FORM SPECIFIC ADAPTATION AND PATTERN RECOGNITION:

AN EXPERIMENTAL AND THEORETICAL STUDY

by

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CONTENTS

ABSTRACT.

Among the theories of visual pattern recognition are structural theories which propose that patterns are encoded in terms of features and their spatial relationships (relations). Structural theories are examined here with both adaptation and pattern recognition techniques. In particular, the effects of changes in the relational-structure of patterns formed from bar and disc features are examined. For this purpose a novel adaptation technique is developed and used for measurements of the contrast threshold elevation effect.

Data are presented which show that the visual system is adaptationally sensitive to the shape of local features, but adaptationally insensitive to their relative positions. An exception to the latter conclusion was the finding of adaptational sensitivity to local periodicity. It is argued, however, that this periodicity sensitivity may simply be a result of size selectivity.

Data are also presented which were obtained in a discrimination-under-uncertainty experiment in which stimuli analogous to those in the adaptation experiments were used. These data reveal sensitivity to local feature changes and insensitivity to feature relative-position changes. Because of the similarity in results from the adaptation and discrimination-under-uncertainty experiments it is argued that both techniques reveal the properties of the initial stages of pattern processing. It is also argued that these results show a fundamental difference in the way in which features and relations are processed prior to pattern recognition.

To investigate how structural theories may be applied in a pattern recognition task a relational-structure encoding model is developed and its predicted pattern recognition performance is compared with experimental data. Once equipped with the capability

of performing certain discrete operations on the relational-structure representation this model provides a good fit to the experimental data.

CHAPTER 1. INTRODUCTION.

An object in the world may be described in terms of physical properties such as position, size, mass and velocity at each instant of time. Only some of these properties are available for analysis by the human visual system, which is restricted to forming a description of an object on the basis of light either emitted by or reflected from the object to the observer. In these terms the best description of the object available to the visual system consists of a labelling of each point in space (relative to the observer) by its energy spectrum at each instant of time. The complex picture that an observer reports as the world of objects about him is in fact a further degradation of the above description of the "outside world" in terms of energy spectra which is available to the visual system.

Vision researchers are therefore concerned with the determination of which parts of this available information are used by the visual system and the ways in which the information used is processed to produce a "sensation of seeing" and initiate some appropriate action by the observer.

The subject of this thesis is an examination of some aspects of the spatial vision abilities of the visual system. (A review of other aspects of vision, e.g. colour vision, flicker perception and motion perception may be found in Graham (1965).) Of particular interest is the way in which the available visual information outlined in the previous paragraph is further selected by the visual system to enable the recognition, discrimination and identification of objects or patterns in the external world. This selected information is often regarded as being used to form an internal representation of the external world (Reed, 1973,p1). The nature of these internal representations and the operations which is concerned with the supposed internal representations of objects in the external world, we might describe recognition as follows. An object is recognized when its internal representation coincides with (as measured by an appropriate similarity measure) the internal representation of another object. The internal representation of the latter object may be either formed from a simultaneously presented object or stored in memory having been previously formed.

Note that recognition should be distinguished from identification for the latter is understood to imply that the pattern can be named or labelled (Forgus and Melamed, 1976, p18). Such a labelling process probably occurs after the formation of the internal representations with which we are concerned here. The use of patterns which may be identified and then classified according to criteria other than their geometry (e.g. all the patterns of Fig. 1.1 may be classified as an "M" despite their widely differing geometries) is often avoided in experiments on pattern recognition for the following reason. Any attempt to relate an observers performance at recognising such identifiable patterns to their physical shape would be of little value, except as a description of some higher order classificatory system which is not of immediate concern here.

Fig. 1.1.

It is because of this difficulty in separating previous context from the present event that many experimenters use stimuli such as random blobs, lines and squiggles with no apparent context. Neisser (1976), when developing his schemata theory criticises such an approach from the viewpoint that our current perception of the world is highly dependent upon our previous perception and is part of an interactive process.

This viewpoint is valid in that the stimuli often used in pattern recognition experiments are far removed from real visual scenes in which movement and continuity play an important part in adding to our information (Gibson, 1961, 1966). To obtain information about which processes either <u>can</u> or <u>cannot</u> occur within the visual system it is necessary, however, to simplify the situation to make the problem tractable. Note, however, that a model based upon findings from such "unreal" experiments may be used to process "real" pictures as an assessment of its generality.

With these limitations in mind the approach to pattern recognition used here will be concerned with patterns that can be classified entirely by reference to their geometrical aspects and have no apparent context. Given this limitation we might assume that the responses recorded in the experiments presented here arise from operations carried out on internal representations formed mainly on the basis of pattern geometry.

1.1.1. "Invariances" of pattern vision.

Among the studies of pattern recognition many have been concerned with the variation in recognition performance with various pattern changes, e.g. pattern translation, rotation and size. It is well known that pattern recognition performance is little effected by certain pattern changes (transformations) and that an observer is often able to ignore differences in irrelevant stimulus properties when comparing the shape of two patterns. This ability to recognize objects when they are presented to the observer in various transformed states, e.g. different sizes, is often termed an "invariance" to the transformation involved, e.g. size invariance. For example, the notions of "size invariance" and "position invariance" have been used (Hake, 1966; Sutherland, 1968). Note that the notion of "size invariance" should be distinguished from "size constancy" (see Forgus and Melamed, 1976, p146); the former is the ability to recognise two patterns as being the same shape despite retinal image size differences whereas the latter is a constancy of perceived size despite changes in either retinal size or object distance. The latter probably involves contextual factors in addition to stimulus geometry and is therefore not of direct concern here.

Among the commonly accepted invariance properties of the visual system are size invariance, position invariance and invariance to local pattern distortion (usually termed "jitter"),(Sutherland, 1968; Reed, 1973).

Reaction time studies, in which same-different shape judgements were made of stimuli of various shapes and sizes, have shown that "same" judgement response times increase monotonically with increases in the magnitude of the relative size difference (Sekuler and Nash, 1972; Bundesen and Larsen, 1975; Besner and Coltheart, 1975, 1976). The "different" judgement response times for stimuli differing in size have been shown to be relatively constant (Besner and Coltheart, 1976), although if the stimulus patterns requiring a "different" response are identical apart from being rotated 180° relative to each other "different" response times were found to increase monotonically in a similar manner to the "same" response times (Bundesen and Larsen, 1975). This latter finding may be related to the "mental rotation" processes suggested by Shepard and Metzler (1971) and Cooper (1975) (see below).

The increase in "same" response time with increase in relative size differences might be interpreted as an indication that the "size invariance" observed is the result of some active process for the reduction of the effect of stimulus size differences on their recognition. This contrasts with an invariance arising from the manner in which the stimuli are represented in their respective internal representations. Thus if pattern recognition performance were measured with a limited time for processing (the patterns in the above response-time experiments were visible until the subject responded) we might expect such performance to show "size non-invariance" for suitable size differences. This effect of technique is demonstrated by the differences in the results from reaction time and recognition performance studies in which rotated patterns were used.

It is well known that pattern recognition performance for briefly presented pattern pairs which differ only in relative orientation does not show "rotation invariance". Studies of the variation of recognition performance with changes of orientation have shown that performance is a maximum when the patterns are identical at 0°, declines with increasing angle and then exhibits an upturn to reach a maximum at 180° (Dearborn, 1899; Rock, 1973; Foster, 1978b). Note that these results from experiments where processing time was limited show pattern recognition performance to be non-monotonic with the relative orientation of the "same" pattern pairs. In contrast, reaction time studies (Shepard and Metzler, 1971; Cooper, 1975) have shown a monotonic increase of "same" response time with increasing relative orientation of pattern pairs. This latter result indicates that "given time" the visual system would show "rotation invariance" but we might argue that such an invariance is a consequence of later active processing and is not a result of the initial internal representation of the patterns. The upturn in pattern recognition performance for angles of 180° when processing time is limited might therefore be interpreted as arising from the nature of this initial internal representation.

The notion of "position invariance" is often accepted although evidence exists to show that many aspects of pattern recognition performance vary with the position in the visual field of the stimulus patterns. For example, perceptual similarity judgements (Attneave, 1950), discrimination of mirror images (Sekuler and Rosenblith, 1964; Sekuler and Pierce, 1973), identification of parafoveal figure pairs (Banks, Bachrach and Larson, 1977; Banks, Larson and Prinzmetal, 1979; Chastain and Lawson, 1979), response time for reporting sameness (Corballis and Roldan, 1974; Bradshaw, Bradley and Patterson, 1976), and symmetry perception (Julesz, 1971; Barlow and Reeves, 1979) have all shown dependence on the relative retinal positions of the stimuli. The discrimination of pairs of transformed random dot patterns has also been examined (Kahn and Foster, 1981) and it was concluded that distance between the stimuli and their symmetry relative to the fixation point are important factors in the determination of discrimination performance. Note that it is often difficult to ensure that patterns are presented at the required retinal positions. With steady fixation, however, it should be possible to measure the qualitative effects of varying pattern positions on performance but quantitative measurements should be treated with care.

It appears from the above discussion that many of the "classical" pattern invariances cannot in fact be truly regarded as being invariant. Seemingly, pattern recognition performance varies strongly with some pattern transformations, such as pattern rotation, and weakly with other pattern transformations, such as pattern size and possibly pattern "jitter". In order to explain both these variations and these "invariances" of pattern recognition the theories discussed in the following section have been proposed.

1.2. Theories of pattern recognition.

Neisser (1967, chapter 3) divides the theoretical approaches to the problem of pattern recognition into two main types, these are template matching and feature analysis. In "template matching" theories each input pattern is compared in some way with a standard template for recognition. In "feature analysis" theories recognition is dependent on the presence of certain "parts" in a pattern. The essential difference between these two approaches is in the nature of the internal representation of the input pattern (see Reed, 1973, p12). A more correct formulation of the division between these two classes of theories may be made with reference to this notion of the internal representation.

In "template" theories the internal representation is a wholistic copy (within acuity limits) of the external object. This internal representation is compared in some way with another "template" representation. Certain operations may be performed on the internal representations before the comparison process, but the wholistic nature of the internal representations is preserved. Theories of the latter kind are often termed transformational theories of pattern recognition but will be included under the heading of template matching theories in the following discussion.

In contrast, the internal representation of an external object in "feature analysis" theories consists of a list (not necessarily serial) of certain attributes of the object, e.g. the presence of a line with a certain orientation. These theories also include the case where items in the internal representation list represent relationships between other items e.g. line A connected to spot B (the so called syntactic or structural theories). Note that in this case the internal representation need not contain all the information contained in an object description in contrast with the wholistic internal representation of template matching theories. These "feature analysis" and "structural" classes of theories will be referred to as pattern encoding theories in the following discussion.

In reality a mixture of these two theory classes may exist with each having a different application at various stages of visual processing. For simplicity in the following discussion, however, this distinction between "template matching" and "pattern encoding" theories is used.

1.2.1. Template matching theories.

The simplest form of template matching theory in which an input pattern of retinal receptor activity is compared with some centrally stored record of that activity pattern is usually quickly dismissed for the following reasons (Neisser, 1967, p.50; Reed, 1973, p11). Consider the letter "A" input to the visual system at a particular retinal position, orientation, and size. For recognition of the "A" to take place it is compared with an "A" template which it totally overlaps (see Fig. 1.2a). The problem arises when the "A" is presented to either a different retinal area (Fig. 1.2b), or at a different size (Fig. 1.2c), or rotated (Fig. 1.2d). In the latter cases overlap with the "A" template is minimal and recognition would be poor or non-existent. The fact that the visual system can recognise patterns at different retinal sites, of different sizes, and different orientations would require a separate template to

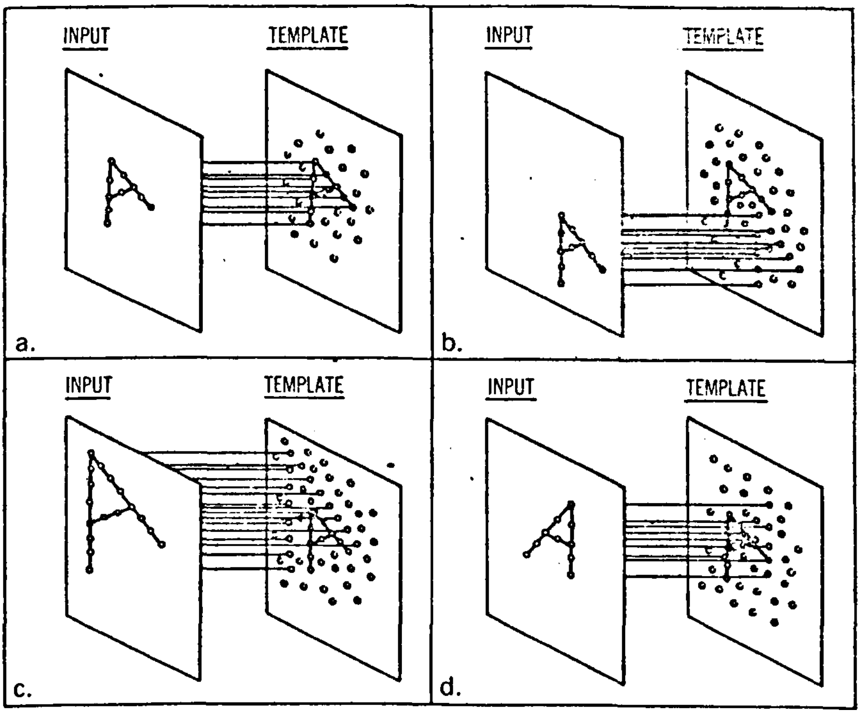


Figure 11. Problems of template-matching. Figure 11a shows an input which matches the template; 11b, a mismatch due to change of position; 11c, a change of size; 11d, of orientation.

Fig. 1.2 From Neisser (1967).

recognise each possible "A" input pattern. In turn this creates a difficulty for the generalisation of pattern classes. For if a new input pattern is presented to the visual system, and belongs to the class of "A's" it may not necessarily have a template for comparison.

One approach to a solution of this problem is to compare the input pattern with each template and to categorise it as belonging to the class with which it has most similarity (measured in an appropriate sense). Although such a theory now only requires a relatively limited number of template classes, discrimination of patterns which are only slightly different would still require the existence of a large number of template classes.

A second approach to solving the difficulties of template matching theories is the use of some form of preprocessing before the template matching process. This notion has given rise to a class of pattern recognition theories usually known as transformational theories. In chapter 10 of this thesis a particular transformational model of pattern recognition is developed and its ability to predict experimental pattern recognition performance is assessed.

Transformational theories.

In a transformational theory of pattern recognition the input pattern undergoes certain internal restoring transformations before comparison with either some other input pattern or some internal "template" (see for example, Pitts and McCulloch, 1947; Hoffman, 1970; Marko, 1973). If the effect of noise in the system is ignored (its effect would be to increase the variability in the measure of coincidence) the operation of such a transformational theory might be represented as in Fig. 1.3.

$$\begin{tikzcd}
A \arrow[r] \arrow[d, dashed, "\tau"'] & \text{i.r.}(A) \arrow[d, "\tau'"] \\
B \arrow[r] & \text{i.r.}(B)
\end{tikzcd}$$

Fig. 1.3 A transformational theory.

In this figure the wholistic internal representations i.r.(A) and i.r.(B) are formed of the input patterns A and B respectively. If some internal transformation τ' may be applied to the internal representations such that

$$\tau'(\text{i.r.}(A)) = \text{i.r.}(B)$$

where equality is measured by some suitable correlation operator $\underline{c}$, then the two patterns would be recognized as the same. Note that the internal compensatory transformation τ' corresponds to some objective transformation τ of the external pattern. The compensatory transformations τ' may take several forms corresponding to transformations τ of the external pattern such as translation, dilation and rotation. When one of the internal representations is a standard template the transformation process is sometimes referred to as normalization (Neisser, 1967, p62).

The following examples illustrate how such transformational theories attempt to explain the pattern recognition abilities of the visual system.

First, the transformation τ' may act to compensate for errors in certain global parameters between the two internal representations (Pitts and McCulloch, 1947, Model II). For example, the input pattern may have its centroid of area shifted by a translation operation to a standard position, its major axis oriented in a certain direction by rotation operators, and its dimensions changed by suitable dilation operators to standard sizes. Note that although these operations are described above as operating on the pattern they correspond to internal transformations performed on the internal representation to produce a standardised internal representation. This standardised internal representation is then compared by the operator $\underline{c}$ with the other internal representation and the amount of "similarity" used as a measure for recognition. Central to this process is the use of certain "allowable" internal transformations, in this case translations, dilations and rotations, to compensate for the differences between the two patterns. The choice of the "allowable" transformations might be, as above, those which compensate for physical movements that can affect the object image (Marko, 1973). In order to account for classification of objects into generalised classes, however, it is necessary in any transformation scheme either to allow the comparison process to select the maximum "similarity" as an indication of class membership or to include certain distortions as "allowable" transformations. For example, Hoffman (1970) proposes the elements of a Lie group as "allowable" transformation operators to allow figure distortions.

Second, a transformation theory of recognition may use the error between the two internal representations being compared to control the internal compensating transformations to maximise the similarity measure (Pitts and McCulloch, 1947; Marko, 1973). Again only transformations belonging to a certain group are allowable in this scheme. Therefore by the appropriate choice of allowable transformation group and comparison method, transformational theories can be devised to overcome the difficulties of the simple template matching procedure.

One of the remaining arguments against transformational/template theories is their inability to deal easily with either picture segmentation or the presence of small changes in the pattern which give rise to a different classification, e.g. an O and a Q (Neisser, 1967, p64).

1.2.2. Pattern encoding theories.

The second class of theories of visual pattern recognition is concerned with the encoding of the input pattern in terms of certain attributes or properties which remain invariant when the input pattern is subjected to certain admissible physical transformations such as translation and dilatation. In such theories two patterns are judged as being the same if their lists of attributes coincide. A pattern is recognised as belonging to a certain class of patterns if its attributes fit the class specifications. Note that the class specifications may allow the inclusion or exclusion of certain attributes of the input pattern without negating its recognition. That is, certain attributes may be regarded as being more critical than others for correct classification.

Three main approaches to the encoding of patterns in terms of their attributes or properties have been proposed, the first concerned with encoding in terms of global attributes, the second concerned with encoding of local pattern attributes. The third approach is an extension of local attribute encoding to include the way in which local attributes are spatially related to each other. This third approach is referred to as a structural encoding theory.

Global attribute encoding.

Pitts and McCulloch (1947) describe a method for the extraction of stimulus properties which remain invariant when the stimulus is subjected to various allowed "transformations". This method forms an invariant property a of a stimulus A by a procedure of "averaging over the group". If G is a group transformations with N members and f is some suitable function the invariant a is formed by:

$$\underline{a} = \frac{1}{N} \sum_{i} \underline{f} \, [\, \tau_i (\underline{a})] \qquad i = 1, \ldots, N$$

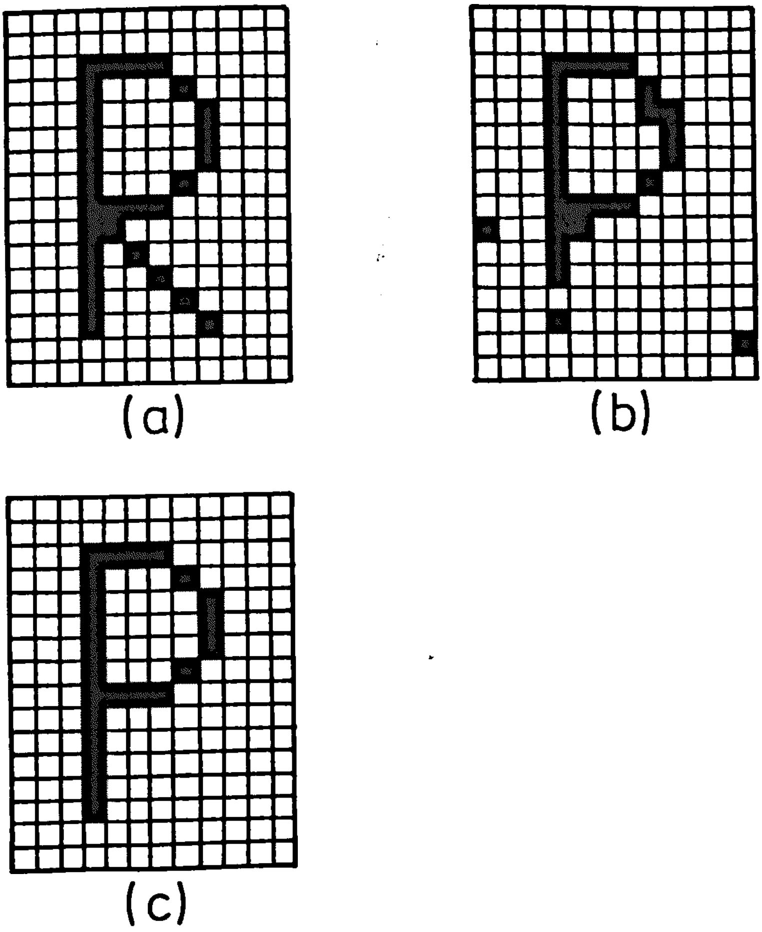
This procedure produces the same value of a for all patterns related to A by transformations τ' belonging to the group G.

Another example of such a global attribute encoding theory is given by Sutherland (1957) for visual discrimination in the octopus. In Sutherland's theory the input pattern is projected onto a rectangular array of receptors and encoded in terms of the outputs from vertical and horizontal columns of the array.

Other recognition theories of this type make use of techniques similar to those used in signal processing. For example, the use of grating stimuli in psychophysical experiments (Campbell and Robson, 1968; Blakemore and Campbell, 1968, 1969; Pantle and Sekuler, 1968) led to the suggestion that input patterns are subjected to a global Fourier analysis (Pollen, Lee and Taylor, 1971; Pollen and Ronner, 1975) and encoded in terms of their spatial frequency components (see section 1.5.1, for a more detailed review).

Marko (1973) has demonstrated the inadequacy of theories, such as global Fourier analysis, which use the distance in some appropriate signal space as a measure of discrimination. For example, the two patterns Fig. 1.4a and Fig. 1.4b have equal distances from the pattern Fig. 1.4c in signal space whilst belonging to different categories.

Each of these global encoding theories attempts to form attributes which are invariant under certain transformations by listing global properties of a pattern which are dependent on the whole pattern structure.



(a) (b) (c)

Fig. 1.4. Pattern "P" and some of its transformations.
(a) pattern "R" transformed from "P",
(b) irregular distorted patterns with same distance as (a) from (c),
(c) original pattern "P". After Marko (1973).

An alternative approach to pattern encoding is the use of local pattern attributes as described in the next section.

Local attribute encoding.

As an alternative to the encoding of global pattern attributes a pattern may be encoded in terms of its local attributes. These attributes are local in the sense that they are independent of the whole pattern structure. Theories of this kind are exemplified by the feature extraction models where the attributes encoded are termed "critical features". Examples of "critical features" that have been proposed are vertical lines, oblique lines, and curves. The use of such a feature extraction procedure for letter discrimination has been investigated by Gibson and her associates (Gibson, Osser, Shiff and Smith, 1963; Gibson, Schapiro and Yonas, 1968). The features they considered included horizontal, vertical and oblique straight lines, curves which were closed, open vertically or open horizontally; discontinuities; and intersections. Fig. 1.5. shows how these "critical features" occur in certain letters. Decisions concerning discrimination and recognition in such feature extraction models are based upon the presence or absence of certain critical features in the internal representations being compared. For example, the letters I and L differ in the presence of the horizontal straight line in the letter L.

Complex hierarchical models have been devised using the notion of critical feature analysis. For instance, the "pandemonium" model of Selfridge (1959) uses a hierarchical model to extract complex features from the input pattern. (see Selfridge and Neisser, 1960; Neisser, 1967, for a more detailed account).

A theory of pattern recognition based on the extraction of "critical features" similar to those listed above is inherently invariant to certain natural transformations. For, it is only the

Features	A	E	F	H	I	L	T	K	M	N	V	W	X	Y	Z	B	C	D	G	J	O	P	R	Q	S	U
Straight																										
horizontal	+	+	+	+		+	+								+				+							
vertical		+	+	+	+	+	+	+	+	+				+		+		+				+	+			
diagonal	+							+	+		+	+	+	+	+											
diagonal	+							+	+	+	+	+	+	+									+	+		
Curve																										
closed																+		+			+	+	+	+		
open vertically																				+						+
open horizontally																	+		+	+					+	
Intersection	+	+	+	+			+	+					+			+						+	+	+		
Redundancy																										
cyclic change		+							+			+				+									+	
symmetry	+	+		+	+		+	+	+		+	+	+	+		+	+	+			+					+
Discontinuity																										
vertical	+		+	+	+		+	+	+	+				+								+	+			
horizontal		+	+			+	+								+											

Figure 2.3. Chart of distinctive features for a set of graphemes. [After Gibson (1969).]

