles measured an empirical function (ξ) which describes which is the relationship between the logarithm of the monochromatic background intensity ($\log W_{\mu}$) and the logarithm of the monochromatic threshold test field intensity ($\log U_{\lambda}$) for the retina as a unitary detection mechanism. The ξ function has a 45^{o} asymptote corresponding to Weber's law ($\frac{dI}{I}$ = constant)^{2}, and a horizontal asymptote corresponding to constant threshold independent of intensity at low intensities for the case of white light, the background and threshold test field intensities are denoted $\log W_{w}$ and $\log U_{w}$ respectively.

The retina is not, however a unitary detection mechanism. The curve of increment threshold as function background intensity of the same spectral composition is fitted by two ξ functions, one corresponding to the scotopic component and the other to the photopic component of the retinal system. (Stiles, 1949). The assumption was made, in Stiles' model, that there are several mechanisms in the retina for the detection of increments. Each acts independently without interaction with the other mechanisms. The observed increment threshold function is determined by the increment threshold of the most sensitive mechanism for each set of conditions.

The sensitivity of each mechanism may be altered by changing the experimental conditions. Stiles altered the wavelengths of the test and background fields, and found that the form of the complete increment threshold curve altered, in such a way as to indicate that a number of mechanisms with different spectral sensitivities were contributing to the curve. The object of the present section is to determine, using Stiles' method, whether there are separate mechanisms contributing to the increment threshold curve with different temporal characteristics and specifically different modulation frequency sensitivities. It will be assumed, for parsimony, that the separate components of the curve are attributable to the mechanisms described by Stiles.

Stiles has reported no systematic study of temporal effects on the increment threshold functions. In view of Kelly's (1962a) reports of frequency selective subpeaks sensitive to chromatic adaptation in a manner suggesting corresponding to the three colour channels and De Lange's (1957) finding of colour

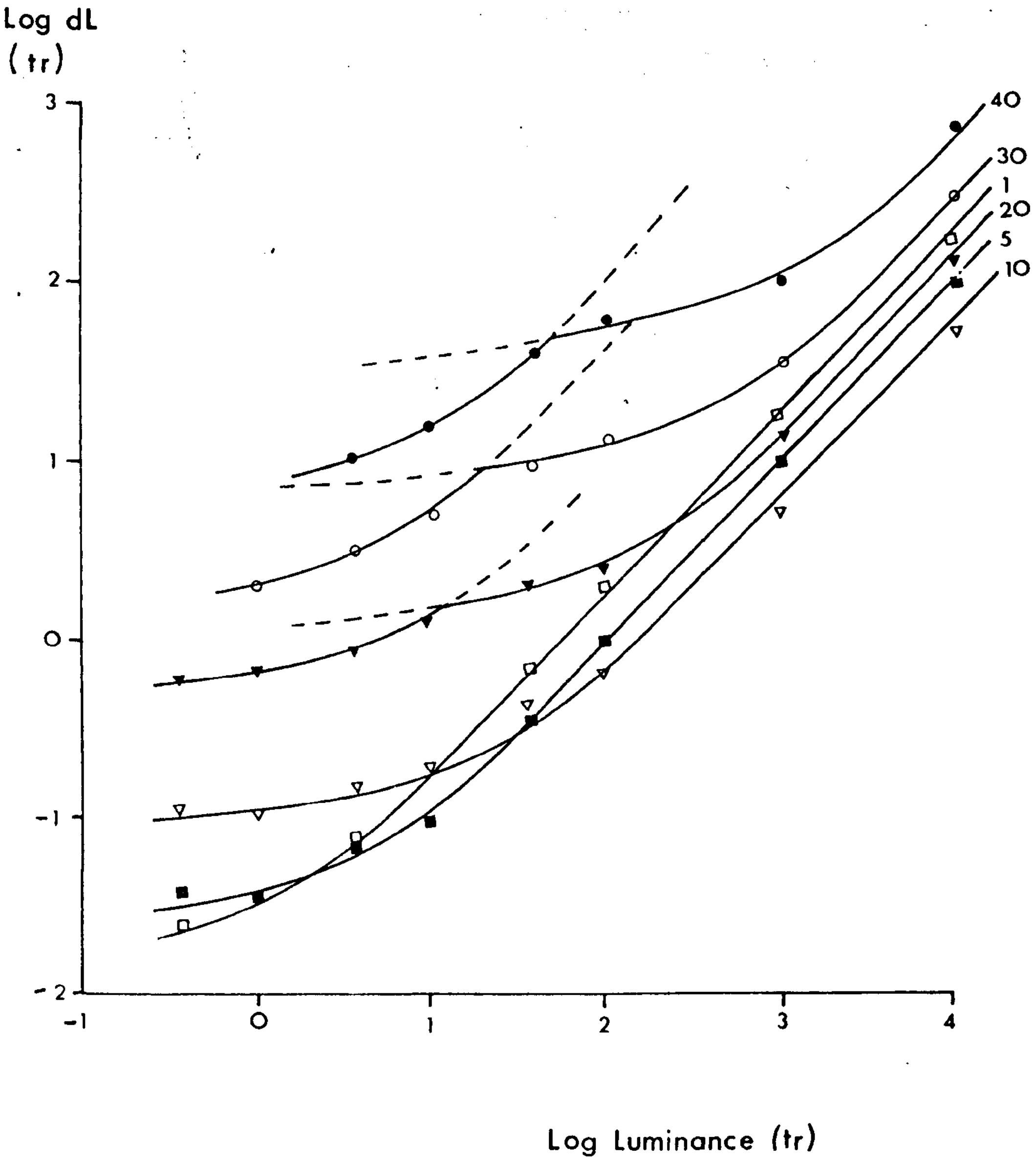


Fig. 7.1.2. De Lange's data (observer V) replotted in terms of absolute modulation sensitivity as a function of luminance, on log-log coordinates, for 6 values of modulation frequency (as indicated). The points are fitted by Stiles' functions. The high frequency curves conform to two branches.

effects on De Lange curves for monochromatic light, it is of interest to know whether the colour sensitive ξ functions reported by Stiles are also differentially sensitive ~~to~~ in the temporal dimension. As a preliminary approach to this problem, existing data of frequency sensitivity to sinusoidally-modulated light may be treated as indicating thresholds to a continuous series of increments.

De Lange's data on frequency sensitivity as a function of luminance (pg 50-51) are replotted as absolute flicker threshold as a function of background (adapting) luminance, for a set of values of modulation frequency. The result is shown in Fig. 7.1.2 together with the best fitting ξ functions for observer V as his data are the more complete.

The curves for frequencies of 10 Hz. and above are clearly fitted by two ξ functions with maximum sensitivity in the low and high luminance regions respectively. The same effect occurs for observer L. It should be noted that the description of the curves in terms of two ξ functions shifting relative to each other as frequency of modulation is changes corresponds to the irregularity of the spacing of De Lange's attenuation characteristics, particularly evident on the high frequency slopes of the characteristics. This irregular spacing was not commented upon by De Lange, but it reflects the emergence of a second mechanism, as luminance is increased, which is more sensitive than the low luminance

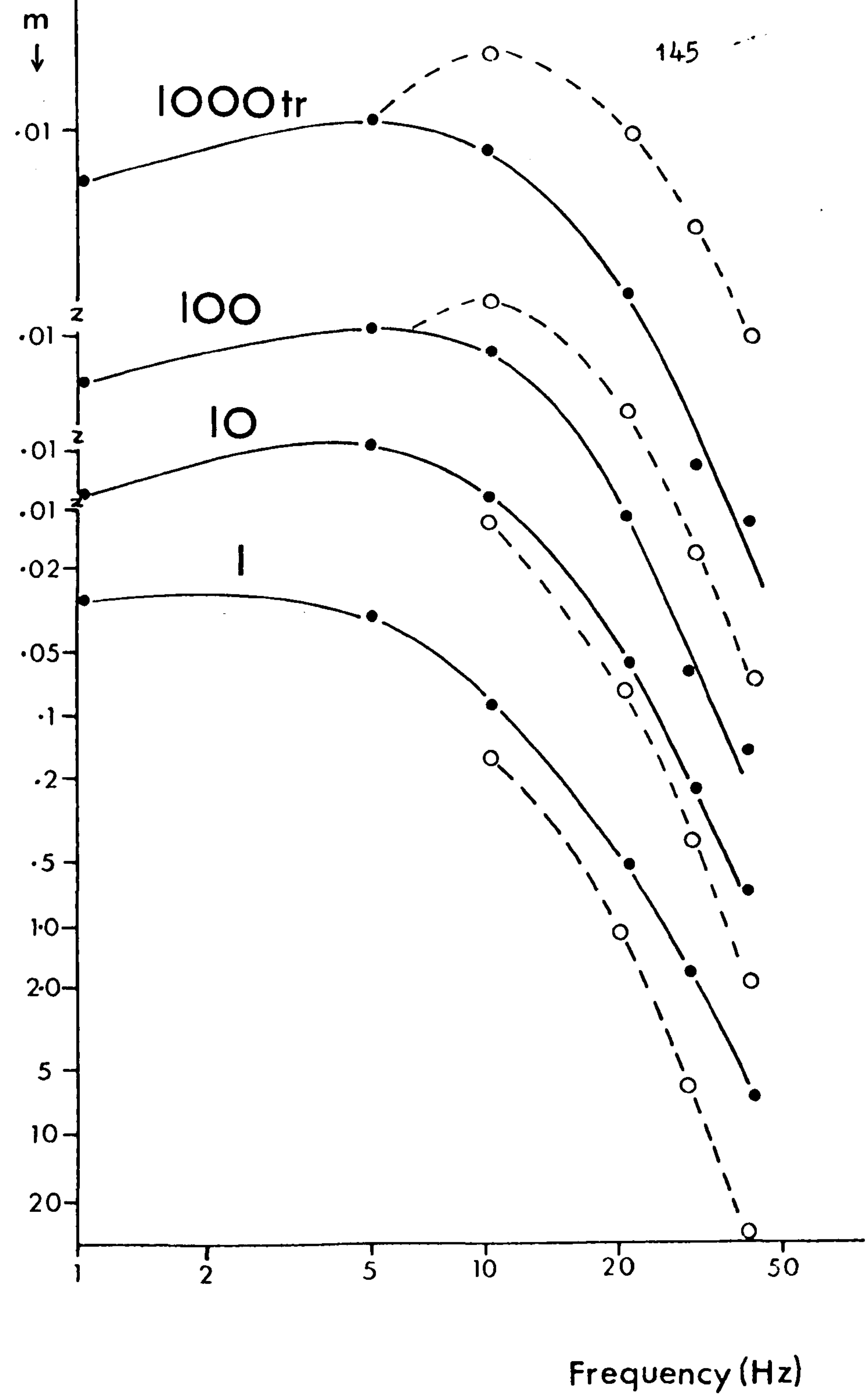


Fig. 7.1.3. Frequency sensitivities of two response systems in De Lange curve, derived from Fig. 7.1.2. Filled points - low luminance system. Open circles - high luminance system. Threshold modulation (m) increasing downwards, plotted as a function of modulation frequency (log-log coordinates). Ordinate arbitrarily displaced for four adapting retinal illuminances (as indicated).

mechanism only at high luminance and high frequency. The flicker sensitivity curves for the two mechanisms may be obtained by a method analogous to that used by Stiles to obtain the spectral sensitivities of his π mechanisms. The result is plotted in Fig. 7.1.3. It appears that both high and low luminance mechanisms change in form as luminance is increased, but the high luminance mechanism develops a marked peak at about 20 Hz.

Equivalent increment thresholds curves for observer C.W.T. using a dark surround (i.e. equivalent to using a background field of the same size as the test field) are plotted in Fig. 7.1.4. The principal difference from the equiluminant surround data is that the overall sensitivity is not reduced as frequency is increased, as much as in the case of the equiluminant surround. The feature of the separation of the curves into two sections is still apparent. Since the transition from low to high luminance curves occurs at about 10 tr, in the mesopic range, the most likely hypothesis is that the two curves represent rod and cone activity. No evidence for different photopic components is apparent, but a thorough investigation of the frequency response of the component colour mechanism, separated by chromatic adaptation in the manner described by Stiles, would show whether the five mechanisms he describes (Stiles, 1953) were involved.

The experiments reported by Green (1969), and described

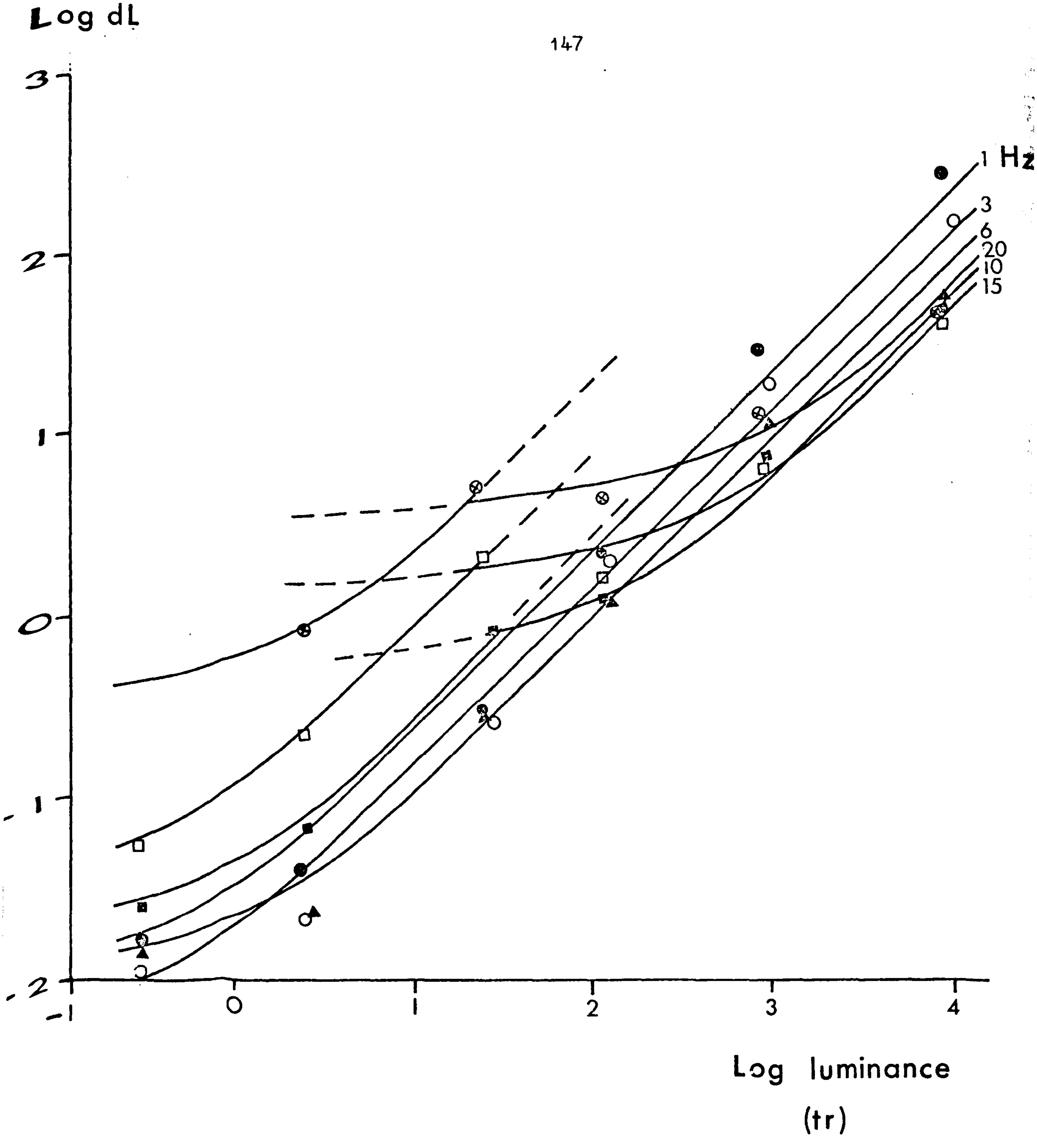


Fig. 7.1.4. Absolute modulation sensitivity as a function of luminance.
As for Fig. 7.1.2. but with subject C.W.T.

in section 3.5, attempt to measure the frequency response characteristics of the red, green and blue colour mechanisms by the use of chromatic adapting conditions similar to those used by Stiles to separate the colour mechanisms. Green did not investigate whether, especially in the spectral region of the three blue mechanisms, (Stiles, 1953) differences in frequency sensitivity may result in the more than one mechanism determining the form of the frequency response functions.

7.1.3 De Lange Curves for Monochromatic Light.

Introduction.

De Lange (1957) studied frequency sensitivity curves for monochromatic light for six wavelengths at approximately 50nm separations across the spectrum. He used an equiluminant white surround. His results can be summarised as follows. The sensitivity varies in approximately similar manner with frequency, at all wavelengths, but shows a greater rise in sensitivity between 1 and 10 Hz. at 641nm that at the other wavelengths examined. Threshold in the low frequency region varies irregularly with wavelength with a range about ± 15%, but the high frequency slopes of the sensitivity curves "practically coincide" (De Lange, 1957, pg 72).

Kelly (1962b) has studied dynamic spectral sensitivity to flicker at three frequencies in four subjects for a 65° blurred edge stimulus consisting of a steady white adaptation beam on which was superimposed a modulated monochromatic beam. Differences in the spectral sensitivity as a function of frequency were evident, in particular in the marked reduction in sensitivity at the blue end of the spectrum as frequency was increased.

Results.

The De Lange curves for one subject obtained with a dark surround at 4 wavelengths are shown in Figs. 7.2.1-4. (section 7.2) They do not exhibit the same features as the curves obtained by

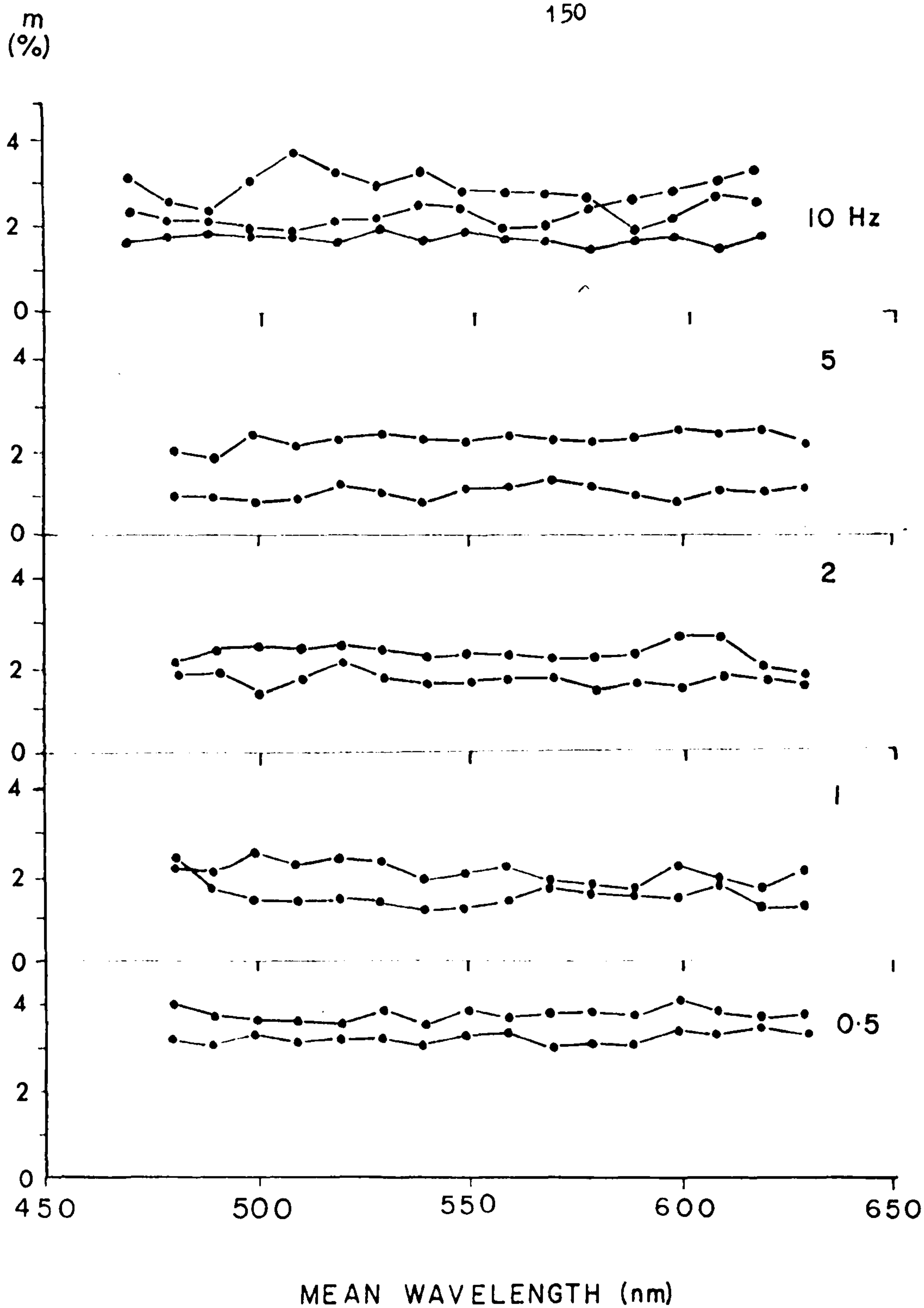


Fig. 7.1.5. Luminance modulation thresholds (m) as a function of wavelength for five frequencies of modulation (as indicated). Each point is the average of two readings. Subject C.W.T. Mean retinal illuminance 25tr. 2°field with dark surround.

De Lange. In the low frequency region below 10 Hz. there is no significant difference between the sensitivities for different colours. In the high frequency region the main difference is that the 527nm curve is of greater sensitivity above 10 Hz. than the other three wavelengths tested. In view of these discrepancies, the results of Figs. 7.2.1-4 were investigated in greater detail. The low frequency region was examined in two subjects by obtaining the subjects' modulation threshold as a function of wavelength of the light at selected frequencies of modulation, each wavelength was equated by means of flicker photometry, using a sector disc. This experiment supplemented the De Lange curves obtained only at selected light wavelengths. In addition, it acted as a control experiment for the dynamic wavelength discrimination experiment described in section 7.3. The results are shown for two subjects in Figs. 7.1.5 and 7.1.6. Within the accuracy obtained in this experiment, it is clear that for a 2° field with a dark surround producing a retinal illuminance of 25 tr there is effectively no variation of modulation threshold with wavelength up to 10 Hz. between the wavelengths of 480-630nm. The curve obtained at 20 Hz. in one subject did show fluctuations, but these were very variable. The high frequency region was not, however, examined in detail.

There is an apparent discrepancy between the dark surround

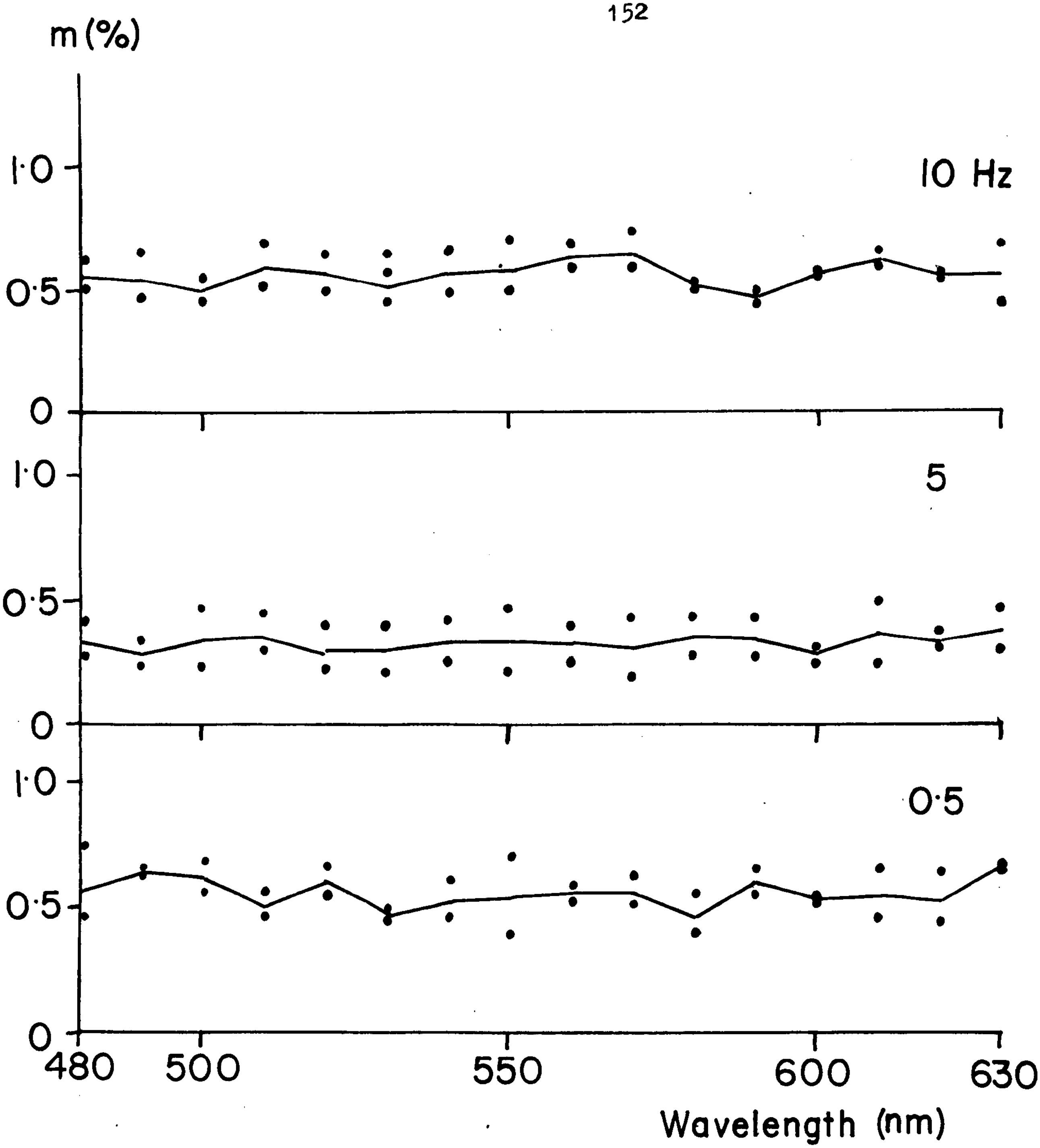


Fig. 7.1.6. Luminance modulation thresholds as a function of wavelength. Conditions as for Fig. 7.1.5. but with subject L.K.T.

results reported above and those obtained by De Lange using an equiluminant surround, described in section 3.5. However, there are various reservations concerning De Lange's methodology in this instance (section 3.5.), which may account for the discrepancy between dark and equiluminant surround data.

