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THE EFFECT OF SATURATION ON THE RECOGNITION
OF COLOURED OBJECTS

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Thesis submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

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LIST OF SYMBOLS

b	Absorbtion coefficient
B	Cone fundamental (Vos and Walraven)
C_{uv}^*	Metric chroma
D_{65}	Standard illuminant (daylight)
f, F	Spatial or temporal frequency
G	Cone fundamental (Vos and Walraven)
H_a	Actual information content
H_c	Constraint uncertainty
H_e	Excess channel capacity
H_{max}	Maximum information
H_{uv}^0	Metric hue angle (CIE 1976 L^*, u^*, v^*)
I_e	Radiant intensity
k	Scattering coefficient
K_1, K_2	Constants
L	Long wavelength cone fundamental
L^*	Metric lightness (CIE 1976 L^*, u^*, v^*)
L_a	Adapting luminance
L_e	Radiance as seen from a detector
L_h	Radiance of horizon sky
$L_{h,\lambda}$	" " " " at wavelength lambda
L_o	" at zero distance
$L_{o,\lambda}$	" " " " and wavelength lambda
LSF	Line spread function
M	Medium wavelength cone fundamental
M_v^*	Metric colourfulness
n	Exponent (wavelength dependent scattering)

LIST OF SYMBOLS

N	No. of alternatives
p_e	Excitation purity
p_i	Probability of event i
Q	Constant
r_λ	Diffuse reflectance of surface at wavelength lambda
R	Cone fundamental (Vos and Walraven) (also Redundancy - see context)
R'	Range of object from detector
R_c	Constraint redundancy
R_e	Discrimination redundancy
S	Short wavelength cone fundamental
S_A	Saturation
S_{uv}	Metric saturation (CIE 1976 L^*, u^*, v^*)
S_v	Visual response space
td	Troland
u'	CIE 1976 chromaticity coordinate (sample)
u_o'	" " " " (reference)
u^*	CIE 1976 L^*, u^*, v^* space
v'	CIE 1976 chromaticity coordinate (sample)
v_o'	" " " " (reference)
v^*	CIE 1976 L^*, u^*, v^* space
V_λ	Visual range
V_1, V_2, V_3, V_4	Prestriate cortical areas
V	Relative luminous efficiency function
x	CIE 1931 chromaticity coordinate (sample)
x_o	" " " " (reference)

LIST OF SYMBOLS

y	CIE 1931 chromaticity coordinate (sample)
y_0	" " " " (reference)
$(r-g)$	
	Opponent colour mechanisms
$(y-b)$	
β	Power function exponent
λ_c	Complementary wavelength
λ_d	Dominant "
μ	Extinction coefficient
μ_λ	Extinction coefficient at wavelength λ
ω	Solid angle
π, π_s	Stiles colour mechanisms

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ABSTRACT

Very little research has been carried out into how chromatic information affects observer performance in tasks other than detection. As well as being useful in determining further properties of the human visual system, data from such an investigation is of direct application to colour changes produced by atmospheric scattering. This is the principle aim of the present research.

Data is presented to illustrate the likely magnitude of these changes.

A series of experiments were carried out in which a set of targets (Smets patterns) were presented under neutral adaptation conditions and with varying amounts of contrast and purity. Temporal and spatial conditions were designed to produce predominantly sustained or transient responses. The response measure used in the majority of the experiments was reaction time. Results indicated that with low contrast targets colour information can influence thresholds other than detection, but when reaction time is used to test for such effects the results are more ambiguous. A method is also suggested for assessing the contribution made by the chromatic information under low contrast conditions.

CHAPTER ONE

A SUMMARY OF RELATED AREAS OF STUDY

- 1.1 Introduction
- 1.2 Task definition
- 1.3 Stimulus parameters
- 1.4 Visual processing
- 1.5 Physiological evidence for multiple channel processing
- 1.7 Latency
- 1.8 Summary

1.1 Introduction

Recognition is a perceptual task which not only requires complex stimuli, but is also inextricably linked with memory, and as such is less easily approached by the rigorous psychophysical methods discussed by Brindley(1970). In addition, attempts to determine relevant physical dimensions suitable for the description of spatially structured targets have, with the possible exception of spatial frequency and orientation, not provided more than empirical methods for the prediction of observer performance. Even spatial frequency is only applicable at threshold (Burton 1978).

It is apparent that not only should the task performed by the observer in a recognition study be carefully and precisely defined, but also that the experimental conditions and procedure be as rigorously controlled as possible. With these aims in mind the present investigation attempted to answer the following two questions:-

1. Does the perceptual correlate of excitation purity - saturation - influence recognition?
2. Can the results obtained be explained in terms of modern theories of how the visual system operates?

The first question in addition to providing fundamental information about the visual system, also has a direct application to predicting recognition thresholds in real situations, involving observation along relatively long optical path lengths in the atmosphere. In addition to contrast reduction by the atmosphere it can readily be observed

that objects placed at some distance (greater than one kilometer say) differ in colour compared with when viewed at close range. This change in colour is effectively a change in saturation and it is important to determine whether an additional constraint is placed on the ease with which an object may be recognised as it recedes towards the horizon, since any model which predicts recognition thresholds and includes atmospheric degradation, would need to assess chromatic changes, if it was found that colour in addition to contrast significantly affected thresholds.

The second question is perhaps the more difficult to answer, particularly as colour and spatial information are mainly considered in isolation even though the visual system collects spatial, temporal and chromatic information simultaneously, and in channels which are only partially separated. It may be possible therefore to determine new properties of the human visual system by finding out how information in one domain (spectral) may influence information in another (spatial).

The present chapter provides a summary of those parts of the literature on vision considered relevant to the present research. Chapter two describes the patterns used as targets in all the recognition experiments performed, while chapter three describes the computation of likely changes in the colorimetric properties of several surface colours when viewed at different ranges⁺. Chapters four to eight describe the experimental work carried out and chapter nine summarises the results and discusses their likely interpretation.

+ The information on how the atmosphere degrades the colour of objects was originally intended to be supplied by British Aerospace, but the methodology chosen was found to be too imprecise for the collection of reliable data. Chapter three is an attempt to obtain an "order of magnitude" estimate of likely colour changes using a relatively simple model of atmospheric scattering.

1.2 Task Definition

A full understanding of recognition as a perceptual task requires that it be defined as one of a sequence of possible operations an observer may be called on to perform. The following set is due to Hake (1957).

1. Detection: This is the most frequently used task in psychophysical experiments and requires an observer to judge whether a stimulus is present or absent.
2. Discrimination: In this case the observer determines whether a test target is a member of a set of targets. The set size may be equal to or greater than one.
3. Recognition: The observer must select a response, usually "yes" or "no" on the basis of whether or not a presented target belongs to a previously seen set.
4. Identification: This task requires the observer to decide whether a particular target has been presented. Usually the target must be named.
5. Judgement: In this case the stimulus (usually supra-threshold) is placed on a continuum using some prelearned code (eg. brightness scaling).

No hierarchy was implicit in Hake's (1957) classification but Dember (1960) placed the tasks in the following ascending order of complexity - detection, discrimination, recognition and identification. Judgement has an indeterminate position.

Discrimination and recognition appear to represent the same task in this classification, but it is usually understood that the comparison target in a discrimination experiment is presented either simultaneously with, or closely sequential to the test target eg. Arend and Lange, 1979.

The use of memory during a perceptual task may form the basis of a two part hierarchy. This has important implications for the modelling of a task however, since the use of memory implies some stage at which the neurally coded test target is compared with the memory representation of previously seen and learned targets. (Hunter 1964, page 32). Any model which assumes such a stage exists would therefore also need to incorporate a memory set dependent decision device (Ratcliff 1978).

This dichotomy may be criticised, however. One might argue that the repeated measurement of a detection threshold by the method of adjustment requires the observer to "memorise" the threshold appearance of the test target. Alternatively an observer in a recognition experiment involving complex backgrounds, may make decisions relative to the local background structure (discrimination) rather than to the memory set of targets.

Overington (1976) presents a hierarchy of tasks made up of detection, recognition and identification which together form an "acquisition" task, and

"...involves the detection of the presence
of some characteristic structure..."

(page 2)

The burden of the definition is now with the stimulus, but it is not clear what is meant by "some characteristic feature". Brown and Owen (1967) for example isolated over twenty measures of physical components of patterns which could be correlated with such perceptual features as "compactness", "jaggedness", "skewness", etc. Overington (1976) implies (page 2) that moving up the hierarchy from detection to identification, requires a concomitant change in the fineness of the detail attended to. Although a part of the answer, such a definition cannot take into account changes in recognition thresholds which can occur with no change in the amount of detail present, for example rotated objects may be much more difficult to recognise (Cooper and Shephard 1978).

It seems therefore that a definition based on the perceptual task is more useful than one based on the presence in a test target of some proportion of fine detail, or some characteristic feature. Furthermore the two part division of tasks, according to whether a comparison of memory is assumed or not, is also rather poor therefore the following definition will be used whenever recognition is referred to, unless otherwise stated:-

Recognition is a task performed by an observer, in which a single test target is compared with a predetermined and previously learned set of stimuli. The response set available to the observer will always be smaller than the size of the memory set and will usually consist of two responses.

1.3 Stimulus Parameters

The search for a single, or a set of independent orthogonal parameters in the physical domain, by which patterns might be described, and from which recognition thresholds might be predicted, has not only led to a multitude of characteristics (Zusne 1970), but has also resulted in the creation of some novel sets of patterns, for example the random polygons of Attneave (1951). Consideration of the various parameters suggests that they may be categorised as shown in Figure 1.1.

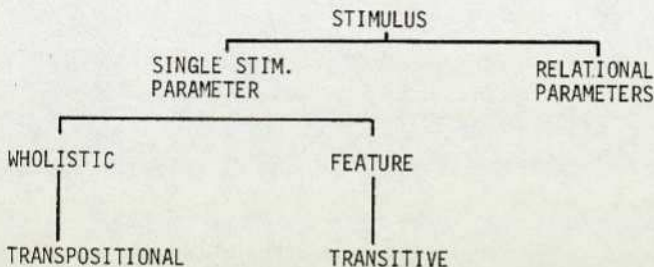


Figure 1.1 Hierarchy of stimulus parameters

The initial division into single stimulus parameters, versus relational parameters is made on the basis of whether the particular parameter is applicable to single patterns, eg. the number of line segments required to construct the pattern, or whether consideration of the set from which the pattern was drawn is required. The latter, in which the probability of a target occurring is important, relies heavily on information theory (Attneave 1959).

The next division into wholistic versus feature parameters was suggested by Attneave and Amoult (1956) who distinguished between a description of local parts of a pattern eg. a corner, and what they termed "Gestalt-variables" eg. the area of a pattern. Such descriptions have given rise to feature - detector and Gestalt models of recognition respectively (Caelli 1978). Zusne (1970), derived a similar but more detailed categorisation, and this is listed in Table 1.1 (Zusne's transpositional and transitive parameters may be equated with the wholistic and feature descriptors respectively).

The usefulness of the transpositional class of parameters in the definition of stimulus dimensions is not clear, although their importance to visual perception is (Cooper and Shephard 1978) and as pointed out by Sutherland (1968), any theory of vision must explain certain constancies associated with these transformations. (It must also be capable of explaining the breakdowns that occur in such constancies Gregory 1978, Campione 1977).

The remaining transitive parameters described by Zusne (1970) have all been tested both as stimulus descriptors, and as

TABLE 1.1

CATEGORIES OF PARAMETERS OF THE SINGLE PATTERN

	Produces changes in	
	measured information content	self- congruence
A. Transpositional		
1. Translation	no	no
2. Transposition to another size	no	no
3. Rotation	no	no
4. Reflection	no	no
B. Transitive		
1. Informational		
(a) Number of turns	yes	yes
(b) Linearity of contour	yes/no	yes/no
2. Configurational		
(a) Moments of distribut- ion of contour	no	yes

components of the stimulus, with some fundamental relationship to the method used by the visual system to process patterns.

1. Informational transitive parameters

Attneave (1951) demonstrated that in a two dimensional shape, information (see Appendix I for a technical definition of this and other information theory terms) is concentrated along its contours, and in particular at points where the change of direction is greatest. Evans (1967) suggested that by manipulating the choice of source, channel and encoder, such that pattern elements represented the source, and the observer the encoder, decoder and channel, it was possible to compute a redundancy value for a single pattern. Unfortunately this measure can only be applied to patterns based on a matrix structure where the probability of each element can be computed, eg. the dot patterns used by Garner (1974).

2. Configurational parameters

These became particularly relevant after the work of Hübner and Wiesel (1962), which emphasised the importance of lines and edges as stimulus characteristics. Several authors (Brown and Owen, 1967, Michels and Zusne 1965, Zusne, 1965) attempted to compute a single number which would be representative of each pattern and could be assessed by considering sides, angles, edges etc. The result, was a strong correlation between moments of side length, perimeter, and pattern area (moments are computed in the same way as the mean, standard deviation, skewness etc. (Moroney 1951) of a statistical sample) and the perceptual tasks required of their observers. They find a parallel with the autocorrelation theories of pattern

recognition which have proved capable of predicting texture discrimination thresholds (Julesz 1978), although as pointed out by Caelli (1978) when applied to pattern processing the output is just another pattern - the autocorrelogram.

There are of course much simpler configurational parameters which have been tried, for example the perimeter - area ratio which is a good predictor of recognition thresholds for simple geometric shapes (Bitterman et al 1954).

3. Relational parameters

Every pattern is a member of a population of patterns. Usually in any experiment this population is defined in a rather arbitrary manner. Information theory (Brown 1966) provides a more rigorous method of defining such a stimulus set. Fitts and Leonard (1957) introduced the idea by developing patterns made up from square matrices, each element of which could be either black or white. This binary alternative allows the amount of information in a pattern to be computed, thus a 16 element pattern possesses a maximum of 16 bits of information.⁺ This information maximum is only obtained if the complete population of possible patterns is used. Normally however only a subset of the population is selected and this may be interpreted in redundancy terms although care should be taken on how this redundancy is computed (Appendix I).

One stimulus parameter not yet considered, since it is not within the classification outlined above is the Fourier transform of the pattern i.e. the spatial frequency amplitude and phase content

of the pattern. Two spatial frequency spectra are illustrated in figure 1.2, one of a square wave grating, the other of a square checkerboard.⁺⁺ The latter has proved particularly useful in modern research since not only are the fundamental frequencies orientated at a different angle from the pattern edges but Kelly (1976) has shown that the amplitude of the square wave grating fundamental is $\pi/2$ times the amplitude of the checkerboard fundamental.

Fourier spectra have probably been the most successful parameters in the development of models of visual detection thresholds (Burton 1978) and it seems likely they will prove to be fundamental to recognition thresholds (Ginsburg 1975 for example has postulated a pattern recognition model using a low pass spatial frequency filter).

⁺ If each element had three alternative states eg. white, grey and black the maximum information would rise to $16 \log_2 3$.

⁺⁺ Intensities are approximately estimated by spot diameter. Zero order spots have been omitted for clarity.

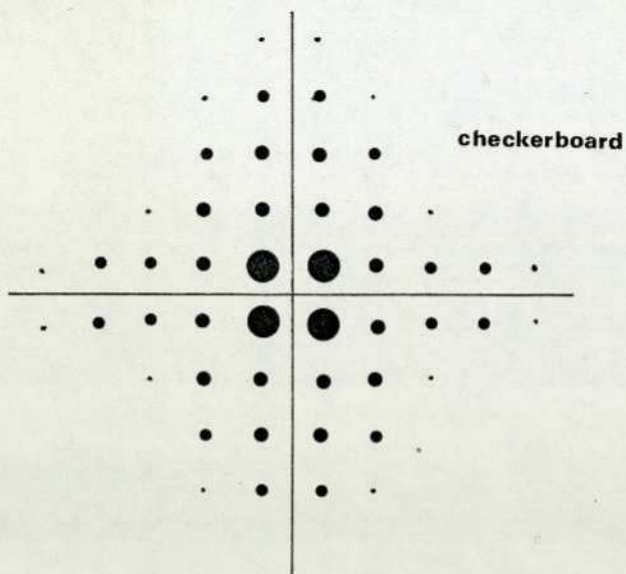
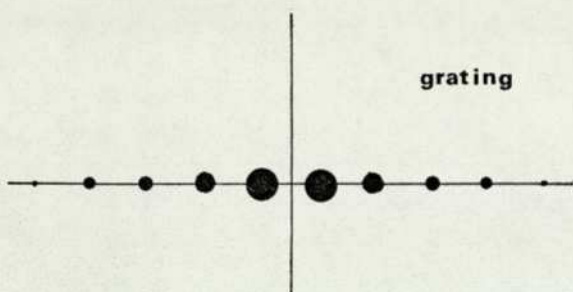


Figure 1.2 Fraunhofer diffraction patterns of
 a) a square wave grating
 b) a square checkerboard

1.4 Visual Processing

Processing of a stimulus begins at the retina with the absorption of light by three classes of cell with overlapping spectral sensitivity curves. These are followed by a neural network which transforms the receptor outputs to provide the percepts of hue, saturation and brightness. In addition the distribution of light in space and time is maintained through the neural network to provide pattern and flicker information.

Consider first the percepts of hue, saturation and brightness. A knowledge of the receptor spectral sensitivities would allow prediction of these percepts under a range of conditions, and several attempts have been made to determine them, either directly or indirectly.

Manipulation of the psychophysically determined colour-matching functions of the human observer, using linear algebraic methods permits the derivation of receptor sensitivities but unfortunately no unique solution exists (Wysocki and Stiles, 1967), if constraints are not applied.

Direct measurement of 'in situ' receptor absorbance is incapable of defining receptor sensitivity to more than 0.6 log units below peak absorbance (Boynton 1979).

Only three indirect methods have proved capable of providing detailed information regarding these receptor sensitivities. One (microspectrophotometry) is an 'in vitro' technique and therefore open to the usual criticisms (Bowmaker et al 1980), while the

other two methods require specific assumptions to be made.

(a) Stiles mechanisms (Stiles 1978)

The derivation of these mechanisms relies on the assumption that the threshold of the most sensitive component mechanism at each wavelength determines the resultant sensitivity, except for a small 'summation' effect where two mechanisms approach equality. Seven such mechanisms were isolated by the two-colour increment threshold technique and three of these seem like probable candidates for receptor sensitivities (π_1 , π_4 and π_5). The additional mechanisms cast doubts upon the validity of such an assumption and Mollon and Pugh (1979) eg. suggest that π_5 is the result of more than one class of cone.

(b) Derivation from dichromatism

An alternative approach is to determine valid constraints which might be applied to the manipulations of the colour matching functions. The two outstanding examples are the analyses of Vos and Walraven (1970) and more recently Smith and Pokorny (1975). Vos and Walraven (1970) made the following assumptions:-

- (a) Colour vision is mediated by two antagonistic neural processes: one of a red versus green type and the other of a yellow versus blue type.
- (b) Dichromatism is caused by the non-functioning of one of these antagonistic channels.

The authors then computed transformation equations by linking data from dichromatic confusion loci, receptor Weber fractions and hue-stable wavelengths of the Bezold - Brücke effect.

Smith and Pokorny (1975) also used dichromatic data but their derivation requires manipulation of macular pigment densities and the assumption that the short wavelength receptors do not contribute to the perception of luminance.

Figure 1.3 illustrates the receptor sensitivities derived by these various techniques. Considering the diversity of methods used, the agreement is good. (The larger bandwidth of the Stiles mechanisms may be methodological in origin c.f. spatial frequency channels).

A quantitative exposition of a possible model of the transformation performed by the neural network beyond the receptors, was put forward by Jameson and Hurvich 1955, 1956, and Hurvich and Jameson 1955, 1956. The chromatic cancellation technique used by the authors provided direct evidence for an antagonistic (opponent) organisation of the visual system. Their results could be described by assuming two "colour-opponent" operations in which red/green and blue/yellow differences are computed, and a single "achromatic-opponent" operation in which a black/white difference is computed (and whose resultant was equated to the relative luminous efficiency function).

The equations derived from this model are linear and as such are incapable of describing phenomena which demonstrate non-additivity.

DERIVED RECEPTOR FUNDAMENTALS

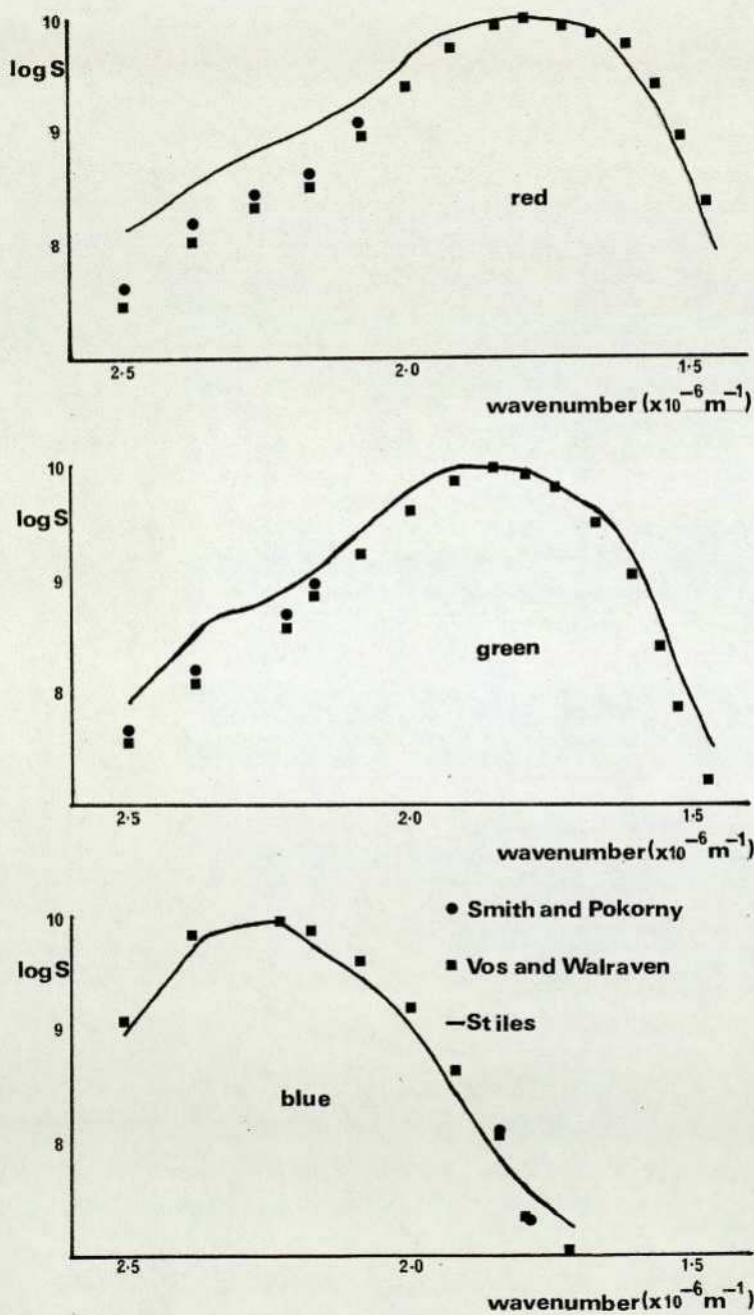


Figure 1-3

A particular example of such non-additivity involving chromatic stimuli is presented by Guth et al (1969). To overcome this Guth and Lodge (1977) proposed a vector model of threshold colour vision. A similar model was developed by Ingling and Tsou (1977), in which a visual response space (S_v) is defined. A point within this (three dimensional) space is then described by a vector sum of opponent mechanisms as in equation 1.1. (Figure 1.4 illustrates the remarkable similarity between the derived space and the CIE 1976 L^*, u^*, v^* space. The diagram of the Ingling model also illustrates the various receptive fields thought to contribute).

$$S_v = Q \left[(r - g)^2 + (y - b)^2 + V_\lambda^2 \right]^{\frac{1}{2}} \quad 1.1$$

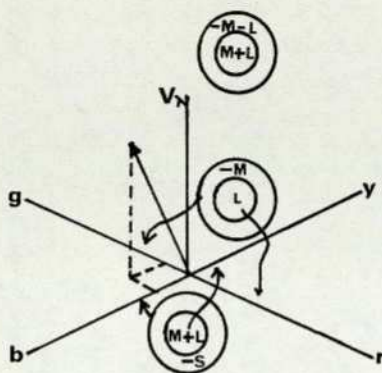
$(r - g)$ and $(y - b)$ represent two opponent colour channels similar to those of Jameson and Hurvich and V_λ is the equivalent of the opponent achromatic (luminance) channel. These three channels are defined by equations 1.2, 1.3 and 1.4 which allow the opponent channel values to be computed from the receptor fundamentals of Smith and Pokorny (L , M and S).

$$(r - g) = 1.2L - 1.6M \quad 1.2$$

$$(y - b) = K_1 (0.24L + 0.18M) - K_2 (0.75) - 0.05M \quad 1.3$$

$$V_\lambda = 0.6L + 0.4M \quad 1.4$$

INGLING VECTOR SPACE



CIE (1976) $L^*u^*v^*$ SPACE

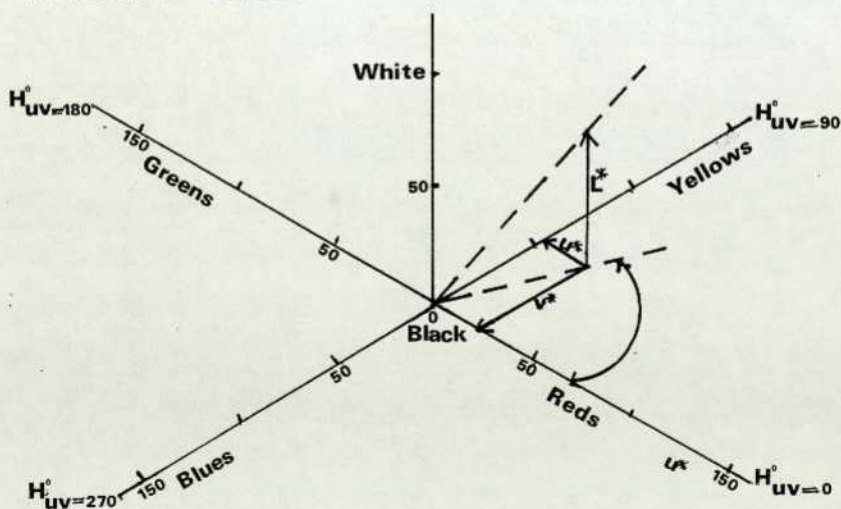


Figure 1.4 Comparison of Ingling and Tsou vector space with C.I.E. (1976) L^*, u^*, v^* space.

By setting S_v to be constant (i.e. threshold is a constant irrespective of the value of the controlled variable) and manipulating the constants K_1 and K_2 it is possible to obtain an approximate fit to data from spectral sensitivity experiments with a white background, purity discrimination experiments, and Guth's additivity results near threshold. (To obtain a good fit however differential weightings must be given to the opponent channels of equation 1.1).

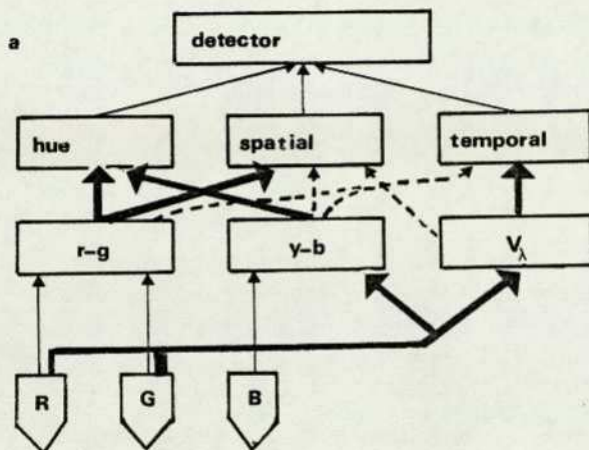
As an alternative Kranda and King-Smith (1979) suggested that spectral sensitivity and bichromatic mixture results can be fitted by assuming independent weighting and simple probability summation of opponent channels (this time derived from Vos and Walraven (1970) fundamentals). In addition they suggest that the yellow-blue mechanism be replaced by a green minus red mechanism and an independent blue mechanism. This model is not at odds with that of Ingling and Tsou however, since, as pointed out by Boynton (1979) the vector sum equation closely approximates a probability summation model if the value of the exponent is approximately two (this assumes that at most points of the spectrum only two channels significantly contribute to a threshold and when similar in value this is equivalent to probability summation). Thus if the $(y - b)$ of Ingling and Tsou is replaced by a $(g - r)$ function the two models are equivalent (although the Ingling and Tsou model has more free parameters).

Bird and Massoff (1978) have suggested a very detailed theoretical model which is fundamentally non-linear, but which reduces to linearity under certain limiting conditions. Although complex the model incorporates spatial and temporal parameters and therefore may

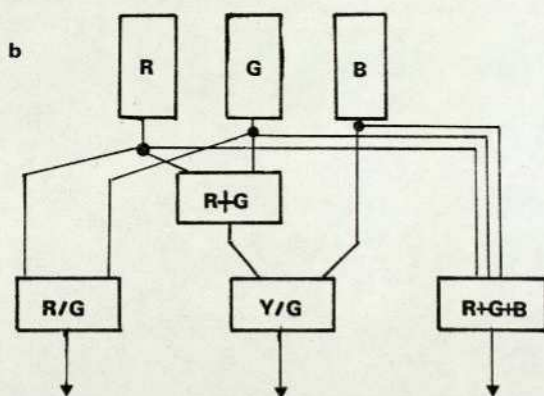
be a better predicative mechanism than either Kranda and King-Smith or Ingling and Tsou's.

The model of Kranda and King-Smith (1979) was an extension of work by Carden and King-Smith (1976) which did attempt to estimate the contributions of spatial and temporal components in a qualitative manner (small or short stimuli enhanced the achromatic component). Ingling (1978) has however criticised the postulated equivalence between the so called 'transient' system (Cleland et al 1971), and the achromatic channel of the visual system isolated by Carden and King-Smith. To overcome this difficulty Ingling suggested that two luminance channels exist (figure 1.5 illustrates this idea along with the zone model of Vos and Walraven). These have the same spectral sensitivity but different spatial and temporal properties. A similar model has also been put forward by Bauer and Röhler (1977) and it seems obvious that a thorough understanding of chromatic processing cannot be obtained by considering it in isolation. Before discussing the interaction of spatial and chromatic dimensions however it is necessary to consider how spatial information is processed.

The isolation of features which characterised stimuli in physiological terms was given a boost by the discoveries of Hübner and Wiesel which emphasised the importance of lines and edges. More recently Marr (1975) has constructed a computer model of spatial vision which extracts a "primal image" from measurements of lines and angles and their relationships to each other. Surprisingly however the ideas which dominate now, actually predate the work of



INGLING MODEL



VOS and WALRAVEN MODEL

Figure 1.5 a) Ingling opponent - colour model. Dotted lines indicate nonpreferred or comparatively insensitive pathways, which can be used for discrimination if conditions are unfavourable.
b) Zone model of colour vision (From Vos and Walraven, 1971).

Hübner and Wiesel by several years (eg. Schade 1948). These early psychophysical experiments suggested that the visual system operated as a band-pass spatial frequency filter. Hoekstra (1974) has recently criticised the band-pass idea however and has suggested that the low frequency loss of sensitivity is an experimental artifact. Estevez and Cavonius (1976) on the other hand have refuted this idea.

Campbell and Robson (1968) however, hypothesised that the contrast sensitivity function represented a probability summation envelope of a set of narrow bandwidth spatial frequency channels (Figure 1.6). Further support came from Graham and Nachmias (1971), Watson and Nachmias (1977) and Furchner (1977). Determinations of the bandwidth of these channels relied upon adaptation (Pantle and Sekuler, 1969, Blakemore and Campbell 1969, Blakemore et al, 1973) and masking (Carter and Herning 1971, Stromeyer and Julesz 1972) or subthreshold summation methods (Graham and Nachmias 1971). The estimates ranged from 0.4 to 1.5 octaves (for comparison, the bandwidth of a receptor in the spectral domain is approximately half an octave). The wide range is a result of methodology according to Braddick et al (1978) and Stecher et al (1973) who suggested that summation under-estimates, and adaptation or masking over-estimates bandwidth.

The multiple channel model also predicts effects at frequencies other than that selected for adaptation. Such effects have been found, eg. Blakemore and Sutton (1969) showed that exposure to a high contrast grating altered the perceived frequency of other gratings. A similar effect can be induced simultaneously (Klein et al 1974). Such effects are contingent upon other variables -

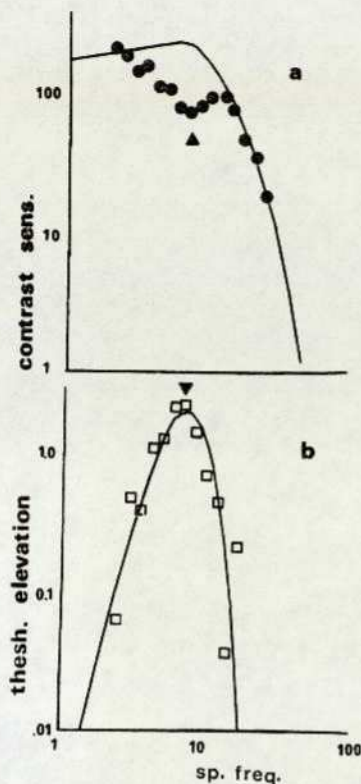


Figure 1.6 a) Solid line is contrast sensitivity function in absence of adaptation, and data points are contrast sensitivities following adaptation to a grating of 7.1 c/deg.
 b) Relative threshold elevation due to adaptation, expressed as sensitivity ratio minus one. Adapting frequency indicated by arrow. (Effectively this is a plot of channel sensitivity).
 From Blakemore and Campbell, 1969.

orientation (Campbell and Maffei 1971), colour (Stromeyer 1978), and orientation plus colour (Wyatt 1974) for example.

The idea of the visual system as a spatial frequency analyser has not advanced unchallenged. Nachmias et al (1973) could find no elevation of the third harmonic after adaptation to a square wave. This was explained by Abadi and Kulikowski (1973) as being due to suprathreshold, channel interaction. Tolhurst (1972) measured detection thresholds for different Craik-Cornsweet profiles, and invoked edge-detectors in preference to frequency channels to explain the results. Kulikowski and King-Smith (1973) measuring edge, line and frequency thresholds found that separate edge, line and frequency detectors were required. Bar detectors were proposed by MacLeod and Rosenfeld (1974). Mostafavi and Sakrison (1976) and Stromeyer and Klein (1974), however, demonstrated that on computing point spread functions from single channel characteristics "edge-detectors" or "line-detectors" could be generated by assuming odd or even symmetry respectively in the Fourier transform. Furthermore Graham (1975) demonstrated that the different thresholds found by Kulikowski and King-Smith could be explained by assuming probability summation between channels. Evidence specifically implicating spatial frequency and not edges as the relevant dimension was provided by Kelly (1976) and Kelly and Magnuski (1975) who compared thresholds to one and two dimensional patterns.

The model of pattern analysis is not quite so simple however. Burton (1979) has found evidence of non-linearities. Suprathreshold contrast sensitivity functions differ from the standard threshold

curve (Cannon 1979). Wilson and Bergen 1979, and Wilson 1978 have proposed that only four channels operate at each retinal site and the bandwidths of these channels are dependent upon retinal eccentricity. Blakemore and Campbell 1969, were unable to adapt out a channel below 3 cycles/degree. Some of these results require a consideration of the temporal response properties of the visual system before they can be explained.

Studies of the detection thresholds for flickering uniform fields (eg. Kelly 1974) have suggested that the visual system may be described as a low-pass temporal filter. When grating stimuli were manipulated in the temporal domain however, it became apparent that this simple filter model was incomplete and that the visual system is better described in terms of two separate channels. Evidence for such an idea originated from several different experimental paradigms.

Kulikowski and Tolhurst (1973) and King-Smith and Kulikowski (1975) found that thresholds for flicker and pattern detection were different and independent functions of spatial and temporal frequency. Similarly when stationary gratings were set in motion (Tolhurst, Sharpe and Hart 1973) a different detection threshold was found. Flicker (motion) sensitivity demonstrated a low pass spatial and a band-pass temporal frequency sensitivity. This band-pass temporal characteristic is supported by Kulikowski's (1971) finding that exaggerated eye movements reduced sensitivity to low spatial frequencies.

Tolhurst (1975) using a grating spatially superimposed on a sub-threshold grating of the same frequency as a test stimulus, found that its detection threshold was spatial frequency dependent. At low spatial frequencies test detectability was affected only for part of the time that the sub-threshold grating was present. At high spatial frequencies the detection threshold was altered throughout the period the background grating was on. Similarly King-Smith and Kulikowski (1975) tested sub-threshold summation and found non-linear summation for flicker, but linear summation for pattern detection thresholds.

Legge (1978) and Arende (1976) on the other hand manipulated stimulus duration under both masked and unmasked conditions and found that critical duration was a function of spatial frequency.

All of the methods described used a rapid stimulus onset. Breitmeyer and Julesz (1975) however, found that detection of low frequency gratings was enhanced by rapid, compared with gradual onset.

The properties of the two channels may be summarised as follows. One - the "transient" - is sensitive to medium to high temporal frequencies but only low spatial frequencies. The other - the "sustained" - is sensitive only to low temporal frequencies and shows a band-pass characteristic in the spatial domain. The former is a single low-pass spatial frequency channel, but the latter is the resultant of probability summation between multiple narrow-band spatial frequency channels. The

minimum adaptable channel of Blakemore can now be understood since his experimental conditions gave preference to the "sustained" channel.

Having considered spatial and temporal processing in isolation it is now possible to discuss how chromatic variables influence contrast and flicker sensitivity functions. Two different tests may be applied. In one, luminance is modulated either with or without chromatic adaptation, while in the other luminance is held constant and the wavelength of the test area is modulated (either about the white point i.e. purity modulation, or more commonly about another hue eg. red and green are modulated about yellow).

Kelly (1974) using the former method with appropriate background colours, isolated a red, green and blue mechanism. The blue mechanism demonstrated a much poorer resolution, with a peak contrast sensitivity at one cycle/degree. The red and green mechanisms had similar shaped contrast sensitivity functions but the green was much more sensitive than the red. Estevez and Cavanus (1976) have criticised these results on methodological grounds although they agree that the blue mechanism is significantly different, as do others (Voke 1979). The similarity between the red and green sensitivity functions and that obtained with achromatic stimuli supports the conclusion that the blue mechanism plays little or no part in achromatic sensitivity.

Contrast sensitivity functions determined in wavelength modulation experiments are even more interesting. If modulation

is about a neutral point (Schade 1958, Van der Horst 1968) the computed line spread function shows evidence of slight inhibiting side-bands. When modulation is about an intermediate hue, no such side-bands are found (Van der Horst 1969). The former case implies that inhibition occurs between channels, while the latter suggests that none occurs within mechanisms.

Mauderbocus and Ruddock (1973a) found that size selective responses were not wavelength dependent whereas May (1972) suggested the opposite. Estevez and Spekreijse (1974) found no low frequency attenuation (equivalent to a lack of side-bands in the line spread function) when long and medium wavelength mechanisms were isolated. More recently May et al (1978) have demonstrated that colour contingent after-effects are the result of Fourier components and not edges.

Turning to temporal modulation studies, Kelly (1974) found that the temporal modulation sensitivities of the blue, green and red mechanisms all demonstrated a low frequency attenuation with uniform fields, which disappeared when the optimum spatial frequency for each mechanism was selected. In both cases the green mechanism was the most sensitive, followed by the red, then the blue. Green (1969) found similar sensitivities for the red and green mechanisms above 10 Hz, but a greater red sensitivity at lower frequencies. Regan and Tyler (1971a, b) using wavelength modulation found no low frequency attenuation and a much poorer sensitivity to high flicker rates, compared with achromatic luminance modulation.

Kelly and van Norren (1977) used three test conditions:-

- (i) Chromatic modulation (red and green about yellow)
- (ii) Chromatic plus achromatic modulation
- (iii) Achromatic modulation.

In the first case a very slight low frequency fall in sensitivity occurred, while in the third situation the standard result was obtained. The results in the second case could be fitted by a curve which was the resultant of probability summation between (i) and (iii). This seems to support the idea of separate processing of flicker by the chromatic and achromatic channels.

Kelly (1976) in searching for a retinal site for Fourier analysis by the visual system combined all three variables and used chromatic flickering checkerboards (and gratings) on an adapting chromatic background. His comparison of checkerboard and grating detection thresholds indicated that Fourier effects are associated both with the achromatic (Ingling's "chromatic" - luminance channel since fine detail stimuli were used) and chromatic channels.

Ingling and Drum (1973) using hypothetical receptive field⁺ profiles (Figure 1.7a) were able to show that the chromatic channel when stimulated only by a chromatic gradient produced a gradual perceived gradient between the two hues, but when a luminance difference is added the chromatic channel response is "sharpened up" (Figure 1.7b). They were also able to show that change in

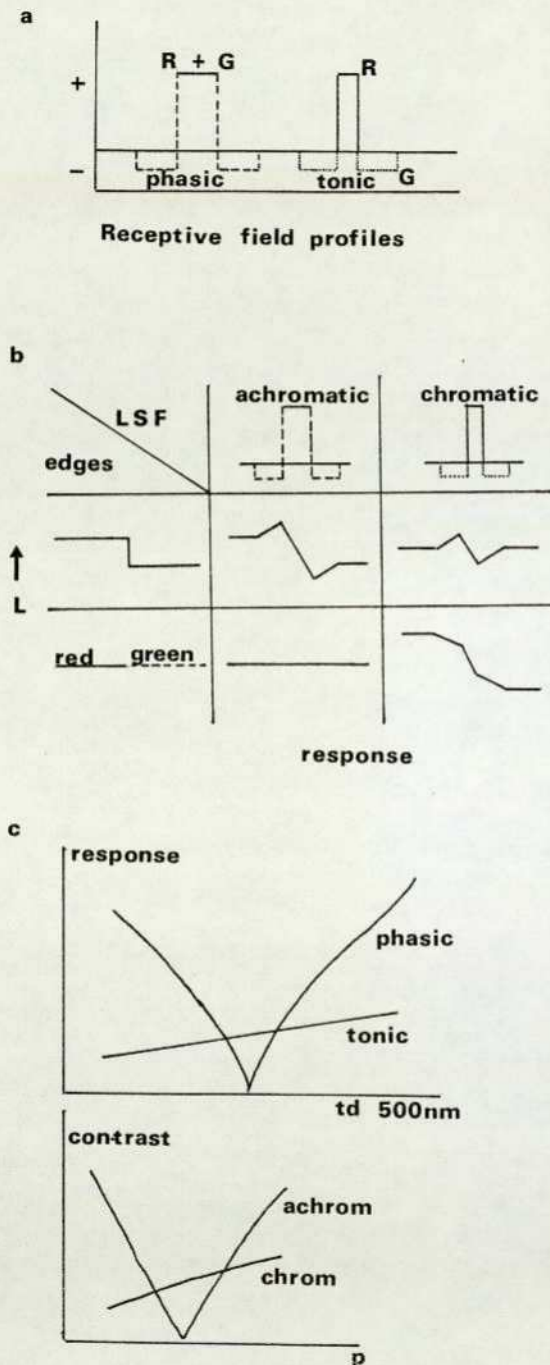


Figure 1.7 Hypothetical receptive fields a) profiles b) responses and c) psychophysical vs cell responses.

contrast (either chromatic or achromatic) between a fixed white field and a variable 500 nm field produced psychophysical chromatic and achromatic responses which could be paralleled by considering the responses of tonic and phasic cells (De Valois et al 1966). This comparison is illustrated in Figure 17c. Probably the most interesting conclusions from the Ingling and Drum results are:

- (a) that very close to (and including) the isoluminance situation ($p = 1$ in Figure 17c) the chromatic system produces a larger response than the achromatic system, for the wavelength used.
- (b) Even though both chromatic and achromatic retinal units have inhibitory surrounds, the chromatic units do not enhance borders unless an achromatic contrast is present.

The evidence from the various sources appears to suggest that when purely chromatic information is available the visual system shows a poor temporal and spatial resolution, but this is altered by the addition of even a very small amount of achromatic information. This would appear to imply that at very low contrasts i.e. when a small amount of achromatic information is present, a high purity stimulus (i.e. large chromatic gradient) might aid discrimination or recognition, compared with the achromatic situation (i.e. low purity stimulus).

⁺Footnote:

The use of square profiles can be criticised since transients are introduced. Gaussian profiles would have been better.

1.5 Physiological Evidence for multiple channel processing

Space limits a discussion of electrophysiological evidence, therefore preganglionic structure and function will not be discussed, but Table 12 summarises the main findings.

The first steps towards a quantitative description of ganglion cell activity began with Kuffler's (1953) description of concentric receptive fields. Rodieck and Stone (1965) were able to predict ganglionic responses to simple moving targets, by making assumptions regarding cell firing rate, and using an idealised receptive field structure - Figure 12a-derived from spatial sensitivity profiles mapped with flashing spots of light. The assumption of linear spatial summation in these calculations could not account for small differences between actual and computed responses. This required non-linear components (Rodieck, 1965, Cleland and Enroth-Cugell 1966).

An independent classification based on the presence or absence or a "null-response" to sinusoidal gratings was proposed by Enroth-Cugell and Robson (1966). Cells demonstrating this "null-response" showed linear summation of centre and surround responses and were termed X-units. Those showing no "null-response" were termed Y-units. Table 13 summarises their properties.

SCHEMATIC RECEPTIVE FIELDS

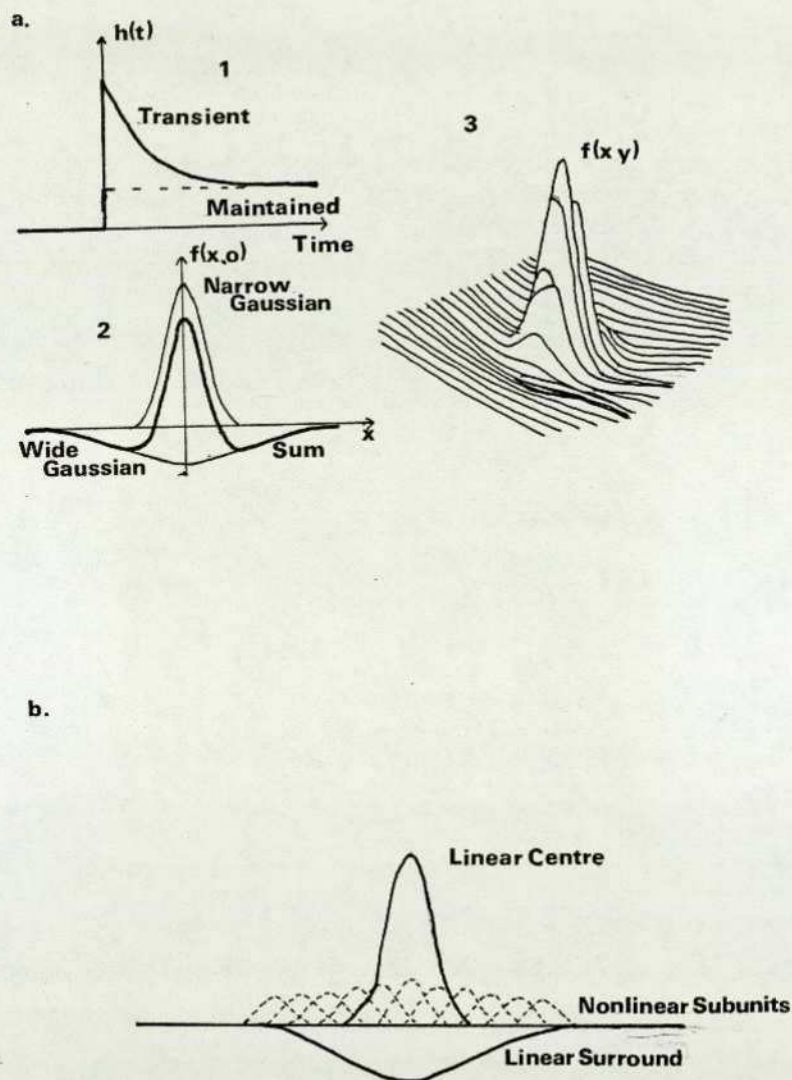


Figure 1.8 a) 1. temporal response, 2. spatial profile (sum of two gaussians), 3. two dimensional spatial profile.
b) components of Hochstein receptive field.

TABLE 1.2

PREGANGLIONIC NEURONE PROPERTIES

Structure	Classes	Comments
Receptors	4	Three cone types isolated by intracellular recording. Hyperpolarise in response to light.
Horizontal Cells	2	"Luminosity units" and "chromatic units" respond differentially to different wavelengths. Receptive fields of C-units are twice the size of L-units.
Bipolar Cells	2	Centre-surround organisation. Type 1 centre depolarises to light, surround hyperpolarises. Type 11 centre hyperpolarises, surround depolarises to light stimulation.
Amacrine Cells	-	Show transient responses to light (on receptors). Concentric receptive field structure. First site of action potential type response.

TABLE 1.3

PROPERTIES OF X- AND Y-UNITS

Stimulus variable or property	X-units	Y-units	Author
1. Terminology	Type II Sustained	Type I Transient	Fukuda (1971) Cleland et al (1970)
2. Standing contrast	Display a sustained level of firing throughout stimulus period	Transient increase in activity at onset and off-set	Saito et al (1970)
3. Flashing spots of light	Initial transient followed by constant firing rate	Only initial transient	Saito et al (1971)
4. Grating stimuli	Contrast sensitivity function characterises cell in the frequency domain. Response is modulated in phase with the stimulus	Contrast sensitivity function does not demonstrate the invariance of X-units. Response is a general increase in cell firing rate	Enroth-Cugell and Robson (1966)
5. Flicker	High CFF but average firing rate varies little with frequency	CFF lower than X-units but average rate of firing rises then falls as frequency increases	Fukuda and Saito (1971)

TABLE 1.3 CONTINUED...

Stimulus variable or property	X-units	Y-units	Author
6. Movement	Respond to slow movement. No response to fast movement	Respond to slow movement. Respond to fast movement	Cleland et al (1970)
7. Periphery effect	Weak or absent	Strong	Cleland Lewis and Dubin (1971)
8. Receptive field centre size	$0.55^{\circ} - 2.9^{\circ}$	$1^{\circ} - 7^{\circ}$	Fukuda (1971)
9. Retinal distribution of receptive field	Predominate in central retina	Predominate in peripheral retina	Fukuda (1971)
10. Conduction velocity of axons	Slow (26 m/s)	Fast (40 m/s)	Fukuda (1971)

Hochstein and Shapley (1976a) tested the proposed dichotomy, and found that their "non-linearity index", (a measure of the presence of harmonics of the stimulus repetition rate in the Fourier transform of the cell's response) correlated well with the method of Enroth-Cugell and Robson (1966) and also with the spatial timing measure of Maffei and Fiorentini (1973). It also indicated that X- and Y-units were separate classes and not extremes of a continuum. Furthermore the index was independent of receptive field type (on - or off-centre) and retinal eccentricity.

The lack of linearity demonstrated by the Y-units may be explained by postulating the existence of small non-linear sub-units (Hochstein and Shapley 1976b) - Figure 1.8b. These sub-units are not detected by flashing spots of light, explaining why Rodieck (1965) found only linear units.

The responses of ganglion cells to chromatic stimuli led Gouras (1968) to distinguish two classes of cell. The first, referred to as phasic, received inputs from both long and medium wavelength receptors, each organised in a centre-surround manner, and responded transiently at on-set and off-set of a stimulus. The second he referred to as tonic, had a centre receiving input from one cone type and an antagonistic surround with an input originating in another cone type, and responded in a sustained manner.

A more detailed analysis performed by De Monasterio et al 1975a, b, c, 1978a, b, c) reached the following conclusions:

1. Three general classes of cell subserve the central 40° of vision in rhesus monkey.

(a) Colour opponent

These show a sustained response to light and possess concentrically organised receptive fields. Many of the cells demonstrated a trichromatic input eg. red sensitive centre, cyan (blue + green) sensitive surround. (This resolves the apparent conflict between a dichromatic retina (Gouras 1968) and a trichromatic cortex (Gouras 1970).

(b) Broad band

These cells responded transiently and had concentrically organised receptive fields in which usually the same two cones mediated both the centre and surround responses. Sensitivity profiles were much broader spatially than those of colour opponent cells.

(c) Others

This class was relatively rare and responded in an extremely transient manner. There was little evidence for a structured receptive field.

2. Colour opponency is often concealed when neutral adaptation is used - chromatic adaptation is required to reveal it.
3. Responses to drifting chromatic gratings revealed that colour opponent cells fit the X - classification and broad band cells the Y - classification.
4. Surround sensitivity profiles of colour opponent neurones are bimodal (spatially) and it has been suggested by Granger and Heurtley 1973 that such a profile can explain the higher, low spatial frequency and the lower, high spatial frequency sensitivity found with chromatic modulation.
5. Blue centre opponent colour cells are almost 100% on-centre types and possess a lower critical flicker frequency (De Monasterio 1979).

From the retinae information passes to the lateral geniculate nuclei (LGN) where the input is organised retinotopically (Szentagothai 1973) with X-units segregated from Y-units (parvocellular versus magnocellular layers respectively, Weller et al 1979). Within the LGN Wiesel and Hübner, 1966 distinguished four classes of neurone. These have been related to the X/Y classification by Dreher et al 1976 as follows (based on Wiesel and Hübner (1966) classification):-

- Type I These were found exclusively in the parvocellular layers. Their receptive field centre is mediated by one cone type and their surround by another. Very few "blue-centre" neurones were found.
- Type II This class demonstrated colour opponency but not spatial opponency.
- Type III The spectral sensitivity of the centre was the same as the surround. Two sub-types occurred.
- (a) Type III_x with X-like properties
- (b) Type III_y with Y-like properties
- Type IV These demonstrated phasic Y-like properties.

Both types I and II demonstrate X-like properties, type III show mixed properties, and type IV have Y-like properties, and are only found in the magnocellular layer.

Marrocco and Brown (1975) on the basis of sustained versus transient responses obtained four classes of response - sustained opponent, sustained non-opponent, transient opponent and transient non-opponent. Derrington and Fuchs (1979) have shown that the sustained/transient analysis is a poor indicator of the X/Y dichotomy however.

The contribution made by the LGN to neural processing is somewhat unclear, as suggested by the repeated references in the

literature to it as a "relay station". It seems likely that it acts to reorganise inputs from the two eyes into functional columns made up of alternate right and left eye inputs (Freund 1973), without rearranging the receptive field structure. There is also evidence for purity discrimination at LGN level (De Valois and Marocco 1973) but it seems unlikely that this is the site at which it's perceptual correlate arises. De Valois and Marocco (1973) do imply that purity discrimination can be mediated solely by opponent neurones (spectrally) however.

Cortical neural properties were elegantly investigated by Hübner and Wiesel (1959, 1960, 1963, 1965, 1968, 1972, 1974a, 1974b) who determined the two fundamental processes performed - incoming LGN axons are rearranged in such a way that cortical cells require a particular stimulus orientation, and the input from two eyes is brought together.

Cells with common stimulus requirements are grouped together in vertically organised functional columns.

(a) Ocular dominance columns

Within these columns all cells respond preferentially to stimulation of the same eye. Columns are arranged as alternate left- and right-dominated slabs about 400 micrometers thick.

(b) Orientation columns

Cells of a like orientation preference are grouped together into much narrower vertical sheets, arranged in an orderly sequence such that moving through a series of successive adjacent sheets results in small shifts in the orientation to which the cells are most sensitive.

These functional columns are organised independently of each other and are superimposed on the retinotopic representation of the visual field.

Receptive fields mapped in a vertical penetration through the cortex show a scatter in position roughly equal to the average size of the fields themselves, and the area thus covered - the aggregate receptive field - increases with distance from the fovea. A parallel increase is seen in the number of degrees of visual field corresponding to one millimeter of cortex. Effectively a decreasing amount of cortex is devoted to analysing a fixed area of the visual field on moving away from the fovea.

The properties of cortical neurones derived by Hübner and Wiesel (1968, 1970) were elucidated using bars of light (usually achromatic) and were of four types.

1) Circular symmetric cells

These showed no orientation preference and resembled LGN neurones (they could be distinguished from such neurones

however by their responses).

II) Simple cells

These cells responded to a line stimulus orientated in a particular direction. If the line was moving there was usually a preferred direction. The greater response to a line compared with a spot of light was interpreted as meaning that simple cells received inputs from several circularly symmetric cells whose receptive fields if plotted would fall in a line and would overlap each other.

III) Complex cells

These showed the same sensitivity to an orientated line as simple cells, but possessed a greater generality for the position of the stimulus which suggests that several simple cells make up the receptive field of a single complex cell. The simple cells would be required to have the same orientation sensitivity in this theory.

IV) Hypercomplex cells

These cells were more evident in areas 18 and 19 and resembled complex cells in all respects but one - extending the stimulus line beyond a certain length markedly reduced the response of the cell. This implies that unlike the simple and complex cells the hypercomplex cells possess an inhibitory region (simple and complex cells do have inhibiting regions but these tend to be dominated by any excitatory regions present).