Fig. 1.5. From Reed (1973).

presence of certain critical feature and not its size or retinal position that is decisive in the recognition of the pattern.

In the list of "critical features" used by Gibson and her associates certain features are of a more global kind, e.g. symmetry. This illustrates the fact that the internal representations formed in a feature extraction theory may contain information about both global and local properties of the pattern. In this way pattern discrimination may be based on global properties such as area, and local properties such as the presence of a particular critical feature. For example, if we consider the discrimination of the letters O and Q, this is difficult for a template matching theory (see section 1.2.1), but could be simply effected in the feature extraction theory by including in the internal representation a critical "oblique line" feature. This explicit inclusion of the critical "oblique line" feature in the internal representation allows this feature to have a much greater weight in the decision process than it would have in a template matching theory.

The results from electrophysiological receptive field mapping studies in animals are often quoted as evidence for a feature extraction theory of pattern recognition. In particular, the demonstration of neurones in the cat and monkey cortices which are optimally stimulated by lines of certain orientations, lengths and widths (Hubel and Wiesel, 1962, 1965, 1968) led to the notion of cortical cells as "feature analysers". It is apparent, however, from a study of the receptive field excitatory and inhibitory regions that many other "features" would also cause these cells to respond. This is illustrated by the response of cortical neurones to visual noise in addition to bar stimuli (Hammond and MacKay, 1975). Indeed certain LGN and retinal cells give a response to stimulation outside their "classical" receptive field (the periphery effect: McIlwain, 1966; Fischer and Kruger, 1974; Fischer, Barth and Sternheim, 1978; Derrington, Lennie and Wright, 1979). Marr (1976) in developing a model for picture analysis, illustrates computationally how the outputs from general units having typical excitatory and inhibitory regions of differing sizes must be combined to form a "feature analyser" capable of extracting line features. This model implies the necessity of a combination of cortical cell responses for feature extraction and Frisby (1979) suggests that the hypercolumn structure of the visual cortex (Hubel, Wiesel and Stryker, 1978) may provide the physiological basis for such an operation.

The encoding of patterns in terms of global and local features appears to be suitable for classificatory purposes where a simple population of features is available (as in the case of letter recognition). Computer simulations based on feature extraction (global and local) alone have proved inadequate for the analysis of complex scenes where the spatial arrangment of the individual local features becomes important (Barlow, Narasimhan and Rosenfeld, 1972; Foster, 1977). In order to overcome this inadequacy theories which include a description of both features and their spatial arrangement have been proposed. Such theories are often referred to as "structural" or "syntactic".

Structural theories of pattern recognition.

The difficulty encountered by a local feature encoding model when presented with patterns in which the spatial arrangement of the features is important may be illustrated by considering Fig. 1.6a, b. The local features of Figs 1.6a and 1.6b are identical and a feature encoding scheme would therefore produce identical internal representations for the two different patterns. To overcome this difficulty of describing objects where the spatial arrangement of the "features" is important (e.g. Fig. 1.6a,b) structural (syntactic) theories of visual pattern recognition have been proposed (e.g. Sutherland, 1968; Leeuwenberg, 1968; Reed, 1975; Barlow, Narasimhan and Rosenfeld, 1972).

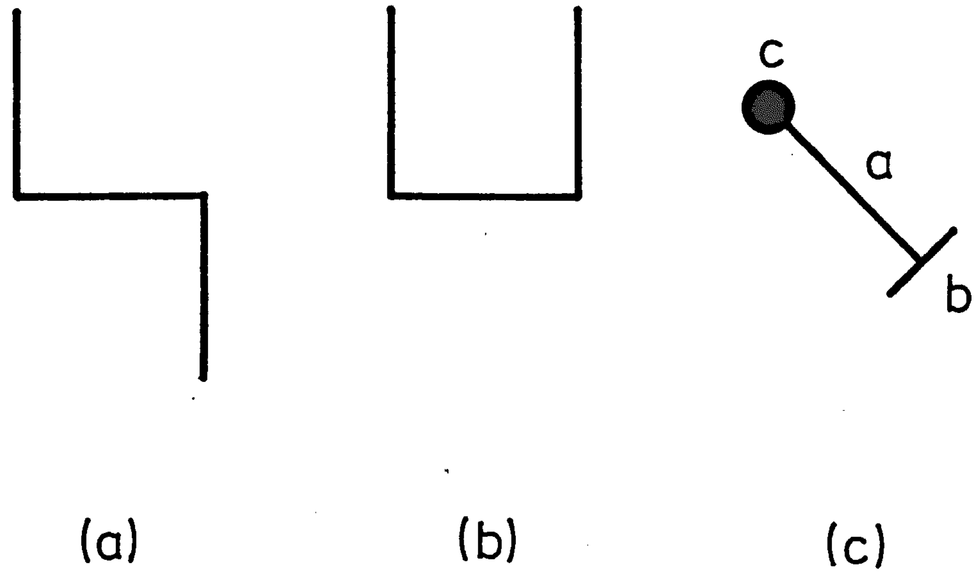


Fig. 1.6 Features in (a) are the same as in (b) but relations are different.

In structural theories the internal representation is considered to consist of a list of the pattern "features" as in feature extraction models, but in addition the spatial relationships ("relations") between these pattern features are included. Typical relations might be: above, below, to the left of, to the right of, connected to. For example, the object in Fig. 1.6c might be described as follows: The feature list might be, a long diagonal bar <u>a</u>, a short diagonal bar <u>b</u>, and a blob <u>c</u>, and the relation list might be, lower end of feature <u>a</u> connected to centre of feature <u>b</u>, upper end of feature <u>a</u> connected to feature <u>c</u> along a diameter. The relations given in the above example may be further reduced to descriptions in terms of "simpler" relations e.g. above, below connected to. In general a finite and relatively small set of features and relations would suffice for pattern encoding. Thus an internal representation i.r.(A) of a pattern A is formed by some process which selects the appropriate features and relations from the set of available features and relations and assigns them to i.r.(A). In such a scheme two patterns A and B are recognized as being the same if their internal representations are the same, that is, i.r.(A) = i.r.(B).

It has been suggested that the assignment of features and relations to a particular internal representation may take place in a probabilistic way (Sutherland, 1973; Foster, 1977). Some evidence that this probabilistic assignment occurs in the discrimination of simple dot and line figures has been given by Foster (1980a,b). The internal representations formed by such a probabilistic process would not necessarily be unique (Sutherland, 1973) and need not be a complete description of the pattern in terms of information content (Foster, 1978a). Foster (1978b) has also suggested that in the pattern comparison process giving rise to "same" responses pattern features cannot be compared without contemporaneous comparison of their spatial relationships. He (Foster, 1978b) found that subjects were unable to ignore shape information when asked to compare random-dot pattern pairs on the basis of equality of dot number.

Such schemes in which the internal representation is considered to contain information about the pattern local features and their spatial relationships has all the advantages of a feature-only encoding scheme. In addition structural theories of this kind have the capability of analysing patterns in which spatial relationships of local features are important. Structural theories of pattern recognition have also been shown to be particularly powerful in the analysis of complex scenes by computer models (Barlow, Narasimhan and Rosenfeld, 1972; Winston, 1975).

Most of these computer models have been concerned with the solution of a problem, that is, recognition of objects. In chapter 10 of this thesis (see also Foster and Mason, 1979) a computer model is developed for the investigation of the limitations of a structural theory in predicting certain aspects of human pattern-recognition performance. The abilities of this model are also compared with those of a model based on a transformational theory of pattern recognition.

The following section therefore summarizes and compares transformational and structural-encoding theories of pattern recognition.

1.2.3. Summary and comparison of transformational and structural-encoding theories.

In section 1.2.1. it was described how the difficulties of a strict template matching process could be overcome by transforming the input pattern before the comparison process. In general, such a transformational scheme may be used for pattern recognition in any circumstance provided that the appropriate compensatory transformations are incorporated into the scheme's repetoire. For example, every possible transformation of a figure A that the system might meet could be incorporated into the scheme (with suitable weights to explain variations in performance) therefore allowing all figure A's to be reduced to a standard. In such a transformational scheme (taken to the extreme) each input pattern would have its own transformation sequence to a particular template. Such an extreme scheme seems unlikely.

Using feedback methods in a transformational theory (Marko, 1973; Pitts and McCulloch, 1947), however, it is possible to control the use of "allowed" transformations to give maximal overlap with the template and thus reduce "search" requirements by a reduction in the numbers of different templates required.

As a method by which these transformations might be effected Shepard and Metzler (1971) and Cooper (1975) have suggested that an internal "dynamical" rotation process occurs in some reaction-time sense-discrimination tasks. In such a case a rotation ρ_θ through the angle θ would be achieved by the application of the 1-parameter family of transformations, $\rho_{t\theta}$ $(0 \leqslant t \leqslant 1)$, to smoothly transform the pattern A to its rotated form ρ_θ A. Such "mental rotation" effects are compatible with the analysis of pattern recognition and visual apparent motion effects by Foster (1972a, 1973a,b, 1978a); see also Kolers (1972).

A dynamical scheme of this type, however, cannot alone account for certain properties of human visual pattern recognition. In particular, if pattern rotations are considered the following argument may be constructed. If a rotation θ_1 has probability of p_1 of being effected by the visual system and θ_2 probability p_2 where $0 < \theta_1 < \theta_2 < 180^\circ$. Then, p_2 is the product of p_1 and the probability of the rotation from θ_1 to θ_2 being effected once θ_1 has been reached. Thus $p_2 \leqslant p_1$ which implies that the probability of effecting a rotation must decrease monotonically with increasing angle. Support for this notion has been reported, in the case of visual apparent motion, by Foster (1972b) and Frisby (1972). Note that this argument concerning the probability of a transform being dynamically effected decreasing with increasing transform parameter is valid for any parametric family of transforms.

Although this monotonic performance is shown in the results of reaction time experiments concerning "mental rotation" of objects (Shepard and Metzler, 1971; Cooper, 1975) it is not shown in the results of pattern recognition experiments. In particular, there is an upturn at 180° in the recognition performance for comparing rotated pattern pairs (Dearborn, 1899; Rock, 1973; Foster 1978b). Thus in order to explain this non-monotonic probability of visual recognition for pattern rotation angle it is necessary to allow the use of other transformations prior to those belonging to the parametric family (for such an implementation see chapter 10).

Thus by the ad hoc inclusion of additional transformations it seems probable that the transformational template model could be made to fit recorded recognition data.

Unlike transformational theories encoding theories (unless they are indistinguishable from a transformational theory) do not transfer the total information content of the stimulus to the comparison process. This encoding or attribute extraction process (or reduction of redundancy; see Barlow, Narasimhan and Rosenfeld, 1972) may be a desirable characteristic for pattern recognition. This encoding process may provide a natural reduction and removal of information that is not required in later processes. Marr (1976) illustrates how such attribute encoding may be used to form a "primal sketch" consisting of attribute lists at particular spatial positions (thus preserving both feature and relational information) which may be used for later processing. The primal sketch thus formed has "redundant" information in the grey level input largely removed leaving a description in terms of lines and edges of various types.

By reduction of the recognition problem to relatively few variables encoding theories are relatively simple compared with the equivalent transformational theories.

It seems likely that for an encoding theory to be able to adequately explain observed pattern recognition performance the internal representation formed should contain both global (Pitts and McCulloch, 1947) and local attributes (Neisser, 1967; Gibson, Osser, Shiff and Smith, 1963). Indeed in the local feature encoding model of Gibson et al (1963) for letters some global features such as symmetry and cyclic change are included in the feature lists (see Fig. 1.5).

The most powerful of the encoding theories are those based on encoding of both local features and their spatial relationships (Sutherland, 1968; Barlow, Narasimhan and Rosenfeld, 1972). These structural theories incorporate all the advantages of an encoding theory as well as the capability to recognize patterns where spatial relationships are important.

A structural theory has an inherent ability to allow for pattern jitter provided the spatial relations are appropriately chosen. In contrast, a transformational theory must have invariance to pattern jitter explicitly incorporated into its repertoire of internal compensatory transformations. This difference allows a considerable simplification of a structural scheme compared with an equivalent transformational scheme (see chapter 10). Another advantage of a structural theory is its ability to explain recognition performance either when small parts of an object are decisive in determining pattern differences (e.g. between O and Q) or when patterns are segmented. A transformational theory would experience difficulty in explaining pattern recognition performance in both of these circumstances.

It should be noted that if pattern dependent transformations are allowed in a transformational theory then, operationally, the theory may be indistinguishable from certain types of encoding theory (see Nickerson, 1972). In view of this it is possible that the most general recognition theory would contain both encoding and transformational elements. Thus, for example, a pattern may be encoded in terms of features and relations with transformations operating at various levels of the encoding process (see Amari, 1968, 1978). The internal representation in such a general theory may also contain both discrete and continuous attributes (Foster, 1980a,b).

1.3. Pattern adaptation.

The pattern recognition theories outlined above have found application mainly in the analysis of the results from experiments in which an observers performance at either comparing or discriminating patterns is measured. In contrast, pattern adaptation has been used as a technique to investigate the mechanisms involved in pattern processing. It is one of the aims of this thesis, therefore, to relate these theories of pattern recognition (in particular structural theories) to the properties of the mechanisms involved in pattern adaptation. The contrast threshold elevation effect was chosen as the appropriate technique for the investigations presented here. This choice was motivated by the ease with which patterns of any configuration may be used as stimuli in this technique. Other adaptation effects are often linked to a particular stimulus geometry (e.g. the curvature aftereffect, the tilt aftereffect, the spatial frequency-shift effect) and are not appropriate for generalized patterns. Some of these adaptation effects are described in the following paragraphs and a more detailed discussion of the contrast threshold elevation effect follows in section 1.4.

Gibson (1933) reported how the prolònged viewing of a curved line had the effect of making a subsequently viewed straight line appear curved in the opposite direction. He observed that this negative after-effect was induced after a ten minutes adaptation period, was retinotopically localised, and was transferred interocularly.

Gibson's observations were followed by reports of other such phenomena where adaptation to a spatially structured stimulus produced some after-effect on other spatially structured stimuli. These adaptation effects have been the basis of much research in spatial vision and have given rise to various hypotheses concerning pattern vision.

Further examples of these adaptation phenomena are the tilt after-effect (Gibson and Radner, 1937), the spatial frequency-shift effect (Blakemore, Nachmias and Sutton, 1970), and the contrast threshold elevation effect (Gilinsky, 1968; Blakemore and Campbell, 1968, 1969; Pantle and Sekuler, 1968).

The tilt after-effect occurs when the visual system is adapted to a sloping line pattern (for about 2 minutes; Gibson and Radner, 1937) before viewing, say, a vertical line pattern. The after-effect produced is such that the vertical line pattern appears to tilt in the direction opposite to that of the adaptation pattern. The tilt after-effect was subsequently studied by, among others, Campbell and Maffei (1971).

Following the suggestion of an inhibitory interaction between orientation specific channels (Blakemore, Carpenter and Georgeson, 1970) it was conjectured that the tilt after-effect might be the result of prolonged inhibition of orientation specific channels (Blakemore, Carpenter and Georgeson, 1971; Magnussen and Kurtenbach, 1980a). An alternative "fatigue and exitation" hypothesis (Sutherland, 1961; Coltheart, 1971) was rejected as a result of the "disinhibitory" cancelling effect of adaptation to a third orientation (Magnussen and Kurtenbach, 1980b). For further discussion of the tilt after-effect see Tolhurst and Thompson (1975) and Kurtenbach and Magnussen (1981).

The spatial frequency-shift effect was described by Blakemore, Nachmias and Sutton (1970) as an apparent shift in spatial frequency (number of light bars per degree of visual angle) of a subsequently viewed grating after adapting to a grating of a different spatial frequency. The direction of this apparent shift is such that it increases the difference in spatial frequency between the test and adaptation gratings. This effect may be explained in a similar way to the tilt after-effect but in terms of channels selective for particular spatial frequencies. Investigations of the spatial frequency shift effect which have given particular attention to the spatial structure of the grating stimuli used (Burton, Naghshineh, and Ruddock, 1977; De Valois, 1977) have suggested that the light and dark portions of the stimuli are processed by independent channels.

In general, adaptation studies of the visual system assume that the prolonged exposure of a stimulus produces a subsequent change (usually a decrement) in the responsiveness of the mechanisms involved in the detection of that stimulus. Indeed, in electrophysiological studies of single cells prolonged stimulation can give rise to pattern specific adaptation (Movshon and Lennie, 1979) and this psychophysical assumption would, therefore, seem reasonable. More direct psychophysical evidence for this assumption is given in the contrast threshold elevation effect discussed in the next section.

1.4. Contrast threshold elevation effect.

The contrast threshold elevation effect has been described by Gilinsky (1968), Blakemore and Campbell (1968, 1969) and Pantle and Sekuler (1968) for grating stimuli. These authors observed that prolonged viewing of a grating stimulus of a particular orientation and spatial frequency reduced the visibility of a subsequently presented test grating of similar orientation and spatial frequency. This effect therefore provides more direct psychophysical evidence for a loss of sensitivity of the mechanisms detecting the adaptation grating. It might, therefore, be supposed that with a suitable choice of the adaptation and test stimuli the contrast threshold elevation effect would reveal the limitations of the detecting mechanisms and by inference the nature of pattern processing. Much of the investigation of this effect has been motivated by consideration of hypotheses concerning the detecting mechanisms. For example, grating stimuli have been used to investigate the hypothesis that the visual system analyses patterns by means of channels "tuned" to different spatial frequencies (Campbell and Robson, 1968). Before considering the various hypotheses that have been proposed concerning the contrast threshold elevation effect and pattern vision, a review of the relevant measurement procedures and properties of the effect are given in the following sections.

Quantification.

In order to quantify the extent of the response decrement produced by pattern adaptation, the change in the test stimulus contrast is usually measured. The measure of contrast normally used is the Michelson contrast C, (Michelson, 1927), defined by:

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

where I_{max} is the maximum luminance of the spatial stimulus and I_{min} is the minimum luminance (see Fig. 1.7). Most experiments compare the contrast C_1 before adaptation with the contrast C_2 after adaptation. The contrast change is usually measured by the ratio C_2/C_1 and is generally represented on a logarithmic scale by a variable, say Δ, such that

$$\Delta = \log_{10} \frac{C_2}{C_1}$$

Note that if the mean luminance $\overline{I} = (I_{max} + I_{min})/2$ is the same in both pre-adaptation and post adaptation conditions the contrast change is simply related to the change in $I_{max} - I_{min}$, a quantity which is easily measurable.

It is important that the overall mean luminance of the various stimuli presented to the eye during a spatial adaptation experiment remains constant to prevent the state of light adaptation having an effect on the results.

Procedure.

Two methods of measurement of the contrast threshold elevation effect have been used, these are suprathreshold contrast matching and contrast threshold measurement. In suprathreshold contrast matching procedures the contrast of the test grating is determined by matching it to another variable-contrast grating. This matching procedure takes place before and after adaptation to measure the apparent reduction in contrast of the test grating (Blakemore, Muncey and Ridley, 1973). This procedure requires careful fixation and controlled eye movement as it usually relies on the matching grating being presented to an unadapted section of the retina (it also assumes that intraretinal transfer of the effect does not take place). Another difficulty with such a suprathreshold technique is the extent to which the test grating may "self-adapt" and thus reduce its own apparent contrast.

The second more commonly used procedure consists of measuring the contrast of the test grating when its spatial structure is just apparent (i.e. contrast threshold) in the pre-adaptation and post-adaptation states (Blakemore and Campbell, 1968, 1969; Maudarbocus and Ruddock, 1973). This method has the advantage that careful eye movement control is much less important because the stimuli all occur in the same retinal area and the assumption that intraretinal

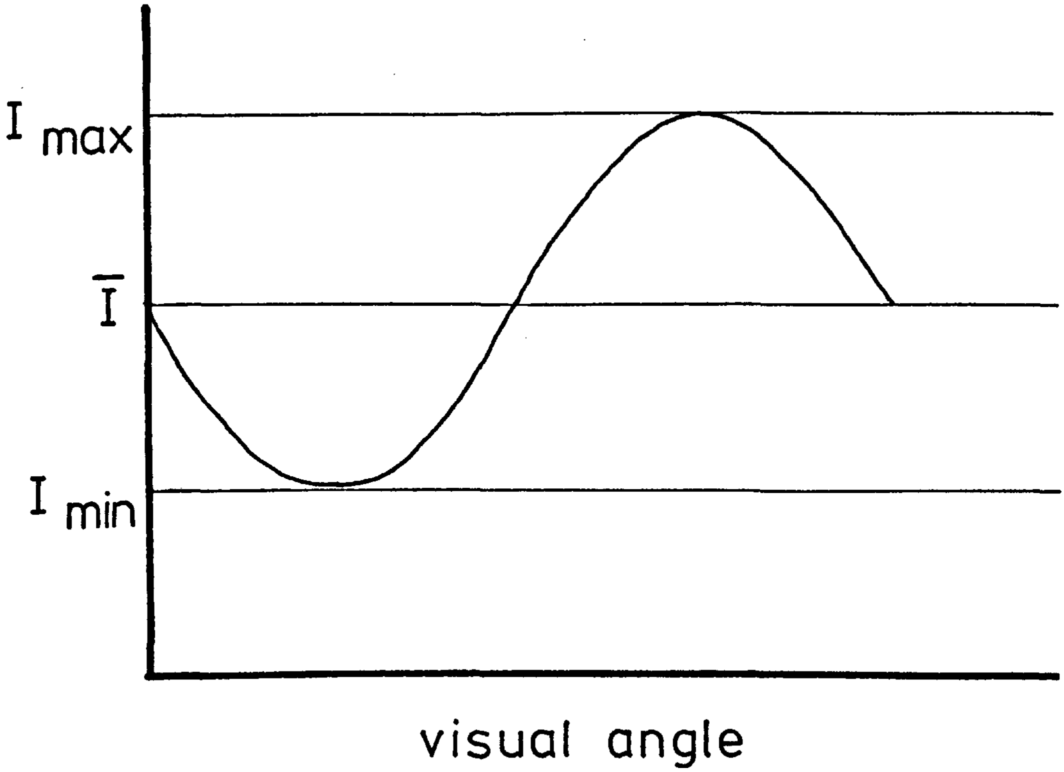


Fig.1.7. Michelson contrast $= \dfrac{I_{max} - I_{min}}{I_{max} + I_{min}}$

transfer does not take place is unnecessary. Also because the test stimulus is at a relatively low contrast "self-adaptation" may be assumed to be negligible. This method measures stimulation in "unrealistic" threshold conditions, however, as most patterns encountered are normally suprathreshold. Blakemore, Muncey and Ridley (1973) conclude that the contrast threshold elevation effect may be considered as a special case of the "contrast reduction effect" measured using their matching procedure.

In both of these measurement procedures the "baseline" pre-adaptation contrast is usually measured before and after the experiment. During the experiment several post-adaptation contrasts are measured and contrast elevations calculated with reference to the "baseline" contrast. This procedure assumes relative stability of the baseline contrast throughout the experiment (which may have a duration of greater than 1 hour). It is known, however, that periodic fluctuations of absolute and contrast thresholds occur with periods as little as 8 minutes (Lee, Finch and Pounds, 1945; Bornschein, 1951; Wertheimer, 1953; Home, 1978). Such threshold fluctuations may be of the order of 0.2 log units which are often comparable with the magnitude of contrast elevation. The effect of these periodic threshold fluctuations is partially removed in the above procedures by repetitive measurements of each post-adaptation contrast. Clearly a measurement procedure which more directly takes into account these threshold fluctuations is desirable. Such a procedure is used in the contrast threshold measurement described in this thesis.

The most commonly used method for determination of either the matching contrast or the threshold contrast of the test stimulus is one of adjustment (Blakemore and Campbell, 1969; Maudarbocus and Ruddock, 1973). In such a method of adjustment the observer controls the test stimulus contrast and adjusts it until it either matches (in the case of suprathreshold procedures) the other stimulus, or is at contrast threshold. It is usual in contrast threshold measurements to approach the final threshold from subthreshold values to minimise the effects of self-adaptation. Although some form of forced-choice design would be preferable for these measurements, the need to re-adapt between each presentation of the test stimulus and the time course of the effect (see below) makes such forced choice measurements extremely lengthy. The increase in subject fatigue and consequent loss of performance make the use of forced-choice methods impracticable for these adaptation measurements.

A further complication in the measurement of the effects of adaptation to spatially non-uniform stimuli is the occurrence of local retinal adaptation.

Effect of local retinal adaptation.