7.1.4 Spectral Sensitivity: Implications for Heterochromatic Flicker Photometry.

The effect of wavelength on flicker sensitivity has a bearing on the procedure involved in heterochromatic flicker photometry (H.F.P.). As pointed out in section 3.6., HFP is based on the assumption that flicker sensitivity varies with luminance but is independent of wavelength of the light. Thus when two monochromatic fields are alternated, a point of minimum flicker occurs as the luminance of the test field is varied (i.e. the point at which the flicker due to one field being switched on and off is most nearly cancelled by the flicker due to the second field being switched on and off in antiphase with the first). The point of minimum flicker, or optimal cancellation of flicker, is taken as corresponding to equality of luminance. But if the flicker sensitivity is dependent on the wavelength of the light the minimum flicker point, and hence the luminosity function obtained by this method, would be dependent upon the exact frequency at which HFP was performed. It is therefore important to establish under what conditions, if any, the measured luminosity function remains independent of frequency. The dark surround data reported above indicate that flicker sensitivity is independent of wavelength below 10 Hz. This suggests that if the ~~depth~~ data of the two subjects (section 7.1.3) is representative of the general population HFP for retinal illumination of about 25 tr. utilising the dark surround stimulus configuration, would be most accurate and reliable if performed at frequencies near 10 Hz. (To lower the frequency too far would enhance the colour flicker effect and thus reduce the setting accuracy). It would therefore be of value to conduct an extended study to verify the above conclusions on a greater number of subjects.

Spectral Sensitivity Determined by Threshold Modulation Depth of Flicker.

Ives (1922) examined several methods for determining spectral sensitivity including the use of CFF measurements for across the spectrum. He concluded that the CFF method was far less accurate than the HFP method, and was therefore of little value in determining spectral sensitivity. However, the use of flicker of variable modulation depth increases the flicker threshold method (corresponding to Ives' CFF method) to the same order as that of the HFP method. Moreover, it allows the measurement of spectral sensitivity to be performed at any selected flicker frequency, whereas the HFP method is limited to frequencies giving the clearest minimum. Kelly's (1962b) measurements of spectral sensitivity by means of a 65° field are described in section 3.5.

The data of Fig. 7.1.5 have so far been regarded as showing the flicker sensitivity as a function of wavelength with luminance equalised. These data may equally be considered as showing the deviation of spectral sensitivity determined by threshold modulation depth from that determined by HFP. Clearly, within the spectral limits studied, there is no apparent deviation between the spectral sensitivity measured by the two methods, for frequencies up to 10 Hz. Within this range, therefore, it appears that for the present subjects spectral sensitivity measured with a 2° field and dark surround is not frequency dependent.

Discussion.

Green (1969) has reported large differences in the De Lange characteristics in conditions designed to isolate the three cone mechanisms alone (described in section 3.5). If Green's characteristics were the sole contributing factors to flicker sensitivity across the spectrum, much larger variations in spectral sensitivity would be predicted. However, Green used a 12° adapting background, which would provide a continuously present spatial comparison field as well as temporal comparisons of test field changes. His results therefore are not strictly comparable with the dark surround data.

Boynton and Ikeda (1962) reported differences in the spectral sensitivity of a subject as a function of the duration of the flash presentation. They used only two flash durations, 12 msec and 50 msec. However, comparison between transient and steady-state data is not possible in the absence of a model of the system concerned (see, for example, section 8.5).

Kelly's (1962b) measurements of spectral sensitivity under dynamic conditions show a large frequency dependence. But again his 65° "edgeless" stimulus condition differs considerably from the 2° dark surround used in the present experiment.

It appears, therefore, although that the frequency independence of the spectral sensitivity holds for a 2° stimulus with a dark surround for frequencies up to 10 Hz., it has not been found to apply under any of the other stimulus conditions examined by other authors.

7.1.5 Phase Measurements

Introduction

The threshold amplitude measurements for sinusoidal imputs described in previous sections give only one aspect of the visual system steady-state response. The complementary aspect is provided by the phase of the signal at the locus of perception relative to the input. This is a difficult measurement to take, since the time relationships involved are far shorter than are reportable by the subject directly. De Lange (1957) consequently states that it is not possible to measure the phase characteristics psychophysically. The purpose of this section is to develop a method by which the phase can be measured. It has only been possible to apply this method to luminance modulation of the stimulus, since the luminance compensation necessary for constant-luminance wavelength modulation (see section 6.0) was not accurate enough to apply to a composite signal as is described below.

The approach to phase measurement relies on the finding of Levinson (1964) that the threshold for a composite waveform consisting of summed fundamental and second harmonic modulation varies with the relative phase of the two components. This non-linearity in the perception of composite waveforms provides a method of measuring the relative phase between fundamental and second harmonic components as a function of frequency, at the locus of the non-linearity in the system. The assumption must be made that the non-linearity is essentially independent of frequency over the range of interest, and also that the Fourier components of the waveform are treated independently up to the locus of the non-linearity. The method involves measuring the threshold for a composite fundamental and second harmonic modulation waveform, as a function of the relative phase of the two components. Measurement of this phase non-linearity function is then repeated taking the frequency of the previous second harmonic as fundamental, and adding its second harmonic. At very low frequencies the phase difference is assumed to be negligible, so the shift in the phase non-linearity function for any given fundamental and second harmonic pair of frequencies relative to the position for a low frequency pair is a measure of the extra phase shift between the given pair of frequencies. In this way the extra phase shift for each octave of frequency may be measured. The method of summing phase shifts over a range of frequencies to form a measure of the total phase shift is analogous to that used by Vos & Walraven (1965) in measuring phase shift between two stimuli as a function of luminance. This method of summing the extra phase shift at each octave has a 360° uncertainty, e.g, a relative phase lead of 60° could equally be a lag of 300°. However, a check was made on the change in relative phase between each octave and the octave approximately half an octave higher. The change in relative phase over half an octave was never greater than ± 70° (or less than ± 290°). The smaller of the two changes was therefore unambiguous, and was always selected on the grounds that the most parsimonious system was thus obtained. The phase shift may be measured at more frequency points by repeating the procedure for a set of fundamental frequencies at

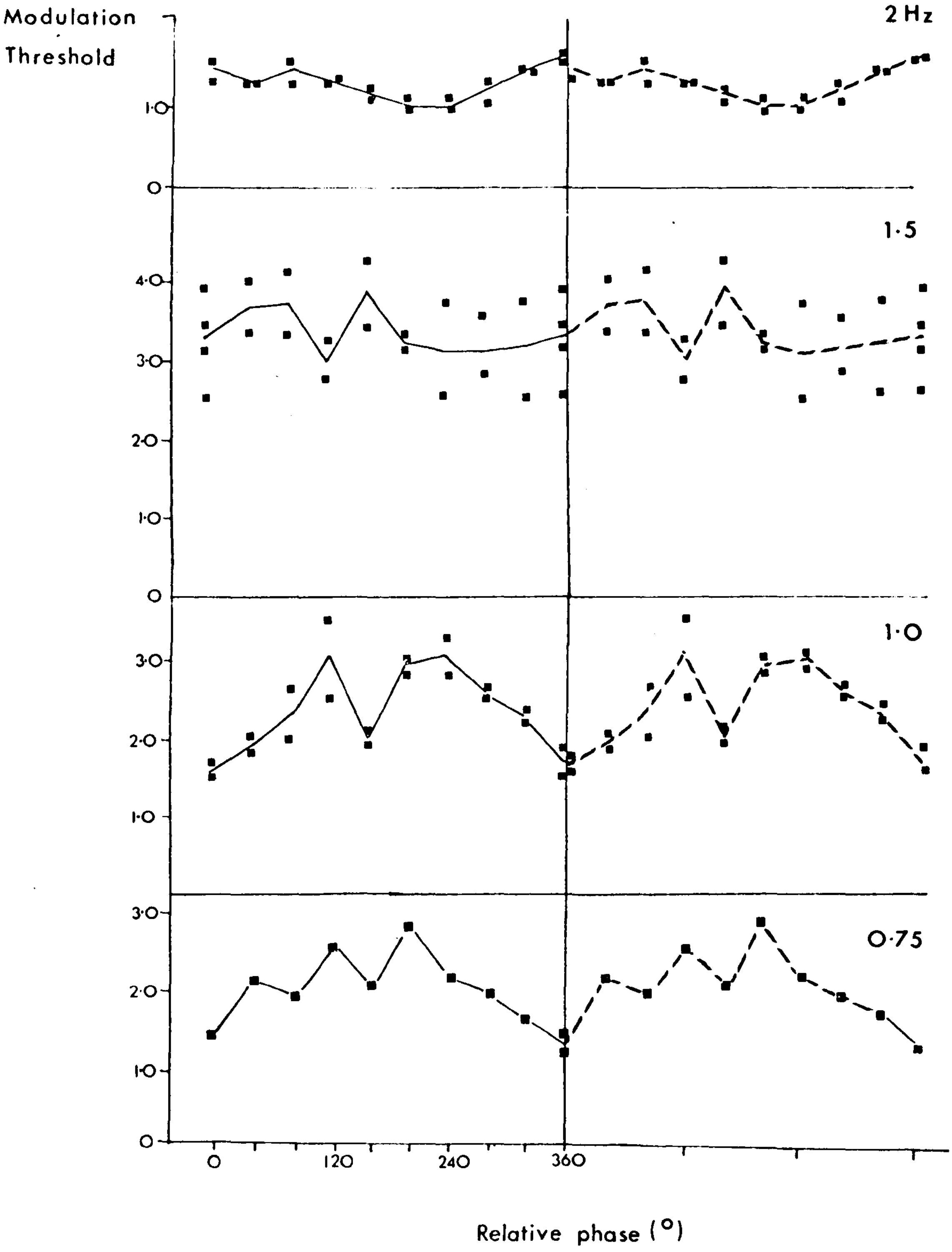
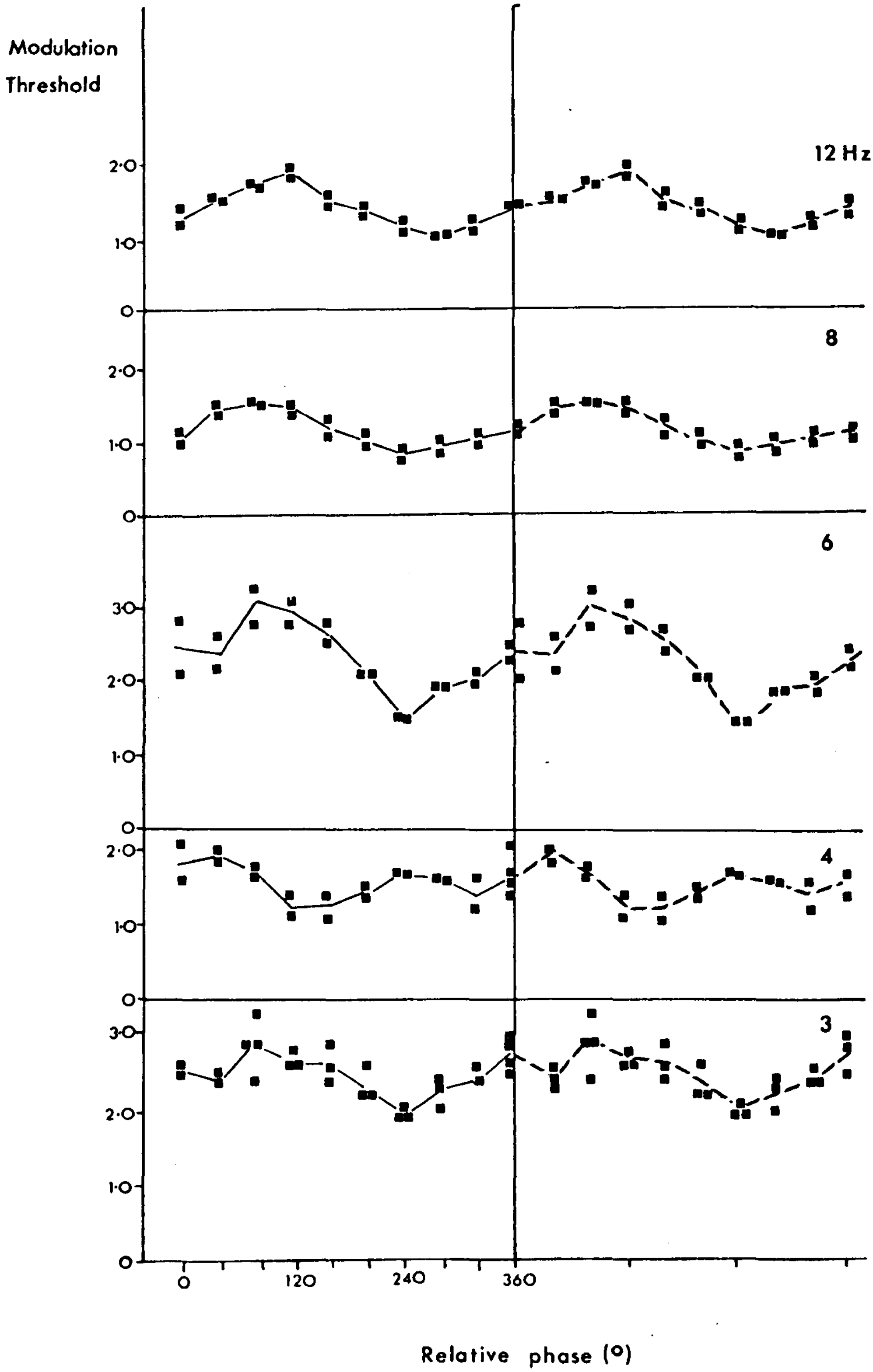


Fig. 7.1.7. Modulation threshold for composite waveform as a function of relative phase. Ordinate - amplitude of fundamental component when composite waveform is at threshold. Abscissa - relative phase of (cont)



second harmonic in degrees of second harmonic cycle. Data replotted for second cycle for clarity. Subject C.W.T. Wavelength 527nm. Mean retinal luminance 25tr.

approximately half an octave spacing from the first set. The assumption of negligible phase shift at low frequencies implies that the phase non-linearity functions are at similar positions for all low frequency pairs. The assumption that the phase non-linearity is independent of frequency implies that the phase non-linearity functions has a similar form at all frequencies.

In order that the fundamental and second harmonic components of the composite waveform are of constant relative amplitude through the experiment, each component is set to threshold separately before the composite waveform is formed.

The amplitude of the composite is then adjusted to threshold for the phase non-linearity function measurements. The assumption must therefore be made that no significant frequency dependent attenuation occurs between the site of the non-linearity and the site of perception. This assumption could be tested by measuring the phase non-linearity function for a number of fundamental/second-harmonic amplitude ratios, but this was not attempted in the present study.

The results were obtained on one subject (C.W.T.) using monochromatic light with a mean retinal illuminance of 25tr and wavelength of 527 nm.

Results: A 2^{o} field with a dark surround was employed. The stimulus conditions were thus similar to those in force in the amplitude function of fig 7.4.1. Fig. 7.1.7. shows the phase non-linearity functions for two sets of frequency octaves (interlaced in the diagram) starting at 0.5 & 0.75 Hz. It is evident that some

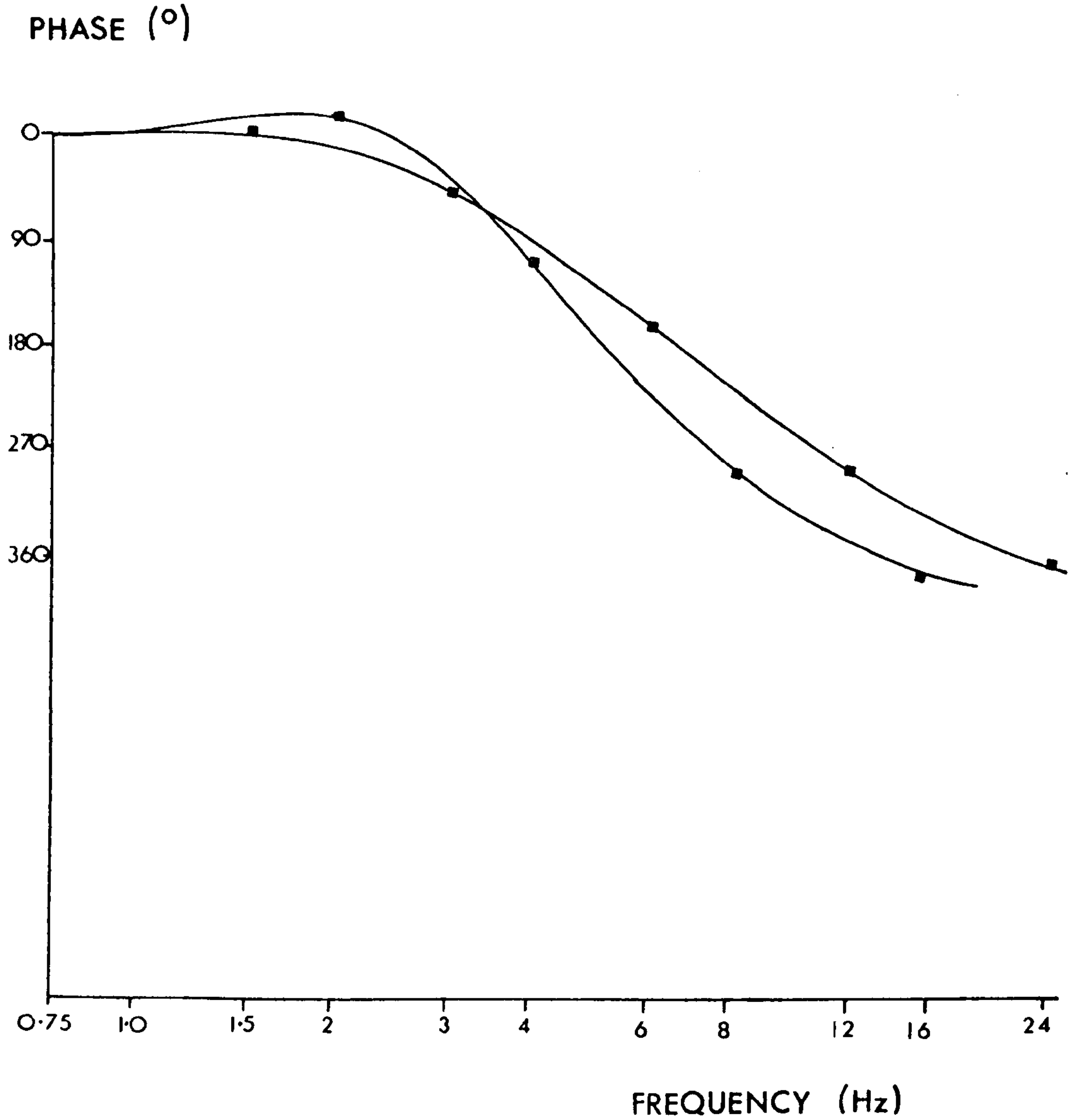


Fig. 7.1.8. Phase function derived from data of Fig. 7.1.7. Phase differences summed for each curve, as described in text.

similarity in form holds over the whole frequency range studied, supporting the assumption that the phase non-linearity is essentially independent of frequency, although differences in detail are evident. The phase characteristics derived from the relative shifts in the phase non-linearity function for the two sets of octaves are plotted in Figure 7.1.8. The low frequency points are fairly close to zero, giving justification for the use of the lowest frequency positions to define zero. The two sets of functions starting at 0.5 and 0.75Hz have similar overall form and give an indication of the accuracy of the method. The main features of the phase characteristic under these conditions are that the maximum rate of phase shift occurs at about 6Hz, and that the phase shift appears to be approaching a limit of about 2π radians.

Conclusion

The method developed in this section of measuring relative phase shifts by utilising a non-linearity in the system has produced encouraging results. The two independent summed octave phase functions are similar in form and correspond to phase functions which commonly occur in electrical systems. A comparison with the minimum phase function computed from the amplitude function obtained under similar stimulus conditions is made in section 8.5.

7.2. De Lange Curves with Wavelength Modulation

Introduction

Most of the results in this section have been previously reported by Regan and Tyler (1971a). The controls described in section 6 indicate that it is possible to measure thresholds determined by the equiluminant (i.e. colour-varying) component, of wavelength-modulation light. It is assumed that for small amplitudes of wavelength-modulation (up to 20 nm) the amplitude of the visual system response is a monotonic function of the modulation amplitude.

Method

For each reading, the optimal cancellation of the luminance flicker induced by wavelength modulation was obtained; the subject set the compensatory luminance modulation amplitude such that flicker was at a minimum and colour flicker predominated. The subject then reduced the signal to both modulators by means of a single control, until no further changes in the field were perceptible. The subject was asked to report if the flicker appeared to be of colour or brightness just before threshold, and the compensation procedure repeated if the flicker appeared to be of brightness. The luminance compensation did not appear to be adequate in a few of the more extreme conditions i.e. at the lower luminance, and high frequency for the blue stimulus. In these circumstance it was necessary for the subject to report the threshold of colour flicker when some residual luminance flicker was evident. The results, and those of section 7.3., suggest that this task gave equivalent results to the reporting of overall threshold when luminance flicker was compensated

Figs. 7.2.1-5. De Lange curves for luminance and wavelength modulation under various mean wavelength and retinal illuminance conditions. Ordinates of threshold luminance modulation (m) and wavelength modulation ($d\lambda$) plotted increasing downwards and arbitrarily placed with 1% m corresponding to 1nm. Each point represents two readings; thresholds for each condition were measured for two pairs of readings plotted separately to indicate session-to-session variability. Subject C.W.T. 2° field with dark surround. Clear differences occur in each case between the form of the luminance and wavelength De Lange curves.