These four cell types were believed by Hübner and Wiesel (1977) to be organised in a hierarchical manner proceeding from LGN axons to concentric cells, simple cells, complex cells and hypercomplex cells, with each stage leading to a greater generalisation of the position requirements of the stimulus.

A detailed quantitative analysis of cortical neurones by Schiller et al (1976 a, b, c, d) and Finlay et al (1976) supported the general classification of Hübner and Wiesel but reached the conclusions that any theory of cortical mechanisms should produce the qualities of orientation and field size selectivity by separate mechanisms, and that simple and complex cells represent different principles of neuronal organisation. The best discrimination of simple and complex cells was response modulation to a grating target.

The introduction of sinusoidal gratings as stimuli gave rise to doubts as to whether the edges, or the spatial frequency components were the relevant features as far as a cortical neurone was concerned. The work of Hübner and Wiesel implies the former, where as Glezer (1973) and Andrews and Pollen (1979) proposed the latter. Tyler (1978) has criticised the assumptions of Glezer but De Valois et al (1979) using an elegant method similar to that of Kelly (1978) demonstrated that cortical neurones respond to the orientation of the Fourier components.

Maffei and Fiorentini (1977) went further and postulated that the cortex possessed a functional organisation for spatial

frequency just as it did for orientation and ocular dominance.

These postulated spatial frequency columns are arranged orthogonally to the orientation columns and a vertical penetration of the cortex meets cells whose spatial frequency sensitivity moves progressively to lower values. In support of this Schiller et al (1976c) found a broadening of orientation tuning on descending through the cortex, which is consistent with a decreasing peak spatial frequency.

This evidence favouring Fourier components over edges as the critical features makes the idea of a hierarchical organisation less clear, particularly as the modulation responses to gratings of complex cells are different to those of simple cells. In addition the subcortical two channel theory is difficult to reconcile with the single hierarchy of Hübner and Wiesel. Stone and Dreher (1973) proposed that X-units project to area 17 and Y-units to prestriate cortex. Alternatively, Ikeda and Wright (1974) suggested that simple cells receive X-axons and complex cells Y-axons, yet the stimuli used by De Valois et al (1979) which would have been expected to stimulate Y-units produced no response from complex cells.

It is apparent that the two channel model is rather an oversimplification at cortical level although the fact that it was also deduced psychophysically implies that it is still important at this level.

When chromatic stimuli were used by Hübner and Wiesel, only about 10% of the cortical cells were sensitive. This apparently small percentage is probably a result of the large proportion of perifovea sampled by the authors, since Daw (1974) for example, found 30% of cortical neurones were sensitive to colour when only the fovea was sampled.

Bertullis et al (1977) found neurones sensitive to both colour and orientation in the foveal representation in monkey cortex. This was at variance with Daw and Gouras (1973) and Gouras (1974) who had stated that cortical neurones were either "spatially coded" or "colour coded". Michael (1978 a, b, c) using methods similar to those of Hübner and Wiesel demonstrated a double hierarchy. One resembled that of Hübner and Wiesel and was insensitive to chromatic contrast. The other required chromatic plus achromatic edges and had an additional step in the hierarchy - double opponent neurones without orientation sensitivity, in which two cone types mediate a centre response and are antagonistic to each other. The same cones mediate the surround response but show a reversed antagonism i.e. if the centre is +R-G, the surround is +G-R.

Such a hierarchical system could explain simultaneous contrast effects and the McCollough effect (Stromeyer 1978, Sharpe and Mädl 1977) although Mauderhous and Ruddock (1973) have denied the existence of colour dependent orientation effects. The results of Michael provide good evidence that colour contrast is segregated from achromatic contrast at cortical level. When pure chromatic contrast (i.e. no luminance difference) is used only 3% of cortical

neurones are responsive and these require much larger stimuli (Gouras and Krüger 1979).

This functional segregation and specialisation appears to continue in the cortical areas connected with striate cortex. Zecki (1969, 1973, 1975, 1978 a, b, c) and Van Essen and Zecki (1978) have shown that the prestriate cortex is subdivided into functional areas, each dominated by cells responsive to a particular stimulus dimension and organised in one or more retinotopic maps. Table 1.4 lists the main areas, functional types and connections.

The most interesting area is V_4 since it shows definite specialisation for colour and a breakdown of the well organised single retinotopic map found at lower levels. Zecki (1980) has provided evidence not only that cells in this area show a much narrower spectral bandwidth (0.1 octaves) compared with receptors, and a bimodal distribution of peak sensitivities, but are mapped in an orderly manner across this part of the cortex. He has further shown that it may be more appropriate to use complex stimuli when testing such high level cells. The conclusion from these studies seems to be that there is a region of the cortex in which the spectral domain is analysed by multiple overlapping channels which are organised in a functional manner. This is reminiscent of how the spatial domain is organised.

TABLE 1.4

CLASSIFICATION OF PRESTRIATE CORTEX

Area	Inputs (Main)	Primary stimulus attribute analysed
V ₁ (also area 17)	LGN axons	Orientation plus spatial frequency plus colour
V ₂	1. Direct from V ₁ (fine fibres). 2. Direct from V ₁ (coarse fibres).	1. Orientation (70% of cells) 2. Orientation (70% of cells) Larger receptive fields than V ₂
V _{3A}	Input from V ₃ (Multiple topographic visual representations)	As area V ₃
V ₄	Foveal V ₁ direct. Extrafoveal V ₁ via V ₂ . Multiple visual field representations	54% of cells colour opponent. Large receptive fields.
Superior temporal sulcus	Direct from V ₁ .	Motion (Cells direction selective).

1.6 Saturation

The percept of saturation is related to the psychophysical quantity of excitation purity by a power function (Stevens 1975)

$$S_A = k p_e^{\beta} \quad (1)$$

and so it is necessary to consider the purity discrimination function before discussing the variables which may influence the perception of saturation.

The classical purity discrimination function (eg. Boynton 1979) shows a minimum purity sensitivity at 570 nm. The assumption in the determination of such a function is that the threshold change in purity varies inversely with the ratio of chromatic to achromatic excitations in the visual response. A similar assumption may be applied to the vector models of vision to provide a wavelength dependent function which matches the experimental function (eg. Ingling and Tsou 1977). Jameson and Hurvich (1955) as well as modelling the standard purity discrimination function (i.e. white adapting field) used their model to predict the effect of other adapting fields on the function. Unlike the luminosity function which is relatively independent of the adapting field, the purity function showed marked changes in shape.

Troscianko (1978) has investigated the effect of several other factors on saturation, in addition to wavelength.

(a) Luminance factor

Saturation reaches a maximum when there is a

brightness match between the test area and its surround. This is in agreement with other workers (Pitt and Winters 1974). The effect is itself dependent upon purity however.

(b) Test field size

With a light surround the saturation of a 1° field was higher than that of either $1/6^{\circ}$ or a 2° field. This was interpreted by Troscianko in terms of a "chromatic cell" receptive field, but an alternative explanation might be the effect of the proportion of x- to y-units (chromatic to achromatic) which is thought to decrease on moving away from the central fovea (eg. De Monasterio 1975b). There is also the additional contribution to the chromatic but not the achromatic system of the blue cones which are not present in the central fovea (eg. Burton and Ruddock 1972).

1.7 Latency

Measurements of latency have provided evidence for two particularly relevant aspects of visual processing.

1. Dual channels - evidence from latency.

Breitmeyer (1970) and Breitmeyer and Ganz (1975) demonstrated that reaction time is a function of spatial frequency and this was supported by neuromagnetic latency measurements (Williamson et al 1978). Breitmeyer and Julesz (1975) investigated the effect of

stimulus rise time and suggested gradual onset (100 ms) isolated responses from the sustained system, whereas a rapid onset only stimulated the transient channel. Tolhurst (1975) provided convincing evidence by demonstrating that latency distributions (relative to stimulus onset and offset) were dependent upon spatial frequency, near threshold. At low frequencies, reaction times were grouped around sudden stimulus transients, but for high frequencies they were spread throughout the presentation period. With supra-threshold stimuli the relationship between latency and grating contrast was monophasic for high and low frequencies but biphasic for medium frequencies (Harworth and Levi 1978, Levi et al 1979).

Recently measurements of threshold and suprathreshold reaction times along with duration and frequency effects using monkeys (Harworth, 1980) produced results similar to those with human subjects, providing a link between psychophysical and electrophysiological evidence for a dual channel model.

2. Hue effects on latency

Attempts to measure hue effects on latency are not new (eg. Helmholtz 1922). Several authors (Holmes 1977, Pollack 1968, Litt et al 1971 and Guth 1964) found no effect at photopic intensities (using test spots on an achromatic background, usually at supra-threshold intensities). Mollon and Krauskopf (1973) on the other hand using the two colour increment threshold method of Stiles found that the latencies of π_1 , π_4 and π_5 mechanisms are independent and also that the latency of π_1 is longer than either π_4 or π_5 . Jones and Wilkinson (1975) using a disjunctive

reaction time paradigm found a significant dependence of latency on wavelength. Breton (1977) compared an incremental with a substitution (no luminance change) presentation, and was able to match the resulting wavelength dependent latency effect found using the substitution method, with an electrophysiological measurement of red-green opponent activity. The lack of yellow-blue opponency is interpreted as being due to the low retinal illuminance (4 tds) used. Nissen and Pokorny (1977) found no wavelength dependent latency effects with a dim background, but with a background luminance equal to that of the chromatic test, reaction time was dependent upon wavelength and the function resembled the shape of the purity discrimination function (570 nm minimum latency).

The results of Nissen and Pokorny (1977) and Breton (1977) are in agreement with the statement by DeValois and Marrocco (1973) that purity discrimination is mediated solely by the opponent mechanisms (chromatic).

1.8 Summary

It is apparent from this discussion of both psychophysical and physiological evidence related to the operation of the visual system that information flow to higher cortical levels proceeds along functional channels. These are not identifiable anatomically since a single neurone may be part of more than one channel, and this has the further consequence that an investigation of any single stimulus parameter, in an attempt either to isolate the

properties of a single channel or to predict how several channels will respond to other stimuli is impossible without a consideration of those other factors in the stimulus domain which may be influencing the results. An investigation of the effect of purity on recognition thresholds is no exception since for example the spatial dimensions of the test targets might easily influence the perceived saturation of those targets. In addition it has been shown that reaction time as a response indicator is a variable in itself, dependent upon the chromatic spatial and temporal properties of the stimulus.

CHAPTER TWO

SELECTION AND CONSTRUCTION OF TARGETS FOR RECOGNITION AND IDENTIFICATION EXPERIMENTS

- 2.1 Description of targets
- 2.2 Advantages and criticisms
- 2.3 Construction

SELECTION AND CONSTRUCTION OF TARGETS FOR RECOGNITION
AND IDENTIFICATION EXPERIMENTS

2.1 Description of targets

It was decided that patterns organised on information theory measures should be used, and the total pool of patterns from which targets could be selected is shown in figure 2.1. Each pattern may be classified by two numbers (dimensions):

(1) Maximum information content ($H_{\max}$)

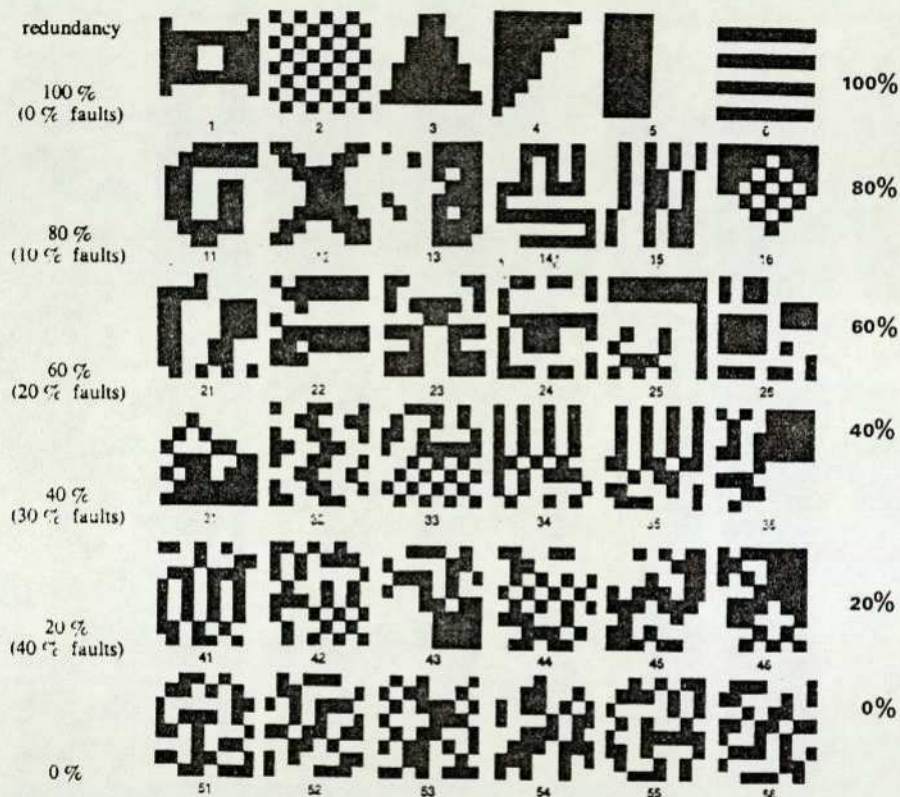
This was determined by the matrix size chosen and could be 64 bits (8 x 8 matrix) or 225 bits (15. x 15 matrix).

(2) Redundancy (R)

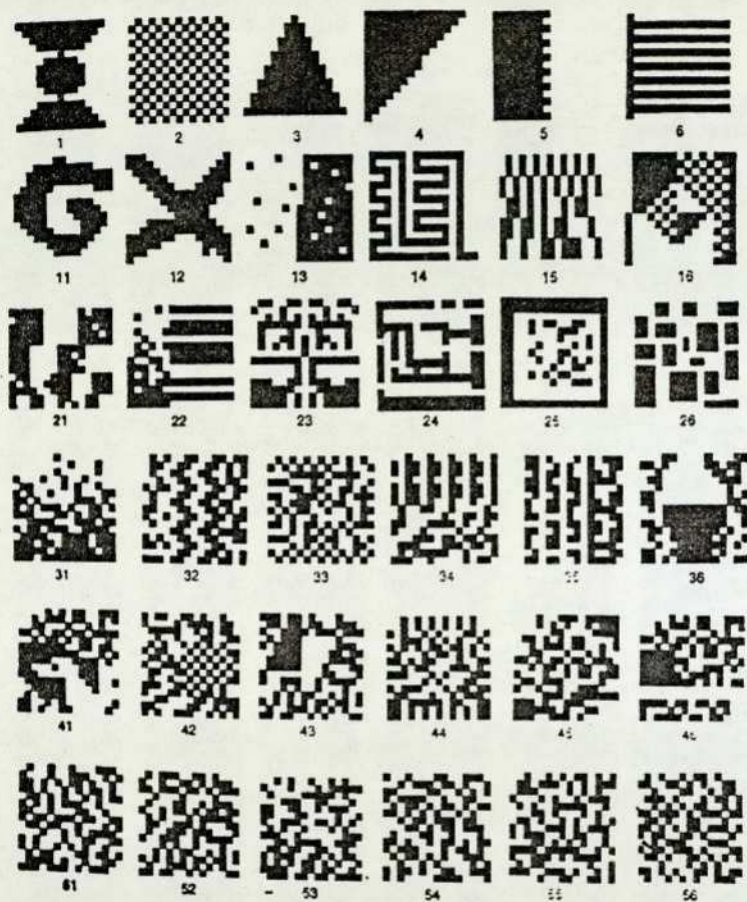
This was expressed as a percentage in 20% steps as indicated in the right hand margin of figure 2.1.

Maximum information is simply computed but redundancy needs to be estimated. This was done by Smets (1973) in the following manner:- an observer viewed a pattern for two seconds and was then required to reproduce it using black and white blocks, without further reference to the original. For each of the squares in the pattern the observer was informed after choosing either a black or a white block whether his choice was correct, and the selected block replaced if wrong. The number of errors per pattern was recorded. Sufficient blocks were available such that a choice still remained for the final square (if only 64 (or 225) blocks were available the final square would be determined by the 63rd (or 224th)). This task fits into Brown's second category of information measures (Appendix I), i.e. each pattern

Figure 2-1 Smets patterns



a) Stimuli with $H_{\max} = 64$ bits



b) Stimuli with $H_{\max} = 255$ bits

element is a source.

From a number of patterns tested the average results permitted the 36 patterns at each $H_{\max}$ in figure 2.1 to be selected. These were divided into 6 groups of 6 patterns each such that,

Group 1	gave	0 - 2%	errors and was assigned a redundancy of 100
" 2	"	8 - 12%	" " " " " " " 80
" 3	"	18 - 22%	" " " " " " " 60
" 4	"	28 - 32%	" " " " " " " 40
" 5	"	38 - 42%	" " " " " " " 20

The final group included those with greater than 42% errors and were assigned a redundancy of 0%.

When the patterns were used in the present study, Brown's third category became more appropriate, and hence one could compute a value for the excess (unused) channel capacity. Consider 8×8 matrix pattern. Suppose that only eight patterns are selected for use in a recognition task. The source uncertainty (H_s) is then $\log_2 8 = 3$ bits. Furthermore if the patterns are constrained to a ratio of black to white squares of 1:1 then the constraint uncertainty (H_c) is 32 bits. It follows therefore that the excess channel capacity (H_e) is $H_{\max} - (H_s + H_c)$ i.e. 29 bits. This is the average amount of information available to discriminate one pattern from the other seven in the selected set.

2.2. Advantages and criticisms

Several reasons may be put forward for using Smets patterns as recognition targets.

1. Since the targets are made up of square elements they are relatively easy to construct.
2. Results obtained with such patterns might be related to real objects in a relatively simple manner. Imagine a grid of N cells placed over a picture of a real object. Each cell of the grid is filled in according to the

following rules:-

- (a) If the cell contains a part of the object it is made black.
- (b) If a cell does not contain a part of the object it is made white.

This effectively transforms the pattern to a one bit grey scale. By selecting the fineness of the grid used the object outline can be manipulated. This procedure places the object into a limited population of $N \log_2 2$ alternatives, and in fact such an approach has been attempted for the coding of video signals (Pratts, 1978). The loss of detail within the outline of the object is probably not important during either a detection or recognition task.

A problem with such a scheme for dealing with real objects is the assessment of the excess channel capacity e.g. the source uncertainty, depending as it does on the subset of patterns actually selected from the $N \log_2 2$ population, may not be easily determined. Observers tend to reduce the number of possible targets by setting up "internal" categories and subsets.

3. Each of the patterns has the same ratio of black to white squares which means that the total flux through a transparency of any of the patterns is the same.

4. The targets have been placed along a single dimension (subjective redundancy).

1 The use of these particular patterns may be criticised however. Firstly in view of the dominance of spatial frequency models of detection, a more suitable set of targets might have been mixtures of spatial frequencies of known phase and amplitude. Construction of such patterns is more of a problem however, particularly if two dimensional patterns are to be created.

2 Secondly there is some justification for using representations of real objects, since the results obtained would at least be applicable to the particular objects used. Results from these objects might even be extended to a larger population via such indices of detection, recognition and identification as Johnston's criterion⁺ (Biberman 1973).

3 Finally it became obvious on discussing with observers, the tasks required of them, (Chapter 4) that they were attending to only part of the presented test patterns. Assessment of this "perceived area" rather than measurement of the actual area is impossible but it may still be relevant to certain conclusions.

⁺ Johnston criterion

This is a statement of the resolution required to detect or recognise or identify objects, and is the no. of just resolvable line pairs which can be fitted into the minimum dimension of the object. For example 4.0 ± 0.8 line pairs are required for recognition.

Target Construction

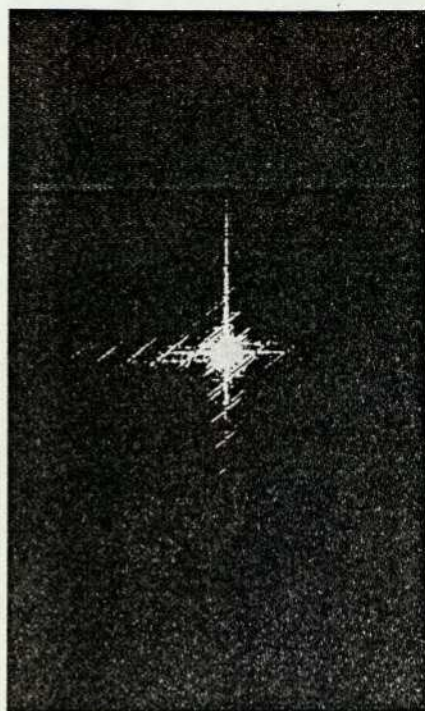
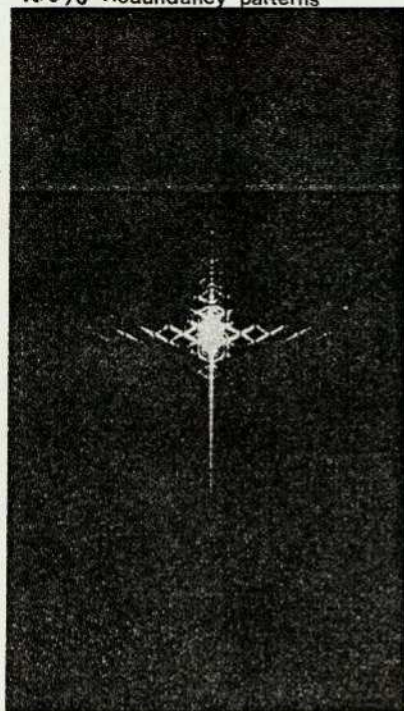
Targets were constructed as follows:- a set of slide mount glasses (one inch square) were sprayed with matt black paint. Another set was sprayed with white. These were then laid out in the form of each pattern in turn and photographed (Kodak Ortholith negative film). After development[†] a sample of the patterns was checked by microscope to ensure a reasonable reproduction had been achieved. Each pattern was then aligned in its slide mount such that the central elements of each pattern projected onto the same point.

In two experiments (Chapter 4 and 8) patterns used were photographic reductions of prints of the original negatives (Polaroid line film). This unfortunately led to a degradation of the subelement edges to some extent.

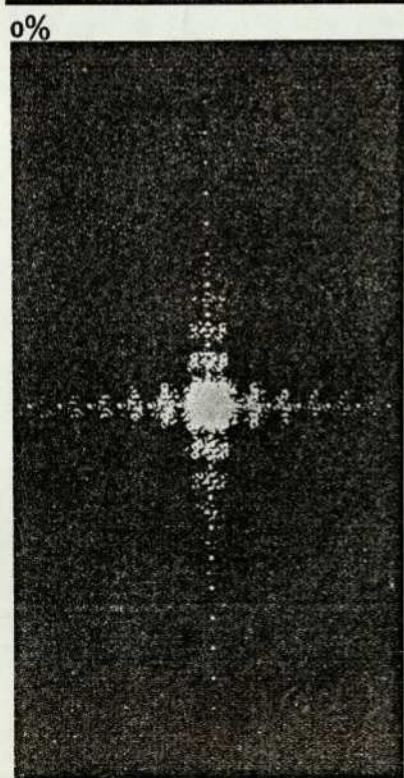
In an attempt to determine how the patterns related to spatial frequency models, two dimensional Fourier transforms of four of the Smets' patterns were performed optically (Longhurst 1973). These are illustrated in figure 2.2. Figure 2.3 shows the Fourier transforms of a checkerboard and grating produced by the same apparatus for comparison. No quantitative measurements were attempted on these diffraction patterns. The main qualitative difference between the diffraction patterns in figure 2.2(a) and 2.2(b) is the presence of much higher frequencies in the latter. These are transforms of two patterns with zero redundancy, while the former are transforms of patterns with one hundred percent redundancy (on the Smets' scale).

[†]The same development time was used for each pattern.

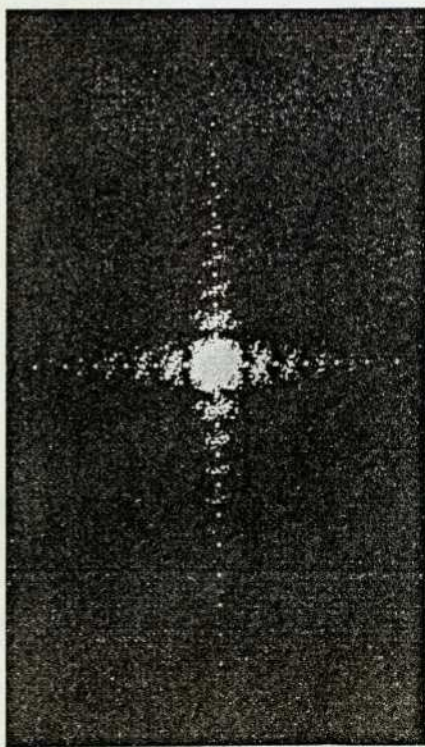
100% Redundancy patterns



a



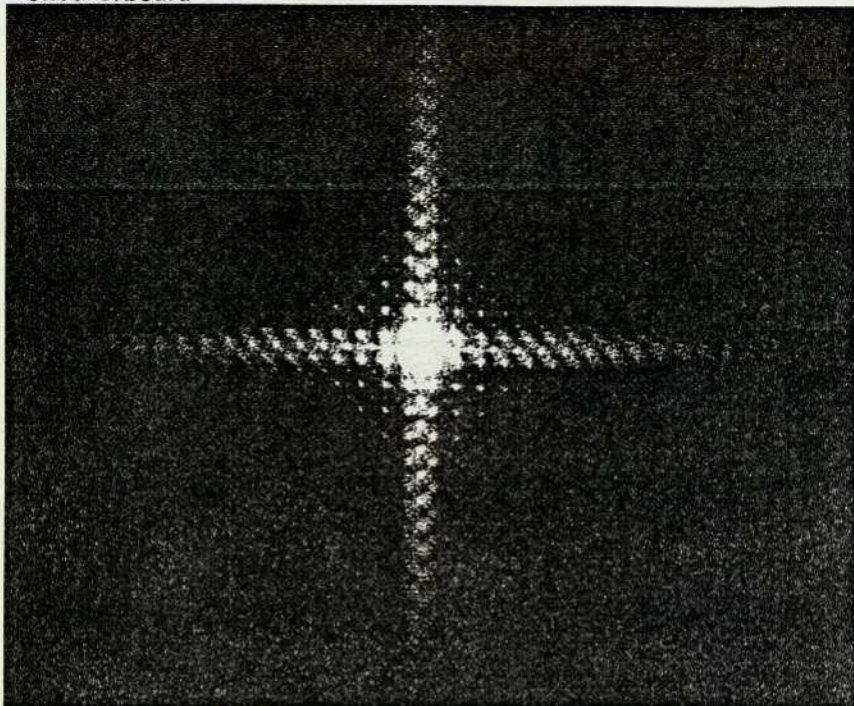
0%



b

Figure 2.2 Fourier Transforms - Smets patterns

Checkerboard



Square grating

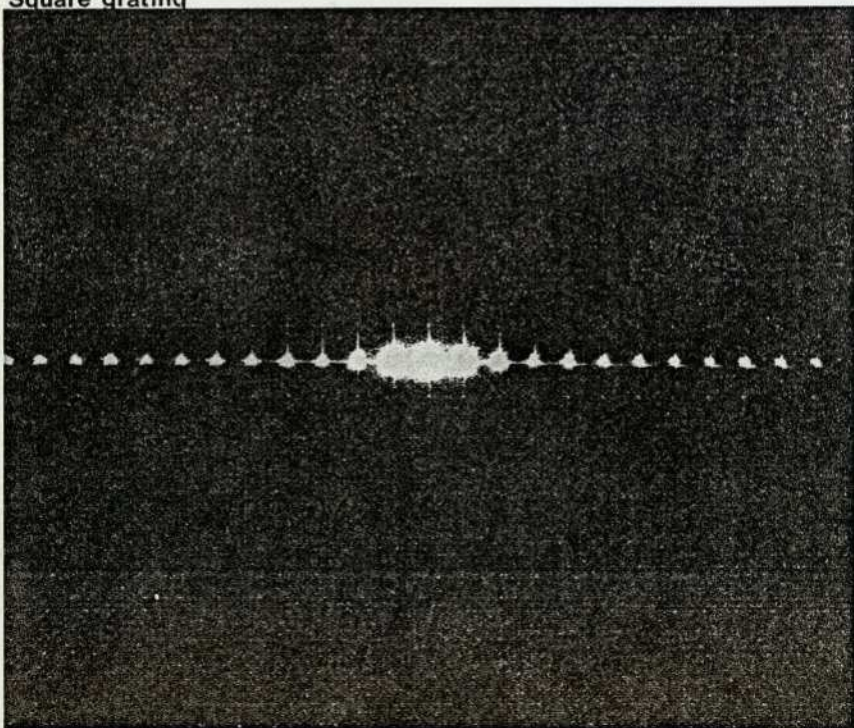


Figure 2-3 Fourier Transforms

CHAPTER THREE

COLORIMETRIC CHANGES IN SURFACE COLOURS PRODUCED BY ATMOSPHERIC SCATTERING

- 3.1 Introduction
- 3.2 Theory of model
- 3.3 Discussion and conclusions

COLORIMETRIC CHANGES IN SURFACE COLOURS PRODUCED

BY ATMOSPHERIC SCATTERING

3.1 Introduction

One of the requirements for the present research was a knowledge of the magnitude of the likely changes in saturation to be expected in natural atmospheres. Qualitative changes in the lightness and colour of objects produced by atmospheric scattering and absorption are readily observed, e.g. distant objects appear blue-grey irrespective of their colour at close range. Attempts to quantify such effects have been less successful (Middleton 1963) however mainly because of the long path lengths, atmospheric inhomogeneities and the high instrument stabilities required. An alternative approach is to compute the changes which might be expected to occur given certain simplifying assumptions, and this is the approach presented here.

3.2 Theory of model

The method is an extension of Koschmeider's derivation (Middleton 1963) for computing contrast reduction and requires two assumptions:-

- (1) The attenuation of light on passing through a medium is described by an exponential function (Lambert's or Allard's law).
- (2) The medium itself may be characterised by a single variable - the extinction coefficient (μ). This coefficient is the sum of the scattering and absorption coefficients but the latter is generally small (Middleton 1963).

With these assumptions it is possible to derive expression 3.1 which relates the spectral radiance (L_{λ}) of a reflecting surface at a distance (R') as a function of it's radiance at zero range ($L_{o,\lambda}$) and the horizon sky radiance ($L_{h,\lambda}$).

$$L_{\lambda} = L_{h,\lambda} \left[\frac{1 - \exp(-\mu_{\lambda} R')}{A} \right] + L_{o,\lambda} \frac{\exp(-\mu_{\lambda} R')}{B} \quad 3.1$$

Appendix II outlines the derivation. Part A of the equation represents the proportion of light scattered into the viewing path and part B the proportion scattered out of the viewing path.

The extinction coefficient in equation 3.1 is a function of wavelength and this is generally taken to be a power law.

Middleton (1963) measured the value of the exponent on several occasions and found that most values were clustered around 1.3, although a value as high as 2.09 was obtained on one occasion.

By combining equation 3.1 with the assumption that a surface is a vertically positioned Lambertian reflector, viewed horizontally

$$\text{i.e. } L_{o,\lambda} = r_{\lambda} \cdot \frac{L_{h,\lambda}}{2} \quad 3.2$$

it may be simplified to

$$L_{\lambda} = L_{h,\lambda} \left[1 - (1 - r_{\lambda}/2) \exp(-c\lambda^n R') \right] \quad 3.3$$

In order to determine the value of the constant (c) a relationship derived by Middleton (1963) is required

$$c = \frac{3.912 \cdot 1}{V} \frac{1}{\lambda^n} \quad 3.4$$

where the visual range (V) is defined as that distance at which the contrast of a black object falls to 0.02. This value of the liminal contrast is taken from Blackwell (1946) as representative of the contrast required for detection.

Equation 3.3. was used to compute the spectral radiance distribution of a number of different colours (surfaces) when viewed at different ranges through the following three types of atmosphere:-

- (1) Rayleigh atmosphere i.e. an exponent value of 4. No estimate of visual range was available and so it was estimated from equation 3.5 (Middleton 1963)

$$n = 0.0585(V)^{1/3} \quad 3.5$$

where n is the exponent.

- (2) $n = 2.09$ i.e. the extreme value obtained by Middleton.
- (3) $n = 1.3$, the modal value found experimentally by Middleton.

D₆₅ was chosen as the illuminant for all colours.

Computations were performed for 7 surfaces whose names and chromaticity coordinates are presented in figure 3.1. The surfaces included three which demonstrated a peak in the red, green and blue portion of the spectrum respectively. Reflectance values were either obtained from the literature (Krinov 1953, surface colours 1 and 2) or measured spectrophotometrically (Pye - Unicam SP8 - 100).

The program was run on an HP 9825A and in addition to chromaticity coordinates and luminance, u^* , v^* , metric lightness, hue angle saturation,

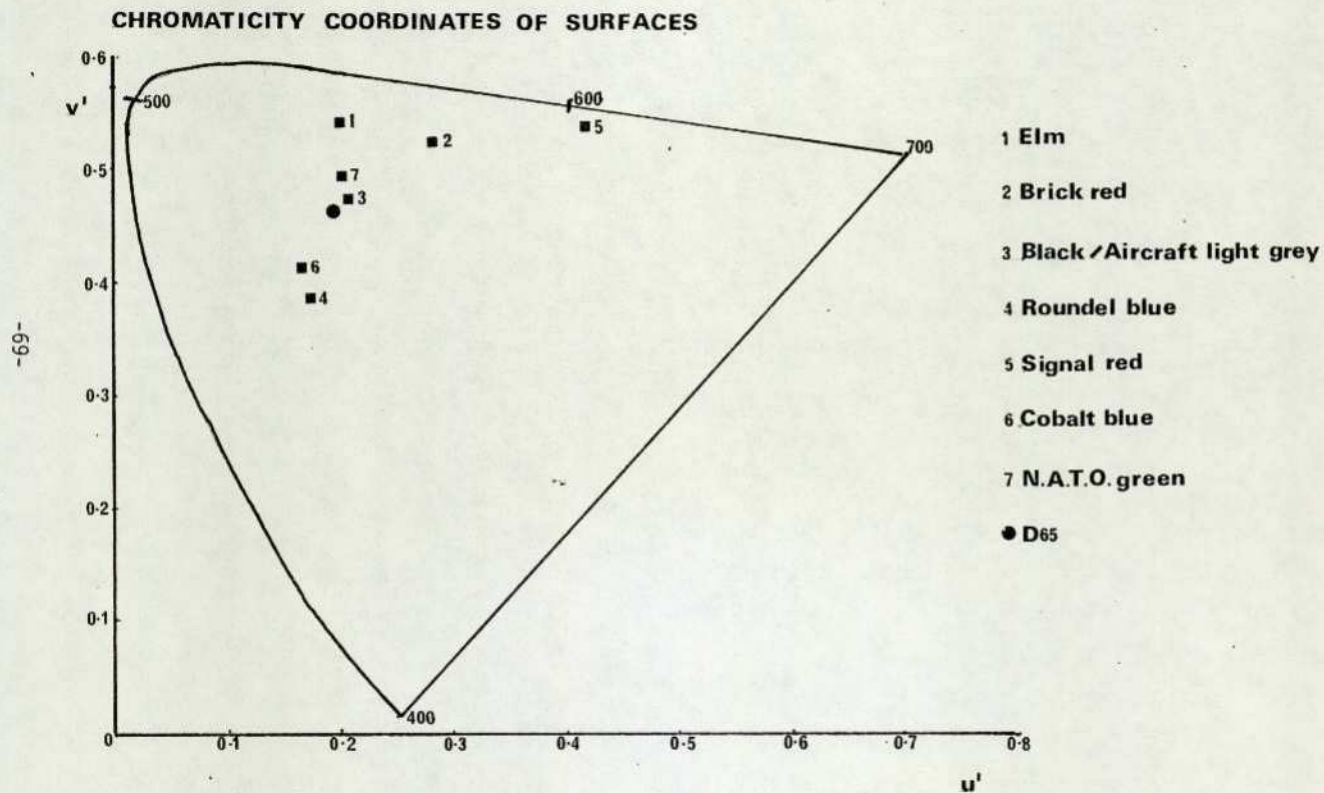


Figure 3-1

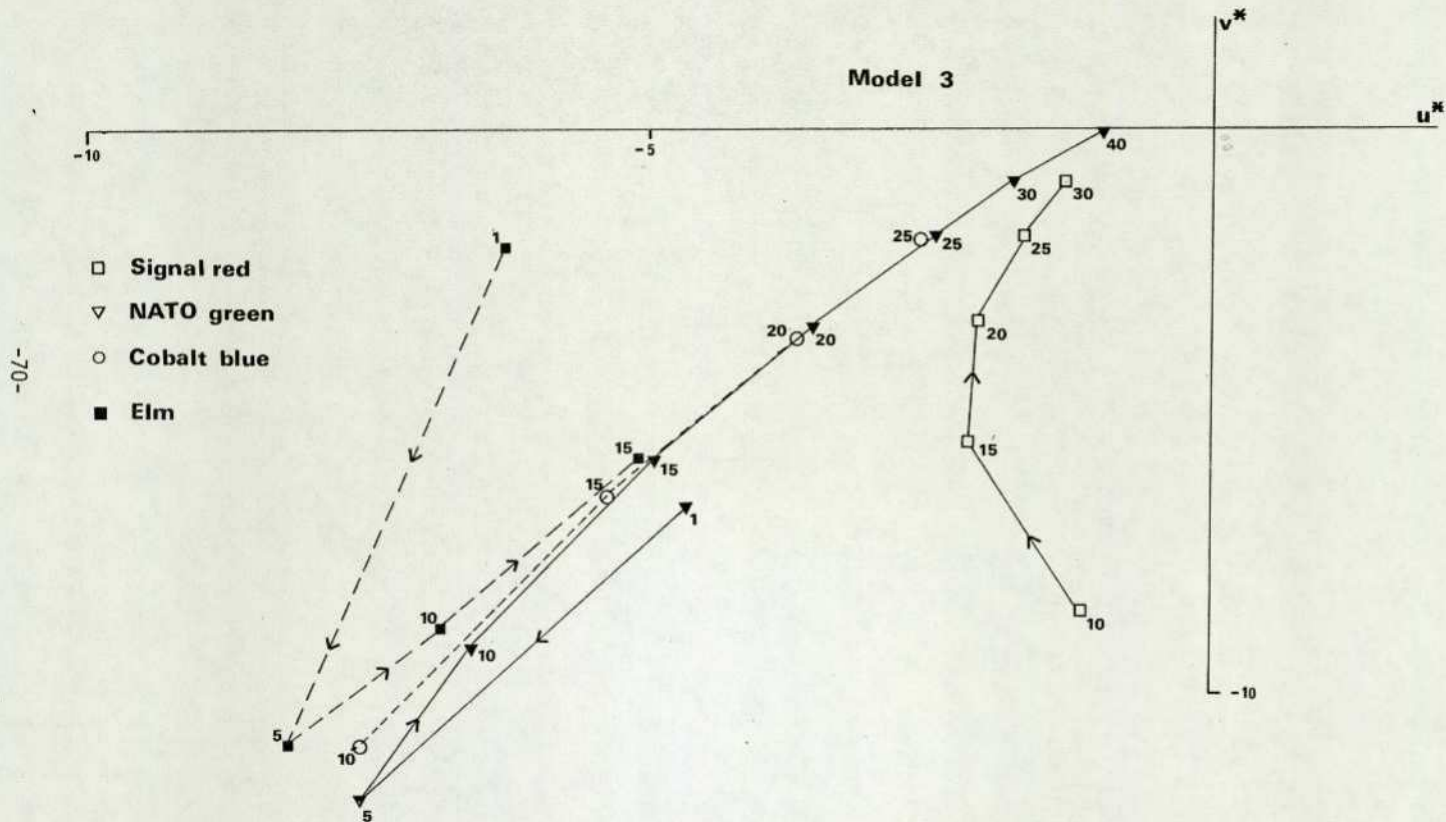


Figure 3-2 u^* , v^* diagram - parameter is range in kilometers

and chroma were computed.

3.3 Discussion and conclusions

Two general effects occur as the range between an observer and a surface is increased. The luminance of the surface tends to that of the horizon sky and the colour of the surface becomes bluer. The former effect is exponential as would be expected from the theory used. The colour change is illustrated in figure 3.2 for four of the surfaces considered (exponent value $n = 1.3$). Coordinates were computed relative to D_{65} hence when the surface is the same colour as the horizon it will plot at the origin. Interestingly some of the colours may actually move away from the origin before gradually becoming similar to D_{65} . This even includes colours such as signal red which are in the first quadrant at zero range. The effect is less marked as the type of atmosphere becomes similar to a Rayleigh type.

The phenomenon is in effect an increase in colour contrast and may be expressed as a change in purity. An example of purity change with range is shown in figure 3.3 and further data are available in appendix II. Log. metric purity values covered a 3 log unit range for the surfaces considered and extended from 2.84 (signal red, 0 km) to 0.01 (aircraft light grey, 25 km). Under conditions when colour may be important visually i.e. at low contrast the values fall within a 1 log unit range.

In conclusion therefore it may be stated that for a number of different types of atmosphere and at a range where contrast is close to threshold i.e. at the visibility range, metric purity values are between 1 and 0.1, although precise values will depend upon the colour chosen and the type of atmosphere.

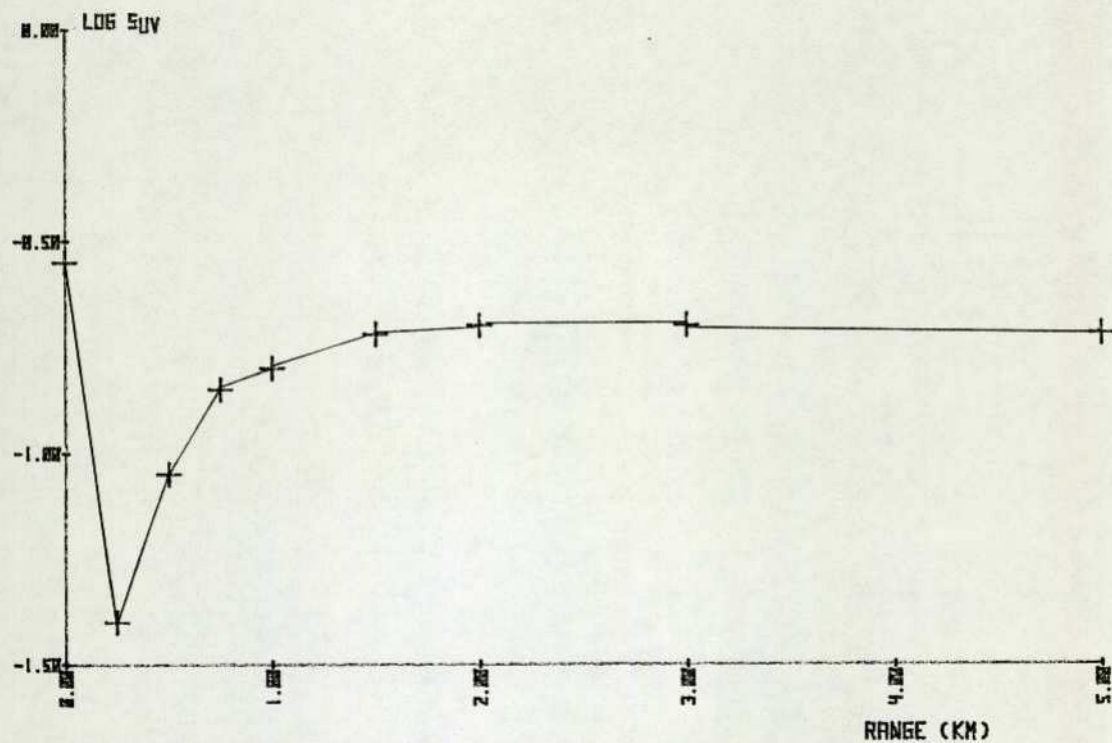


FIGURE 3. 3 LOG METRIC PURITY AS A FUNCTION OF RANGE - N.A.T.O. GREEN

CHAPTER FOUR

A MULTIVARIATE INVESTIGATION OF FACTORS AFFECTING REACTION TIME IN A RECOGNITION TASK

- 4.1 Introduction
- 4.2 Method
- 4.3 Subjects
- 4.4 Procedure
- 4.5 Results
 - (a) Subjective remarks
 - (b) Training sessions
 - (c) Experimental data
- 4.6 Discussion
- 4.7 Conclusions

A MULTIVARIATE INVESTIGATION OF FACTORS AFFECTING
REACTION TIME IN A RECOGNITION TASK

4.1 Introduction

The statement by Hilgendorf (1974) that "there is little or no information available concerning the effects of colour on target acquisition" suggests that the amount of research on acquisition in which chromatic, as well as achromatic contrast is considered as a variable, is minimal. (Fowler and Jones (1972) who did investigate the problem found that (in contrast to Hilgendorf), a chromatic display device provided no advantage over an achromatic device). It is not surprising therefore, to find little evidence in the literature of attempts to determine the effect of purity on an acquisition task. This fact combined with the rather novel stimulus set selected, suggested that the first experiment of this study should be of a general nature. It was hoped that such an approach would provide an indication of which stimulus attributes might be important to a purity effect on recognition, if such an effect existed. In addition it was felt necessary to determine the validity of the redundancy dimension under conditions which differed from those used by Smets, particularly whether response time would correlate in any way with redundancy.

The rather confused position as to whether chromatic contrast can enhance performance of an acquisition task, combined with the fact that the saturation of spectral colours is not equal (although their purity is by definition one) suggested that the hue of the targets used should also be incorporated as a variable.

The experimental design and procedure used, attempted to model a general acquisition task with certain constraints applied. Although no archetypal task exists, a very common one involves recognition of a target which is visible for a limited period of time (referred to as a "single glimpse" situation by Overington, 1976), followed by an appropriate motor response (such a task is performed by a motorist several times every minute for example).

The constraints applied were as follows:- firstly targets were viewed binocularly, since monocular tasks are relatively infrequent outside the laboratory situation. Secondly a uniform adapting field was selected. (Although the effect of background structure on recognition tasks has been investigated (e.g. James et al 1975) there is as yet no simple model to account for such effects. It seemed unwise therefore, to include this parameter as part of an initial experiment. Thirdly in an attempt to simulate the purity changes resulting from atmospheric effects, an experimental method was used which added a veiling light to the target luminance. This is equivalent to the airlight introduced by atmospheric scattering. In addition the luminance of the target was manipulated using neutral density filters thus simulating the contrast reduction produced by the scattering of light out of the viewing path (the use of neutral filters provides no way of emulating the wavelength dependency of such scattering however). Such a procedure confounds the effects of purity and contrast and necessitates the introduction of a control condition - neutral targets - from which the effect of contrast reduction alone can be estimated. The chromaticities of these neutral targets, the

veiling light source and the surround were adjusted to be similar for simplicity. The final experimental design incorporated redundancy, hue and proportion of veiling light as the main variables. In addition the response given by the observers was considered as a separate variable since there is evidence that different responses may give significantly different latencies under some circumstances (e.g. same versus different responses - Keuss, 1977).

4.2 Method

The two channel backprojection apparatus used is illustrated in figure 4.1. The targets were presented to the observer by projection onto a square perspex diffusing screen D measuring 4.6 by 4.6 cm, mounted in a circular white screen sc , 124 cm in diameter. When viewed by an observer from 1.3 metres this provided a target two degrees square in an adapting field subtending fifty degrees. The target slides T were illuminated by projector P_1 (Kodak S-RA 2000 random access carousel) and imaged on the perspex screen by lens L_1 . The projector was controlled from a numerical key pad and enabled the experimenter to present any one of eighty slides in a random manner. A filter holder F permitted neutral density and colour filters to be inserted into this beam.

The veiling light added to simulate air light was provided by projector P_2 (Kodak S-AV 2000 carousel) and after filtering to match the surround, was mixed with light from the target by a glass pellicle G.

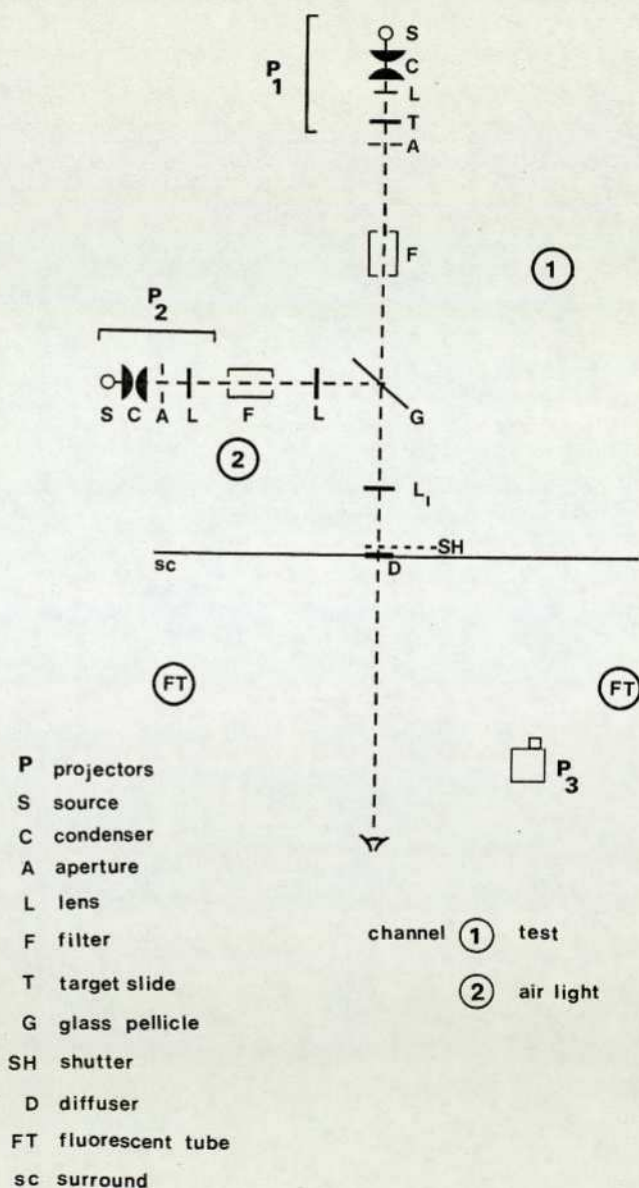


Figure 4.1 Apparatus

The colour filters used were wideband Lee and Cinemoid filters. The neutral density filters which provided coarse adjustment of luminances were gelatine (Ilford). Fine control of luminance was achieved by inserting apertures into each beam at A. These were prepared from slide mounts masked off to varying degrees, and allowed the luminance as measured ⁺ from the observers position, to be controlled to within 5% (typically 2%) of a required value.

The luminance uniformity across the perspex screen was also checked, with no target present, using a photometer which measured over a five minute of arc circle, and was found to be within 5% of the central luminance up to 3/4 of a degree on either side of centre. At the edges values were within 10% but in the extreme corners, the luminance was often only 80% of the centre value.

The surround screen was illuminated by two vertically positioned fluorescent tubes (artificial daylight, 60W) which provided an illumination with a chromaticity approximating that of D₆₅.

+

A range of instruments was used for the measurement of photometric, colorimetric and temporal properties of stimuli, both in this and other experiments. These are documented in appendix III, which includes calibration information.

The tubes were shielded from the observer in such a way that radiation direct from either tube could not be seen. The luminance of the screen adjacent to the perspex diffuser was 85 Cd m^{-2} falling to 71.4 Cd m^{-2} (84%) at the edge of the surround. The luminance was still within 4% as far as 12 degrees on either side of centre however.

An additional projector P_3 , imaged a slide on the lower right quadrant of the surround and was under the control of the observer. The beam colour was adjusted using colour correcting filters cc, to approximate that of the surround. The same filters acted to reduce the luminance of the projected slide, which displayed examples of the memory set of targets, as a learning aid (see procedure).

Presentation of the targets was regulated by a rotary solenoid mounted shutter SH, driven from a process timer. The front surface of the shutter was matt white, giving the central perspex area a light grey appearance when no target was present. The timer was set to present a target for 1,000 ms every thirty seconds. Observer response times were measured to within one millisecond. Timing was initiated by the timer controlling the shutter, and was terminated by the observer.

Two targets were selected at random from each of the 6 redundancy levels of the 64 bit patterns and presented in combination with one of four coloured filters and one of three levels of veiling light. One of each pair of targets was designated as a member of the group to be recognised by the observer. Figure 4.2 illustrates the chromaticities of the various hue/veiling light conditions. The contrast of the targets under these different conditions are listed in table 4.1.

TABLE 4.1 Contrast between chromatic
 and achromatic areas

Hue	Veiling Light Level*		
	1	2	3
Red	0.81	0.56	0.30
Green	0.83	0.60	0.35
Blue	0.81	0.57	0.31
White	0.83	0.60	0.36

* The amount of veiling light added to the main test beam is indicated by arbitrary numbers. Condition one is no veiling light, while condition three is a maximum amount. Corresponding numbers are used in figure 4.2.

Contrast is defined as follows:-

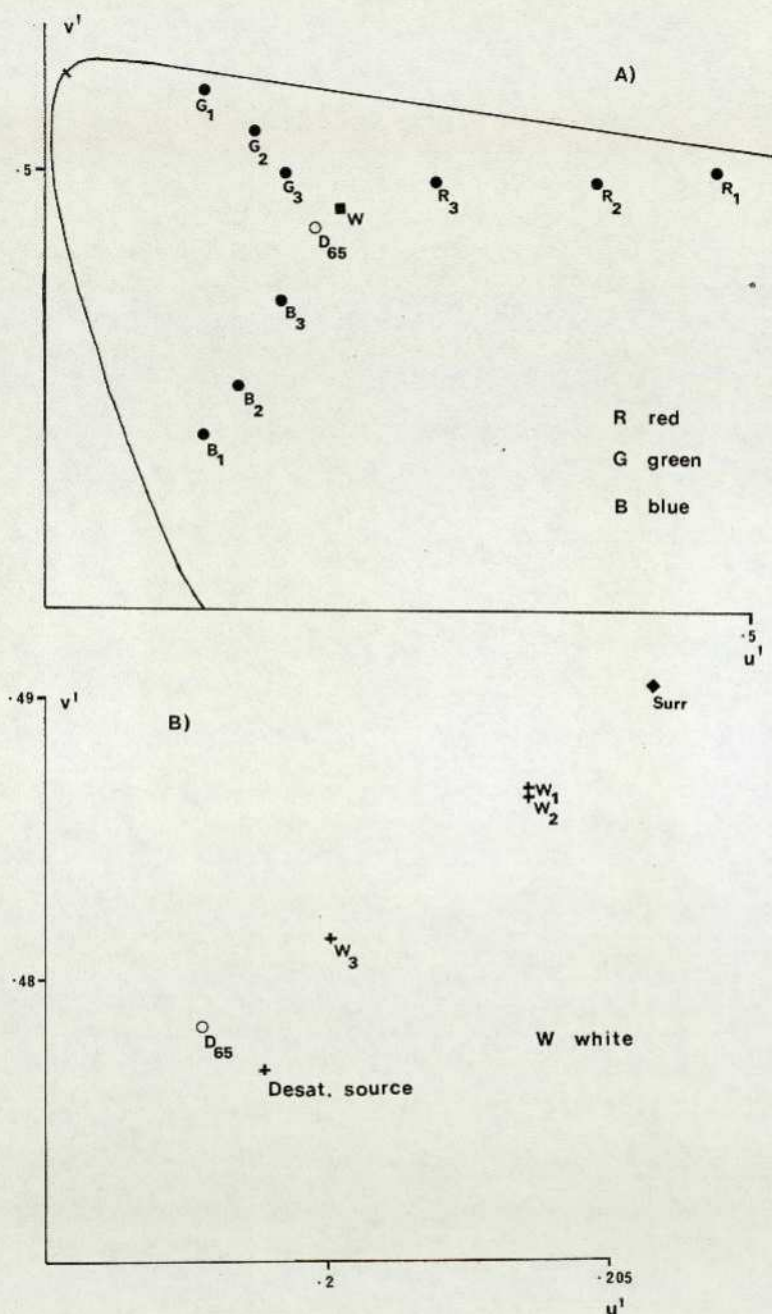


Figure 4.2 A) Chromaticity diagram illustrating stimuli used in multivariate experiment.

B) Expanded scale to show "neutral" stimuli and illuminants.

$$C = \frac{L_T - L_B}{L_B} \quad 4.1$$

where C is the contrast

L_T " " luminance of the target

L_B " " " " " background

In the present case L_T will be taken as the luminance of the chromatic area, while L_B will be taken as the luminance of the achromatic area.