It might be argued that the contrast threshold elevation effect after adaptation to a spatially structured stimulus is simply a result of local photoreceptor adaptation giving rise to an afterimage effect where the bright portions of the pattern fall on the retina. Attempts to prevent this local adaptation taking place have been made using various methods. For example, controlled fixation patterns, pattern drift, and counterphase modulation have all been used. Unless some form of retinal stabilization technique is used in addition to the two latter methods it is unlikely that the time averaged luminance at all points of the retina exposed to the stimulus would be the same. This non-uniform adaptation is a result of the observer not being capable of maintaining a rigid and accurate fixation pattern (Arend and Skavenski, 1979); for example, involuntary tracking of a drifting grating may occur. Even given stabilized fixation the temporal structure of the light intensity at each retinal point may give rise to other effects. For instance, Virsu and Laurinen (1977) reported the existence of afterimages at twice the stimulus spatial frequency when using a counterphase modulation technique.

It seems, therefore, that modulation in either spatial position or time give rise to afterimage effects. A complete removal of such local effects thus seems unlikely. Much of the local adaptation effect may be removed by such techniques, however, and it seems likely that fixation patterns which do not give rise to repetitive changes would be the most satisfactory.

The most often used technique requires the observer to move his fixation point along a fixed path when viewing the pattern. For example, backwards and forwards along a line-perpendicular to the stripes of a grating (note that the choice of path is important: motion around a circular path in such a case (Blakemore and Campbell, 1968) may allow the eye to fixate bright portions of the grating for a greater part of the adaptation time).

In order to investigate the contribution of local retinal adaptation to the contrast threshold elevation effect Jones and Tulunay-Keesey (1975), and Jones (1977) carried out a series of experiments using various fixation paradigms designed to give maximum and minimum effects of local adaptation. These authors concluded that the contrast threshold elevation effect was not simply a result of local retinal adaptation, but afterimages formed, especially at low spatial frequencies, could distort the results unless steps were taken to eliminate them.

1.4.1. Properties of the contrast threshold elevation effect.

Time course of adaptation.

With grating stimuli, Blakemore and Campbell (1969) found that increasing the period of viewing an adaptation grating increased the contrast threshold elevation of a test grating for adaptation periods up to 60 seconds. A further increase of adaptation period had no further effect. The decay of the contrast threshold elevation after a 60 second adaptation period followed a simple exponential function with a time constant of 20 seconds. These authors also found that the time course remained essentially unchanged if gratings of different contrasts were used.

This finding is supported by the results of Blakemore, Muncey and Ridley (1973) from contrast matching experiments. Maudarbocus and Ruddock (1973) report a similar time course for interocular adaptation measurements.

Bodinger (1978), however, found that increasing the adaptation time from 1 minute to 10 minutes increased the threshold elevation effect by about two and a half times. Heggelund and Hohmann (1976) also reported that after an adaptation period of 1 hour the decay of the threshold elevation effect was prolonged to a period of over half an hour with normal visual experience between adaptation and testing. Heggelund and Hohmann also found a "storage effect" which maintained the contrast threshold elevation effect for up to 4 hours if the subject was blindfolded between adaptation and testing. In both of these long-adaptation period studies the authors were interested mainly in decay characteristics of the contrast threshold elevation effect and it is not clear whether the plateau observed in other studies after one minute of adaptation occurred. If such a plateau did occur it might be the result of a relatively short term adaptation effect superimposed on an effect with a much longer time course. Most experimental interest has been in the short term effect described by Blakemore and Campbell (1968, 1969).

Effect of adaptation pattern contrast.

Blakemore and Campbell (1969) found that if the contrast of an adaptation grating was increased the resultant contrast threshold elevation of the test grating was also increased. The effect of adaptation grating contrast on the magnitude of the contrast threshold elevation of the test grating has been more thoroughly investigated by Maudarbocus and Ruddock (1973) using dichoptic presentation of the stimuli. (see below). These authors found that the contrast threshold elevation of a grating test pattern increased linearly with the logarithm of the adaptation pattern contrast over a range of approximately 5 log units before reaching a saturation condition. This saturation effect became apparent at a retinal illuminance of 4-5 log photopic trolands. Maudarbocus and Ruddock (1973) also report that the effect of superimposing a uniform background field on the adaptation grating was found to decrease the contrast threshold elevation effect progressively with increasing uniform background field luminance.

Consequently, it is important in measurements of the contrast threshold elevation effect to use adaptation stimuli of a high and reproducible contrast if a large and stable threshold elevation is required. The apparatus described in chapter 3 of this thesis was designed with reference to these requirements.

Interocular transfer of the contrast threshold elevation effect.

When a test grating is presented to the opposite eye to the adaptation grating a contrast threshold elevation effect is still observed (Gilinsky and Doherty, 1969) although its magnitude is less than in the monocular case (Blakemore and Campbell, 1969). The time course of the adaptation to similar to that found monocularly (Maudarbocus and Ruddock, 1973).

1.4.2. Spatial properties of the contrast threshold elevation effect.

The spatial properties of the contrast threshold elevation effect have been widely investigated and these properties in particular have been the basis for much theorising about pattern vision (see section

1.5).

Size selectivity.

Fig. 1.8. shows a typical response * obtained when adaptation gratings of various spatial frequencies are each used to elevate the contrast threshold of a 2 cycles/degree test grating. As can be seen the magnitude of the contrast threshold elevation effect is dependent on the relative spatial frequencies of the adaptation and test gratings. The maximum contrast threshold elevation is obtained when adaptation and test grating spatial frequencies are equal. (Blakemore and Campbell, 1968; 1969; Pantle and Sekuler, 1968; Maudarbocus and Ruddock, 1973). Blakemore and Campbell (1969) were unable to obtain this relationship for spatial frequencies below 3 cycles/degree of visual angle where they found that adaptation to a lower spatial frequency gave a maximum contrast threshold elevation at 3 cycles/degree. Using larger overall field sizes (Maudarbocus and Ruddock, 1973) enables a peak in contrast threshold elevation to be obtained at lower spatial frequencies than 3 cycles/degree.

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* These responses were recorded from preliminary experiments conducted on the apparatus described in chapter 3. Contrast thresholds were obtained using the method of adjustment with final thresholds being approached from subthreshold values. The diameter of the adaptation field was 16° and the diameter of the test stimulus was 5°. All stimuli had a mean luminance equal to 4.0 log trolands. Each contrast threshold was determined in a presentation sequence consisting of a preliminary 2 minutes adaptation followed by a 2 second test period alternating with a 20 second "topping-up" adaptation period (see chapter 3). The presentation sequence consisted of 7 presentations of a grating adaptation stimulus interleaved with a uniform adaptation stimulus in the manner described in chapter 3. Each point plotted in Fig 1.8 is the mean of six contrast threshold elevation determinations.

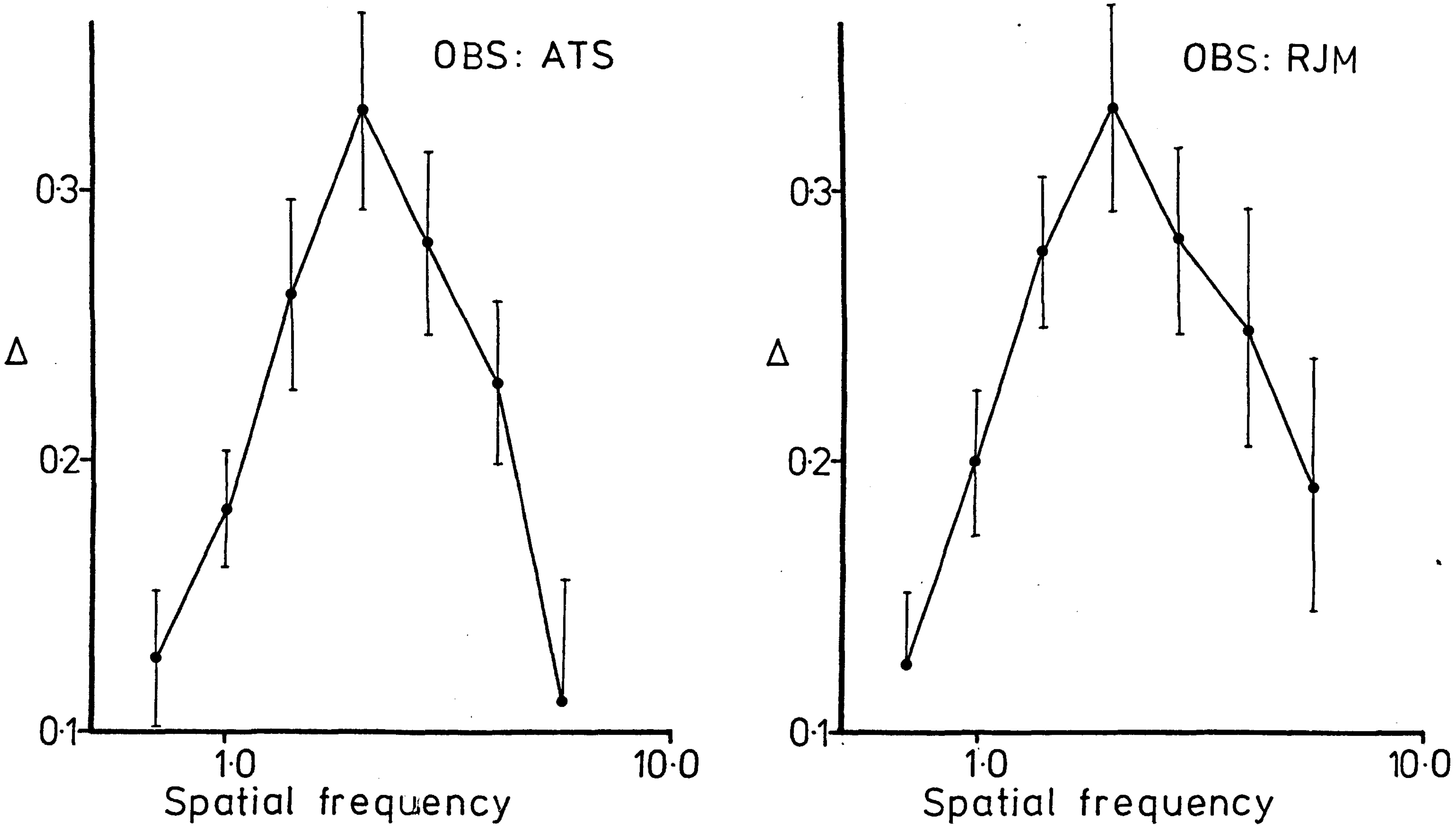

Fig. 1.8 Spatial frequency tuning curves. Contrast threshold elevation Δ in log units against spatial frequency in cycles/degree (log scale).

The differences between these two studies may be a result of the stimulus geometry, for it has been found that the visibility of gratings is independent of field size provided more than approximately 5 cycles of a grating stimulus are included in the field (McCann, Savoy and Hall, 1973; Hoekstra, van der Goot, van den Brink and Bilsen, 1974; Savoy and McCann, 1975). These authors also report a monotonic dependence of grating visibility on cycle number for gratings containing less than five cycles. Estévez and Cavonius (1976) suggested that the dependence of grating visibility on number of cycles occurs with dark luminance surround and that certain of Savoy and McCann's (1975) results using mean luminance surrounds were artefacts of their apparatus. In a reply to this suggestion McCann, Savoy and Hall (1978), using a modified apparatus, replicated their earlier results and argue that those of Estévez and Cavonius (1976), are likely to be a consequence of uncontrolled parameters in their stimuli. This dependence of grating visibility on number of cycles may explain the difference between the results of Blakemore and Campbell (1969) who used a 1.5° diameter stimulus resulting in 5 cycles in the field for gratings of 3 cycles/degree. In contrast, Maudarbocus and Ruddock (1973) using a 5° diameter stimulus found a maximum in contrast threshold elevation for grating stimuli down to 1 cycles/degree. The results of Fig. 1.8 were obtained by the present author with a test stimulus diameter of 5°.

A significant contrast threshold elevation is still obtained in all of the above studies when the spatial frequency of the adaptation grating is unequal to that of the test grating. For example, Blakemore and Campbell (1969) found that in general adaptation to grating stimuli of spatial frequencies less than $\frac{1}{4}$ times and more than 4 times (±2 octaves) the test stimulus spatial frequency gave no contrast threshold elevation effect.

Therefore although a peak in contrast threshold elevation is obtained when test and adaptation gratings are of equal spatial frequency the effect is not unique to this equality. The adaptational sensitivity of the mechanism being adapted thus appears to be restricted to a range of sizes (or spatial frequencies) around the adapted size but with a decreasing sensitivity for stimuli of sizes either larger or smaller than the adapted size.

In the studies considered above, grating stimuli with unity mark/space ratio, that is equal widths of bright-bar and dark-bar portions, were used. Studies using stimuli with mark/space ratios other than unity have shown that the contrast threshold elevation effect is dependent mainly upon the width of the bright bars of the grating, the dark bars having little or no effect on the size selectivity of the effect (Naghshineh and Ruddock, 1978). It should be noted that this finding differs from that found with the frequency-shift adaptation effect where both dark-bars and light-bars are found to be of importance (Burton, Naghshineh, and Ruddock, 1977; De Valois, 1977).

Nakayama and Roberts (1972) examined the selectivity of the contrast threshold elevation effect for the length of the grating bar-elements and concluded that their results were consistent with the existence of units adaptationally sensitive to line length. Burton and Ruddock (1978), using two dimensional patterns of bar elements, also investigated the line length-sensitivity of the contrast threshold elevation effect. These authors found that the effect was selective for line length when the length/width ratio of the stimulus bars was less than three. With bar length/width ratio greater than three a saturation like effect was observed, the maximum in contrast threshold elevation of the test stimulus being replaced by a constant value of contrast threshold elevation.

These results concerning line length selectivity are further examined in chapter 5 of this thesis using the adaptation technique developed here.

All the studies considered above used stimuli which were periodic in one-dimension or two-dimensions. From these studies it may be concluded that the adapted mechanisms are sensitive to the bright portions of the stimulus and are selective for both bar width and, within limits, bar length. Studies of the contrast threshold elevation effect where the stimuli were either of a non-periodic nature or not bar shaped are few in number but have revealed interesting results concerning the spatial properties of the effect.

Thomas and Kerr (1971), Kerr and Thomas (1972) and Bagrash (1973) used single rectangles and circular spots as adaptation and test stimuli. These authors also found size specific contrast threshold elevation. During these studies the subject maintained steady fixation, however, and these results are possibly a consequence of local adaptation effects. If the effect of local adaptation does not affect the general conclusion of these studies they indicate the possibility of obtaining a contrast threshold elevation effect using single rather than repetitive stimuli.

The use of single rather than repetitive stimuli allows the interpretation of the contrast threshold elevations to be related more directly to local pattern structure. This facility is to be desired in experiments to examine theories based on local structure encoding and the adaptation technique developed in chapter 4 incorporates the use of stimuli which are simple to interpret.

Naghshineh and Ruddock (1978) measured the contrast threshold elevation of either a square wave grating, or dots arranged in a regular matrix, or dots arranged randomly after a period of adaptation to a similar range of stimuli. These authors conclude that under monoptic conditions adaptation to spot patterns gives a significant threshold elevation of both spot and grating test stimuli. The magnitudes of the contrast threshold elevations of the grating and spot test stimuli after adaptation to either of the spot stimuli are similar (~ 0.3 log units). The authors also conclude that the random and matrix arrangements of spots are essentially equivalent in this effect. When the adaptation stimulus was presented in one eye and the test stimulus in the other eye these authors found that adaptation to a spot stimulus had little effect on either type of test stimulus (although significantly non-zero results were obtained for both types of test stimulus using the dot matrix pattern). In both monoptic and dichoptic conditions adaptation to a grating stimulus produced a significant contrast threshold elevation of a similar grating stimulus. Perhaps one of the most interesting findings of this study is that maximum contrast threshold elevation of a grating test stimulus occurred when the diameter of the spots in the adaptation stimulus was equal to the width of the grating bars.

Orientation selectivity.

In addition to the size selectivity shown by the contrast threshold elevation effect is has been shown that the effect also exhibits selectivity for the orientation of line stimuli. This orientation selectivity was first reported by Gilinsky (1968) and later corroborated by Blakemore and Campbell (1968, 1969), Pantle and Sekuler (1968), and Maudarbocus and Ruddock (1973). All these studies were performed using either sinusoidal or square-wave grating stimuli. The maximum contrast threshold elevation of the test grating occurred when the orientations of the adaptation and test gratings were the same. A minimum contrast threshold elevation of the test grating occurred when the gratings were orthogonal. Blakemore and Nachmias (1971) and Maudarbocus and Ruddock (1973) measured the magnitude of the orientational selectivity of the contrast threshold elevation effect for grating stimuli and found the effect to have a typical "half width" of the orientation turning curve of about 7°.

Burton and Ruddock (1978) have argued that the orientation tuning shown by the contrast threshold elevation effect is consistent with their findings of length selectivity for bar length/width ratios less than 3 (see above).

Using a simultaneous masking paradigm with grating stimuli Campbell and Kulikowski (1966) found a half width of the orientation "tuning curve" of 12°. Blakemore and Nachmias (1971) suggest that this larger value found by Cambell and Kulikowski may be the result of experimental differences, in particular Campbell and Kulikowski used higher luminance levels in their study.

The orientation selectivity of the contrast threshold effect may be summarised as follows. Maximum contrast threshold elevation occurs when the adaptation and test stimuli are of the same orientation but falls monotonically to half its maximum value as the orientation difference between the two stimuli increases to approximately 7°.

Shape selectivity.

Very little is known about the shape selectivity of the contrast threshold elevation effect. Most studies have been concerned with stimuli which are related by some simple dilatation transformation, to give, for example, gratings of different spatial frequencies. The study of Naghshineh and Ruddock (1978), see above, considered the effect of adaptation to spot "shaped" stimuli on a grating "shaped" test stimulus and vice versa. These authors found that maximum contrast threshold elevation occurs when the adaptation spot diameter is equal to the test grating bar width. They also found that the magnitude of the contrast threshold elevation obtained from this different-shape condition was similar to the magnitude of the contrast threshold elevation from a grating adaptation - grating test same-shape condition. These results might be interpreted as a lack of detailed shape selectivity in the adapted mechanism. This interpretation is also supported by the report of these authors that the use of either a regular or a random array of dots for the adaptation pattern produces the same contrast threshold elevation of the grating test stimulus. This latter observation also supports the notion that the adapted mechanisms are only sensitive to the bright portions of the stimulus and not the relative positions of those bright portions. The contrast threshold elevation effects these authors report seem consistent, therefore, with mechanisms selective for stimulus size but relatively insensitive to stimulus shape or arrangement. If bar length tuning effects are considered, however, this suggestion is inadequate to explain the results because a short "spot" stimulus would not be expected to significantly raise the contrast threshold of a long "grating" stimulus after adaptation. These authors suggest that their results are consistent with the existence of two types of mechanisms, the one detecting spots, the other detecting bars. These two suggested mechanism types must, however, remain insensitive to the global spatial arrangement of the pattern spots.

In conclusion, it seems possible that mechanisms exist which are adaptationally sensitive to stimulus size but not to the spatial arrangement of the bright portions of the stimulus. It is also possible that different mechanisms exist which adapt to the presence of either bars of spots in the stimulus.

1.5. Contrast threshold elevation effect: theories and models.

In the previous section a summary of the properties of the contrast threshold elevation effect was given with particular reference to the spatial properties of the effect. The present section discusses the various theories and models which have been proposed either as an explanation for, or as a result of, the contrast threshold elevation effect.

Two main approaches to the nature of the mechanisms underlying the results from contrast threshold elevation effects have been proposed, the one based on the notion of mechanisms sensitive to the spatial frequencies contained in the input pattern, the other based on the notion of edge, bar, and other such feature detectors. The former approach has received most attention, in particular for models of pattern vision using Fourier analysis techniques. For reviews see Sekuler (1974) and De Valois and De Valois (1980).

1.5.1. Fourier analysis and the contrast threshold elevation effect. The Fourier transform.

Fourier analysis is a mathematical technique whereby a pattern, either in time or in space, of some variable, e.g. intensity, may be represented as the weighted sum of several sinusoidal patterns. For example, the square-wave pattern of spatial frequency f (Fig. 1.9a) is obtained by adding together appropriately weighted sinusoids of spatial frequencies f, $3f$, $5f$, etc. Fig 1.9b shows the first four of these sinusoids and Fig. 1.9c their sum. In general we may represent a periodic spatial pattern $V(x)$ by the sum of the form.

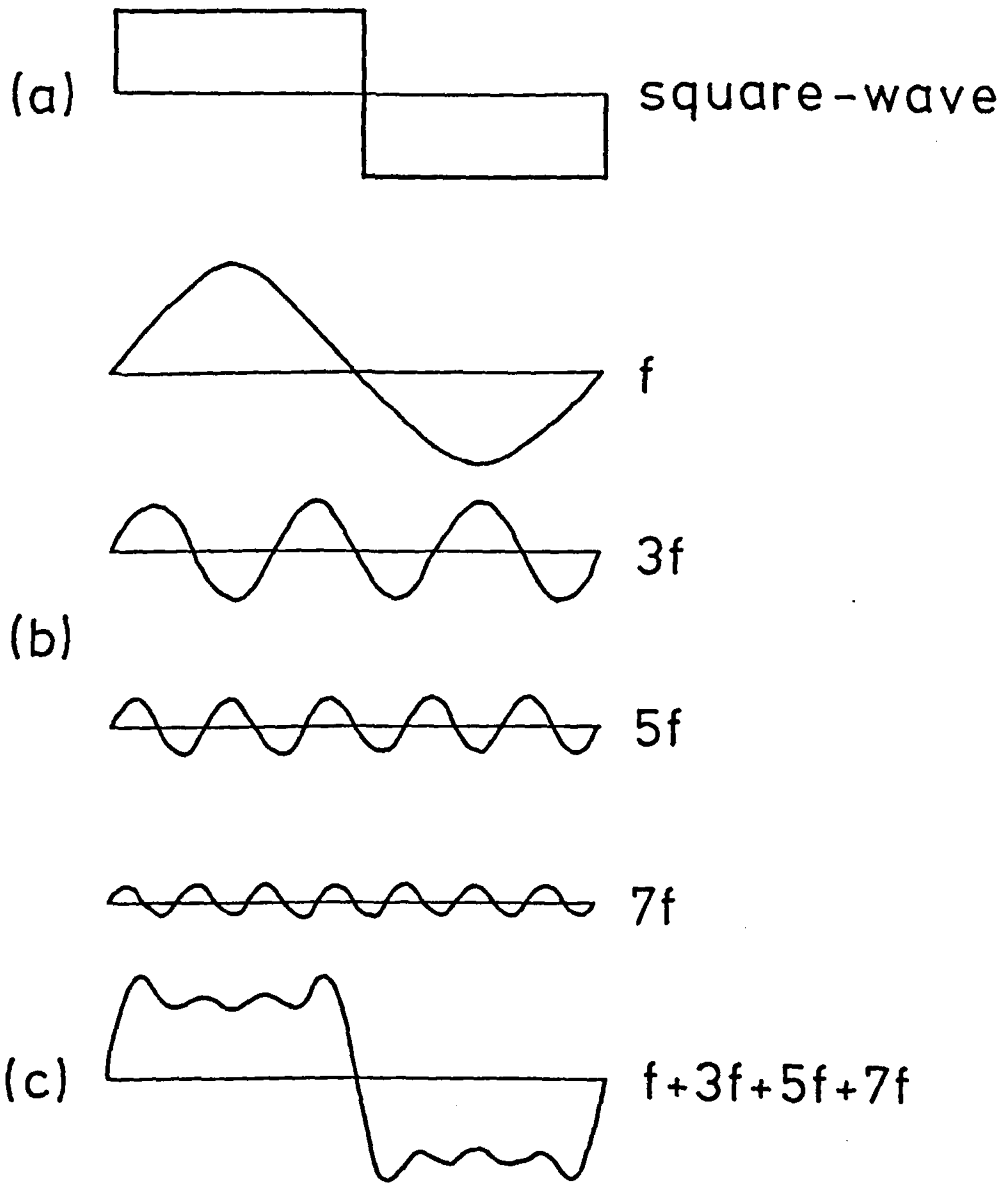

Fig. 1.9 Example of Fourier analysis of a square wave.

$$V(x) = A_o + \sum_n A_n \cos n\omega_1 x + \sum_n B_n \sin \omega_1 x$$

where

$$A_o = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} V(x)dx$$

$$A_n = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} V(x)\cos n\omega_1 x \, dx$$

$$B_n = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} V(x) \sin n\omega_1 x \, dx$$

<u>OR</u>

$$V(x) = A_o + \sum_n C_n \cos (n\omega_1 x - \varphi_n)$$

Where

$$C_n = \sqrt{(A_n^2 + B_n^2)}$$

$$\tan\varphi_n = \frac{B_n}{A_n}$$

$$\omega_1 = \frac{2\pi}{T} = 2\pi f$$

T = period of spatial waveform

f = spatial frequency

n = is an integer

A periodic stimulus may thus be represented in terms of the coefficients C_n and the phase angles φ_n and these are usually plotted as a function of the spatial frequency, to give amplitude and phase spectra (see Fig.1.10a). In this way a pattern in the space domain may be represented in the spatial frequency domain.