FIG. 7.2.1

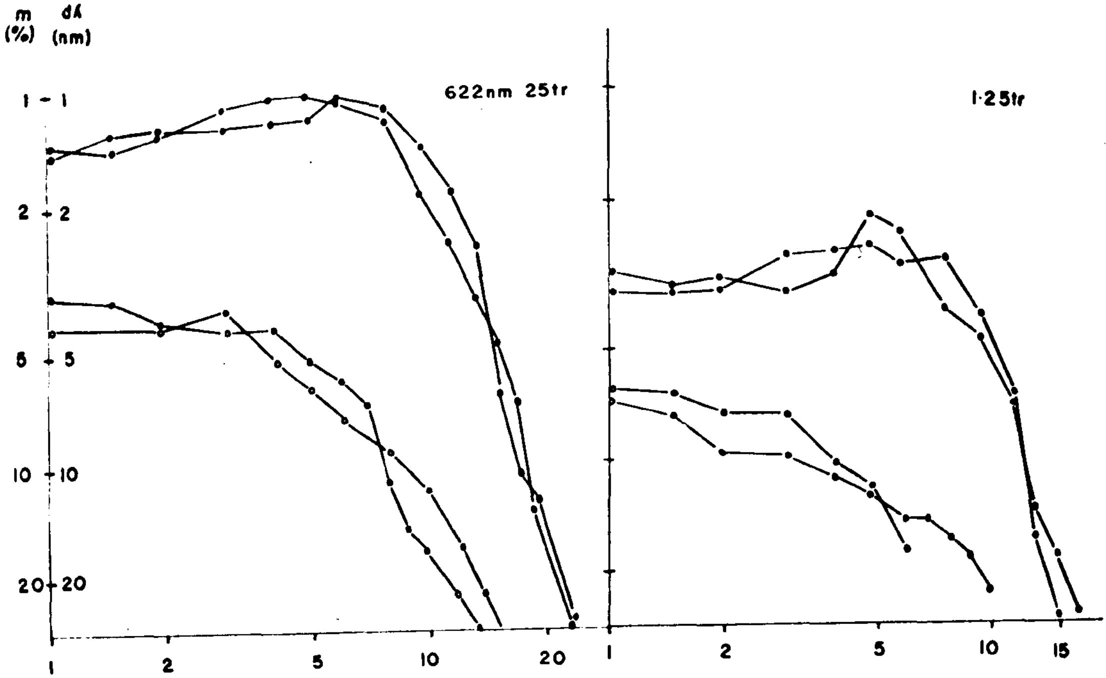
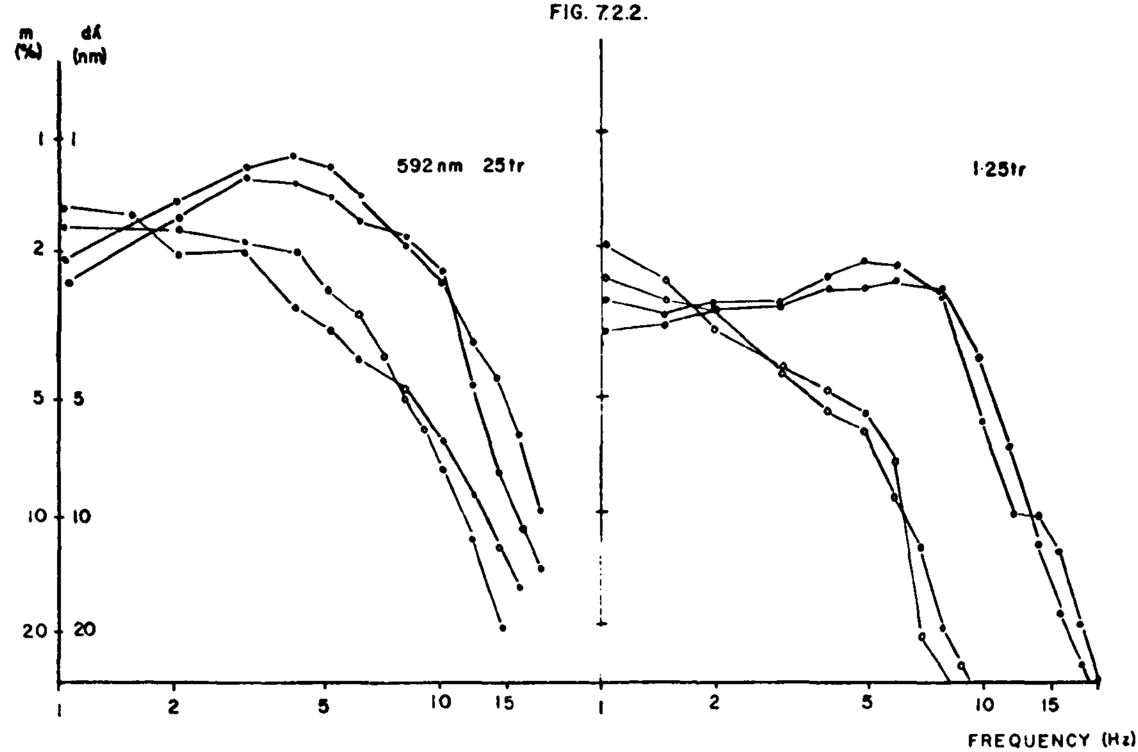


FIG. 7.2.2.



<u>Fig. 7.2.1.</u> De Lange curves for luminance (filled points) and wavelength (open circles) modulation. Mean wavelength - 622nm for two mean retinal illuminances as indicated. Other conditions as for full caption(7.2.1-5)

<u>Fig. 7.2.2.</u> De Lange curves - conditions as above but with mean wavelength 592nm.

FIG. 7.2.3.

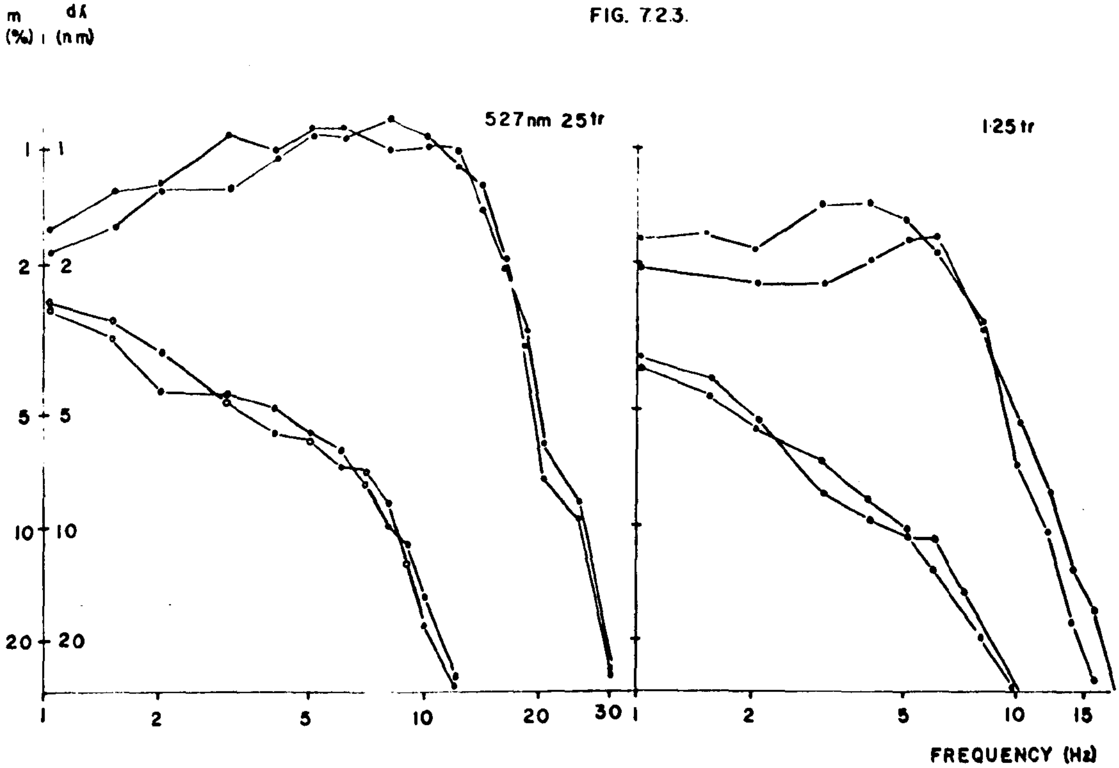


FIG. 7.2.4.

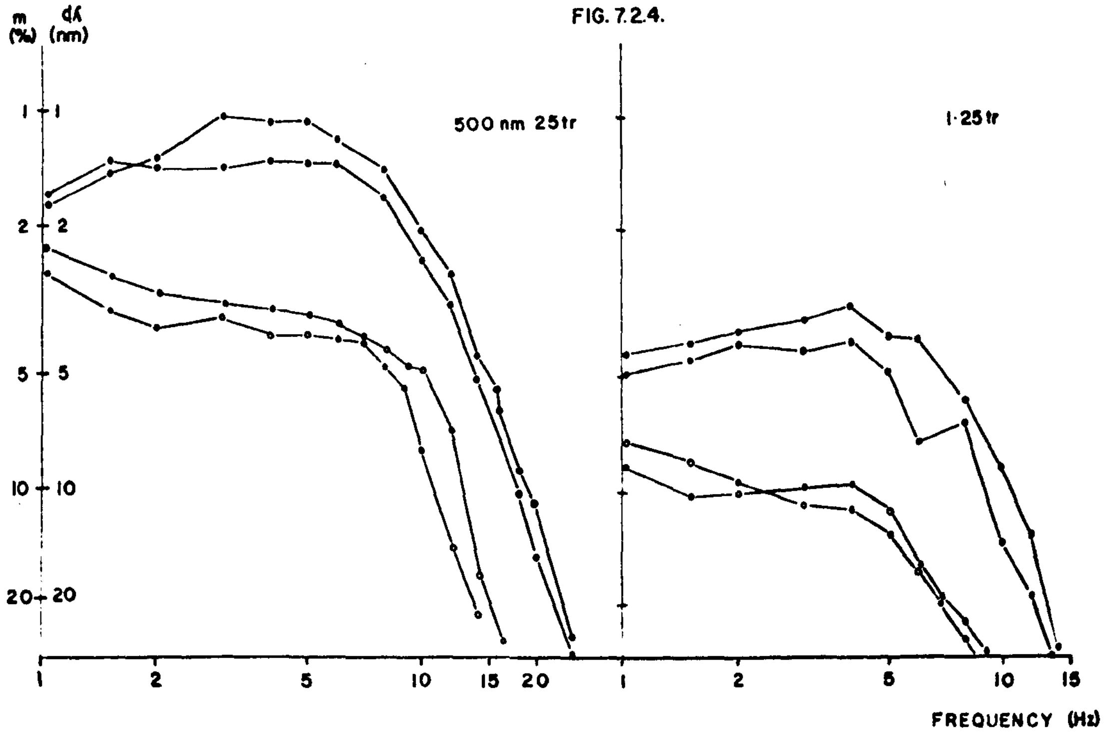


Fig. 7.2.3. De Lange curves - conditions as in Fig. 7.2.1.,but with mean wavelength 527nm.

Fig. 7.2.4. De Lange curves- conditions as in Fig. 7.2.1., but with mean wavelength 500nm.

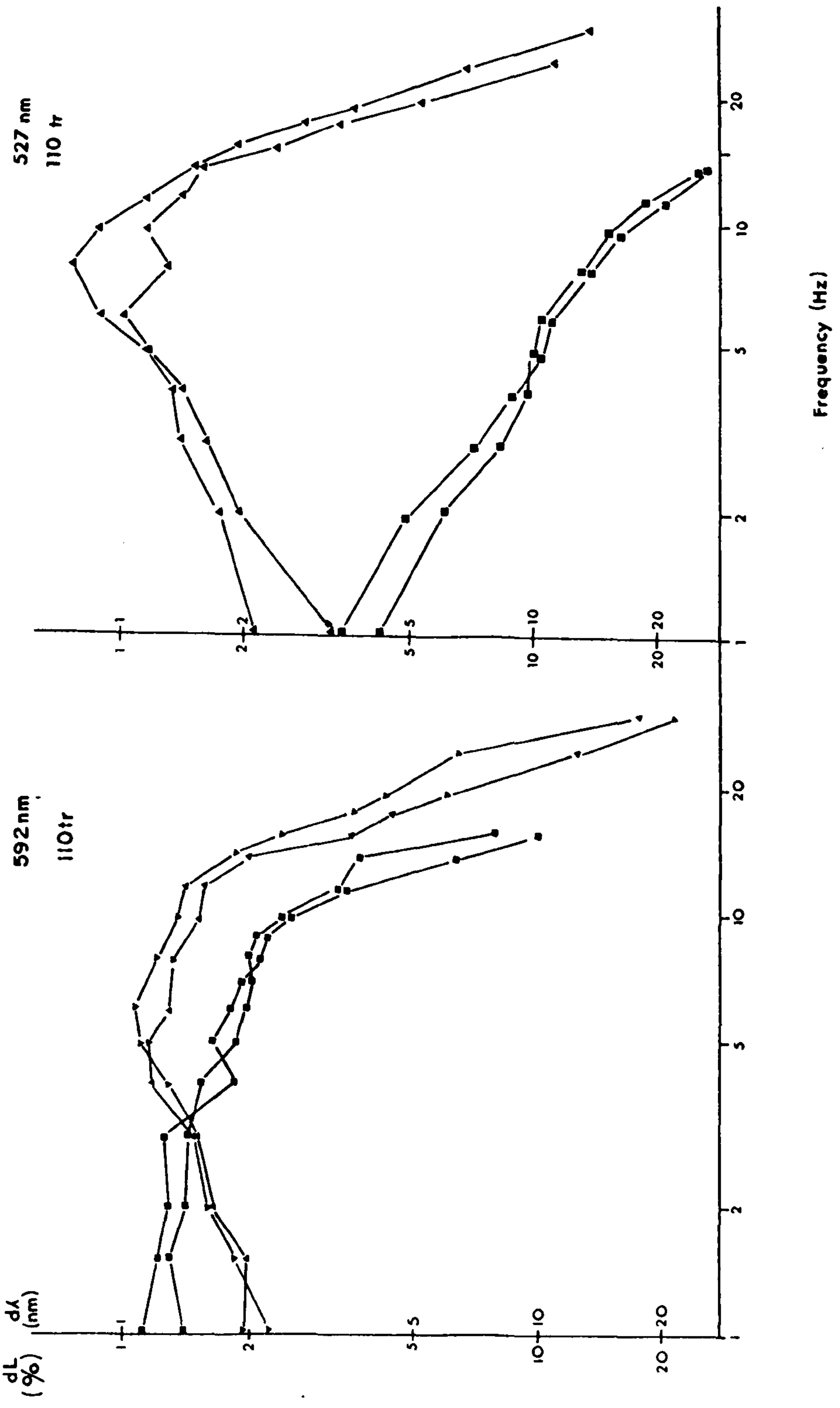


Fig. 7.2.5. De Lange curves for luminance (triangles) and wavelength (squares) modulation. Mean retinal illuminance - 110tr. Mean wavelength 592nm (left-hand figure) and 527nm (right-hand figure). Other det-

to below threshold, as in most conditions used here.

As a comparison, data on sensitivity to luminance modulation under the same conditions as the wavelength modulation was also obtained. Since the data De Lange (1951) and Van der Horst (1969) have indicated that there is likely to be a difference in the frequency sensitivity function for the two types of modulation.

Both luminance and wavelength modulation thresholds were obtained at four centre wavelengths across the spectrum (500, 527, 592 & 622) and two mean retinal illuminations 1.3 log units apart (25 + 1.25 tr.). The 1.25 tr. was obtained by inserting 1.3 log units ND filters in the beam. A set of thresholds was also obtained at 110 tr. for the 527 & 592 nm wavelengths. Four settings at each point were then taken in alternate ascending and descending order and plotted as two averages of pairs, to provide a visual estimate of the variation in the results.

Results

The results are shown in Figs, 7.2.1.-5. The fitted points refer to luminance modulation (m) and the open points to wavelength modulation $(d\lambda)$.[2] The two modulation axes (m & $d\lambda$) are independent, but are arbitrarely set so that 1% luminance modulation corresponds to 1 nm wavelength modulation. The threshold modulation amplitudes are plotted downwards for increasing amplitude on a log scale, so that the log modulation sensitivity may be read as increasing upward.

The luminance modulation curves at 25 trolands do not contradict the finding of section 7.1.3. that there were no significant variations

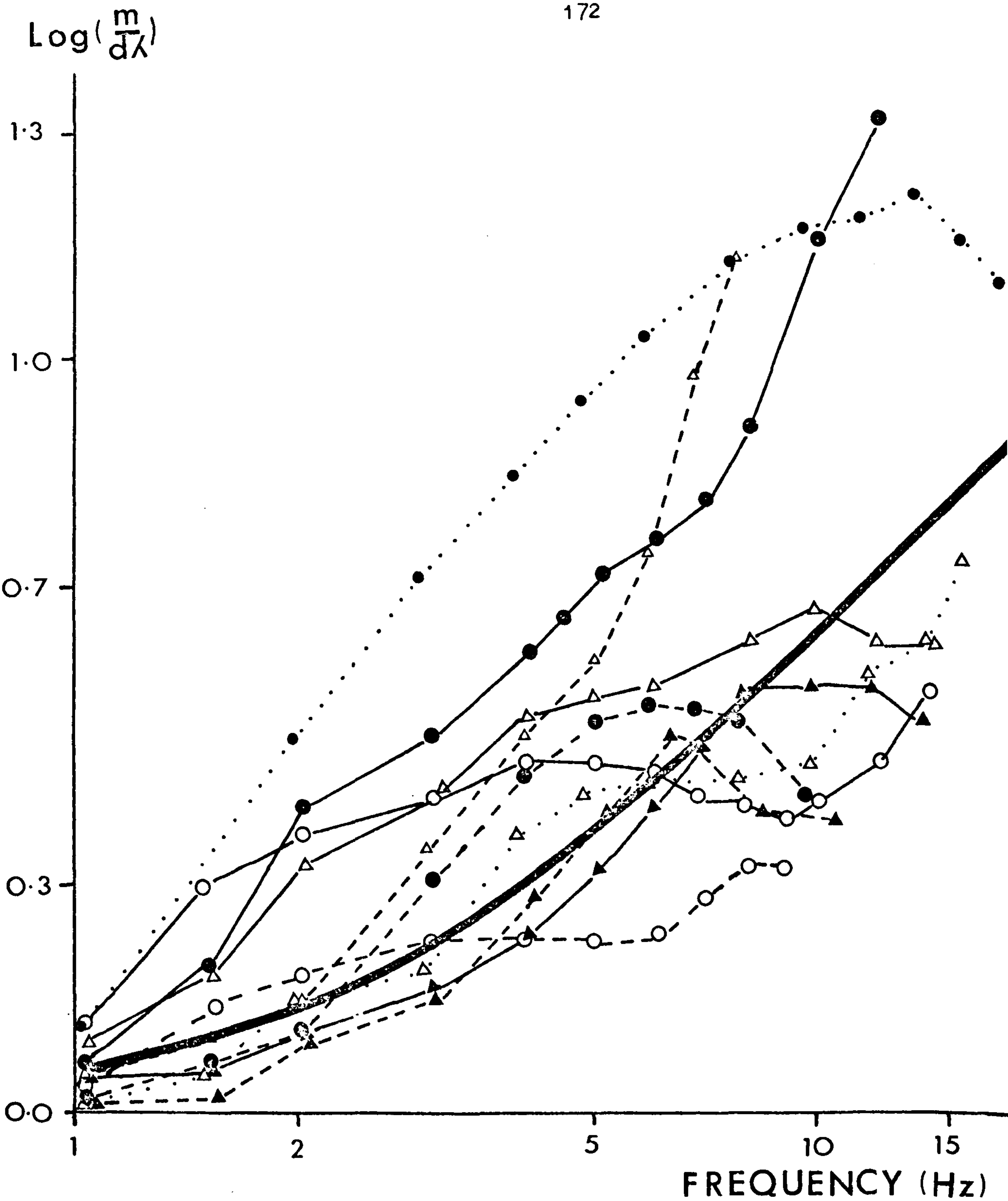


Fig. 7.2.6. Log difference curves of luminance minus wavelength modulation (Log $\frac{m}{d\lambda}$). De Lange curves for all conditions of Figs. 7.2. 1-5. Dotted curves - 110tr., full curves - 25tr., dashed curves - 1.25tr. Filled triangles - 622nm, open triangles - 592nm, filled circles - 527nm, open circles - 500nm. Full line - theoretical function (see text).

in sensitivity with stimulus wavelength up to about 10 Hz., but thereafter quite large differences are evident. The effect of reducing the retinal illuminance is also different at different wavelengths, but the lower retinal illuminance (1.25tr) is in the mesopic range, so that these results may be confused by scotopic influences.

The wavelength modulation sensitivity curves are each clearly different from their respective luminance modulation counterparts. If both scales are assumed to be linear it is possible to divide each luminance modulation sensitivity curve by the wavelength modulation sensitivity curve under the same conditions and obtain the log difference curve. The form of the log difference curve is unaffected by the scaling ratio between the two types of modulation. Fig 7.2.6. shows for all ten conditions the plots of difference curves between luminance and wavelength threshold functions.

Discussion

De Lange (1957) concluded that the difference at 595 nm dominant wavelength was well represented by a small number of first-order stages of attenuation of the same time constant in cascade. (1 at 285, 3 at 2.85tr). My data for 1.25tr at 592 nm does appear to have a similar form to De Lange's low luminance curve, but few of the curves at the other wavelengths and luminances fit De Lange's model, (fig 7.2.6.) or a model of any number of attenuation stages with any desired time constants. A number of the difference curves have slopes well below the prediction for even one first-order filter stage. Furthermore, the available data indicates that the high frequency slopes of many of the wavelength modulation curves is less than the high frequency slope of the corresponding luminance modulation curve. This is indicated by a fall in the difference curves at higher frequencies. The De Lange model would require the wavelength modulation high frequency slope to be greater than that for luminance modulation. Van der Horst's (1969) chromatic flicker curves are in accord with the above observation.

It appears, then, that De Lange's model of the formation difference curves cannot be applied generally to wavelength-modulation thresholds. The significance of this result in terms of linear systems analysis is discussed further in section 8.1.

The variability of the difference curves may be seen as evidence for a high degree of independence between the systems processing colour and luminance in the freqeuncy domain, for related lines of evidence see section 2.5. In other words, the frequency sensitivity to each type of stimulus is set by the characteristics of each processing system after it has diverged from the other.

De Lange (1957) and Van der Horst (1969) measured thresholds as a function of frequency for constant luminance colour alternation stimuli (see section 3.7).

De Lange's curves (at 595 nm) appeared to divide roughly into two portions, a shallow rise low frequency part and a steep rise high frequency slope, whereas Van der Horst's (570 nm) low frequency portion was fitted by a horizontal line. The present results at four wavelengths show both forms, the flattest low frequency portion being at 500 nm. (Figs 7.2.1-5.)

Van der Horst' concluded that the colour attenation curves show no evidence of the inhibitory interactions to which the pseudo-resonant characteristic of the De Lange curve has been attributed (e.g. Levinson, 1964). The wavelength modulation curves in all ten conditions examined are in support of Van der Horst's conclusion, thus extending the evidence for the independence of luminance and colour processing. This point is discussed more fully in section 8.6.

7.3. Dynamic Wavelength Discrimination

7.3.1. Introduction

The general method used in this study of wavelength discrimination during temporal modulation of wavelength is described below. The apparatus and controls for minimising luminance fluctuations and other artifacts are described in sections 5 and 6. The waveform of the wavelength modulation was usually sinusiodal, but in one experiment a square-wave was used. It should be noted that the waveform of wavelength modulation does not necessarily have a physiological significance e.g. in terms of cone activity, or psychophysical significance, e.g., in terms of hue or saturation. It was desirable in this initial study of wavelength modulation to have the physical stimulus specified simply. For discussion of this point, see sections 3.7 and 6.1. Such a stimulus may then be used to compare the results of the different experimental approaches of physiological activity, discrimination, colour matching etc.

The limitations of the luminance compensating method are described in section 6.2. It limits both the spectrum width and the frequency range that can be studied, since any further increase in either would involve an increasing modulation amplitude, and hence unacceptable degree of non-linearity in the compensation procedure.

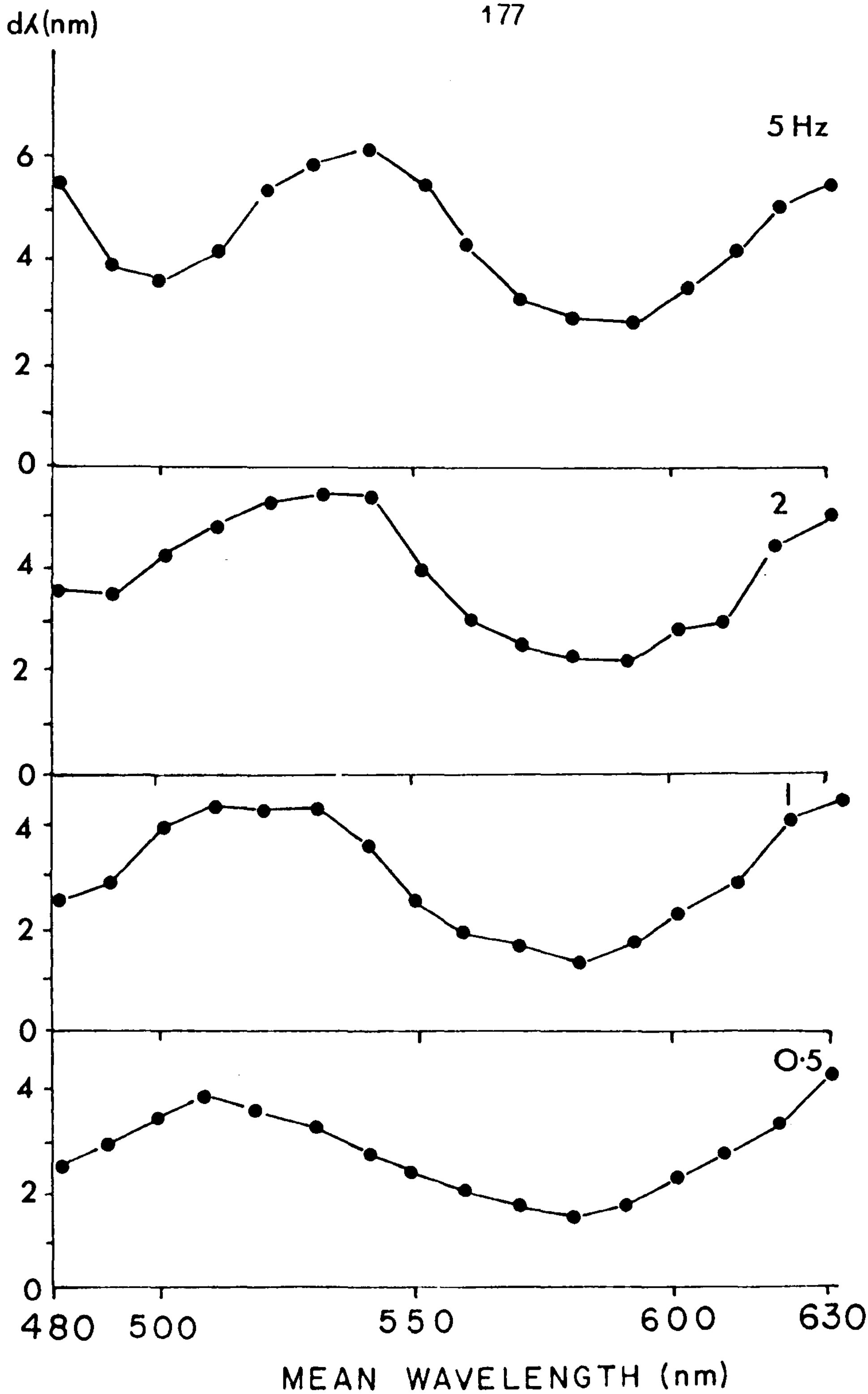


Fig. 7.3.1. Dynamic wavelength discrimination. Wavelength modulation thresholds (dλ) as a function of wavelength for four frequencies of modulation (as indicated). Subject C.W.T. Retinal illuminance 25tr. 2° field with dark surround. Each point represents four readings.