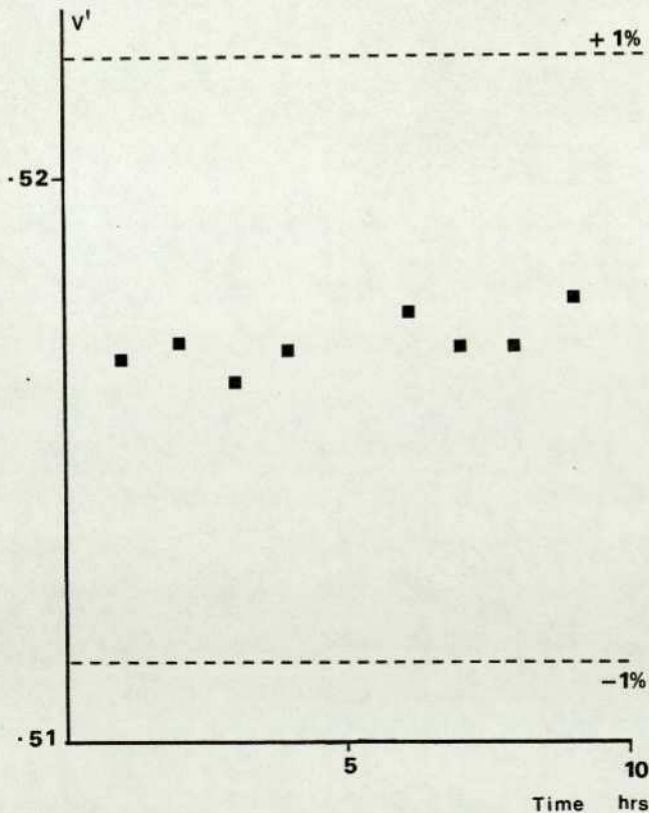


Figure 4.3 Change in v' chromaticity coordinate with time - Lee filter continuously exposed.

Prolonged exposure of the Cinemoid filters to high light levels produced no significant fading effects (personal communication, T. Troscianko) while measurements on Lee filters indicated that over a ten hour period of exposure u' values were within 3% of the initial value while u' values were within 1% of the initial value. Filters were considered to be sufficiently stable for the duration of the experiment therefore (figure 4.3 illustrates the chromaticity variation with time).

4.3 Subjects

Five observers (including the author) took part in the experiment. Each was screened for colour vision abnormalities using Ishihara and anomaloscope tests. All were found to be normal. Where necessary, observers wore their normal ophthalmic correction. Two were experienced observers (C.A.P. and T.T.) and were familiar with the aims of the experiment while two (S.F. and E.M.M.) were naive observers. The author had taken part in a limited number of psychophysical studies.

4.4 Procedure

Observers were seated 1.3m from the target screen and head movements were prevented by means of an ophthalmic headrest. Before collecting any experimental data for analysis, each observer took part in a minimum of eight training sessions. Learning was monitored by three separate variables:-

1. Mean reaction time (averaged over a session).
2. Response errors per session.
3. Amount of time spent viewing memory set stimuli (see page 86 for clarification).

The procedure used during training sessions was the same as during experimental sessions with the exception that only high contrast, achromatic stimuli were used. Before the experiment was begun a set of record sheets was generated by computer for each subject. The program used to produce these, arranged a random sequence of target/hue/purity combinations, such that over twelve experimental sessions each combination was presented five times. Similar sheets were generated for the training sessions. At the beginning of each session one of the record sheets for the particular observer was selected at random. Each sheet consisted of sixty target/hue/purity combinations.

Subjects adapted to the surround luminance for ten minutes, then were presented with a target pattern every thirty seconds. Six seconds before a target was to be presented the subject was given an auditory cue lasting four seconds. On hearing this he depressed two microswitches and waited till a target was presented. If the target was one of those designated as belonging to the memory set, the subject released one microswitch, if not he released the other. If by accident, or due to uncertainty the subject released both switches this condition was re-presented

at the end of the session (although the observer was not informed of this). Both reaction time and response were recorded. Between presentations, projector P_3 which contained examples of the memory set could be operated by the observer and the time this projector was used was monitored.

4.5 Results

(a) Subjective remarks

When discussing with each observer the task they had performed, after each session, certain remarks appeared to be common to all five observers. Most of these were rather general criticisms or comments. One however, regarding the targets was more interesting. Within three to four training sessions, all observers had selected a portion of each pattern which provided them with a way of recognising it. The portions selected were often related to more everyday objects e.g. one observer referred to a target looking like a train. It was felt that these subjective comments indicated that the experimental paradigm was providing a reasonable model of everyday recognition tasks, i.e. the observers were selecting key features from each target, - the same method applied by military observers e.g. photographic interpreters, to recognition problems.

(b) Training Sessions

The three indications of learning mentioned in the methods section - percentage correct responses, exposure time to memory set and mean reaction time are illustrated in figure 4.4. Although it is apparent that each function shows a general trend, there are large variations from observer to observer. A major contributory factor to this variation was the irregularity of observing sessions for certain observers. This is illustrated by observers E.M. and C.A.P. in particular. The error rates were quite similar and all five observers were achieving over 75% correct responses by the fifth session. Similarly the time spent viewing the memory set examples had declined to a negligible amount by session five. Mean reaction time is undoubtedly the most sensitive indicator of learning, and is only beginning to plateau by the seventh session. In addition it is susceptible to interruptions in the learning session schedule (observers C.A.P. and E.M.M.). Gaps between training sessions of greater than one week as occurred with these two observers elevated the reaction time, although recovery is relatively fast.

(c) Experimental data (Appendix IV)

The experiment was designed to permit a factor analysis of the data using an ICL 1900 XDS3/22 statistical routine. This provides estimates of the statistical

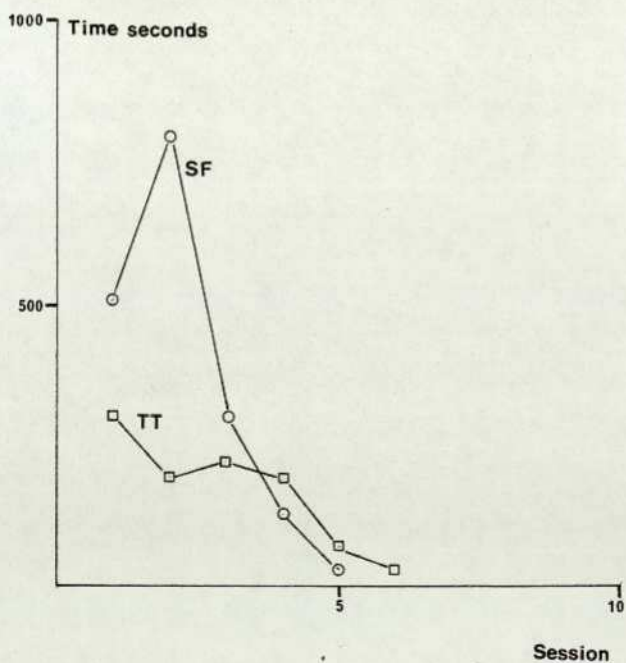
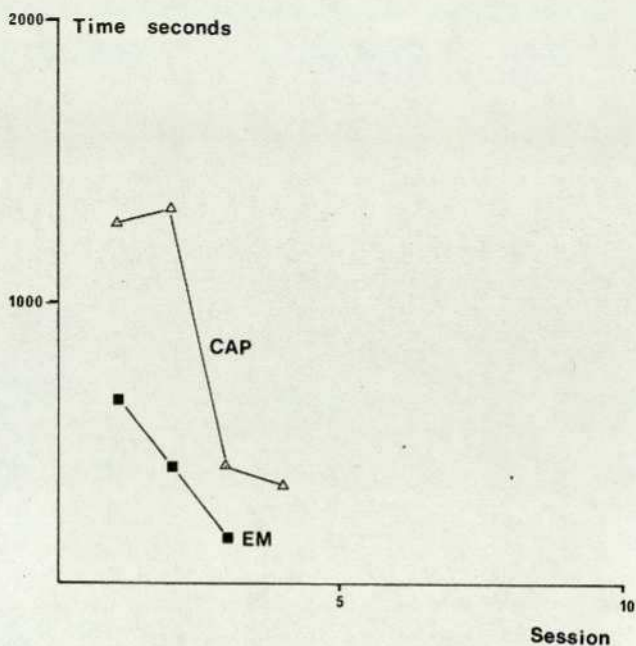


FIGURE 4.4(C) TRAINING SESSION DATA

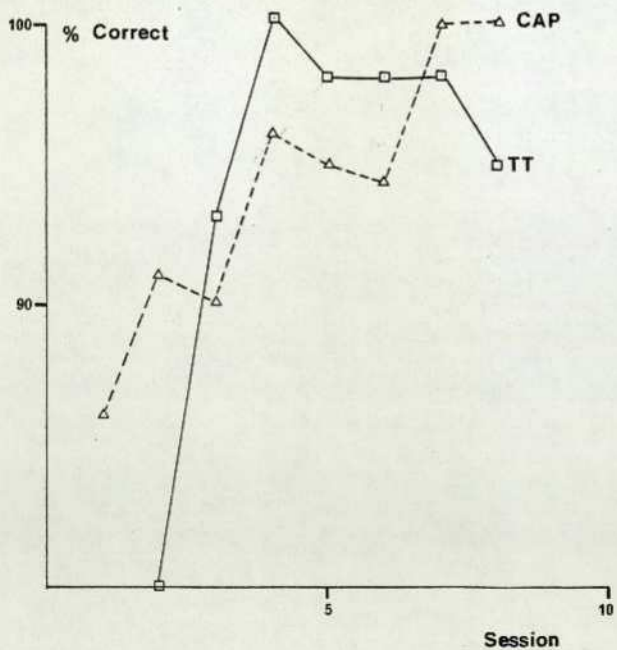
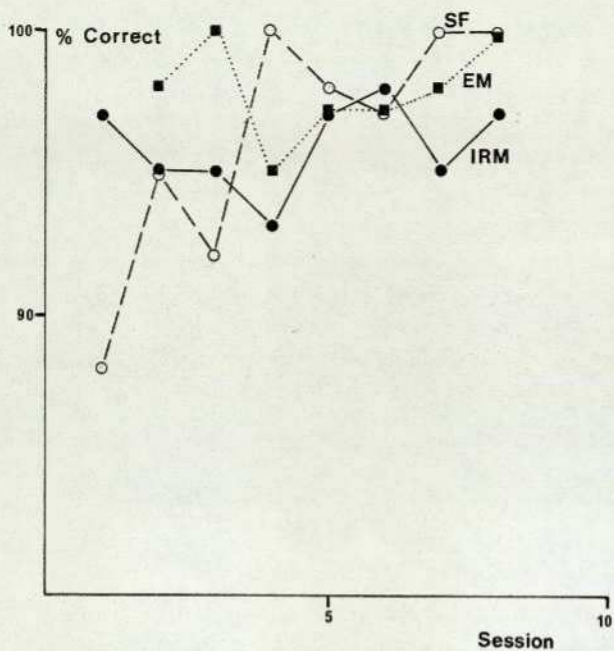


FIGURE 4.4(B) TRAINING SESSION DATA

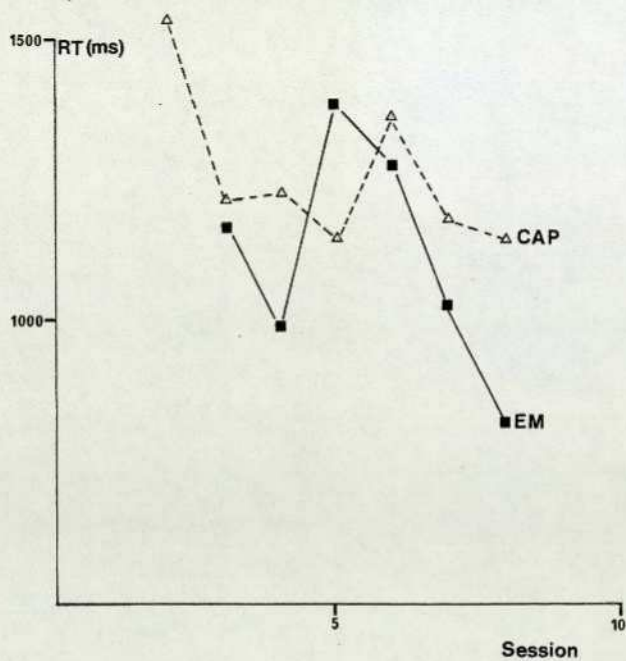
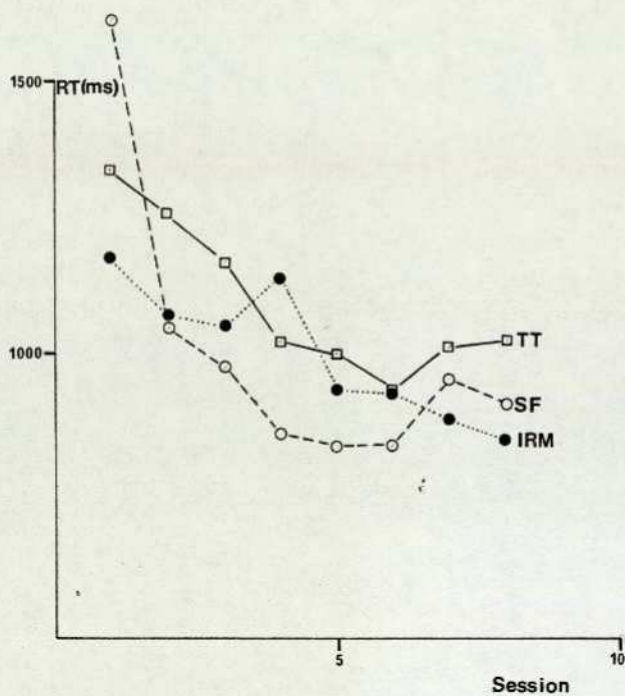


FIGURE 4.4(C) TRAINING SESSION DATA

significance of the main factors and their interactions. Mean reaction times computed from the five estimates obtained for each combination of the variables were used in the analysis. Data for observer E.M.M. was excluded however since gaps existed in the data array.

The following main effects were found to be significant ($p = 0.05$): redundancy, hue, veiling light level and observer. Interactions occurred between redundancy and hue; redundancy and observer; hue and observer; redundancy, hue and observer; redundancy, veiling light and observer; and veiling light level, response and observer.

To simplify these results data for each observer was analysed separately. Table 4.2 presents the results.

TABLE 4.2

INDIVIDUAL OBSERVER FACTOR ANALYSIS RESULTS

Factor or interaction	Observers for which factor or interaction was significant ($p \leq 0.05$)
Redundancy	4 I.R.M., T.T., S.F., C.A.P.
Hue	0
Veiling light level	3 I.R.M., S.F., C.A.P.
Response	1 T.T.
Redundancy x hue	0
Redundancy x veiling light	0
Redundancy x response	4 I.R.M., T.T., S.F., C.A.P.
Hue x veiling light	2 T.T., S.F.
Hue x response	0
Veiling light x response	0
Redundancy x hue x veiling light	0
Redundancy x hue x response	0
Redundancy x veiling light x response	1 T.T.,
Hue x veiling light x response	0

It is apparent that redundancy is significant for each of the four observers (in fact this was at the 1% level) but that this is conditional upon the response given. Hue is not a significant factor for any of the observers, but adding veiling light to the test target is for two of the four observers. Observer T.T. was the only one to show a significant response effect which was contingent upon both redundancy and veiling light level. As an illustration, table 4.3 below lists reaction times averaged over hue for observer T.T., for each response.

TABLE 4.3

REACTION TIMES FOR DIFFERENT RESPONSES - OBSERVER T.T.

(I) Redundancy 0%

<u>Veiling light level</u>	<u>Reaction time (ms)</u>	
	<u>"Yes"</u>	<u>"No"</u>
1	892	931
2	828	954
3	859	1010

(II) Redundancy 10%

<u>Veiling light level</u>	<u>Reaction time (ms)</u>	
	<u>"Yes"</u>	<u>"No"</u>
1	749	917
2	791	845
3	818	850

It is apparent that the reaction times for a "no" response are consistently slower than for "yes" response.

Returning to redundancy, figures 4.5 and 4.6 illustrate the relationship between reaction time and redundancy. Each point is the mean reaction time computed from the four observers' data. Only data from correct "yes" responses was included. Data from each hue is plotted separately, and the parameter in each figure is the amount of veiling light added (numbers to the right correspond to those used in table 4.2). Vertical bars represent $\pm$ one standard error of the mean and are only indicated on a selection of the data for clarity.

It is clear that increasing redundancy generally results in a decrease in reaction time, however the relationship is dependent upon hue and the proportion of desaturating light added to the test beam. When the test beam is presented alone or only with a small proportion of veiling light (curves 1 and 2 respectively) there is a definite decline in reaction time on moving from low to high redundancies. This is less true for curve 3, when a larger proportion of achromatic light is added to the test beam. In this case the curve is much more erratic, particularly in the case of targets without any chromatic contrast (figure 4.6 (b)) where the function exhibits large excursions. Red targets on the other hand exhibit very little difference between curves 1, 2 and 3. The dependence of reaction time on redundancy is conditional upon hue (table 4.2) in a statistically significant way, and this is reflected in this higher stability of red targets to achromatic targets.

Although reaction time generally declines as redundancy increases, it should be noticed that the reaction times to targets

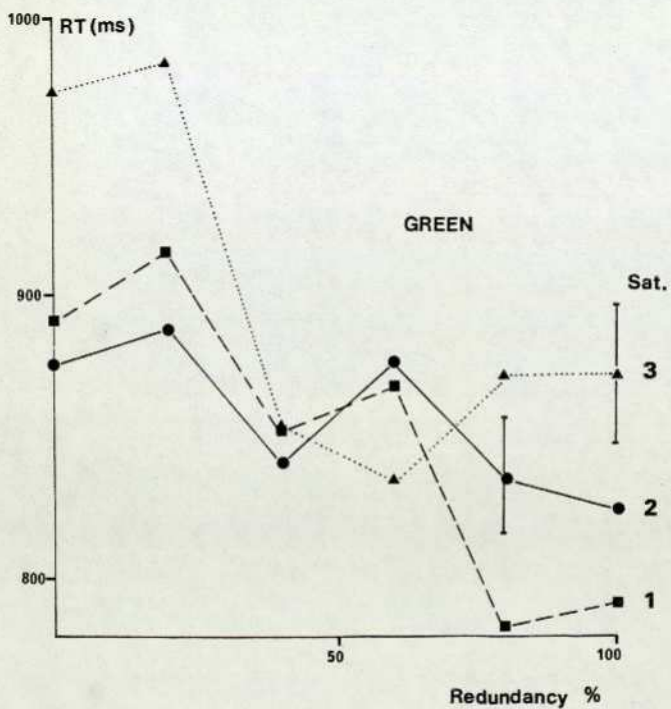
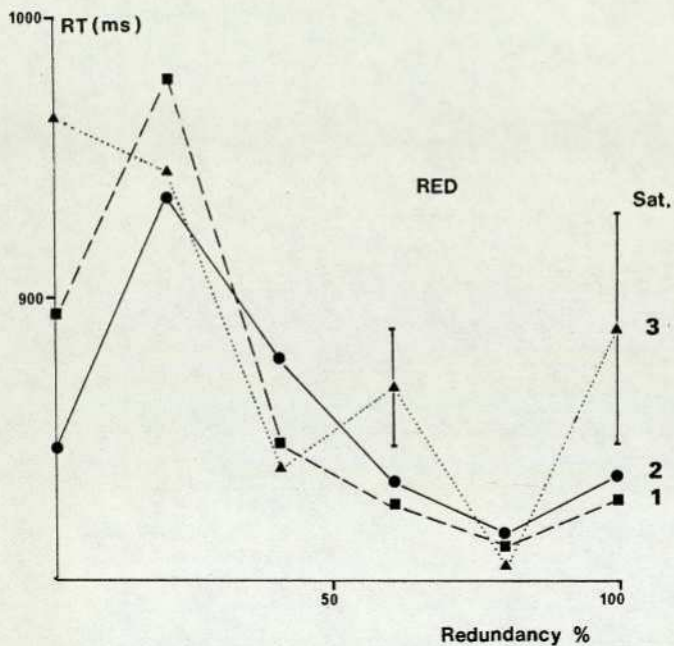


FIGURE 4.5 REDUNDANCY VERSUS MEAN REACTION TIME

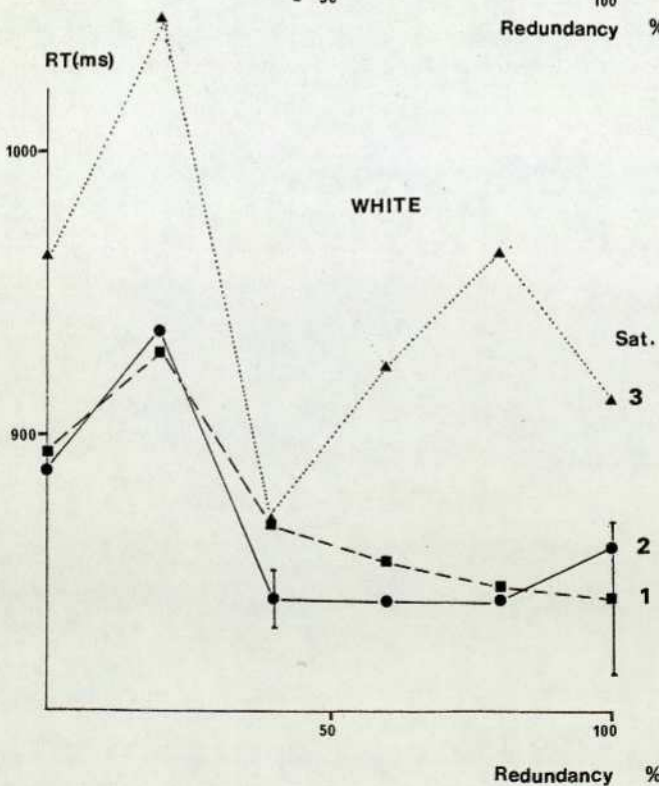
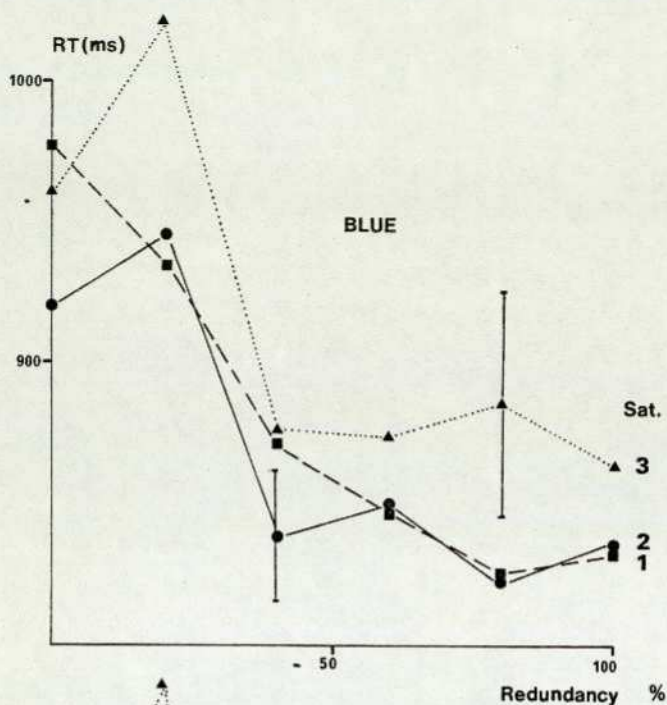


FIGURE 4.6 REDUNDANCY VERSUS MEAN REACTION TIME

with a redundancy of 20% are slower, irrespective of hue or veiling light level, than either 0% or 40% redundancy targets, with the exception of red (curve 1) and blue (curve 1) targets.

Turning to the effect of veiling light level on reaction time, this was a significant factor for three of the four observers (C.A.P., S.F. and I.R.M.). For one of these three (S.F.) this was conditional upon the target colour. In addition, although observer T.T. did not show a significant dependence of reaction time on veiling light there is a significant interaction between this factor and target colour.

As discussed already, adding a veiling light field to a target produces two changes; reduction of luminance contrast and a change in target purity. Figures 4.7 and 4.8 illustrate the relationship between mean reaction time and target excitation purity. Data are plotted separately for red, green, blue and white targets. Since redundancy proved to be a significant factor, results are presented for four different redundancies. Figure 4.7 (a) and (b) illustrate results obtained with 0 and 20% targets while figure 4.8 (a) and (b) similarly provide data for 100 and 80% redundancy. The vertical bars represent a mean of the standard errors of the data

The data for low redundancy targets (figure 4.7) indicate a reduction of reaction time with increasing purity for red, green and blue targets. This is not the case for the high redundancy coloured targets (figure 4.8), where reaction time demonstrates little

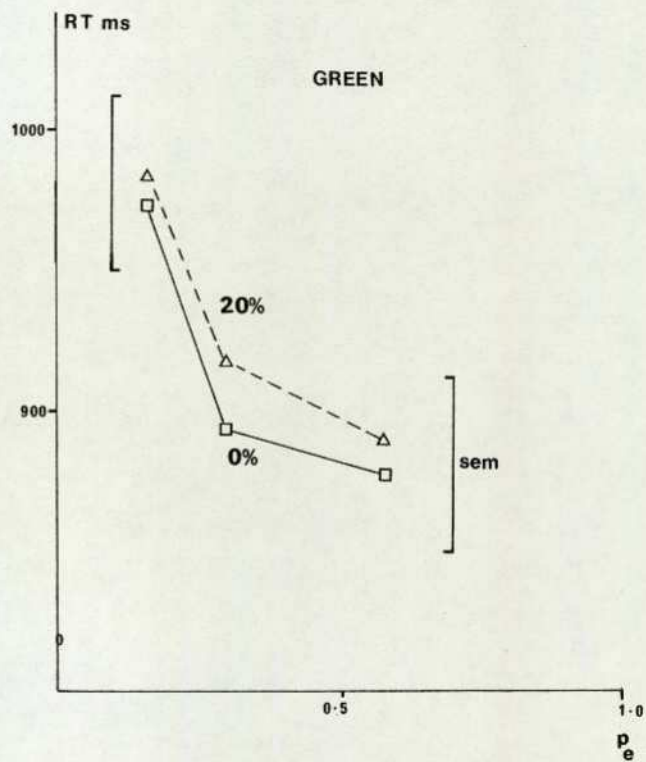
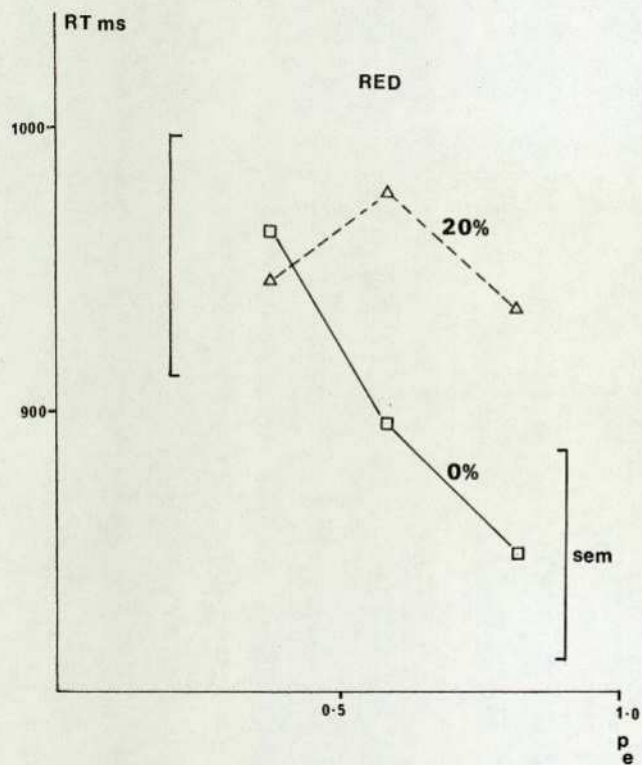


FIGURE 4.7(A) REACTION TIME AS A FUNCTION OF EXCITATION PURITY

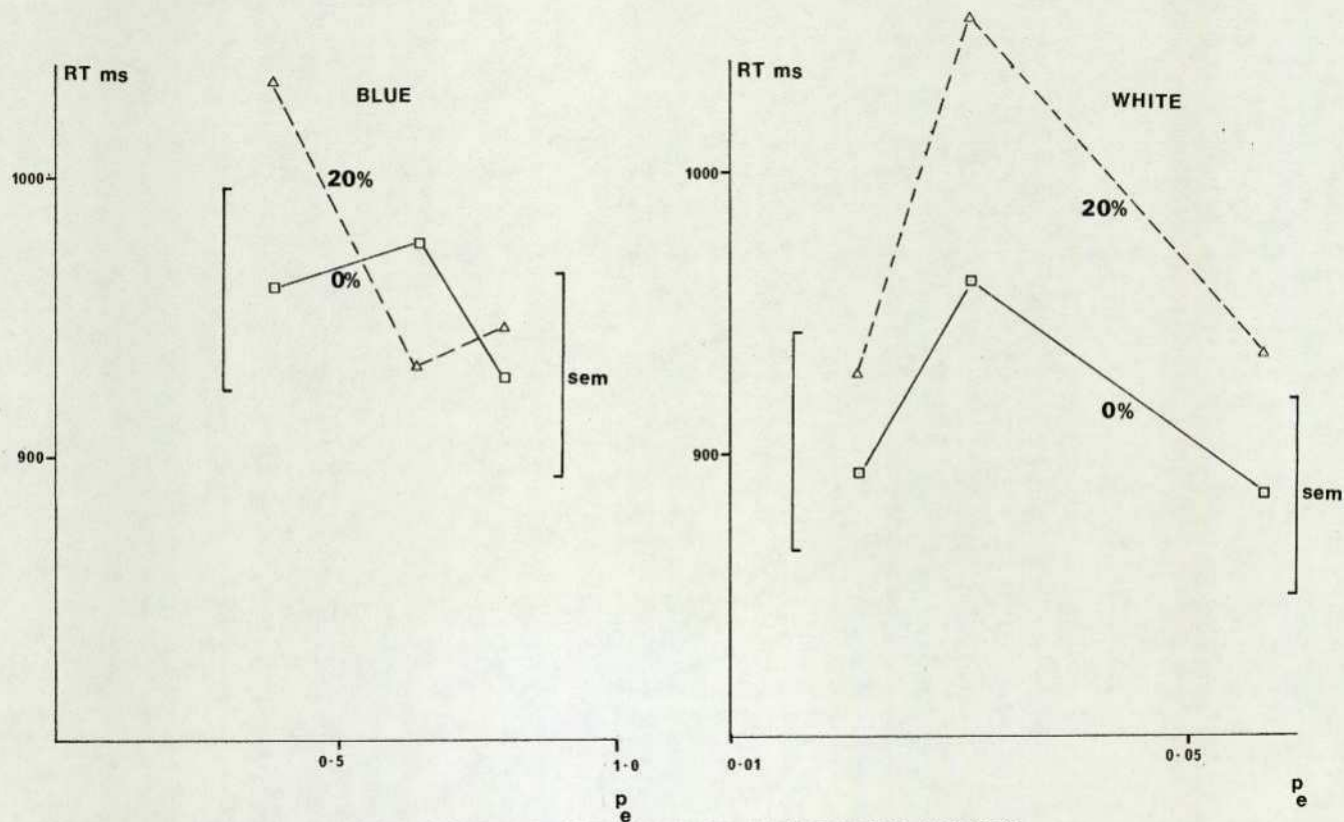


FIGURE 4.7(B) REACTION TIME AS A FUNCTION OF EXCITATION PURITY

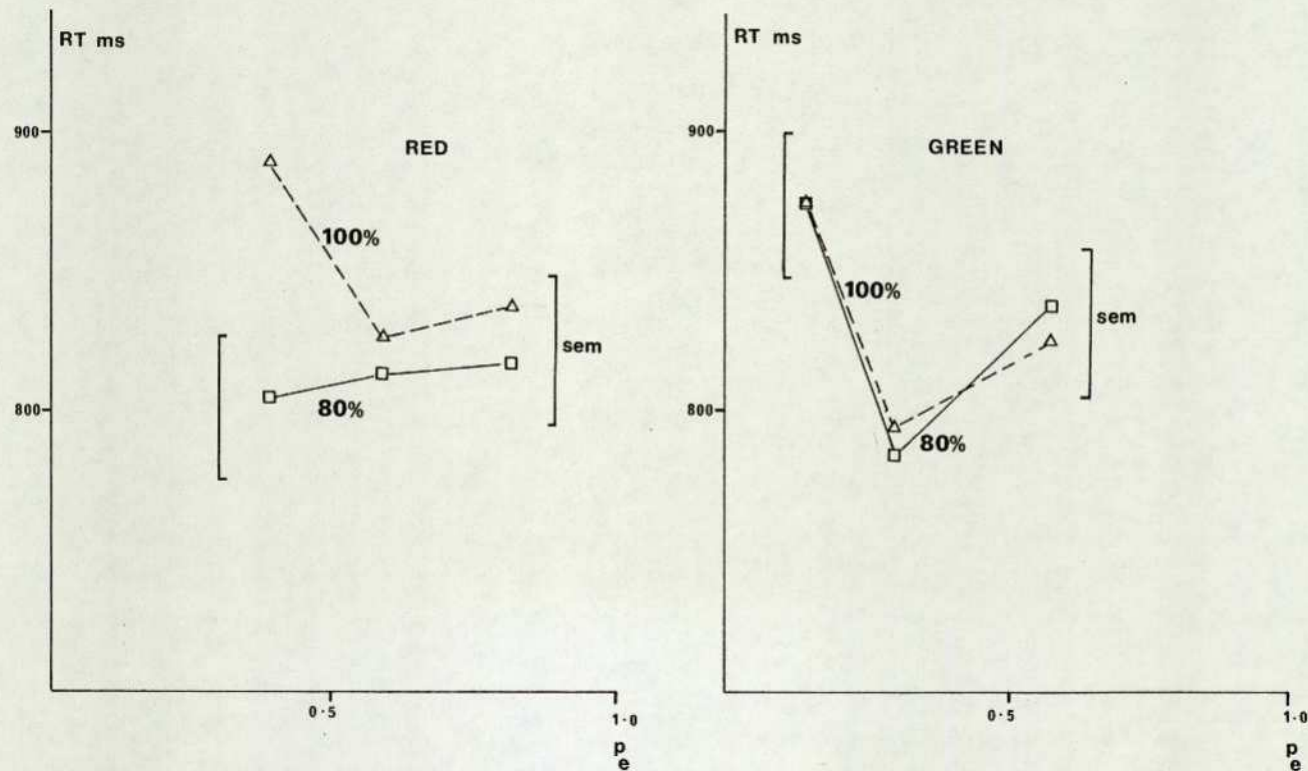


FIGURE 4.8(A) REACTION TIME AS A FUNCTION OF EXCITATION PURITY

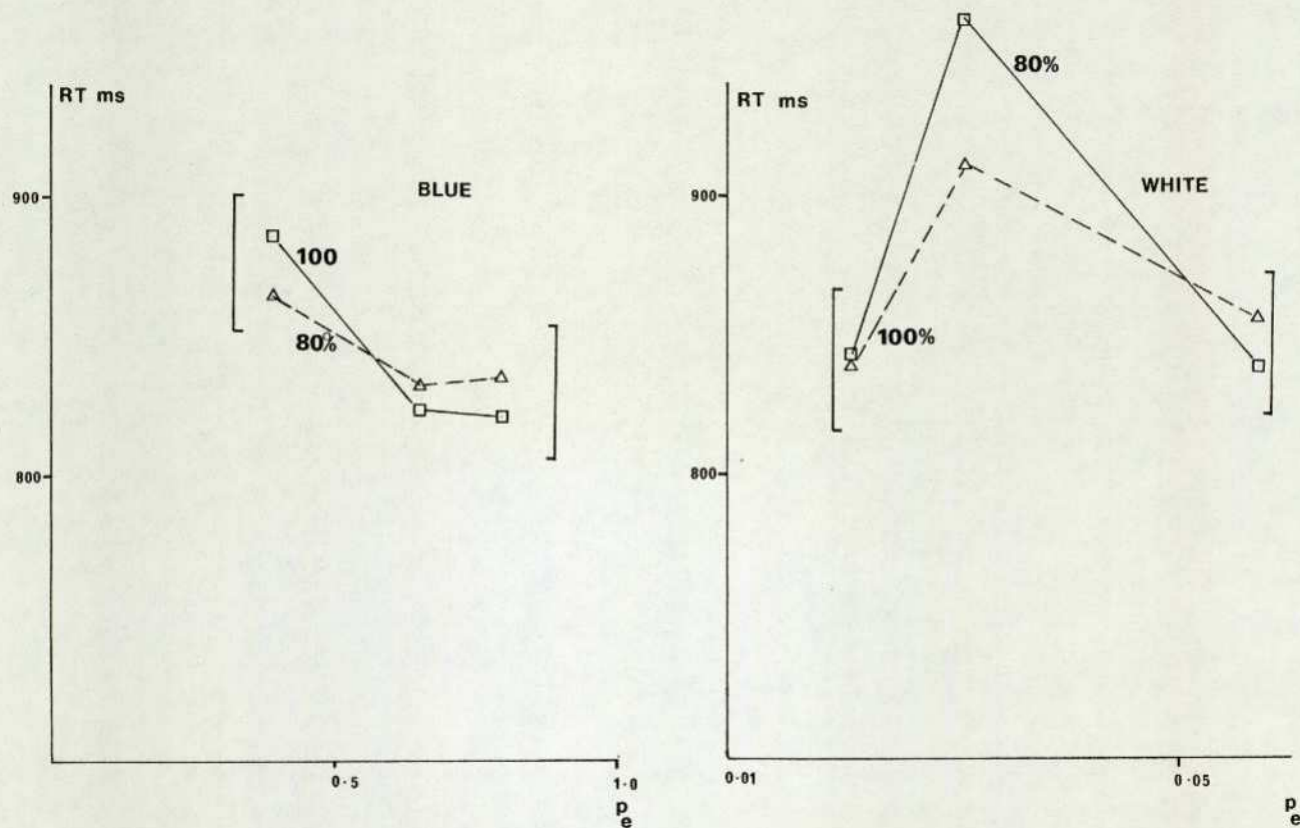


FIGURE 4.8(B) REACTION TIME AS A FUNCTION OF EXCITATION PURITY

dependence upon purity. This apparently simple conclusion is misleading however, since inspection of the results for the achromatic targets suggests a peak reaction time at an excitation purity of approximately 0.025 (note the much expanded scale). The inference from this data is that reaction time oscillates rapidly at low purities and then declines at higher purities. A more likely explanation however is that the other effect of the veiling light - contrast reduction - is the more important. The data from figures 4.7 and 4.8 were replotted therefore as a function of target contrast (table 4.2 (b)) and this is illustrated in figures 4.9 and 4.10.

The former shows data for redundancies of 0% and 100%, while the latter is for 20% and 80% data. Generally there is a decline in response time as contrast increases, irrespective of colour and redundancy of the targets, however comparing 0% and 100% targets the difference between maximum and minimum RT is small in the latter case. The data for 20% and 80% redundancy are less well ordered with red targets in particular displaying little or no dependence on contrast.

4.6 Discussion

The results obtained in this experiment reflect a particular problem with performing a multivariate experiment - the determination of which variable is producing the significant effect. The most satisfactory method would have been to separate the effects of contrast and purity change and assess these separately, but the

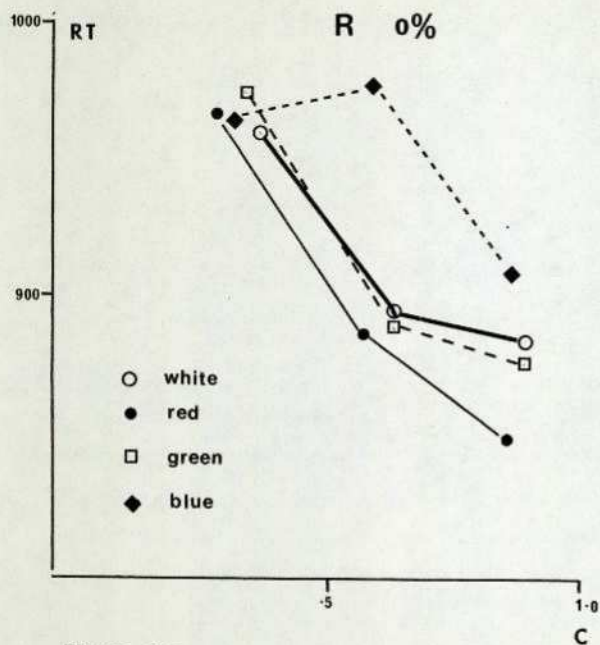
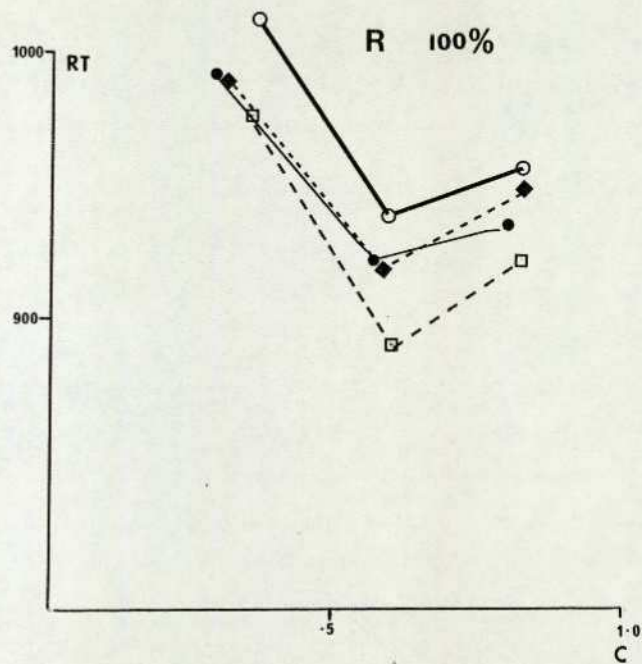


Figure 4.9



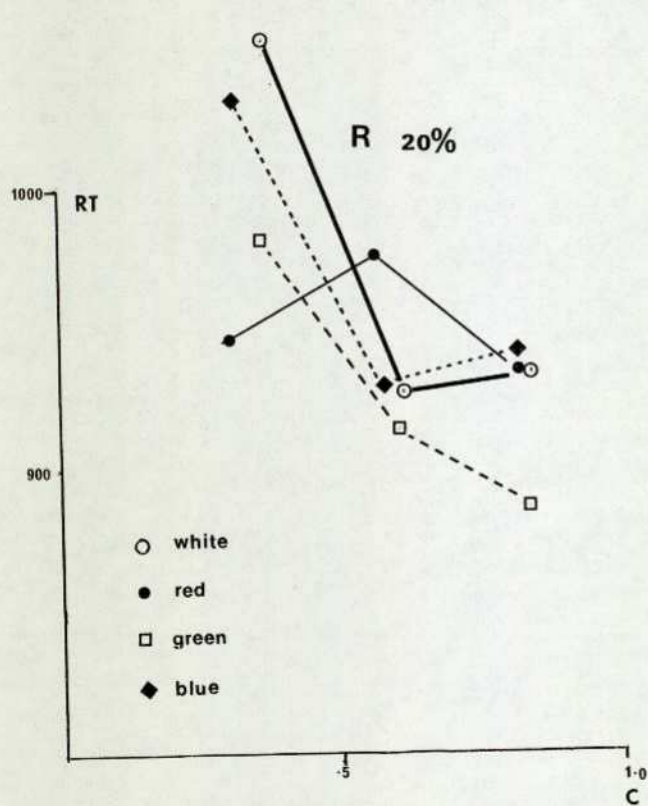
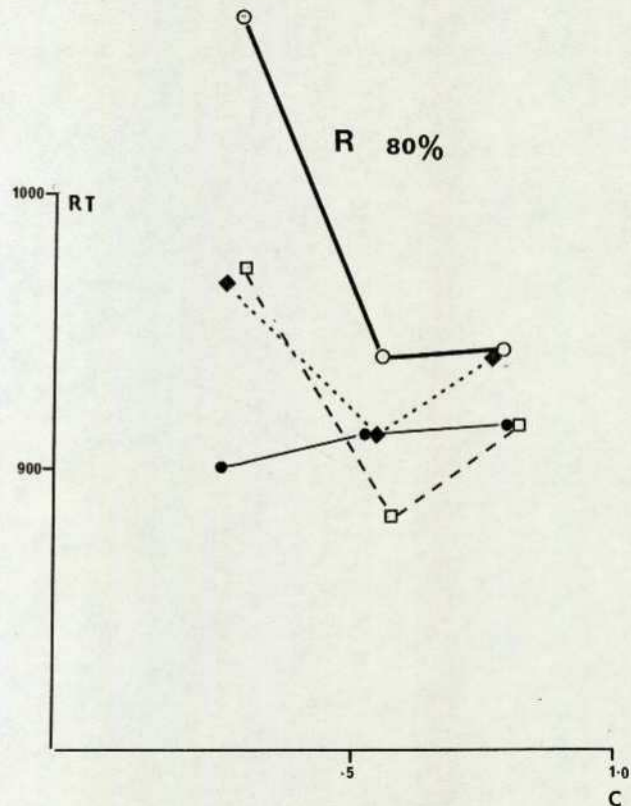


Figure 4-10



principal purpose in the present case was to simulate the effects found in the normal environment, by adding a veiling light field. The result is to confound the two variables, and although the statistical analysis indicates a significant effect care must be taken in attributing this to a particular variable. An alternative approach would have been to find a variable which included the two phenomena associated with the veiling field but it was felt that such an approach tended to hide the underlying factors.

By using a control condition - a neutral test target - and testing this in the same manner as the chromatic targets, it was possible to determine the effect of contrast changes alone.⁺ In terms of excitation purity the data imply large changes in reaction time for very small purity changes (of the order of 1%) when the results for the achromatic test targets are considered. A more reasonable explanation is that contrast is the important factor, and this is consistent with results for detection reaction times (e.g. Harwerth et al, 1980), in which reaction time decreases as contrast increases. This is the case in the present experiment also. This dependence of reaction time on contrast is however a function of the target presented, since the statistical evidence strongly supports the idea that reaction time is also a function of redundancy. This point will be discussed further in later

⁺ Assuming contrast and purity are separable variables.

chapters, but it is worth pointing out at this stage that such a result is consistent with a model of the visual system in which two channels operate in parallel. Harwerth et al (1980) demonstrated that changing the structure of a target altered the mean reaction time and the distribution of reaction times in a detection experiment. The present results extend such a model to a recognition task, if one assumes that presenting increasingly complex targets (with target complexity assessed by redundancy) requires the visual system to detect increasingly higher spatial frequencies to perform the task.

If as discussed in chapter one saturation is a measure of the relative activities of chromatic and achromatic channels then one might expect that the move from transient to sustained responses resulting from the increasing target complexity would be enhanced by more highly chromatic targets - in other word purity would be important. Two reasons exist to explain why this is not the case in the present experiment. Firstly the target contrasts used were high. Targets were above detection threshold to all observers, and it is suggested by Ingling and Drum (1973) that chromatic contrast may only be of importance when luminance contrast is low.

Secondly, the temporal properties of the stimuli enhanced neither one nor the other of the two channels, according to the results of Breitmeyer (1975).

4.7 Conclusions

It is apparent that target structure is an important factor in recognition tasks. Although not a novel conclusion in itself the present data are based upon stimuli which have been ordered along a particular dimension, and this dimension can be applied to new stimuli. Furthermore it is conceivable that a link may be made between information theory description and the Fourier spectra of the targets.

The results also indicate that purity is not a significant factor in the recognition of complex targets when these are presented at contrasts of between 0.3 and 0.9, when target position is known and presentation time is long. These results are consistent with the model of the visual system outlined in chapter one, since the conditions of the experiment are predominantly in favour of the "luminance" channel.

CHAPTER FIVE

PURITY DEPENDENT RECOGNITION - A FUNCTION OF STIMULUS RISE TIME AND CONTRAST

5.1 Introduction and experimental design

5.2 Method

5.3 Targets

5.4 Observers

5.5 Procedure

5.6 Results

(a) Training sessions

(b) Experimental

5.7 Discussion

5.8 Conclusions

PURITY DEPENDENT RECOGNITION - A FUNCTION
OF STIMULUS RISE TIME AND CONTRAST

5.1 Introduction and experimental design

Kranda and King-Smith (1979) and Carden and King-Smith (1976) demonstrated the existence of two separate visual channels the temporal properties of which indicate that transient mechanisms are achromatic and sustained mechanisms are chromatic, at least at threshold. Breitmeyer and Ganz (1971) were able to stimulate each channel selectively by choosing rise times appropriate to their temporal characteristics. In addition the spatial frequency sensitivity of each channel peaks at a different frequency (Lennie 1980). The experiment described in this chapter aimed to select rise times and spatial structures (redundancy) which preferentially stimulated one or the other of these channels, and to test for purity effects on recognition under these conditions and near threshold. The experimental design used two information levels, two redundancy levels, and two rise times along with a range of purity and contrast levels. Dominant wavelength of the stimuli was constant however.

5.2 Method

Figure 5.1 illustrates the front projection optical system used. Target slides T were imaged in the middle of a circular, matt white screen by projector P (S - RA 2000 random access carousel) and lens L. The contrast of the image (relative to the background) was regulated by the neutral density wedge W (2 log unit vacuum coated OEC Ltd). Wedge position was controlled by the experimenter and monitored by a potentiometer. Figure 5.2 (a), illustrates the voltage versus

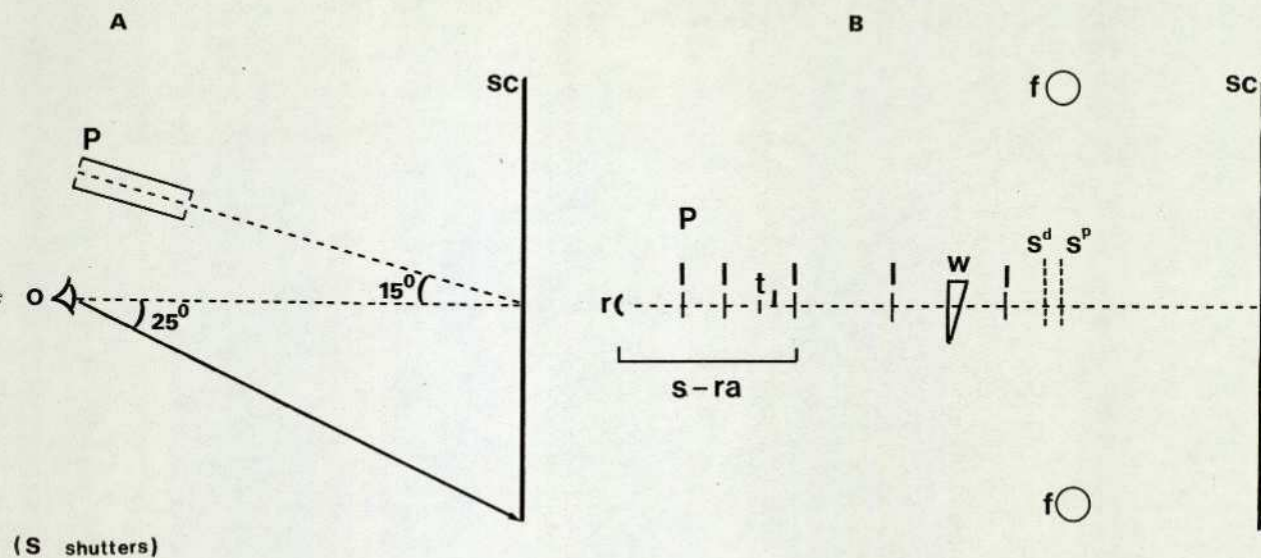


FIGURE 5-1 Apparatus (a) side view (b) plan

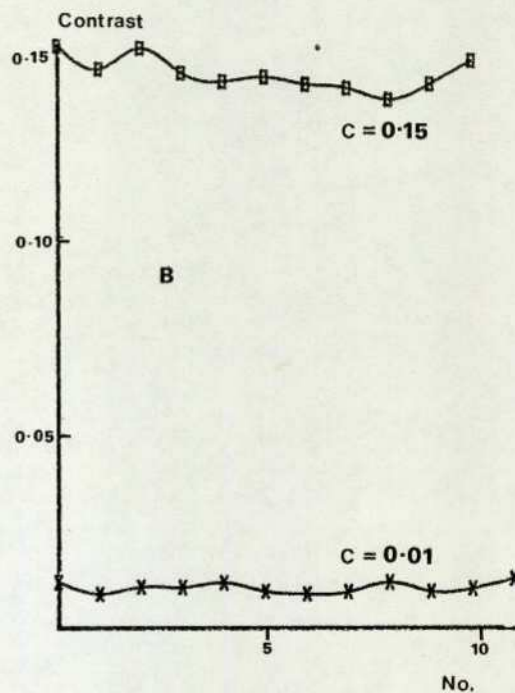
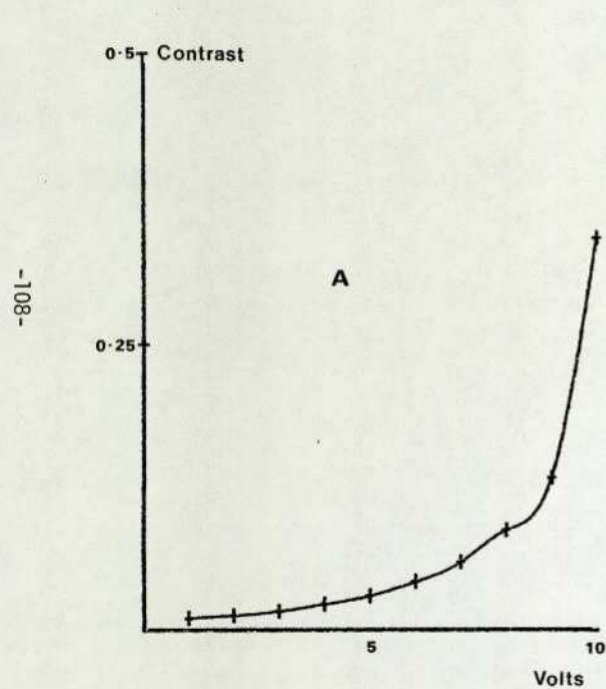


Figure 5.2 Wedge calibration

contrast relationship while figure 5.2 (b) shows the variation with time of two contrasts (measured at the screen photometrically). The abscissa is an arbitrary scale although generally the calibration was checked every week.

The circular background field subtended 50° at the observer and was produced by two "artificial daylight" fluorescent tubes F. Both these and the projector were operated from a stabilised supply (240 ± 0.5). The observer viewed this field binocularly from a distance of 1.3 metres, and head movements were prevented by means of an ophthalmic headrest. A high brightness red LED was mounted 10 cm above the centre of the field and was used to provide visual cues to the observer.

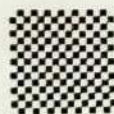
5.3 Targets

As stated in the introduction two redundancies were selected. These were 0% and 100%. Initially it was intended to use only 64 bit patterns, however it was later felt that using patterns with a higher (225 bit) information content would provide preferential stimulation of the sustained mechanism. Eight patterns were selected from two bit levels (giving two per redundancy level). Bit levels were not mixed in any session. The four patterns selected from the 225 bit set are illustrated in figure 5.3. The patterns used from the 64 bit set were the "equivalent" patterns (see figure 2.2). All targets subtended $1.9^{\circ} \times 1.9^{\circ}$ at the observer. The coloured filters used (Cinemoid and Lee) were mounted along with the targets in their slide mounts.

The experiment was conducted in two parts:-



1



2

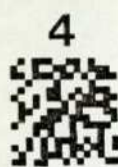
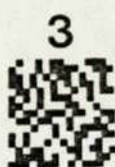


Figure 5-3 225 bit patterns

1 & 2	Red.	100%
3 & 4	Red.	0%

- (a) All the targets were presented with a rapid rise time. This was achieved by using a rotating sector disc, driven by a synchronous motor. Rise time was 15 ms and presentation time was 260 ms.
- (b) All targets were presented with a slow rise time. Two polarisers (Polaroid HD4), one of which could be rotated through 90^0 by means of a rotary solenoid produced an approximately linear change in target luminance with time. Time to peak luminance was 400 ms and it was maintained at this peak value for 600 ms. Changes in spectral transmittance during rotation of the polarisers was not taken into account. These polarisers were not present during the first part of the experiment when stimuli were presented with a fast rise time alone, and their insertion in part (b) required a separate assessment of the photometric and colorimetric properties of the targets.

Four contrasts were used in part (a) - 0.15, 0.10, 0.05 and 0.01. Note that one of the three colour filters used reduced the test beam to such an extent that the maximum contrast achievable was 0.058. For part (b) of the experiment only three contrast levels were used - 0.10, 0.05 and 0.01. Colorimetric data are illustrated in figure 5.4 and 5.5. The former presents the chromaticity coordinates for the stimuli used in fast rise time experiments, while the latter those used in slow rise time experiments. 'S' indicates the chromaticity of the surround. The values were determined from the observer's viewing position by telespectoradiometer as described in appendix III.