The series given above are only applicable to patterns of a periodic nature. The Fourier series, however, may be generalised to pattern which are aperiodic, e.g. single bars. This generalised technique known as Fourier transformation calculates the amplitude and phase spectra of a given pattern as follows.

If V(x) is a function of a spatial parameter x, as before, and $v(\omega)$ is the (complex) Fourier spectrum then.

$$v(\omega) = \int_{-\infty}^{\infty} V(x) e^{-j\omega x} \, dx$$

and the inverse transform is given by

$$V(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} v(\omega) e^{j\omega x} \, dx$$

where $j = \sqrt{-1}$

The amplitude and phase spectra of the pattern are obtained by taking the modulus and argument of $v(\omega)$ respectively. Fig. 1.10b shows the amplitude spectrum of a single retangular distribution, the phase spectrum in this case is zero at all spatial frequencies.

The Fourier transform thus provides a method of describing a pattern in frequency space. The usefulness of this type of pattern description becomes apparent when linear systems are considered.

Linear systems.

Consider a system with one input and one output which responds to an input $V_1(x)$ by giving an output $G_1(x)$. If the input signal is

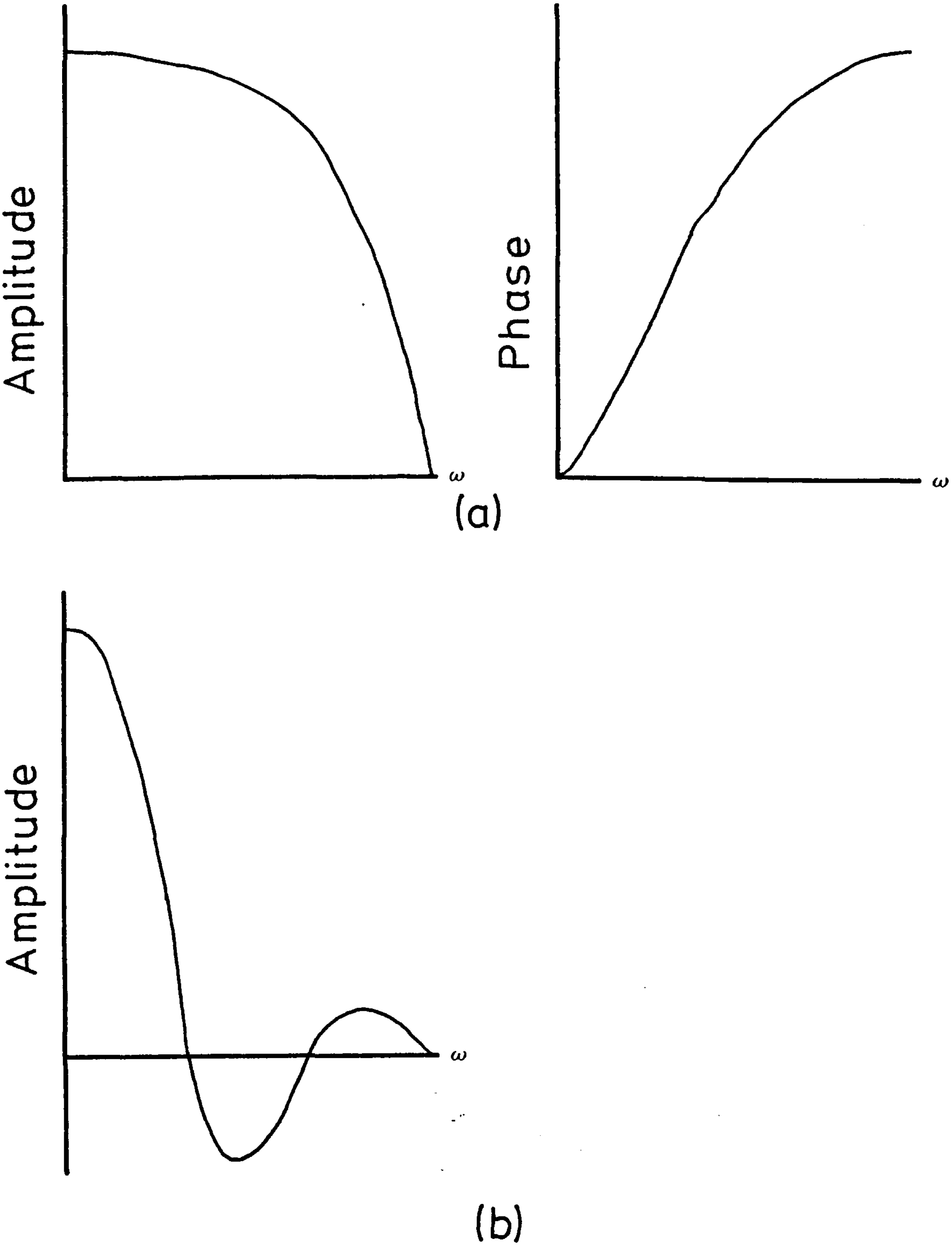

Fig. 1.10 Examples of amplitude and phase spectra.
(a) Amplitude and phase plotted against spatial frequency.
(b) Amplitude spectrum of a rectangular distribution.

$$V(x) = aV_1(x) + b\,V_2(x) \qquad 1.1$$

then the system is said to be a linear system if the output is

$$G(x) = aG_1(x) + b\,G_2(x) \qquad 1.2$$

The property of a linear system which is of interest here is that it can be shown that a sinusoidal input to a linear system gives rise to a sinusoidal output (Goodyear, 1971, p64). The output sinusoid may differ in amplitude and phase from the input sinusoid but the waveform shape is unchanged. If the input is a sum of several sinusoids then from the definitions of a linear system the output will also be a sum of the same sinusoids with, perhaps, altered amplitudes and phases. Thus the input-output response of a linear system may be characterised by the way in which the amplitudes and phases of sinusoids with various frequencies are affected in passing through the system. For example, we may define two functions $a(\omega)$ and $\phi(\omega)$ as follows:

$$a(\omega) = \text{output amplitude/input amplitude.}$$

$$\phi(\omega) = \text{output phase - input phase}$$

or equivalently a complex function.

$$h(\omega) = a(\omega)e^{j\phi(\omega)} \qquad 1.3$$

The function $a(\omega)$ is commonly referred to as the modulation transfer function and $h(\omega)$ as the transfer function of the system.(the two being equal when phases remain unchanged in passing through the system).

The usefulness of the description of a pattern in terms of its Fourier transform now becomes apparent. For if each of the sinusoids composing the pattern are multiplied by the appropriate factor and

and phase corrected for passage through the linear system they may then be resummed to form the Fourier transform of the output pattern $u(\omega)$. This operation is simply performed by multiplying the input $v(\omega)$ by $h(\omega)$.

i.e.

$$u(\omega) = h(\omega).\ v(\omega) \qquad 1.4$$

By taking the inverse Fourier transform of the output spectrum, $u(\omega)$, the output pattern in the same space as the input pattern may be obtained.

It is not necessary for two Fourier transforms to be performed as the equation 1.4 above may be equivalently represented by the convolution integral,

$$G(x) = \int_{-\infty}^{\infty} H(x-x')V(x')dx'$$

For a linear system the function $H(x)$ is known as the impulse response of the system (i.e. the output from the system given a single impulse input) and is related to $h(\omega)$ by Fourier transform as follows.

$$h(\omega) = \int_{-\infty}^{\infty} H(x)e^{-j\omega x}\,dx$$

This method of analysis has found wide application in communications and the analysis of optical systems which are generally of a linear nature (see Longhurst, 1967; Goodyear, 1971; Born and Wolf, 1975 for a further description of these applications).

Thus the input-output relations of a linear system may be completely characterised by the complex impulse response function of the system $H(x)$ or equivalently its modulation transfer function $h(\omega)$.

Non-linear systems.

If we again consider a system with one input and one output then a non-linear system is one such that the output G(x) is related to the input V(x) by a non-linear function f such that.

$$G(x) = f\,(V(x)) \qquad 1.5$$

For example, the non-linear function may be in the form of a power series with coefficients c_i as follows.

$$G(x) = c_0 + c_1\,V(x) + c_2\,V^2(x) + c_3\,V^3(x) \qquad 1.6$$

It can be shown that if the input to such a system is the sum of two sinusoids of frequencies ω_1 and ω_2 then the output will, in contrast to that of a linear system, not only contain output sinusoids of frequencies ω_1 and ω_2 but also sinusoids at combination frequencies, e.g. $2\omega_1$, $2\omega_2$, $\omega_1 \pm \omega_2$, $3\omega_1$, $3\omega_2$, $2\omega_1 \pm \omega_2$. The most prominent of these combination frequencies are the first order terms $2\omega_1$, $2\omega_2$, $\omega_1 \pm \omega_2$.

The term $\omega_1 - \omega_2$ is known as the "beat frequency". When ω_1 and ω_2 are close in value the "beat frequency" term can be of a very low value.

From the above it can be seen that a non-linear system cannot be simply represented by a modulation transfer function owing to the production of these combination frequencies in the system.
The Fourier transform of the input pattern is, in this case, only useful as a pattern description and the non-linear function of the equation 1.5 must be applied directly to obtain the correct output.

If the input to a non-linear system is of a small magnitude or changes by a small amount the non-linear system may approximate to a linear system.

For example, in such a circumstance the terms $c_2V^2(x), c_3V^3(x)$, etc., of equation 1.6 either become very small or approximately constant to leave a linear system of the form

$$G(x) = c + c_1V(x) \qquad 1.7$$

The application of Fourier techniques in vision.

Fourier analysis has been used widely in the analysis of linear optical systems because it provides a convenient methodology for the calculation of the transmission properties of a complex optical instrument, (Longhurst, 1967; Born and Wolf, 1975). In vision research, Fourier analysis techniques were first used to define the transmission properties of the optical media the eye. One of the methods used to measure the modulation transfer function of the optics of the eye consists of measuring the spatial luminance distribution of the image of a spatial impulse (bright bar) formed by reflections from the fundus. In this way the input pattern passes twice through the eye optics and by analysis of the reflected output pattern the modulation transfer function (MTF) of the eye optics may be calculated. (see Westheimer, 1963, for a review).

In an essentially psychophysical determination of the MTF of the optics of the eye Campbell and Green (1965) used the concept of a "neural" MTF. Using laser interferometry techniques these authors were able to form sinusoidal grating patterns at the retinal surface, thus "bypassing" the optics of the eye. By also measuring psychophysically the threshold contrast of sinusoidal grating patterns presented normally via the optics of the eye these authors were able to calculate the MTF of the optics of the eye alone. The only assumptions necessary for these measurements to be valid are that the optics of the eye are linear and that sinusoidal grating images formed either by passage through the eye optics or by interference at the retina give rise to the same threshold sensitivity when presented at identical wavelengths and luminances. Both of these assumptions are reasonable and this method provides a powerful means of measuring the MTF of the ocular media. Note that the "neural" MTF used in these experiments was only a description of the threshold contrast sensitivity of the visual system when the ocular media are bypassed and the null technique used ensures the validity of the measurements. In particular, the measurement of this "neural" MTF does not imply the linearity of neural processing.

The notion of the visual system as a whole (including the neural MTF) behaving as a linear system is attractive in that it allows the application of techniques, such as Fourier analysis to its input-output relations. Indeed, some authors have proposed that the visual system achieves pattern vision by means of Fourier analysis (Pollen, Lee and Taylor, 1971; Ginsburg, 1973). The validity of any such "Fourier theory" is dependent upon linearity of the visual system. Therefore before considering these "Fourier theories" the evidence concerning the linearity of the visual system will be considered.

The visual system as a linear system.

Campbell and Robson (1968) conducted a series of experiments using grating stimuli of various spatial frequencies in order to show how Fourier analysis may be applied to the visual system. In the first of their experiments they considered the threshold contrast at which gratings of various profiles and spatial frequencies became visible to the observer. These authors observed that the threshold contrast required for detection of a grating could be predicted by Fourier analysis. In their second experiment they observed that, in accordance with Fourier analysis of the stimulus, gratings of different profiles were discriminable when their higher harmonics reached contrast threshold. Campbell and Robson proposed that their results could be explained by the existence of a number of independent channels consisting of detectors and spatial filters which are tuned to a narrow band of spatial frequencies. They proposed that the "neural" MTF would constitute the envelope of the individual MTFs of these putative spatial frequency channels. These authors also conclude that the proposed spatial frequency channels are of a linear nature.

The measurements of Campbell and Robson (1968) all involved threshold decisions. It was shown earlier in this section that a restricted range of input to some non-linear systems can make the system appear linear over its input range. Because of this "linearising" effect it is possible that the results of Campbell and Robson are only valid for the small "threshold" range they used and for these reasons are only of a limited value in the consideration of visual system linearity. In particular, these results do not show that the visual system would behave as a linear system in response to patterns whose contrast varied over a large range.

The suggestion of Campbell and Robson (1968) that channels existed which are tuned to a narrow range of spatial frequencies gained considerable support from the results of contrast threshold elevation experiments. Blakemore and Campbell (1969) suggested that the spatial frequency tuning curves they obtained may represent the sensitivity functions of neurones selectively sensitive to spatial frequencies and size. Such spatial frequency tuning curves might represent the sensitivity functions of spatial frequency selective channels which would be required if a Fourier analysis of the input pattern was being performed by the visual system.

To test this hypothesis Blakemore and Campbell (1969) also investigated the effect of adaptation to square wave gratings on the contrast threshold of sinusoidal test gratings. From Fourier analysis a square wave grating may be considered as a sum of the fundamental frequency sine wave, ω, and its odd harmonics (suitably weighted) at 3ω, 5ω, etc. It might be argued therefore that adaptation to a square wave grating would, if its Fourier components were being "analysed", elevate the contrast threshold of "spatial frequency channels" tuned to 3ω and 5ω. This effect should be detectable by testing with sinusoidal gratings at these spatial frequencies. In their experiment, Blakemore and Campbell (1969) found that the contrast threshold of the third harmonic frequency 3ω was elevated as predicted by the above hypothesis. These findings were interpreted as evidence for the existence of channels tuned to a limited spatial frequency range which, as Fourier analysis would require, act independently.

Because of the theoretical importance of Blakemore and Campbell's (1969) findings, Nachmias, Sansbury, Vassilev and Weber (1973) repeated Blakemore and Campbell's experiments using square wave adaptation patterns and using both the method of adjustment (as used by Blakemore and Campbell, 1969) and a forced-choice method and were **not** able to replicate the original study. They (Nachmias, Sansbury, Vassilev and Weber, 1973) conclude that no contrast threshold elevation occurs at the third harmonic frequency and that Blakemore and Campbells' results may be due to methodological differences.

Tolhurst (1972) had previously conducted a detailed quantitative study of the contrast threshold elevation caused by adaptation to a square wave stimulus. He concluded that in order to explain the elevations of contrast threshold at each spatial frequency harmonic it was necessary to propose some inhibitory interaction between the proposed spatial frequency channels. In a later paper Dealy and Tolhurst (1974) again investigated the interactions between spatial frequency channels and these authors also concluded that inhibition exists between channels. These authors suggest that the different channel bandwidths measured by subthreshold summation (Sachs, Nachmias and Robson, 1971; Kulikowski, Abadi and King-Smith, 1973) and adaptation (Blakemore and Campbell, 1969; Blakemore and Nachmias, 1971) may be a result of this inhibitory interaction. They suggest that the adaptation technique may reveal the broader bandwidth of the inhibitory interactions between spatial frequency channels.

One of the requirements of a linear system is that input sinusoids of different frequencies should not interact. In the model of the visual system as a series of channels responsive to different spatial frequencies this linearity would imply independence of these channels. The results of Tolhurst (1972), Dealy and Tolhurst (1974) indicating inhibition between spatial frequency channels may be interpreted as evidence for non-linearity of the visual system at least for suprathreshold patterns where channel inhibition should be significant.

Burton (1973) demonstrated that if the visual system was presented simultaneously with two sinusoidal patterns of spatial frequencies above the acuity limit spatial "beats" were visible. That is, the observer was able to see a grating pattern with spatial frequency equal to the difference of the two non-visible grating frequencies. The visibility of these spatial "beats" again indicates interaction between the supposed spatial frequency channels and is contrary to the hypothesis that the visual system is linear.

In addition to the above psychophysical studies, electrophysiological studies of cat and monkey cortical cells have revealed sensitivity to a limited range of spatial frequencies (Maffei and Fiorentini, 1973; Ikeda and Wright, 1975; Schiller, Finlay and Volman, 1976; Albrecht, 1978; Movshon, Thompson and Tolhurst, 1978) and a time course of adaptation similar to that for the contrast threshold elevation effect (Maffei and Fiorentini, 1973). Inhibition between cells has also been found (De Valois, 1978; Movshon, Thompson and Tolhurst, 1978). Cortical cells of this nature may underlie the psychophysically observed effects discussed above. The non-linear responses shown in the experiments discussed above suggest that the notion that the visual system may be regarded as a Fourier analyser is unlikely to be true. The demonstration of some spatial frequency selectivity in both psychophysical experiments (e.g. Blakemore and Campbell, 1969) and in single cell responses (e.g. Maffei and Fiorentini, 1973) has led some authors despite the demonstrated non-linearity of the visual system, to suggest that the visual system does behave as a Fourier analyser.

The visual system as a Fourier analyser.

If the notion that the visual system performs a Fourier analysis of an input stimulus by means of independent spatial frequency channels tuned to a narrow range of frequencies is accepted, it is then possible to expand on the utility of such a system. Many authors with this viewpoint have attempted to suggest how such a Fourier analysis based system may be realised.

Blakemore and Campbell (1969) remark that the advantage of a system based on frequency analysis is that it simplifies the recognition of objects presented at unfamiliar magnifications. For, if an object is encoded in terms of its spatial frequency content and the relative harmonic content calculated, the latter is invariant with magnification of the object and may be used therefore for recognition. This property is not unique to a Fourier analysis model of the visual system for similar properties invariant to magnifications may be constructed in the space domain. For example, the ratios of various dimensions of an object are invariant with magnification of the object.

A property of the Fourier transform of a spatial pattern is that the amplitudes of the frequency components are invariant with object position whilst the phase components reflect position changes. Pollen, Lee and Taylor (1971) suggest that this property may be used to give position invariance for pattern recognition purposes. Although such position invariance may arise from a Fourier analyser model of the visual system such an invariance is not observed in the pattern recognition performance of the visual system (section 1.1.1.). The existence of such an invariance in a Fourier analysis model may therefore be an argument against its accuracy as a model for vision.

Many of the spatial frequency analysis models have argued that the visual striate cortex is the substrate for the Fourier analysis of the visual input. This conjecture follows the findings that most cortical cells are fairly narrowly tuned for spatial frequency and that the peaks of the tuning curves recorded from cells with inputs in the same part of the visual field show a large range of spatial frequencies (Maffei and Fiorentini, 1973; Ikeda and Wright, 1975; Schiller, Finlay and Volman, 1976; Albrecht, 1978; Movshon, Thompson and Tolhurst, 1978). Thus these cells could provide the basis for the spatial filtering reguired for Fourier analysis.

Two main Fourier analysis models have been proposed, their division being on the basis of the spatial extent of the region in which the Fourier analysis takes place. In the one, Fourier analysis takes place globally (Pollen, Lee and Taylor, 1971; Pollen and Ronner, 1975) whilst in the other the analysis takes place on a patch-by-patch basis (Robson, 1975).

If Fourier analysis were taking place over the whole visual field as proposed by the former global model, cells would be required that have extremely large receptive fields accompanied by narrow spatial frequency bandwidths. The physiological evidence for such cells is extremely small (the periphery effect (McIlwain, 1966; Fischer and Kruger, 1974; Fischer, Barth and Sternheim, 1978; Derrington, Lennie and Wright, 1979) displayed by some retinal and LGN cells provides some evidence). The inhomogeneous nature of the retina would also complicate such a scheme (Van Doorn, Koenderink and Bouman, 1972).

If analysis of the visual field were on a patch-by-patch basis, as proposed in the latter model, with patches of the order of minutes of arc to one or two degrees of visual angle, the Fourier analysis model becomes much more workable. In this instance the problems of receptive field size and retinal inhomogeneity do not arise because the patch size is comparable to the cell receptive field sizes. Such a local model sacrifices much of the attractiveness of the Fourier analysis scheme for the size and position invariance capabilities can only operate, a priori, within one patch. Thus, if frequency analysis does take place on such a local basis, recognition of a pattern as a whole must be accompanied by some convergence of the outputs from these patches. This latter model could be interpreted as a form of structural model of pattern recognition, (section 1.2.2.) with the features being represented by spatial frequency amplitudes and the relations represented by the relative patch positions. Local relations could also be defined, if necessary, based on relative phases of the spatial frequency components within a patch. Evidence for sensitivity to local relative phase has been found in texture discrimination experiments (Caelli and Julesz, 1978; Caelli, Julesz and Gilbert, 1978) although data presented in this thesis (chapter 6) show a lack of adaptational sensitivity of such local phase sensitive mechanisms (see also Foster and Mason, 1980). No physiological mechanisms sensitive to local relative phase has yet been recorded (De Valois and De Valois, 1980) but this may simply be a consequence of no serious attempt having been made to identify such a mechanism. Conversely, local phase information may be processed at a higher level than those examined by current electrophysiological techniques and may not be associated with the response of a single neurone.

1.5.2. "Feature detectors" and the contrast threshold elevation effect.

An alternative approach to one based on spatial frequency analysis for the exploration of the contrast threshold elevation effect is one based upon the proposed existence of mechanisms sensitive to the presence of certain spatial features such as dots, bars or edges in the input pattern. In such a case the input pattern is "analysed" in terms of these features rather than its spatial frequency content (see above).

Much of the support for the notion of mechanisms sensitive to spots, bars and edges came from electrophysiological investigation of the spatial sensitivity of neurones in animal visual systems. In particular, the work of Hubel and Wiesel (1962, 1966) has been used to support this notion. These workers determined "receptive fields" of cat and monkey cortical neurones using various stimulus shapes. They reported cells in the visual cortex which were best excited by either edges, bars, corners or spots. They classified these cells into three main categories: simple, complex and hypercomplex. The simple cells responded maximally to a bar or an edge of a particular orientation placed at a particular position within the receptive field of the cell. Simple cells sensitive to bar stimuli also gave maximum response when the bar was of an optimum width, a similar selectivity for bar length was not shown by these cells. Complex cells showed responses similar to those from simple cells except that a maximum response could be elicited by the optimally oriented bar or edge placed in many different positions within the receptive field of the cell. That is, complex cells exhibit some position invariance. Cells were classified as hypercomplex if they displayed responses similar to those from complex cells but in addition showed some "end stopping" that is, they responded best to the ends of bars, bars of an optimal length or corner like stimuli.

The finding of cells in the visual cortex of cat and monkey which were optimally sensitive to simple spatial features like bars, edges and corners was taken as evidence for a pattern analysis scheme based on the concept that these cortical cells "extracted" these features from the visual input. As mentioned earlier (section 1.2.2.), this idea has one major difficulty for these cells also respond to non-optimal input features and thus the response of a single "bar detector" cell cannot signal absolutely the presence of a bar. This response to non-optimal features is illustrated by the results of a study by Creutzfeldt and Nothdurft (1978) of LGN and cortical neurones. These authors correlated cell activity with the part of a complex pattern that was falling on the cells receptive field. Typical cortical cell responses exhibited sensitivity to such pattern features as lines and ends of bars. These responses, however, were not localised, for example to bars of one orientation and cells were found to respond to a range of bar orientations.

It is necessary, therefore, that the outputs of a number of such cells, responding to different edges or bar widths, are used to detect the presence of a bar input (see Marr, 1976). Frisby (1979) has argued that the hypercolumns in the visual cortex (Hubel, Wiesel and Stryker, 1978) may provide the physiological basis for such computation and combination.

Several psychophysical studies have provided results which have been used in support of the notion that the visual system analyses patterns in terms of simple pattern features.

Tolhurst (1972) investigated the effects of adapting to an edge-like stimulus of one contrast polarity on test edges of both contrast polarities. He found that the greatest contrast threshold elevation occurred for the test edge of the same contrast polarity as the adaptation edge. From measurements of the contrast sensitivities for edges of various profiles and square-wave gratings Tolhurst (1972) suggests that the gratings might be detected as a series of edges. This author also suggests that mutual inhibitions between bar and edge detectors may subserve certain visual illusions including Mach bands.

In a further study using subthreshold summation techniques Shapley and Tolhurst (1973) measured the spatial properties of the hypothesised edge detectors and found that the visibility of ramp and edge stimuli could be explained largely in terms of these edge detector mechanisms.