7.3.2. Dynamic Wavelength Discrimination for Sinusoidal Wavelength Modulation

The variations in threshold wavelength modulation with mean wavelength for a set of modulation frequencies are shown for the two subjects in figs. 7.3.1.-2. These plots will be described as dynamic wavelength discrimination curves. Within the spectral limits tested, the curves each appear to exhibit similar features to the classical form of wavelength discrimination (see section 2.3.2.) with minima in the blue and yellow regions, and a maximum in the green. The possibility that these results were contaminated with residual luminance flicker was checked by the experimental results of Fig. 7.1.5. (section 7.1.3.). This experiment examined luminance flicker for monochromatic stimuli of a set of wavelengths. The results indicate that up to frequencies of twice the highest frequency used in the wavelength modulation experiment, there is no significant variation of luminance flicker theshold with stimulus wavelength. It is therefore unlikely that the presence of a small amount of residual luminance flicker would produce the variations evident in threshold to wavelength modulation with mean wavelength (Figs. 7.3.1.-2).

The dynamic wavelength discrimination curves are equivalent to the reciprocal of a vertical cross-section through a set of wavelength modulation De Lange curves across the spectrum. They should therefor contain the same information as the set of wavelength modulation curves. Comparison of the two types (Figs. 7.3.1.-2. and 7.2.1.-4.) suggests that this is indeed the case. One main feature of the wavelength modulated De Lange curves is a contimuous loss in

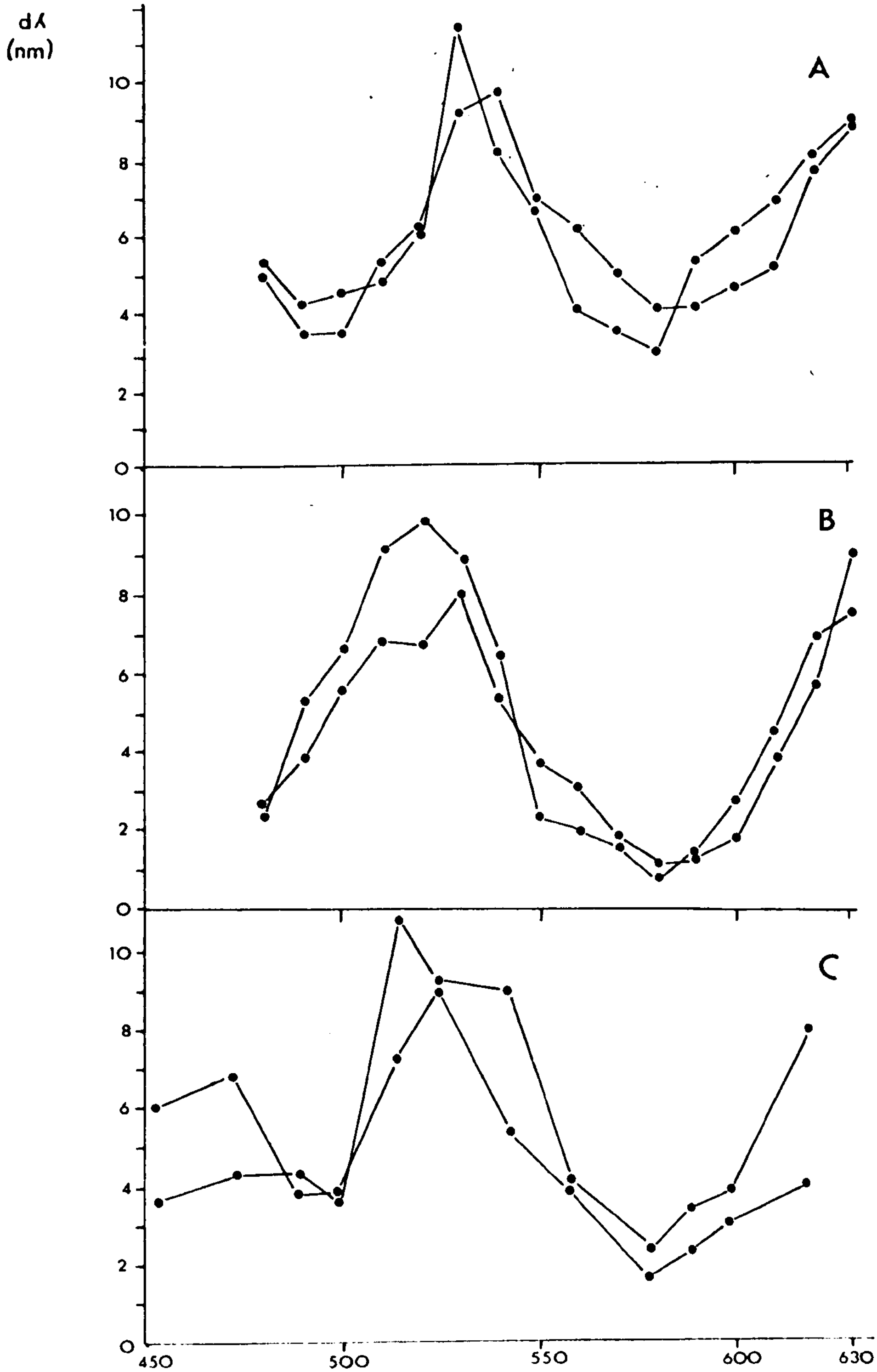


Fig. 7.3.2. Dynamic wavelength discrimination. Conditions as for Fig. 7.3.1., but subject L.K.T. A - 5 Hz. B - 0.5 Hz. C - bipartite (static) wavelength discrimination.

sensitivity as frequency is increased. A similar loss is clearly apparent in the wavelength discrimination curves, in which the mean threshold increases as frequency is increased.

The other main feature of the wavelength modulated De Lange curve is a difference in shape for different centre wavelengths. This would be expected to appear as a difference in shapes for dynamic discrimination curves at different frequencies. Such differences are apparent in Figs. 7.3.1-2 and they correspond to the shape differences in the wavelength-modulation De Lange curves, in that the least change between 1 and 5Hz occurs at about 500nm in each case, with greater changes at other wavelengths. However, the shape change is perhaps better described as a shift of the short wavelength minimum towards longer wavelengths as modulation frequency is increased. Similar shift also occurs in the classical wavelength discrimination function when luminance is increased, (see section 2.3.3.), so that the effect of frequency may thus be described in terms of previously established phenonemon. The shift in the short-wavelength minimum is of the order of 30 nm over one log unit of frequency for both subjects, while the long wavelength mimimum remains essentially unaffected apart from the general increase in threshold as frequency is increased. The frequency dependence of the dynamic wavelength discrimination function does not correspond to a tendency towards tritanopia (McCree, 1960a) which involves a relative raising of threshold in the 500 nm region. No tendency for the subjective hue of the wavelength modulated light to shift was reported by the subjects, but the possibility of a hue shift was not investigated systematically.

The results clearly show that the dynamic wavelength discrimination function is frequency dependent. The implications of this dependence in terms of three theories of colour discrimination are discussed in section 8.

7.3.3. Wavelength Discrimination with Various Forms of Stimulation

Introduction & Method

Classical wavelength discrimination involves judgement of colour difference across a spatial edge i.e. a bipartite field (Wright & Pitt 1934), whereas the dynamic wavelength discrimination data of section 7.3.2. involve no spatial colour edge, but a sinusiodal variation of wavelength with time. These stimuli differ in two major respects; in changing from spatial to temporal variation of the colour, and in changing from step (or edge) to sinusoidal form of the variation. The intermediate form of stimulus most easily produced with the present apparatus is a stimulus with no spatial edge but a temporal wavelength step. Such a temporal step is produced by feeding a low frequency square wave into the modulators. A comparison between the classical bipartite and temporal square wave stimuli is thus one of mode (spatial to temporal) rather than waveform. (Hilz & Cavonius (1970) have measured wavelength discrimination using spatial square-wave colour gratings. At their lowest spatial frequency (2.4. cpd), there was no evidence that grating discrimination differed from bipartie field discrimination, although they did not measure the latter directly).

For the bipartite measurements the method described by Wright & Pitt (1934) was followed as closely as possible. A 2° split-half circular field was used, and the subject set the smallest percetible wavelength difference, with luminance continually matched, in each direction from the nominal mean wavelength. For the temporal square-wave modulation of wavelength, a frequency of 0.5 Hz was used, as

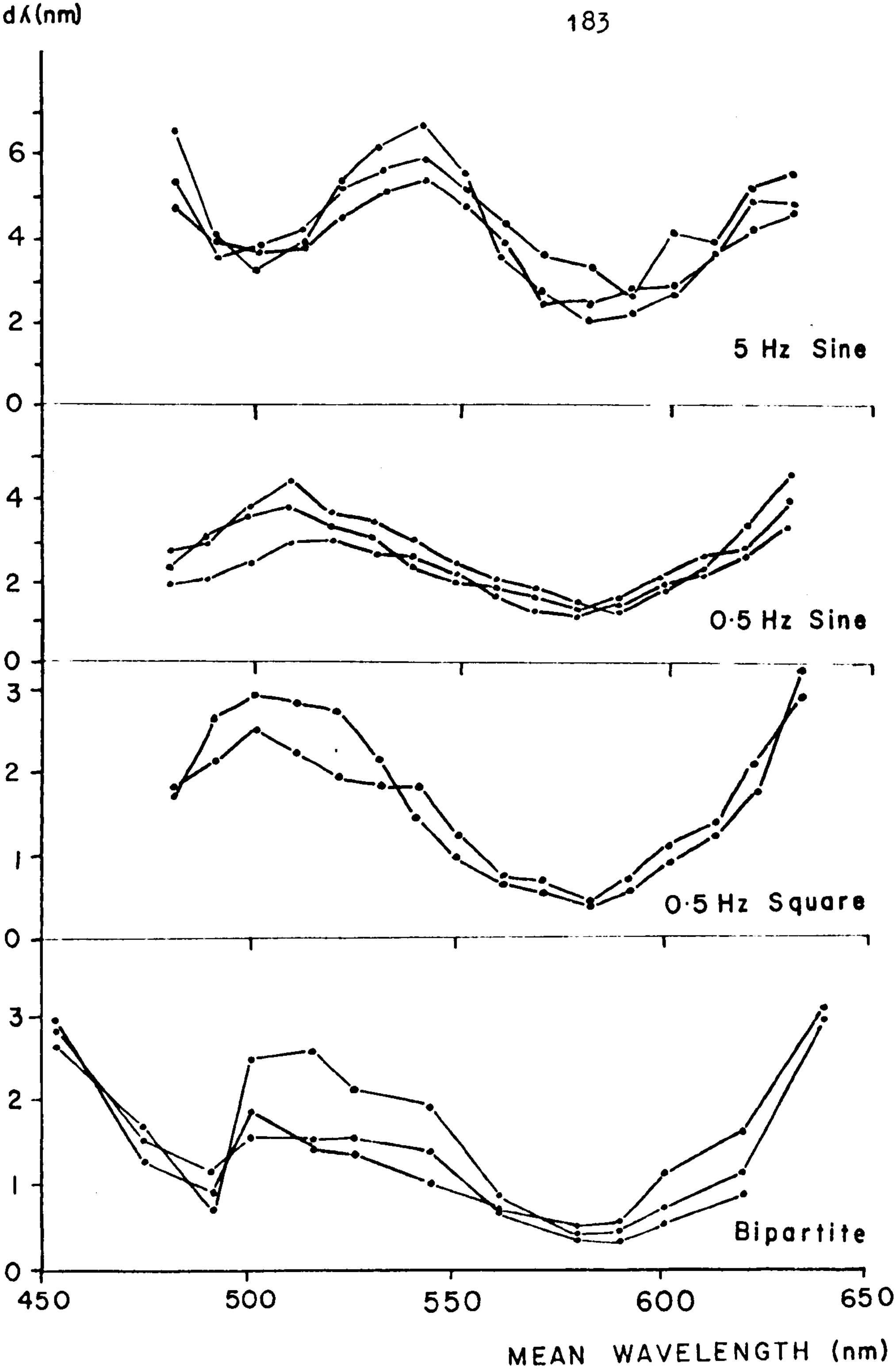


Fig. 7.3.3. Dynamic wavelength discrimination. Conditions as for Fig. 7.3.1. Upper two figures - same data as Fig. 7.3.1.,but with extra repetitions. Centre figure - square-wave modulation. Lower figure - bipartite (static) wavelength discrimination. Each point represents two readings.

this was a convenient frequency for which there is no interaction between the response to one step and the next (as shown in section 7.3.1.)

Results

The results shown in Fig. 7.3.3. for subject C.W.T. indicate that the details of the discrimination function are different for each of the three types of stimulus used. However, there is an overall loss in sensitivity for all temporal stimuli compared to the bipartite discrimination function. It appears that in whatever form the colour stimuli are temporally "replaced", the absence of a spatial comparison field and consequent reliance on some form of memory storage of the comparison stimulus produces impaired wavelength discrimination compared with that for a spatial edge.

For both subjects C.W.T. (Fig. 7.3.3.) and L.K.T. (Fig. 7.3.2.) there appear to be small differences in the positions of the minima between the bipartite and dynamic wavelength discrimination functions at high and low frequencies. However, a more extensive study is required to determine whether the bipartite function differs from the dynamic function at all frequencies.

With regard to the three temporal conditions, it might be expected that the square wave function would show improved discrimination over either low or high frequency sine-wave discrimination, since the square wave contains both high and low frequency components, and these are organised in such a way that there is the maximal transient information at each step.

The results shown in Fig. 7.3.3. do not support the hypothesis that square wave modulation will produce improved sensitivity in all spectral regions relative to that for sinusiodal modulation.

The wavelength difference threshold to square wave modulation is similar to sine-wave threshold in the yellow region, and somewhat higher than the sine-wave threshold in the blue-green region. This result is not necessarily in contradiction with the square wave wavelength difference threshold of Van der Horst (1969) which are lower by a factor of 0.7 than the sine-wave wavelength difference threshold, since the latter data were for a mean dominant wavelength of 565 nm.

It appears that the presence of a temporal edge does not always improve sensitivity over that for temporal sine wave modulation, but in the blue-green (480-530 nm) region of the spectrum sensitivity in the square-wave case is markedly reduced.

7.4. Effect of Spatial and Temporal Stimulus Configuration on De Lange Curves: **Introduction.**

In section 7.3.3. it was found that stimulus waveform and field configuration produced complex effects on the wavelength discrimination function. The purpose of the present section is to examine the effects similar stimulus attributes on the form of the De Lange curve, for both wavelength and luminance modulation. The modulation sensitivity was obtained down to very low modulation frequencies, for sine and square-wave modulation using either an equiluminant or dark surround. The experiments were performed on subject C.W.T.

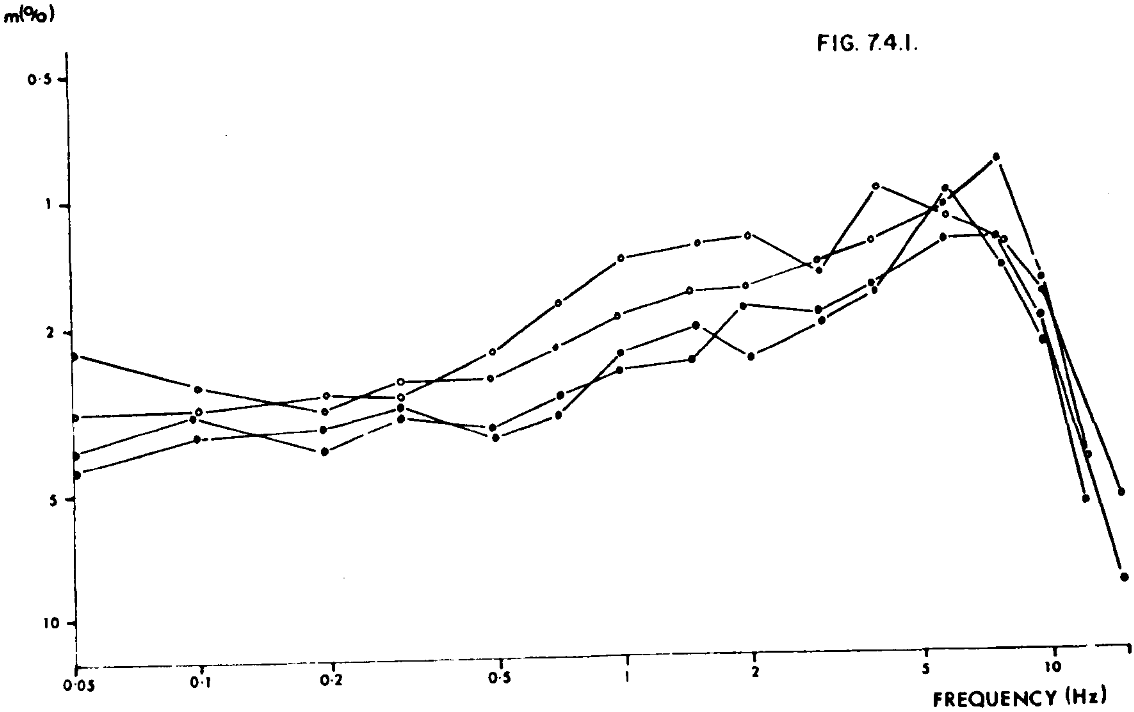
7.4.1. Luminance Modulation at Low Frequencies

Method

De Lange's (1957) original stimulus configuration was first replicated, with the exception that monochromatic light was used for the surround. For most experiments, a wavelength of 527 nm was used for the dark surround, and 544 nm for the equiluminant surround, since this was the nearest available interference fitter to the standard 527 nm used in many experiments in this thesis. Checks were made that the dominant wavelength difference did not exert a significant effect on the conditions described. As in previous experiments, the flickering field was 2^{o} in diameter, with a 10^{o} equiluminant, equichromatic surround when required. Threshold modulation depth was set by the subject for frequencies extending down to 0.05 Hz. Although tedious, this task was not found particularly difficult by the subject. Readings were taken in two sets of two readings for each set for every experimental condition. Readings for sine and square-wave modulation were alternated at each modulation frequency.

Results

Fig. 7.4.1. shows that for both sine-ware and square-wave modulation using an equiluminant surround, the main features of De Langes results with white light are evident, although the sensitivity does not level off at 1-2 Hz, as suggested by De Lange, (1957, pg27), but continues to fall to 0.5 Hz, before reaching a steady level of about half the sensitivity at 2Hz. This low frequency steady level presumably represents, for the square wave modulator, a transient regime in which the threshold to each luminance step is unaffected



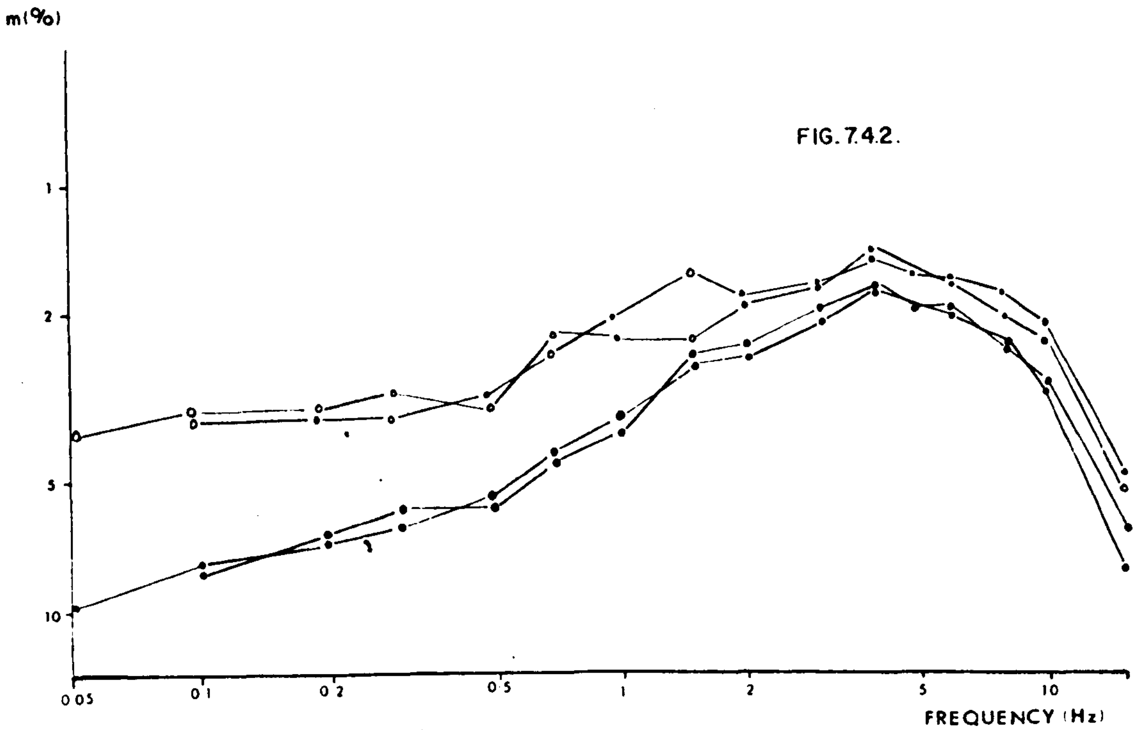


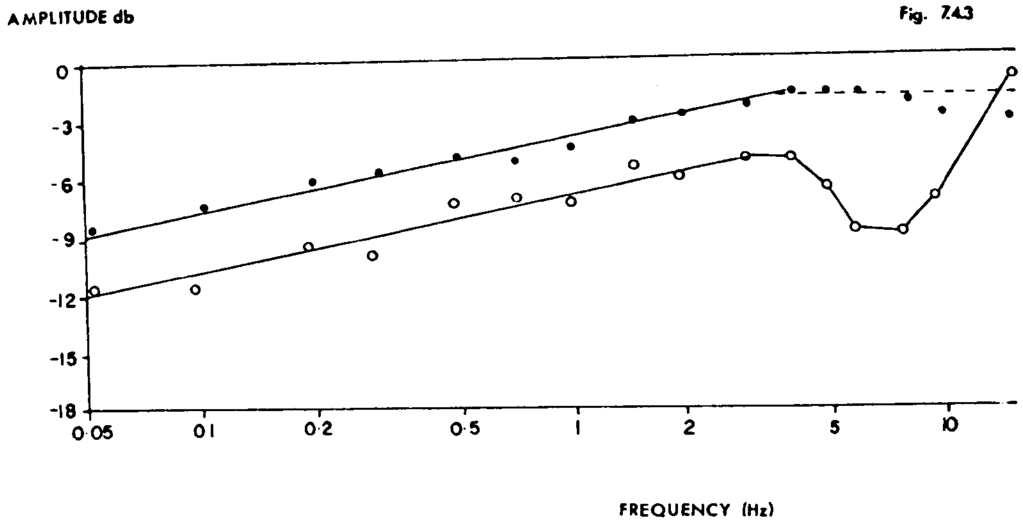
Fig. 7.4.1. De Lange curves with equiluminant surround. Open circles - square wave modulation. Filled points - sine-wave modulation. Other conditions as in Figs. 7.2.1-5. Wavelength - 527nm.

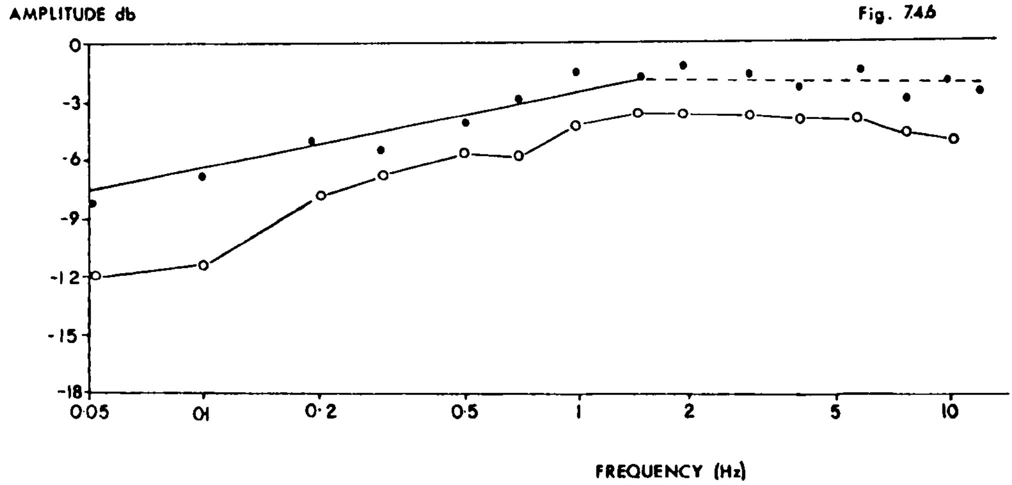
Fig. 7.4.2. De Lange curves with dark surround. Other conditions as for Fig. 7.4.1.

by the preceding step. The sine - wave case is considered below.