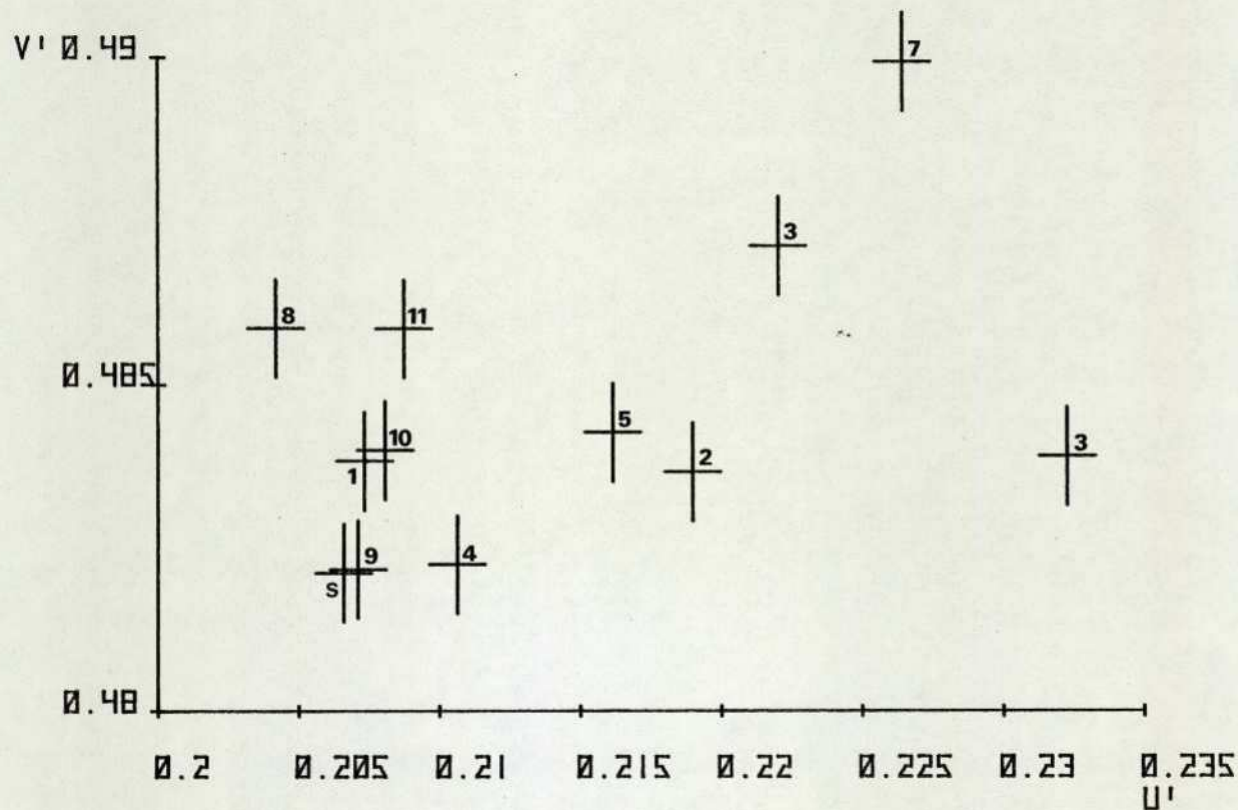


Figure 5-4

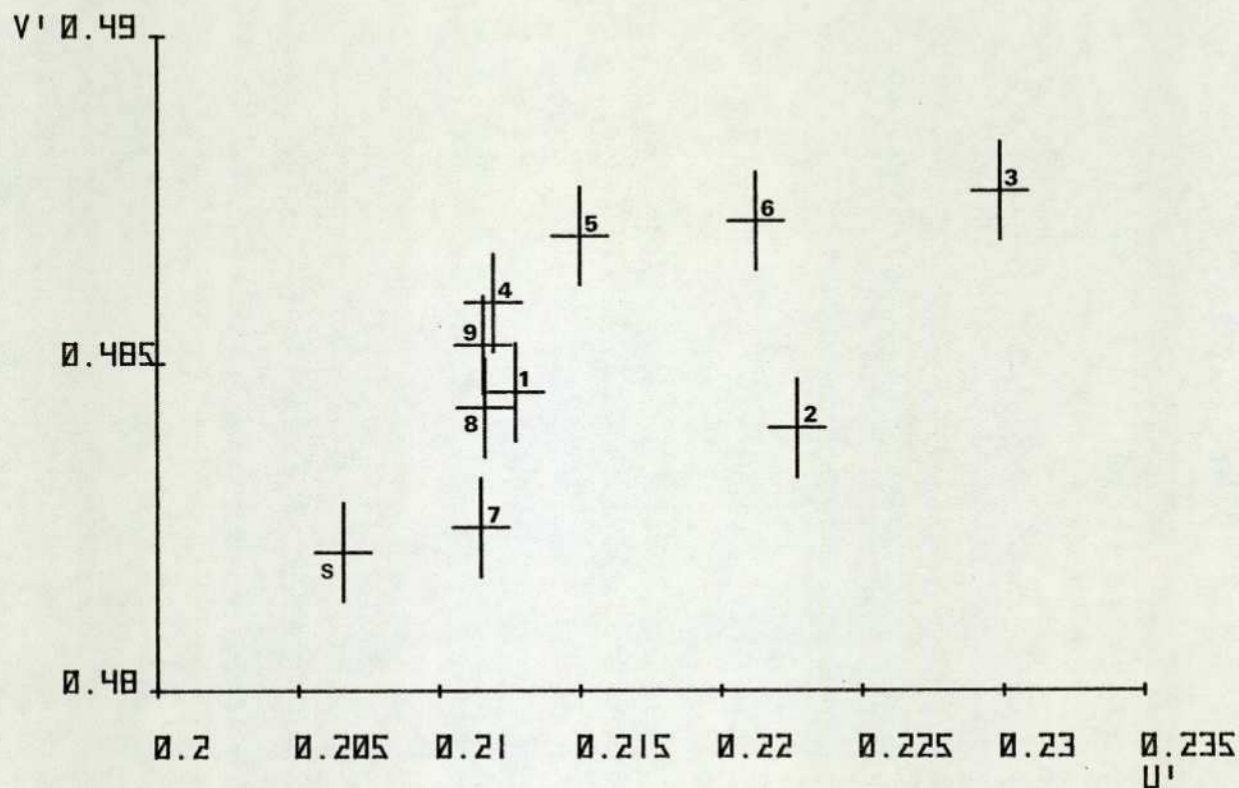


Figure 5.5

5.4 Observers

Only one observer (the author) took part in part (a), while two (the author and S.F.) were used in part (b). Both had taken part in the first experiment and were therefore familiar with the task.

5.5 Procedure

Each session lasted approximately thirty minutes, including a ten minute adaptation period. Targets were presented at the rate of three per minute. Subjects were provided with training sessions to familiarise them with the targets, before the main set of experimental sessions. The stimulus presentation sequence (randomised over purity, contrast and redundancy) including record sheets were prepared by computer (HP9825A), using a pseudorandom number generator. Two seconds before presentation of a target a red LED mounted in the background provided a ready signal to the observer. After selecting a response the observer depressed the appropriate microswitch and gave an auditory indication of which switch had been pressed. Both reaction time and response were recorded by the experimenter.

5.6 Results

(a) Training sessions.

Training session data is illustrated in figure 5.6. Circles and solid lines indicate the number of correct responses per session, while squares and dotted lines plot mean reaction time averaged over a session. The solid arrows in parts (a) and (b) indicate the point at which conditions were changed from high contrast achromatic test targets to variable contrast achromatic targets (i.e. conditions as in experiments proper). The effect on reaction time is marked as one might expect, although observer I.M. showed no change in accuracy of response. In figure 5.6 (c) stimuli were presented as in the main experiment throughout the training sessions.

In all cases observers had reached either a stable response time or a level similar to that found with high contrast targets.

No separate training sessions were given for the two different stimulus onset conditions used.

(b) Experimental data.

As discussed in chapter four, the first experiment provided temporal conditions which failed to stimulate one channel in preference to the other. In addition data was insufficient to permit assessment of the mechanisms contributing to the recognition task. An assumption of the present experimental design is that manipulation of the temporal characteristics can alter or rather select the mechanism (channel) used by the visual system to perform the task. A test of this assumption is provided by comparing the reaction time distributions obtained under

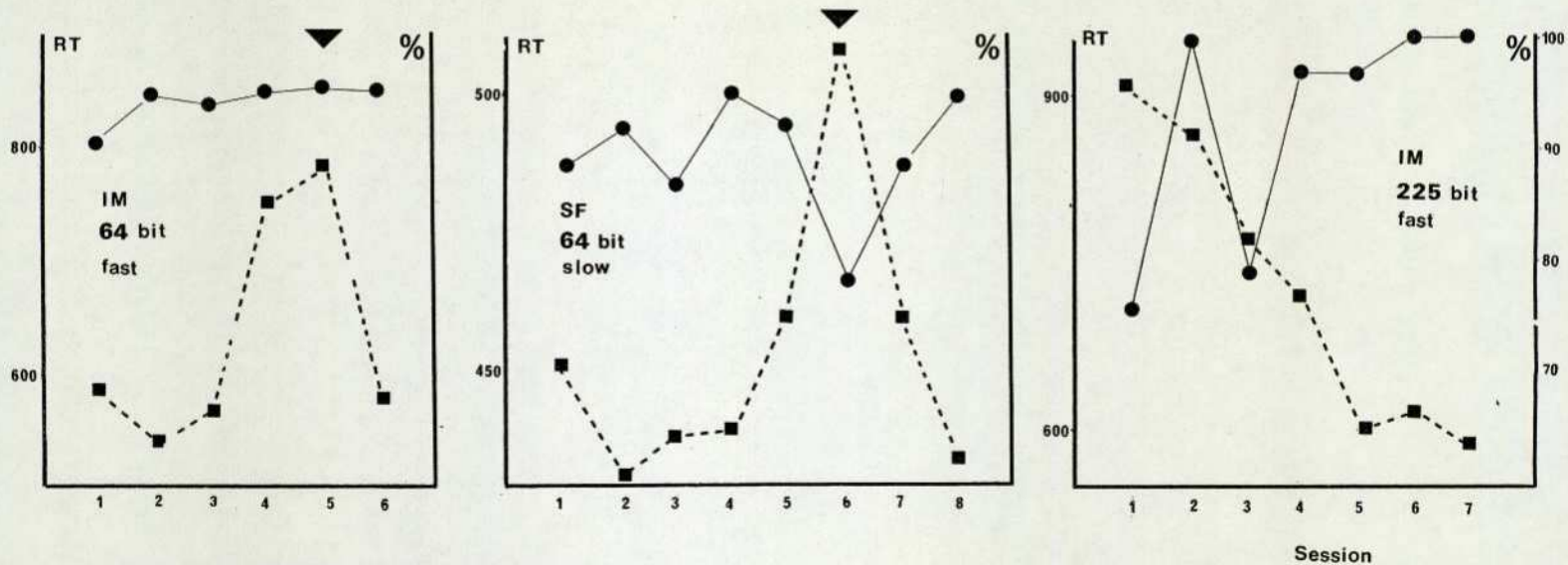


FIGURE 5.6 TRAINING SESSION DATA

different temporal conditions.

Histograms of reaction times were prepared using only correct responses, and these are illustrated in figures 5.7 to 5.10. Each histogram is labelled to indicate the redundancy, contrast and rise time. Values for all purity levels and responses under these conditions were pooled.

The most striking effect is that of contrast. For all redundancies and rise times (both observers) decreasing contrast produced a broader more "sustained" distribution of reaction times. Similar results have been found in detection tasks. Figure 5.11 illustrates data replotted from Harwerth et al (1980) in which two contrast levels are compared. Stimuli closer to threshold produced this broader, squatter distribution of reaction times.

More difficult to assess is the effect of redundancy and stimulus rise time on histogram shape. Irrespective of rise time, targets with a high redundancy (100%) produced a more "transient" distribution. The effect was more marked at low contrasts. In addition however, those targets presented with a fast rise time produced a more transient histogram still.

A continuum seems to exist - targets which had a slow onset and a low redundancy produced a broad distribution, while targets of a high redundancy and presented with a fast rise time resulted in a markedly transient distribution.

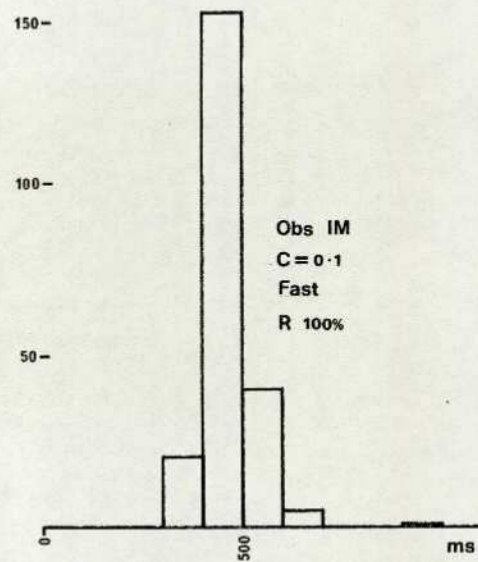
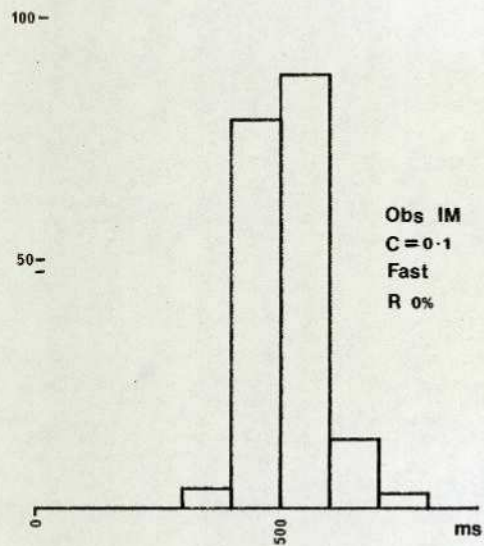


FIGURE 5.7 REACTION TIME HISTOGRAMS - FAST RISE TIME

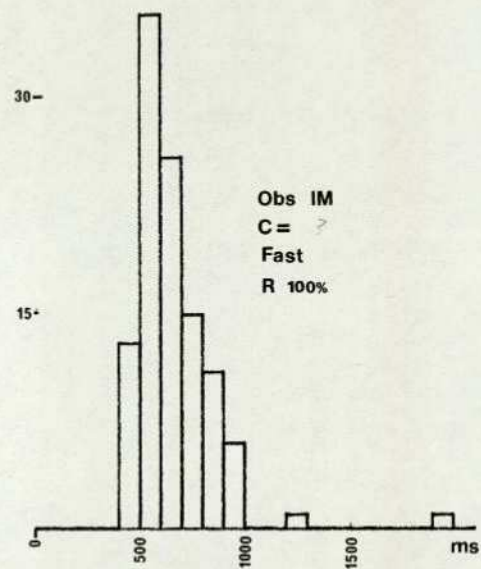
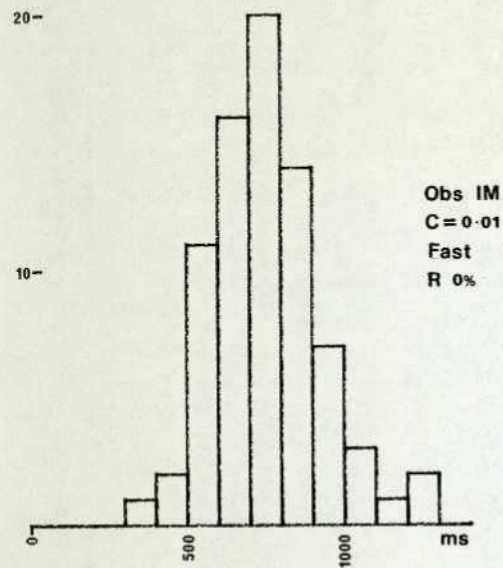


FIGURE 5.8 REACTION TIME HISTOGRAMS - FAST RISE TIME

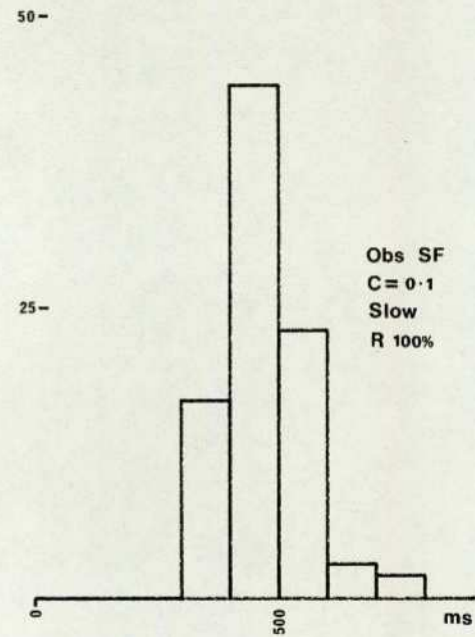
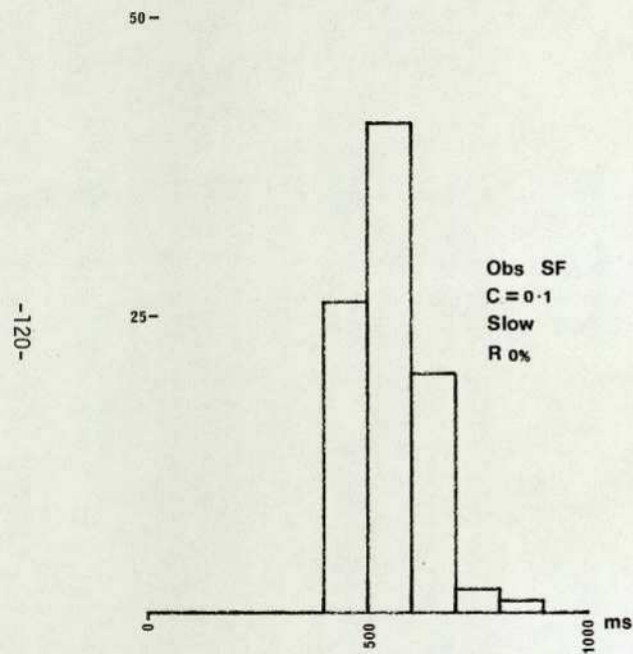


FIGURE 5.9 REACTION TIME HISTOGRAMS - SLOW RISE TIME

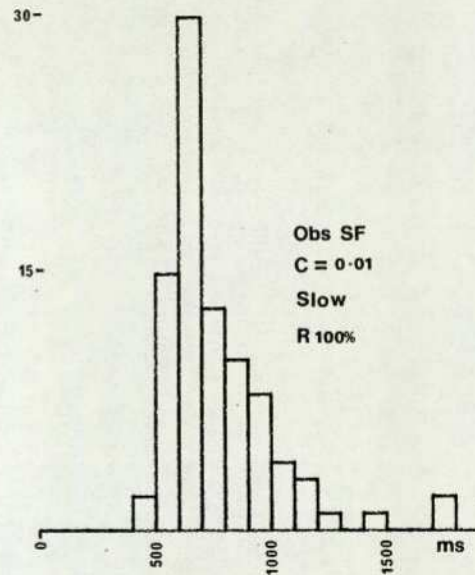
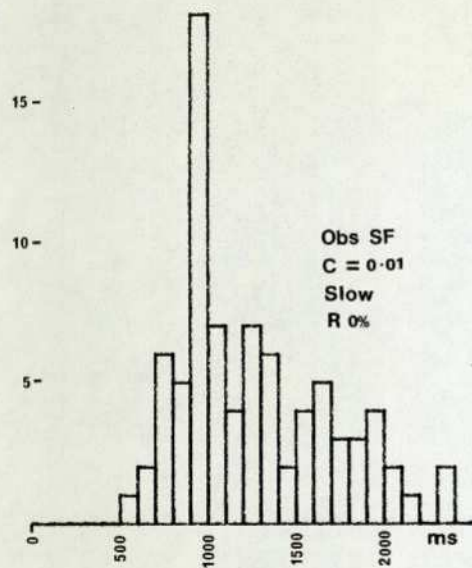


FIGURE 5.10 REACTION TIME HISTOGRAMS - SLOW RISE TIME

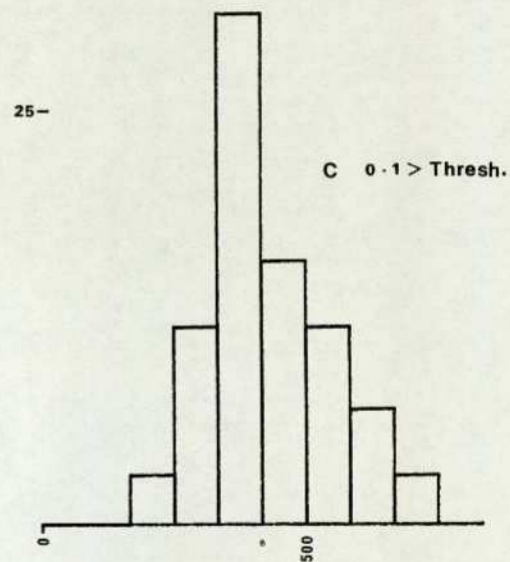
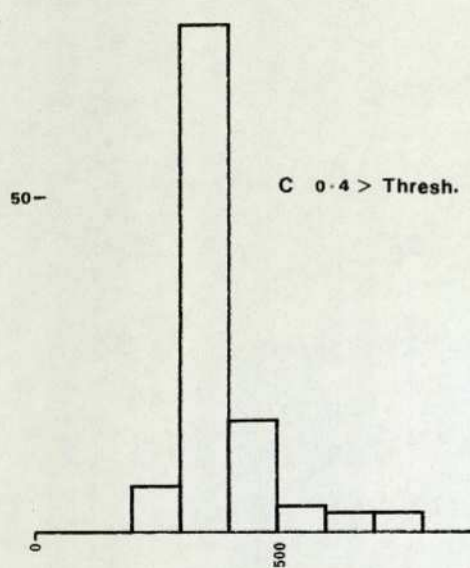


FIGURE 5.11 REACTION TIME HISTOGRAMS - DATA FROM HARWERTH ET AL

A quantitative estimate of the deviation from a normal distribution is provided by the third moment about the mean (skewness) which is defined as follows:-

$$\int [x - \mu]^3 \phi(x) dx$$

where μ is the population mean and $\phi(x)$ is the function defining the distribution. This function was computed for the experimental data and the results are presented in table 5.2. All of the values obtained were positive indicating that the histograms deviated to the lower reaction times to some extent. This is generally typical of reaction time distributions.

TABLE 5.1 THIRD MOMENTS OF THE MEAN

FAST	0.93
0%	
SLOW	0.63
FAST	2.57
100%	
SLOW	1.54

The values in the table were obtained from data collected over contrast, response and purity. They confirm the subjective remarks describing the histograms i.e. that a slow target onset combined with a low redundancy results in a minimally skewed

distribution, while a rapid onset and a high redundancy leads to a reaction time distribution which is skewed to fast reaction times.

Turning to the effect of purity on reaction time, figures 5.12 and 5.13 illustrate the effect of target excitation purity upon reaction time, for low contrast targets (0.01). The former is for "yes" responses and the latter for "no" responses. Data for both slow (S) and fast (F) onset rates are included. Vertical bars indicate $\pm$ one standard error. Circles represent data from targets with a redundancy of 0% and squares, data from targets of 100% redundancy. It is clear that the type of presentation used significantly affects reaction time. Increasing target purity under fast rise time conditions leads to a lowering of reaction time while the reverse is true for slow rise time stimuli.

Figures 5.14 and 5.15 present similar data for targets with a greater $H_{\max}$ value. In this case only the high redundancy targets produced a decline in reaction time with increasing purity, when a fast rise time was used. There is a suggestion of an opposite effect for slow rise times but the data are less consistent than for the lower $H_{\max}$ targets.

Figures 5.16 and 5.17 illustrate data for observer S.F. with low contrast stimuli (only slow rise times). Data from I.M. are replotted for comparison. Both sets of data are consistent with each other apart from differences in absolute level.

Reaction times to targets presented at a contrast of 0.05 are

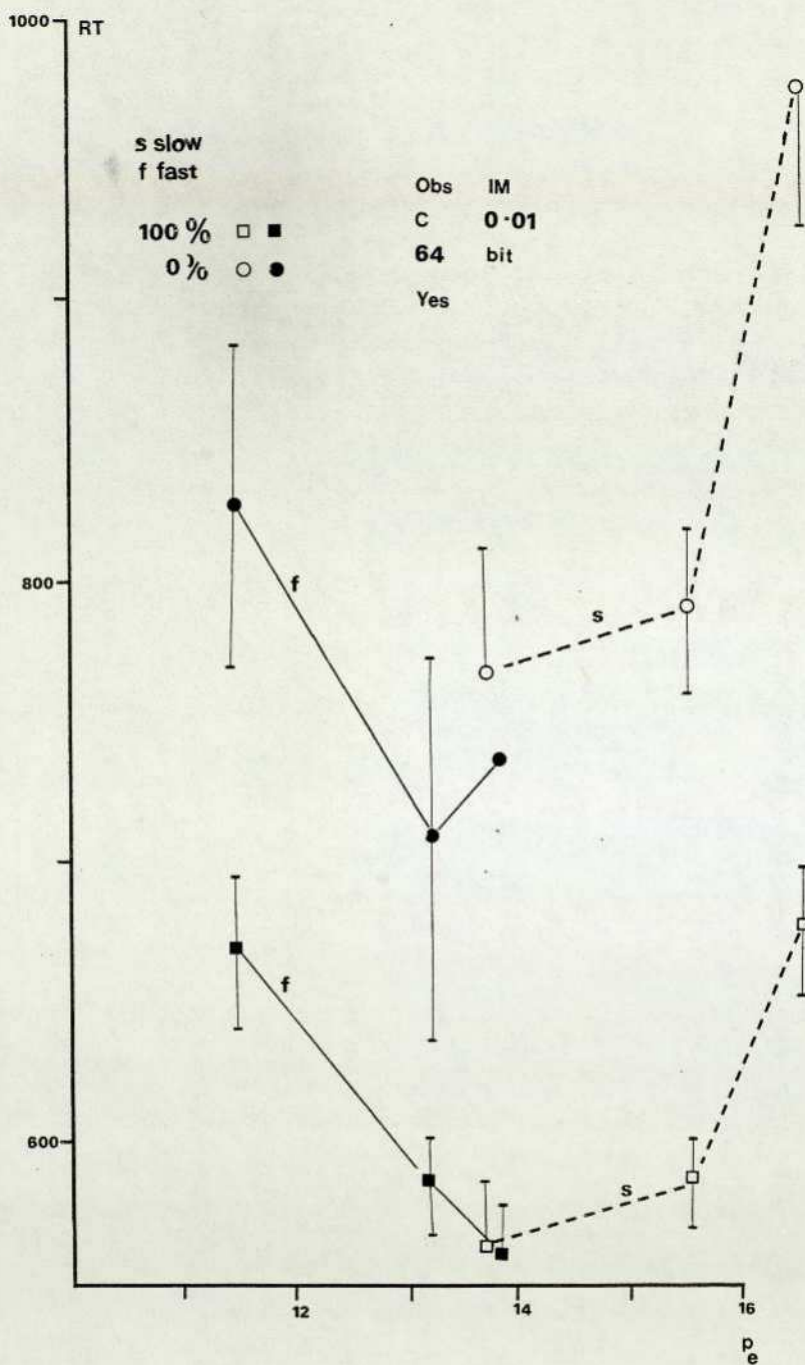


FIGURE 5.12 REACTION TIME AS A FUNCTION
EXCITATION PURITY

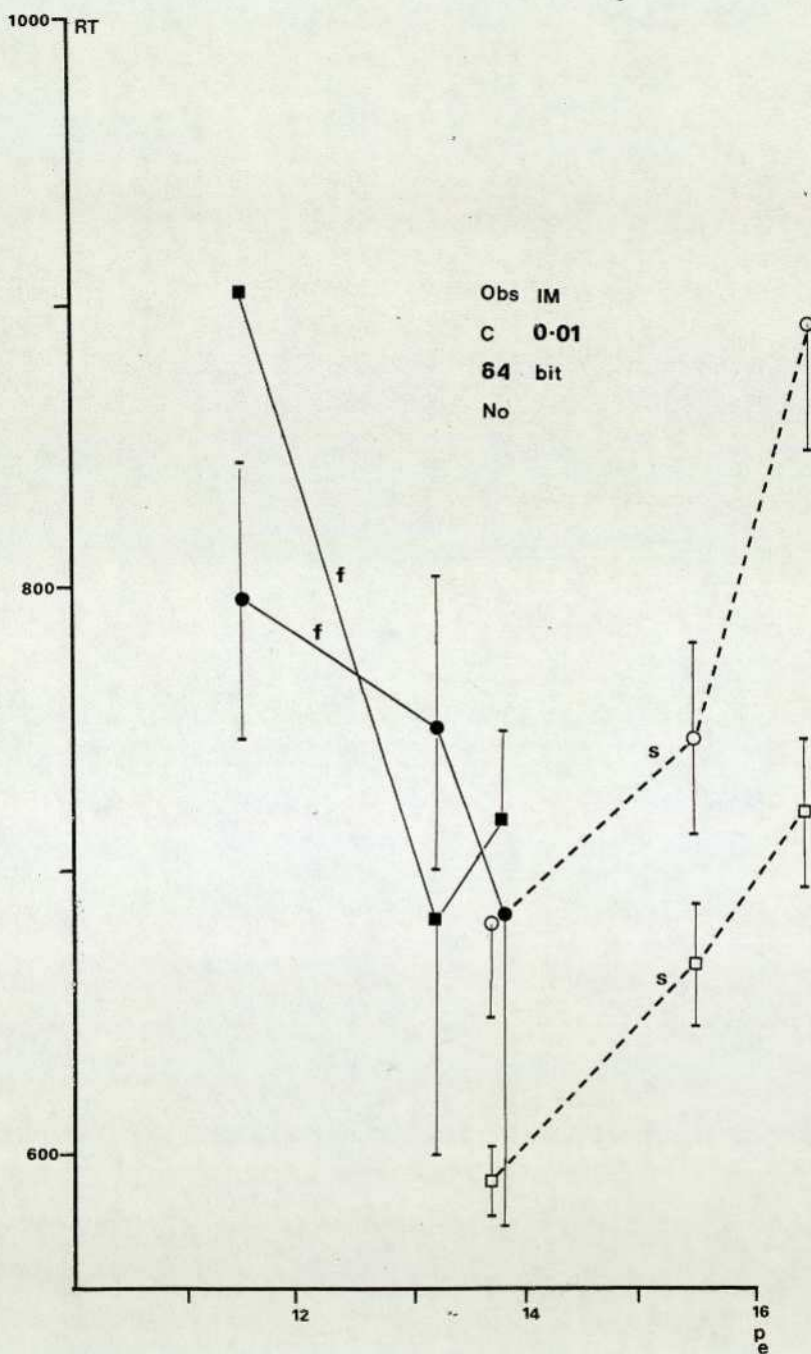


FIGURE 5.13 REACTION TIME AS A FUNCTION
EXCITATION PURITY

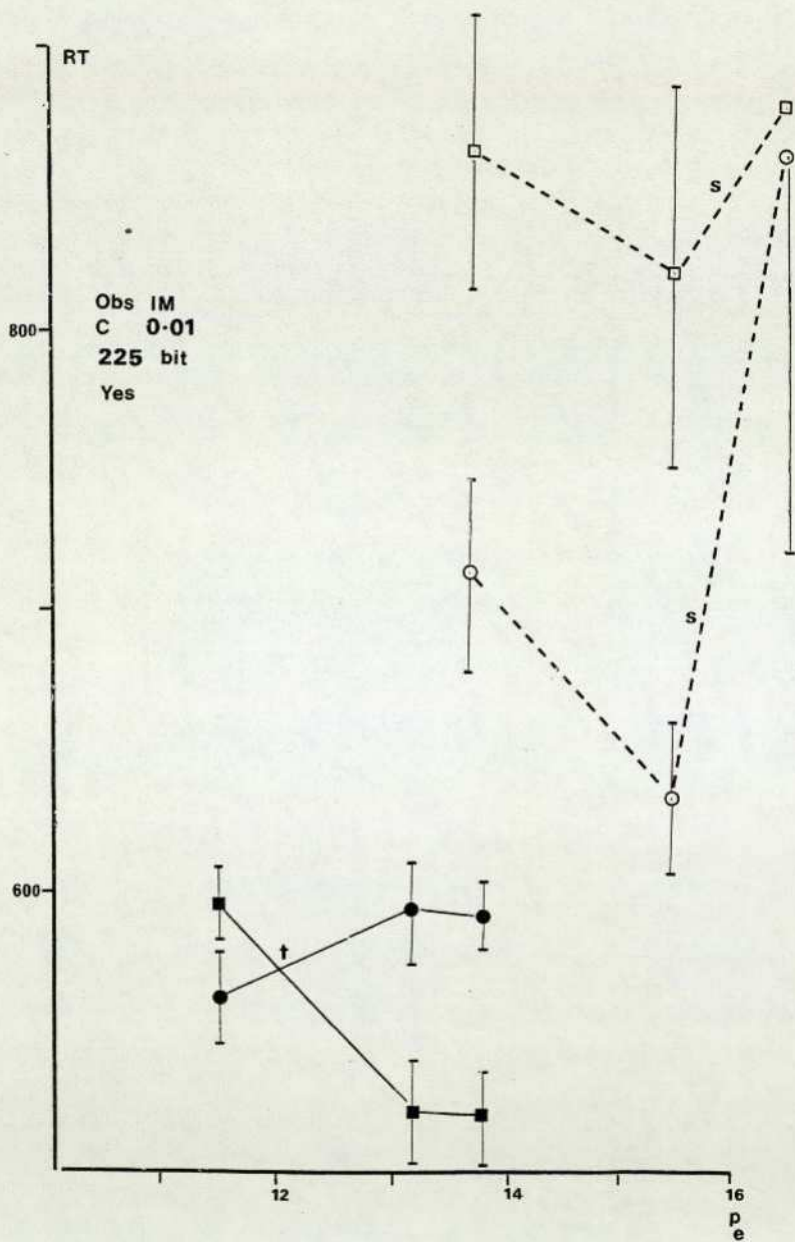


FIGURE 5.14 REACTION TIME AS A FUNCTION
EXCITATION PURITY

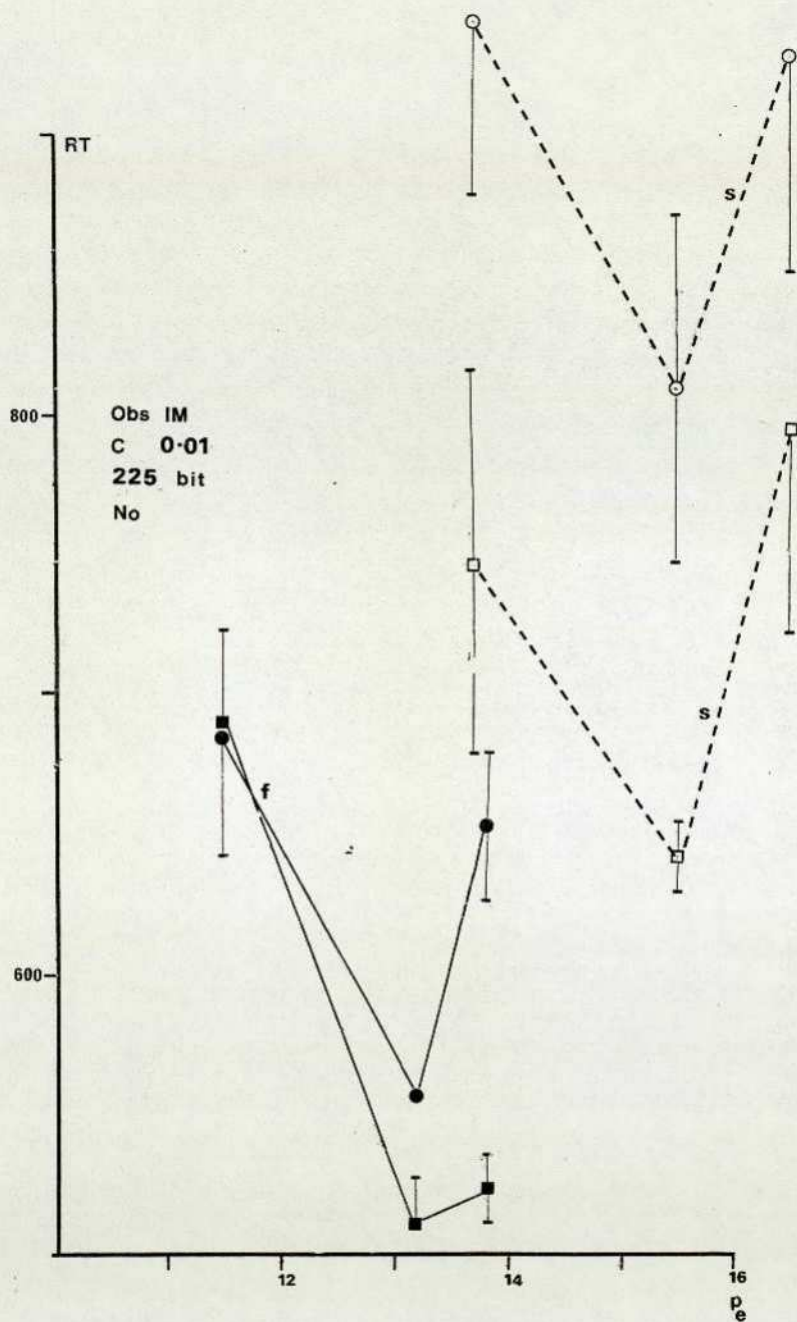


FIGURE 5.15 REACTION TIME AS A FUNCTION
EXCITATION PURITY

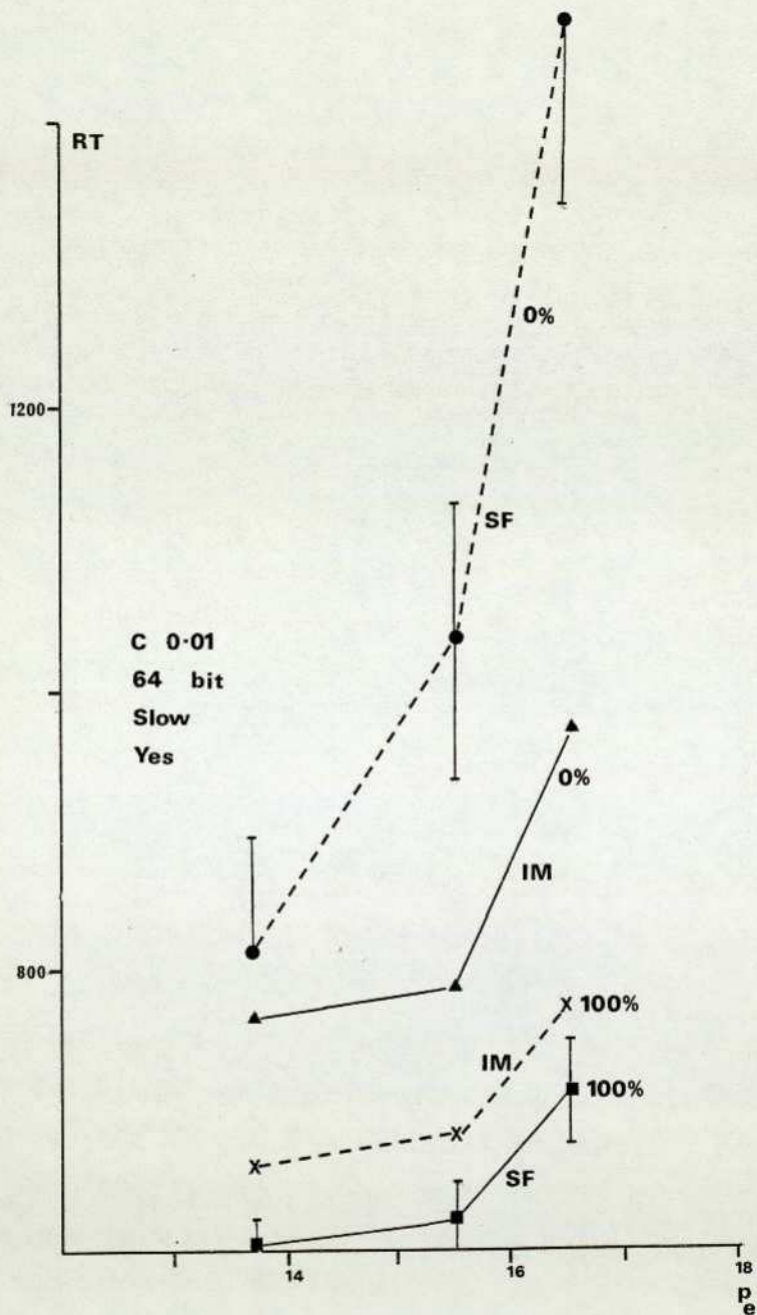


FIGURE 5.16 REACTION TIME AS A FUNCTION
EXCITATION PURITY

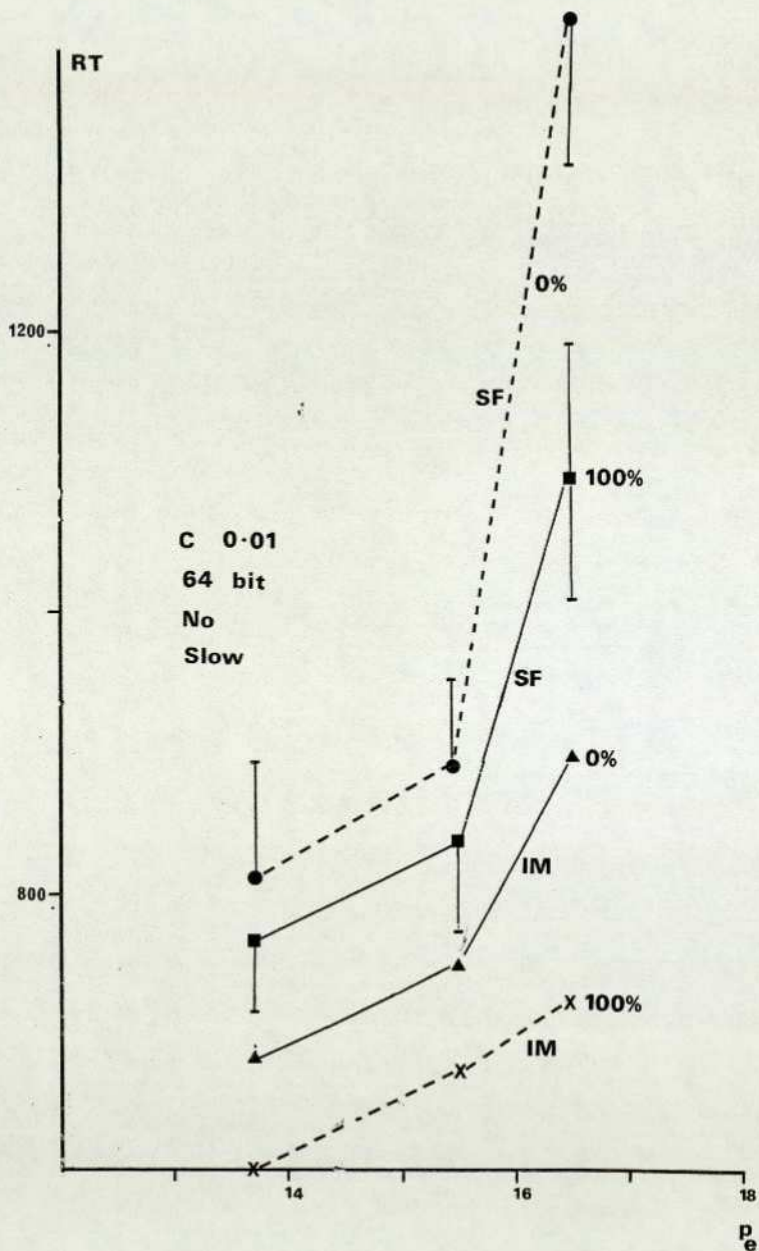


FIGURE 5.17 REACTION TIME AS A FUNCTION
EXCITATION PURITY

illustrated in figures 5.18 and 5.19. These should be compared with figures 5.20 and 5.21 in which data for higher $H_{\max}$ targets are plotted. The data form no clear pattern. Reaction time seems to decline with increasing purity for a fast rise time, but the effect is much less than that observed with low contrast targets. For slow rise times the data are more consistent with a minimum reaction time at a purity of approximately 17%.

Finally the data in figures 5.22 to 5.25 were obtained at a contrast of 0.1 and 0.15 (data were plotted together). Figures 5.22 and 5.23 are for targets with an $H_{\max}$ of 64 bits for observer I.M. Again the results form no clear pattern although "yes" response data indicate a decline in reaction time as purity increases. This is irrespective of rise time however. Figures 5.24 and 5.25 are data for observer S.F., again with I.M. data replotted for comparison. In each case for both observers, the results indicate a minimum reaction time for targets with excitation purities between 15 and 18% (recall that this data is only for slow rise times).

5.7 Discussion

Although the reaction time histograms obtained in the present work are consistent with those of Harwerth et al (1980) as far as the effects of contrast are concerned, this is not the case when the efficacy of different methods in isolating sustained and transient mechanisms is considered. Harwerth et al (1980) found that double peaked histograms could be obtained under certain circumstances, and this was taken as evidence for response only at onset and offset of the stimuli i.e. responses by a transient mechanism. No evidence