Using both subthreshold summation techniques and detection probability measurements Kulikowski and King-Smith (1973), and King-Smith and Kulikowski (1975) investigated the notion that the detection of composite stimuli can be explained in terms of line and edge detectors. These authors conclude that a model based on independent line detectors is a useful first approximation for a description of grating detection. These authors also argue that their results for the detection of sinusoidal gratings and single lines can be explained by probability summation among line detectors.

As mentioned previously (section 1.4.2.) studies of the contrast threshold elevation effect have shown adaptational selectivity for the width of bright bars (Naghshineh and Ruddock, 1978), the size of rectangles and spots (Thomas and Kerr, 1971; Kerr and Thomas, 1972; Bagrash, 1973; Nagshineh and Ruddock, 1978) and the length of bars (Nakayama and Roberts, 1972; Burton and Ruddock, 1978).

These psychophysical studies may be interpreted as an indication that the visual system contains mechanisms sensitive to certain geometric features of a pattern. In particular, most of these results can be explained by mechanisms sensitive to edges, bars and spots. Although these mechanisms show some maximum in their response to a range of say bar widths it must be remembered that they also show a response to a range of widths. That is, they are not true "feature detectors" in the sense that they respond exclusively to a single feature. The responses of these mechanisms might be combined at some stage of processing to produce a feature extraction process as in the model described by Marr (1976).

Given the existence of mechanisms capable of the extraction of local pattern features it is necessary to consider if this implies the existence of other properties of the visual system. In the discussion of pattern recognition (section 1.1.) it was found that a scheme based upon the extraction of pattern features alone was inadequate for the description of patterns in which spatial relationships were important. This problem was overcome in computer models of vision by using a structural approach to pattern encoding in which local features and their local spatial relations were used to form the internal representation of a pattern. Thus if the visual system is supposed to analyse local pattern features it would seem likely that it should also analyse position information. No direct evidence, either electrophysiological or psychophysical, for the existence of local relation sensitive mechanisms in the visual system has been presented. The texture discrimination experiments of Caelli and Julesz (1978) and Caelli, Julesz and Gilbert (1978) showing sensitivity to local pattern arrangement might be interpreted as a relational sensitivity, although their results might also be explained by the existence of local feature detectors sensitive to certain pattern shapes.

Relative position information is preserved in the early stages of visual processing by the preservation of the topology of the retinal map at the visual cortex. Thus any analysis of relative position (relational) information may take place at a later stage of processing than the feature extraction process. The experiments described in this thesis examine the relational sensitivity of the visual system using both adaptation and discrimination techniques. Two different techniques are compared in order to assess the processing stage at which relational information becomes important.

1.5.3. Fourier theories and feature theories.

Much debate has taken place about the question of whether the visual system utilises spatial frequency analysis or feature analysis for pattern vision (Sekuler, 1974; De Valois and De Valois, 1980).

The initial success of the spatial frequency model in predicting the results of adaptation experiments (e.g. Blakemore and Campbell, 1969) has led to little experimentation designed to investigate models of adaptation based on more generalized pattern recognition theories, e.g. structural theories. The stimuli used in most adaptation experiments are typically gratings periodic in one or two dimensions. Such periodic stimuli are easily describable in terms of their Fourier components but are often spatially complex (e.g. the sum of two sinusoidal patterns). For the investigation of structural theories stimuli which can be described simply in terms of their spatial features (e.g. bars and spots) and spatial relations (e.g.

left of, above and connected to) are likely to be of most use.

It should be noted that the ability to describe a stimulus in terms of its Fourier components, does not imply that the mechanism being studied performs a Fourier analysis of that stimulus. This point has often been overlooked and Fourier analysis techniques have been applied to pattern vision without the acknowledgement that their use requires certain assumptions about the system being analysed. In particular, the use of Fourier analysis assumes linearity of the system being studied. The experiments described above (section 1.5.1) with results indicating non-linearity at some stage of visual processing cast serious doubt therefore on the notion that the visual system performs a Fourier analysis of the input pattern. These experiments have demonstrated non-linearity in the visual system for large stimuli, therefore it might be argued that Fourier analysis is being performed in small localized patches by cells with linear responses (Robson, 1975). Such a patch might, however, be renamed as an array of local feature detectors sensitive to various sizes. This complementarity of detectors sensitive to a band of spatial frequencies and detectors sensitive to a range of sizes is argued by MacKay (1981) for the case of cortical neurones. Macleod and Rosenfeld (1974) illustrated this complementarity in a space-domain model of pattern analysis. This model was based on detecting units which could be regarded either as bar-sensitive units or as localized spectral analysers. The model was found to be consistent with the results of psychophysical studies of pattern vision.

Thus although local feature detectors may be thought of as localised spectral analysers such a distinction may be misleading. MacKay (1981) notes that the sensitivity profiles of cortical cells seem to be weighted in favour of spatial resolution rather than spatial frequency resolution and Macleod and Rosenfeld (1974) state their preference that it seems more natural to regard processing in terms of bar-like elements. The present author also considers an interpretation in terms of bar-like features to be a more natural approach, especially for consideration of structural theories of pattern recognition.

1.6. Summary and motivation.

The first part of this introduction was concerned with the way in which a pattern might be encoded to form an internal representation of that pattern and how this internal representation might be used for pattern recognition. Two main types of theory were discussed, the one considered to be based on wholistic internal representations (template matching theories), the other considered to be based on internal representations containing information about particular pattern attributes (pattern encoding theories).

Among the template matching theories, the most versatile ones were found to be those based on the use of internal compensatory transformations. In these transformational theories recognition is supposed to be achieved by the action of the internal compensatory transformations on wholistic internal representations in such a way that they are brought into coincidence either with each other or with some standard template.

Among the pattern encoding theories, ones based upon the notion of structural descriptions were found to be most versatile. In such structural theories patterns are supposed to give rise to an internal representation based on pattern features (such as bars and spots) and their spatial relations (e.g. above, right of and connected to). As in a transformational theory, patterns in a structural theory are recognized as being the same when their internal representations coincide.

The second part of this introduction discussed pattern adaptation effects. In particular, the contrast threshold elevation effect was discussed. This effect was found to be dependent upon the relative sizes and orientations of the adaptation and test patterns used in its measurement. The range of pattern types used in the investigation of this effect has been, however, limited to either periodic patterns or simple single element patterns. It was noted (particularly in the case of single element patterns) that local retinal adaptation caused difficulty in measurements of the contrast threshold effect and should therefore be taken into consideration in all such measurements.

Two theories of pattern vision which have been proposed as an explanation of the results of contrast threshold elevation studies were discussed. In the one theory patterns are considered to be Fourier analysed by the visual system and encoded in terms of their spatial frequency components. This theory was rejected as an explanation of pattern vision for the whole visual field for the following reason. Much experimental evidence has been presented which indicates that the visual system contains non-linearity in its response to spatial stimuli. Fourier analysis, however, assumes linearity of the system under study and is therefore an inappropriate model for a non-linear visual system. In order to counter these arguments against Fourier analysis it was suggested that such analysis might take place on a patch-by-patch basis, which would only require local linearity. It was shown that such a patch theory might be equated to the local feature analysis theory discussed below.

The other theory of pattern vision proposed as an explanation of the results of contrast threshold elevation studies suggests that mechanisms sensitive to local features such as bars and dots are responsible for pattern vision.

Both the local patch-by-patch Fourier analysis theory and the local feature theory might be classed as types of encoding theories of pattern recognition. In the discussion of these encoding theories it was noted that in addition to the encoding of pattern features the encoding of the local spatial relationships between these features was necessary to enable the recognition of certain patterns. If such a structural theory (in which local features and their relations are encoded to form an internal representation of a pattern) is to be used as a framework for the interpretation of the results from contrast threshold experiments the following questions arise.

First, can the contrast threshold elevation effect be produced by stimuli which can be simply described in terms of their local features and the spatial relations between these features? The stimuli used in previous studies have generally been of a form which cannot be described simply in these structural terms. Stimuli and techniques more appropriate to an investigation of the contrast threshold elevation effect in the context of structural theories therefore need to be developed.

Second, if stimuli of the form outlined above do give rise to a contrast threshold elevation effect is this effect dependent on both the feature and the relation content of the stimuli? If, for example, the adapted mechanisms were adaptationally insensitive to local relative position information it might be supposed that these mechanisms were only concerned with the processing of feature information. In such a case the processing of the relational information might be supposed to occur at a later stage of pattern analysis.

Third, if the contrast threshold elevation effect is supposed to reveal the characteristics of early stages of pattern processing and a different experimental technique, say pattern discrimination, is supposed to reveal the characteristics at later stages of pattern processing, we might expect the results obtained with these two techniques to indicate the stage at which different pattern attributes are processed. For example, the early stages of pattern processing may only contain mechanisms selective for pattern features. Thus a technique capable only of revealing this peripheral selectivity might not show sensitivity to changes in spatial relations which are analysed more centrally. In contrast, a technique capable of revealing the characteristics of more central mechanisms might show sensitivity to changes of both features and relations.

The answers to these questions are capable of revealing whether there is a fundamental difference in the way in which the putative features and relations are encoded prior to the "recognition" process. For example, pattern feature information may be encoded at an early stage in the form of neurone firing rates, whereas relational information is preserved by preservation of the retinal topology as far as the relational analysis stage.

The experiments reported in this thesis were designed to investigate these questions using both adaptation and pattern recognition techniques. The next chapter outlines the plan of the present research.

CHAPTER 2. PLAN OF INVESTIGATION.

As mentioned previously (section 1.6) both the patch-by-patch Fourier analysis theory and the feature analysis theory proposed to explain the results of contrast threshold elevation effect experiments might be regarded as types of structural theories of pattern recognition. It might be suggested therefore that the contrast threshold elevation effect provides a means of investigation of the way in which a structural description of a pattern is formed. In particular, if the mechanisms involved in the contrast threshold elevation effect precede those involved with pattern recognition we might expect the mechanisms involved in adaptation to show less sensitivity to pattern changes than those involved in recognition. For example, in the context of structural theories of pattern recognition we might expect a difference in the way changes in local features affect contrast threshold elevation from the way changes in local spatial relations affect contrast threshold elevation. Such a difference might be interpreted as an indication of a fundamental difference in the way in which local features and local relations are encoded prior to their use in pattern recognition.

Before the contrast threshold elevation effect may be used in the above manner it is necessary to develop an adaptation technique which is sensitive to local pattern changes. Such a technique would not necessarily employ repetitive or periodic stimuli similar to those of previous studies and therefore might reveal local properties that differ from the more global ones revealed in earlier studies.

If the mechanisms involved in the contrast threshold elevation effect precede those involved in pattern recognition as suggested above, then a comparison of the results from experiments employing these two techniques should be interesting. In particular, if the pattern recognition technique chosen is one in which it is supposed that pattern processing is limited then we might expect the internal representation on which recognition is based to be limited to information about the stimulus pattern which is extracted at an early stage of processing. In such a case we might therefore expect the results from the contrast threshold elevation effect and pattern recognition experiments to be similar for similar stimulus patterns.

It is of interest also to examine how a structural theory of pattern recognition may be applied to interpretation of typical pattern recognition data. In particular, how may such a theory be used in the prediction of pattern recognition performance and how good are these predictions?

In view of the above discussion the aims of the present research may be formulated and summarized as follows.

First, an adaptation technique suitable for the examination of local pattern structure will be developed and used to examine some basic properties of the contrast threshold effect for localised stimuli.

Second, this adaptation technique will be used to investigate the adaptational sensitivity of the mechanisms involved in the contrast threshold elevation effect to changes in either local pattern features or local relational structure.

Third, the results of the above adaptation experiments will be compared with the results of a pattern recognition experiment in which similar stimuli are utilized and processing is supposed to be limited.

Fourth, a model based on structural theories of pattern recognition will be developed and used to predict typical pattern recognition data.

The plan of this thesis is therefore as follows.

In Chapter 3 the apparatus developed for investigation of the contrast threshold elevation effect and the calibration of this apparatus are described. The general methods used in the contrast threshold elevation measurements are also described.

In Chapter 4 the technique used in the contrast threshold elevation experiments is developed and the validity of its use is investigated.

In Chapter 5 the stimulus specificity of the technique is investigated, particularly with reference to such questions as size, orientation and shape specificity.

In Chapters 6-8 experiments to measure the role of various spatial relations in producing contrast threshold elevation are described.

In Chapter 9 the relative importance of features and relations in a contrast threshold elevation task and in a pattern discrimination task is examined and the results from the two tasks compared.

In Chapter 10 a model based on structural theories of pattern recognition is developed and its predictions of pattern recognition performance are compared with experimental data. The implications of this model for structural theories of pattern recognition are also discussed.

In Chapter 11 the findings of the previous chapters are summarized and general comment and conclusions are given. The general implications of the present experiments for structural encoding theories and the usefulness of the adaptation technique are included in this discussion.

CHAPTER 3. GENERAL METHODS.

In the Introduction (section 1.4) the contrast threshold elevation effect was discussed. In this discussion it was noted that the effect was dependent on the spatial and temporal parameters of the stimuli, and increased with increasing adaptation contrast (section 1.4.1.) In section 1.4. it was also noted that careful attention to experimental procedure and statistical design is important in measurements of the contrast threshold elevation effect. This need for care was highlighted by the discussions of the effect of local adaptation and the effect of threshold fluctuations on measurement of the contrast threshold elevation effect.

In measurements of the contrast threshold elevation effect it is important therefore to employ stimuli with high spatial fidelity, a high and stable contrast and well defined temporal structure. It is also important that the experimental procedures and statistical designs for making these contrast threshold elevation measurements enable the effects of local retinal adaptation and threshold fluctuations to be either removed from or accounted for in the results.

The above considerations are critical for the production of the contrast threshold elevation effect and the reliability of the experimental data. In the following sections the methods used in the present study of the contrast threshold elevation effect are described with particular reference to these considerations.

3.1. Apparatus.

The contrast threshold elevation effect has been studied by previous workers using various forms of apparatus including tachistoscopes, cathode-ray display tubes, and high intensity optical imaging systems. The present apparatus was chosen to maximise the contrast threshold elevation effect, enable precise measurement of thresholds and minimise the contribution of other factors in the measurements e.g. the effects of local retinal adaptation.

It was decided that the use of a tachistoscope for the present experiments was inappropriate owing to the difficulty in maintaining the spectral composition of the tachistoscope channels as their intensity is varied. Similar problems occur during the interchange from one tachistoscope channel to another.

These problems arise as a consequence of the differences in rise and fall times of the various phosphors used in tachistoscope tubes (Mollon and Polden, 1978).

Although cathode-ray display tubes have often been used in contrast threshold elevation measurements with periodic stimuli (e.g. Blakemore and Campbell, 1969) such displays are not easily adapted to the types of discrete stimulus used in the present study. In particular, the random line stimuli used in the present studies would require some form of computer controlled cathode-ray display for their generation. Because cathode-ray tubes use phosphors in their construction they are also subject to the problems mentioned above for tachistoscopes. The major disadvantage of both tachistoscopes and cathode-ray display tubes is the low retinal illuminances that can be attained using such devices. As the magnitude of the contrast threshold elevation effect increases with adaptation pattern luminance up to retinal illuminances of 5 log trolands (Maudarbocus and Ruddock, 1973; Blakemore and Campbell, 1969) an apparatus capable of providing such high intensities would optimise the threshold elevation effects measured.

In order to provide such high retinal illuminances some form of high intensity optical imaging system is required. Two types of high intensity optical imaging apparatus have been used in pattern vision studies, the one employing laser sources to produce patterns directly on the retina by interference and the other employing conventional optical techniques, i.e. Maxwellian view. Laser based systems are only appropriate for investigation of patterns which may be easily constructed by interference techniques e.g. sine wave gratings. These laser based systems are also restricted to monochromatic light, which although very useful in colour vision studies gives rise to laser speckle which introduces a "dynamic noise" background to the pattern.

It was decided, therefore, that a Maxwellian view optical system would be constructed for the studies of the contrast threshold elevation effect reported here. Naghshineh and Ruddock (1978) also used Maxwellian view in their investigations of the contrast threshold elevation effect.

3.1.1. The Maxwellian view system.

Maxwellian view, as its name suggests, was first described by Maxwell in 1860 for colour mixing experiments. Maxwell described how the faces of the prisms in his instrument appeared uniformly illuminated. This uniformity is one of the advantages of this type of imaging which is exploited in the system used here.

The modern form of Maxwellian view is discussed fully by Westheimer (1966) and it suffices here to list the advantages of such a system.

a) Because stimuli are illuminated by a parallel light beam they have a luminance strictly related to the transmission properties of the stimulus field used, i.e. with total transmission the field viewed would have a uniform luminance at each point within the usable aperture. In particular stimuli which may be reproduced photographically can be used. The discrete stimuli used in the present studies may therefore be produced by a photographic process from off-line computer produced drawings.

b) Imaging of the light source at the eye pupil enables very high retinal illuminances to be achieved, limited only by source luminance.

c) By the use of an artificial pupil smaller than the eye pupil a constant retinal illuminance can be obtained.

d) The image "depths" may be adjusted with ease.

e) Because a single primary light source is used, stimuli derived from different channels of the system maintain constant luminance ratios despite source variations. A constant Weber fraction is therefore maintained between the different channels.

By the use of high contrast film for the stimulus masks high stimulus contrast and high stimulus luminance can be obtained, compared with the low stimulus contrast and luminances obtainable with tachistoscopes and cathode-ray display tube systems.

3.1.2. Present Maxwellian view apparatus.

Fig 3.1. shows a diagram of the apparatus and plate I shows the finished system.

Light from the source S was collimated by lenses L1 and L2 and then divided into four channels by semi-reflecting mirrors SM1 and SM2. Each of the first three of these channels was shuttered at an intermediate focus by an electronically controlled mechanical shutter (i.e. SH1, SH2 and SH3). The fourth channel was used by the experimenter to monitor the light source intensity. The three shuttered channels were collimated again by the achromatic doublets DL1, DL2 and DL3 and then combined by beam-splitter cubes BS1, BS2 and BS3. The light combined from these three channels was then focussed at the exit pupil EP by achromatic doublet DL4. Stimuli were produced by placing stimulus masks at positions T1,T2 and T3.

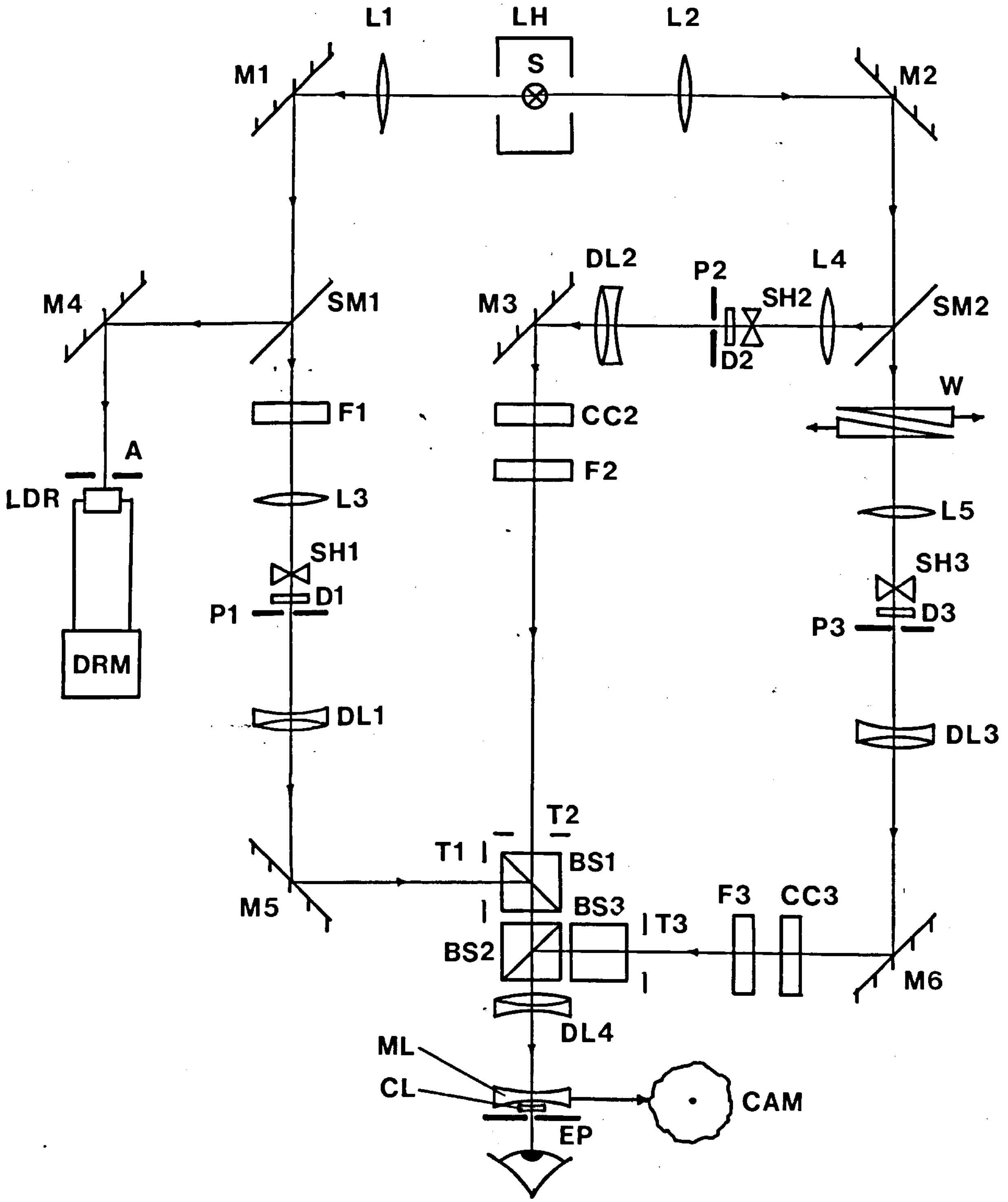

Fig. 3.1. Diagram of Maxwellian view apparatus.

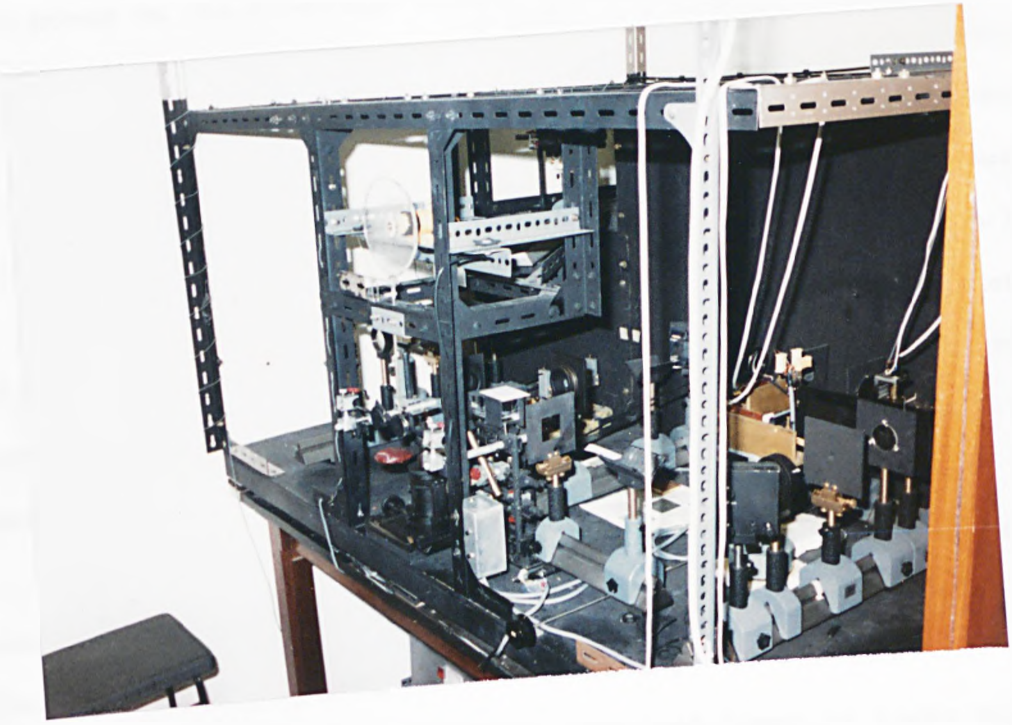

Plate I Photograph of Maxwellian view apparatus.

The colour and luminance of the three stimulus channels was controlled by filters placed at positions F1, F2, F3, CC2 and CC3, and by a neutral density wedge W. A small negative lens ML placed behind the exit pupil and moved by a cam mechanism allowed the stimuli to be moved in the observers visual field. A detailed description of the Maxwellian view apparatus is given in the following paragraphs.