The separation between sine and square wave thresholds at high frequencies was attributed to, by De Lange, the greater amplitude of the fundamental Fourier component of the square-wave compared with the sine wave. The separation above 5 Hz is consistent with the predicted separation of a factor of $\frac{4}{\pi}$. As found by De Lange, the separation increases in the zone around 1 Hz. He suggested that this was due to the effect of higher harmonics in the square wave response. However, these would be expected to have maximum effect in the transient region, where in fact the sine/square separation appears to decrease again. The suggestion is discussed in the next section, that the peak sine-wave amplitude is detected against the spatial reference of the surround, whereas the peak square-wave amplitude detection involves a temporal reference. If this is the case, the sensitivity to square-wave modulation may be enhanced by transient temporal overshoot whereas the sine-wave sensitivity may be increased by spatial edge enhancement. The sine/square separation would therefore reflect differences between the two types of enhancement.

The data of fig. 7.4.2. depict sine- and square-wave modulation thresholds for a 2° field with a dark surround. As found by Kelly (1959) for a 4° field with a dark surround, the sensitivity is much reduced for frequencies below 10Hz, for both sine and square-wave modulation. The separation between the sine and square wave sensitivities to be expected from the amplitudes of the fundamental Fourier components.



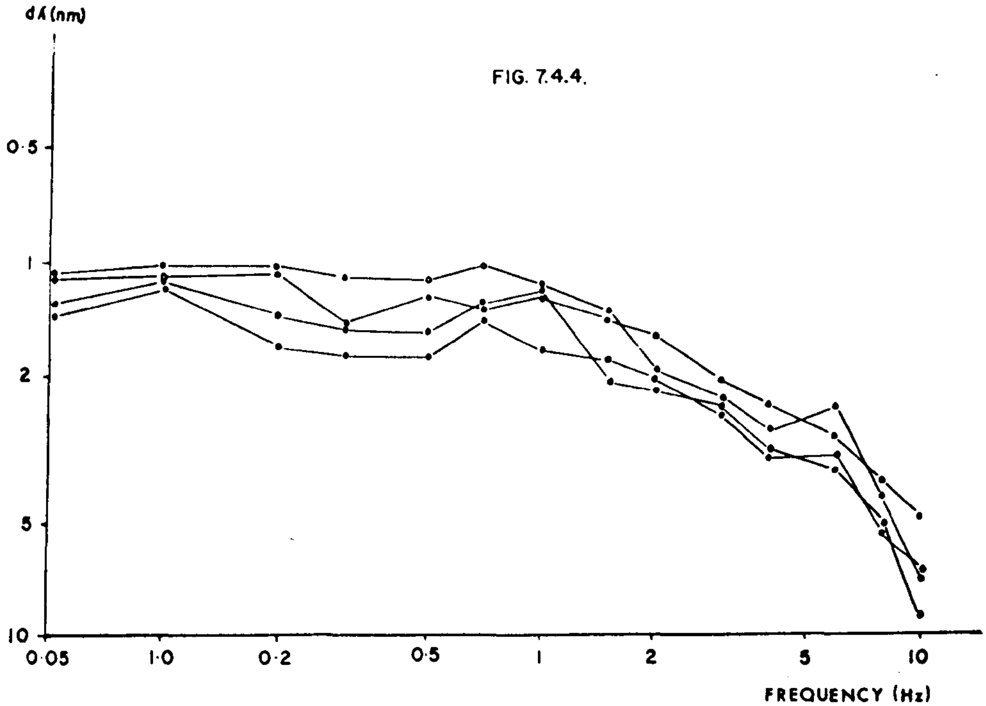


<u>Fig. 7.4.3.</u> Subtraction curves for luminance modulation De Lange curves (in db). Filled points - square minus sine-wave conditions (Fig. 7.4.2.) Open circles - equiluminant minus dark surround conditions. (Fig. 7.4. 1-2).

<u>Fig. 7.4.6.</u> Subtraction curves for wavelength modulation De Lange curves. Filled points - square- minus sine-wave conditions (Fig. 7.4.5.) Open circles - equiluminant minus dark surround (Figs. 7.4.4-5).

is maintained for frequencies above about 3 Hz. In the frequency region below 3Hz, the form of the square-wave sensitivity curve appears to be closely similar for equiluminant and dark surrounds, although the dark surround curve is about 6 db lower than the equiluminant surround curve (see Fig. 7.4.3.). This implies that no frequency dependent spatial interactions are significant in terms of square wave threshold. On the other hand the sine-wave dark-surround sensitivity falls progressively as frequency is reduced, relative to the sine-wave equiluminant surround sensitivity. The ratio of the two responses is plotted in the log subtraction curve (Fig. 7.4.3.), which makes it clear that the decline is steady at 4 db /decade over nearly two decades of frequency. Fig. 7.4.3. also depicts the log subtraction curve for square form sine-wave modulation, each with dark surround. The 4 db /decade decline is replicated in this case, indicating that the presence of either a spatial edge (sine, equiluminant surround case) or a temporal step ("edge") (square, dark surround case) will prevent the low frequency adptation effect. Similar results on the effect of a surround are evident in the data of Keesey (1970). The same frequency sensitivity difference is present in each case although the amplitude of the response with a temporal step is evidently larger than that of the response with a spatial edge by about 3 db. In the frequency region above 3 Hz, the equiluminant: dark surround response ratio reflects a peak of 7 Hz in the equiluminant surround response, which is less marked in the dark surround case. The spatial configuration thus affects the details of the form of the sensitivity curve, as found in other conditions by

Kelly (1969, 1969b). However, examination of spatial, colour interactions in De Lange curves is beyond the scope of the present study.



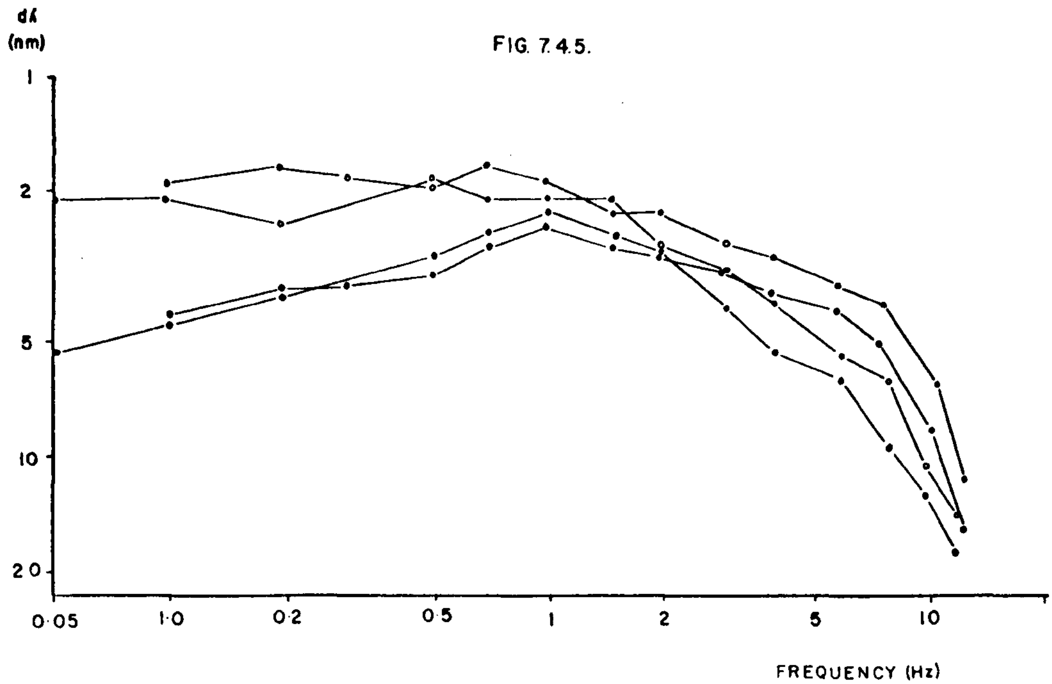


Fig. 7.4.4. De Lange curves for wavelength modulation with equiluminant surround. Other conditions as for Fig. 7.4.1.

Fig. 7.4.5. De Lange curves for wavelength modulation with dark surround. Other conditions as for Fig. 7.4.1.

7.4.2. Wavelength Modulation

Using similar conditions to those in section 7.4.1. the effects of modulation waveform and presence of a surround were studied for a wavelength modulation about a mean wavelength of 527 nm or 544 nm (for the reasons as outlined in section 7.4.1.)

Results

As Figs. 7.4.4. and 7.4.5. indicate, the configuration of both temporal waveform and spatial surround have effects similar to those for luminance modulation. In the high frequency region (above 1 Hz for wavelength modulation) the separation between square and sine-wave modulation for both equiluminant and dark surround seems to fit quite well the $4/\pi$ difference predicted if the fundamental Fourier component of each waveform determined threshold. This accords with the conclusions of Van der Horst (1969) who found the same effect of waveform in an investigation of only the equiluminant surround case and at a different mean wavelength. There is no significant effect of the surround on the square-wave sensitivity over the whole frequency range. (The possible overall increase in sensitivity is obscured by the change in mean wavelength between the two conditions). In the case of sine-wave modulation, however, the absence of a surround (Fig. 7.4.5.) produces a steady decrease in sensitivity as frequency is reduced below 1 Hz. The sensitivity falls at a similar rate to that for luminance modulation, i.e. 4 db /decade. The log subtraction curves for square-from sine-wave modulation and dark from equiluminant surround conditions are depicted in Fig. 7.4.6. The 4 db /decade adaptation slope is a good fit for the sine/square ratio below 1 Hz. The data for the dark/equiluminant log subtraction curve do not conform well to the same adaptation slope, but further experimentation would be required to determine whether this can be ascribed to experimental error or represents an additional effect.

Thus for wavelength modulation, as for luminance modulation, the general forms of the square-wave modulation sensitivity for either surround condition, and for sine-wave sensitivity with an equiluminant surround, are quite similar, whereas if the surround is removed with sine-wave modulation, a low frequency slip-in effect (De Lange, 1957 pg 40) or adaptation is evident. However, the slope of this adaptation is far shallower than the cut-off of a single stage first-order filter (i.e. 20 db /decade).

There are differences in the frequency at which the adaptation slope begins. For luminance modulation, it appears at about 3 Hz, whereas with wavelength modulation it is not present above about 1 Hz. This difference in the temporal characteristics of the adaptation between wavelength and luminance modulation suggests that the adaptation is occurring after the separation of the luminance and colour processing channels, but before the modulation detector stage. The similarity in slope, however, suggests that similar processes are involved in each channel.

7.5. Transient Stimulation

7.5.1. Introduction

The results of section 7.2. indicate that the visual system frequency response functions for steady state wavelength modulation differ markedly from those for luminance modulation. There are not, on the other hand, great differences between the frequency characteristics compared at different mean wavelengths for either type of modulation. This is perhaps surprising in view of the marked differences that have been reported in various measures of the transient response to different stimulus wavelengths, (reviewed in section 3.10.). It was therefore decided to examine the response of the visual system to pulses of wavelength change (at constant luminance), in order to shed light on the discrepency between the steady-state and transient approaches to colour change stimuli. The use of a constant-luminance wavelength pulse was designed to be comparable in the transient regime to the sinusoidal wavelength modulation in the steady-state regime. The object was to stimulate the colour detection mechanisms while presenting no effect to the luminance detection mechanism. The response to constant-wavelength luminance pulse[3] stimuli will be examined, with wavelength as a parameter, as a comparison with the effects of the wavelength pulse. The threshold response to luminance pulses is known as the increment threshold. (Graham & Kemp, 1938). Increment thresholds as a function of pulse duration have not previously been studied at different wavelengths, as far as I could ascertain, except for the special case of zero background retinal illuminance, i.e. absolute threshold.

The values of critical duration will be compared for luminance pulses at different wavelengths, for wavelength pulses relative to luminance pulses under otherwise similar conditions, and for wavelength pulses at different mean wavelengths. In addition the effect of variations in mean retinal illuminance on the critical duration for a selected condition was measured. The results of this section have been ~~submitted~~ accepted for publication (Regan and Tyler, 1971 b).

7.5.2. Method

The wavelength of a 2^{o} field was modulated by means of the wavelength modulator described in secion 5.2. The modulator produced a stimulus of contimously variable wavelength, Consequent variations in stimulus luminance are cancelled to below subjective threshold by means of a crossed polaroid luminance modulator (section 5.1.) which was also used alone to produce the luminance flashes for the data on critical duration for luminance. The modulators were fed with pulses of variable duration triggered at 10 sec. intervals. The performance of the modulators under these conditions was ascertained by means of a fast STC photovoltaic diode placed at the exit pupil as described in section 5. The performance was satisfactory for the conditions used.

For a range of pulse durations presented randomly the subject was required to reduce the wavelength increment[4] to subjective threshold. The luminance change produced by the wavelength pulse was cancelled by an inverse pulse to the luminance modulator. The subject adjusted the amplitude of the latter until the percived luminance change was at a minimum for each individual observation. The signal to both modulators was then reduced in parallel by a single control, thus allowing the subject to set the wavelength increment to threshold while luminance changes were maintained at a subthreshold level.

All the experiments were performed on a single subject. (C.W.T) Four readings were averaged for each data point. The readings were made in random order for each of the four sets of durations used.

FIG 7.5.1

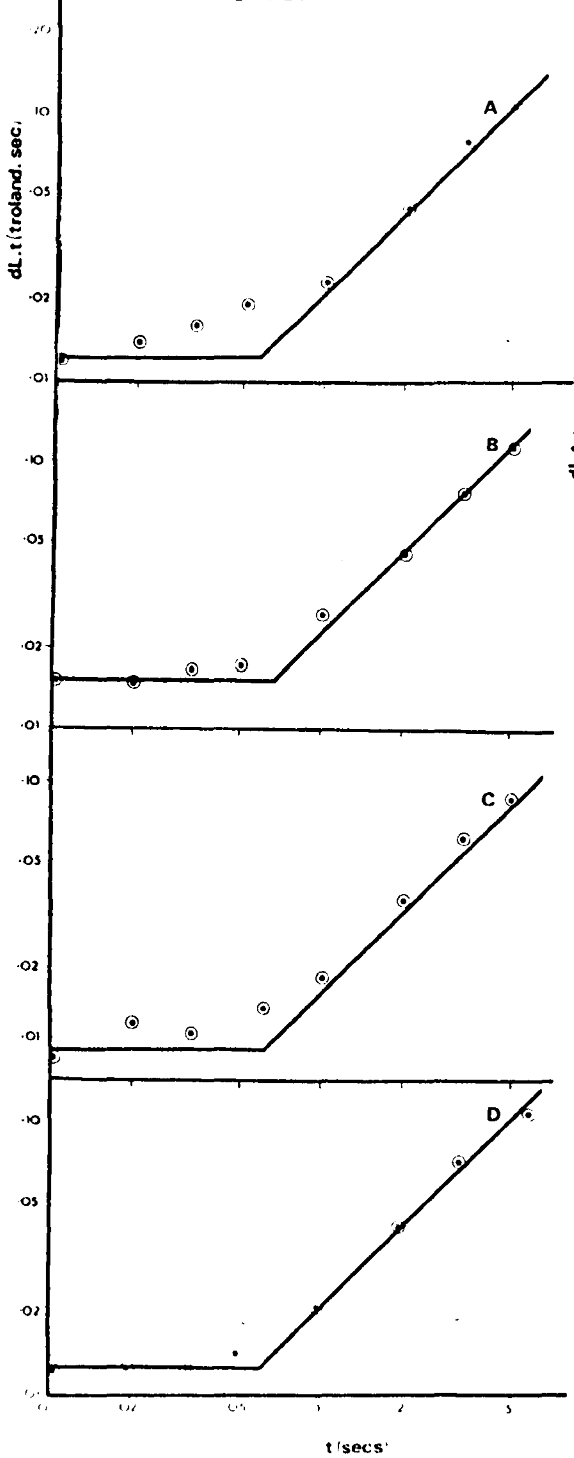


FIG. 7.5.2.

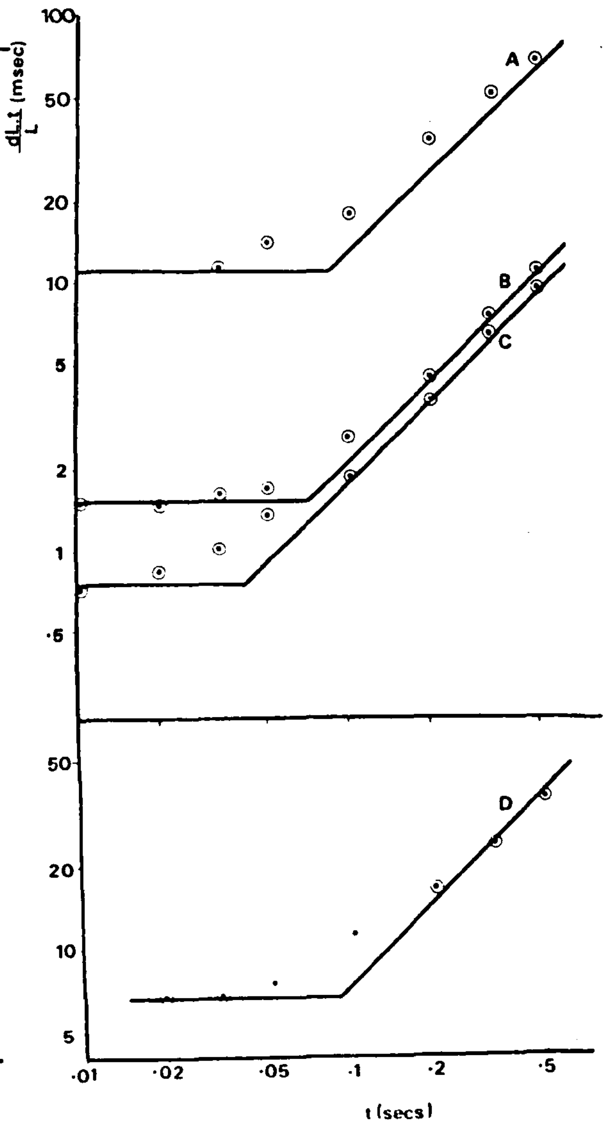


Fig. 7.5.1. The product of threshold pulse luminance (dL) and pulse duration (t) as a function of t. Log-log coordinates. For other conditions see text.

Fig. 7.5.2. The product of threshold relative pulse luminance ($\frac{dL}{L}$) and pulse duration (t) as a function of t. For other conditions see text.

7.5.3. Results.

The results are plotted in the form common in studies of increment threshold as a function of time of log dL.t.

(or log dλ.t) against log t in which Bloch's law is represented by a horizontal line, and time independence by a 45° line. The lines are fitted by eye as asymptotes to the more extreme values. Fig. 7.5.1. A,B,C,D confirms the classical form of the time function of luminance increment thresholds. The extrapolated critical durations (t_c) for wavelengths 480, 527, 580 & 600 nm at 10 trolands are about 56(± 8), 65(± 4) and 62, (± 5), 6(± 2) msec, respectively. These values are not significantly different within the limits of experimental error. The error terms in this section are computed as follows. Asymptotes were fitted to the first and second pairs of readings taken. Half the difference between the two values of critical duration thus obtained is quoted as the modulus of the error. No order effects were evident on inspection.

The critical duration does not therefore appear to be significantly affected by stimulus wavelength within a range of 120 nm and at a mean (adapting) retinal illuminance of 10 tr, with a field size of 2°.

It was possible to repeat the 527 nm luminance pulse experiment at a retinal illuminance about 1 log unit higher (110 tr) and two log units lower (0.1 tr). (Fig. 7.5.2. C and A). The critical durations obtained were 43 (± 2) msec and 96 (± 5) msec respectively, In the o.1 tr condition the field appeared colourless.

The 600 nm experiment was also repeated at 0.1 tr (fig. 7.5.2.D). The luminance pulse critical duration was 90 (± 7) msec. i.e. similar

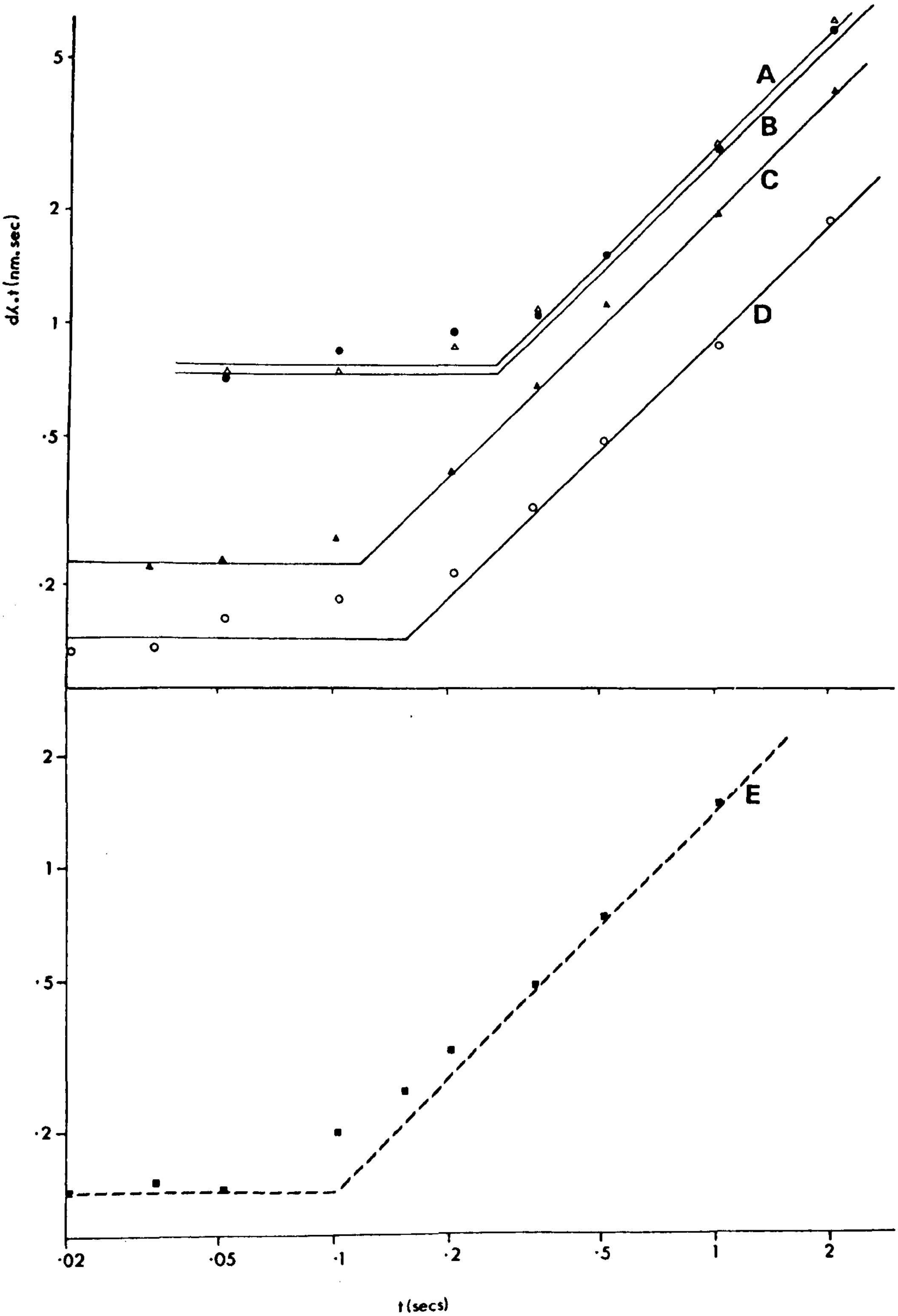


Fig. 7.5.3. The product of threshold wavelength pulse amplitude (dλ) and pulse duration (t) as a function of t. Log-log coordinates. For other conditions see text.

to that for the 527 nm condition at the same retinal illuminance.

The results for wavelength pulses at a retinal illuminance of 10 tr. are shown in Fig 7.5.3. For all four wavelengths tested (480, 527, 580 + 600 nm) it is clear that a phase approaching reciprocity between wavelength change and time exists, for the threshold of short duration wavelength pulses. The threshold wavelength change for long duration pulses conforms to the 45° asymptote, indicating time-independence.

Thus within the limits of wavelength change used (up to 20 nm) the form of the increment threshold function for the wavelength pulse is similar to that for luminance increments. The extrapolated critical durations for the wavelength pulses (t_{cw}) at the four wavelengths tested (fig. 7.5.3. A,B,D,C.) were about 250 (± 15), 250 (± 20), 160 (± 5), and 110 (± 3) m sec for 480, 527, 580 and 600 nm respectively. These durations are between two and three times the critical duration for luminance pulses under the same conditions. They also vary by a factor of at least two across the spectral locations tested.