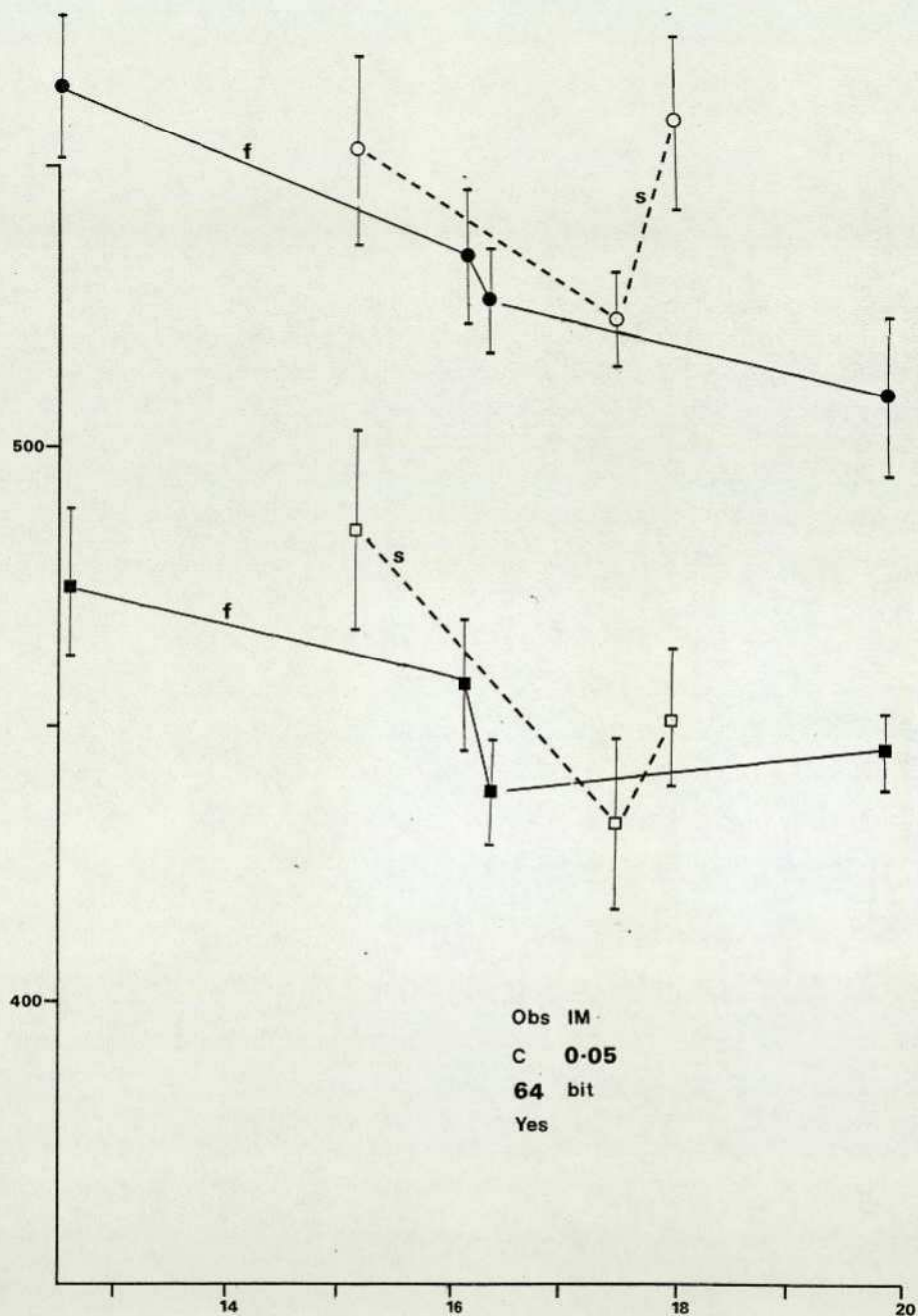


FIGURE 5.18 REACTION TIME AS A FUNCTION
EXCITATION PURITY

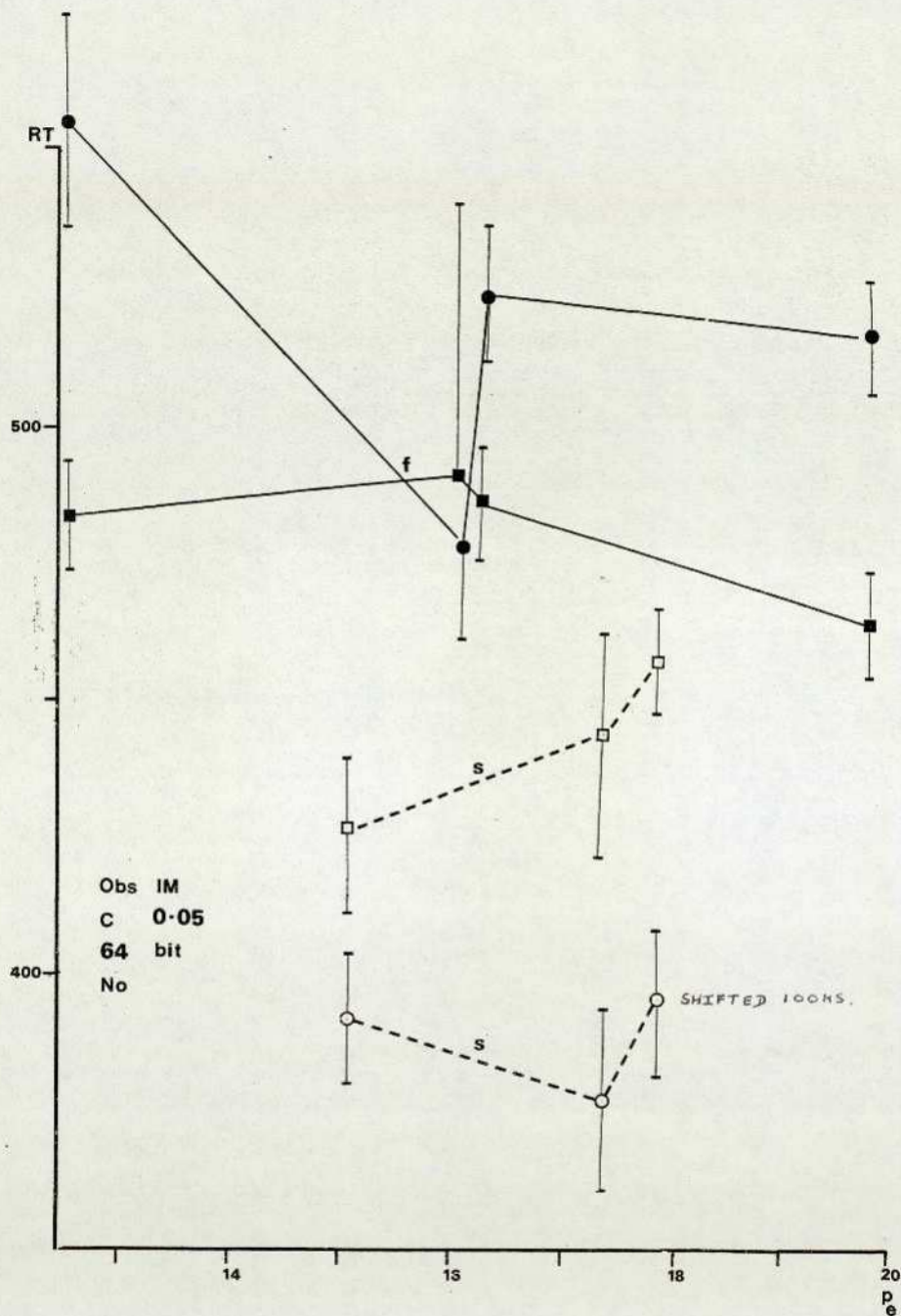


FIGURE 5.19 REACTION TIME AS A FUNCTION
EXCITATION PURITY

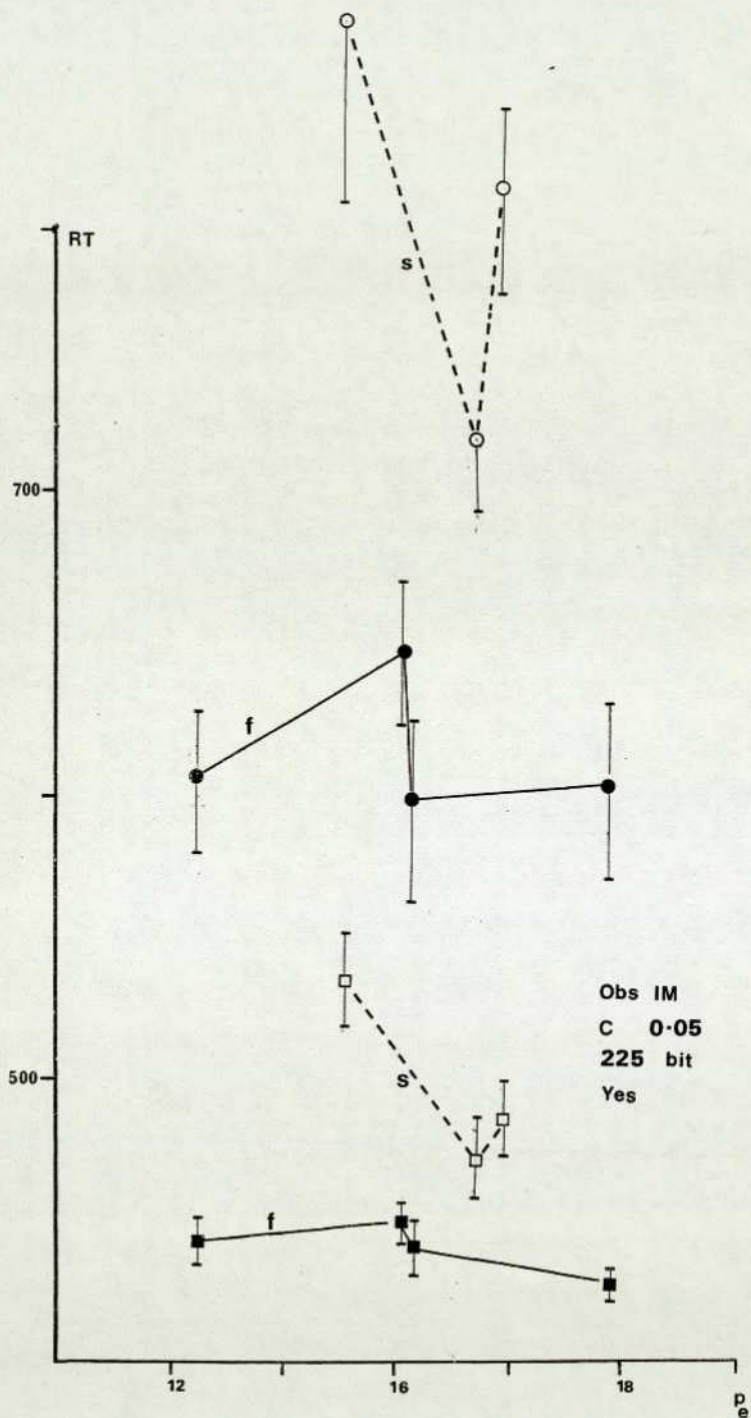


FIGURE 5.20 REACTION TIME AS A FUNCTION
EXCITATION PURITY

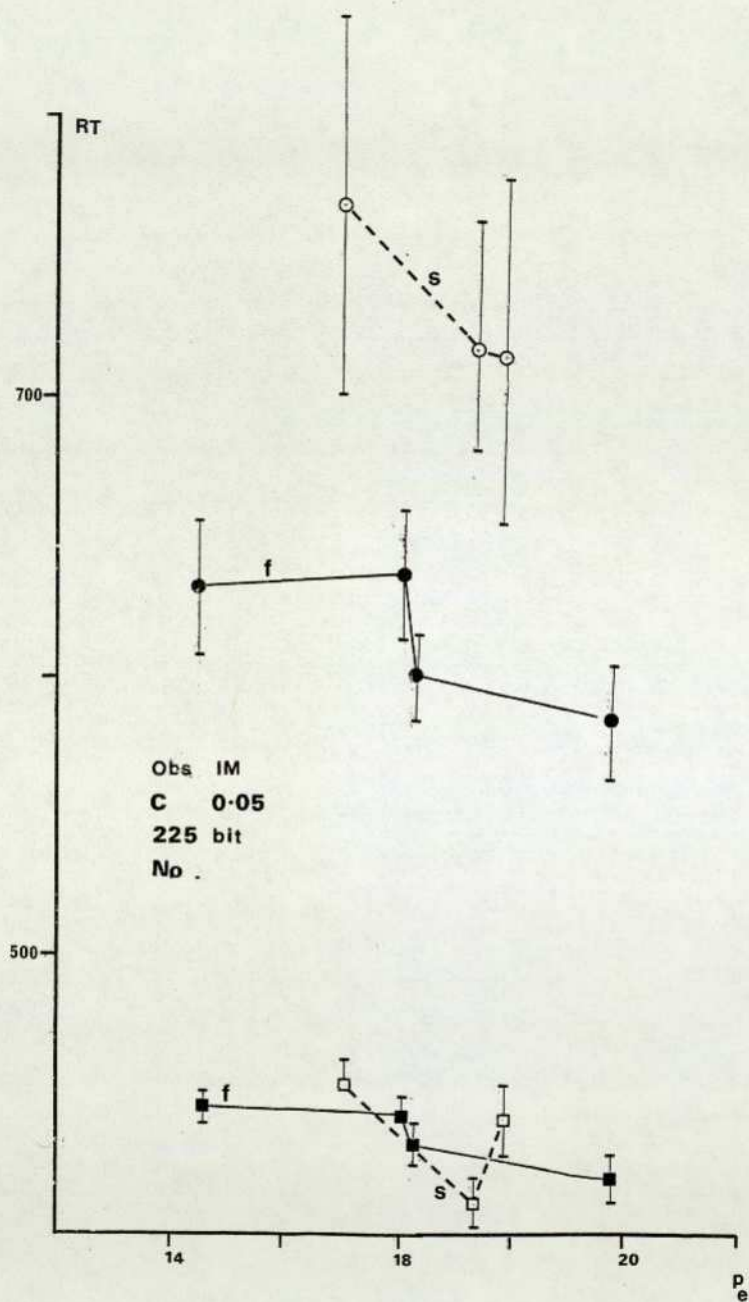


FIGURE 5.21 REACTION TIME AS A FUNCTION
EXCITATION PURITY

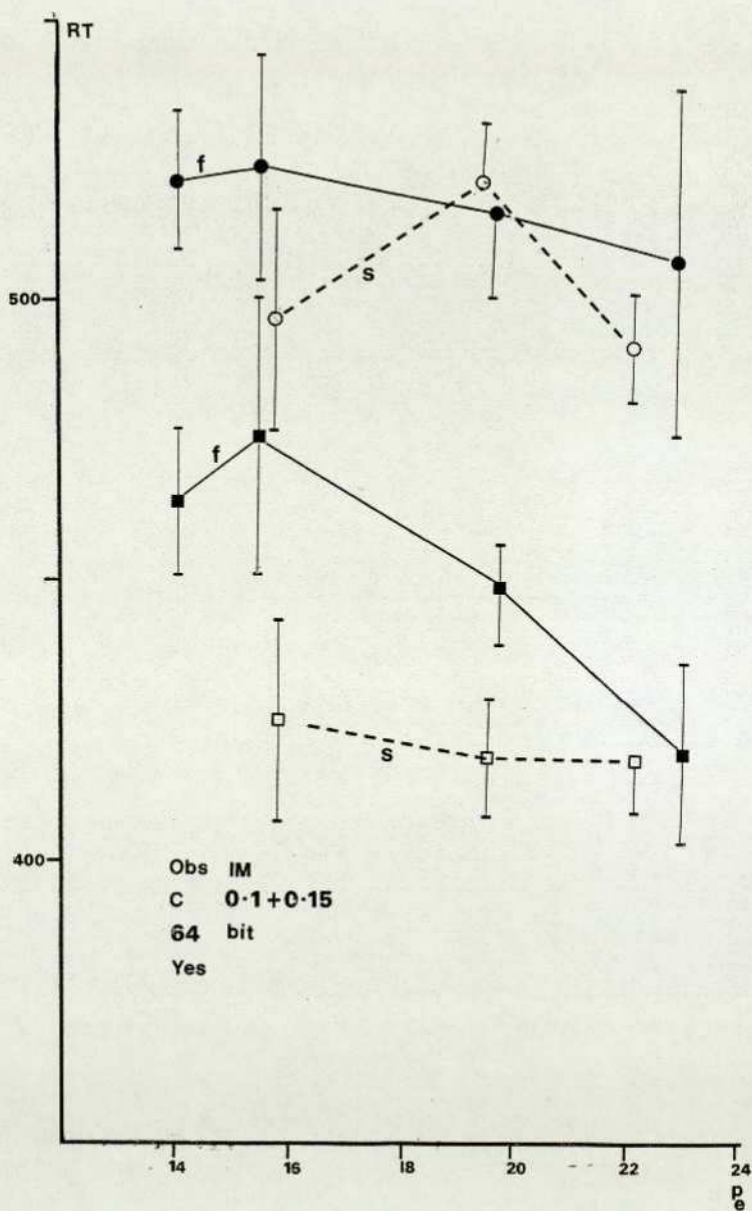


FIGURE 5.22 REACTION TIME AS A FUNCTION
EXCITATION PURITY

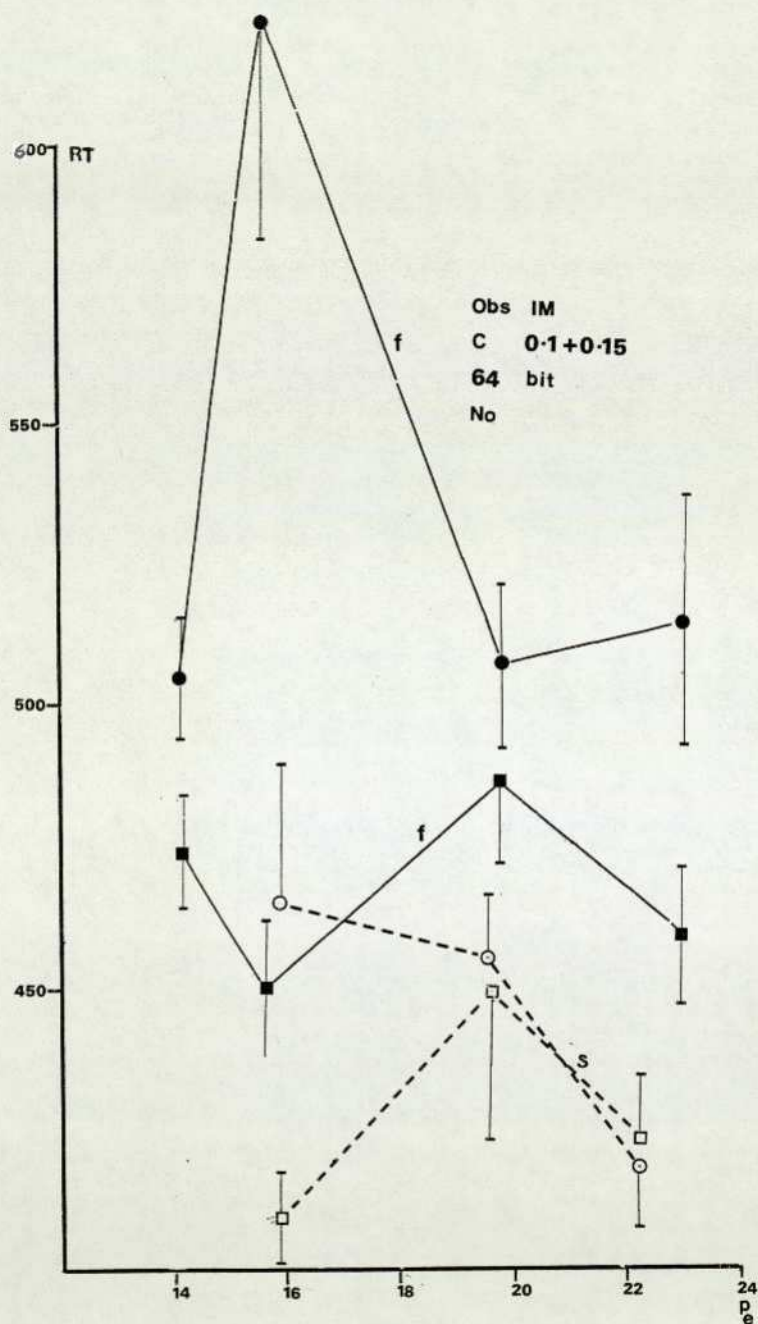


FIGURE 5.23 REACTION TIME AS A FUNCTION
EXCITATION PURITY

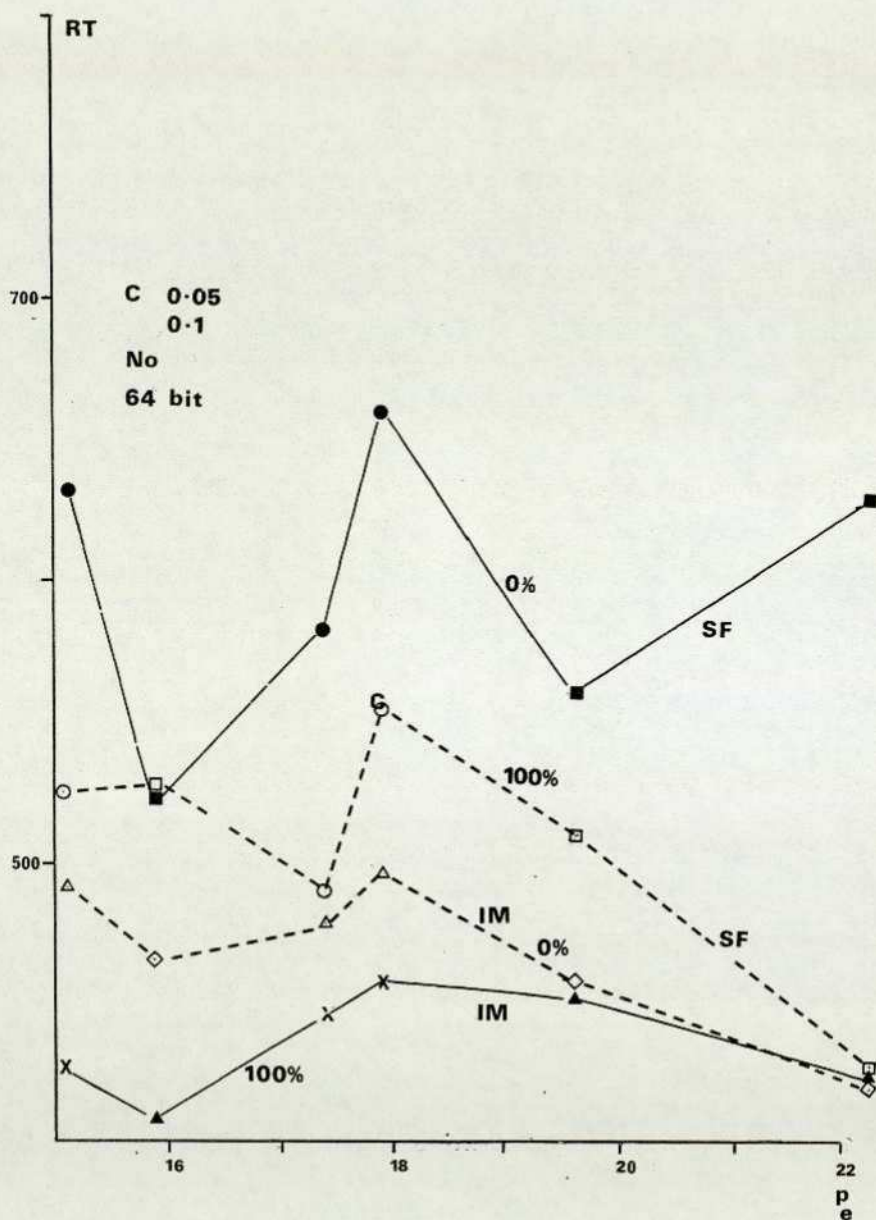


FIGURE 5.24 REACTION TIME AS A FUNCTION
EXCITATION PURITY

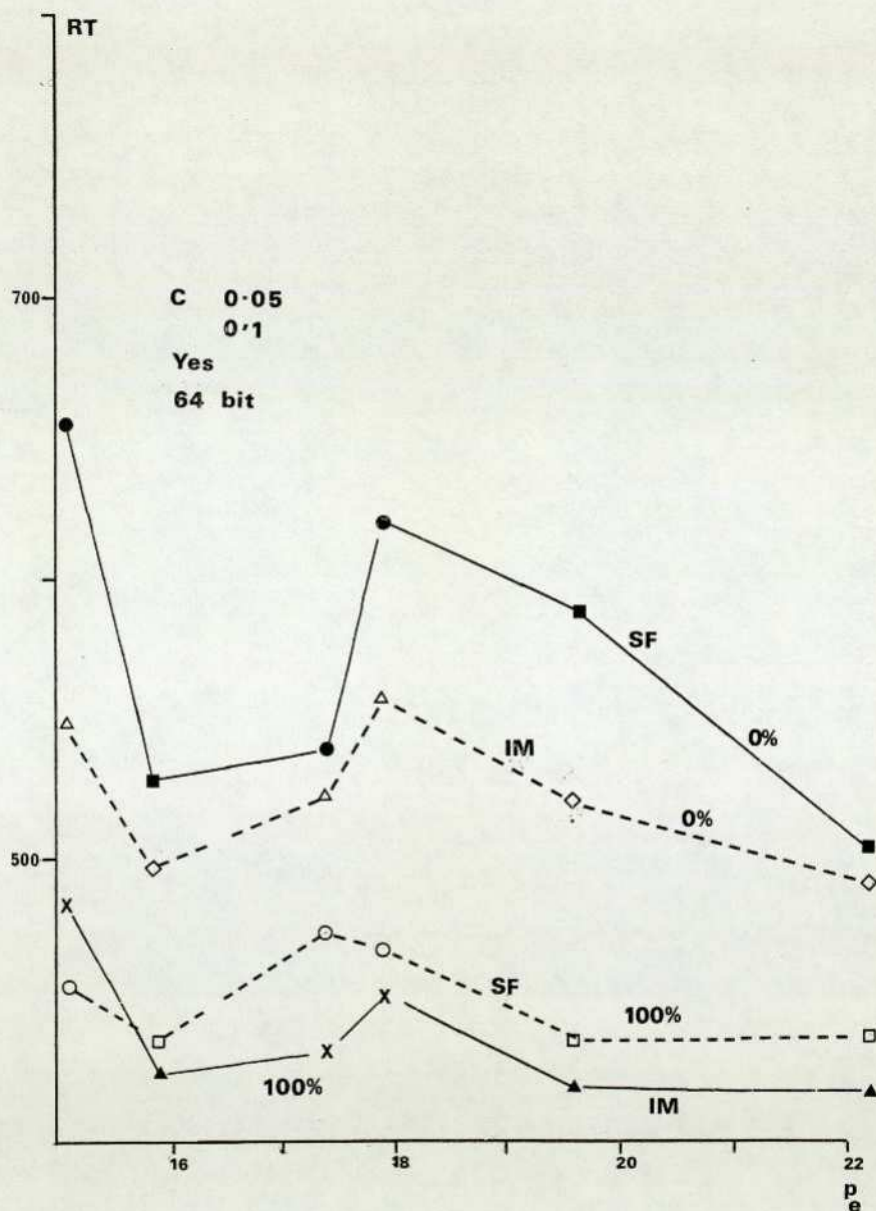


FIGURE 5.25 REACTION TIME AS A FUNCTION
EXCITATION PURITY

for double peaked histograms was found in the present data, therefore it is difficult to conclude that only the transient mechanism was stimulated. This is not surprising however, since the presentation time used was relatively short, and the observer's task different from that required in Harwerth's work. The data do emphasise however, that by choosing stimulus conditions appropriately a more sustained or a more transient response can be obtained. This is in contrast to the electrophysiological evidence of for example Hochstein and Shapley (1976a), who stated that X - and Y - units do not form a continuum but were different cell populations. What is more likely is that both populations can be stimulated under certain circumstances and by changing the conditions the probability of either channel being stimulated is also changed. This results in the apparent continuum of responses. At the single cell level however each responding cell is still either sustained or transient.

Since the clearest separation of sustained and transient responses occurred at the lowest contrast the marked effect of purity, at low contrast is also perhaps not surprising. What is odd is the difference in response to the two temporal conditions employed. The data appear at first sight to be contradictory. However a hidden assumption in the present experiment was that transient and sustained responses could be isolated, as is the case with single cells. This assumption appears to be false, thus the prediction that rise times (transient or achromatic channel only) would produce reaction times independent of purity, and slow rise times (sustained or chromatic channel only) would produce a purity dependent reaction time are also false.

On the other hand the rise in reaction time with increasing purity is consistent with an increasing proportion of sustained cells responding to the stimuli, i.e. if sufficient data were available to plot histograms at each purity level, one would expect the skewness of the distributions to decrease as purity increased.

The data for a fast rise time imply that increasing purity somehow increases the proportion of transient channel responses. This is conceivable if it is recalled that chromatic stimuli can show additivity failure (Guth et al, 1969) as a result of the chromatic channel contribution to the luminance channel (present conditions are unlike those found in flicker photometry experiments which isolate only achromatic mechanisms). If this is the case (and the effect would be most marked near threshold) then increasing target purity is effectively increasing target luminance, i.e. contrast. This would be undetected by a standard photometry method of monitoring the stimuli. One must postulate that the achromatic channel does not feed information to the chromatic channel however. The reduction of reaction time with increasing purity would simply be the more familiar reduction found as contrast increases.

The lack of significant effects at higher contrasts is also consistent with this explanation since the transient, achromatic channel dominates at higher contrast.

The minimum in reaction time displayed in figures 5.24 and 5.25 is a little harder to explain. A possible explanation is that it

represents the result of an antagonism between the two effects discussed above - increasing transient responses due to additivity failures, and increasing sustained responses due to increasing chromatic stimulation. This idea must await more evidence however.

5.8 Conclusions

The experimental data only permit tentative conclusions for the following reasons:-

- (a) The two separate methods used to produce the rise times required prevented a large overlap in data points at low contrast.
- (b) Slow and fast rise times were presented separately. Observer criteria could have been altered by knowledge of which was being used.
- (c) The probability of occurrence of a particular target and purity was only controlled between sessions, and not within sessions, as was the case in chapter four.
- (d) Relatively few points along the purity continuum were tested.

With these factors in mind, the data seem to support the hypothesis that a two channel model of vision as suggested by Ingling and Tsou (1979), for example, is still tenable under conditions requiring recognition rather than detection, and furthermore, that the dominance of one channel over another can be manipulated by

altering the following conditions:-

- (1) Target complexity (assessed by redundancy). Increasing target complexity produces a more sustained (chromatic) response.
- (2) Stimulus temporal properties. Slower onset of a stimulus results in a more sustained response.
- (3) Contrast. Increasing luminance contrast enhances the transient channel.
- (4) Stimulus purity. This may apparently produce two effects. Either a chromatic channel contribution to the luminance channel may result in a higher contrast than that indicated by the CIE relative luminous efficiency function, and hence faster reaction times or enhanced stimulation of the chromatic channel by stimuli of a high purity, under temporal and spatial conditions which promote sustained responses and hence slower reaction times.

CHAPTER SIX

THE INFLUENCE OF PURITY AND DOMINANT WAVELENGTH ON REACTION TIME DURING A RECOGNITION TASK NOT REQUIRING LEARNING

- 6.1 Introduction
- 6.2 Method
- 6.3 Targets
- 6.4 Observers
- 6.5 Procedure
- 6.6 Results
- 6.7 Discussion
- 6.8 Conclusions

THE INFLUENCE OF PURITY AND DOMINANT WAVELENGTH ON
REACTION TIME DURING A RECOGNITION TASK NOT REQUIRING LEARNING

6.1 Introduction

The experiments described in chapters four and five relied on the observers being trained before beginning data collection. The use of a recognition task in which the test target is presented simultaneously with several others from which it must be selected overcomes this problem. This method was used in the present experiment.

The following variables were investigated:-

- (a) Rise time - both slow and fast as in chapter 5
- (b) Redundancy - only one level (100%) was used
- (c) Purity - the effect was assessed in the same way as in chapter 4, by comparing high purity chromatic targets with low purity (achromatic) targets
- (d) Contrast - only one contrast was used throughout.

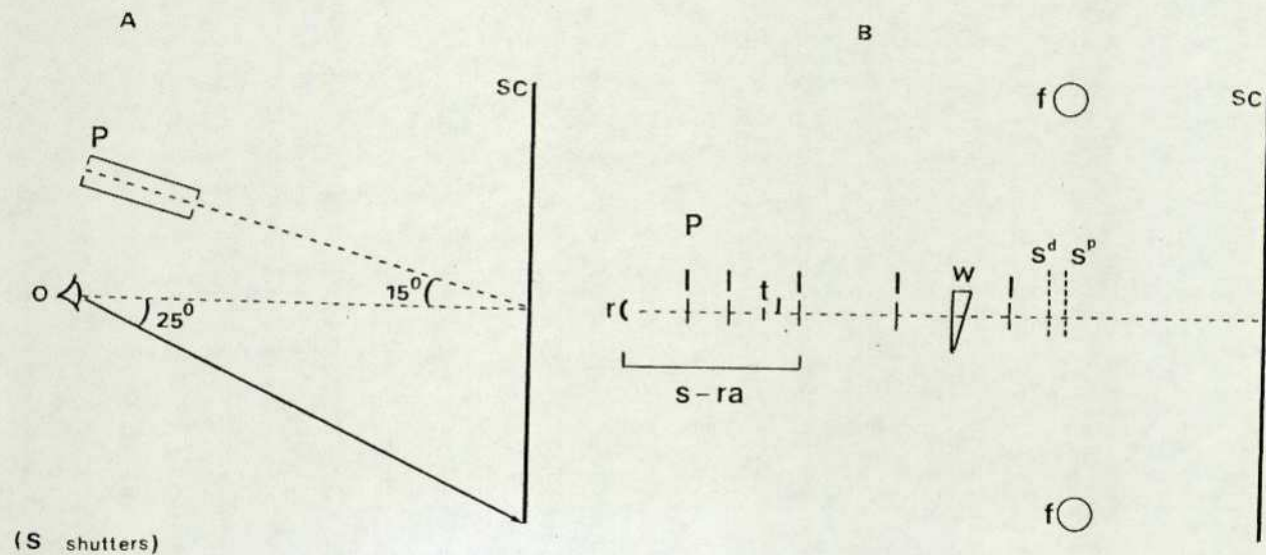


FIGURE 1 Apparatus (a) side view (b) plan

6.2 Method

The apparatus used (figure 6.1) was a modified version of that described in chapter 5. In the present experiment, the filters controlling the colour of the targets were placed in a separate filter holder FH, rather than in the target slide mounts. In addition, to permit a direct comparison of data from slow and fast rise time conditions the two methods of controlling target presentation - rotating sectorised disc SD, and rotating polaroid P, for fast and slow rise times respectively - were both placed in the test beam together. The experimenter was able to select one or the other during an experiment. The shutter not selected was positioned so as to transmit maximum intensity. The result of this arrangement was to remove the small shifts in chromaticity when the Polaroid was inserted into the test beam (chapter 5).

Stimulus onset was detected by a light activated switch which sampled the test beam after the two shutter mechanisms, and this initiated timing. The observer halted the timer by depressing one of the four microswitches. The temporal characteristics of the stimuli are illustrated in figure 6.2.

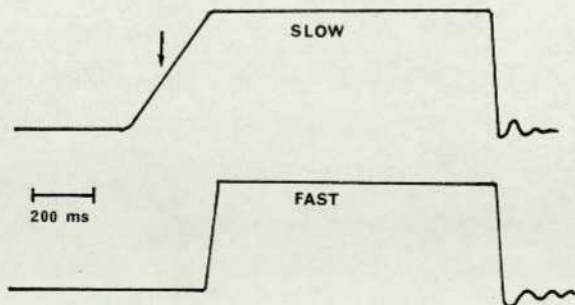


Figure 6.2

The arrow indicates the approximate time of onset of timing. There is obviously some uncertainty as far as the slow rise time condition is concerned, however the threshold of the light activated switch was set initially to begin timing approximately at half peak intensity and this was unchanged during the experiment. The longer presentation time (1,000 ms) allowed for the search involved.

The dimensions and spacing of the targets are illustrated in figure 6.3.

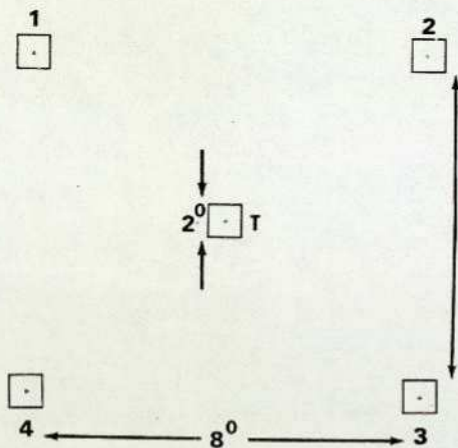


Figure 6.3

The central target (T_1 test target) was the same as one of the four outer targets. The observer's task was to select which of 1, 2, 3 or 4 was the same as the central target. To minimise conflict with the motor response given by the observer, the response keys were arranged in a similar square pattern, thus each key in the square was appropriate to the equivalent pattern in the square.

Target contrast was fixed by a circular neutral density wedge and as before was monitored via a potentiometer. Three filters (Cinemoid) provided high purity targets of red, green and blue hue, while the chromaticity of the test beam was matched to the surround using a mixture of Lee and Cinemoid filters for the fourth, achromatic test condition. Table 6.1 presents the colorimetric data for these filters.

TABLE 6.1 STIMULUS COLORIMETRIC DATA

Filter	x	y	u'	v'	Pe	λ_d	S_{uv}^*
Red	.3515	.3456	.2182	.4827	.16	590	1.95
Green	.3343	.3584	.2016	.4864	.15	570	1.17
Blue	.3190	.3343	.2002	.4721	.14	480	1.82
Neutral	.3364	.3466	.2074	.4809	.12	580	0.13
Surround	.3353	.3471	.2065	.4810	-	-	-

* Computed relative to D_{65}

Contrast was set at 0.04

The neutral targets acted as a reference for the chromatic targets, as in chapter 4.

6.3 Targets

Four Smets patterns were selected from the 64 bit, 100% redundancy set (figure 2.2) and these were used throughout the experiment. The targets were prepared by printed the originals and then rephotographing. For each test pattern at the centre of the display, slides were produced with a matching pattern at each of the four corners i.e. four slides were prepared for each target, giving sixteen slides in all.

6.4 Observers

Four observers took part in the experiment. All were naive as to the aims of the experiment, and had normal colour vision as tested by the Ishihara and Anomaloscope methods. No observer wore an ophthalmic correction normally, and no attempt was made to correct any residual refractive error.

6.5 Procedure

Rise time and hue were randomised by pseudorandom number generator such that each hue was presented with each rise time (8 conditions). For each of these conditions sixteen target slides were also randomised (i.e. a different slide sequence was used for each condition). Once a particular rise time and hue had been selected each of the sixteen slides was presented to the observer. The only uncertainty therefore, as far as the observer was concerned was which of the four patterns matched the test pattern in the

centre of display. An observer began with a number of practice sessions (usually five) to familiarise him with the task required. These were performed under the same conditions as the experiment. Observers then proceeded through each of the eight conditions in random order. Each of the sixteen test slides was presented before a new condition was selected. Both before the practice sessions and after any breaks in the sessions, observers adapted to the surround field for three minutes before beginning observations. Presentation of a target was signalled to the observer by an LED mounted in the background screen. This was switched on for one second, before target onset.

The particular hue, rise time and target slide combination to be presented was provided by computer on a terminal, to the experimenter. This was also used by the experimenter to enter reaction time and response to the computer after each target presentation. At the end of a sequence of sixteen slides, the data was divided into correct and incorrect responses (correct responses to each target were stored in the computer) and then mean, standard deviation etc. values for the correct response reaction times computed.

6.6 Results

The results of the practice sessions for the four observers are illustrated in figure 6.4, which shows mean reaction time versus session. Vertical lines represent $\pm$ one standard error of the mean. (The dashed line joining sessions two and four for observer G.Q. indicates that no data is available for session three).

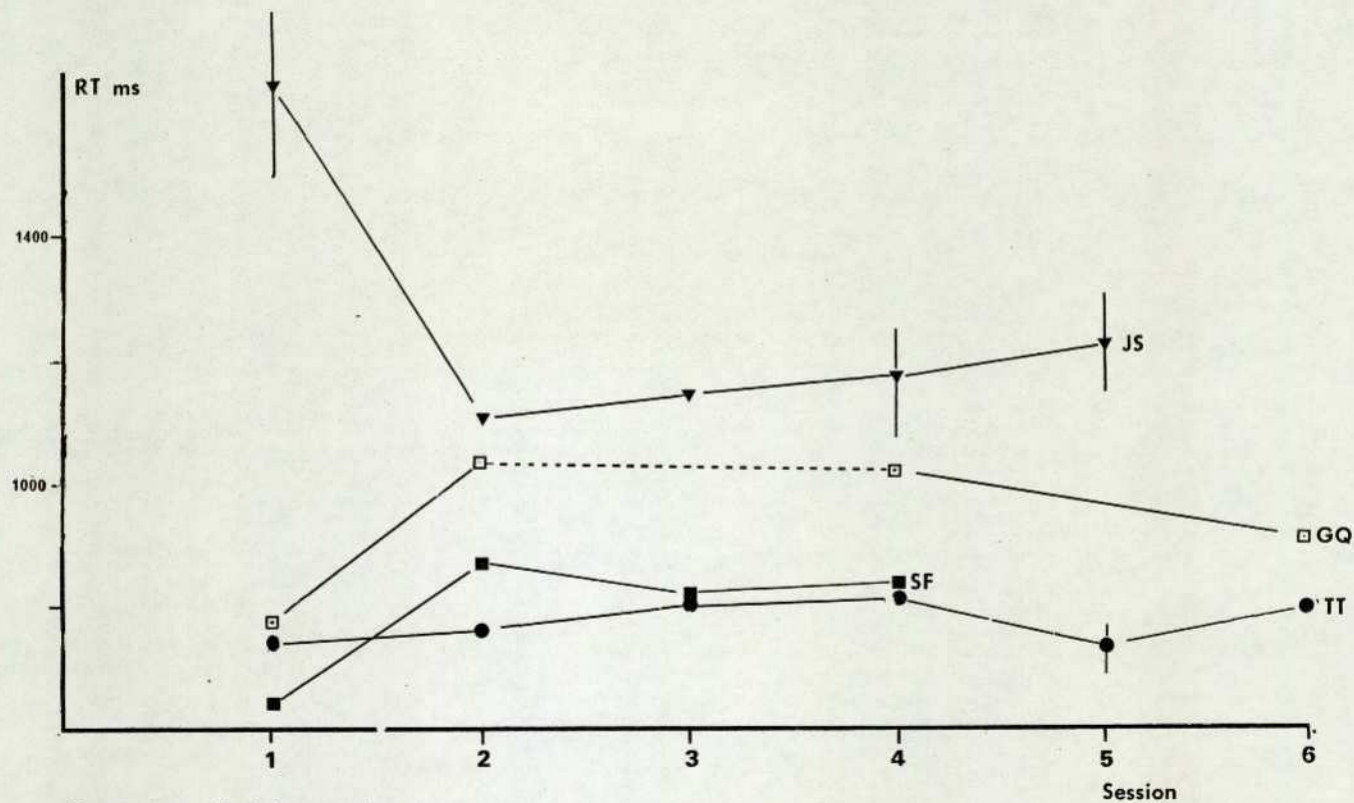


Figure 6-4 Training session data

Although there are wide differences in absolute terms between observers, by session five apart from observer S.F. the curves are relatively flat, suggesting that observers were familiar with the task by this point.

The data are plotted as a function of excitation purity in figures 6.5 to 6.10. Open symbols indicate a slow rise time and closed symbols a fast rise time. No consistent relationship emerges from the results, although there are some data points which deviate significantly from the average e.g. observer J.S. A more rigorous test of the effect of purity was performed by applying a t-test to the difference in reaction time to chromatic and achromatic targets. No significant difference was obtained for any of the hues, with either slow or fast rise times

when mean data from all observers was tested. This was the case also when individual data were t -tested. General trends are apparent however when reaction times to red green and blue targets are ranked. The slowest reaction times occurred with green targets irrespective of whether a fast or slow presentation method was used. In the fast rise time condition very little difference exists between reaction times to red and to blue targets, but in the slow rise time condition responses to red targets are consistently slower than to blue targets. Thus the data may be summarised as follows:-

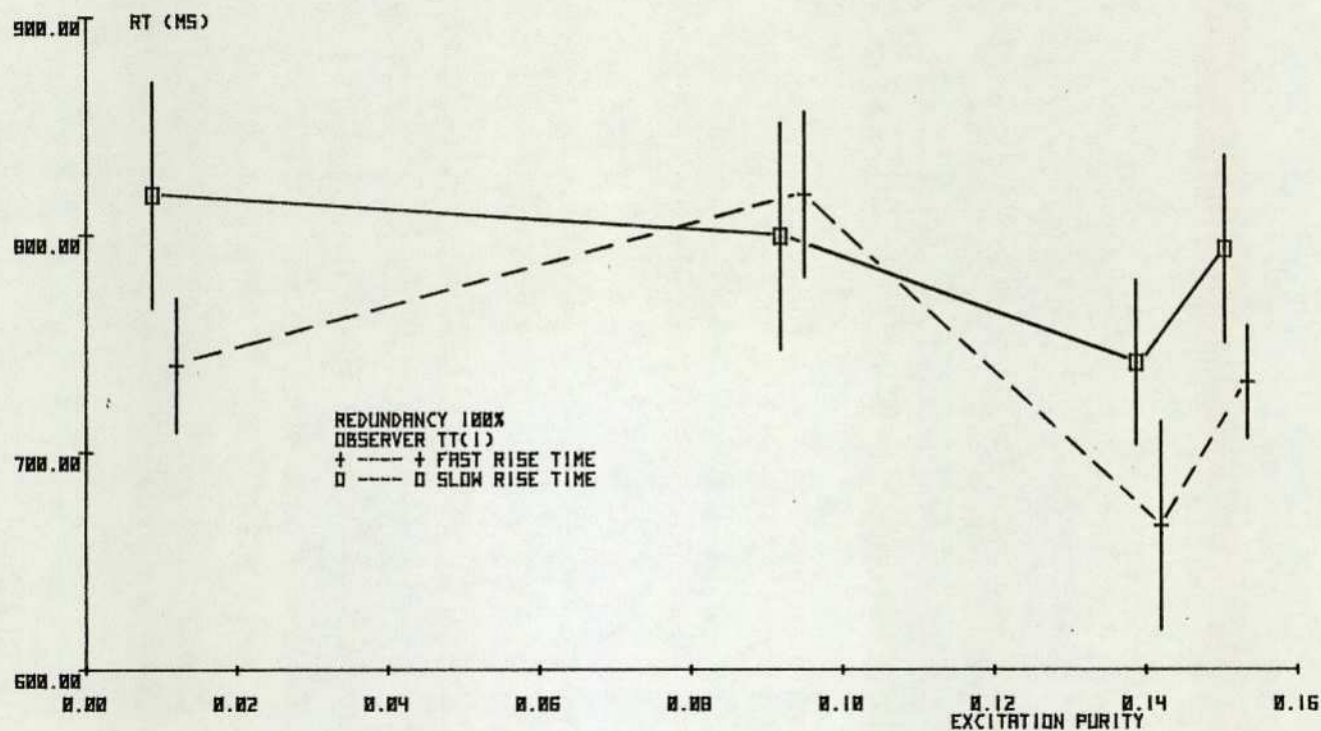


FIGURE 6-5 REACTION TIME AS A FUNCTION OF EXCITATION PURITY

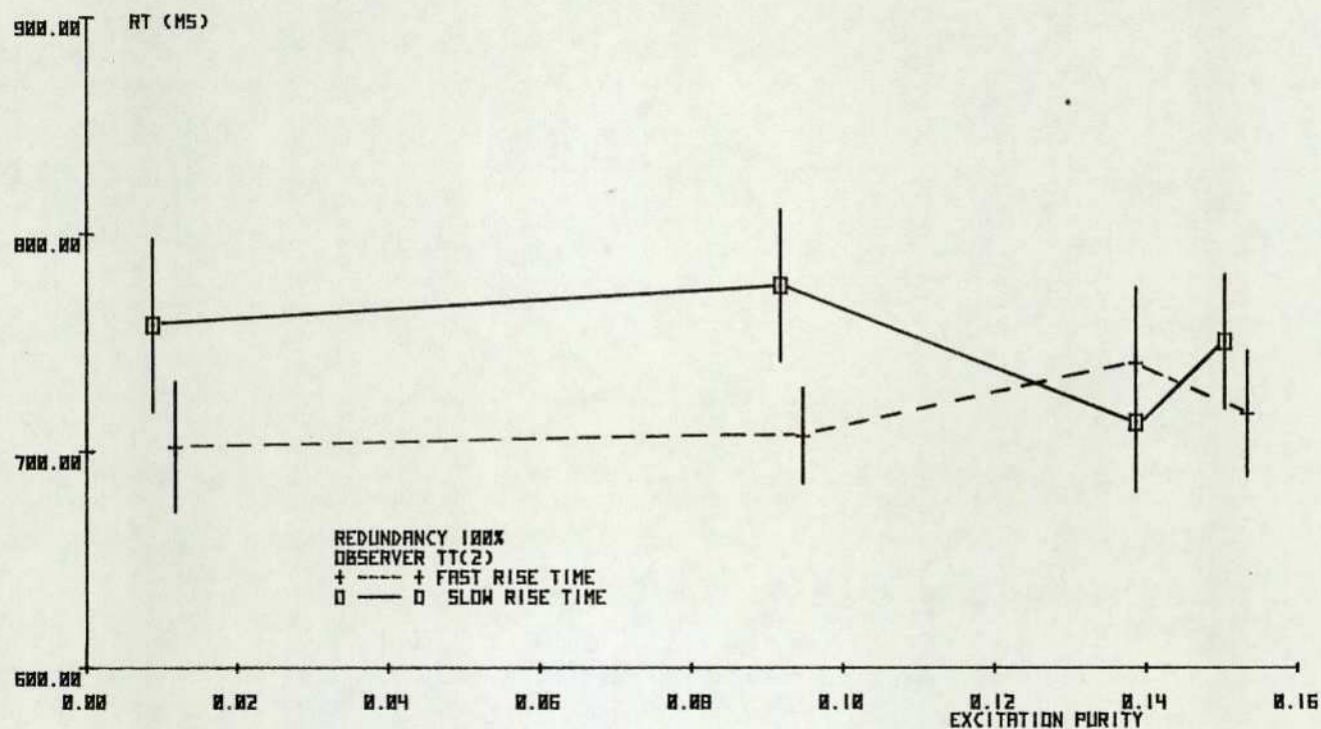


FIGURE 6-6 REACTION TIME AS A FUNCTION OF EXCITATION PURITY

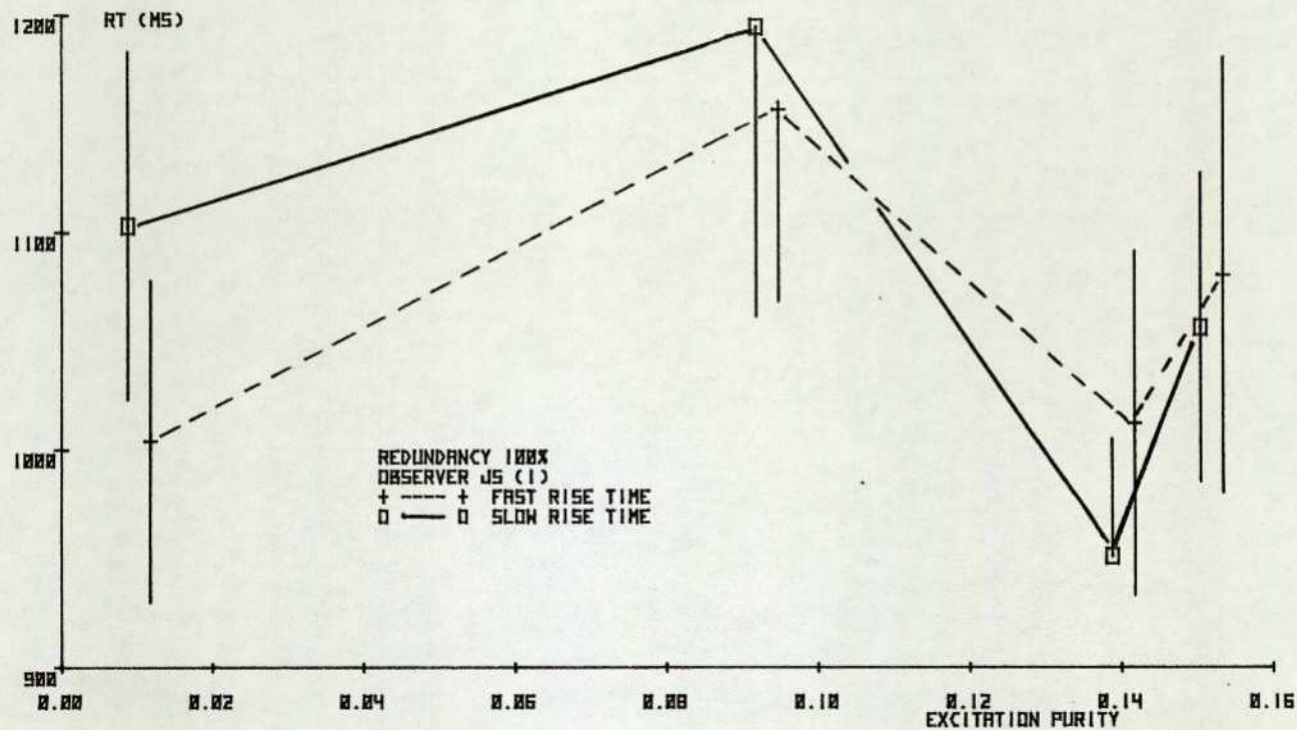


FIGURE 6-7 REACTION TIME AS A FUNCTION OF EXCITATION PURITY

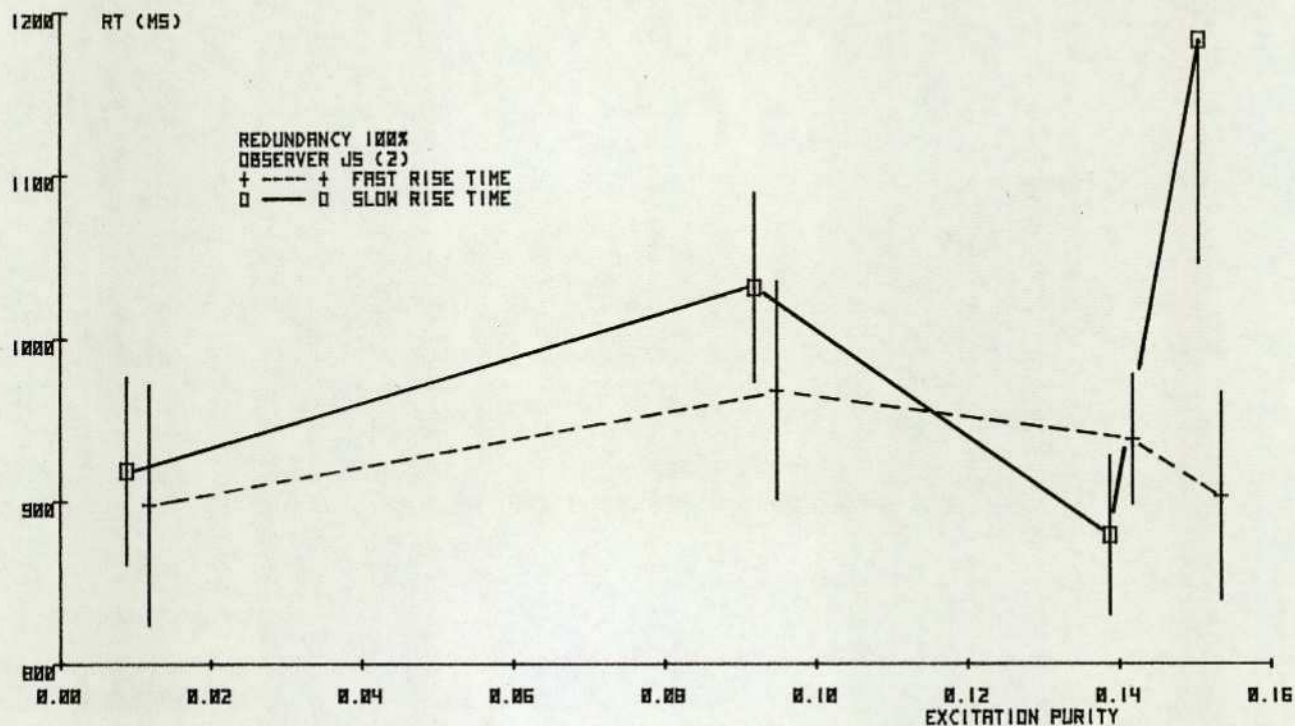


FIGURE 6-8 REACTION TIME AS A FUNCTION OF EXCITATION PURITY

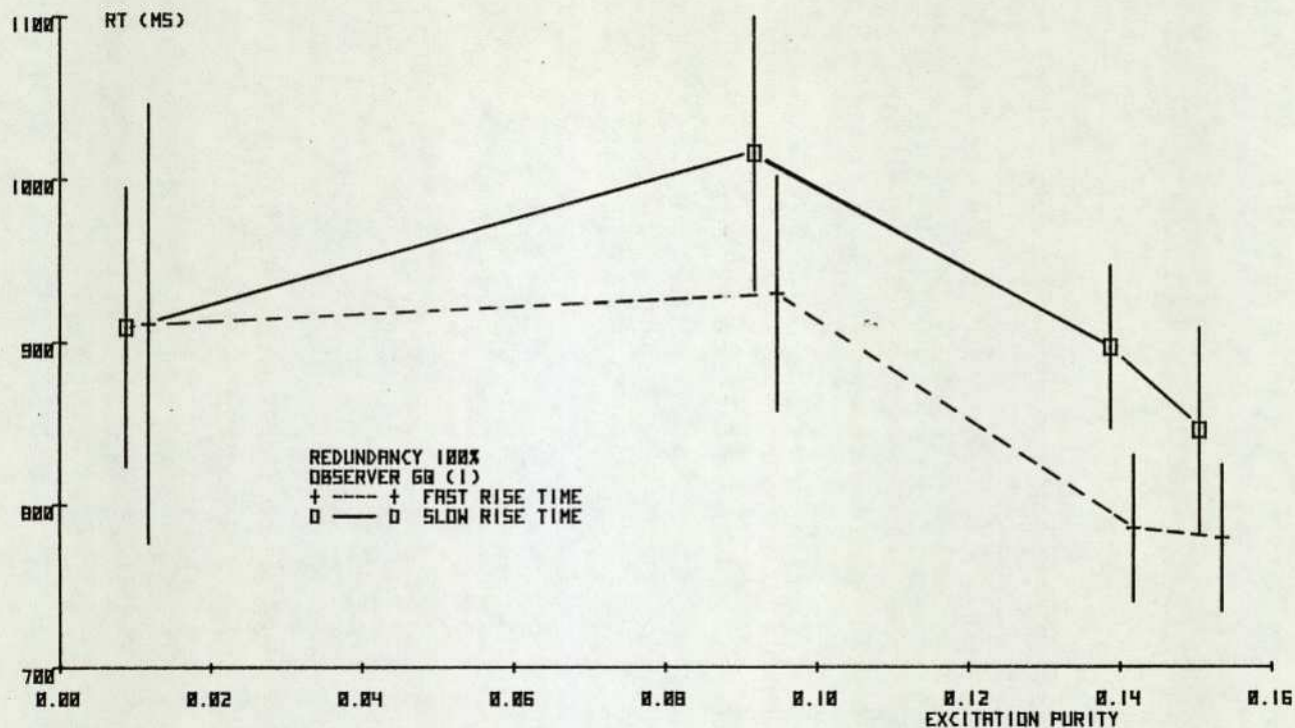


FIGURE 6-9 REACTION TIME AS A FUNCTION OF EXCITATION PURITY

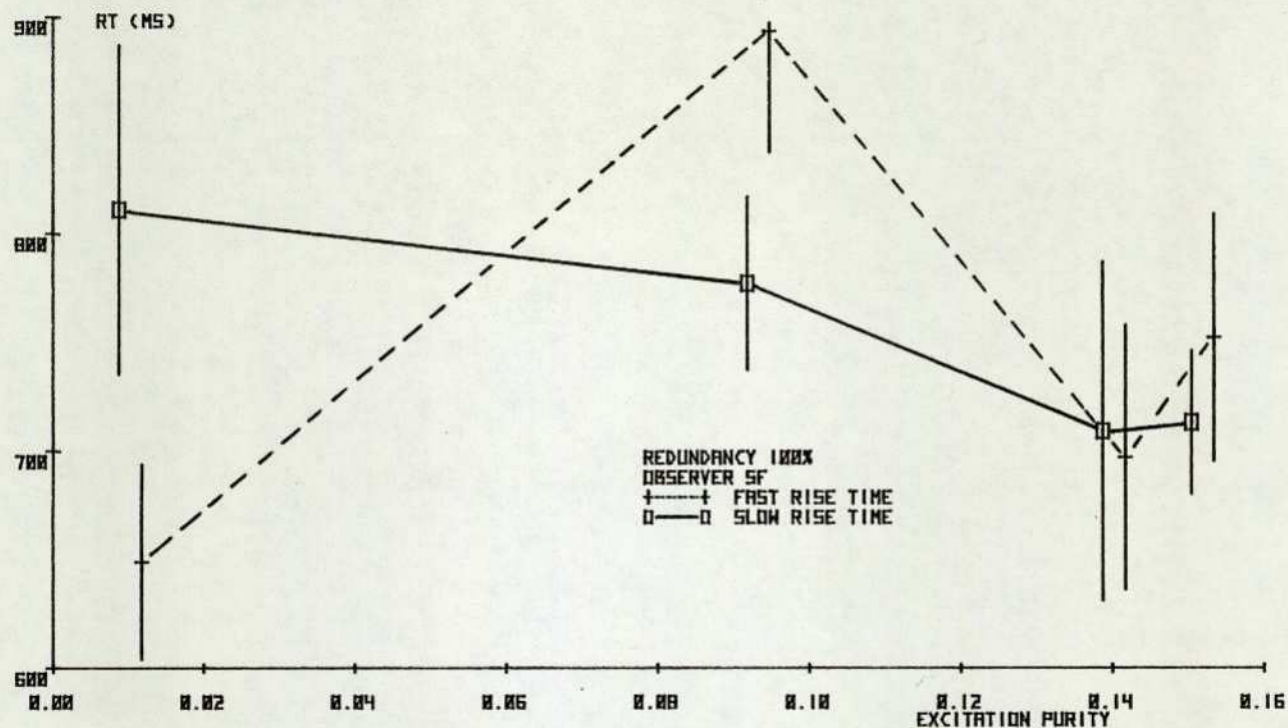


FIGURE 6.10 REACTION TIME AS A FUNCTION OF EXCITATION PURITY

fast rise time - reaction time increases in the
sequence red/blue, green

slow rise time - reaction time increases in the
sequence red, blue, green

6.7 Discussion

The data clearly indicate that adding chromatic information to test targets neither increases nor decreases reaction time in a significant manner. This implies that at the contrast used (0.04) sufficient information is provided by the achromatic contrast for the observer to perform this modified recognition task.

The fact that the task is significantly different from that employed in chapters four and five precludes a direct comparison of the data, however the present data suggest that the trends evident at contrasts of 0.05 and 0.1 found in chapter five may have been insignificant in statistical terms, since no effect (i.e. a minimum reaction time) was found using a similar contrast. Alternatively the trend evident in chapter five may have resulted from the use of a memory task, or the variable probability of occurrence of the test targets. The probability of occurrence in the present experiment was fixed and equal for all targets.

6.8 Conclusions

The purity of a test target presented at a contrast of 0.04 in a search task has a statistically insignificant ($p=0.05$) effect on reaction time. Furthermore this is the case if the temporal onset gradient of the test target is steep or shallow - conditions which have been shown (Breitmeyer and Ganz, 1977) to enhance transient and sustained mechanisms respectively, in detection tasks.

CHAPTER SEVEN

DO SUSTAINED AND TRANSIENT MECHANISMS RESPOND DIFFERENTIALLY TO PURITY LEVEL DURING A RECOGNITION TASK?

- 7.1 Introduction
- 7.2 Method and programming
- 7.3 Observers
- 7.4 Procedure
- 7.5 Results
 - (a) Training sessions
 - (b) Experimental data
- 7.6 Discussion
- 7.7 Conclusions

DO SUSTAINED AND TRANSIENT MECHANISMS RESPOND
DIFFERENTIALLY TO PURITY LEVEL DURING A RECOGNITION TASK?

7.1 Introduction

The results presented in chapter five suggested that under conditions of low contrast, target purity may influence the time taken to recognise objects. As pointed out however any conclusions drawn from so few points must only be tentative.

The principal aim of the experiments reported in this chapter was to extend the data of chapter five to test in a more rigorous manner the conclusions reached. To further this aim the experiments were designed to be performed under the control of a laboratory computer. In addition the variables used were re-assessed in the light of the results already obtained.

One important parameter of the target not considered so far is its size. The potential importance of this variable is apparent when it is recalled that in addition to the familiar retinal cone receptor density inhomogeneity (e.g. Graham 1966) a functional inhomogeneity, resulting from a change in the relative proportion of X- and Y-cells on moving peripherally exists (Shapley 1977). Thus the increase in the relative proportion of Y- to X-cells on moving towards the peripheral retina suggests that the optimum stimulus characteristics may change as target size increases. Wilson (1978) for example has found evidence for changes in the size tuning (or LSF) of the retina on moving peripherally and that in addition the LSF's can be modelled as either "sustained"

or "transient". It was felt therefore that two levels of target size should be included in the experimental design, to test for any effect of this functional inhomogeneity.

An additional factor not considered in the experiments described in chapter five is dominant wavelength. If purity does prove to be significant in low contrast recognition tasks it is important to discover if any wavelength dependency exists.

The introduction of target size and dominant wavelength as experimental variables necessitated a reduction in the number of levels of another variable*. Since the previous results had pointed to significant effects only at low contrasts a single low value close to threshold was selected. The following factors therefore were incorporated in the experimental paradigm:-

- (a) purity
- (b) dominant wavelength
- (c) target size
- (d) stimulus rise time
- (e) redundancy

The latter was retained to provide a continuity with the work already carried out, while the two rise times were used to isolate transient and sustained responses.

*in order to contain the experiment to a reasonable size.

7.2 Method and Programming

A schematic plan of the projection system used is shown in figure 7.1, while figure 7.2 provides a profile view to illustrate the relative positions of observer, projector and surround illuminants. All equipment used a stabilised voltage supply ($240 \pm .5V$). An image of target slide T was projected onto the background screen S by the random access carousel R and supplementary lenses L. The intensity of the beam was regulated by neutral density wedge W (OEC circular two log unit vacuum coated). The hue of each target was determined by filter wheel F. The filters used were broadband Cinemoid and Lee. In addition certain filters had gelatine neutral density filters mounted with them in the wheel. Both the wedge and filter wheel were driven by stepper motors.

Two shutter mechanisms provided the different rise times required. One (S_1) consisted of a 12V relay adapted to form a flag shutter and was positioned at a focal plane. This gave a stimulus rise time of 10 ms, and a duration determined by the computer. Relay bounce accentuated by the flag was reduced by stops. Although effective at the onset, a large amount of damped oscillation lasting between 50 and 100 ms was present at the offset. It was felt however that this would not significantly influence the results.

The second shutter (S_2) consisted of a fixed polariser P_1 and a moveable polariser P_2 mounted on a rotatory solenoid with a rotation angle of 90° . The time from zero to maximum target luminance was 250 ms and the increase occurred in an approximately

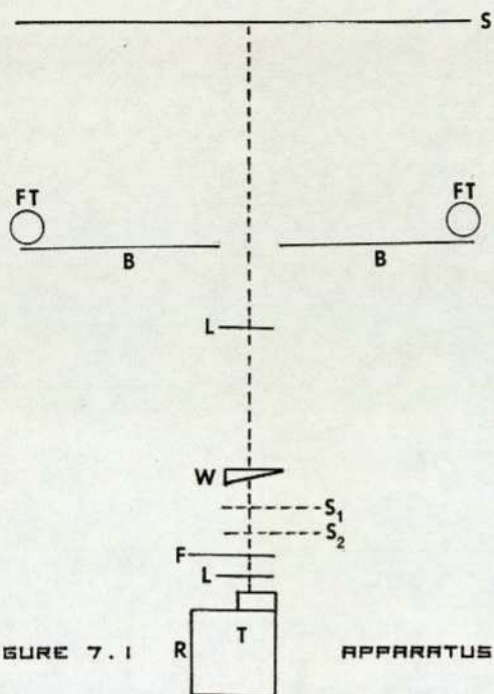


FIGURE 7.1

APPARATUS - SCHEMATIC

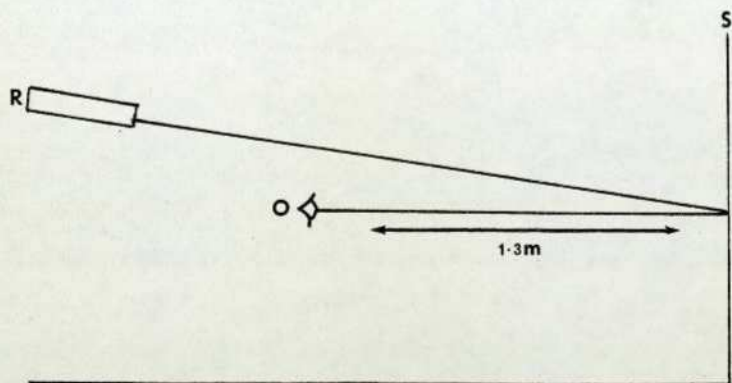


FIGURE 7.2 APPARATUS - SIDE VIEW

linear fashion (this was the result of the non-linear rotation of the solenoid and the approximately cosine squared relationship for rotating polarisers).