The light source for the apparatus was a single tungsten-halogen lamp (Atlas type A1/216) S powered by a high stability D.C. power supply with slow turn-on and turn-off designed to prolong lamp life and improve light output stability (see section 3.2.1.). As mentioned earlier luminance level stability is important in contrast threshold elevation measurements because the magnitude of the elevation is dependent on luminance (section 1.4.1.).

To reduce scattered light, the source was mounted within a lamp house LH with apertures which allowed light from the source to illuminate the converging lenses L1 and L2.

These lenses produced approximately parallel beams of light which after reflection at front silvered mirrors M1 and M2 respectively, were split into the four channels of the system by semi-silvered mirrors SM1 and SM2. Reflecting the light beams whilst they are parallel and of large aperture reduced the effects of any irregularities in the reflecting surfaces. The selective reflection properties of these semi-silvered mirrors, however, cause a colour change of the transmitted beam with respect to the reflected beam; this problem also occurs with the beam splitters, BS1, BS2, BS3. The system was designed therefore so that all the channels used for stimuli underwent reflection once and transmission twice at semi-silvered surfaces in order to equalize these effects for the channels.

The parallel light beam of the channel used for light level monitoring passed via mirror M4 through an aperture A to completely cover the sensitive surface of the light dependent resistor (LDR). A resistance meter (DRM), connected to the light dependent resistor, was used by the experimenter to monitor the light level from the source to check for the effects of lamp ageing.

Each of the other three channels was interrupted by electromagnetic shutters, SH1, SH2 and SH3 at an intermediate focus formed by lenses L3, L4 and L5 respectively. Interrupting the light beams at intermediate foci required only a small movement of the mechanical shutter to switch the light channel on or off. Fast shuttering times did therefore not require high velocity shutters. The driving circuit for the relay shutters was designed to give fast, repeatable rise and fall times and yet enable the shutter to remain open for long periods without damage to the relay coil. This was achieved by a system using two-current-levels with a high constant current pulse being delivered for a short (adjustable) time to pull the shutter open rapidly, followed by a reduced holding current to prevent relay overheating. The shutter closed under the action of the return spring and the low level holding current ensures that magnetic field collapse time, and hence shutter fall time, is small compared with shutters using higher holding currents. Light flash rise and fall times between 10% and 90% of maximum were better than 1.5 ms and 2.1 ms respectively. These rise and fall times were measured by means of a photodiode at the apparatus exit pupil. This fast shuttering system, in contrast to tachistoscopes and cathode-ray display tubes, interrupts all wavelengths in the light source with the same time course.

To increase the source uniformity, at each of these intermediate foci small ground-glass diffusing plates (D1, D2, D3) were placed. These diffusers were mounted in front of small circular 3mm diameter apertures which were smaller than the images of the bulb filament. In this way any spatial structure in the image of the bulb filament is reduced and also dispersion of the image (visible by the 'spectrum' at the image edge) is stopped by the apertures. This procedure effectively produced three spatially uniform secondary sources whose luminances were proportional to the primary source luminance.

To verify this spatial filtering effect a test was made in which a coarse 0.3 cycle/degree grating was placed in the parallel light beam before a typical intermediate focus. With the diffuser in place no spatial structure was visible in the field when viewed at a point in the parallel light beam after the intermediate focus.

Light from each of these secondary sources was formed into a parallel light beam by achromatic doublets Dl1, DL2, DL3 which after reflection in front silvered mirrors M3, M5, M6 transilluminates the stimulus transparencies at positions T1, T2, T3 with parallel light. The transmitted light was then combined by beam splitter cubes BS1, BS2 and BS3 and passes through final achromatic doublet lens DL4. (The other surface of BS3 was used to combine light from the 4th channel when used for a stimulus). The use of beam splitter cubes and achromatic doublets after the secondary sources prevents double images due to multiple reflections in semi-silvered mirrors and reduces chromatic abberrations in the final image.

For most experiments in this study a small negative lens ML driven by a cam system (Fig. 3.2.) was placed immediately behind the exit pupil EP of the system.

Movement of this lens in a vertical direction caused movement also in the vertical direction of the stimuli seen by the observer. This system was used to introduce small saccade-like motions to the stimulus field and Fig. 3.3. shows a recording from an X-Y photocell device for the image position for 2 rotations of the cam.

The maximum excursion of the image is controlled by the use of various values of the lens ML and a summary of the cam motion is given in Table I.

TABLE I

lens value (diopters)	movement range (deg)	average stationary phase (ms)	average moving phase (ms)	average saccade magnitude (deg)	average velocity (deg.sec^{-1})
-10	2.86	138	29	1.1	38
- 6	1.95	138	29	0.7	24

Note: deg = degrees visual angle.

As can be seen from the summary data the saccade-like motion is of a form which cannot be tracked by voluntary eye movement (see Carpenter, 1977 for review of eye movement data).

Another lens CL was also included behind the exit pupil to enable the subject's vision to be corrected to normal in the case of either myopic or hypermetropic subjects. The stimulus mask positions T1, T2, T3 were at equal 'optical distances' from the lens DL4 thus ensuring that the stimuli appeared in the same focal plane.

The colours of the three stimulus fields were matched visually using Kodak colour compensating filters inserted in the appropriate channels (at positions CC2 and CC3 in the diagram).

Luminances of the stimuli in the three channels were controlled by neutral density filters inserted at positions F1, F2 and F3 and a fine control of the right hand (stimulus position T3) channel was achieved by the use of two 2.3 log-unit neutral density wedges. These wedges were arranged to move in opposite directions by means of a rack and pinion arrangement driven by a small D.C. motor. This arrangement gave compensation of the wedge gradients across the parallel light beam and approximately 4 log units of density range (see calibrations

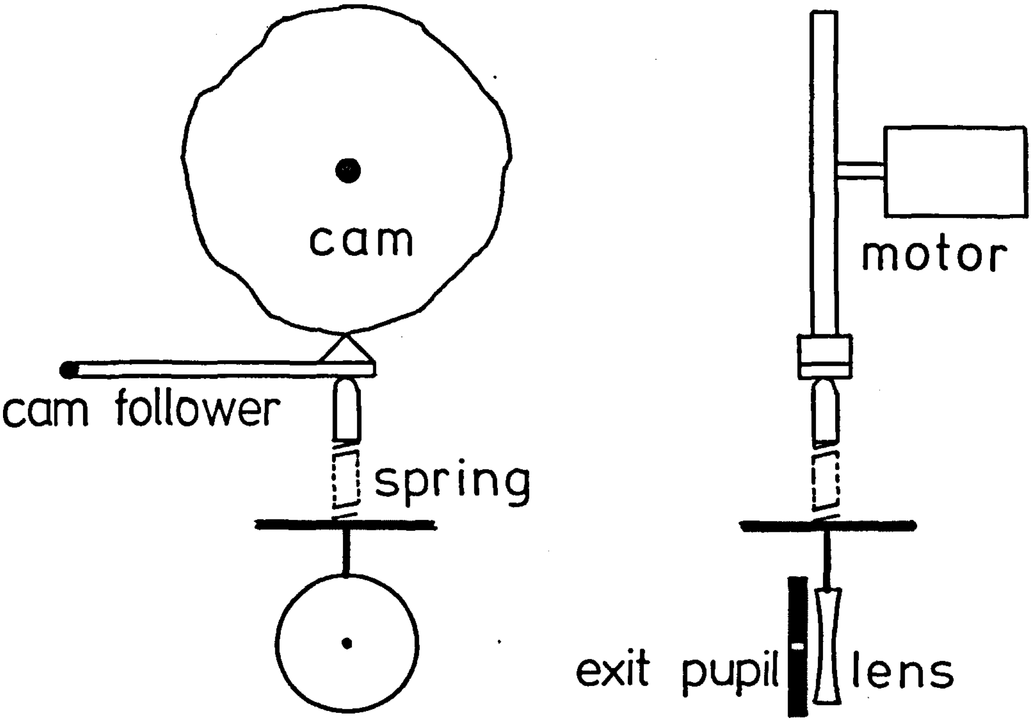

Fig. 3.2. Diagram of cam system and lens.

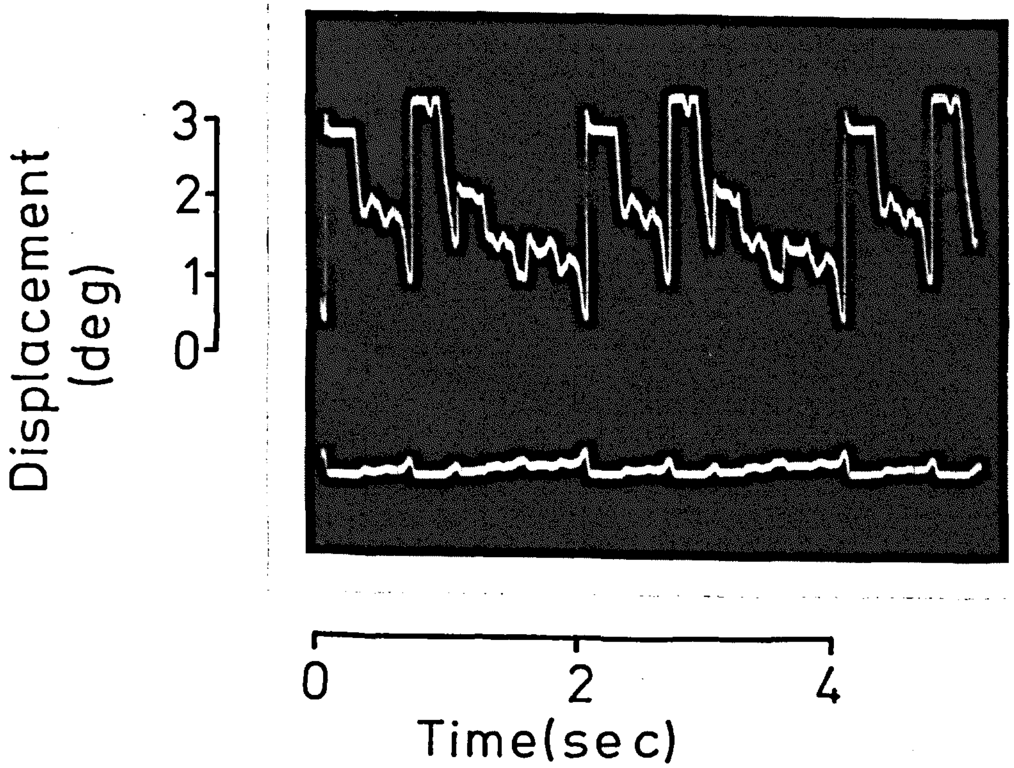

Fig. 3.3. Displacement of image recorded at exit pupil in degrees of visual angle. The top trace shows vertical displacement and the bottom trace shows horizontal displacement.

of wedge, section 3.2.2.). The D. C. motor was controlled by two push buttons, the one to increase density and the other to decrease density. Any non-visual knowledge of the absolute position of the wedge was thus precluded. Recording of the wedge position was by means of a multiturn potentiometer. The potentiometer spindle was attached directly to a spring loaded rack and pinion on the wedges to remove backlash errors. This potentiometer was connected to a digital multimeter (DMM) whose output was recorded in one of three ways. First, the experimenter could record the data; second an assistant at a remote recording station could record date; and, third an automatic serialiser and printer could be used. Either the remote station or the printer was used when the experimenter was the subject. In this circumstance the experimenter did not view the results until the end of all the runs for a particular experiment.

The timing of the shutters SH1, SH2 and SH3 and the periods during which the cam is in motion are controlled by a timing and sequencing circuit. Fig 3.4 shows a block diagram of the control circuit which enabled any combination of shutters to be either open or closed during each timing period. The switch SW initiated the automatic timing cycle. The cam could also be activated in each timing period as required.

The subject's head was stabilised by means of a dental bitebar firmly attached to an adjustable mount. This enables the centre of the observer's eye pupil to be adjusted to coincide with the centre of the exit pupil EP of the apparatus.

The retinal illuminances used in this study were less than 4 log trolands thus the average eye pupil diameter was 2.5mm. (Wyszecki and Stiles, 1967; Spring and Stiles, 1948) Diffraction limiting of visual acuity occurs for pupil diameters less than 1.5mm (Riggs, 1965). An artificial pupil of diameter 2mm was chosen therefore to lie

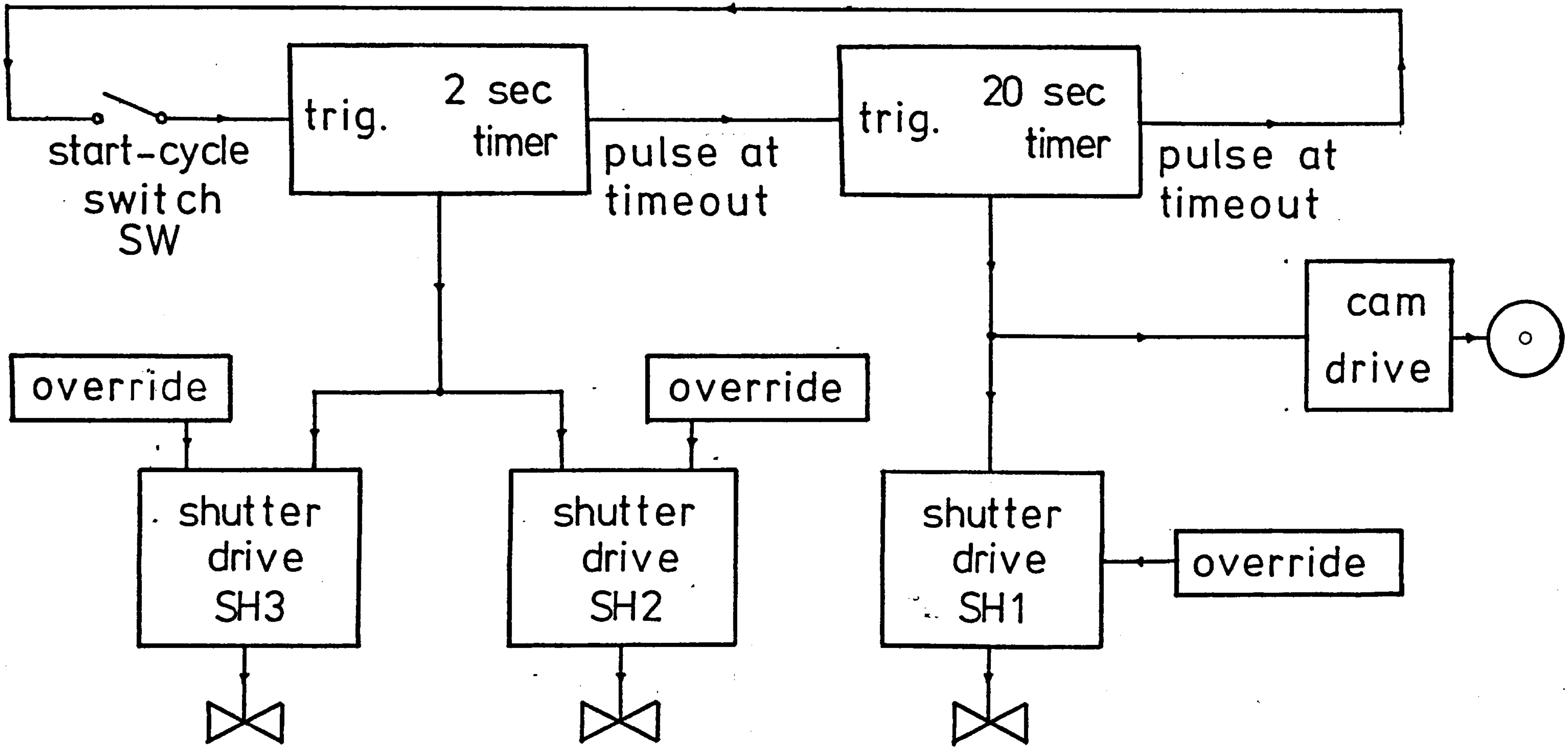

Fig. 3.4. Block diagram of control electronics:

between these limits and was placed at the exit pupil EP of the apparatus.

3.2. Calibrations.

3.2.1. Light source stability.

Fig 3.5. shows a plot of light output against time for the source as measured with a photomultiplier at the exit pupil of the apparatus.

The bar indicates the effect of the interposition of a sheet of optical glass (equivalent to 0.033 log unit neutral density filter) on the plateau level of the source. The maximum variation from the plateau level after an initial warm up period of 30 seconds was less than 0.0033 log units which represents 1% of the light output. Lamps were replaced when their monitored luminance deviated by more than 0.033 log units from the standard setting to which they were adjusted when new. Thus a highly repeatable and stable source of high intensity light was available.

3.2.2. Calibrations of neutral density filters and wedge.

The neutrality of the neutral density filters between 300nm and 800nm was confirmed using a scanning spectrophotometer (Unicam SP.800).

The neutral density wedge system was calibrated in situ using a photomultiplier to monitor the light intensity at the exit pupil of the apparatus. It is important that such a calibration is carried out on the finished apparatus because reflections between the optical components of the system can modify the relationship between wedge position and density.

The calibration of the neutral density wedge was performed at

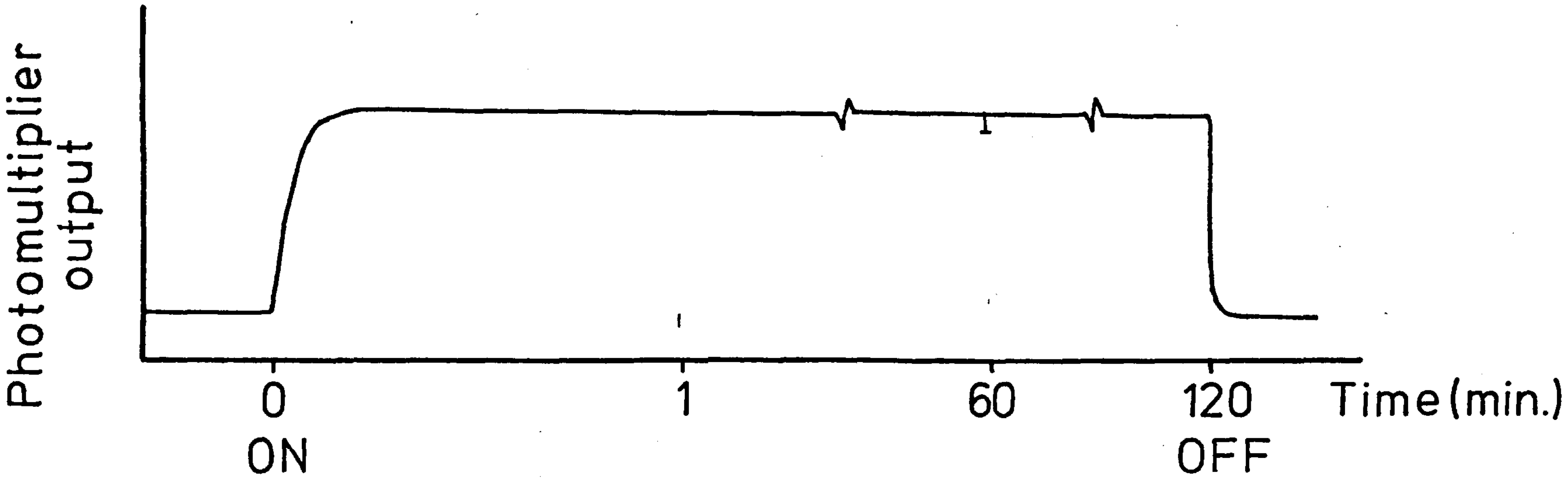

Fig 3.5. Light output from lamp.

wavelengths of 398nm, 424nm, 499nm, 556nm, 597nm, and 640nm and for the "white" (colour temperature 3500K) light used in experiments reported here. The results are given in Fig 3.6. The ordinate represents wedge density and the abscissa wedge position as measured by the digital multimeter. These results confirm the linear relationship between wedge transmission and the reading on the digital multimeter at the various wavelengths measured. There is little change of the gradient of this linear relationship with changing wavelength and the use of a constant conversion factor from digital multimeter reading to wedge density of 0.0022(indicated by the continuous line in Fig. 3.6.) over a range of 4 log units introduces a maximum total error of 0.09 log units. Thus on a typical contrast threshold elevation of 0.4 log units a relative error of 0.009 log units is introduced. The close agreement of the calibrations using narrow-band light and "white" light indicates that the wedges neutrality was acceptable at least for the range of wave-lengths measured.

3.2.3. Stimulus colour and absolute luminance.

The three channels of the Maxwellian view system were colour matched with Kodak colour compensating filters in the following way. The two halves of a 2° diameter bipartite field were viewed through the apparatus exit pupil. Each half of the field was derived from a different channel. Colour correcting filters were inserted in the channels until a visual match between all three channels was obtained. Channel luminances were matched by inserting neutral density filters during this colour matching procedure.

The colour temperature of the resultant matched white light from the three channels was determined as follows. First, a colour temperature meter (Megatron) was used to measure the colour temperature of the "white" light from the apparatus. Second, a sub-standard lamp

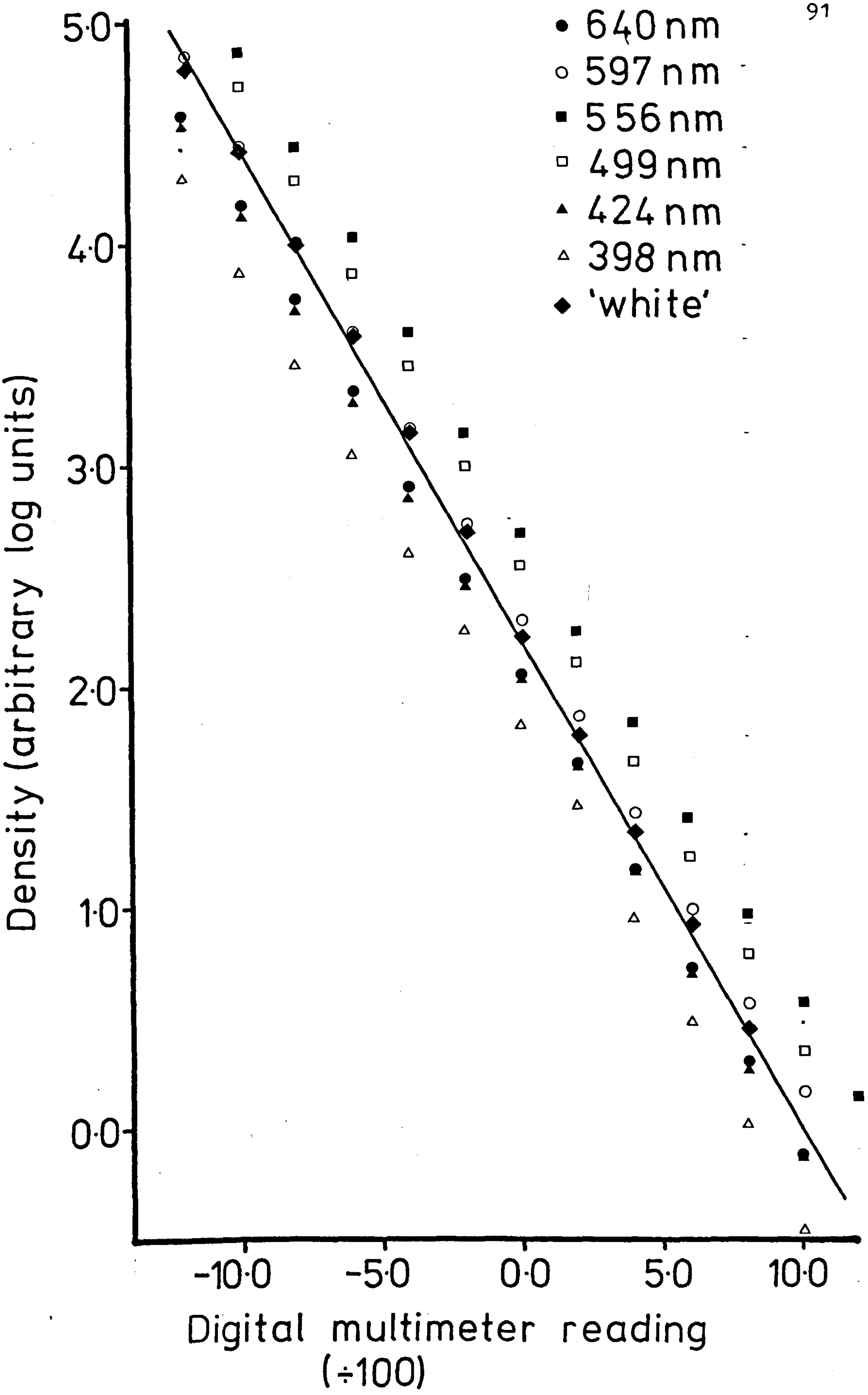

Fig. 3.6 Wedge density as a function of digital multimeter reading.

of known colour temperature was visually colour matched to the "white" light from the apparatus. This matching was achieved by shifting the colour temperature of the light from either the sub-standard lamp or the apparatus by known amounts with Kodak colour conversion filters.