Fig. 7.5.3 also shows a wavelength pulse threshold curve (E) for 527 nm at a retinal illuminance increased by about 1 log unit (110 tr). The critical duration is about 104 (± 2) m sec, as compared with 250 (± 20) m sec for the 10 tr. condition. Thus at this wavelength the luminance of the stimulus has a marked effect on the wavelength pulse threshold.

7.5.4. Luminance Pulse Responses

The response to luminance pulses conform to the classical data of Graham & Kemp (1938). Using white light, they obtained measures of critical duration for a range of values of mean luminance using a natural pupil.

Computation of the approximate values of retinal illuminance using the measures of pupil diameter quoted by Le Grand (1957 pg 96) allows comparison of the critical durations obtained for white and the present monochromatic light. Graham & Kemp's values are about 90 m sec at 0.1 trolands, 60 msec at 10 trolands and 40 msec at 110 trolands, which correspond well with the values for monochromatic (527 nm) light in fig. 7.5.2. for the present subject.

The values for critical duration for luminance pulses at 10tr adapting retinal illuminance (fig 7.5.1.) show no influence of mean wavelength within the experimental error. This is in accordance with the very small field data of Rouse (1952) and the 4.5' field data of Sperling and Jolliffe (1965). However, Sperling and Jolliffe found that a 200 nm wavelength difference produced a significant difference in critical duration with a stimulus configuration (45' field, dark surround) similar to the present one (2^{o} field, dark surround). Their data were obtained with zero adapting retinal illuminance in the stimulus field, in contrast with the 10 troland adapting retinal illuminance used for the results in Fig. 7.5.1.. This difference in adapting conditions may be a factor in the discrepency between the results of Sperling & Jolliffe and those of the present experiment.

7.5.5. Validity of the Constant Luminance Wavelength Pulse Stimulus

The procedure for minimising the luminance change produced by a pulse change in stimulus wavelength is described in section 7.5.2. The possibility remains that threshold was not determined solely by chromatic changes either a) because at the minimum the cancellation was not complete, and some luminance change still present, or b) because, even if cancellation was completely effective, the separate pulses in each cone mechanism due to the constant-luminance wavelength pulse stimulus are by some means (e.g. a temporal difference) still processed as luminance signals, or c) because rod intrusion became a significant factor in the determination of threshold.

The critical duration for rods as measured in the peripheral retina at the mean retinal illuminance used in the principal wavelength pulse experiment is not known, but at absolute threshold, it was not found to be longer than the longest value for cone (foveal) vision (200 msec. Sperling & Jolliffe, 1965). It is therefore likely that the critical duration for rods at 10 tr photopic retinal illuminance would be similar to that of the cones. This will be assumed to be the case for the moment.

Given the assumptions concerning critical duration for rod vision just discussed, the data described in section 7.5.3. support the idea (section 2.5), that wavelength pulses are not processed by the same system as luminance pulses. The critical durations for wavelength pulses (t_{cw}) are considerably longer (by between 80% and 430%) than luminance pulses under the same conditions, and also vary by a factor of 2 as a function of mean wavelength, whereas luminance pulses are not significantly affected by mean wavelength (compare Figs. 7.5.1. & 7.5.3.). Furthermore, the effect of mean retinal illuminance on t_{cw} is much greater at the wavelength tested (527 nm) than is the effect on t_c. t_{cw} is reduced to 70% of its 10 tr value by a 1 log unit increase in mean retinal illuminance, whereas t_c is only reduced by 35% In combination, these facts suggest that changes corresponding to those induced by luminance pulses (as in a,b or c) are not involved in the determination of thresholds to wavelength pulses.

The assumptions made concerning critical duration for rod vision may be incorrect, for example due to the scotopic retinal illuminance having a very different value from the stated photopic retinal illuminance. The standard C.I.E. date (C.I.E. 1951) for photopic and scotopic luminosity (which are used to determine the values of the respective types of retinal illuminance) shows a difference of not more than about 1 log unit sensitivity between the two functions within the range 480-60 nm. An experiment was therefore conducted using a stimulus designed to stimulate only rods at a reduced adapting retinal illuminance. The 527 nm stimulus was presented at a retinal illuminance reduced by 2 log units (0.1 tr). It appeared colourless to the subject. The critical duration was computed as 90 (± 7) msec for the 600 nm condition. It was not comparable with the wavelength critical duration obtained at the same spectral locus until the retinal illuminance was increased by about 3 log units (104 (± 2) msec at 527 nm and 110 tr). The decrease in retinal illuminance required for the critical duration for rod vision to equal that found using the wavelength pulse stimulus is thus considerably larger than should be expected from the difference between rod and cone luminosity functions, if the C.I.E. luminosity functions approximate to those for the present subject.

It therefore appears that the possibility of contamination of the wavelength pulse data with luminance change information from a number of possible sources is not supported by the data described above.

7.5.6. Discussion

If the considerations of the preceding section are correct, the data of fig. 7.5.3. represent psychophysical thresholds to wavelength-change pulses for the subject tested. The data have a similar form with respect to pulse duration as the luminance pulse data. They appear to fit the 45° asymptote ($d\lambda = C_1$) within the limits of error at long pulse durations. The fit to the horizontal asymptote ($d\lambda.t = C_2$) is limited by the large amplitudes of pulse required at short durations, but is nevertheless satisfactory. A critical duration (t_{cw}) can be computed for the wavelength pulse data which is 80 - 430% longer than the critical duration for luminance pulses under otherwise similar conditions, and which varies by a factor of about two over the spectral region examined. The critical duration (t_{cw}) is not proportional to the variation in threshold at longer duration (shown by the vertical displacement of the 45° asymptotes for different wavelengths in fig. 7.5.3.).

A widely accepted theory of the form of the response to pulse stimulation is that of Hartline (1934), based on physiological observations in the limulus eye. He found that the Bunsen-Roscoe law of temporal summation held up to a certain pulse duration (the critical duration) at which point there was an abrupt change in the function fitted by the response to a form constant for constant intensity. Hartline interpreted horizontal ($dL.t$ = const) part of the curve as resulting from a photochemical integration process. The abrupt change in the response function was considered to have been produced by the occurance of a critical event in the receptor cell (not necessarily the occurence of a recordable spike discharge) after which the temporal integration was no longer relevent in the information transmitted to the brain. A similar explanation has been invoked to explain human psychophysical functions of the same form (Graham & Kemp, 1938). The wavelength pulse data conform reasonably well to the two asymptotes of $d\lambda.t = C_1$ and $d\lambda = C_2$, showing a change from one mode to the other as abrupt as in the case of the luminance pulse data. If Hartline's interpretation is correct, then the wavelength pulse data imply an integration process lasting up to 250 msec for the subject tested, with a distinct critical ev nt in the colour processing channel, as described in section 2.5. The integration process involved is not necessarily photochemical, but, on Hartline's model, it must involve continuous integration up to the critical event in the colour channel. The measured critical duration correspond to the period from the start of the integration to the occurrence of the critical event.

It should be noted that the data of responses to both luminance and wavelength pulses is compatible with other models of visual response to pulses. This point is considered further in section 8. Hartline's model is described here as it has a physiological basis and it is therefore more persimonious to accept it, if it can be applied to the wavelength pulse data.

8. Models of Dynamic Wavelength Discrimination

8.1. De Lange's Model

The first approach to a model of dynamic wavelength (or chromaticity) discrimination was suggested by De Lange (1957). His results indicated that the wavelength modulation threshold function differed by a small number of simple attenuation stages from luminance modulation threshold function for the same stimulus conditions. This approach does not specify the physiological mechanism involved in colour processing, but merely that the system involves a variable number of first-order stages of attenuation depending on the average luminance of the brightness signal during the process. This suggestion should be considered in relation to the evidence (reviewed in section 2.5.) for independence between the brightness and colour channels in the visual system of the form suggested by Walraven (1962), each deriving information from the same photoreceptor stage. De Lange's suggestion implies either a) that the luminance modulation threshold function is produced solely in the stage before the separation of brightness and colour channels or b) that the attenuation characteristics of the separate colour channel are the same as those of the brightness channel, with a small number of extra first-order attenuation stages. Neither of these possibilities are very likely in view of the discrepancies in form of the difference curves for luminance as opposed to wavelength modulation sensitivities under a range of conditions (discussed in section 7.2.)

The difference curves do not conform to the attenuation produced by a small number of cascaded filters, and indicate that the relationship between luminance and wavelength modulation functions is far from simple in the spectrum as a whole. This lack of a consistent relationship lends support to Walraven's concept of the independence of brightness and colour channels developed from Pieron's (1939) ideas, and of the processes involved in each.

Walraven & Bouman's (1966) fluctuation theory model will now be considered in greater detail, in relation to the effects of frequency on the dynamic wavelength discrimination function.

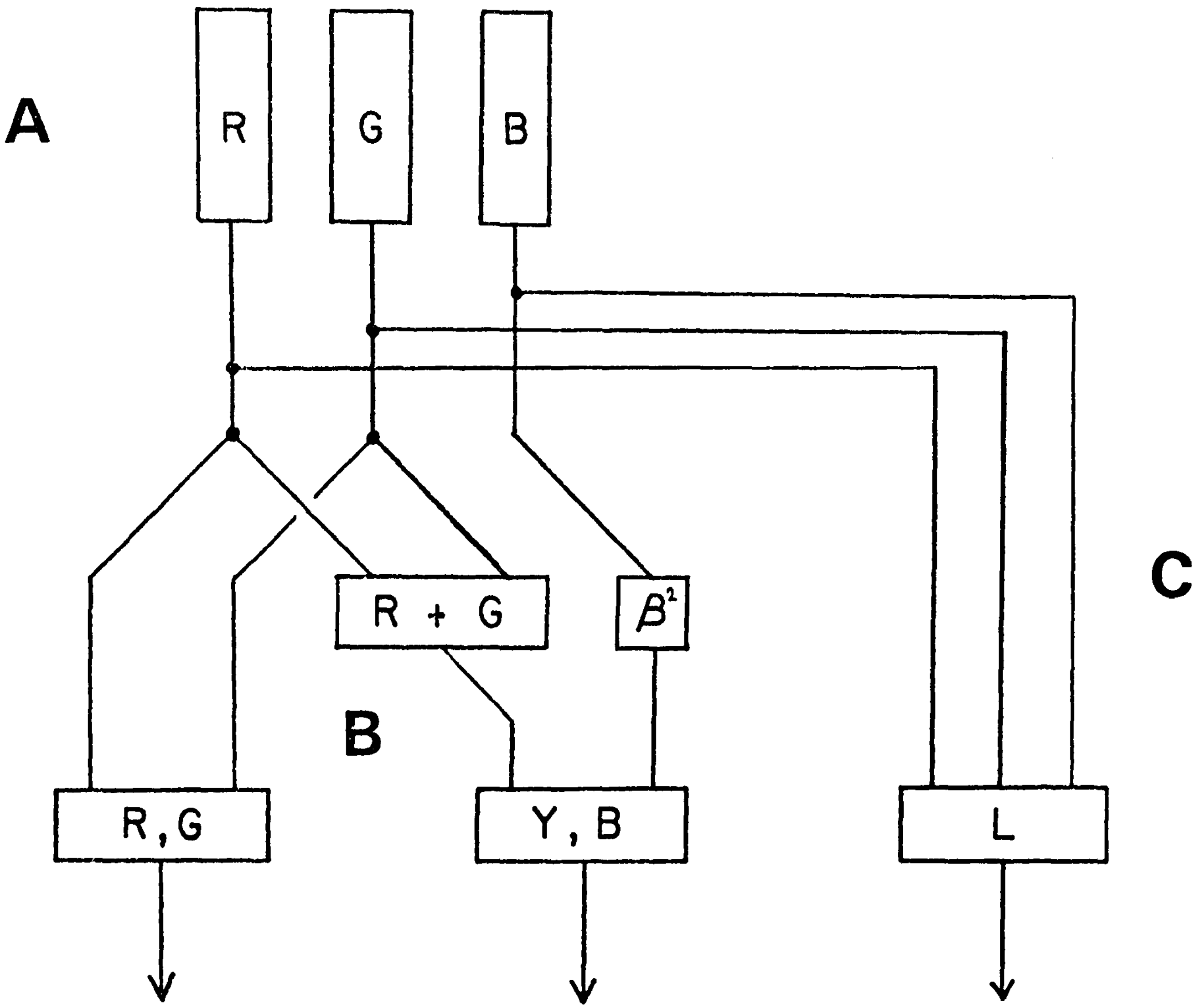


Fig. 8.0. Model of colour processing system (Walraven and Bouman, 1966). For explanation, see text.

8.2. Fluctuation Theory Model

The Walraven & Bouman fluctuation theory, as described in section 2.4.3., is elaborated from a perfect detector model by means of a set of colour-encoding relationships which are embodied in Fig. 8.0. The luminance channel (C) branches from the chromatic channel (B) immediately after the receptor stage (A). The chromatic channel contains a comparator (R,G) which compares the outputs of the red and green cones in some unspecified manner. The second comparator (Y,B) compares the summed outputs of the red and green channels with the output of the blue channel multiplied by a certain factor (β^2) which varies with conditions such as luminance level.

The analysis in the present section is oriented to the question of whether the dynamic wavelength discrimination frequency dependence (section 7.3.) is explicable in terms of the Walraven-Bouman model, and if so which segment of the model determines the frequency dependence. In particular, the question is whether differential cone frequency response functions such as are reported by Green (1969) are sufficient to explain the dynamic wavelength discrimination functions (in which case the functions would be determined in block A), or whether the functions reflect the opponent colour interactions of block B.

The effect of differential cone frequency response functions in the blue green region of the spectrum is to decrease sensitivity to the blue signal relative to the green as frequency is increased. The decrease found by Green (1969) between 1 and 5Hz was by a factor

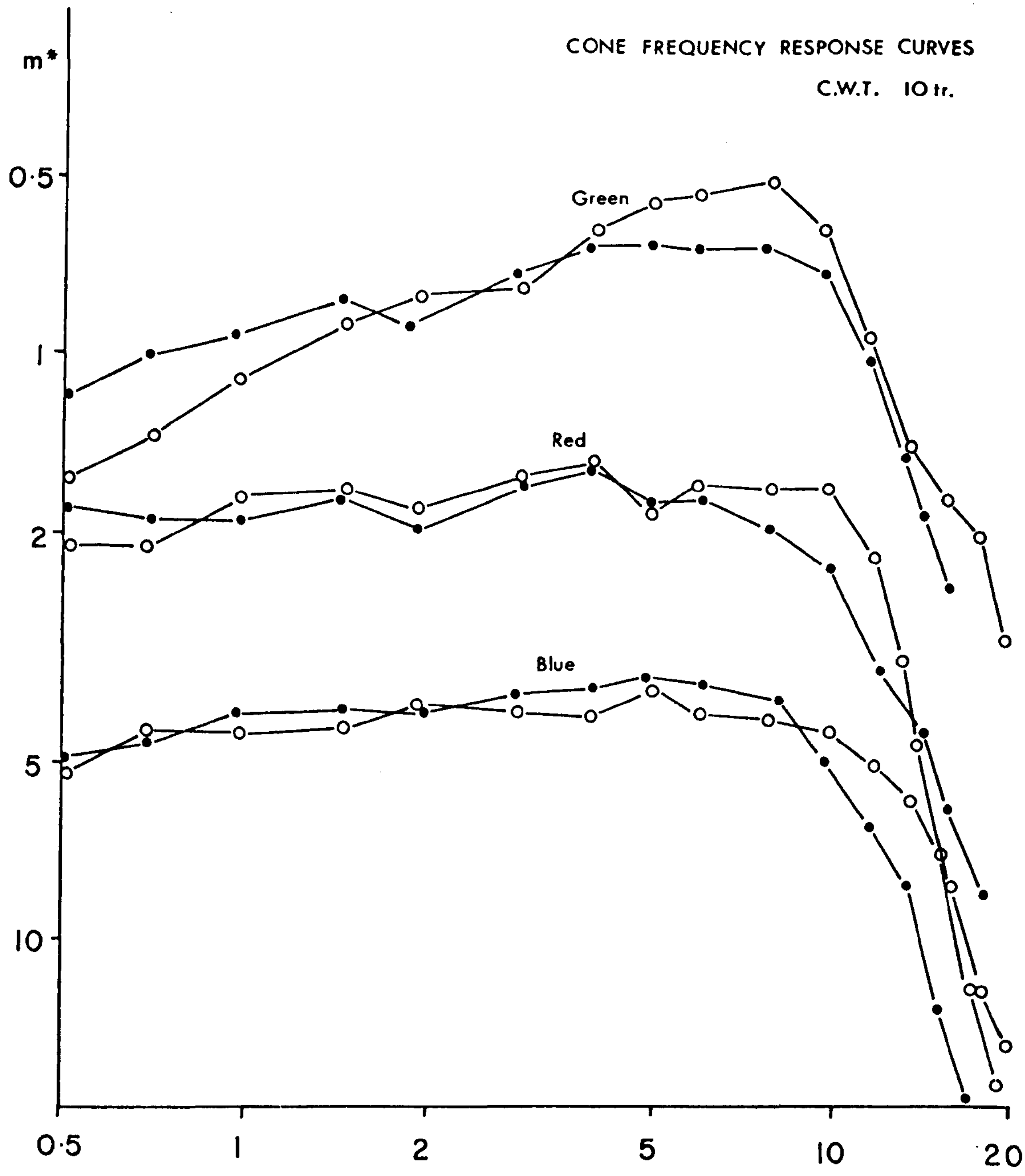


Fig. 8.1. Cone frequency response curves. For method and definition of modulation parameter (m*) see text.

of two.

The method used by Green to measure cone frequency response functions was replicated for subject C.W.T. A stimulus consisting of a 2^{o} centrally fixated test field of a dominant wavelength such as to stimulate one type of cone to which is added a 10^{o} adapting field of a dominant wavelength that favours the other two types of cone. The isolated test field retinal illuminance used was 10 trolands measured by flicker photometry, (as opposed to 125 "effective" trolands used by Green, who does not describe how he arrived at this measure). The cone frequency response functions were measured with an adapting field of a retinal illuminance such as to depress the peak sensitivity so that 10 per cent modulation of the test field was at threshold. Calibration of the actual modulation of the test field was performed by the method described by Green, which consists essentially of finding the change in modulation sensitivity produced by raising the retinal illuminance of the test field by a factor of 4.5. This change indicates the relative extent to which the cone type under investigation in any one of the three adapting conditions is stimulated by the test (modulated) and adapting (steady) fields.

The resulting frequency response functions of the three cone mechanisms are plotted in Fig. 8.1. The three functions are similar in form to those found by Green at a higher retinal illuminance. The red and blue functions are approximately flat to about 10 Hz, then show a sharp fall-off. For the green function, sensitivity increases up to about Hz before showing a similar fall-off. Again, in agreement with Green's data, the blue sensitivity is depressed relative to the other two (though not to the same extent as under Green's conditions).

For the purpose of the present discussion, the feature of interest is the change in sensitivity of the blue relative to the green mechanism between 0.5 and 5 Hz. It is clear from Fig. 8.1. that for subject C.W.T. at a retinal illuminance comparable with that used for the dynamic wavelength discrimination experiments, this change is somewhat less than the factor of 2:1 found by Green. Since brightness variations are cancelled at all times, the flux entering the blue cone must be approximately doubled at 5Hz relative to 1Hz.

There are two possible effects of this relative change in cone sensitivities.

a) If the difference between frequency response functions occurs before the separation of luminance and colour-processing channels (i.e. in block A) the brightness cancellation will ensure that the amplitude of the signals entering the colour processing channel (block B) is independent of frequency. In this case no part of the frequency dependence of wavelength descrimination is attributable to the frequency characteristics of the cone mechanism (block A).

b) On the other hand, the difference between the frequency response functions might occur after the separation of the luminance and colour-processing channels in block C. If this is the case, then the cancellation of the brightness variations at the site of flicker perception, will produce an increase of the order of a 2:1 in the ratio of blue to green signals at the cones as frequency is raised from 0.5 to 5 Hz. This increase will enter the colour channel without being compensated, and will consequently alter the ratio of blue to green signal available for hue discrimination. Walraven & Bouman (1966) have studied the effect of altering the blue-green signal ratio on wavelength discrimination in terms of their quantum fluctuation theory of discrimination. Doubling the blue-green signal ratio will shift the threshold discrimination minimum of the blue region of the spectrum approximately 5 nm towards the long wavelength. This prediction is in the same direction as the results shown in figure 7.3.1 (pg 177), but is only about one quarter of the magnitude of the empirical results. Thus differential frequency sensitivities of the three colour signals occurring after the separation of brightness and colour channels, would result in a small shift of the blue discrimination minimum, but sufficient to account for only a part of the experimental shift.

It is concluded that whichever part of the luminance processing pathway is responsible for the differing frequency response functions of the three colour sensitive mechanisms, the colour processing channel (block B) must be responsible for a large part of the frequency dependence of the wavelength discrimination functions.

The above analysis has attempted to show whether differences in the cone mechanism frequency response functions (fig. 8.1.) could account for the 30 nm shift in the blue minimum of the dynamic wavelength discrimination curves with frequency. This appears not to be the case. However, the assumption that the blue channel gain factor $\beta 2$ (Fig 8.0) is frequency dependent does allow the dynamic wavelength discrimination results to be modelled by fluctuation theory. The gain factor β^2, which is postulated to operate only in the colour channel (block B), has been shown to vary with stimulus luminance by Walraven and Bouman (1966). Their results indicate that the required shift in the blue minimum would be produced if β^2 changed from 16 to 250 over the range 0.5 - 5 H_z. This would require a 1·2 log unit increase in the relative sensitivity of the blue colour channel, or decrease in relative sensitivity of the summed red and green (yellow) channel. Such a change, together with an approximately twofold decrease in sensitivity of all channels, would account for the frequency dependence of the dynamic wavelength discrimination function.

8.4. Opponent Process Theory and Dynamic Wavelength Discrimination

As is described in section 2.4.4. the Opponent Process theory as outlined by Hurvich and Jameson (1955) maintains that the wavelength discrimination function can be derived from the rate of change of relative hue coefficients together with the saturation discrimination function through the spectrum. There have been no studies of the frequency dependence of either the hue coefficients or the saturation function, so that no direct prediction from the Opponent Process theory is possible. (The hue shift of flickering lights measured by Van der Horst & Muis (1969) is not relevant in this connexion as their stimuli were over 100^{0} per cent modulated in luminance and several log units brighter than those reported herein, whereas the frequency dependence of wavelength discrimination was found for threshold wavelength modulation).

It is therefore of interest to examine whether the frequency dependence of wavelength modulation may be described in terms of the previously known dimensions of variation of the parameters determining the wavelength discrimination function according to the Opponent Process theory. As in the case of the fluctuation theory, the Opponent Process theory has been applied to the wavelength discrimination luminance levels 1 log unit apart (data from Weale , 1951).

As described in section 2.4.4. the predicted wavelength discrimination function was derived from a combination of the rates of change of the hue coefficient and the saturation discrimination function at each wavelength interval. The effect of altering luminance level on the hue (and hence saturation) coefficients was found to correspond to a 10 nm shift towards the red in the blue minimum over the luminance range used by Weale. Hurvich & Jameson suggest that the effect of increasing luminance level corresponds to a change in the summing constant of the two opponent mechanisms, that for the $r_\lambda - g_\lambda$ mechanism increasing relative to that for the $y_\lambda - b_\lambda$ mechanism. The main effect of this change in summing constants is that a shift in the hue discrimination short-wavelength minimum towards the longer wavelengths occurs, and in the case of the saturation discrimination function, a minimum appears at around 500 n.m. There is little change in the long wavelength end of the spectrum. These effects combine in the wavelength discrimination function to produce the shift of the blue mimimum. If these effects increase as luminance is further increased, it is plausible to suppose that the blue minimum would move as far as 500 nm, as in the 5Hz dynamic wavelength discrimination curve. If this were the case, the frequency dependence of the dynamic wavelength discrimination curve would be accountable in qualitative terms by a change in the summing constants of the opponent mechanisms, together with a general decrement in discrimination sensitivity. It therefore appears that the dynamic wavelength discrimination data can be accommodated within the Opponent Process theory.

8.5. Linear Systems Analysis

8.5.1 Introduction

The systems analysis approach to visual system dynamics described in section 4 has inspired the techniques utilised in this study. It is therefore of value to know whether the visual system can be analysed in terms of the linear mathematical concepts inter-relating various aspects of system performance, (transient, steady-state, etc.,), or whether the measures must remain purely descriptive and specific to each types of stimulus. In particular, is there a linear relationship between amplitude, phase and transient response characteristics for luminance or wavelength-varying inputs?

Bode (1945) has derived the relationship between the logarithmic amplitudes characteric A(W) and the least possible phase shift that a physically realisable system with that amplitude characteric may have. The minimum-phase characteristic (W) is given by the Hilbert transform

$$\varphi(W) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\log A(u)}{u - W}\, du \qquad (1)$$

at each frequency (W) of interest.