Only onset of the target presentation was controlled by both shutters. At off-set the fast flag shutter dominated, providing a rapid reduction of target luminance.

The presentation time used throughout was 400 ms excluding rise time. The temporal characteristics of the stimuli are illustrated in figure 7.3

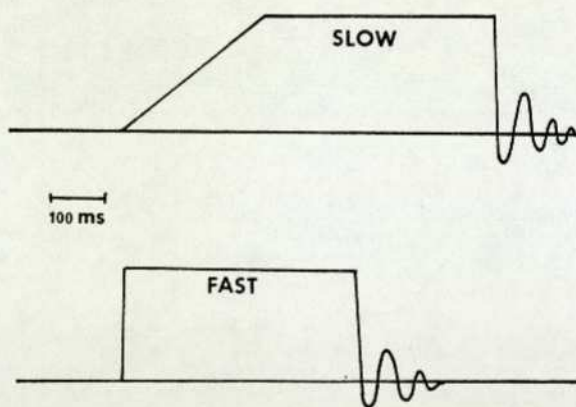


Figure 7.3

The observer was positioned 1.3m from the background screen and shielded from the illuminants FT by baffles B. An ophthalmic headrest prevented excessive head movements during observing sessions. Viewing was binocular. The background screen subtended 50 degrees at the observer and, as before consisted of a matt white

circular field 125 cm in diameter. In addition a central region 17 by 17 degrees square was slightly raised above the rest of the field and provided a smoother more uniform surface. This also helped the observer maintain a steadier fixation since the target was presented at the centre of this square area. Immediately above the central square region was positioned a red light emitting diode which was used to provide cues to the observer.

A block diagram of the main components under computer control is shown in figure 7.4. Apart from the teletype which used a standard RS232 serial interface the components of the apparatus were linked to the HP9825A computer via a bidirectional sixteen bit parallel input/output interface.

Programming and peripheral control used the computer specific HPL language. This was found to be sufficiently fast for the operations carried out during an experimental session. A single instruction required approximately 1 ms for execution, allowing a reaction time resolution of 4 ms. The observer interacted with the control programme via three microswitches positioned conveniently on a table in front of the viewing position. Two were used to indicate either a positive or negative response to targets, while the third enabled the observer to start or pause the experiment. A facility existed whereby the experimenter could interact with the computer in a way which allowed experimental sessions to be run in two separate ways:-

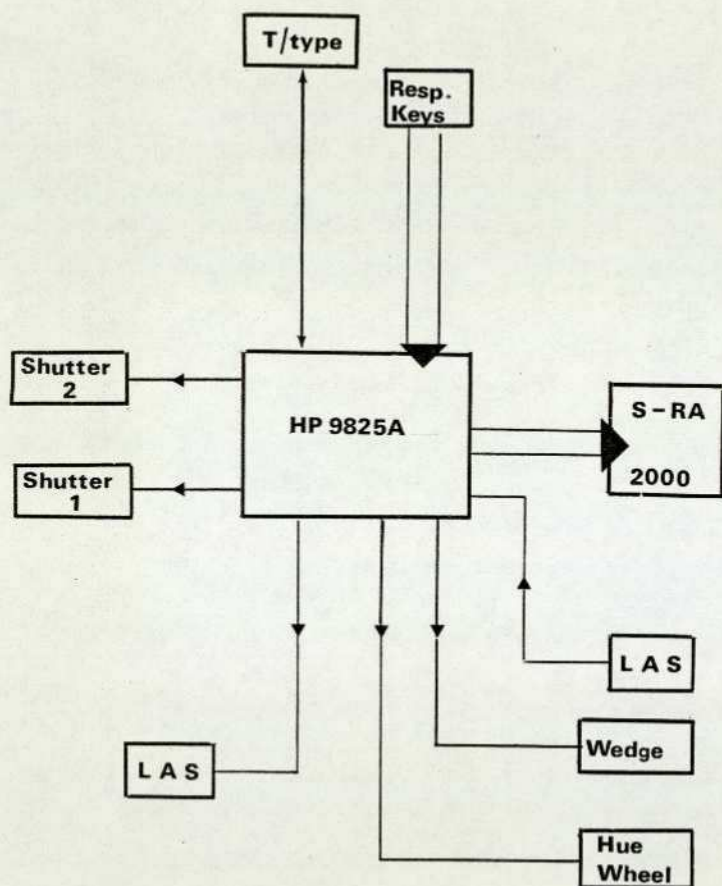


Figure 7.4 Block diagram of apparatus

- (1) Presentation rate controlled by the experimenter
- (2) Presentation rate controlled by the observer

Stepper motor position was checked automatically with the aid of light activated switches and LED's positioned to detect a start position for the wedge and the filter wheel. Wedge position was checked before each presentation and filter wheel position every 15 presentations.

Table 7.1 lists the variables investigated.

TABLE 7.1 FACTORS AND NUMBER OF LEVELS ASSESSED

Factor	No. of levels	Values
Target size	2	1°/2° square
Redundancy	2	0 /100%
Rise time	2	fast/slow
Hue (dom. wavelength)	3	15 combinations
Purity	5	
Response	2	yes/no

Difference between the chromaticity coordinates for the different filters were extremely small therefore an estimate was obtained of the luminance stability of the surround illuminants. Figure 7.5 shows the change in background luminance with time (switch on at zero time), and figure 7.6 shows the background chromaticity at similar times. A reasonable stability is achieved after 20 minutes as far as luminance is concerned. The chromaticity differences are similar to typical discrimination ellipses for this region (v' 0.002, u' 0.001) and are undetectable therefore. Target chromaticities (with no background) are illustrated in figures 7.7 (1°) and 7.8 (2°). Contrast was set at 0.014 for 2° targets and 0.035 for 1° targets.

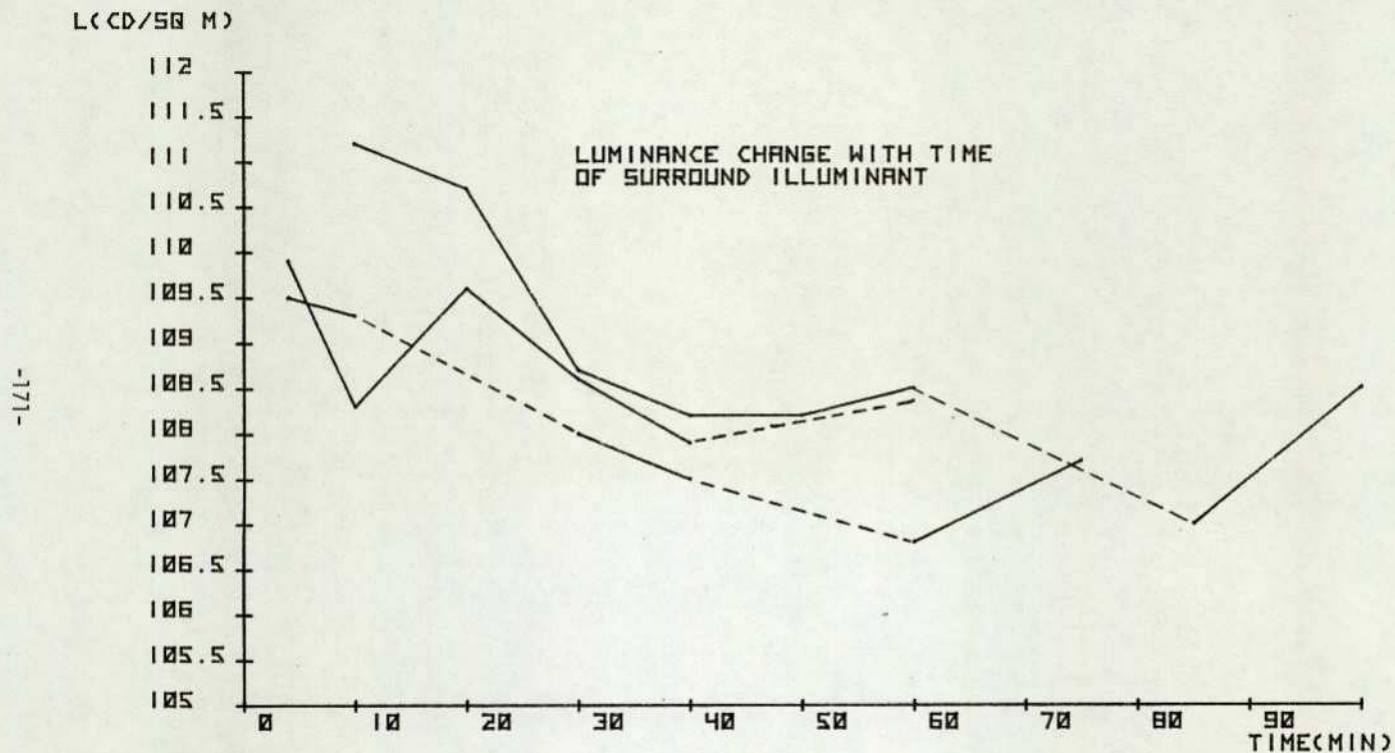


Figure 7-5

CIE UNIFORM CHROMATICITY DIAGRAM

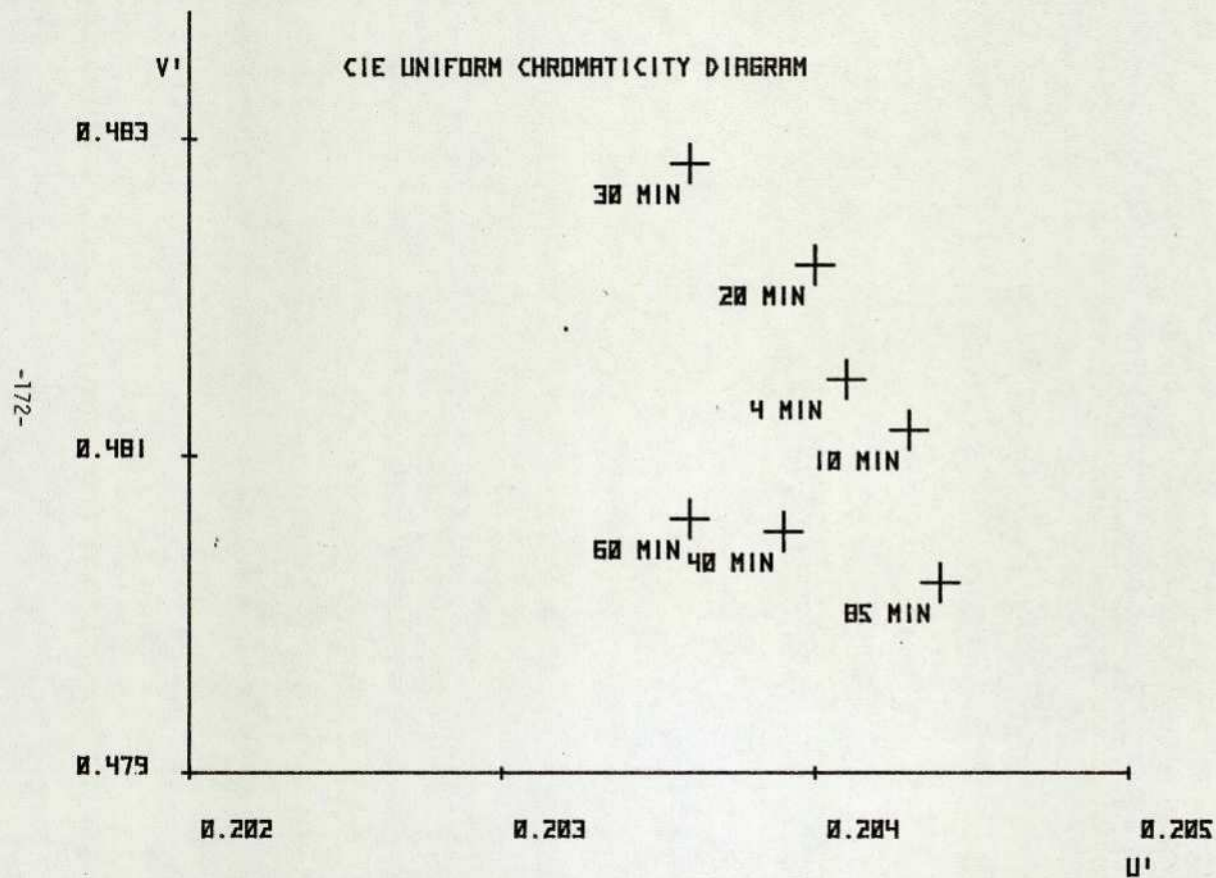


Figure 7-6

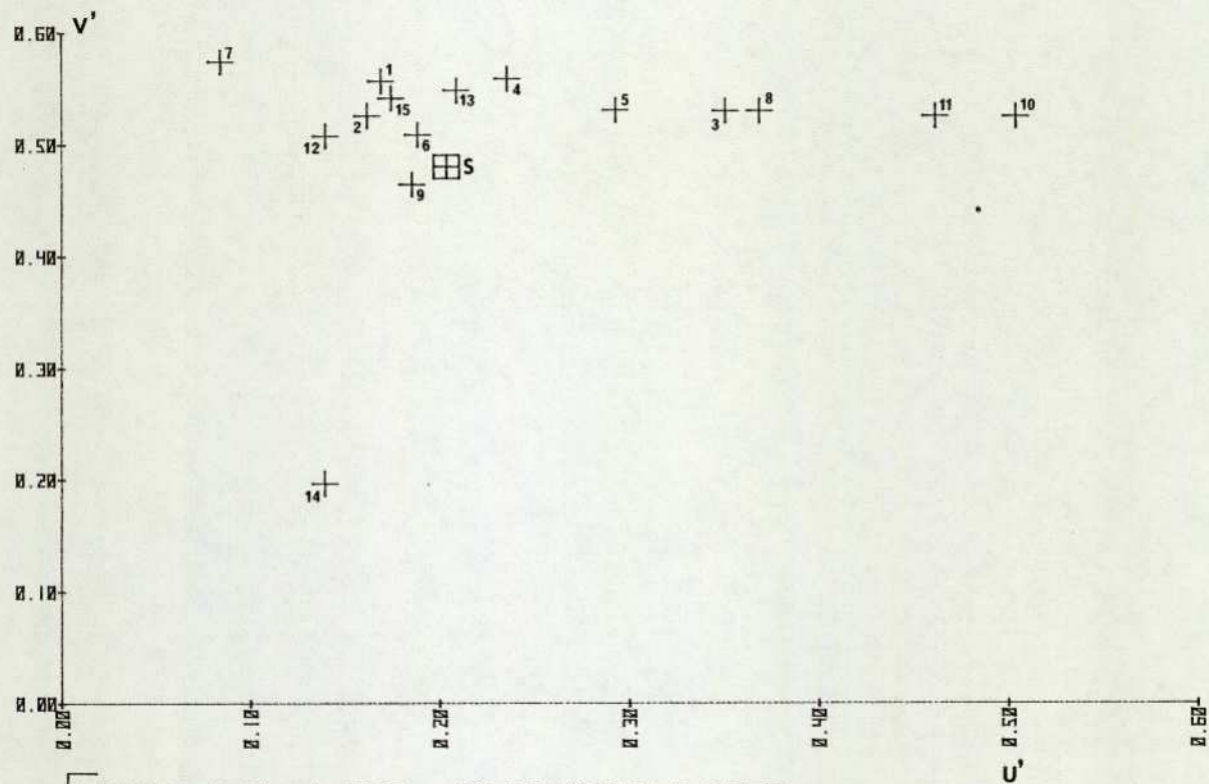


FIGURE 7.7 1 DEG. COLORIMETRIC DATA

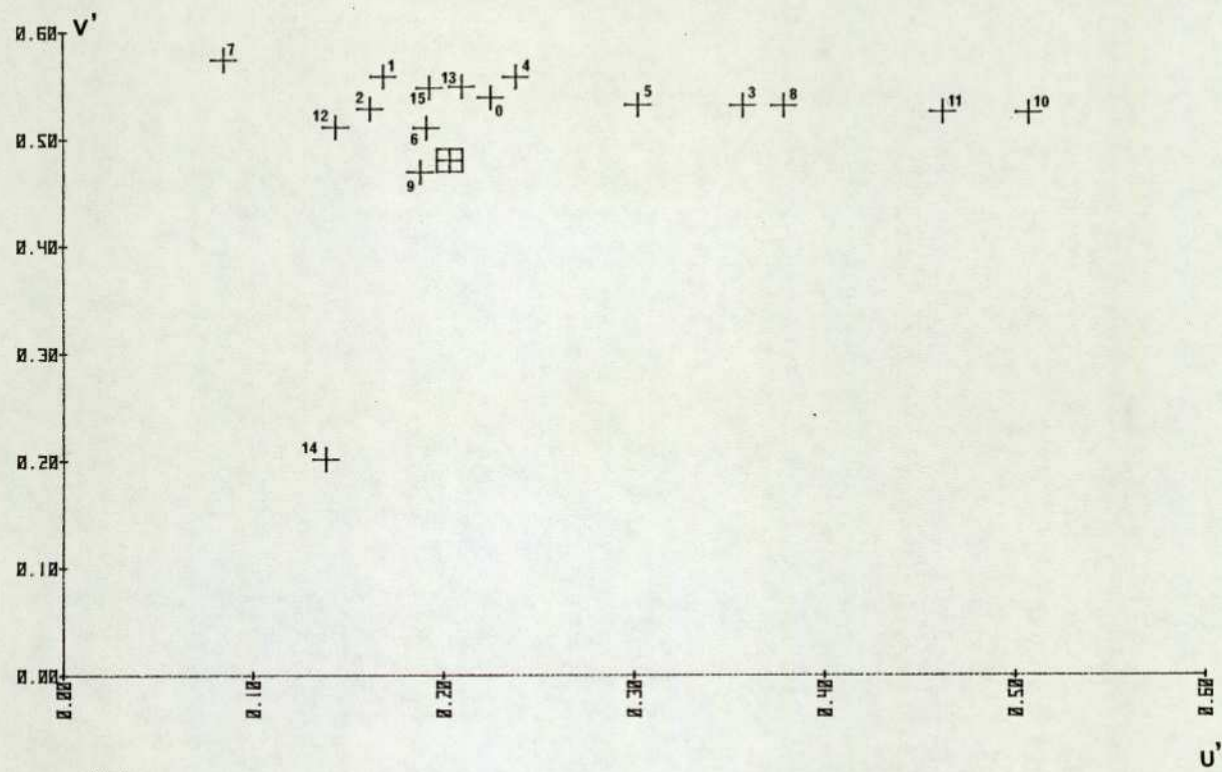


FIGURE 7.8 2 DEG. COLORIMETRIC DATA

Mean surround chromaticity coordinates were $u' = 0.2039$ and $v' = 0.4804$. Dominant wavelengths were computed using D_{65} as reference. Surround luminance was taken as 110 Cd m^{-2} . The low luminance value for filter 14 of the one degree targets was due to the density of the filter used. Insufficient light was available to achieve the required contrast.

7.3 Observers

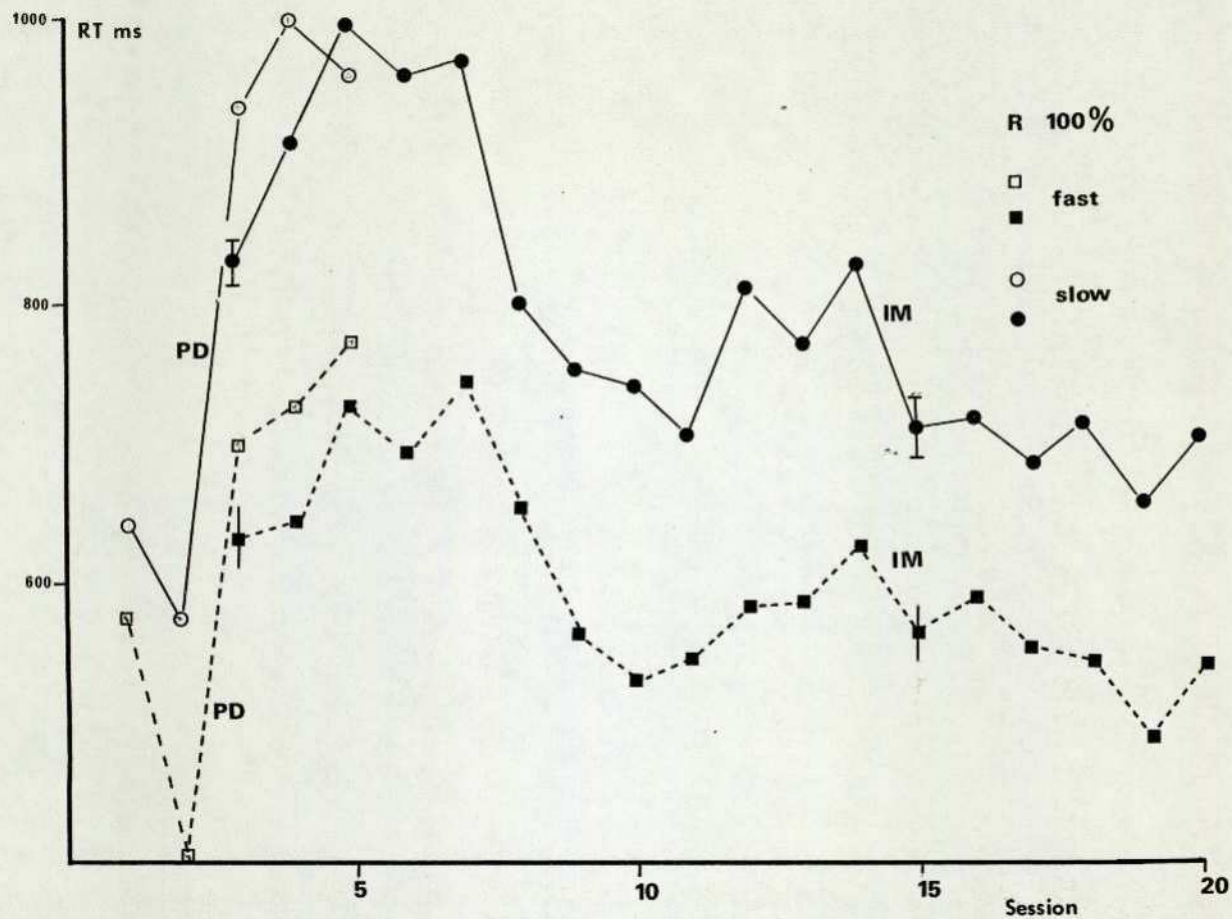
Only one observer took part in the experiments using two degree targets. This was the author. Two observers were used in the experiments with one degree targets. (The author and P.D.). The latter was not familiar with the aims of the experiment and had not taken part in psychophysical experiments before.

7.4 Procedure

The observers were provided with a series of training sessions to familiarise them with the task and the targets. Four targets at each redundancy were used. These were divided arbitrarily into two groups before the experiment was begun. To four of the targets the observer responded "yes" (right hand response key) and to the remaining four he responded "no" (left hand key). The observer was shown one group (the "yes" group) before the start of each training session. The first two sessions used only high contrast stimuli (filter 0). Thereafter conditions were as in the experiment.

After an adaptation period lasting eight minutes (during which the stimulus sequence was randomised) the observer was informed that the session could start by the LED mounted in the surround. The

Figure 7.9 Training session data



session commenced when he depressed the "ready" key. The observer was given a one second warning, two seconds before presentation that a target was to be presented, by the same LED. The observer responded by depressing one of the two keys. The time and response was recorded and then the next stimulus prepared. Failure to respond within three seconds of the end of the presentation was also noted and the next stimulus prepared. Rise time after being initially randomised, was alternated between slow and fast, thus midway through the session each pattern and filter had been presented with at least one of the rise times. At this point the observer could either interrupt the session for a short period or continue. (If the former an additional adaptation period was added). At the same time the rise time sequence was reversed. At the end of each session the data - response time and response - were checked automatically then printed and stored on magnetic tape.

7.5 Results

(a) Training data.

Both observers took part in five training sessions. Mean reaction time was computed for each session and for each redundancy. Data for a redundancy of 100% are plotted in figure 7.9 for both observers. In addition for observer I.M. the mean reaction time for a series of experimental sessions are also included. The rise in the mean after the second session reflects the change to experimental session presentation methods. Observer I.M.'s data tend to decline gradually over a large number of sessions suggesting that learning is still taking place a long time after training has ended. Very little could be done about this however without having an inordinately long experiment. (The difference in the mean over 15 sessions amounts

to 100ms).

(b) Histogram plots.

Figures 7.10 and 7.11 illustrate histograms computed from all data at a particular redundancy and rise time (correct responses only). Data from both responses and all filters were combined. Each histogram also shows the best fitting normal distribution. A good fit is achieved when the targets were of low redundancy. High redundancy targets, and particularly when presented with a fast onset produced a particularly skew distribution.

(c) Experimental data.

The reaction times obtained may be dependent upon two properties of the stimulus assuming that contrasts are sufficiently similar for each filter - dominant wavelength and excitation purity. Figures 7.12 to 7.14 illustrate examples of reaction time dependence upon the former, while figures 7.15 to 7.17 illustrate examples of reaction time dependence upon the latter.

As well as data points and examples of the size of standard errors obtained each figure shows the best fitting polynomial. (This has no theoretical validity but is determined upon purely statistical grounds. Data for observer P.D. were shifted to the left by a small amount for clarity.

The data when considered overall do not demonstrate any dependence upon either of the two variables, although in one case (figure 7.13) reaction time seems to be a function of dominant wavelength. There is a suggestion that reaction time is faster at higher purities and longer

Figure 7.10

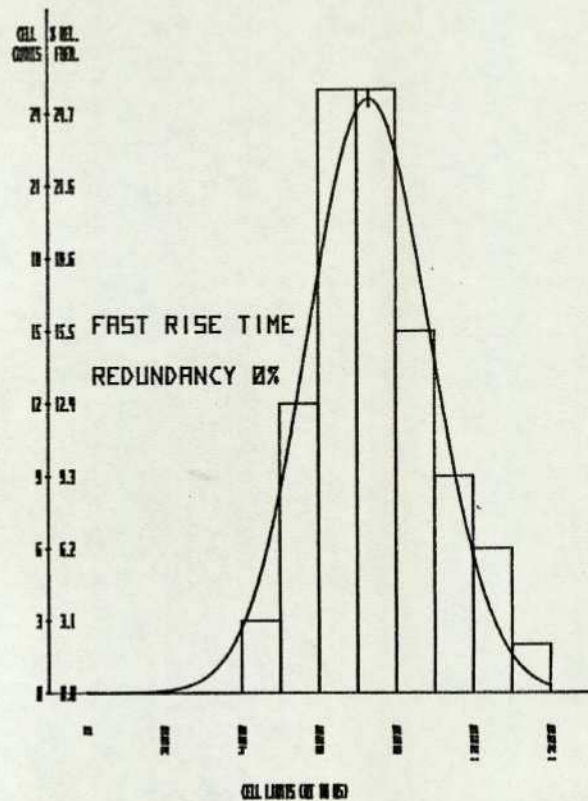
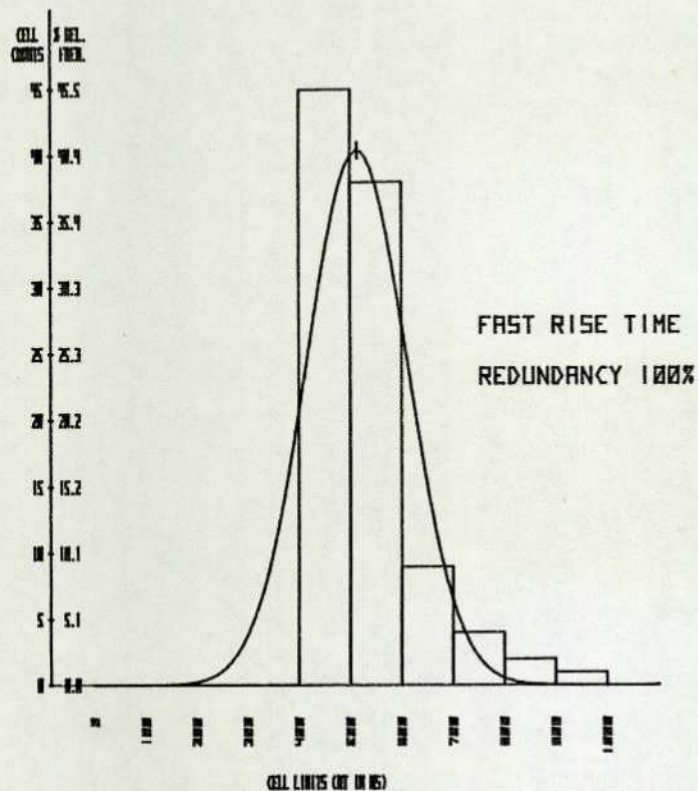
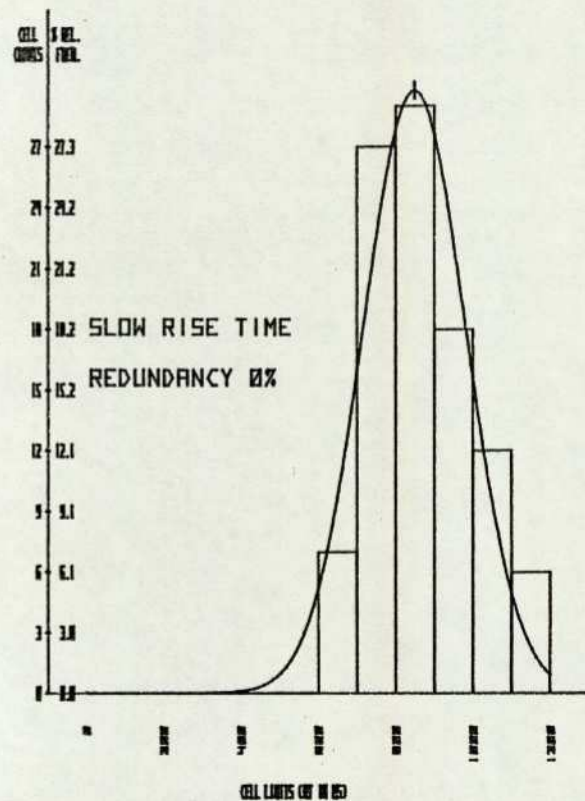
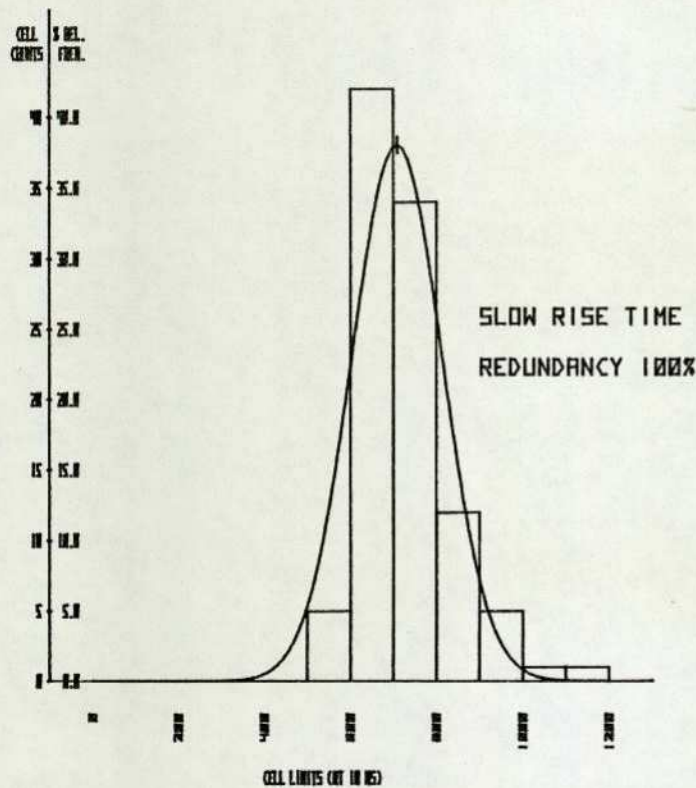


Figure 7.11

-180-



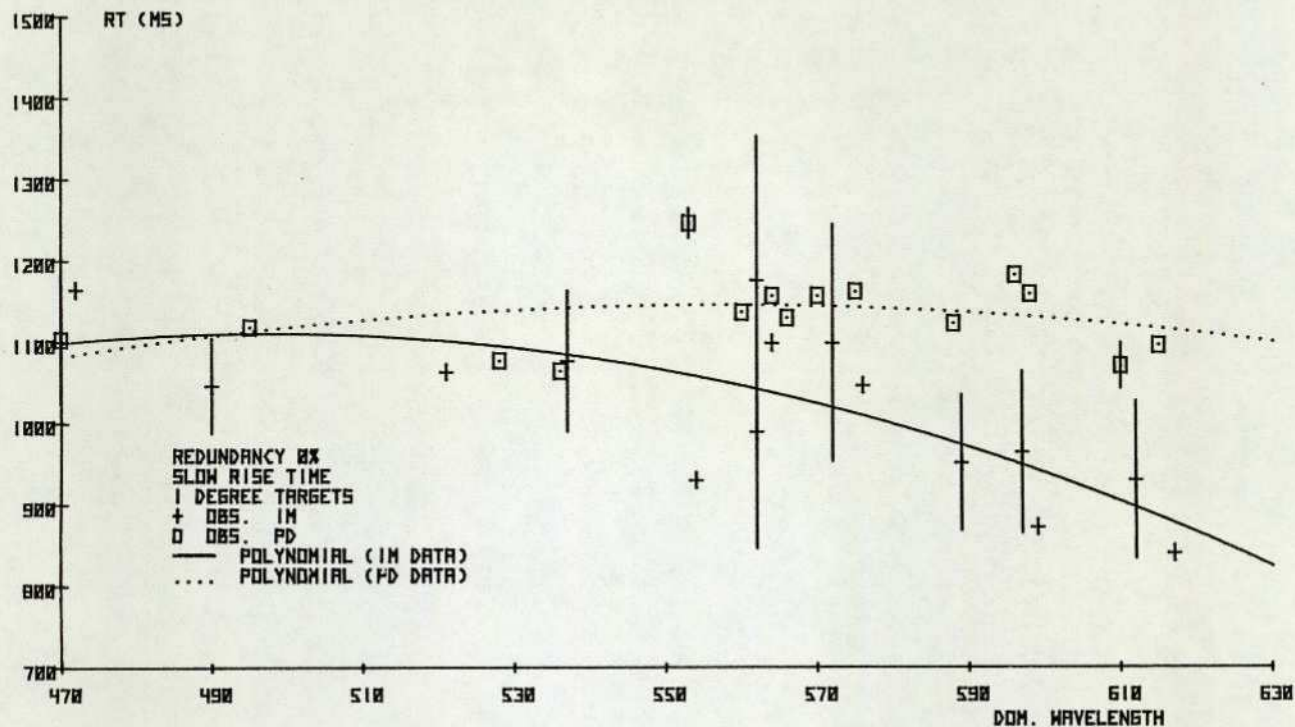


FIGURE 7-12 REACTION TIME AS A FUNCTION OF DOMINANT WAVELENGTH.

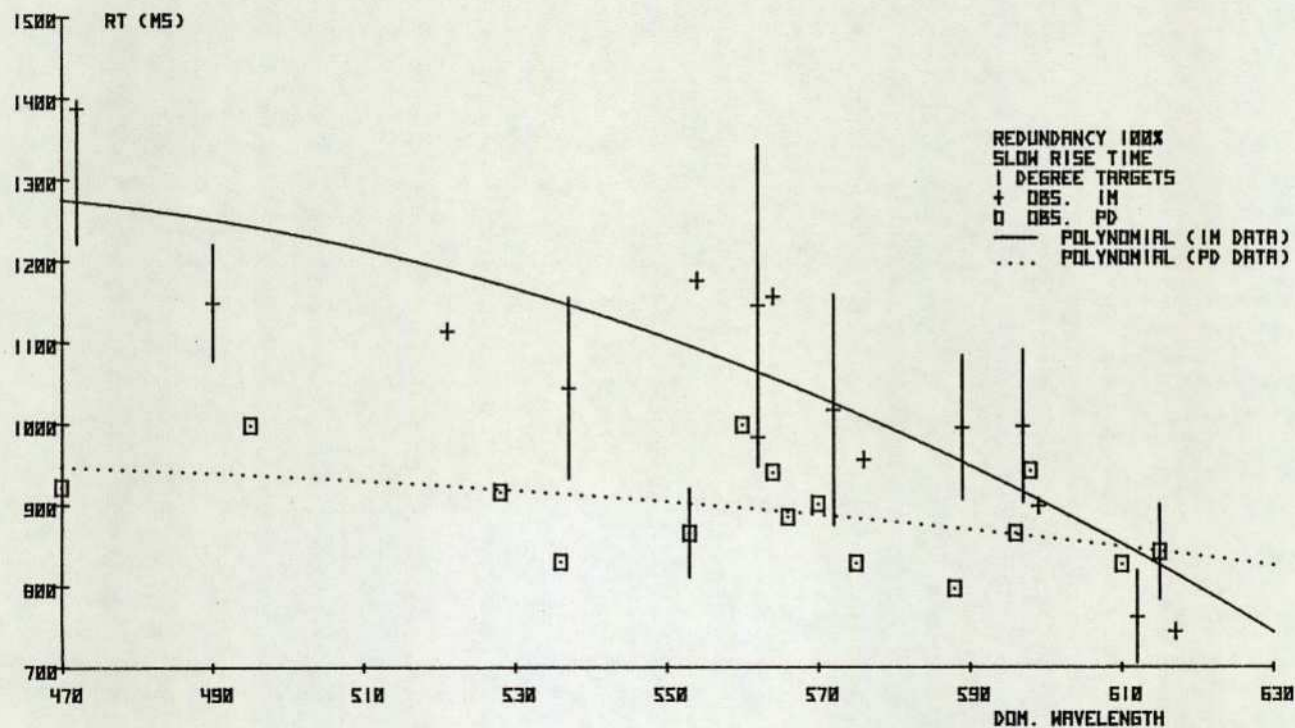


FIGURE 7-13 REACTION TIME AS A FUNCTION OF DOMINANT WAVELENGTH

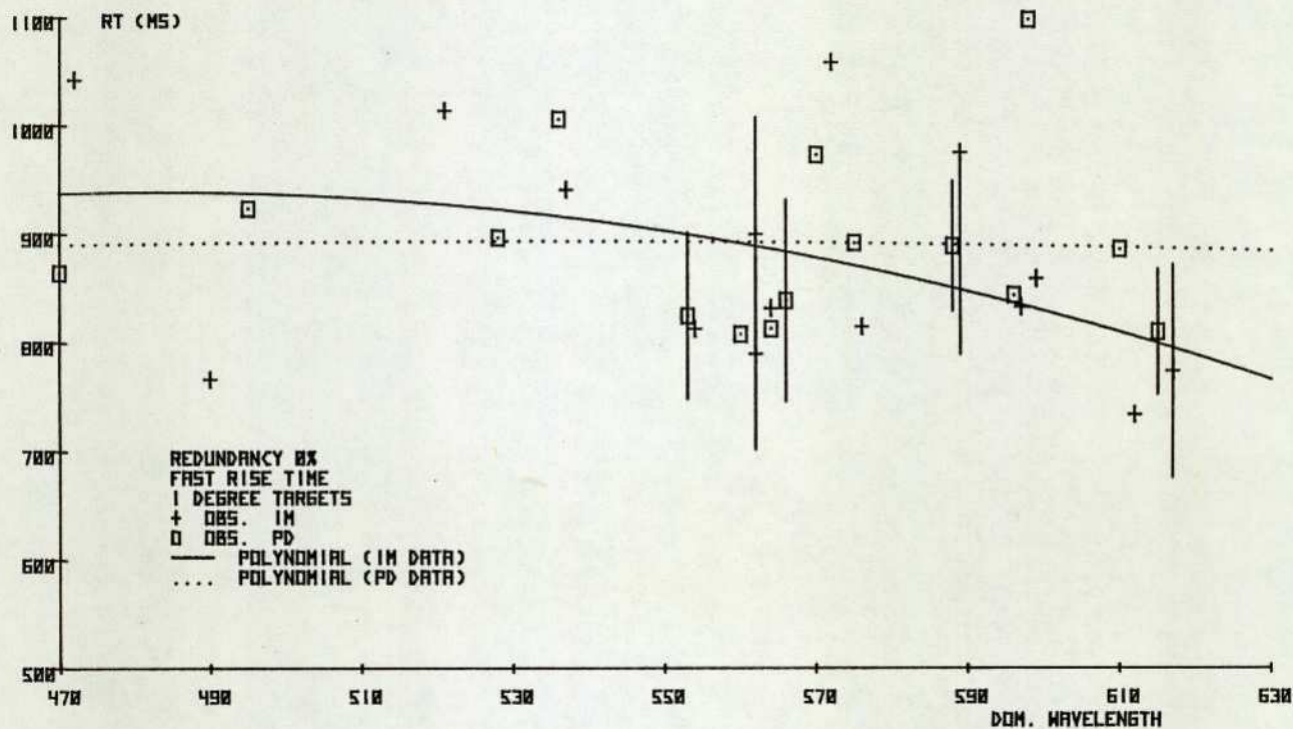


FIGURE 7-14 REACTION TIME AS A FUNCTION OF DOMINANT WAVELENGTH

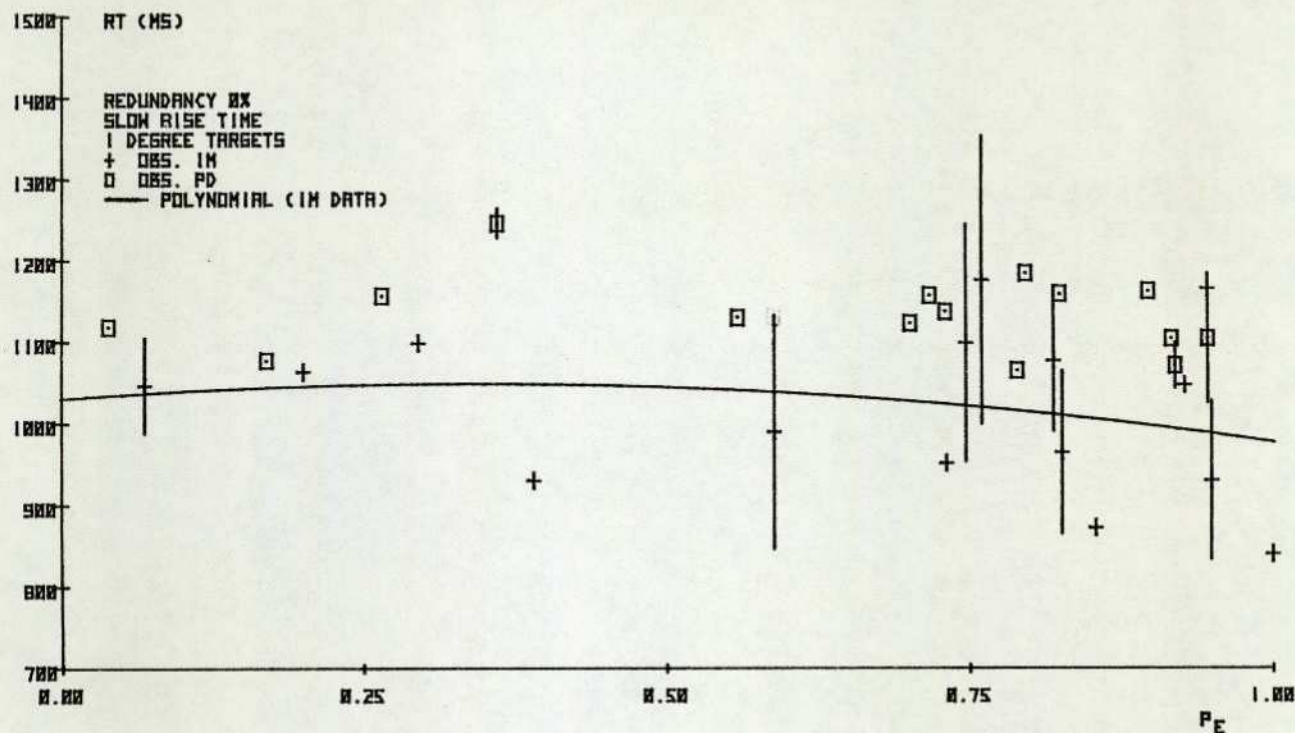


FIGURE 7-15 REACTION TIME AS A FUNCTION OF EXCITATION PURITY

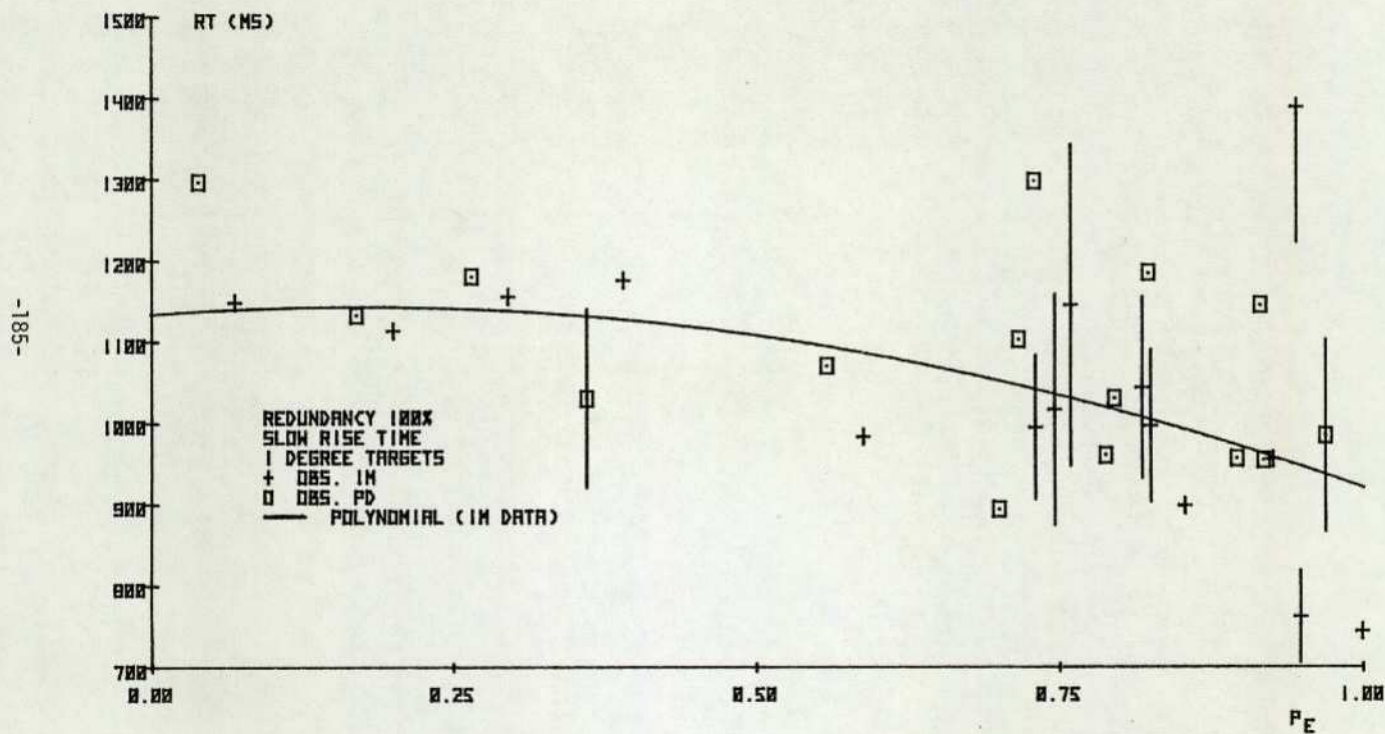


FIGURE 7-16 REACTION TIME AS A FUNCTION OF EXCITATION PURITY

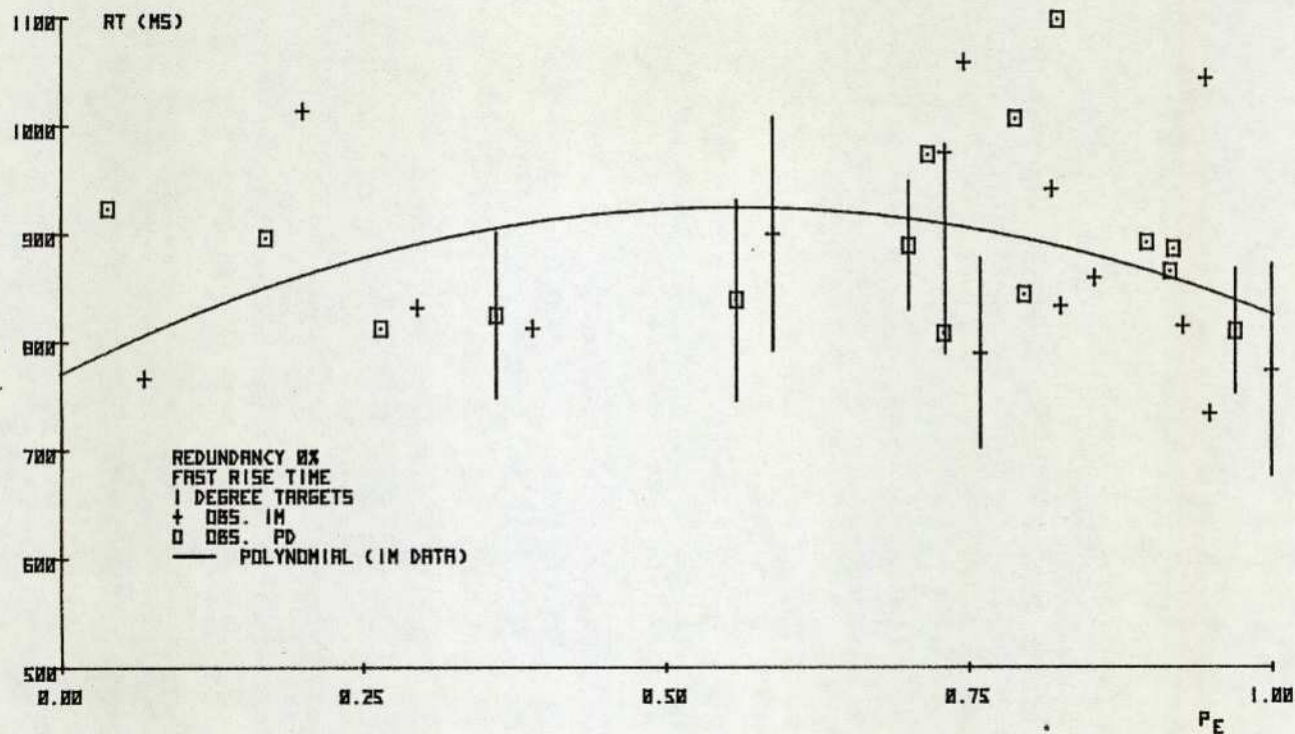


FIGURE 7-17 REACTION TIME AS A FUNCTION OF EXCITATION PURITY

dominant wavelengths, but the scatter of the data make this inconclusive.

7.6 Discussion

The data do not appear to support the conclusions reached in chapter five that reaction time is a function of excitation purity. Several factors may have a bearing on this apparent contradiction. Firstly in the present case additional care was taken over the photometry of the stimuli i.e. the stimuli were monitored radiometrically and then photometric quantities computed from these values. The targets used in chapter five were monitored using an ordinary photometer.

Secondly the randomisation paradigm used in the present case was different from that used in chapter five. The present method ensured an equal likelihood for each target within a session.

Thirdly the two presentation methods were set up within the same apparatus and used together in each session, thus permitting direct comparisons to be made, and yet no significant differences between the results obtained with the two different methods are apparent.

Fourthly the histogram results for the present experiment do not seem to indicate such good separation of the two postulated visual channels, as was the case in chapter five.

Finally a subjective observation made by both observers may be of relevance - the targets with the higher excitation purity values appeared "brighter".

The significance of these various factors to the results is difficult to assess, although the relatively transient appearance of the histograms compared with those of chapter five, combined with the trend towards lower reaction times at higher purity values implies that the present conditions have somehow selected transient channel responses. This would be consistent with the results from chapter five where reaction time decreased as purity increased for transient responses. This raises the question of what difference in the present conditions produced the change in selectivity?

The remarks regarding the subjective brightness of the different targets on the other hand produces doubts as to the validity of the standard relative luminous efficiency function under low contrast recognition of chromatic targets.

7.7 Conclusions

Two conclusions can be drawn from the present data taken in conjunction with the results of chapter five. Either reaction time is not a function of purity and the results of chapter five were an experimental artifact, or reaction time is dependent upon purity and present conditions were not suitable to demonstrate this.

An alternative explanation may exist for these data however - reaction time may be a function of some variable other than those discussed. In particular contrast, where contrast is taken to mean not only luminance contrast but also that resulting from chromatic

differences. Chapter eight describes an experiment which attempts to assess the relevance of using the CIE efficiency function to describe targets on a neutral background when a task other than detection is being performed. In the light of the data obtained from that experiment the results of the present experiment will be reassessed in chapter nine.

CHAPTER EIGHT

CONTRIBUTION OF CHROMATIC AND ACHROMATIC MECHANISMS TO A LIMITED RECOGNITION TASK

- 8.1 Introduction
- 8.2 Method
- 8.3 Calibration
- 8.4 Apertures and patterns
- 8.5 Experiments
- 8.6 Results
- 8.7 Discussion and conclusions
- 8.8 Models of colour vision

CONTRIBUTION OF CHROMATIC AND ACHROMATIC MECHANISMS

TO A LIMITED RECOGNITION TASK

8.1 Introduction

By reconsidering the qualitative definition of saturation - a judgement of the proportion of pure chromatic colour in the total sensation Hunt (1978) - it is possible to rephrase the question of recognition dependence upon saturation as follows:- what are the relative contributions of the chromatic and achromatic channels to recognition thresholds?

If recognition relied mainly upon the higher resolution achromatic channel, then manipulation of the relative proportions of chromatic and achromatic contrast in a stimulus would not influence the wavelength dependency of the recognition threshold except near isoluminance. On the other hand if the resolution of the chromatic channel is sufficient under some circumstances for reliable recognition to occur, then it is obvious that the proportion of chromatic to achromatic contrast becomes much more important, since reduction of the chromatic contrast (or increasing the achromatic contrast eg. figure 1.7c) will move the threshold to that of the achromatic channel. King-Smith and Carden (1976) and Kranda and King-Smith (1979) have already demonstrated that two different detection thresholds can be obtained by manipulation of the spatial and temporal properties of the test stimulus. Furthermore Carden and King-Smith (1976) demonstrated that the detection of relatively large stimuli presented for a long time (one degree, 250 ms) is performed by a chromatic channel, since detection of the stimulus

COINCIDES WITH DETECTION OF ITS COLOUR.

The results are illustrated in figure 8.1 along with a purity discrimination function determined by normal means (Ingling and Tsou 1979). The functions are similar except in the region where the achromatic mechanism is dominant i.e. 570 nm. The sharp dip in the purity function at this wavelength is not evident in the detection curve. This suggests that for conditions where increment thresholds are seen as coloured, prediction of purity discrimination by any visual model should also predict a detection threshold.

The aim of the present experiment was to determine whether similar rules could be applied to the task of recognition. If one considers Overington's (1978) hierarchy of tasks, then the use of recognition rather than detection would be expected to favour the achromatic channel, since recognition requires finer detail than detection, and the achromatic channel is more sensitive to stimuli which are small.

Preliminary experiments using simple circular test patterns one degree in diameter and presented for 500 ms confirmed the results of Kranda and King-Smith (1979) for detection of monochromatic stimuli.