Both of the above methods gave a value of colour temperature of 3500 °K.

Absolute luminances of the stimili (where quoted) were determined using a heterochromatic matching technique. For this technique a calibrated and filtered lamp* , which appeared green, was placed alongside the exit pupil of the apparatus and its intensity was adjusted by varying its supply voltage until a brightness match was obtained. This matching procedure was repeated using a bracketing technique and the mean voltage required for a match was calculated. From the lamp calibrations the absolute source luminance in log photopic trolands was determined. These absolute luminance values were always determined at the apparatus exit pupil to ensure that all light which entered the eye, including that scattered within the apparatus, was included in the luminance measurement.

3.2.4. Stimulus mask calibrations.

The original stimulus drawings were produced on an incremental plotter under the control of a mainframe computer (CDC 7600 series). The stimulus masks used in the Maxwellian view apparatus were produced on high-contrast Kodalith film by a reduction process from these computer generated drawings. The density of the clear portion of the resultant masks and that of the dark portion were determined with a scanning microdensitometer and were

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* The calibrated lamp was provided by Dr. B. H. Crawford, formerly of the National Physical Laboratory.

found to be 0.076 (± 0.005) log units and 5 (± 0.5) log units respectively. These density values allow stimuli with a maximum contrast of 0.999 to be produced.

The geometry of the stimulus masks was confirmed by measuring the final films with a travelling microscope and these measured dimensions were used in all calculations. These dimensions were converted into visual angles with a conversion factor determined as follows. The image of a stimulus mask placed in the Maxwellian view system at positions T1, T2 and T3 was projected through the exit pupil. The distance between two extreme points of the stimulus projection was then measured and their angular subtense at the exit pupil calculated. By measuring the distance between the same two points on the stimulus film the conversion from film dimensions to visual angle is simply the ratio of the measured projected angle and the film dimension. This conversion factor was incorporated into the computer plotting program which drew calibration marks for the reduction process and scaled the stimuli appropriately. Also incorporated into the computer program was a correction factor for errors introduced by the photographic process. Thus accurate stimulus masks could be produced from the computer drawings.

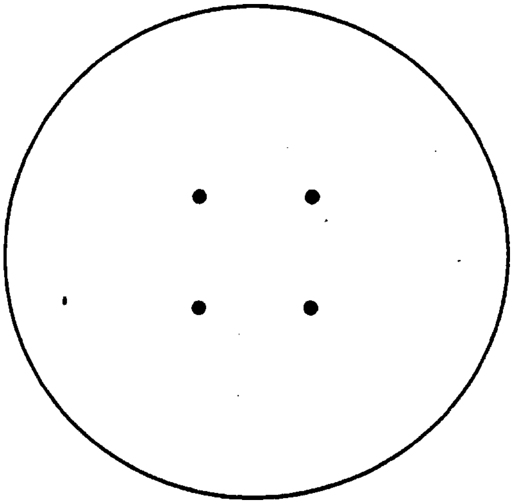

Fig. 3.7 Test background field.

3.2.5. Stimulus arrangement.

Channel 1, containing the stimulus at position T1, provided the adaptation stimulus used in the experiments to be described. Channel 2, containing the stimulus at position T2, provided a uniform white 15^{o} diameter circular background field for the test stimulus and also contained 4 circular 25' diameter dark fixation spots arranged in a 3.5^{o} square centred within the circular field. (Fig. 3.7). Upon this background field the test stimulus provided by Channel 3, containing the stimulus at position T3, was superimposed.

3.2.6. Stimulus luminance equating procedure.

To prevent artefacts in the results arising from changes in mean luminance when changing from either an adaptation stimulus to a test stimulus or from one adaptation stimulus to another it is necessary to match these stimulus mean luminances. The procedure followed for this luminance matching process is described below.

The adaptation stimuli in Channel 1 consisted of either a uniform field of 15^{o} diameter, identical to the test background field in Channel 2, or a patterned field. These adaptation stimuli were equated for mean luminance by inserting neutral density filters at position F1 as appropriate for each type of stimulus. The values of these filters associated with a particular adaptation stimulus mask were determined using the following null procedure. A photomultiplier was used to measure the light emerging from the exit pupil of the apparatus. The filters associated with each stimulus mask were adjusted until each stimulus mask-filter combination gave the same output from the photomultiplier.

The test background stimulus* in channel 2 was luminance matched to the uniform adaptation field by masking half of each field and then adjusting the luminance of the test background stimulus with neutral density filters in Channel 2 until the two half fields visually matched in brightness. In this way no changes in mean luminance occurred in changing from the test field condition to any adaptation field condition.

3.3. General methods.

In this section the experimental statistical designs and general experimental procedures used in the contrast threshold elevation experiments are described. In particular, the bracketing procedure with a uniform adaptation field used for contrast threshold elevation **determination is discussed.**

3.3.1. Measurement of contrast thresholds.

The test stimuli used in this study were provided by channels 2 and 3 of the Maxwellian view apparatus (Fig.3.1.) Channel 2 provided the 15°-diameter uniform field and fixation spots as described in the previous section. Superimposed on this background field was the test stimulus provided by Channel 3; the test stimulus thus appeared bright against the background field. Fig 3.8. indicates the luminance distribution of this composite stimulus.

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* The test stimulus provided by Channel 3 made a negligible addition to the space average luminance of the test background field provided by Channel 2 in the experiments described here. For, the area of the test stimulus was less than 0.5% of the area of the test background field and was also set at increment threshold when measurements of contrast thresholds were made in the present experiments.

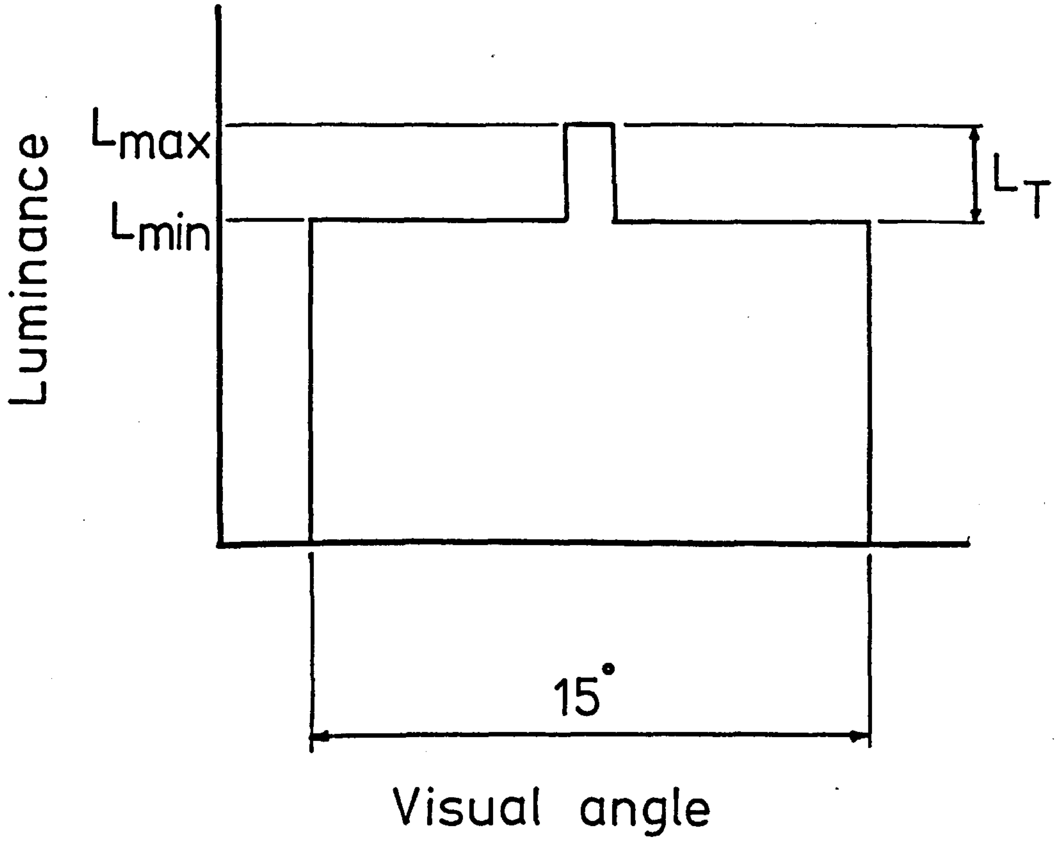


Fig. 3.8. Luminance distribution of test pattern.

The luminance of the test stimulus relative to its background, L_T, was controlled by the neutral density wedge in Channel 3. The Michelson contrast C (see section 1.4) of the test stimulus is related to L_T as follows:

$$C = \frac{L_T}{2\ L_{min} + L_T}$$

Now at contrast threshold

$$L_T << L_{min}$$

$$\therefore\ C \approx \frac{L_T}{2\ L_{min}}$$

Thus by measuring wedge position L_T may in principle be calculated. Hence as L_{min} is constant the contrast at threshold may also be calculated.

3.3.2 Measurement of contrast threshold elevation.

In the previous section the method used to determine contrast thresholds was described. In order to measure the contrast threshold elevation of the test field it is necessary to compare the contrast threshold before and after adaptation to a structured adaptation field. The "before" unadapted condition is usually provided by measuring contrast threshold after adapting to an unstructured uniform field of equal mean luminance to the structured adaptation field to be used. (section 1.4.) Thus two measures of contrast threshold are obtained, the one for the unadapted condition and the other for the adapted condition. If these are represented by C_u and C_A respectively, then

$$C_u \approx \frac{L_{ut}}{2\ I_{min}}$$

$$C_A \approx \frac{L_{at}}{2\,I_{min}}$$

and the relative contrast threshold elevation R, is given by:

$$R = \frac{C_A}{C_U} \approx \frac{Lat}{Lut}$$

Log relative contrast threshold elevation Δ is more commonly used as a measure of the contrast threshold elevation effect and is defined here as

$$\underline{\Delta = \log R = \log L_{at} - \log L_{ut}} \qquad 3.1$$

In the measurements of the contrast threshold elevation effect other workers (Blakemore and Campbell, 1969; Naghshineh and Ruddock 1978) have measured the unadapted contrast threshold before and after the experimental run in which several adapted contrast thresholds were measured.

The contrast threshold elevation of the test stimulus was subsequently calculated in such experiments with respect to these unadapted measures. This procedure is subject to error if variations of the unadapted contrast threshold should occur during the measurements of the adapted contrast thresholds. Such variations of contrast threshold have been demonstated by Home (1978) who reported changes in contrast threshold with periods of the order of 8 minutes (see section 1.4.).

In the present study the effects of changes in unadapted contrast thresholds have been minimised by using a bracketing procedure. Thus during an experimental run each measurement of an adapted contrast threshold is preceded and followed by an unadapted threshold measurement. The log contrast threshold elevation is based on the unadapted contrast thresholds preceding and following the adapted contrast threshold i.e.

$$\Delta = \frac{\Delta_1 + \Delta_2}{2}$$

where Δ_1 is based on the adapted contrast threshold and the preceding unadapted contrast threshold.

Δ_2 is based on the adapted contrast threshold and the following unadapted contrast threshold.

3.3.3. Contrast threshold measurement procedure.

Contrast thresholds were determined by the method of adjustment with the final threshold being approached from subthreshold values of the test pattern contrast to reduce any effects of self adaptation (section 1.4.). Fig 3.9 shows the timing sequence for a typical measurement.

The procedure for measurement of a contrast threshold was as follows. The adaptation stimulus was presented to the observer for an adaptation period of 2 mins consistent with reaching a plateau value of contrast threshold elevation (see Section 1.4.1.).

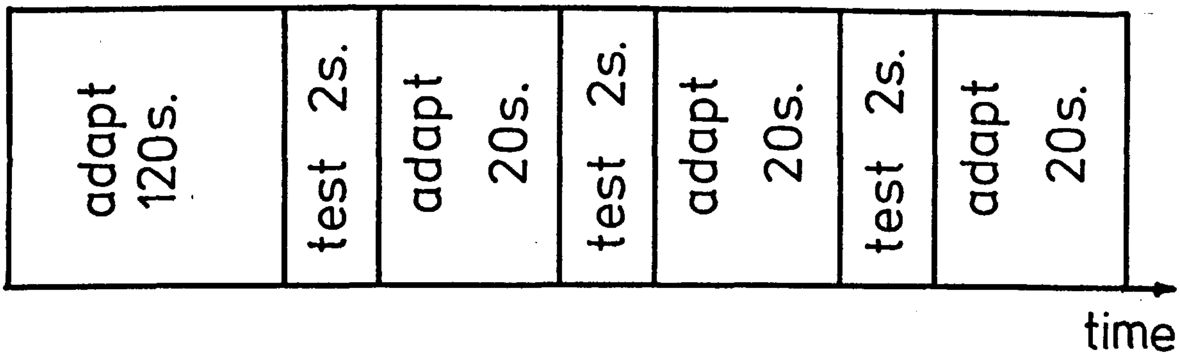


Fig. 3.9. Typical timing sequence.

After this initial period a 2 second test period in which the composite test field replaced the adaptation field occurred during which the observer noted whether the test stimulus was above contrast threshold. The test field was then again replaced by the adaptation field for a 20 second "topping-up" period to restore the contrast threshold elevation to its plateau value (section 1.4.1.). During this "topping-up" period the observer adjusted the wedge density using the two push buttons to bring the structured test stimulus closer to threshold. This sequence of 2-second test, 20-second adaptation was repeated until the observer was satisfied that the test stimulus was at threshold (usually after approximately 5 such cycles). Adjustment of wedge density was only allowed during the adaptation period to prevent transient effects on sensitivity caused by test-stimulus contrast changing during a test presentation period.

3.4. Experiment statistical design.

A typical experiment consisted of a series of experimental runs during which the contrast threshold elevation effect was determined for a fixed test stimulus after adaptation to various structured adaptation patterns. For two types of structured adaptation patterns A and B a typical experiment run would be in the order shown below.

Uniform field (UF) UF A UF B UF B ...... A UF

The structured adaptation patterns are interleaved with uniform field adaptation to give the unadapted contrast threshold as described in a previous section. A practice unadapted contrast threshold determination is included at the beginning of each experimental run and its result is not used in the subsequent analysis. Each experimental run was preceded by ten minutes dark adaptation by the subject.

A typical experimental run required 1¼ hours for completion and consecutive runs were separated by a period of not less than 4 hours. The experiment statistical design used varied depending upon the number of structured adaptation patterns used in the experiment. All runs comprising a single experiment were balanced for carry-over and order effects (Finney, 1960) and were based on designs given in Patterson (1952)and Sampford (1957). The balancing of each of the designs was checked before being used. The following sections describe these experiment statistical designs in detail.

3.4.1 Design for 2 treatments.

This design was used where the contrast threshold elevation of a structured test stimulus was compared after adaptation to two different structured adaptation patterns A and B. In each run of this design each of the structured adaptation patterns was presented three times interleaved with measurements of the contrast threshold elevation after adaptation to the uniform field (UF). In order for the experiment to be completely balanced for order and carry-over effects four runs are necessary. The resultant design which also includes the practice uniform field trial, is given in Table I.

TABLE I

RUN 1	UF	UF	A	UF	B	UF	A	UF	B	UF	B	UF	A	UF
RUN 2	UF	UF	B	UF	A	UF	B	UF	A	UF	A	UF	B	UF
RUN 3	UF	UF	B	UF	A	UF	A	UF	B	UF	A	UF	B	UF
RUN 4	UF	UF	A	UF	B	UF	B	UF	A	UF	B	UF	A	UF

From these runs 12 estimates of the contrast threshold elevation after adaptation to a structured adaptation pattern are obtained. For each of the structured adaptation patterns the mean of each of these 12 estimates is taken as the contrast threshold elevation of the test pattern caused by adaptation to that pattern. The standard errors of these twelve estimates are also obtained.

3.4.2. Design for 3 treatments.

Here 3 structured adaptation patterns A, B and C were used and the contrast threshold elevation of the structured test stimulus measured after adaptation to each one. Once again adaptation to a structured field is interleaved with adaptation to a uniform unstructured field. Six runs each containing two presentations of each of the three structured adaptation patterns are required for balancing of order and carry-over effects. A practice measurement after adaptation to the unstructured uniform field is included at the beginning of each run.

The balanced block used to generate these runs is based on six different treatments which are grouped in pairs to give the required three treatments.

Table II gives the resulting design.

TABLE II

RUN 1	UF	UF	A	UF	B	UF	A	UF	C	UF	B	UF	C	UF
RUN 2	UF	UF	B	UF	C	UF	C	UF	A	UF	A	UF	B	UF
RUN 3	UF	UF	A	UF	C	UF	B	UF	B	UF	A	UF	C	UF
RUN 4	UF	UF	C	UF	A	UF	B	UF	B	UF	C	UF	A	UF
RUN 5	UF	UF	B	UF	A	UF	A	UF	C	UF	C	UF	B	UF
RUN 6	UF	UF	C	UF	B	UF	C	UF	A	UF	B	UF	A	UF

From these six runs 12 estimates of the contrast threshold elevation caused by adaptation to a structured adaptation stimulus were obtained. The mean of these twelve estimates is taken as the contrast threshold elevation of the structured test stimulus after adaptation to a particular structured adaptation pattern. The standard errors from these estimates were also calculated as a measure of the reliability of this calculated mean.

3.4.3. Design for 4 treatments.

When the contrast threshold elevation after adaptation to four different structured adaptation stimuli was required the following design was used for treatments A, B, C and D. As before a practice measurement after adaptation to the uniform unstructured field was included at the beginning of each run. In each run measurement of threshold elevation after adaptation to the uniform unstructured field was interleaved with measurement after adaptation to the uniform unstructured field as previously.

For balancing of order and carry-over effects eight runs are required in two blocks of four runs each. Table III shows the design used.

TABLE III

RUN 1	UF	UF	C	UF	A	UF	D	UF	B	UF
RUN 2	UF	UF	A	UF	B	UF	C	UF	D	UF
RUN 3	UF	UF	D	UF	C	UF	B	UF	A	UF
RUN 4	UF	UF	B	UF	D	UF	A	UF	C	UF
RUN 5	UF	UF	C	UF	B	UF	A	UF	D	UF
RUN 6	UF	UF	A	UF	D	UF	B	UF	C	UF
RUN 7	UF	UF	D	UF	A	UF	C	UF	B	UF
RUN 8	UF	UF	B	UF	C	UF	D	UF	A	UF

From these 8 runs 8 estimates of the contrast elevation of the test stimulus after adaptation to one of the structured adaptation stimuli were obtained. From these 8 estimates the mean contrast threshold elevation and its standard error were calculated as before.

In each of these experimental designs the number of contrast threshold measurements made in a single run is restricted. Although in some designs (particularly for 4 treatments) it would be desirable to make more measurements with each treatment in a single run the resulting run lengths would lead to excessive subject fatigue and consequent reduction of performance.

3.5. Data analysis.

In the majority of cases examined in this study mean contrast threshold elevations calculated from the data are compared using Students t test to calculate significance levels. In all other cases the statistical tests used are outlined in the appropriate chapter.

CHAPTER 4. PRELIMINARY EXPERIMENTS: DEVELOPMENT OF THE PRESENT ADAPTATION TECHNIQUE.

The paradigmatic experiment in this study was one in which the contrast threshold elevation of a simple test figure consisting of connected bar elements (e.g. Fig 4.1c) was measured after adaptation to various adaptation patterns (e.g. Fig 4.1a,b). The adaptation patterns consisted of either multiple copies of the test figure distributed pseudo-randomly within the adaptation field (Fig 4.1a) or multiple copies of the bar elements comprising the test figure distributed within the adaptation field (Fig 4.1b). These stimuli were used because they may be interpreted simply in terms of structural theories of pattern recognition (section 1.2.2.). For example, the test pattern of Fig. 4.1c might be described as two orthogonal bar features with a relation of "T-connectedness" between them. The test and adaptation patterns used in previous studies of the contrast threshold elevation effect have been either spatially periodic or single dots or single rectangles all of which are inappropriate for the present study of local pattern structure (see section 1.6.). The adaptation technique used in the present study differs from that of previous workers in that a single test figure and adaptation patterns which were of a "multiple" nature were used.

In this chapter, the experimental problems and difficulties entailed in the novel adaptation technique used here are described.

4.1. Experiment 1

It might be argued that test and adaptation patterns with some form of spatial periodicity, as in "classical" grating studies (Pantle and Sekuler, 1968; Blakemore and Campbell, 1969) are required to give a contrast threshold elevation effect. It might further be argued therefore that the novel single test and "multiple" adaptation patterns of the present study will not give rise to a contrast threshold elevation effect.

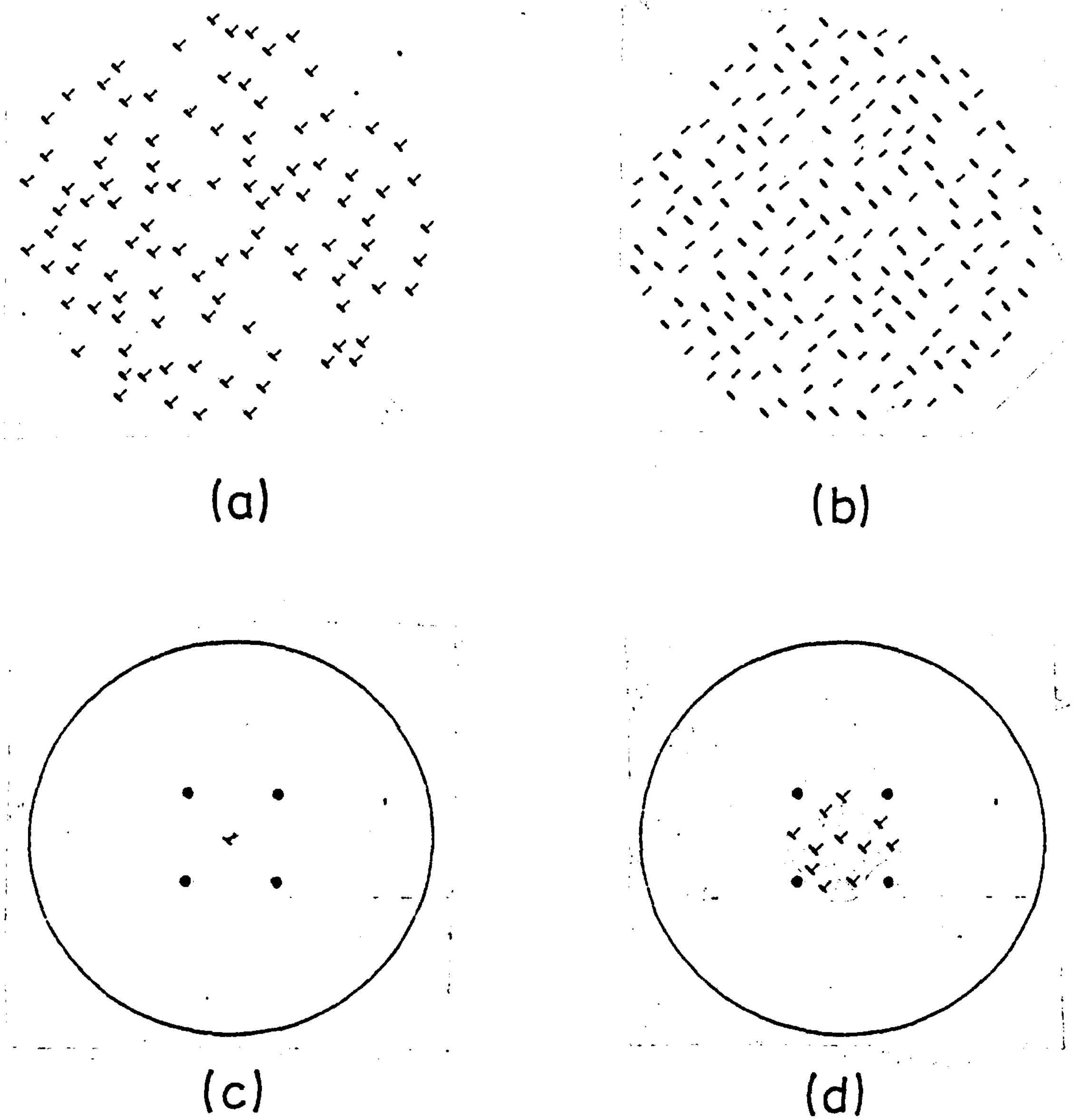


Fig. 4.1. Adaptation and test stimuli. The stimuli were brighter than their backgrounds.

The first experiment was performed therefore to establish whether a contrast threshold elevation of a single test figure could be found in response to adapting to a "multiple" adaptation pattern.

<u>Stimuli</u>.