It is a necessary and sufficient condition of this integral that A(W) corresponds to a physically realisable system. This is the case if the integral

$$\int_{-\infty}^{\infty} \frac{|\log A(W)|}{1 + W^2}\, dW \qquad (2)$$

is finite (Paley-Wiener condition)

The amplitude and phase charecteristics may be combined to form the steady-state transfer function of the system.

$$\Phi(jW) = A(W) \exp[j\,\varphi(W)] \qquad (3)$$

The transfer function may be used to derive the impulse response ($h(t)$) of the system, (from which the transient response to any input may be derived) assuming that the system is linear by means of the Fourier transform,

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \Phi(jW)\, e^{jWt}\, dW \qquad (4)$$

Response to a step input is given by

$$k(t) = \int_{0}^{t} h(t - \tau)\, d\tau \qquad k(t) = \text{step input}$$

An assumption implicit in the application of mathematical analysis to the experimental data is that the visual system is sufficiently linear at threshold that the psychophysical functions are valid measures of the amplitude, phase and transient responses. This assumption was made by previous authors (e.g. De Lange, 1957; Graham & Kemp, 1938). The discovery of a linear relationship between these types of response would strengthen the assumption of the validity of the data in the above sense, although the absence of a linear relationship may merely indicate that the other assumptions below were invalid.

Since the experimentally measured amplitude functions are not exactly describable in analytic terms, the graphic-analytic approximation method described by Solodovnikov (1960) will be used to derive the above functions. The derivation of the phase shift from the amplitude response curve (De Lange curve) assumes that the visual system is acting as a minimum phase network under the present stimulus conditions. This assumption has been subject to test by previous authors. De Lange (1957) proposed a model predicting the usual response to square-wave and "90° impulse-shaped" modulation from the sine-wave response. He made the implicit assumption that minimum phase conditions held in his use of cascaded lumped filter elements, and obtained a reasonable fit to his threshold amplitude response date for square wave modulation, which involves transient components at low frequencies, and is thus sensitive to the relative phase shifts in the processing system. He did not attempt to measure phase shift directly in this connection.

Kelly (1969) has derived a mathematical model of the visual response based on the absolute flicker sensitivity high frequency slope, (see section 3.3). He made the assumption that minimum phase conditions held in his derivation of a theoretical transfer function. He compared the minimum phase condition with direct methods of measurement of phase shift by comparison of luminous and electrically induced flicker (Brindley (1962), Veringa, (1963,1964), Veringa & Roelofs (1966). The phase shift to the point in the system in which the electrical stimulation operates (e.g at the bipolar cells) was found to be a good fit to the minimum phase prediction.

The derivation of the impulse and step responses from the transfer function makes the assumption that the system is linear in the respect that the parameters (e.g. adaptation) of the system operative in the steady state remain constant under transient stimulation at subjective threshold. Some comments relating to these assumptions will be made below.

8.5.2. Phase Calculation

As has been noted, in section 3.4., the amplitude characteristic (De Lange Curve) is non-linear with respect to a mean amplitude (luminance) and is affected by other stimulus conditions. The following calculations, therefore, are applied to data obtained under similar stimulus conditions, both in luminance, wavelength and field configuration.

The minimum phase characteristic (W) is derived from the amplitude characteristic A(W) by the graphical approximation method described by Solodovnikov (1960, pg 585). The log amplitude characteristic is approximated by a set of semi-infinite logarithmic unit components The minimum phase function for a semi-infinite logarithmic component is derived analytically (Bode, 1945). If a system has an amplitude function which is the logarithmic sum of a set of component amplitude functions the minimum phase function is the sum of the phase functions of the components, since if

$$A(W) = A_1(W).\ A_2(W)$$

then

$$\log A(W) = \log A_1(W) + \log A_2(W)$$

and $$\varphi(W) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\log A(u)}{u - W}\, du = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\log A_1(u) + \log A_2(u)}{u - W}\, du$$

$$= \frac{1}{\pi}\int_{\infty}^{\infty} \frac{\log A_1(u)du}{u - W} + \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\log A_2(u)}{u - W}\, du$$

$$= \varphi_1(W) + \varphi_2(W)$$

The Paley-Wiener condition is assumed to be fulfilled since the

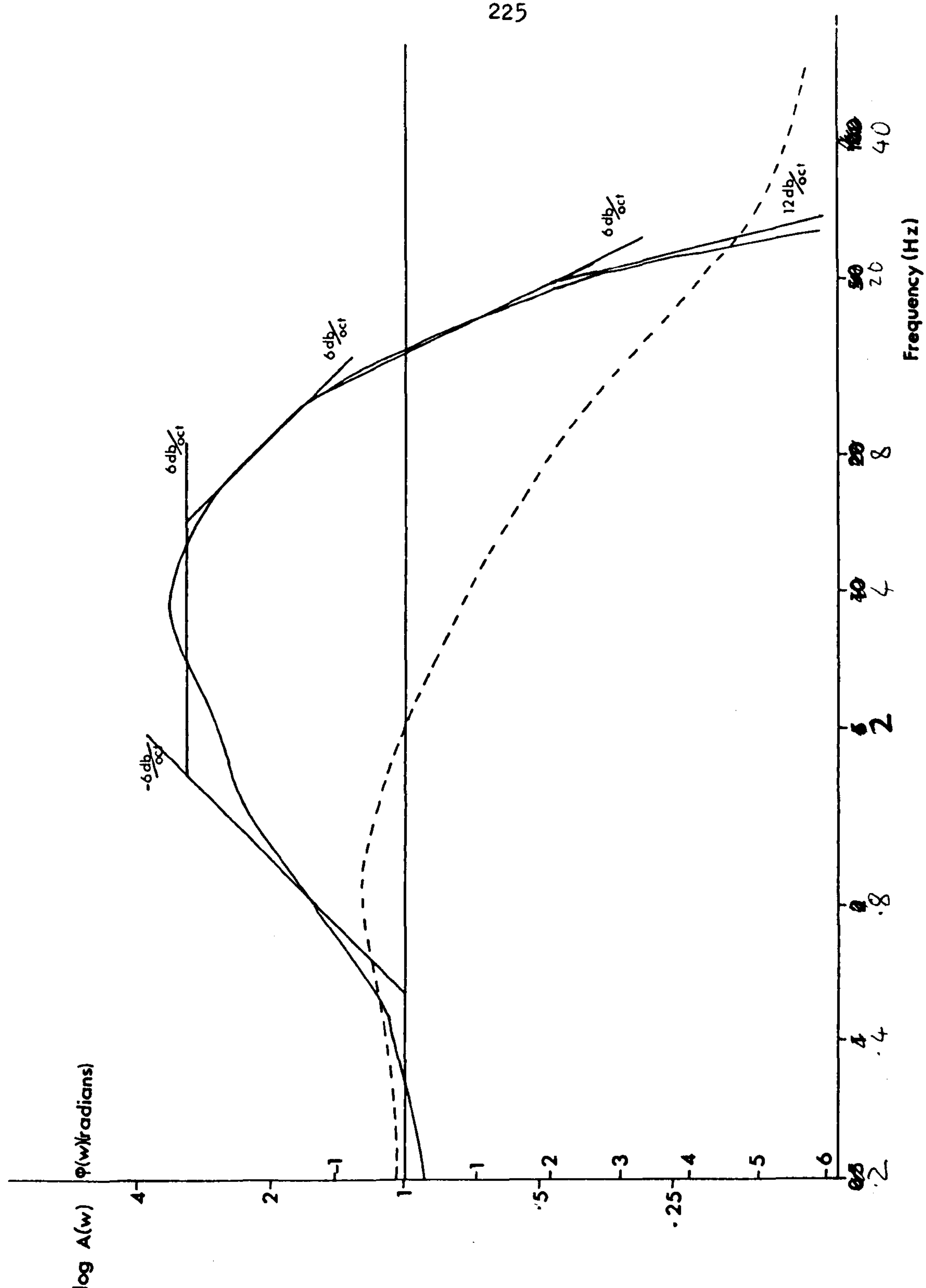


Fig. 8.3. Amplitude characteristics A(w) (full curve and outer ordinate) as in Fig. 7.4.2., showing asymptotes used in computation of minimum phase characteristic φ(w) (dotted curve and inner ordinate).

amplitude functions of the present section are those of the human brain, which is a physically realisable system. Fig. 8.3. shows the straight-line approximation to the log amplitude characteristic for luminance flicker at 25 trolands at 527 nm (section 7.1) together with the minimum phase characteristic derived from the sum of the phase shifts for each individual semi-infinite component. The points indicate the phase shift measured by the method described in section 7.1.5., under the same stimulus conditions as the amplitude measurement. There is some possible discrepancy between the calculated and observed phase shifts (Figs 8.3 and 7.1.8). On the other hand the limiting shift approached at $W = \infty$ seems to be of the order of 2π radians in each case. In view of the uncertainties in the measurements of the phase shifts, the data may be considered to accord with the prediction within the limits of error.

The minimum phase functions were also computed for the wavelength modulation amplitude functions at two mean wavelengths (527 and 622 nm) at 25 trolands retinal illuminance. These were obtained by the semi-infinite logorithmic unit components approximating the amplitude functions and the calculated phase functions for the two conditions. No experimental determinations of the phase functions were attempted for the reasons stated in section 7.1.5.

8.5.3. Impulse Response

Since the experimental phase function is considered to show negligible deviations from the calculated phase function, the latter is used in the foregoing calculation.

The following analysis is taken from Solodovnikov (1960, pgs 5, 31-5). In computing the impulse response, the transfer function (W) must first be calculated. The transfer function may be expressed in terms of real and imaginary components.

$$\Phi(jW) = P(W) + jQ(W) \qquad (6)$$

But the transfer function may also be expressed as in equation (3) in terms of the amplitude and phase components

$$\begin{aligned} \Phi(jW) &= A(W) \quad [\exp(j\,\phi(W))] \\ &= A(W) \quad (\cos\phi(W) + j\sin\phi(W)) \\ &= A(W)\cos\phi(W) + j\,A(W)\sin\phi(W) \qquad (7) \end{aligned}$$

Equating the real parts of 6 and 7, we have

$$\mathrm{Re}\,[\Phi(jW)] = P(W) = A(W)\cos\phi(W) \qquad (8)$$

The real frequency characteristic P(W) is related to the linear impulse response h(t) by the expression

$$h(t) = \frac{2}{\pi}\int_0^{\infty} P(W)\cos Wt\, dW, \quad (t > 0) \qquad (9)$$

which may be solved in approximate form by summation of several trapezoids approximating the real frequency characteristic P(W).

$$h(t) = \frac{2}{\pi}\sum_{i=1}^{n}(P_{oi}\,W_i)\left(\frac{\sin W_i t}{W_i t}\right)\left(\frac{\sin \Delta_i t}{\Delta_i t}\right) \qquad (10)$$

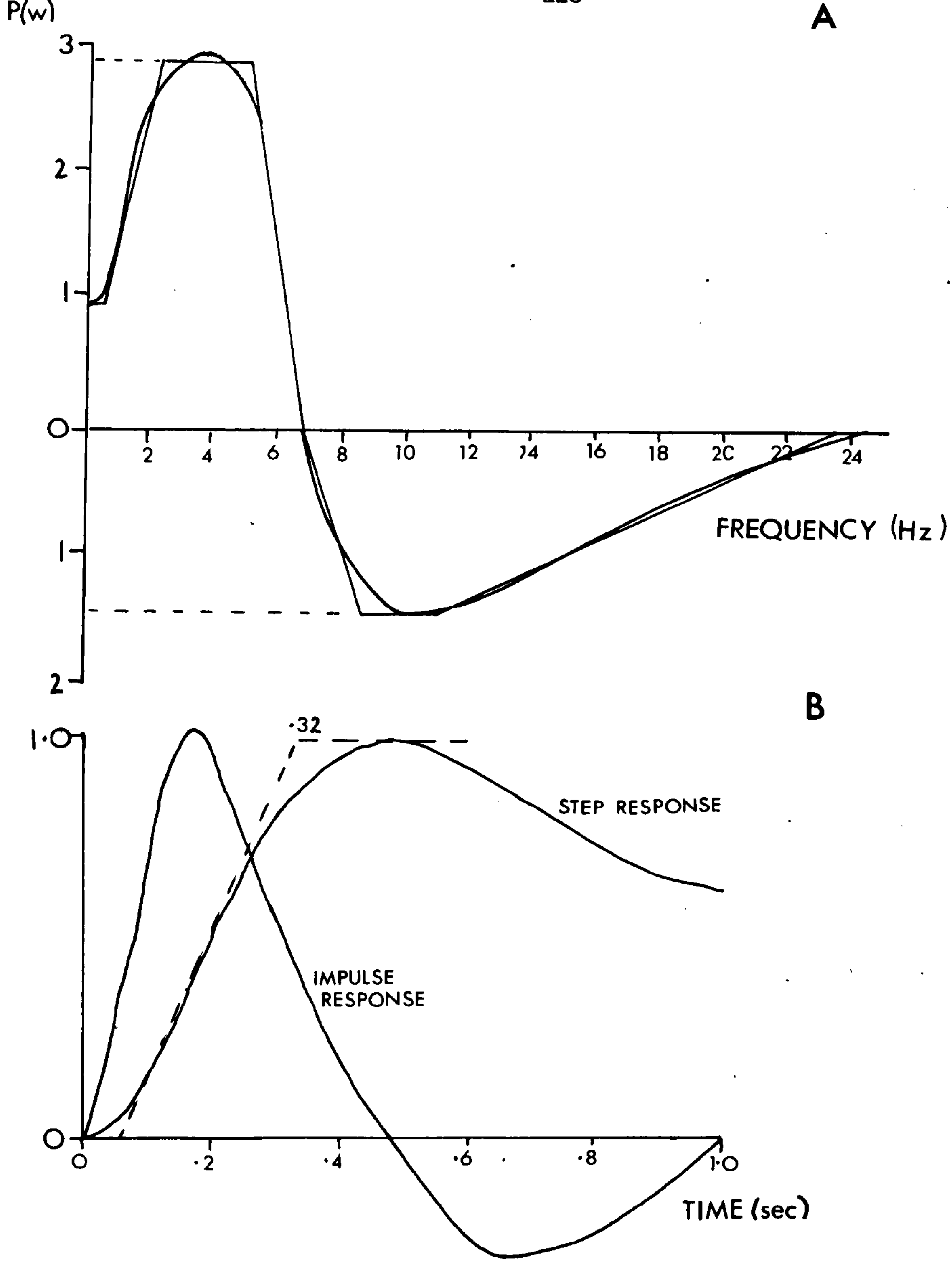
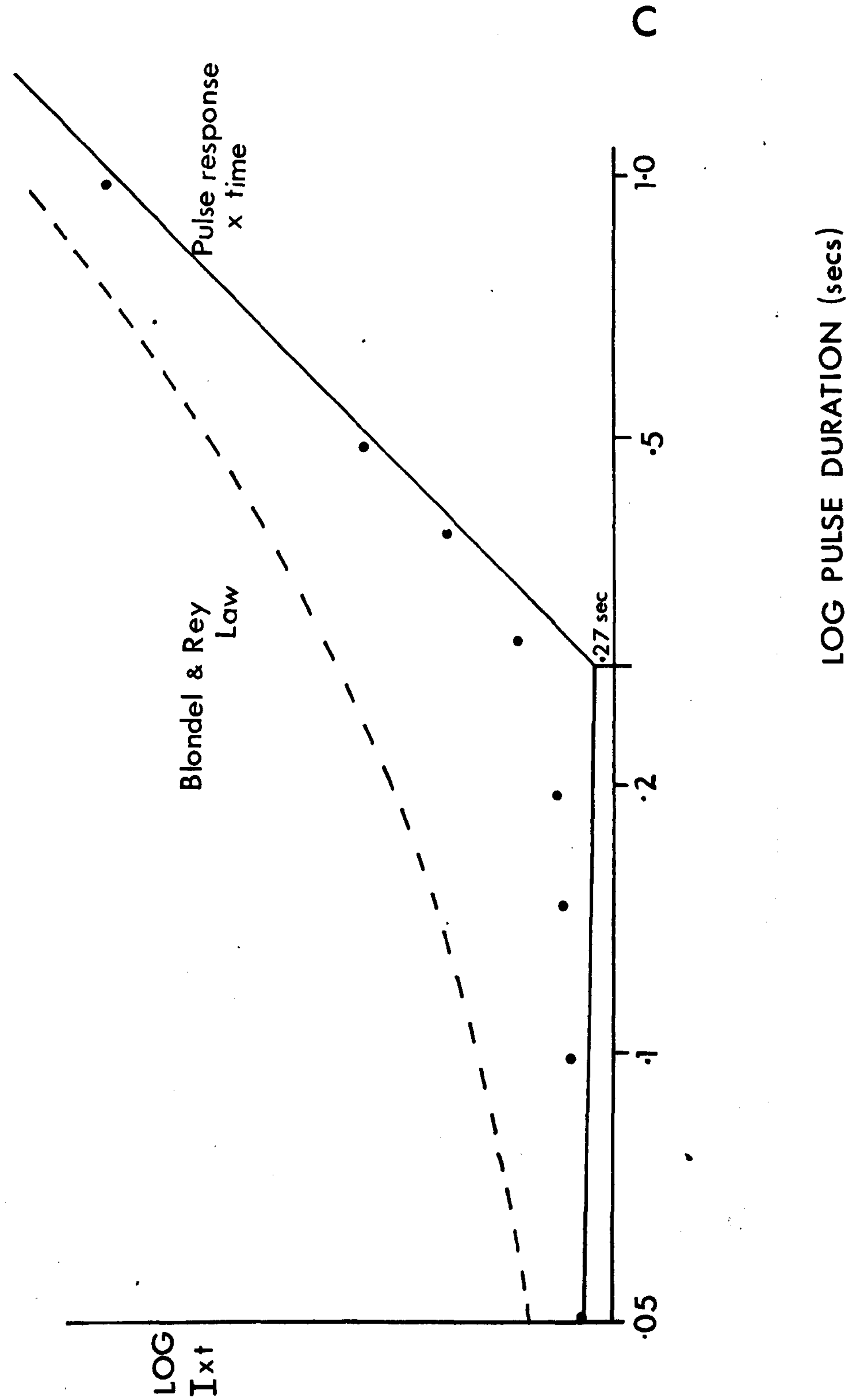


Fig. 8.4. A - Real transfer function (P (w)) computed as in text, and showing trapezoidal approximation used for calculation of normalised impulse response and step response (B) up to 1 sec. (cont.)



The step response was used to compute the response ($k_{\tau}(t)$) to pulses of varying duration (C), which are plotted as the product of (intensity) pulse amplitude (for constant pulse response amplitude) and duration (I x t), as a function of pulse duration.

The impulse response is given by the sum of the trapezoidal approximations to the real frequency characteristic P (W) (depicted for specific examples in Figs 8.4.A., 8.7 and 8.8).

The calculated real frequency characteristic for the luminance modulation data of the previous section shown in fig. 8.4.A. The calculated impulse response is shown in Figs 8.4.B+C together with the response to a unit step which is the integral of the impulse response. The calculations for these functions are given in Appendix I. It can be seen that the form of the step response is similar to that found by Broca & Sulzer (1902) in exhibiting an overshoot before reaching the steady level. Close correspondence should not be expected, as Broca and Sulzer used a brightness-matching rather than a threshold technique, and also used zero adapting luminance (see section 3.8 for review).

For comparison with threshold data, as obtained in the pulse experiments described in section 7.5., a further computation is necessary. The pulse experiments consisted of varying the duration of a luminance or wavelength pulse and finding the threshold amplitude of the pulse at each duration. The results were plotted in terms of the product of amplitude and duration as a function of pulse duration. The equivalent function for the computed system impulse response is obtained as follows. If the assumption of linearity is correct, then the principle of superposition of responses will hold. The pulse response is then given by the sum of the step responses (h(t)) to the onset and offset of the pulse.

$$k_{\tau}(t) = k(t) - k(t + \tau) \qquad (11)$$

where $k_{\tau}(t)$ is the pulse response, and τ is the pulse duration.

In order to translate the pulse response $k_{\tau}(t)$ into a form equivalent to the psychophysical data, the criterion for reaching threshold must be determined. For simplicity, the criterion will be assumed to be that the amplitude of the pulse response reaches a given value. The product of input pulse amplitude and time for the pulse response to reach a criterion value as a function of pulse duration is plotted in Fig. 8.4.C for the luminance modulation data analysed above, It can be seen to conform to the horizontal and 45° asymptotes about as well as the psychophysical data of fig. 7.5.1 B (pg 200) under the same adapting conditions. The theoretical data does not conform to the law of Blondel & Rey (1911)

$$L.t. = L_{\infty}(t + t_c), \qquad (12)$$

where L is the threshold for $t=\infty$ and t_c is a constant which is plotted as the dotted line in Fig. 8.4.C.

This has the same form as the expression derived by Hecht (1934) from his photochemical model of the response to light flashes.

It therefore appears that the model of the pulse response derived above provides a good qualitative description of the pulse response data. However, the quantitative prediction of the critical duration (t_c) at which the two asymptotes intersect is 270 msec, for the pulse

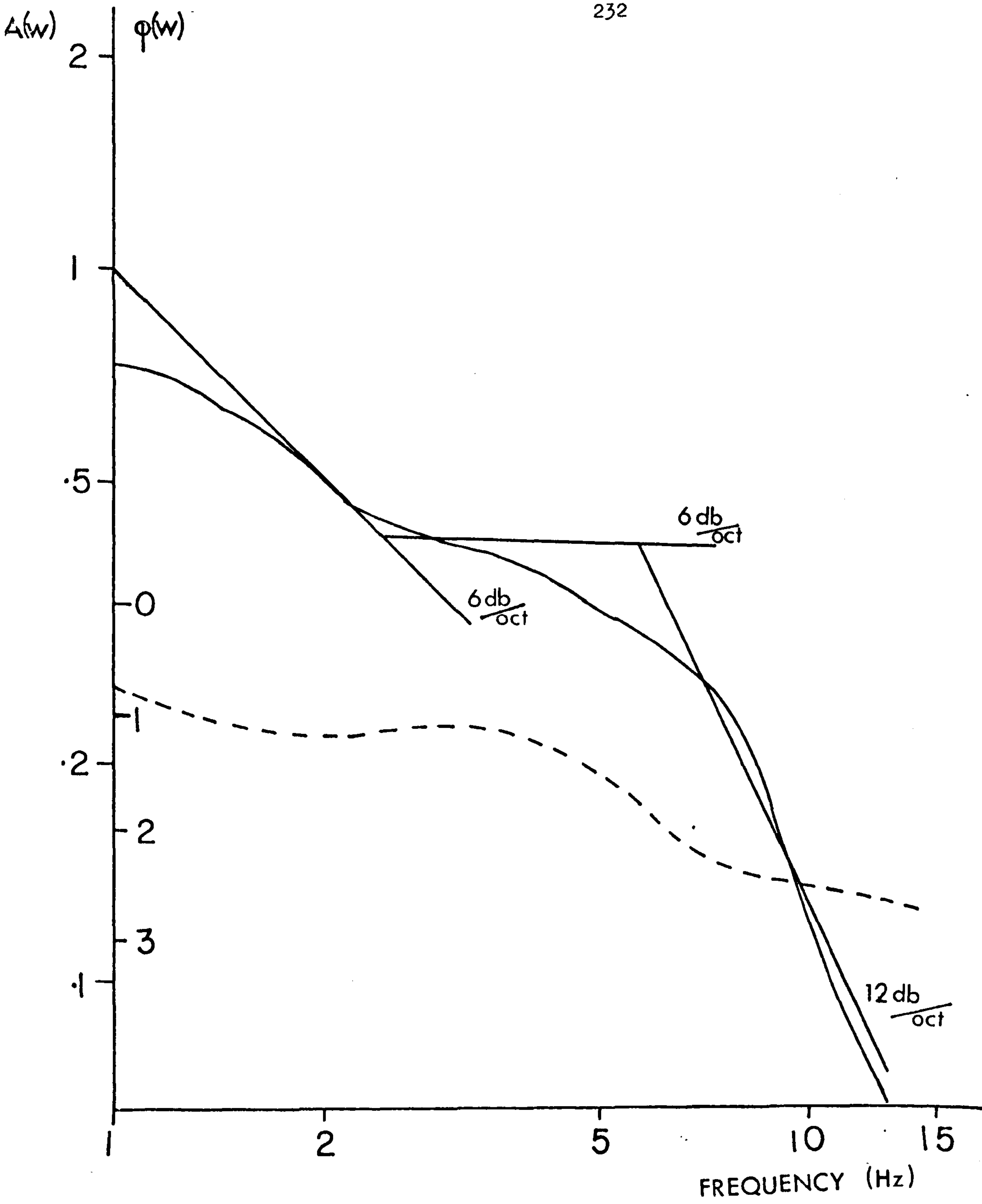


Fig. 8.6. Amplitude and phase functions as for Fig. 8.3. but with wavelength modulation at mean wavelength of 527nm.