The main experiment used two Smet's patterns each of two different sizes presented at sixteen different wavelengths between 400 and 700 nm. Four separate criteria were used to isolate detection, identification, minimum flicker and flicker detection thresholds. In addition control experiments were conducted using four sizes and two temporal conditions to allow comparison with

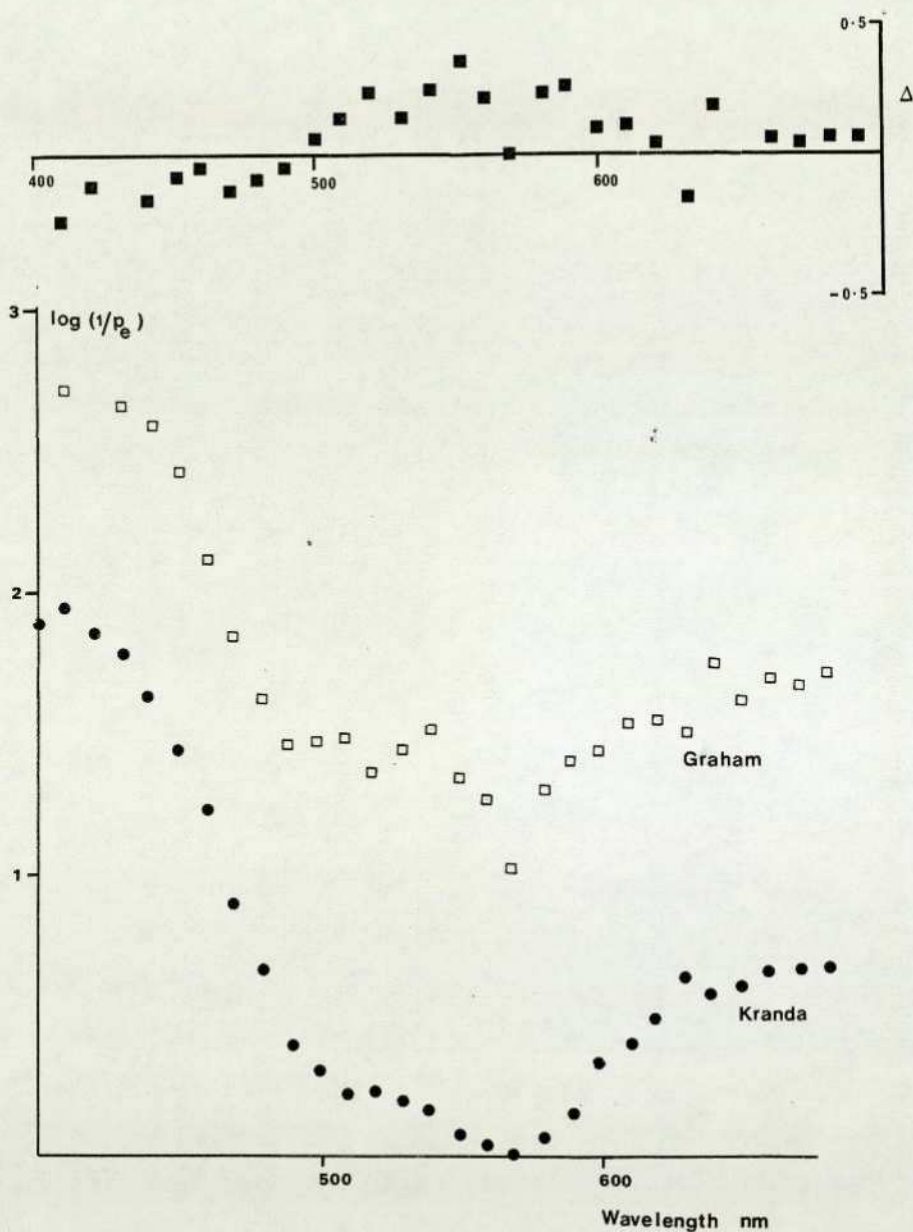


Figure 8.1 Comparison of Kranda and King - Smith detection data (replotted on an excitation purity ordinate) with a typical purity discrimination curve.

previous studies.

The use of identification rather than detection was necessitated by the fact that only two patterns were used (see definition of recognition in chapter one). Although this is a weaker criterion it is felt that it still allows an insight into the factors influencing recognitions.

8.2 Method

A schematic diagram of the optical system is shown in figure 8.2.

A six volt, eighteen amp ribbon filament lamp S, provided both an adapting beam (1) and test beam (2). The former subtended eight degrees when viewed by observer O at the exit pupil P. The colour temperature of the beam was adjusted to $4,500^{\circ}$ K by colour correcting filters cc, and provided a retinal illuminance of 600 td (adjusted by neutral density filters nd). In the majority of the identification experiments a cross-hair fixation target XH was illuminated by this beam.

Beam (2) provided a monochromatic test field of maximum dimensions three degrees by four degrees at the exit pupil P. After passing through heat absorbing glass H_1 , the beam was imaged first on neutral density wedge W (gelatine, 3 log unit continuous), then on the entrance slit of prism monochromator PM, in the plane of the sector disc SD and finally at the exit pupil P. Additional filters could be introduced to reduce test beam energy at ND (vacuum coated)

OPTICAL SYSTEM

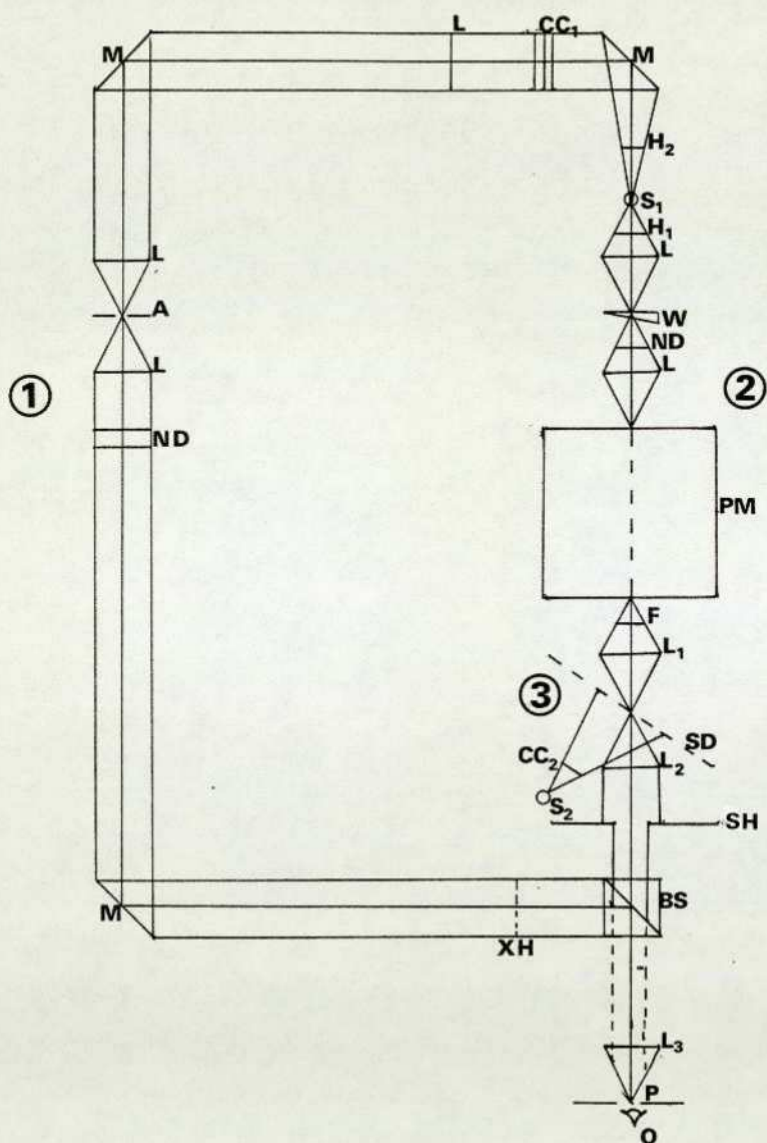


Figure 8-2

and to remove secondary reflections at the exit pupil of the monochromator (F, wideband).

Sectored disc SD was driven by a variable speed stepper motor and consisted of either a matt white four sectored disc used in minimum flicker determinations and flicker detection experiments, or a matt black half-sector disc used to provide a one Hertz presentation rate.

Source S_2 (15V car headlamp) provided a $5,000^{\circ}$ K, 60 td beam which illuminated the sectored disc as a reference during minimum *Flicker R.* measurements.

Apertures and targets for identification experiments were precisely located in a four position click-stop slide holder SH. This eliminated position cues during the identification task.

8.3 Calibration

Colour temperatures were computed from chromaticity coordinates determined radiometrically (Gamma telespectroradiometer). The background beam was found to have a correlated colour temperature of $4,350^{\circ}$ K ($x = 0.377$, $y = 0.401$), although initially set to $6,000^{\circ}$ K at a higher intensity using an EEL colour temperature meter. The discrepancy was found to be the result of non-neutral filters ND, inserted to reduce the retinal illuminance.

The nominal range of test beam wavelengths used was from 400 - 700 nm at 20 nm intervals (half peak bandwidth 10 nm). Calibration

with precision interference filters indicated a scale error of 4 nm however, meaning the true range was from 396 - 696 nm.

Test beam irradiance was measured at the pupil at twenty nanometre intervals from 396 - 696 nm for each of fifteen neutral wedge positions (0.2 log unit steps) using a silicon photodiode (UDT 10 DF) and high gain amplifier (see appendix 3). This provided a complete spectral irradiance calibration for the test beam for all wedge positions, by interpolation.

Neutral density filters used in the test beam were checked for neutrality spectrophotometrically and only those which varied by less than 5% were selected. Corrections were applied for any remaining deviations from neutrality, giving an error in the energy calibration of 0.01 log units.

Wedge densities plus additional filters selected by the observer were converted to log spectral irradiances and then additional corrections for the following factors were applied:-

- (a) only 50% of a Smets pattern transmits light
- (b) the fog level of the clear portions of each test pattern
- (c) the finite density of the opaque portions of the test pattern
- (d) non-neutrality of the film base used.

8.4 Apertures and patterns

Nominal sizes for the patterns used were one and two degrees square. These were measured accurately for each pattern by travelling microscope and are listed in table 8.1, along with the dimensions of the apertures used in control experiments.

Of the two sets of patterns, those referred to as "T" and "L" allowed a more precise calibration than "A" and "B" which had a significantly higher fog level.

Two subjects took part in the experiments. Both were experienced observers, had normal colour vision, and were familiar with the objectives of the experiment. Head movements were prevented by dental bites, during observing sessions.

8.5 Experiments

Four separate sets of experiments were performed.

(a) Minimum flicker determination of V_{λ} .

The results of this set of measurements formed a base line against which other results were compared. Subjects adjusted test beam flicker rate and luminance until a point was reached at which flicker was apparently at a minimum. Four such determinations were made by each observer at each wavelength and the mean spectral irradiance at threshold computed.

TABLE 8.1

Pattern or aperture	Dimensions		Area (sq. deg.)
	Nominal	True (deg.)	
A	1° x 1°	1.00 x 0.97	0.97
B	1° x 1°	0.97 x 1.00	0.97
A	2° x 2°	2.29 x 2.23	5.11
B	2° x 2°	2.26 x 2.20	4.97
T	1° x 1°	1.00 x 1.03	1.03
L	1° x 1°	1.03 x 1.06	1.09
T	2° x 2°	2.26 x 2.32	5.24
L	2° x 2°	2.32 x 2.29	5.31
1° aperture	(circular)	-	-
2° "	(")	-	-
7.5' "	(square)	0.110 x 0.120	0.013
15.0' "	(square)	-	-

(b) Flicker detection

Minimum flicker could not be applied to patterned test fields due to disturbing apparent movement effects at low flicker rates. To determine relative luminous efficiency functions for patterned test fields, a fixed high frequency (25 Hz) flicker rate was used. Subjects were required to adjust test field irradiance alone until flicker could be just detected. Mean spectral irradiance values were computed from four determinations of threshold at each wavelength, for each observer.

(c) Detection - non patterned fields

As an additional point of reference, detection thresholds with either circular or square test beam formats were determined by the method of adjustment. Test fields were presented for 500 ms every second. Four determinations of threshold were made at each wavelength, for each observer.

(d) Detection and identification thresholds

- patterned test fields

In this case the position of the wedge (W) which controlled the spectral irradiance of the test target was set by the experimenter. After randomly selecting a target, size and wavelength the experimenter set the test beam irradiance at

0.75 OR 1.25 log. units below detection threshold (this had been determined approximately by the method of adjustment during a previous experiment). The experimenter then proceeded to increase the test irradiance in 0.05 log unit steps. After each increase the observer indicated whether a target could be detected or not. On announcing that detection had occurred, the observer was then instructed to state when he could identify the pattern (i.e. by giving it the appropriate label). At no time did identification occur before detection. A threshold for identification was accepted after three consecutive correct responses. This procedure was repeated until every combination of wavelength, size and pattern had been presented a minimum of four times. Presentation time was again 500 ms every second.

The major advantage of this technique is that sensitivity is not likely to have shifted over the short time between determination of the detection threshold, and determination of the identification threshold.

8.6 Results

All threshold irradiance values were converted to sensitivities and are illustrated in figures 8.3 to 8.12 as log. sensitivity versus wavelength plots. (DATA IN APPENDIX IV).

In order to obtain some sort of intuitive grasp of which opponent mechanisms were contributing to the various thresholds, each spectral sensitivity function is compared with the mechanisms postulated by Kranda and King-Smith (1979).

The formulae used by Kranda and King-Smith to define these mechanisms are as follows:-

$687R + 356G$	8.1
$3709R - 4306G$	8.2
$2990G - 2182R$	8.3
$1589B$	8.4

These will be referred to as red plus green ($R + G$), red minus green ($R - G$), green minus red ($G - R$) and blue (B) respectively. The symbols R , G and B refer to the spectral sensitivities of the long, medium and short wavelength sensitive cones respectively. Values for these sensitivities were taken from Vos (1978). After computing each of the four functions, log values were taken (thus restricting the functions to those regions of the spectrum where their values were positive). The vertical position of each function was then adjusted relative to the experimentally determined thresholds as follows:- the peak of the $R + G$ mechanism was set equal to the experimental value at 560 nm. Similarly the $R - G$ mechanism was set to equal the 620 nm datum, the $G - R$ was set equal to the 540 nm datum and the B was set equal to the 440 nm datum. No attempt was made to take into account probability summation effects. In each figure the solid line

(—) represents the adjusted R + G mechanism, the dotted line (...) the adjusted R - G, the dashed line (---) the adjusted G - R and the dash/dot line (-.-.) the adjusted blue mechanism.

Figure 8.3 illustrates the results of the minimum flicker determination for observer JES while figure 8.4 shows the results for IRM. As a comparison a similar computation was performed for the CIE relative luminous efficiency function and this is shown in figure 8.5. It is apparent that whereas the CIE function can be fitted by the R + G mechanism alone, the experimental data suggest that both the G - R and the B mechanisms also contribute. The match between the data and the G - R and B mechanisms is better for the larger two degree aperture. Similar plots using data collected by Sperling (1957) suggested that the B mechanism, but not the G - R mechanism contribute to the relative luminous efficiency function. A major criticism of such conclusions however is the uncertainty of the calibrations below 500 nm. This applies to both the present data and that of Sperling.

Similar results were obtained for the flicker detection paradigm (figures 8.6 and 8.7) with the exception that no contribution from the B mechanism was apparent for the smaller aperture.

Detection thresholds are illustrated in figure 8.8 and 8.9. For 1° and 2° patterns respectively. The data represent the means over both observers and both sets of patterns.

The results are consistent with those obtained by other authors eg. Kranda and King-

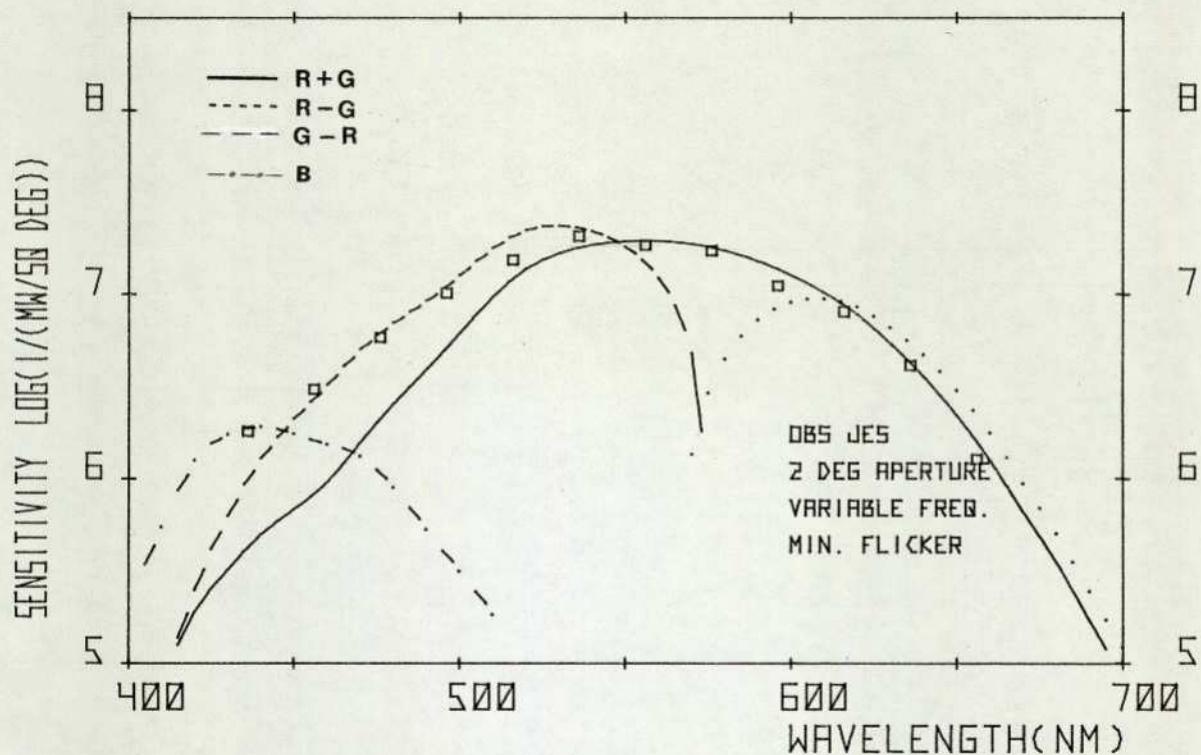


FIGURE B.3 MINIMUM FLICKER THRESHOLD

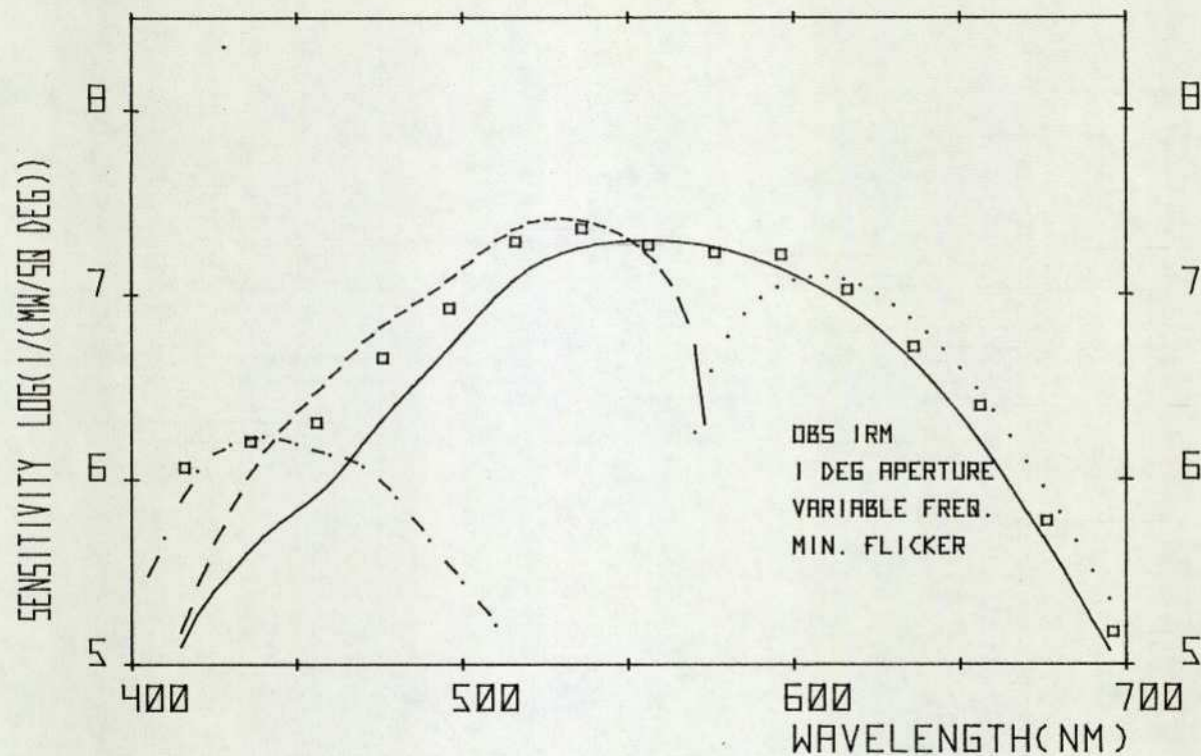


FIGURE B.4 MINIMUM FLICKER THRESHOLD

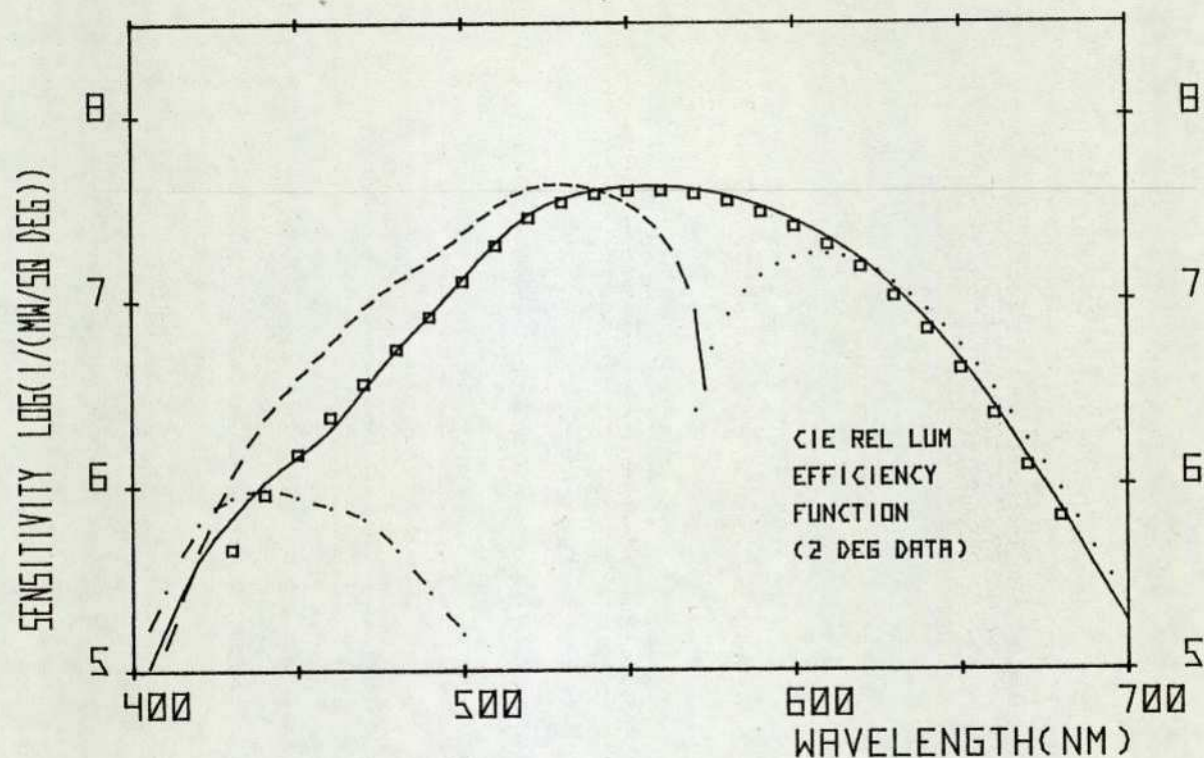


FIGURE B.5 CIE REL. LUMINOUS EFFICIENCY

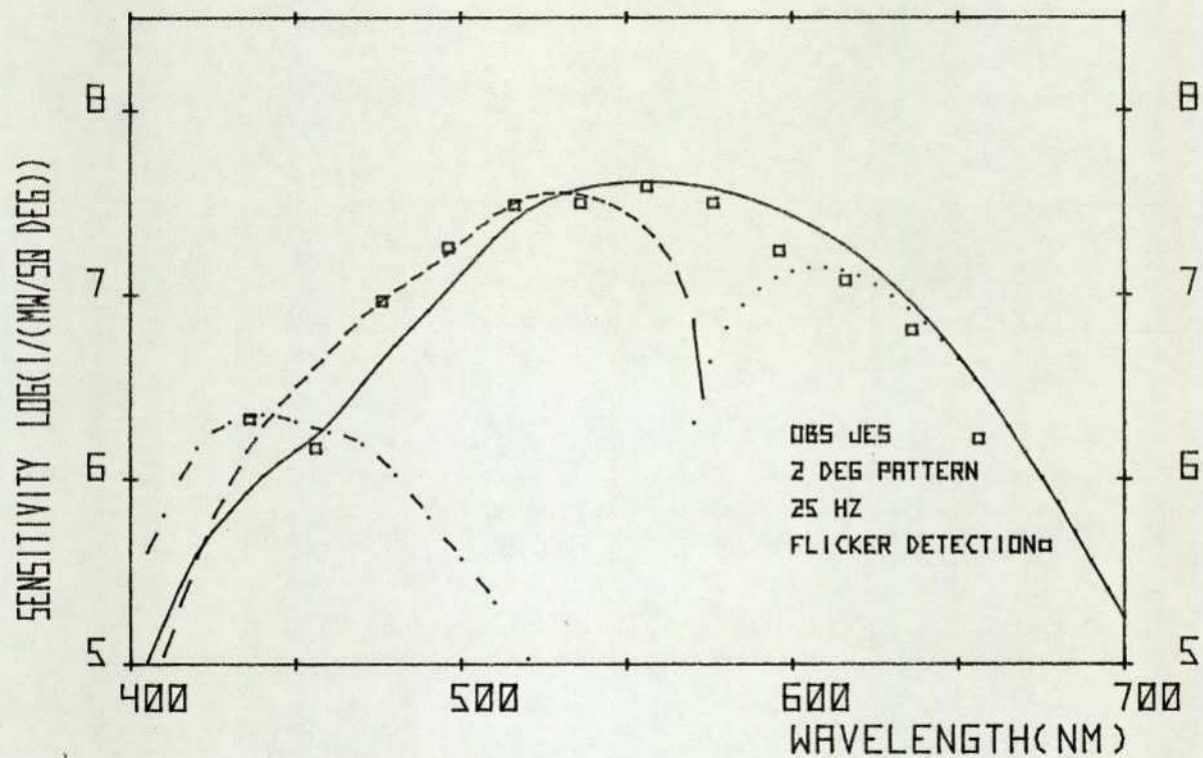


FIGURE B.6 FLICKER DETECTION THRESHOLD

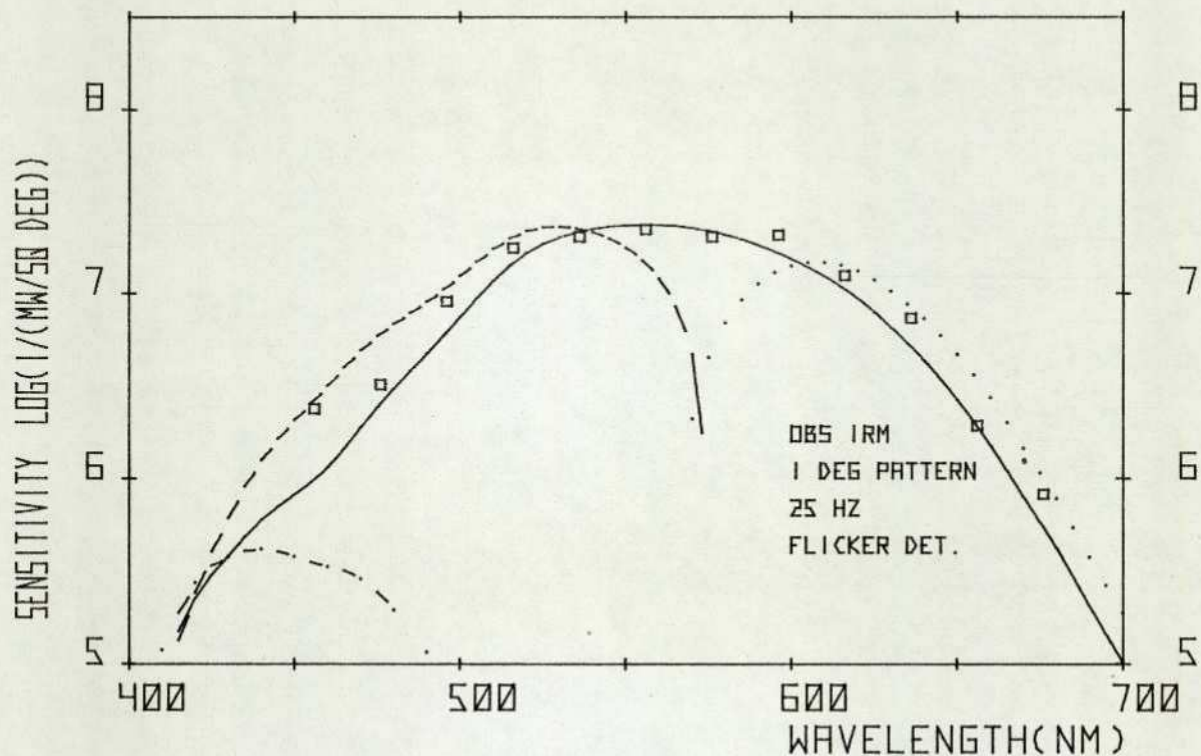


FIGURE B.7 FLICKER DETECTION THRESHOLD

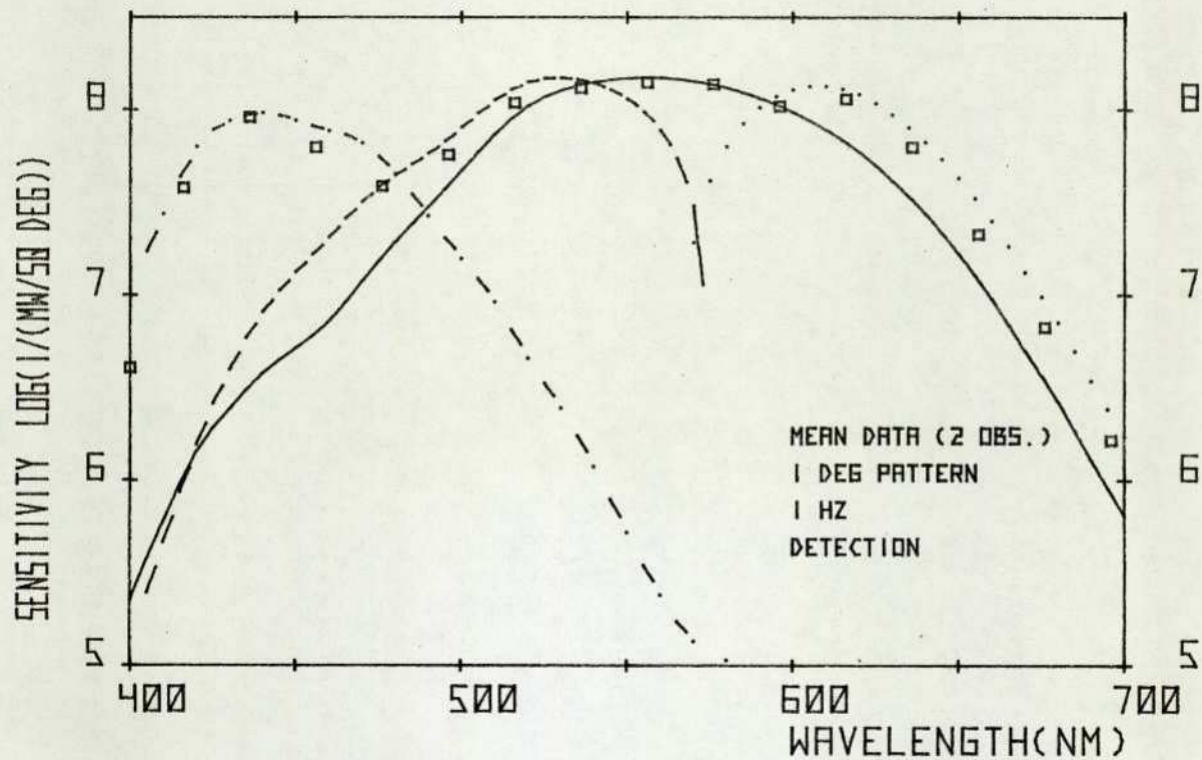


FIGURE B.B DETECTION THRESHOLD

Smith (1979) using a two alternative forced choice paradigm. The deviation from the V_{λ} function is particularly marked in the short wavelength region of the spectrum, where the detection threshold is typically thirty times more sensitive than the flicker threshold. There is however a significant drop in the sensitivity of the blue mechanism (approximately 0.3 log units) on moving from a larger to a smaller test field size. This is similar to the minimum flicker data.

Mean identification thresholds are illustrated in figure 8.10 and 8.11 for 1° and 2° patterns respectively.

Sensitivity is consistently less for identification, compared with detection, for both one and two degree targets. However the absolute difference is a function of wavelength; for one degree patterns the blue mechanism is one log unit less sensitive during identification compared with detection, but at wavelengths greater than 500 nm the difference is more typically 0.2 log units. For two degree patterns the blue mechanisms are only 0.5 log units apart under the two tasks. The 0.2 log unit difference at other wavelengths is maintained however.

Generally the identification thresholds bear a closer similarity to the V_{λ} function than the detection thresholds i.e. the chromatic mechanisms are depressed, particularly the blue, especially with smaller fields. This suggests as might be expected, that when pattern detail has to be identified the spectral sensitivity function is that appropriate to the pattern elements and not the whole pattern. To test this a set of control experiments was performed using a square

aperture of 7.5' arc (i.e. the size of one element of a one degree pattern). The results are shown in figure 8.12. The data proved to be noisy, due to the small target size resulting in fixation difficulties, however it can be seen that a contribution from the chromatic mechanisms is still evident, but without the enhanced blue sensitivity found for either detection or identification of larger patterns.

An estimate of the deviation of the detection and identification thresholds from the relative luminous efficiency function ("achromatic" channel) can be obtained by computing the ratio of threshold sensitivity to flicker detection sensitivity. The results of such a computation performed on the mean data are illustrated in figures 8.13 and 8.14 for 1° and 2° patterns respectively. In these figures, points falling above the abscissa indicate that the detection or identification mechanism is more sensitive than the flicker detection mechanism. (Thresholds the same as the relative luminous efficiency function would fall along the abscissa). As has been found by others (eg. Voke 1979) the blue mechanism is relatively insensitive to flicker. This is demonstrated by the large peak in the short wavelength region of both the one and two degree detection difference curves. A similar peak is apparent in the two degree, but not the one degree identification difference curve. An additional sensitivity difference is apparent at the long wavelength end of the spectrum, for both detection and identification tasks.

Finally, to illustrate how these thresholds might be viewed in terms of purity discrimination, mean detection and identification

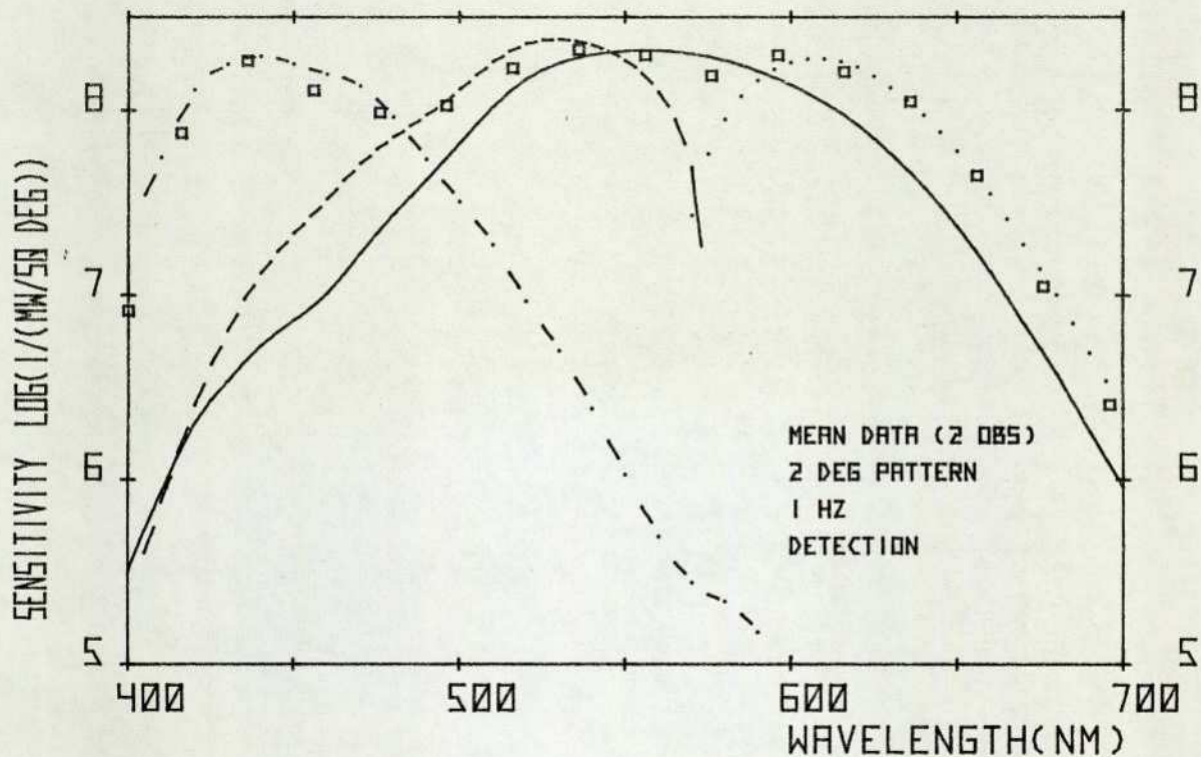


FIGURE B.9 DETECTION THRESHOLD

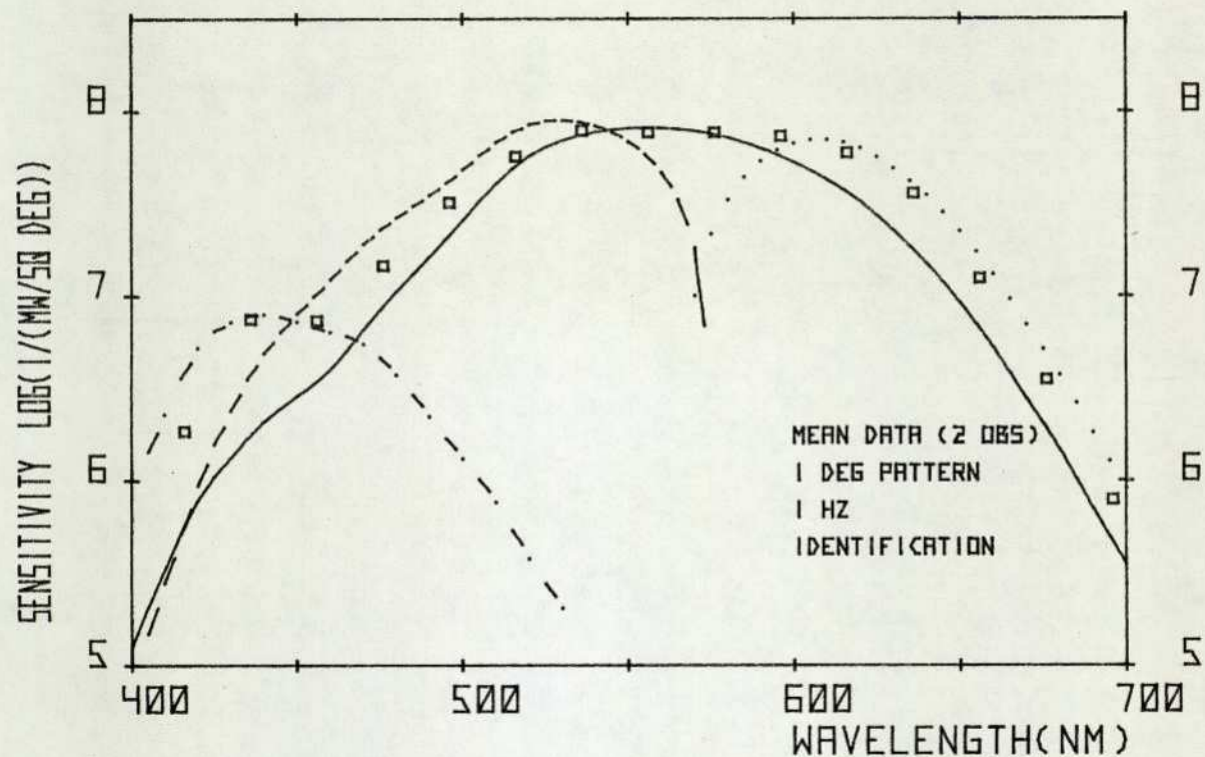


FIGURE B.10 IDENTIFICATION THRESHOLD

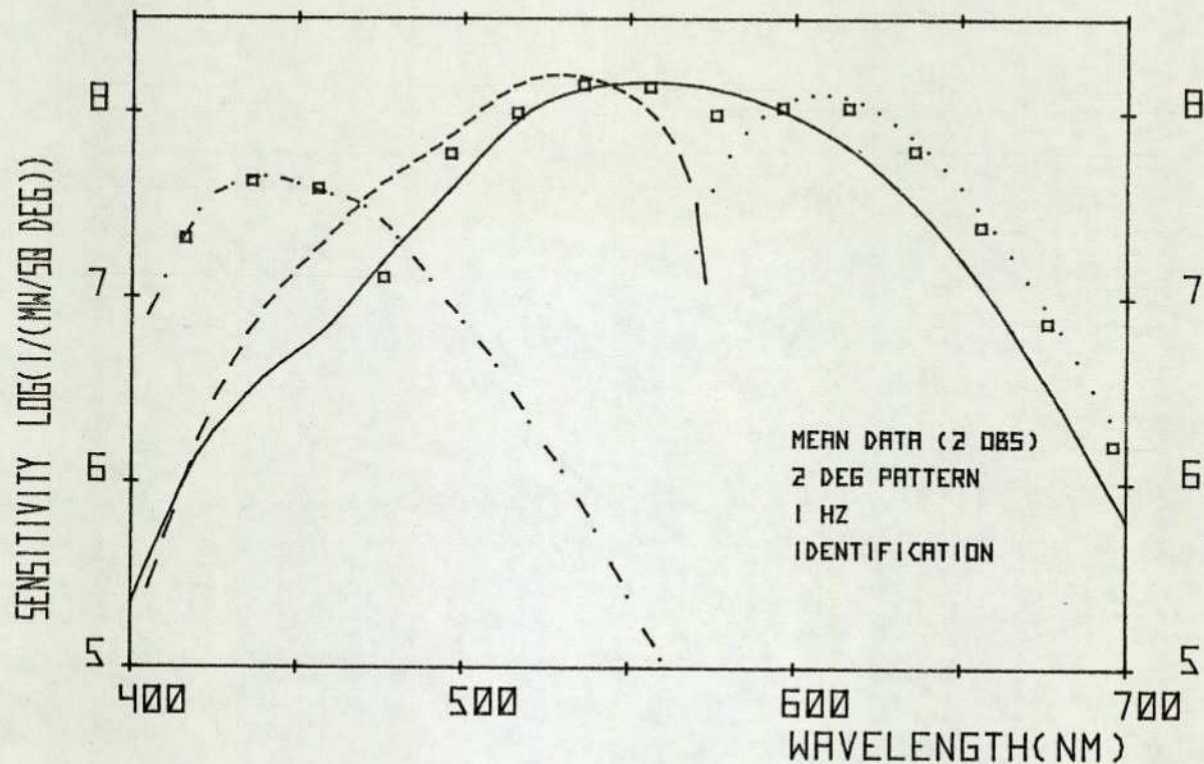


FIGURE 8.11 IDENTIFICATION THRESHOLD

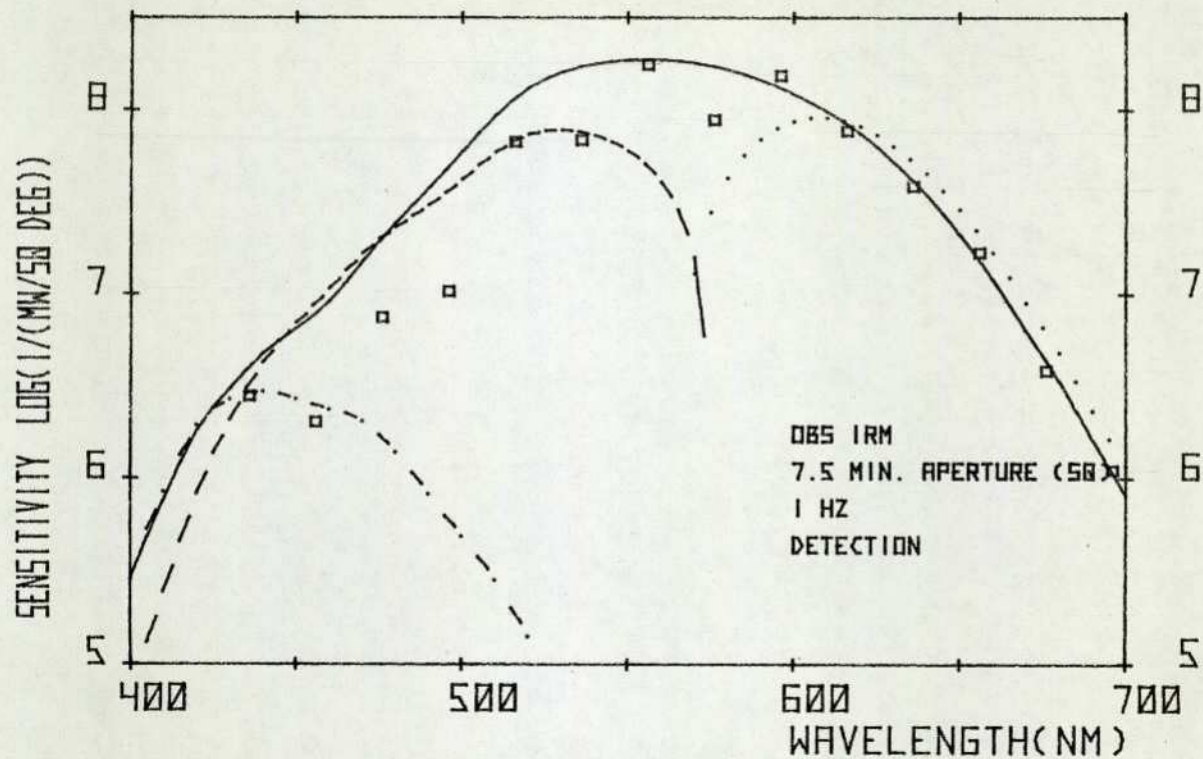


FIGURE B.12 DETECTION THRESHOLD

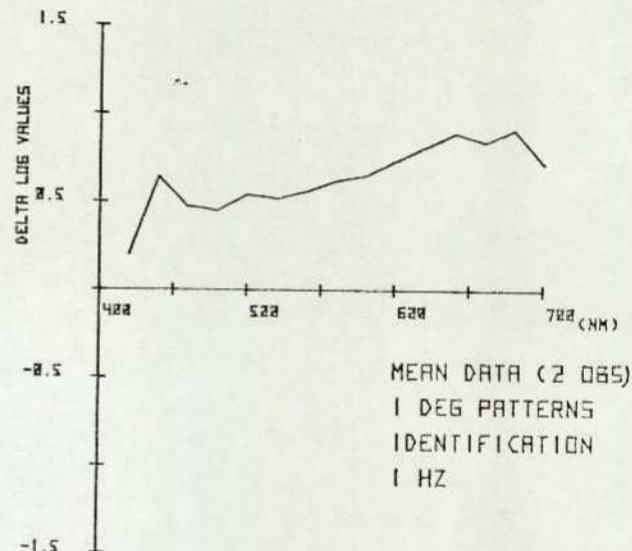
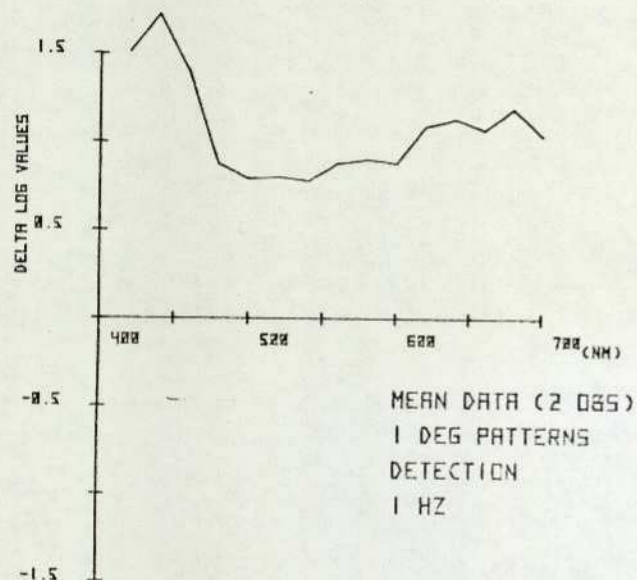


FIGURE B.13 DETECTION AND IDENTIFICATION THRESHOLDS
RELATIVE TO THE REL. LUMINOUS EFFICIENCY
FUNCTION

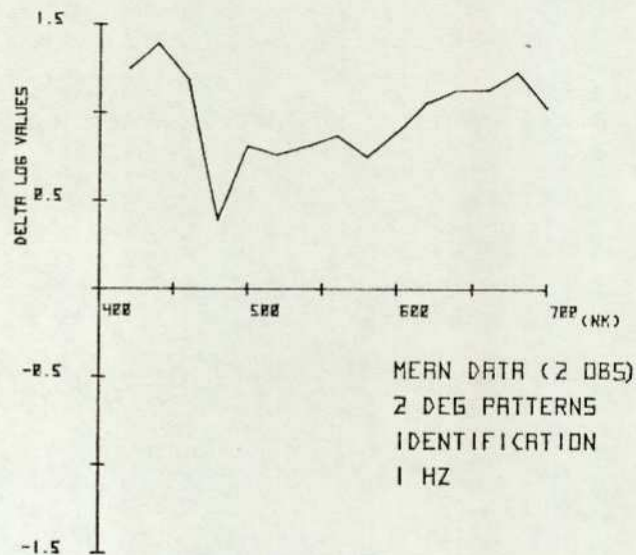
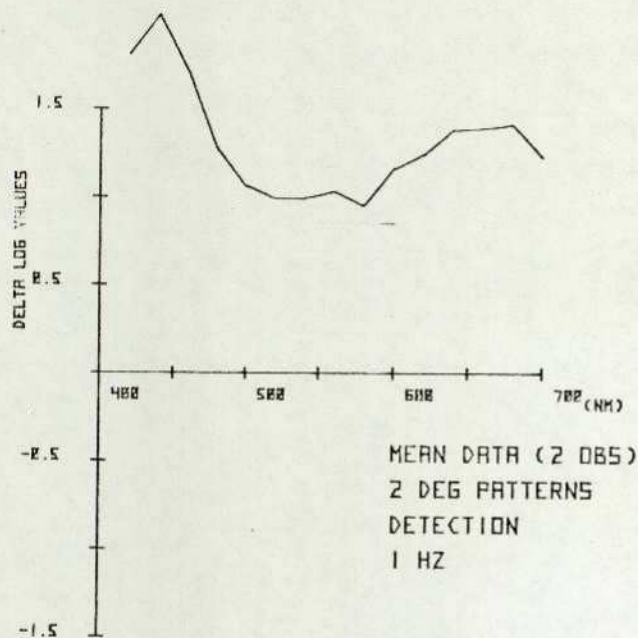


FIGURE B.14 DETECTION AND IDENTIFICATION THRESHOLDS
RELATIVE TO THE REL. LUMINOUS EFFICIENCY
FUNCTION

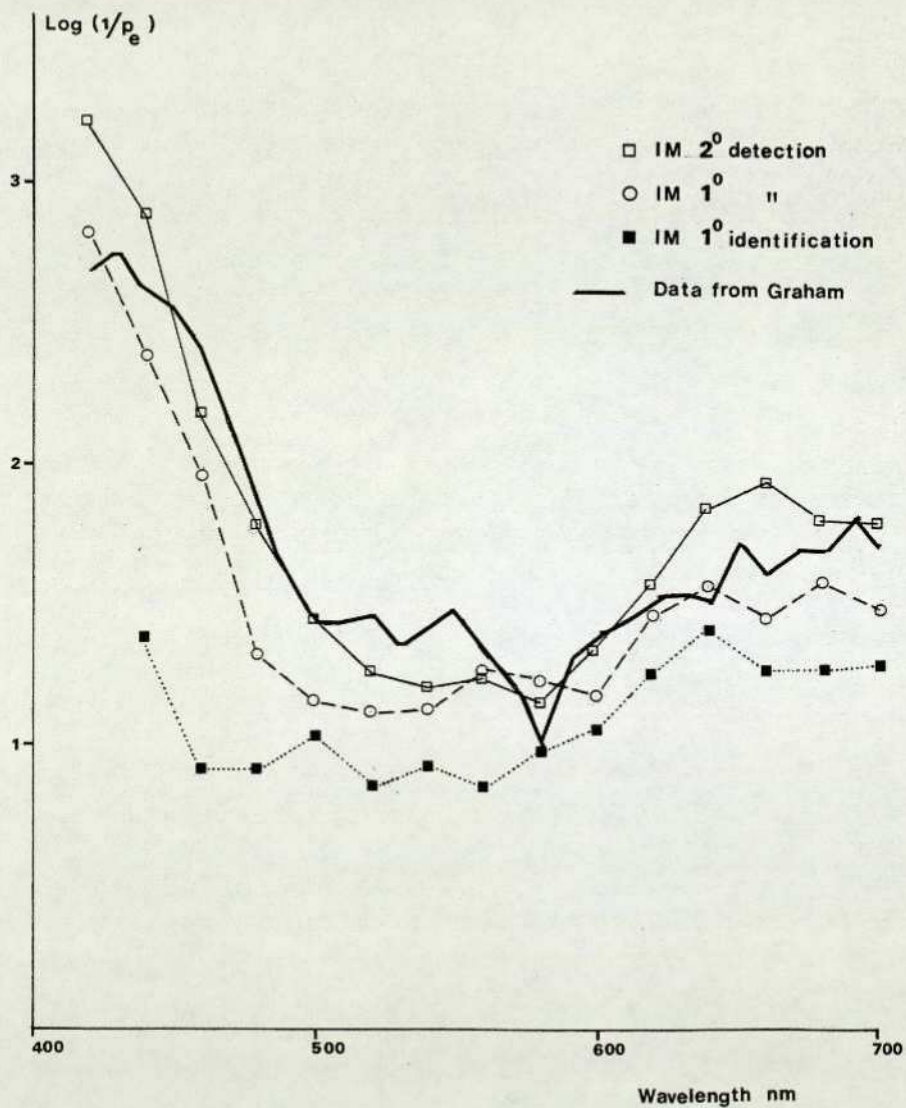


Figure 8.15 Detection and identification thresholds expressed as purity discrimination functions

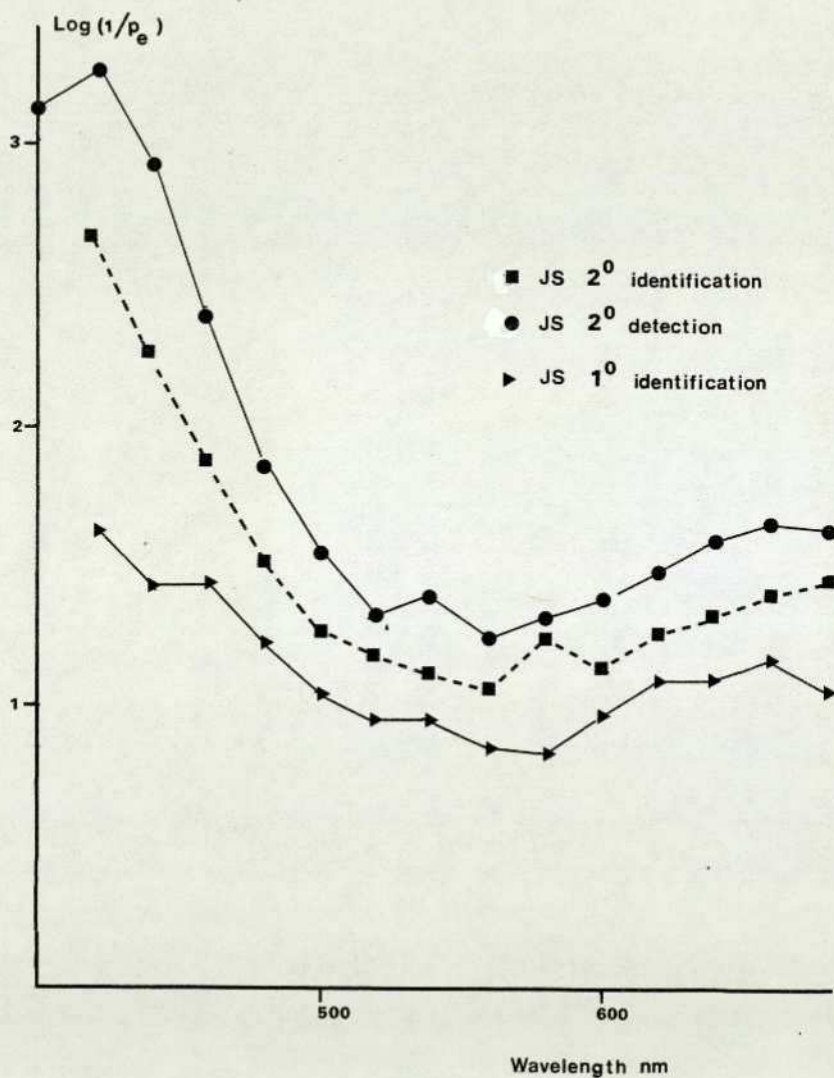


Figure 8.16 Detection and identification thresholds expressed as purity discrimination functions

thresholds were transformed to a purity ordinate. These are illustrated in figures 8.15 and 8.16.

8.7 Discussion and Conclusions

An underlying assumption present in all of the experiments described was that the visual system can be described in terms of two channels. One the achromatic, representing a combination of long and medium wavelength cone signals, and isolated by small flickering test fields. The other, the chromatic channel, representing the outputs of various opponent mechanisms such as G - R and R - G, and isolated by large test fields presented for long durations. The present data suggest that these two channels are not as easily separated as might be imagined. In addition the dominance of one channel over another (i.e. conditions which enhance the sensitivity of one channel compared with the other) appears to be dependent upon a range of parameters, including presentation rate, target size and task.

The fact that detection thresholds for patterned targets were virtually identical to those for circular test fields provides further evidence for the existence of the two types of channel and also suggests that the mechanisms involved (chromatic) do not resolve all the detail of the patterns (since the detection threshold for a 7.5' arc aperture showed much less evidence for chromatic mechanisms operating). The size dependency of the chromatic mechanism is small however over the target sizes used in this study, since the detection thresholds for one and two degree targets were similar in shape.

This is not the case for the identification task however. The results indicate that under the conditions used, the chromatic mechanism provides sufficient resolution for identification to occur, at least in the middle to long wavelength parts of the visible spectrum. The fact that this mechanism fails for the smaller, one degree targets in the short wavelength spectral region, may have important consequences when the atmospheric effects discussed in chapter three are considered. It will be recalled that scattering produces an increase in the proportion of short wavelength energy apparently emanating from a target. This, in combination with the present results suggests that atmospheric degradation of the colour of a target may force the visual system into using the less sensitive achromatic mechanism. In addition, even if the target colour remains in the red green/green portion of the spectrum a reduction in purity (i.e. a removal of chromatic contrast) may cause a shift in threshold. This effect will be much smaller than for blue stimuli however.

8.8 Models of Colour Vision

As mentioned in chapter one several models of how colour is processed have been postulated. Since the present data for identification thresholds do not show any radical difference from detection thresholds an attempt was made to fit the identification thresholds with the vector model of Ingling and Tsou (1979). The curves were fitted by eye. Reasonable matches between data and theory could be achieved, however it became apparent that very little information could be got from this procedure, as no less than six parameters were free to vary. In addition the model

provided no predictive quality of any kind.

In conclusion therefore, it can be seen that an identification task can be treated in the same way as a detection task, provided that care is taken to determine new values for the many parameters upon which the thresholds are dependent. In addition the similarity between the results for the two observers in detection tasks and results reported in the literature support the conclusion that the results obtained were not an artifact or the result of observer bias.

CHAPTER NINE

DISCUSSION AND CONCLUSIONS

9.1 Discussion

9.2 Conclusions

DISCUSSION AND CONCLUSIONS

9.1 Discussion

The results of the series of experiments conducted to determine whether purity affects recognition can be summarised as follows:-

- (1) Purity threshold varies with the task performed by the observer, and the wavelength of the test target (chapter eight).
- (2) Recognition of high contrast targets is unaffected by the stimulus purity both in tasks requiring memory (chapter four) and those not requiring memory (chapter six).
- (3) Recognition of low contrast targets may (chapter five) or may not (chapter seven) be a function of target purity.
- (4) Separation of the two postulated visual channels is dependent upon the spatial, temporal and chromatic properties of the stimulus. The effect of choosing particular conditions is generally to stimulate one channel in preference to the other. The other channel may still respond a percentage of the time however.

Consider first the hypothesis that recognition of high contrast targets is independent of purity. The evidence for the predominantly transient nature of the responses to high contrast stimuli in a

recognition task in chapter six compliments previous work using sinusoidal grating stimuli (Harwerth et al, 1980). If as seems highly likely (chapter one) the transient channel is insensitive to the chromatic information present at the retina, i.e. is sensitive only to luminance contrast, then the lack of purity effect is only to be expected. The "detector" suggested by Ingling (1978) receives inputs from both the chromatic and the achromatic channel however. This implies that if stimulation of the achromatic channel is reduced i.e. luminance contrast is minimised, then one can envisage a condition in which the chromatic channel is the dominant input to the detector. One cannot therefore assume that insensitivity to purity differences between target and surround will extend over the complete range of contrasts. Problems arise from the fact that contrast alone does not determine which of the channels is operative (or dominant). This is evident in the histograms plotted in chapters five and seven.

The spatial and temporal selectivity of the two channels is different (Ingling, 1978) therefore it is possible to select preferentially one or the other of the channels, unless conditions are so extreme that only one channel is functioning as occurs with high contrast rapidly flickering targets. Normally detection experiments fix two of the three stimulus properties (e.g. spatial and temporal) and measure the response of the channel to the third property. For example, small, flickering stimuli enable one to determine the spectral sensitivity of the achromatic channel and this is of course better known as the relative luminous efficiency

function. Such a clear cut isolation of one of the two channels is not always possible however and this seems to be the case in present work in which low contrast stimuli were used. The selected spatial and temporal conditions, combined with the task required of the observer seemed to stimulate both channels, but not equally. This is probably more typical of what happens in the natural environment. The balance between the two channels then becomes a more indefinite probabilistic problem.

Since the two channels can be isolated or conditions can be chosen which emphasise the response of one channel relative to the other, and the two channels have different spectral sensitivity functions, the question must be asked as to whether the CIE relative luminous efficiency function is the most appropriate method for assessing the "luminance" of targets under all conditions. To provide an idea of the differences in efficiency of different wavelengths the mean identification thresholds from chapter eight were replotted as relative spectral efficiency functions. The results are illustrated in figures 9.1 and 9.2. The standard CIE function is shown for comparison.

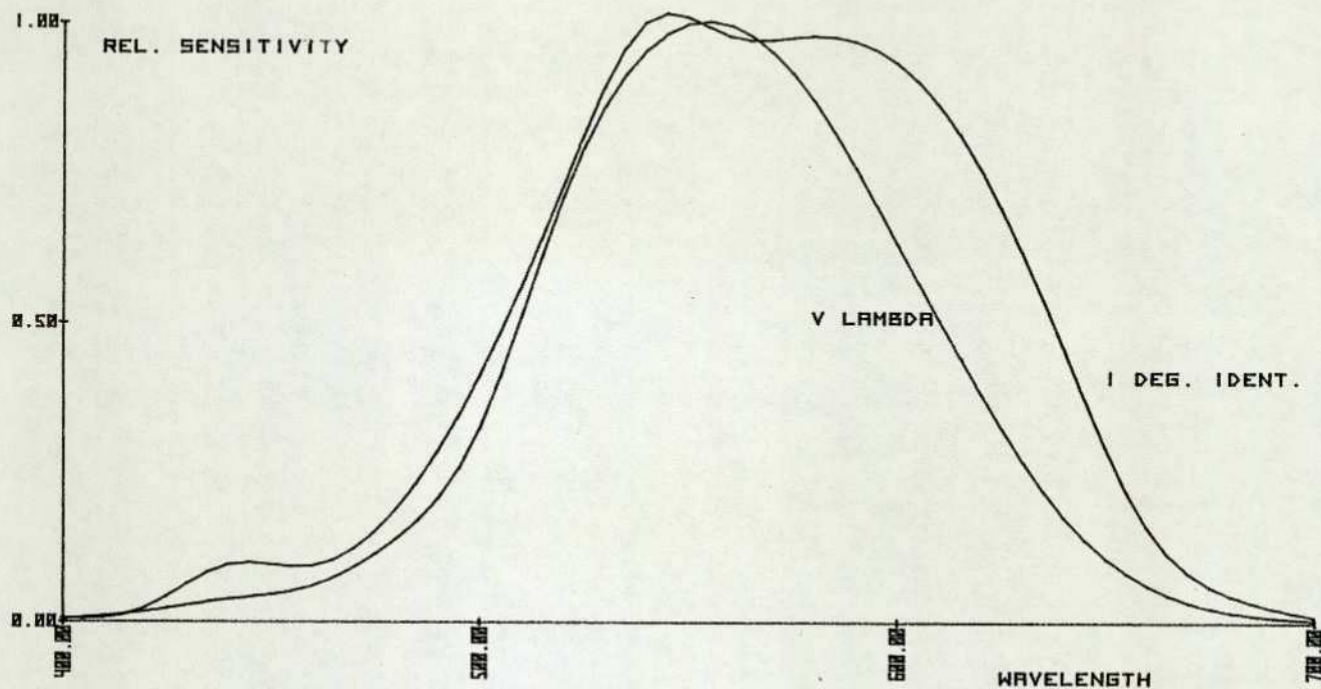


FIGURE 9.1 COMPARISON OF V LAMBDA CURVE WITH REL. SPECTRAL SENSITIVITY FUNCTION DERIVED FROM IDENTIFICATION THRESHOLDS. ONE DEGREE DATA (MEAN OF 2 OBSERVERS)

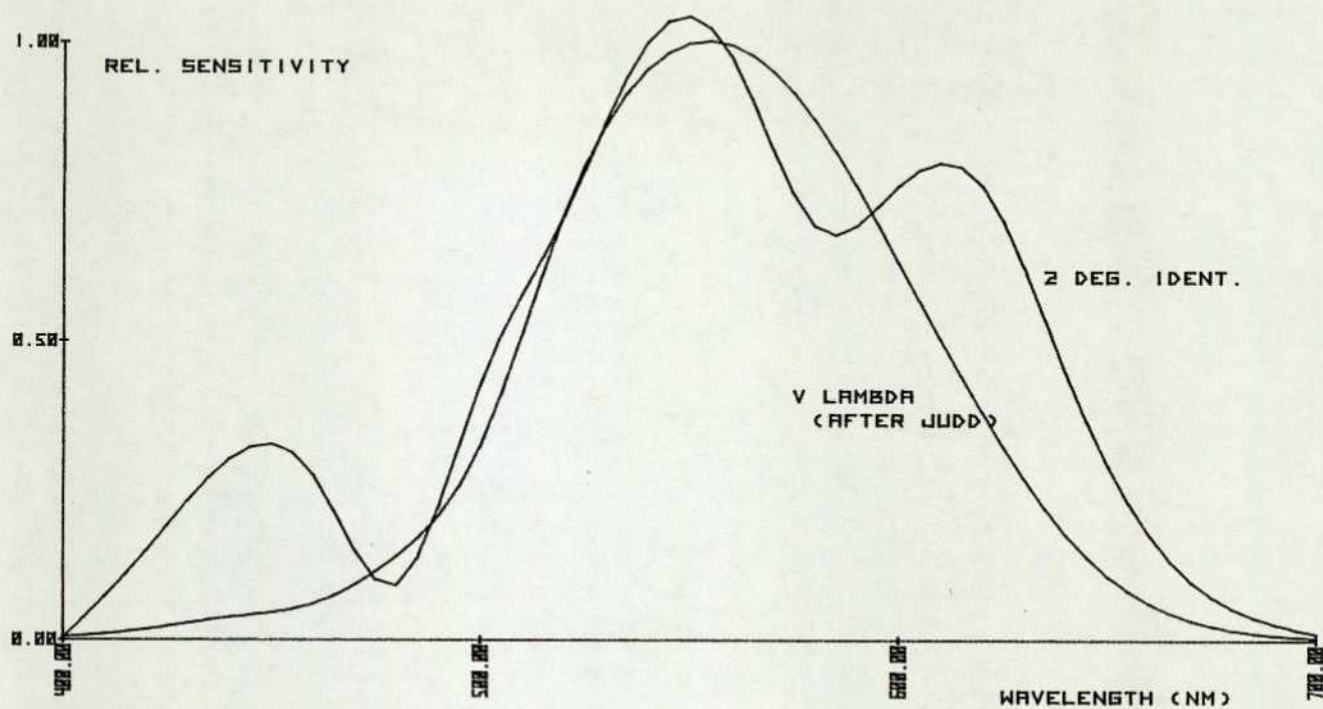


FIGURE 9.2 COMPARISON OF V LAMBDA CURVE WITH REL. SPECTRAL SENSITIVITY FUNCTION DERIVED FROM IDENTIFICATION THRESHOLDS. TWO DEGREE DATA (MEAN OF 2 OBSERVERS)

As already discussed in chapter eight the relative spectral efficiency functions for identification of targets presented on a neutral background differ significantly from the V_λ function and this is emphasised in the two figures. These data can be used to compute a "luminance" more appropriate to the task involved, by weighting the target spectral radiance with one of the two functions. This was done for the targets used in chapter seven (the same method could not be applied to the colorimetric data for targets in other experiments since the radiance values were not available). The 1° square target radiance was weighted with the 1° identification spectral sensitivity function. Similarly the 2° square target radiance was weighted with the 2° identification spectral sensitivity. Mean reaction times were replotted as a function of these new "luminance" values. The results are illustrated in figures 9.3 to 9.4. Data for observer I.M. were either exponentially (1° targets, figure 9.3) or linearly (2° targets) dependent upon this new variable. The results for observer P.D. showed no such dependence however.

The results for observer I.M. support the idea that speed of recognition is a function of target contrast where contrast is that appropriate to the conditions under which the task is performed. Thus high contrast targets tend to preferentially stimulate the achromatic mechanism irrespective of the purity of the target (i.e. colour information becomes irrelevant). As contrast approaches threshold (targets on a neutral background) however, the spatial and temporal properties of the stimulus may give preference to either the chromatic or the achromatic mechanisms in a probabilistic manner. It is then necessary to determine a more appropriate spectral sensitivity function.

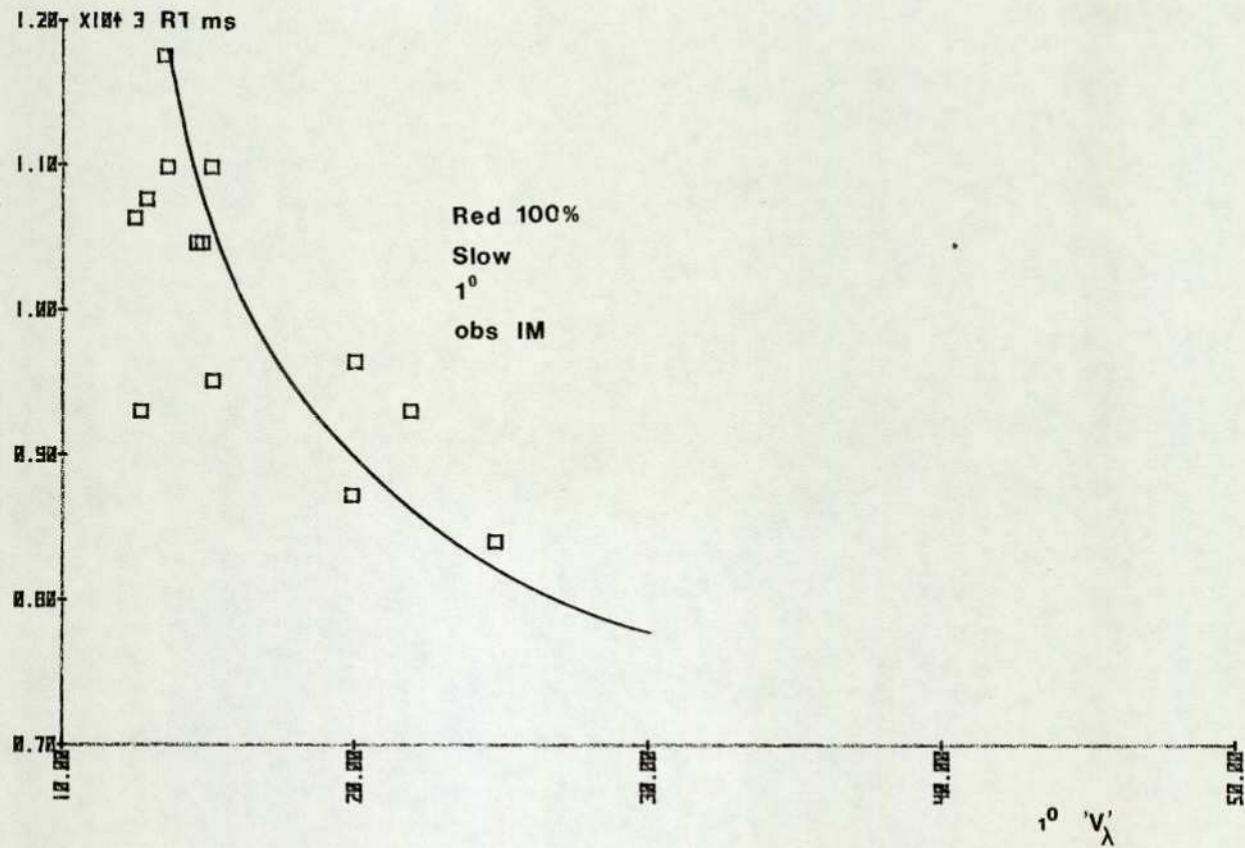


Figure 9-3

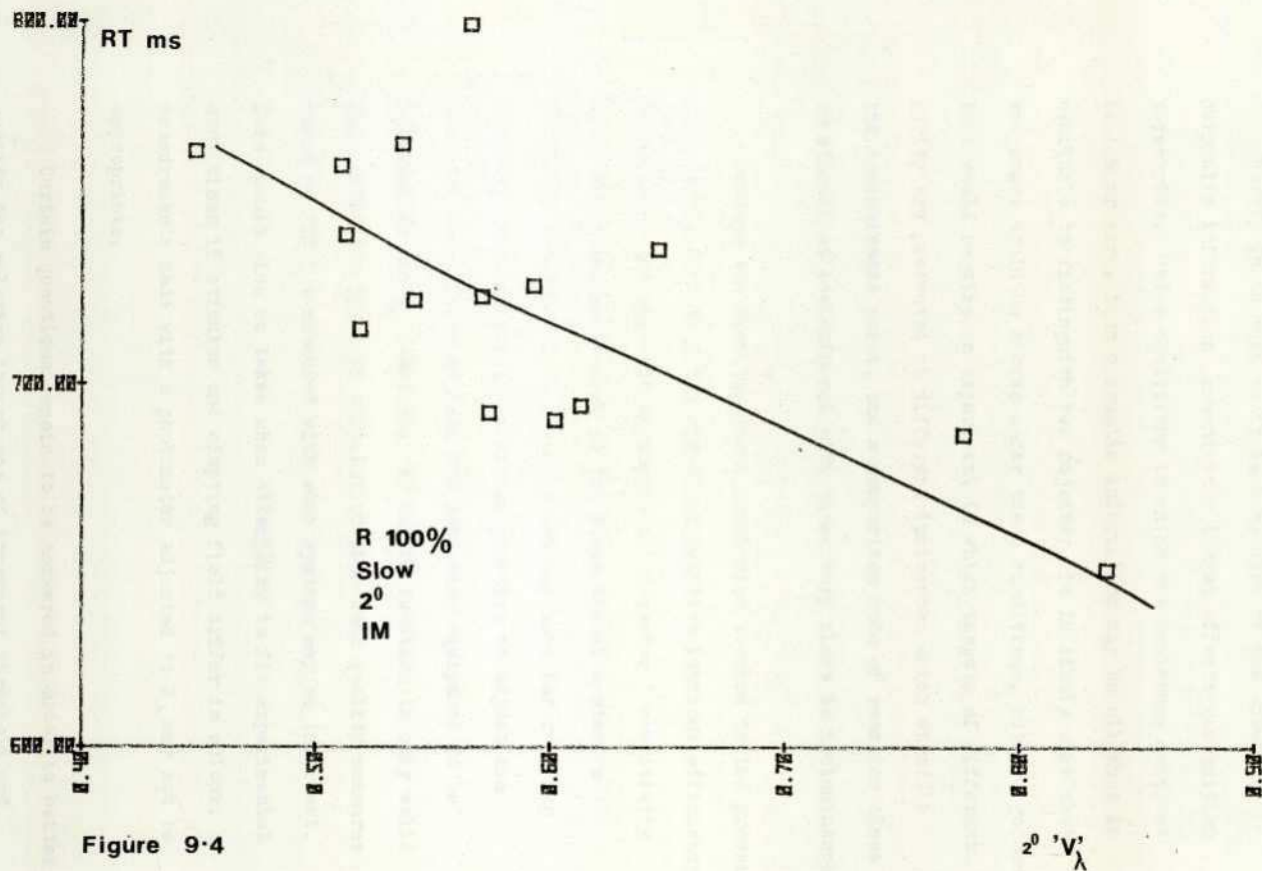


Figure 9-4

9.2 Conclusions and future work

Purity in as much as it is a measure of the amount of chromatic information present in a target affects recognition thresholds. Under conditions in which the luminance contrast is low or zero, then chromatic information may be all that is available to distinguish two objects. It is likely also that responses would be slower under these conditions, but a rigorous test would require an experiment in which targets of different purity are presented at different luminances which straddle the isoluminance point, and a comparison made of reaction times to stimuli at isoluminance with those very close to isoluminance.

Perhaps the most important conclusion reached in the present work is the fact that the classical relative luminous efficiency function is not the most appropriate 'detector' sensitivity when the luminance channel of the human visual system is partially adapted. Such a conclusion may have far reaching effects. For example it is common practice to adjust the spectral sensitivity of lens MTF measuring equipment to be the same as the V_λ function. If the V_λ function is only valid for particular types of stimulation then lens quality measures based on MTF's measured with such systems may be incorrect. Care should also be taken when attempting to fix experimental conditions if stimulus and adapting field differ in colour. Measurements made with a photometer adjusted to V_λ may not be appropriate.

Certain questions remain to be answered in order to better quantify the relative importance of increment threshold and relative luminous efficiency functions.

1. How much does the luminance channel need to be adapted before a significant deviation from the

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APPENDIX I

RELEVANT ASPECTS OF INFORMATION THEORY

The development of a theory of information transfer by Shannon and Weaver (1949) was aimed at telephone communication system and it is not surprising therefore that the authors considered a serial sequence of events. They conceived of information as being a measure of the uncertainty of the occurrence of an event. Since the occurrence may also be described by a probability it seems obvious that information and probability should be related.

The function derived is given by equation (1).

$$H_{\max} = - \sum_i p_i \log_2 p_i \quad (1)$$

where $H_{\max}$ is the total information provided by i events each with a probability of occurrence of p_i . When the probability of every event is the same (p) equation (1) reduces to

$$H_{\max} = - \log_2 p \quad (2)$$

$H_{\max}$ is normally expressed in bits where one bit is the information provided by a knowledge of one of two equiprobable events.

It is conceivable that a series of events might have an information content of $H_{\max}$ as computed by equation (1) but in

actual fact only provide a lower information content H_a (this may occur if the events are not independent as is assumed in the derivation of equation (1)). Shannon and Weaver (1949) attempted to estimate this proportion of unused information by defining a term called redundancy (R).

$$R = 1 - H_a / H_{\max} \quad (3)$$

This function may be applied to more than one part of the four parts of the information handling sequence defined by Shannon and Weaver (1949):

1. Source
2. Encoder
3. Channel
4. Decoder

Redundancy of the source represents a potential decrease in the amount of information to be transmitted, and for a channel loaded beyond capacity this could result in an improvement in performance.

Redundancy of the channel occurs when the information of the source is less than the channel capacity and as such is unlikely to improve performance unless noise is present.

An alternative way of considering how redundancy may be controlled proposed by Evans (1967) is to consider equation (3). An increase of $H_{\max}$ is termed technical discrimination redundancy,

while that due to an decrease in H_a is called constraint redundancy (R_c).

Application of information theory to pattern perception has led to the identification of the four stages in information transfer, with different components of the experimental paradigms used.

- I. The subject as encoder, channel and decoder; patterns as the source.

Each pattern as a whole is identified with a member of the stimulus set and what comprises the pattern is not taken into account. The value of $H_{\max}$ is given by

$$\log_2 N$$

where N is the number of patterns used. The actual uncertainty (H_a) may be less if constraints are placed on the selection of the patterns.

- II. The subject as encoder, channel and decoder; pattern elements as the source.

This identification is best suited to describe methods which use pattern reproduction to test perception, since each element is considered individually (e.g. Smets 1973).

III. Pattern as signal; subject as decoder.

In this case the experimenter is the source and encoder i.e. he determines the probability of each event (pattern). The subject as a decoder may refine the transmitted information e.g. by removing redundancy.

If an experimenter forms a subset of k patterns from the total population of patterns and presents them in a random sequence while the subject attempts to identify (recognise) them then the experimenter is equivalent to a source with k states (H_s).

The patterns may in turn have an uncertainty dependent upon the total number of different patterns which can be produced. This is termed the channel capacity (since the patterns represent channels in the channel).

Excess (unused) channel capacity (H_e) may then be defined by

$$H_e = H_{\max} - H_s$$

Redundancy may then be expressed as

$$R = 100 \frac{H_{\max} - H_s}{H_{\max}}$$

The excess channel capacity is the equivalent of the discrimination redundancy referred to earlier.

As well as randomly selecting k alternative patterns another form of constraint may be applied to the patterns selected (e.g. the central element of the matrix of the pattern may be constrained to be black).

Thus

$$H_e = H_{\max} - H_s - H_c$$

In summary it is apparent that when the model of Shannon and Weaver (1949) is applied to pattern perception it should be used with care since six descriptions are available:-

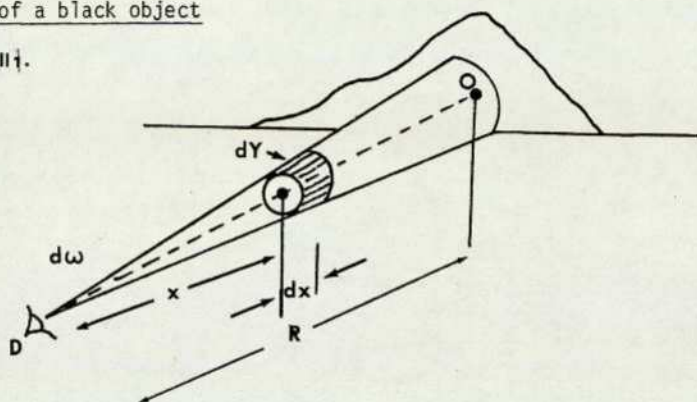
Total channel capacity	$(H_{\max})$
Amount of constraint	(H_c)
Source uncertainty	(H_s)
Excess channel capacity	(H_e)

There is also constraint redundancy (R_c) and discrimination redundancy (R_e).

Appendix II

1. Radiance of a black object

Figure A.II.1.



Consider an elemental volume dY

$$dY \approx x^2 dx d\omega \quad (1)$$

of a cone of air subtending an angle $d\omega$ at the detector (D), originating at an object O above the horizon, at a distance (R).

The radiant intensity of dY in the direction of D will be

$$dI_e = AbdY \quad (2) \quad \begin{aligned} A &= \text{constant} \\ b &= \text{scattering coef.} \\ I_e &= \text{radiant intensity} \end{aligned}$$

The irradiance at the detector will be

$$dE_e = x^{-2} e^{-bx} dI_e \quad (3)$$

Hence the radiance of the elemental volume is

$$dL_e = x^{-2} e^{-bx} dI_e (1/\omega) \quad (4)$$

Using equations (1) and (2) reduces to

$$dL_e = Ab e^{-bx} dx \quad (5)$$

Integrating this over the entire cone gives the apparent radiance of the complete object L_e

$$L_e = \int_0^R Ab e^{-bx} dx = A(1 - e^{-bR}) \quad (6)$$

In the limit as R tends to infinity the object radiance will equal horizon sky radiance $L_{e,h}$

$$L_{e,h} = \int_0^{\infty} Ab e^{-bx} dx = A \quad (7)$$

$$\therefore L_e = L_{e,h} (1 - e^{-bR}) \quad (8)$$

This term represents the air-light (since the object has a radiance of zero).

2.2. Radiance of an object with an intrinsic radiance
at distance R

The radiance of the object will be attenuated according to Lambert's law

$$L_e = L_{e,o} e^{-br} \quad (9)$$

But as shown in section (3) a portion of airlight will be added to the viewing path of the object, thus the apparent radiance is given by the radiance remaining after attenuation, plus that contributed by airlight i.e.

$$L_e = L_{e,h} (1 - e^{-bR}) + L_{e,o} e^{-bR} \quad (10)$$

If absorption as well as scattering is taken into account the scattering coefficient may be replaced by the extinction coefficient (μ).

Hence

$$L_e = L_{e,h} (1 - e^{-\mu R}) + L_{e,o} e^{-\mu R} \quad (11)$$

The radiation may also be restricted to a narrow spectral band whence

$$L_{e,\lambda} = L_{e,h,\lambda} (1 - e^{-\mu_\lambda R}) + L_{e,o,\lambda} e^{-\mu_\lambda R} \quad (12)$$

TABLE A II 1 NAMES AND CHROMATICITY COORDINATES⁺
OF SPECTRAL REFLECTANCE CURVES OF LAMBERTIAN SURFACES

Surface Name	Chromaticity Co-ordinates			
	x	y	u'	v'
Signal Red*	0.5991	0.3369	0.4100	0.5188
Brick Red*	0.4150	0.3727	0.2499	0.5050
Elm (Young)*	0.3613	0.4507	0.1880	0.5278
Aircraft light grey	0.3172	0.3378	0.1976	0.4736
N.A.T.O. Green	0.3311	0.3604	0.1988	0.4869
Roundel Blue	0.2310	0.2108	0.1823	0.3744
Cobalt Blue	0.2306	0.2432	0.1690	0.4011
Uniform diffuser	0.3123	0.3295	0.1974	0.4685
*Source of data - Krinov (1953)				

⁺Assuming D₆₅ illuminant.

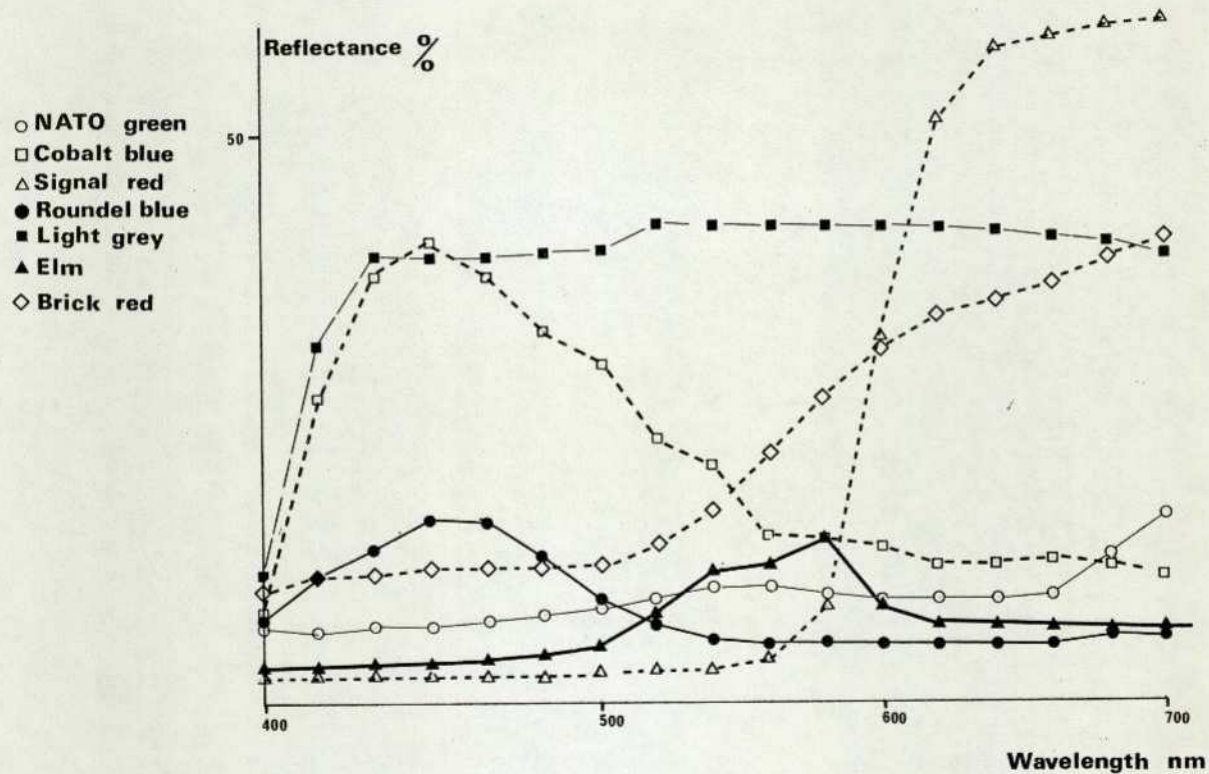


Figure A11 2 Surface spectral reflectance curves

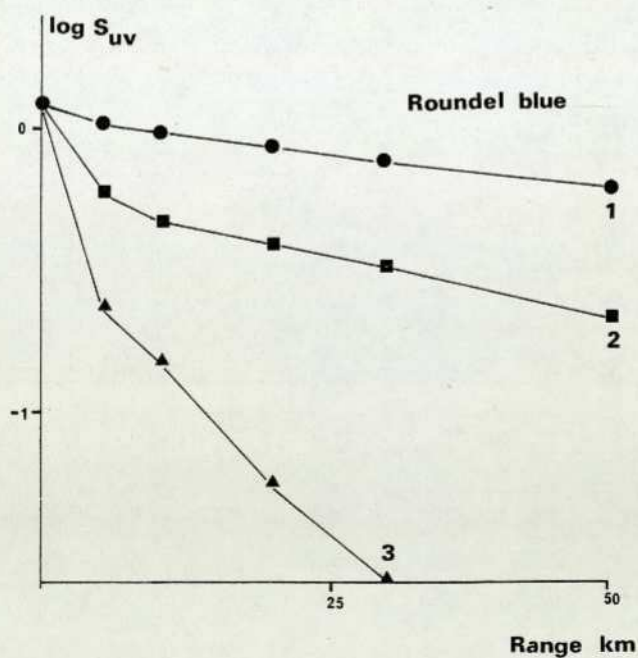
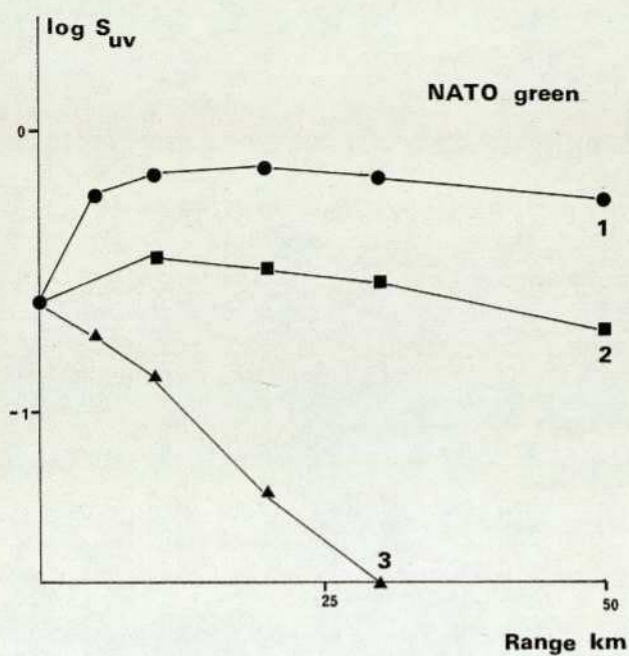


Figure A.11.3 Effect of range on metric purity
 1. Rayleigh atmosphere
 2. & 3. exponent of 2.09 and 1.03 respectively

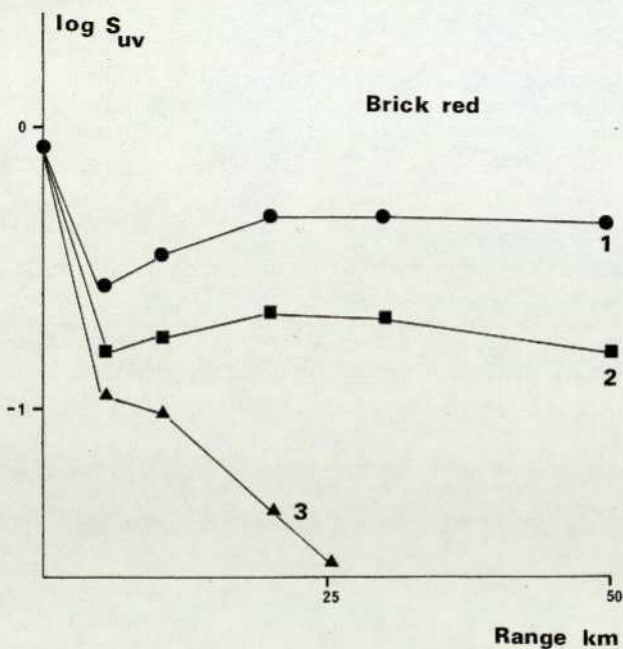
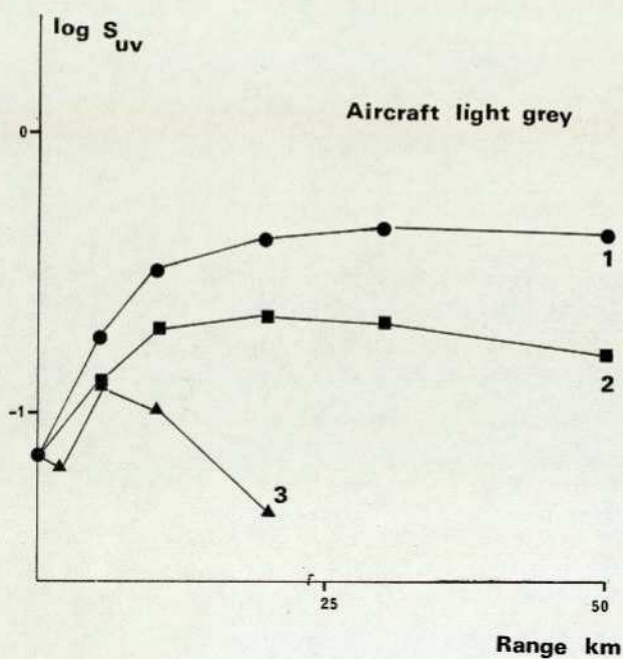


Figure A.11.4 Effect of range on metric purity
 1. Rayleigh atmosphere
 2. & 3. exponents of 2.09 and 1.03 respectively

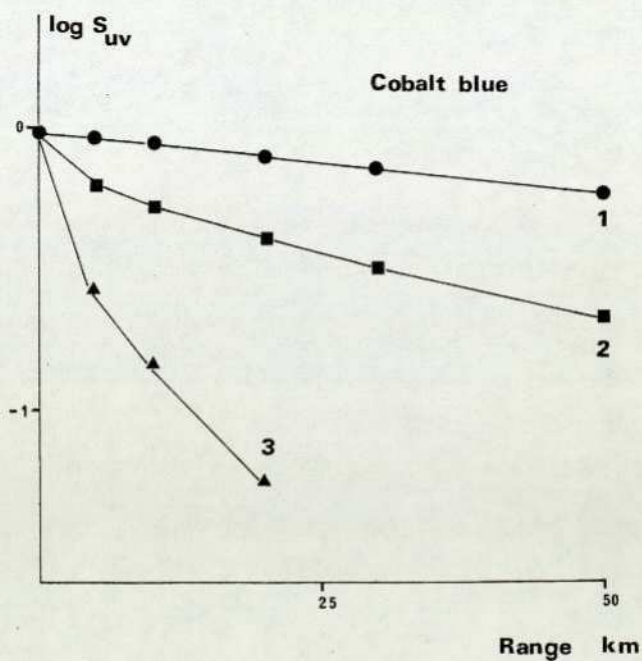
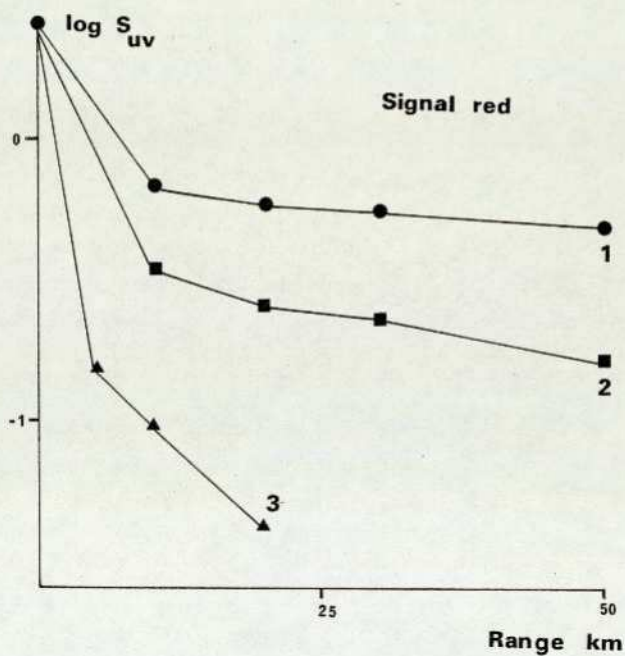


Figure 8.11.6 Effect of range on metric purity
 1. Rayleigh atmosphere
 2. & 3. exponents of 2.09 and 1.03 respectively

APPENDIX III

INSTRUMENTATION

This appendix describes the instruments referred to in the main text, and the procedures used in their calibration.

(a) Timing

The majority of the reaction times were collected using a Campden Instruments timer, which provided a resolution of ± 1 millisecond.

Reaction times measured when an experiment was under computer control were obtained by means of a software loop, i.e. the time required by the computer to perform a fixed set of instructions was assumed to be constant. To obtain an estimate of how long a single loop through the fixed set of instructions took to perform, two additional statements were added - one before and one after the fixed set. These statements controlled an output line which was monitored by means of a (Textronix) oscilloscope. The routine was then run with the fixed instructions being performed a large number of times (e.g. 500). Since an instruction took approximately one millisecond and there were four instructions in the instruction set, the two additional statements which were only performed once each, only added 2 milliseconds in 2000 (0.1%).

500 loops required 1900 milliseconds which is equivalent to 3.8 milliseconds per loop. This was rounded to 4 ms for computational purposes (this gives a 5% error in 200 loops, for example).

When the onset time of the various stimuli was required a silicon photodiode (UDT 10DF) and amplifier (gain of 100) in conjunction with a Textronix oscilloscope was used.

(b) Photometry

Three instruments were used at various times for photometric measurements:

i) Spectra 'Spotmeter'

This instrument uses a dye in glass filter to approximate the relative luminous efficiency (photopic) curve. The area measured subtended 1° at the detector.

ii) Gamma autoranging telephotometer (Model 2009)

This instrument uses the same type of filter as the "Spectra", but is more versatile since the in built fibre optic probe can be changed to measure 2, 6, 20, 60 and 180 minute areas.

iii) Hagner Photometer

This is a portable photometer/illuminance meter and was only used to provide rough estimates of photometric quantities.

iv) Gamma telespectroradiometer

This was used primarily as a colorimetric device but was also capable of providing photometric data.

(c) Colorimetry

Only one device was used to provide colorimetric quantities - a Gamma tele-spectroradiometer. The instrument was capable of measuring stimuli subtending 6, 60 and 180 minutes of arc. It's spectral range was from 380 - 800 nm with a bandwidth of 6 nm. All stimuli and surround chromaticities were computed from measurements made at 5 nm intervals. This approximates the N.P.L. recommended sampling procedure i.e. sampling interval equal to bandwidth. (This is particularly important when sources with emission lines (e.g. fluorescent tubes) are measured.

(d) Spectral reflectance and transmission

These quantities were measured using a Pye SP8 - 100 spectrophotometer (Range 200 - 900 nm, bandwidth 1nm). The wavelength calibration was checked using a high quality interference filter (peak wavelength accurate to $\pm 0.3\%$). Density values were checked using a grid filter.

(e) Spectral irradiance

A UDT silicon photodiode (Pin 10DF) and linear high gain amplifier was used to measure spectral irradiances. The spectral response of the diode was neutral over the visible region of the spectrum to within 5%. (see section (f)).

(f) Calibration

All photometers, radiometer and silicon diodes were calibrated using a secondary standard source (N.P.L. tungsten filament, pyrex envelope lamp).

For photometric and radiometric calibrations a white reflector (pressed Kodak barium sulphate powder disc freshly prepared) with a nominally neutral spectral reflectance curve was positioned 1.0 metres from the source filament. The devices under test were positioned at an angle of 45 degrees and at a distance of 1.0 metres from this surface. Photodiodes were mounted in a tubular baffle system designed to allow the complete filament to illuminate the detector, but to prevent stray light effects. A portion of the baffle system allowed filters to be inserted into the beam path. The detector was placed 1.0 metres from the source.

The lamp was run under the conditions recommended by the N.P.L. certificate of calibration. Lamp current was monitored using a calibrated digital multimeter (calibrated ^{by} courtesy of the Post Office) in conjunction with a 0.01 ohm standard resistor. The lamp was powered by a high quality stabilised d.c. supply.

Using the N.P.L. estimates of changes in radiant emittance resulting from a unit change in lamp current, and the known accuracy of the current measuring system it was deduced that a calibration was no better than within 8% of the true values.

C Calibration of the photometers provided a percentage correction factor for each instrument (e.g. the Spectra Spotmeter was found to be under - reading by 20% thus all measurements were increased by 20%.

The radiometer was calibrated in absolute terms allowing it to be provide the following information:

1. Radiance at 5 nm intervals
2. Chromaticity coordinates
3. Luminance

These data were produced using a suite of computer programs run on an HP9825A desk top computer. (Note that luminance was computed using the CIE 1931 relative luminous efficiency curve. This means that the criticism of the other photometers used does not apply in this case).

The suite of computer programs also allowed information to be input from other sources (e.g. spectrophotometers) and as well as chromaticity coordinates, purity dominant wavelength and psychometric quantities could be computed.

The silicon photodiodes were calibrated in absolute irradiance terms using interference filters (Balzer) of known transmission profiles. It was found however that short wavelength filters were providing additional energy from secondary peaks in the near infra-red. The calibration was therefore repeated using 2 mm thick heat absorbing glass and a suitable

correction applied. When this was done the photodiode response was found to be neutral (± 5%) over the visible spectrum. A mean value was therefore used to compute irradiance.

CLASSIFICATION DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer CAP Hue - red

REDUNDANCY (%) (yes and no responses)	VEILING LIGHT LEVEL		
	1	2	3
0	962,49	1041,111	1181,155
	878,49	960,60	1151,57
20	916,31	950,59	928,61
	1247,167	1464,146	1340,108
40	1015,113	923,43	978,168
	907,67	782,31	834,30
60	837,32	872,76	894,46
	936,76	901,7	954,65
80	746,21	730,49	852,50
	871,69	948,15	845,54
100	800,56	965,103	921,147
	1011,75	790,48	933,68

Observer CAP Hue - green

REDUNDANCY (%) (yes and no responses)	VEILING LIGHT LEVEL		
	1	2	3
0	897,84	975,97	1052,84
	1097,130	1086,73	1044,67
20	994,101	754,31	871,47
	806,32	1200,97	1351,118
40	967,46	1034,85	1045,83
	771,29	861,39	930,79
60	980,112	955,81	990,107
	1005,938	938,62	880,52
80	816,39	794,25	1010,242
	898,38	777,39	816,53
100	795,53	805,35	779,58
	878,49	871,74	793,27

DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer CAP Hue - blue

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

	1	2	3
0	967,53 1050,77	995,30 1150,112	1181,103 1000,67
20	920,79 1389,122	931,62 1111,97	1115,95 1283,106
40	1036,112 832,42	1121,123 964,75	989,87 806,35
60	1051,141 789,40	969,123 906,53	1037,85 879,40
80	833,34 835,35	851,39 837,12	802,54 917,85
100	766,26 870,56	824,45 896,56	892,59 928,65

Observer CAP Hue - white

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

	1	2	3
0	889,70 989,74	981,22 1052,82	1028,27 1029,68
20	977,80 1078,46	969,110 1193,127	1129,103 1396,139
40	1039,84 797,18	1137,181 815,30	934,116 916,49
60	923,84 897,56	1094,113 825,30	1107,100 1221,102
80	918,89 944,61	827,43 875,50	1082,158 910,66
100	933,105 839,64	788,45 946,23	825,33 921,85

DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer EMHM Hue - red

REDUNDANCY (%) (yes and no responses)	VEILING LIGHT LEVEL		
	1	2	3
0	1048	899	1264
	817	858	901
20	926	923	927
	1035	817	-
40	1002	816	799
	855	693	786
60	940	761	881
	753	887	-
80	1040	776	809
	834	886	770
100	816	748	1353
	858	940	1066

Observer EMHM Hue - green

REDUNDANCY (%) (yes and no responses)	VEILING LIGHT LEVEL		
	1	2	3
0	843	820	1043
	894	-	977
20	1140	837	-
	805	839	1032
40	870	726	845
	786	834	784
60	778	831	749
	847	673	713
80	870	847	875
	793	-	814
100	1171	778	-
	803	749	852

DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer ENHM Hue - Blue

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)	1	2	3
0	1076	912	846
	-	993	-
20	804	1073	943
	952	1098	1406
40	841	776	811
	800	786	868
60	778	696	832
	808	824	751
80	855	800	1124
	811	-	896
100	878	825	922
	825	847	979

Observer ENHM Hue - white

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)	1	2	3
0	885	887	1009
	944	1011	949
20	763	837	1152
	798	925	-
40	842	704	800
	742	770	861
60	813	866	907
	799	788	873
80	-	983	-
	832	852	880
100	794	786	-
	853	777	1024

DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer IRM Hue - red

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)	1	2	3
0	737,46	745,50	835,15
	822,38	906,67	878,60
20	835,64	919,68	872,47
	865,45	919,41	909,37
40	924,51	940,101	805,27
	827,28	940,101	805,27
60	812,32	733,44	933,65
	745,22	882,46	901,55
80	782,24	825,41	806,34
	768,20	833,14	784,51
100	784,27	801,11	933,138
	798,46	796,10	845,19

Observer IRM Hue - green

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)	1	2	3
0	789,35	933,59	857,70
	797,18	901,65	1047,83
20	840,28	839,63	940,62
	907,28	869,52	1080,133
40	851,44	850,31	860,51
	731,8	726,20	792,36
60	978,203	917,100	786,36
	831,40	777,29	815,26
80	837,23	780,28	821,40
	905,65	843,92	870,36
100	856,64	841,43	1139,120
	879,55	746,18	870,26

DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer IRM Hue - blue

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

	1	2	3
0	801,27 834,34	891,32 1016,48	835,52 921,45
20	905,32 1015,50	894,34 882,24	1106,94 1116,84
40	763,31 749,12	834,30 773,22	938,66 762,37
60	764,33 806,26	762,30 793,31	853,37 807,45
80	781,52 811,26	829,27 810,34	774,18 878,84
100	855,53 887,66	794,50 920,69	914,71 876,35

Observer IRM Hue - white

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

	1	2	3
0	788,57 831,28	858,31 861,20	962,75 843,20
20	830,62 963,47	942,54 949,56	824,32 993,41
40	877,41 776,25	893,55 829,20	718,40 912,31
60	770,43 848,12	853,105 791,38	868,52 816,60
80	822,22 823,30	792,25 837,38	987,104 943,78
100	792,27 838,42	890,110 910,31	1050,137 1099,146

DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer SF Hue - red

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

1

2

3

0	813,41	797,22	794,47
	863,34	926,50	941,47
20	910,55	856,54	843,18
	954,39	919,41	940,75
40	853,18	900,26	893,70
	799,24	730,38	797,24
60	877,35	797,41	821,30
	828,45	721,10	788,31
80	763,31	770,55	749,16
	736,26	748,30	728,22
100	980,107	801,24	818,51
	784,41	772,40	780,52

Observer SF Hue - green

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no response)

1

2

3

0	811,38	857,32	914,97
	911,34	852,20	913,133
20	958,32	939,41	941,86
	921,16	881,28	867,64
40	865,42	927,55	838,31
	827,52	778,12	792,32
60	863,47	813,31	821,27
	735,25	715,25	771,22
80	742,20	721,36	764,22
	742,24	734,21	825,49
100	753,44	743,14	830,31
	770,50	826,50	819,25

DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer SF Hue - blue

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

	1	2	3
0	819,35	823,38	886,49
	889,26	897,51	1084,120
20	973,85	998,57	813,41
	796,37	827,44	950,49
40	805,62	874,69	935,29
	796,28	772,41	829,30
60	839,46	825,32	843,38
	722,23	769,31	924,29
80	703,10	741,34	867,55
	768,31	834,24	761,29
100	798,36	872,86	827,26
	794,26	798,38	829,26

Observer SF Hue - white

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

	1	2	3
0	855,27	773,33	843,8
	859,31	852,72	924,76
20	899,55	874,80	982,46
	925,58	915,44	939,57
40	888,14	883,53	893,49
	756,11	822,12	837,14
60	828,24	792,29	815,31
	750,46	762,30	852,45
80	808,21	767,5	851,63
	825,44	812,27	772,28
100	864,43	784,31	797,35
	815,44	770,33	853,54

DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer TT Hue - red

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

1

2

3

0

823,29

882,111

840,73

865,44

935,63

880,38

20

745,29

893,67

834,10

946,68

1069,107

812,35

40

935,44

962,58

833,54

825,22

815,36

798,33

60

750,54

893,21

798,29

944,64

835,40

844,39

80

833,17

859,36

823,44

829,74

751,34

864,29

100

723,22

800,57

796,36

800,42

884,36

882,78

Observer TT Hugh - green

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

1

2

3

0

852,70

775,28

827,82

868,56

791,25

1104,65

20

744,58

847,38

902,56

918,59

1034,117

939,56

40

909,60

869,28

745,14

817,20

822,44

844,51

60

729,30

831,40

728,26

967,107

1117,111

941,43

80

886,65

843,98

991,108

858,39

743,26

919,124

100

699,35

797,41

856,59

933,53

774,46

878,42

DATA FROM CHAPTER FOUR

Values are mean reaction time and standard error of the mean (N = 5)

Observer TT Hue - blue

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

	1	2	3
0	897,45	875,41	783,65
	993,97	1224,147	1021,82
20	765,51	770,4	918,62
	862,62	939,127	867,78
40	910,56	904,36	884,53
	825,30	837,24	840,53
60	863,25	821,19	861,24
	1021,128	985,113	824,87
80	987,63	764,34	985,91
	842,51	926,32	938,92
100	779,17	719,12	783,44
	912,56	860,64	810,20

Observer TT Hue - white

REDUNDANCY (%)

VEILING LIGHT LEVEL

(yes and no responses)

	1	2	3
0	998,47	779,48	986,79
	998,62	866,38	1038,131
20	880,44	769,37	959,99
	1014,54	867,26	1107,166
40	887,78	867,84	808,36
	782,18	890,34	993,76
60	837,48	764,37	808,43
	897,56	858,57	896,75
80	802,85	957,23	1249,138
	803,25	787,40	894,64
100	793,29	848,44	838,26
	1024,62	863,60	832,46

INCREMENT THRESHOLD DATA - CHAPTER EIGHT

Wavelength (nm)	Jes 2° flicker (min.)	IM 1° flicker (min.)	JES 2° flicker (det.)	1M 1° flicker (det.)	mean det. 1Hz. 1°	mean det. 1Hz. 2°
396	-	-	-	-	-	6.91
416	-	6.06	-	-	7.58	7.88
436	6.26	6.21	6.33	-	7.95	8.27
456	6.48	6.32	6.18	6.38	7.80	8.11
476	6.78	6.67	6.98	6.52	7.77	8.00
496	7.02	6.94	7.27	6.96	7.96	8.05
516	7.18	6.29	7.51	7.26	8.04	8.32
536	7.32	7.35	7.51	7.32	8.31	8.24
556	7.26	7.26	7.60	7.38	8.16	8.28
576	7.25	7.25	7.48	7.29	8.12	8.18
596	7.06	7.21	7.23	7.30	8.05	8.29
616	6.91	7.02	7.07	7.08	8.00	8.19
636	6.62	6.70	6.80	8.35	7.78	8.03
656	6.11	6.39	6.21	6.29	7.32	7.65
676	-	5.77	-	5.91	6.32	7.04
696	-	5.17	-	-	6.22	6.41

Wavelength (nm)	mean indent. 1°, 1Hz.	mean indent 2°, 1Hz	7.5' arc IM, det.
396	-	-	-
416	6.28	7.32	-
436	6.88	7.63	6.45
456	6.85	7.59	6.31
476	7.18	7.12	6.89
496	7.50	7.78	7.03
516	7.76	8.00	7.84
536	7.90	8.14	7.86
556	7.90	8.12	8.27
576	7.86	7.95	7.97
596	7.84	8.02	8.18
616	7.86	8.02	7.86
636	7.53	7.79	7.56
656	7.09	6.38	7.21
676	6.55	6.86	6.58
696	5.90	6.19	6.04