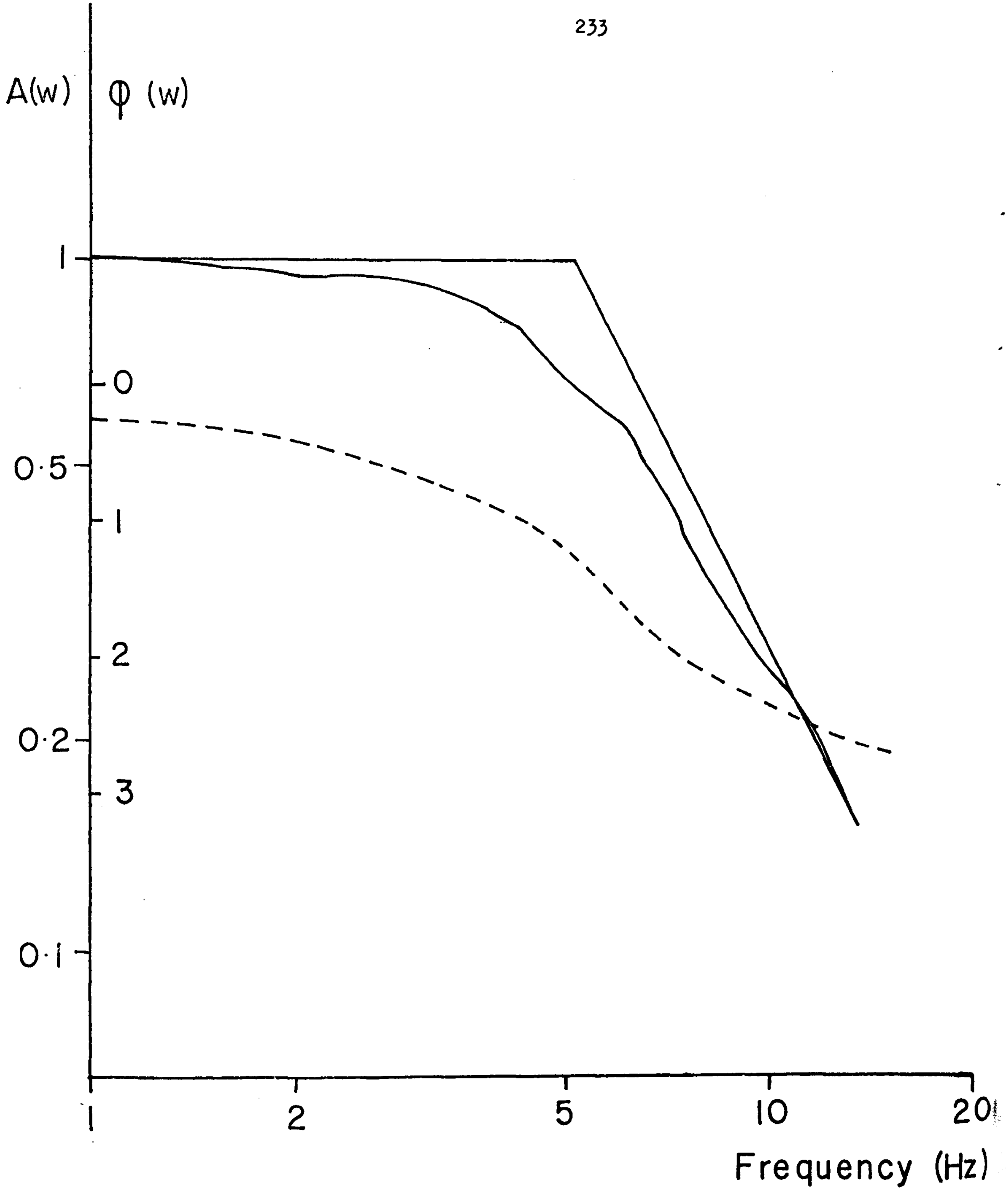


Fig. 8.5. Amplitude and phase functions as for Fig. 8.3. but with wavelength modulation at mean wavelength of 622nm.

response data. It therefore follows that given the assumptions made in the analysis a pulse response such as would be produced by a linear minimum phase system with the amplitude frequency response function of Fig. 8.3. would not have the pulse response obtained in the luminance pulse experiments of section 7.5. The luminance, processing system must consequently be described by some non-linear model, such as that suggested by Sperling & Sondhi (1968). Another possible explanation of the failure of the pulse response prediction is suggested by the analysis of section 7.1.2. The analysis derived from Stiles increment threshold technique suggested that the De Lange curve was composed of (at least) two independent components representing the sensitivities of independent high and low luminance systems. If the pulse responses of each system were linear, and the observer could utilise the responses independently, it is possible that the experimental results might be thus predicted by a linear model with two independent components. Unfortunately, the frequency sensitivity of each component system is not known over a sufficiently wide range to permit this hypothesis to be tested. However, if the component systems could be isolated to a greater extent by manipulating stimulus conditions such as adaptation and wavelength, the hypothesis could be tested.

A similar procedure to the above was followed to determine the linear prediction for the pulse response in the case of wavelength modulation data. The real part of the transfer function was obtained for the amplitude and computed phase functions (section 8.5.2.) for mean wavelengths of 527 nm (Fig. 8.6) and 622 nm (Fig. 8.5). The calculated impulse responses and step responses are also plotted in Fig. 8.8.

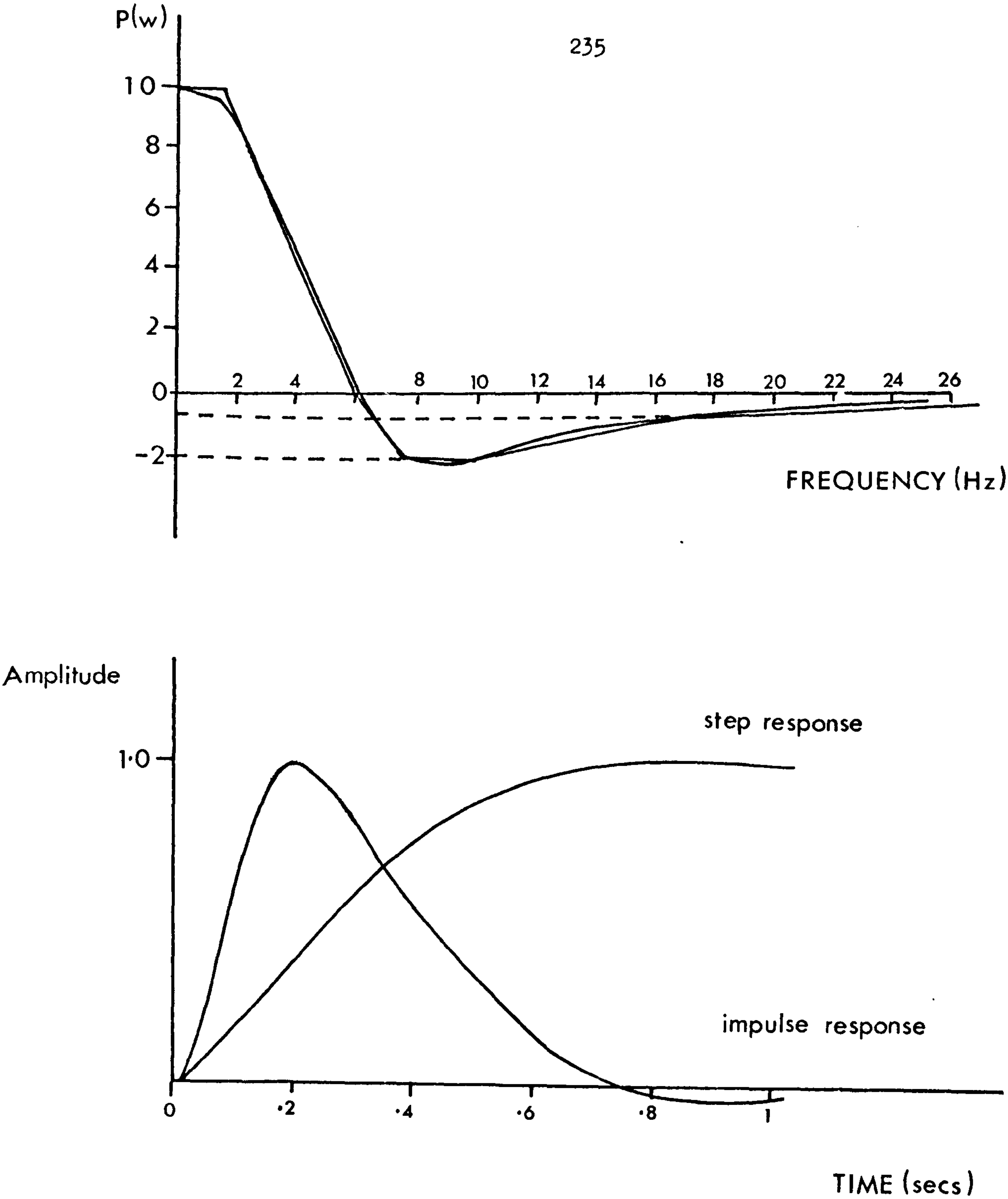


Fig. 8.7. Real transfer function and impulse and step responses, as for Fig. 8.4. but with wavelength modulation at mean wavelength of 622nm.

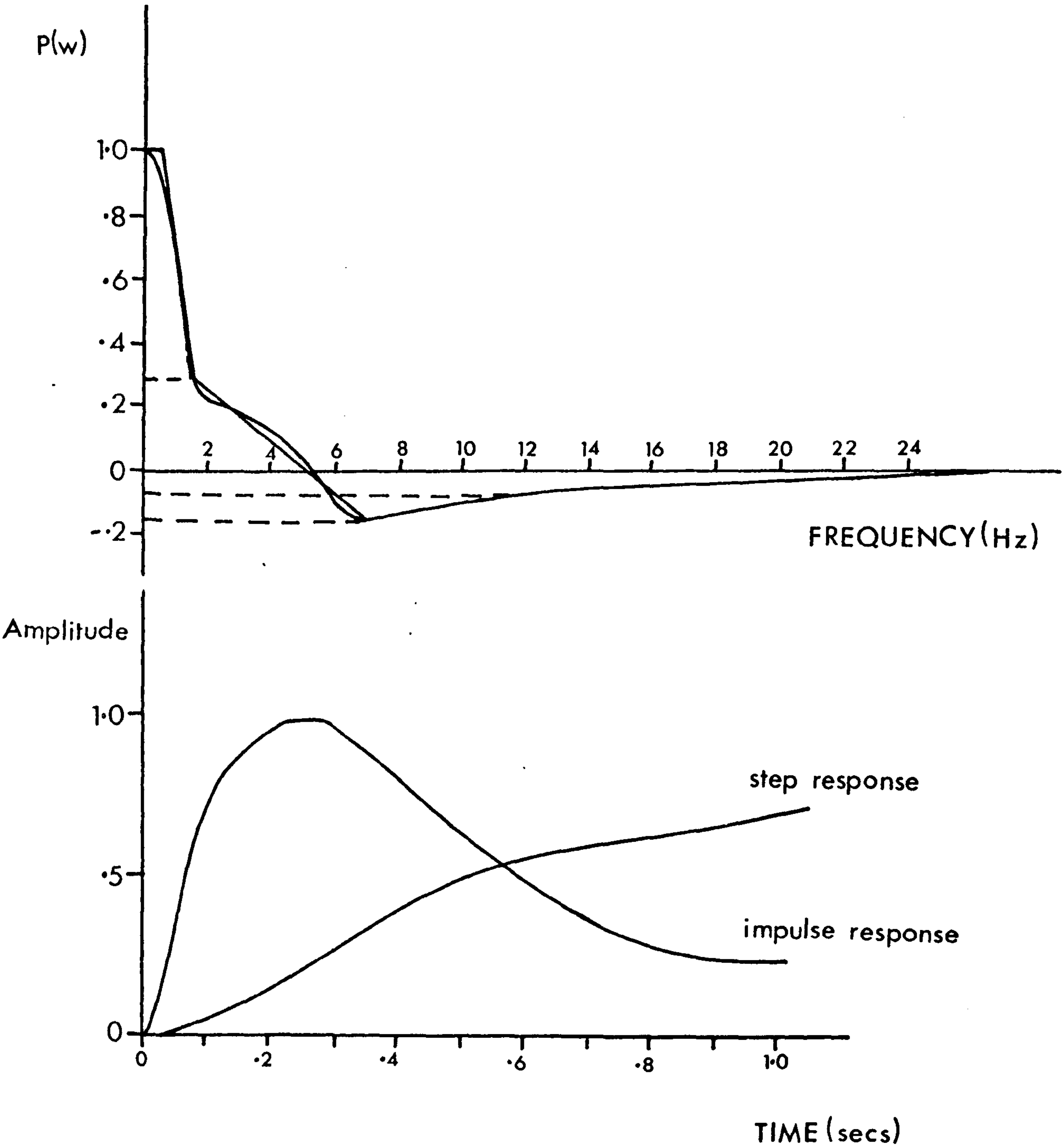


Fig. 8.8. Real transfer function and impulse and step responses, as for Fig. 8.4. but with wavelength modulation at mean wavelength of 527nm.

and 8.7 respectively. The computed critical durations (t_{cw}) from the two step responses are approximately 800 msec for 527 nm and 650 msec for 622 nm. As with the luminance pulse predictions, these values are considerably longer than the measured wavelength pulse (section 7.5.3) durations of 250 msec for 527 and 110 msec for 600 nm, the latter being the nearest mean wavelength to 622 nm tested. The model therefore appears no better for the case of wavelength modulation.

It is concluded that both the luminance and wavelength modulation processing systems show non-linear response characteristics, but determination of the nature of the non-linearity will require further investigation.

8.6. Temporal Independence of the Colour Processing System:

In section 2.5. evidence is reviewed for Walraven's (1962) concept that the colour processing channel of the visual system is independent of the luminance processing channel after the primary receptor stage. The evidence is drawn from a number of sources, but data relating to the temporal characteristics of each system was not considered.

If the luminance and colour processing channels involve independent processes, as the evidence of section 2.5. suggests, it is highly probable that the temporal characteristics of the two channels will differ. In the present thesis, a number of aspects of the dynamics of constant-luminance wavelength-varying stimuli have been investigated. It is argued that the results indicate that the processing of such stimuli is independent of the processing of the equivalent luminance-varying stimuli in the sense outlined in section 2.5.

The evidence concerning temporal independence will be considered in terms of four types of approach - frequency response, wavelength sensitivity, effect of waveform and pulse response. The frequency response data has already been considered in relation to De Lange's (1957) suggested model of the frequency response to chromatic modulation in section 8.1. It was concluded that the data of of the frequency response functions for chromatic and luminance modulation, section 7.2), together with that of Van der Horst (1969) supported the hypothesis of independent rather than sequential processing of chromatic and luminance modulation. There appeared to be no consistent relationship between the two types of frequency response function either in the slopes of the functions at any point or in the position of regions of sudden change in slope. This evidence is in support either of independence of the processing of the two types of stimuli, or of a sequential process of great complexity to explain the frequency response data. The former alternative is to be preferred for reasons of parsimony.

Section 7.3. presents data on dynamic wavelength discrimination as a function of wavelength. Such data may be regarded as a more detailed study in respect of wavelength of the same phenomena present in the wavelength modulation De Lange curves. The data of Figs. 7.3.1.-2 (pg 177,179) concerning the frequency dependence of dynamic wavelength discrimination may be compared with the data of Figs, 7.1.5.-6, (pg 150,152) which show the luminance modulation sensitivity as a function of stimulus wavelength for the same set of frequencies. The latter data show that sensitivity to luminance modulation is independent of wavelength between 0.5 and 5 Hz. The wavelength modulation sensitivity on the other hand varies with wavelength, and furthermore this wavelength variation is frequency dependent between 0.5 and 5 Hz. This evidence supports the hypothesis that the wavelength and frequency dependence of wavelength modulation processing occurs after the divergence of the colour and luminance processing channels.

In section 7.4. the effect of stimulus waveform on a low frequency adaptation phenomenon is examined for both luminance and wavelength modulation. It is concluded that the adaptation has a similar slope for both types of modulation, but began at 1 Hz for wavelength modulation and 3 Hz for luminance modulation. This difference (of 0.5 log units of frequency) suggests that the adaptation is determined separately in independent luminance and colour channels.

Finally, the visual responses to luminance and wavelength pulses showed several differences (section 7.5.). The critical duration for wavelength pulses (t_{cw}) was found to be longer than that for luminance pulses (t_c), and was further found to be dependent on mean wavelength, whereas t_c was independent of wavelength under the conditions used. The effect of mean retinal illuminance in the one condition for which it was studied was proportionally greater on t_{cw} than on t_c.

Thus, although there does not appear to be a linear relationship between the steady - state and transient responses for either luminance or colour processing (section 8.5.), both steady - state and transient colour responses show evidence of extra processing after the divergence from the luminance channel. It may be concluded that the results of the present thesis concerning the dynamics of colour vision are in support of the concept of independence of the colour processing channel at some point after the primary receptor stage.

9. Summary and Conclusion.

A method of producing a constant-luminance wavelength modulation of a light stimulus has been developed. The controls indicated that it was possible to control luminance changes due to wavelength modulation to such an extent that threshold was determined by chromatic changes alone. The frequency sensitivity to wavelength modulation was broadly similar to that obtained by De Lange (1957), and Van der Horst, (1969a), but differs in details. Dynamic wavelength discrimination showed a frequency dependence which can be described as a shift of the blue threshold minimum from below 480 to 500 nm, together with a general impairment of discrimination as frequency was increased. Data of the visual response to constant-luminance wavelength pulses indicated that a phase of temporal integration reciprocity of colour-change information exists, which converted to a phase of time-independence in a manner similar to that for luminance pulses. The critical duration (t_{cw}) corresponding to the change from one mode to the other was substantially longer than that for luminance pulses (t_c), and also dependent on adapting wavelength. The results are interpreted as supporting the concept of independent channels processing luminance and colour information.

In the very low frequency region (below 1 Hz.) for both luminance and wavelength modulation a shallow adaptation phenomenon was found, which was abolished either by an equiluminant surround or by using square-wave modulation. These are considered to introduce respectively spatial and temporal comparison stimuli which masked the adaptation effect.

The dynamic wavelength discrimination data are considered in relation to several models of wavelength discrimination. The main conclusion is that the frequency dependent elements must be located in the (opponent) colour processing channel rather than the receptor stage.

The linear systems analysis approach suggested by De Lange (1952) does not give a correct prediction of the transient visual responses from the steady-state data, in either the luminance or wavelength domains.

In conclusion, it appears that the data of visual responses to wavelength-varying stimuli provide information on the dynamic characteristics of the colour processing channel. This information may be used to test and expand existing theories of colour vision.

Notes.

1. The term "system" is used to denote a set of logical relations between the inputs and outputs of a physical entity, as distinct from the term "mechanism" which denotes the physical and physiological components of an entity, which mediate the input-output relationships.

2. The terms dL and dλ are used throughout this thesis to denote a limiting increment of L and λ respectively, where "limiting" is regarded psychophysical sense of "threshold value of" rather than in the conventional mathematical sense of "arbitrarily small value of". This terminology has been preferred to the terms ΔL and $\Delta\lambda$ as the latter do not denote limiting values in any sense.

3. Invariant hues. Hues of the monochromatic light at wavelengths for which the hue remains unaffected by changes in adapting luminance (rather than chromatic adaptation) (Hurvich and Jameson, 1955).

4. The term wavelength increment is used by analogy with luminance increment and implies a change towards the larger wavelengths. In some cases a decrement in wavelength was used rather than an increment, but pilot data indicated that there was no significant difference between increment and decrement thresholds for a variety of conditions.

5. The terms luminance modulation, luminance pulse and constant luminance, etc., are employed as shorthand to

avoid the unwieldy form of "retinal illuminance modulation" etc. This usage was felt to be justified since in all the experiments described a constant artificial pupil was employed, so that any change in retinal illuminance must have been produced by a proportional change in stimulus luminance. In situations where the absolute value of the retinal illuminance is relevant, the full term has been used.

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Glossary.

a	-	area
A(W)	-	amplitude frequency function
α	-	time constant
b	-	blue chromaticity coordinate
β^2	-	scaling factor
cpd	-	cycles per degree
CCFF	-	chromatic critical flicker frequency
CFF	-	critical flicker frequency
C_i	-	tristimulus value
C	-	constant
db	-	decibel
dL	-	threshold luminance change (see notes 2 and 5)
$d\lambda$	-	threshold wavelength change (see notes 2 and 5)
ΔL	-	luminance change (see notes 2 and 5)
$\Delta\lambda$	-	wavelength change (see notes 2 and 5)
E_i	-	luminous energy
f	-	focal length
F	-	luminous flux
g	-	green chromaticity coordinate
h(t)	-	impulse response
HFP	-	heterochromatic flicker photometry
Hz	-	Hertz
I	-	retinal illuminance
j.n.d.	-	just noticeable difference
k(t)	-	step response
$k_\tau(t)$	-	pulse response
ξ	-	damping ratio (Ch. 4)
	-	Stiles' (1939) empirical intensity function (Ch. 7)
L	-	luminance
λ	-	wavelength
m	-	modulation amplitude

msec - millisecond

nm - nanometers

P - potentiometer

p_c - colorimetric purity

P_λ - radiant flux

P(W) - real frequency function

π_i - Stiles' (1953) retinal mechanisms

φ - phase angle

φ(W) - phase frequency function

Φ(W) - frequency transfer function

Q(W) - imaginary frequency function

r_c - contrast ratio

r.m.s. - root mean square

S - light source

t_c - critical duration for luminance pulses

t_{cw} - critical duration for wavelength pulses

tr - troland

τ -pulse duration

V - luminosity function

w - white

W
- unit solid angle (Ch. 2)
- watts (Ch. 7)
- frequency (Ch. 8)

X, Y, Z - C.I.E. chromaticity primaries

W \ W_o =	0.55	1.6	6	11	21	o(W)	cos o(W)	A(W)	P(W)
	o_i (W) for $A_i(W) = \frac{W_o + W}{W_o}$								
0.2	-0.23	0.08	0.01	0.01	0.00	-0.10	0.99	1.0	0.99
0.5	-0.66	0.20	0.05	0.03	0.02	-0.34	0.94	1.1	1.03
1.0	-1.21	0.42	0.11	0.06	0.03	-0.56	0.85	1.9	1.61
1.5	-1.33	0.70	0.16	0.08	0.04	-0.31	0.95	2.4	2.28
2	-1.39	1.01	0.21	0.12	0.06	0.07	1.00	2.6	2.60
3	-1.46	1.21	0.33	0.17	0.10	0.45	0.90	3.2	2.88
5	-1.50	1.36	0.59	0.29	0.15	1.04	0.50	3.2	1.60
7	-1.52	1.42	0.96	0.43	0.21	1.71	-0.14	2.6	-0.36
10	-1.53	1.47	1.17	0.66	0.31	2.39	-0.73	1.9	-1.39
12	-1.54	1.49	1.24	0.90	0.38	2.85	-0.96	1.4	-1.34
15	-1.55	1.50	1.31	1.07	0.48	3.29	-0.99	0.96	-0.95
20	-1.55	1.52	1.38	1.21	0.71	3.98	-0.67	0.50	-0.34
25	-1.56	1.53	1.42	1.28	0.98	4.63	-0.08	0.22	-0.02
30	-1.56	1.54	1.44	1.33	1.10	4.95	0.24	0.11	0.03
40	-1.56	1.55	1.47	1.39	1.22	5.29	0.55	0.03	0.02
50	-1.56	1.55	1.48	1.43	1.30	5.50	0.81	0.01	0.01

The expression for the impulse response is:

$$h(t) \doteq \frac{2}{\pi}\left\{-1, 1.3\left(\frac{\sin 1.3t}{1.3t}\right)\left(\frac{\sin 0.9t}{0.9t}\right) + 2.9, 5.9\left(\frac{\sin 5.9t}{5.9t}\right)\left(\frac{\sin 0.9t}{0.9t}\right) + 1.4, 7.6\left(\frac{\sin 7.6t}{7.6t}\right)\left(\frac{\sin 0.8t}{0.8t}\right) - 1.4, 17\left(\frac{\sin 17t}{17t}\right)\left(\frac{\sin 12t}{12t}\right)\right\}$$

t	$\frac{\sin 1.3t}{1.3t}$	$\frac{\sin 0.9t}{0.9t}$	$\frac{\sin 5.9t}{5.9t}$	$\frac{\sin 0.8t}{0.8t}$	$\frac{\sin 7.6t}{7.6t}$	$\frac{\sin 17t}{17t}$	$\frac{\sin 12t}{12t}$	h(t)	k(t)
0.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.6	0.01
0.02	1.00	1.00	1.00	1.00	1.00	0.98	0.99	2.1	0.04
0.05	1.00	1.00	0.98	1.00	0.98	0.88	0.94	3.9	0.13
0.1	1.00	1.00	0.94	1.00	0.91	0.58	0.78	8.8	0.45
0.2	0.99	0.99	0.78	1.00	0.66	-0.08	0.28	12.4	1.51
0.3	0.97	0.99	0.55	0.99	0.33	-0.18	-0.12	7.0	2.48
0.4	0.95	0.98	0.30	0.98	0.03	0.07	-0.21	2.7	2.96
0.5	0.93	0.97	0.10	0.97	-0.16	0.09	-0.05	0.1	3.10
0.6	0.90	0.95	-0.09	0.96	-0.22	-0.07	0.11	-3.0	2.95
0.7	0.87	0.94	-0.19	0.95	-0.15	-0.05	-0.10	-3.5	2.62
0.8	0.83	0.92	-0.22	0.93	-0.13	0.06	-0.02	-3.0	2.29
0.9	0.79	0.89	-0.17	0.92	0.08	0.03	-0.09	-1.8	2.05
1.0	0.74	0.87	-0.06	0.90	0.13	-0.06	0.04	-0.2	1.95

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