The adaptation stimuli are shown in Fig. 4.1a,b and the test stimulus in Fig. 4.1c. The stimuli consisted of small bright bars of dimensions 20'x 3' and oriented at 45° to the vertical which were, for the adaptation stimuli, distributed according to one of two rules as follows. For the 'T' adaptation pattern of Fig. 4.1a two of the bars were connected orthogonally to form a T figure and 100 of these figures were then distributed pseudo-randomly over a 15° diameter visual field such that no figure centre came closer than 40' to another figure centre. For the disconnected bar adaptation pattern of Fig. 4.1b an equal number of bars of the two orthogonal orientations were distributed pseudo-randomly over the 15° visual field such that no bar centre came closer than 40' to another bar centre. There were equal numbers of bars in each of the adaptation patterns thus ensuring equal individual bar luminance and mean luminance over the 15° field.

The test stimulus of Fig. 4.1c consisted of a single copy of the 'T' figure superimposed on a uniform background field of luminance equal to the mean luminance of the adaptation patterns. Four dark fixation spots at the corners of a 3.5° square appeared with the test pattern. A 15° diameter uniform field of luminance equal to the mean luminance of the other adaptation patterns was also used as an adaptation pattern. This uniform field adaptation pattern was used for "baseline" measurements in the bracketing procedure described in section 3.3.

Methods.

The stimuli were presented in Maxwellian view (section 3.1.) and contrast thresholds were obtained using the method of adjustment (section 3.3.). Stimulus timing was as described in section 3.3. A sequential counterbalanced design, as described in section 3.4.1 was used for the two adaptation stimuli except only two runs were performed by each subject. The subjects were instructed to move their fixation randomly over the adaptation pattern which remained stationary throughout the experiment.

Subjects.

Three male subjects ATS, DHF and RJM (the author) with ages between 21 and 36 years participated in this experiment. All subjects had normal colour vision and corrected to normal visual acuity.

Results.

Fig 4.2 shows the results from the 3 subjects. The ordinate shows the contrast threshold elevation Δ log units (section 3.3.) after adaptation to one of the adaptation patterns a typical element of which is shown on the abscissa.

All the subjects exhibited a significant ($t \geqslant 3.4, df=5, P < 0.01$) contrast threshold elevation of the 'T' test figure after adaptation to either the 'T' or disconnected bar adaptation pattern. It is also evident from Fig 4.2. that a different contrast threshold elevation occurred depending upon the type of adaptation pattern. The field of T's identical with the single test figure produced a significantly higher ($t > 2.27, df=10, P < 0.05$) contrast threshold elevation than the disconnected bar field for subjects ATS and RJM whilst the same result for subject DHF approaches significance ($t=1.71, df=10, P < 0.1$). The magnitude of the contrast threshold elevation of the 'T' test figure after adaptation to the T adaptation pattern was typically 0.2 to 0.4 log units. A typical elevation after adaptation to the disconnected bar adaptation pattern was in the range of 0.1 to 0.3 log units.

Discussion.

The present results confirm the existence of the contrast threshold elevation effect using the present technique where a test stimulus which is itself only a small part of the adaptation pattern is employed. The results also indicate a greater threshold elevation after adaptation to the pattern containing copies of the test stimulus than after adaptation to the disconnected bar pattern.

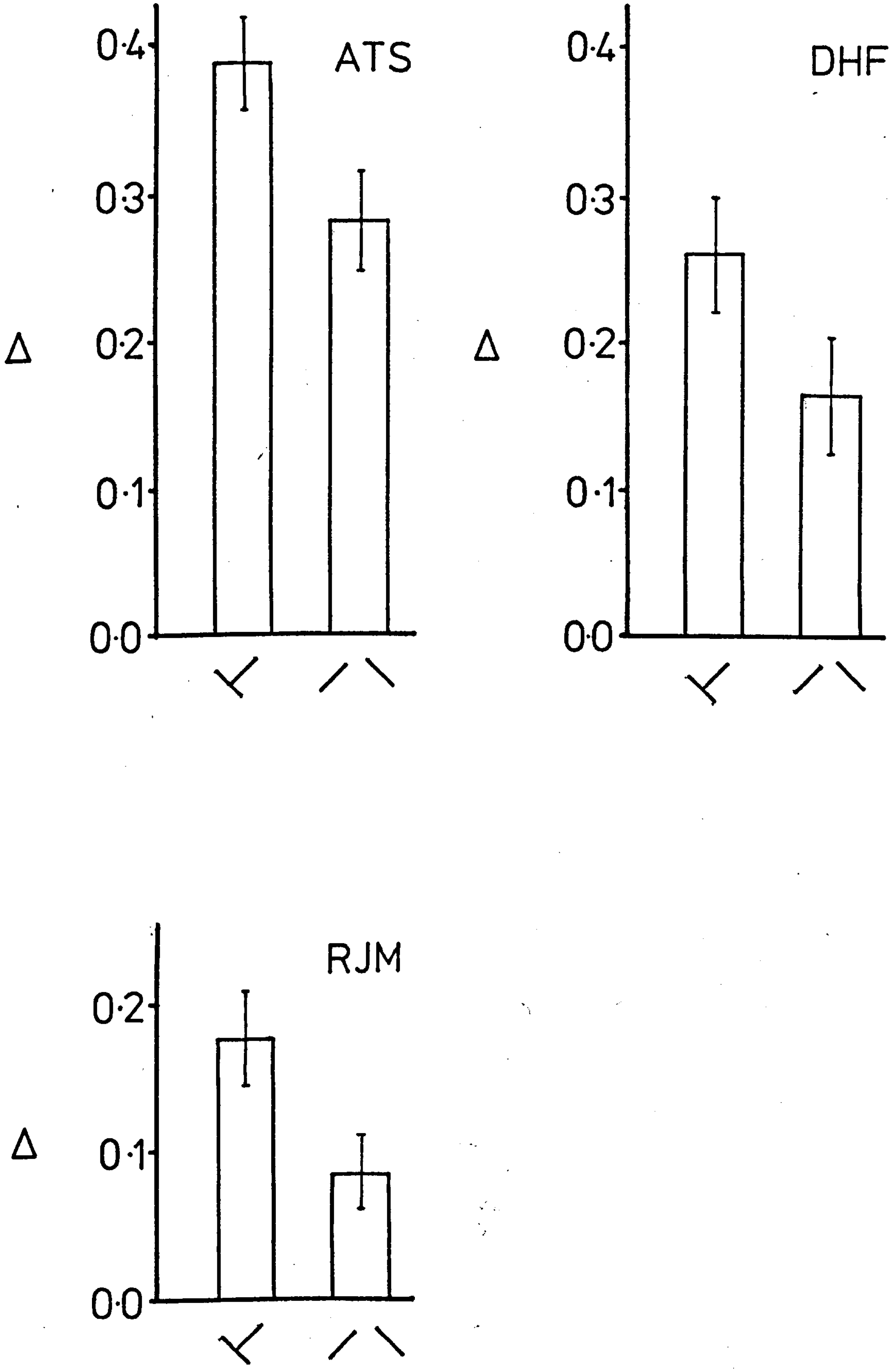


Fig. 4.2 Results of experiment 1. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

This latter result could be interpreted as a loss of sensitivity of a mechanism detecting the spatial relationship of T-connectedness of the pattern (see chapter 6). This result could, however, also be interpreted as a localised adaptation phenomenon. For if the 'T' shapes in the adapting pattern fall on the same part of retina (e.g. the fovea if they are preferentially fixated) a localised retinal adaptation would be produced. In this case we might expect the 'T' shaped test pattern to have a higher contrast threshold after adaptation to the T adaptation pattern than after adaptation to the disconnected bar adaptation pattern for in the latter case the overlap of the desensitised retinal area and the test stimulus is smaller. In order to test this conjecture the next two experiments were performed.

4.2. Experiment 2.

Methods.

In this experiment the stimuli and procedure were identical to those of Experiment 1 except for the imposition of small saccade-like displacements on the adaptation pattern using a cam mechanism (section 3.1.). These saccade-like displacements which could not be visually tracked, were introduced to reduce local adaptation effects. Subjects were instructed to move their fixation randomly over the adaptation pattern during the adapting period as in Experiment 1. The test pattern remained stationary as in Experiment 1 to aid detection. Each subject completed a total of four runs according to the design of section 3.4.1.

Subjects.

The same subjects participated as in Experiment 1.

Results.

The results of this experiment are shown in Fig 4.3. Again all the subjects showed a highly significant ($t > 7.31, df=11, P < 0.001$)

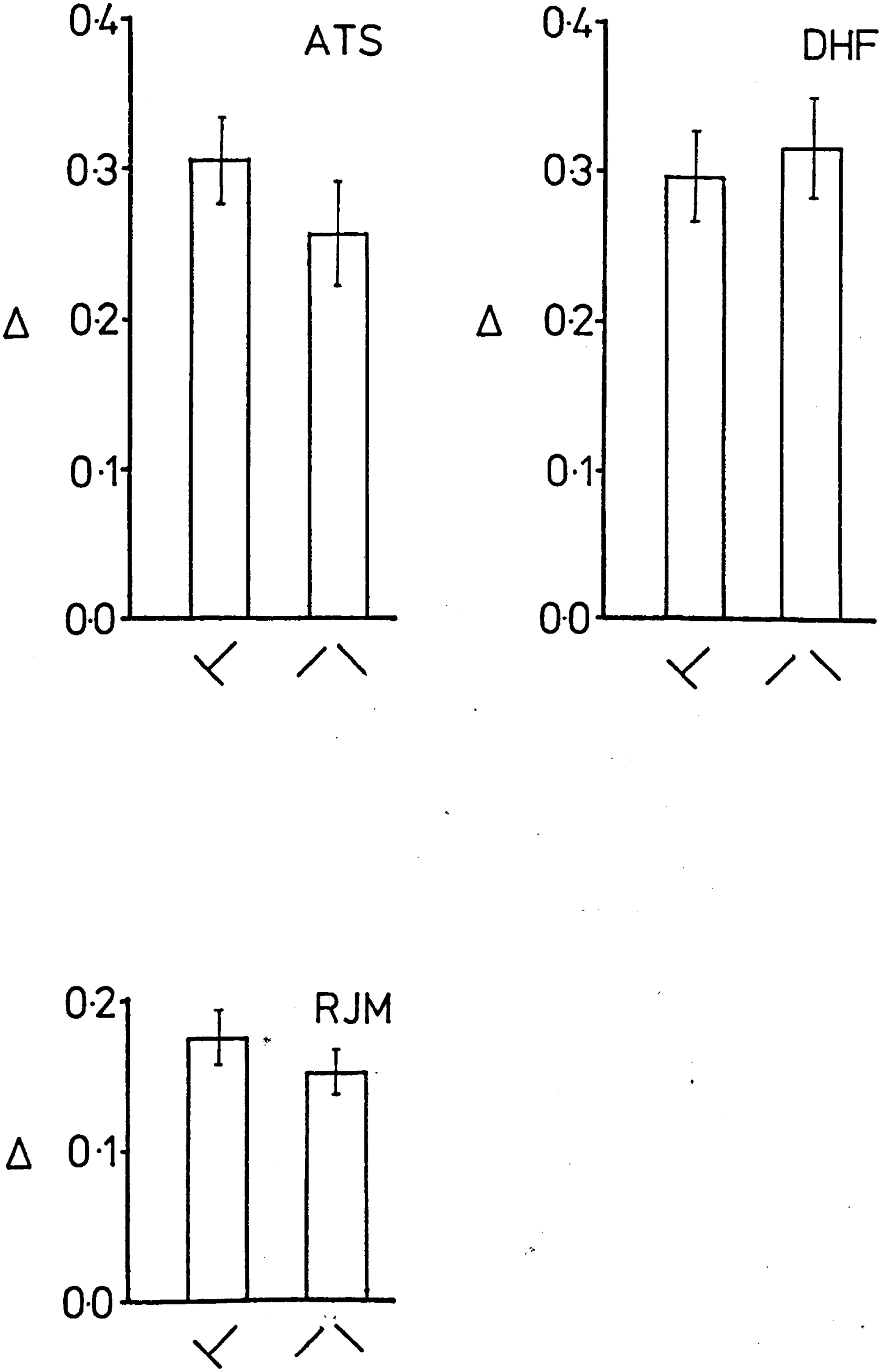


Fig. 4.3. Results of experiment 2. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

contrast threshold elevation of the test pattern after adaptation to either the 'T' or disconnected bar adaptation patterns. Critically however, the imposition of saccade-like displacements on the adaptation patterns has reduced the differential threshold elevation between the 'T' and disconnected bar stimuli to insignificance ($t \leqslant 1.09, df=22, P > 0.1$) for all subjects. The typical magnitude of the contrast threshold elevation effect measured when saccade-like displacements are imposed on the adaptation patterns is 0.2 to 0.3 log units, which is similar to that obtained with stationary adaptation patterns.

Discussion.

The preservation of the contrast threshold elevation despite saccade-like displacement of the adaptation pattern indicates that this threshold elevation effect is not entirely due to localised retinal adaptation and therefore reflects the reduction in sensitivity of some mechanism detecting the test stimulus at some more central stage in the visual system. The removal of the differential contrast threshold elevation effect observed in Experiment 1 by the imposition of saccade-like displacements on the adaptation patterns suggests that the specificity shown in the previous experiment for the 'T' adaptation is due to localised adaptation. It may be argued, however, that the brief motion of the adaptation stimulus between stationary phases prevents the adaptation of the supposed mechanisms sensitive to the connectivity of the individual bars and thus the lack of a differential effect is not due to removal of localised adaptation but is due to the pattern motion. In order to clarify this question Experiment 3 was performed.

4.3. Experiment 3.

Methods.

In this experiment the single 'T' test pattern was replaced by a test pattern consisting of 11 copies of the single 'T' figure distributed within a 5° diameter limiting circle under the same constraints as the adaptation stimuli (Fig. 4.1d). A further constraint was imposed ensuring that no more than two of the test pattern elements coincided with the adaptation pattern elements at any position of the two patterns. This lack of coincidence ensured that local adaptation did not affect detection of the test pattern as a whole. In this experiment the adaptation patterns remained the same as in Experiments 1 and 2 and remained stationary as in Experiment 1. The subject was instructed to vary his fixation randomly over the adaptation patterns and additionally to set the test pattern to a threshold where all of the test pattern was visible.

Subjects.

Two subjects participated in this experiment. The one, RJM had participated in Experiments 1 and 2, the other, IEB, was male, of age 22 years, had normal colour vision and corrected to normal visual acuity.

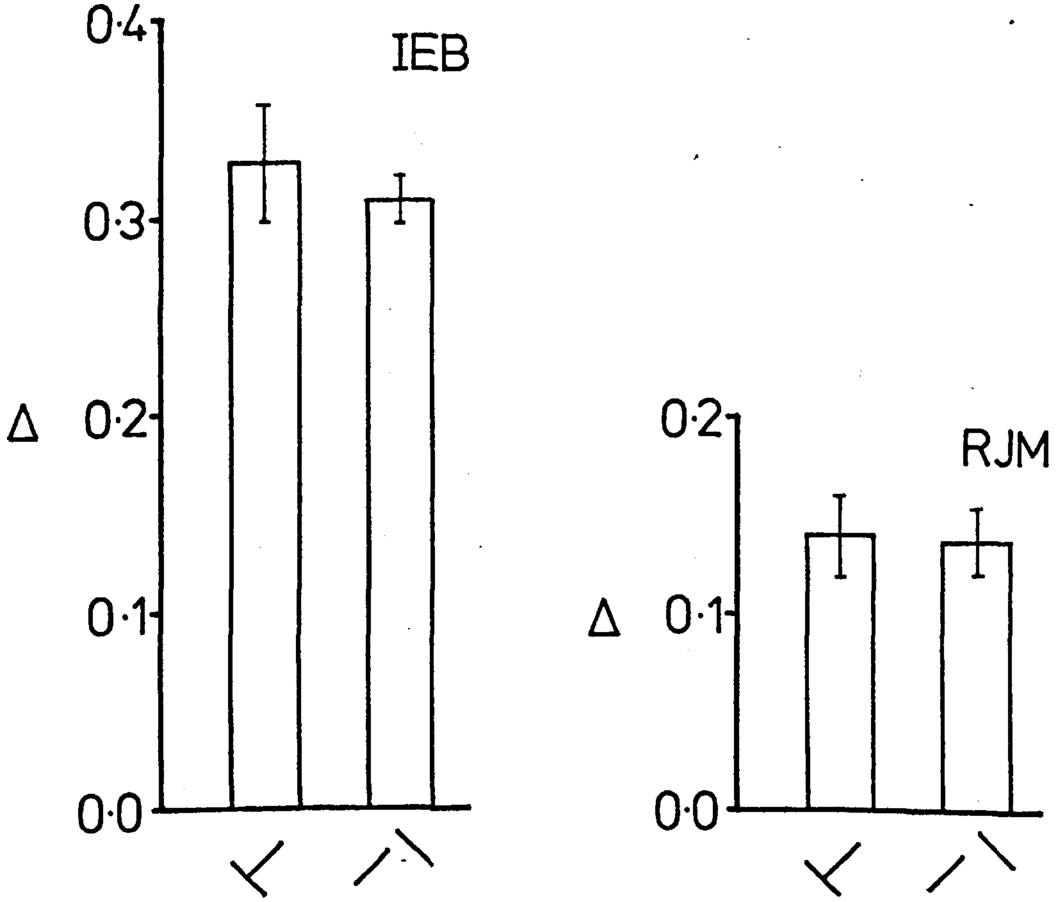


Fig. 4.4. Results of experiment 3. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

Results.

The results of this experiment are shown in Fig. 4.4. A highly significant (RJM, $t > 6.95$, $df=11$; IEB, $t > 11.31$, $df=5$, $P < 0.001$) contrast threshold elevation effect was obtained with both subjects. As found in the previous experiment the contrast threshold elevation after adaptation to the 'T' adaptation pattern was not significantly greater than that after adaptation to the disconnected bar pattern (RJM, $t=0.08$, $df=22$; IEB, $t=0.60$, $df=10$, $P > 0.25$) for both subjects. The magnitudes of the contrast threshold elevations (0.15 and 0.3 log units) were similar to those obtained in the previous experiments. These results were qualitatively identical to those of Experiment 2.

Discussion.

In contrast to the use of saccade-like displacements in Experiment 2 the reduction of the effects of local adaptation in this experiment was achieved by the use of a test pattern consisting of multiple copies of the single 'T' shaped figure distributed randomly over the retina. Because of the lack of total overlap between this multiple test target and any part of the adaptation pattern it was impossible for detection of the whole test target to be a result of local adaptation alone. The abolition of the differential contrast threshold elevation effect observed in Experiment 1 by means of the multiple test pattern as well as by the use of a moving adaptation suggests that the difference in elevations measured in Experiment 1 were indeed due to some form of local adaptation.

4.4 Experiment 4.

It might be suggested that the saccade-like displacements imposed on the adaptation patterns in Experiment 2 reduced the effectiveness of the 'T' adaptation pattern and increased the effectiveness of the disconnected bar pattern at elevating the test pattern contrast threshold. It might also be suggested that a similar effect occurs when a "multiple" test pattern is used. In such a case the results of Experiments 2 and 3 could not be attributed to the removal of local adaptation.

These unlikely suggestions might be examined in the following way. If, indeed, the effects of both saccade-like displacements of the adaptation pattern and the use of a "multiple" test pattern are facilitation of the disconnected bar adaptation pattern effectiveness and inhibition of the 'T' adaptation pattern effectiveness, then we might expect these effects to combine to give the following results. For, if a multiple test pattern is used in conjunction with saccade-like displacement of the adaptation patterns we might expect the contrast threshold elevation after adaptation to the disconnected bar adaptation pattern to be greater than that after adaptation to the 'T' adaptation pattern.

Alternatively, if the effect of both of the above techniques is a reduction of local adaptation, and if the differential contrast threshold elevation observed in Experiment 1 is a result of local adaptation, an experiment in which both techniques are applied should give similar results to those obtained when only one technique is applied.

The present experiment therefore combines the use of a "multiple" test pattern with saccade-like displacements of the adaptation stimuli.

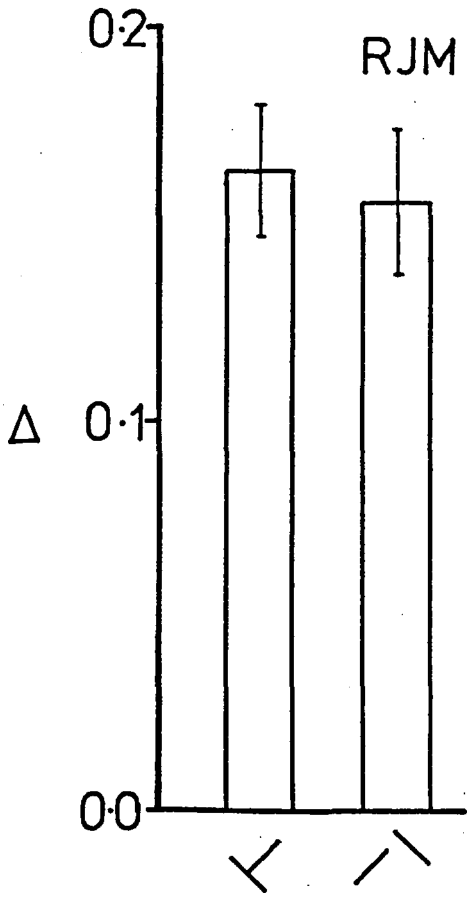


Fig 4.5. Results of experiment 4. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

Methods.

Stimuli and procedure were the same as in Experiment 3 except that the adaptation stimuli were as in Experiment 2. That is, in this experiment saccade-like displacements of the adaptation patterns and a multiple test pattern were used.

Subjects.

Subject RJM participated in this experiment.

Results.

Fig 4.5 shows the results of this experiment. It is evident that a highly significant ($t > 8.16$, $df=11$, $P < 0.001$) contrast threshold elevation effect is obtained and that there is no significant difference between contrast threshold elevations after adaptation to the two types of pre-adaptation stimuli ($t=0.31, df=22, P > 0.25$). The magnitude of the contrast threshold elevation measured here is similar to that obtained for subject RJM in previous experiments. (typically 0.15 log units).

Discussion.

The equality of the contrast threshold elevations of the "multiple" test pattern after adaptation to either the 'T' adaptation pattern or the disconnected bar adaptation pattern when these patterns are also subjected to saccade-like displacements may be interpreted as follows. It was argued in the introduction to this experiment that the results of Experiments 2 and 3 may be the consequence of some differential effect of the adaptation technique on the effectiveness of the different adaptation pattern types in raising test pattern contrast threshold. It was further argued that the combination of the techniques of Experiment 2 and Experiment 3 should, if such a conjecture was true, restore a differential in the contrast threshold elevations produced by adaptation to the two types of adaptation patterns. The results of this experiment, in which the two techniques were combined, do not show such a differential effect. The above suggestion of a differential effect of the adaptation technique is therefore unlikely to be true.

4.5. General discussion.

From the above experiments it can be seen that the above adaptation techniques give rise to reliable and significant contrast threshold elevation of either a single or a multiple test target. This implies that the mechanisms being studied are sensitive to the presence of some form of spatial structure and not just to change in mean luminance over the visual field. (The extent of the specificity of these mechanisms for the shape of the adapting stimulus, however, is still to be determined; see Chapter 5).

The removal of the differential adaptation effect shown in Experiment 1 by either saccade-like displacements of the adaptation patterns as in Experiment 2 or the use of a multiple test stimulus as in Experiment 3 implies that both of these methods significantly reduce the effects of local adaptation.

It is also evident that the effects of local adaptation are important in considering contrast threshold elevation effects and that free scanning of a stationary adaptation stimulus does not completely remove this local adaptation. The continuance of some contrast threshold elevation despite the reduction of local adaptation indicates that the contrast threshold elevation effect is not just due to these local effects, a conclusion which is in agreement with Jones and Tulunay-Keesey (1975) and Smith (1977) who used grating stimuli and controlled fixation procedures. Jones and Tulunay-Keesey (1975) also report that large displacements of the retinal image (as in the present paradigm) are sufficient to remove local adaptation.

Arend and Skavenski (1979) have also reported results showing that free scanning of gratings produces a patterned retinal exposure. These authors monitored eye position relative to the adaptation pattern during adaptation and found that subjects tended to preferentially fixate the bright portions of the patterns.

The results of Experiment 1 here, where the subject was instructed to scan the adaptation pattern freely, supports these authors findings.

Other methods proposed to reduce local adaptation effects are counter-phase flicker of the pattern and drifting of the pattern across the visual field whilst the subject fixates a stationary point. Virsu and Laurinen (1977) reported that counter-phase flicker produces long-lasting after-images at twice the spatial frequency of the adapting counter-phase modulated grating. Jones and Tulunay-Keesey (1980) in a later study were, however, unable to replicate this result. It should be noted that although the time averaged luminance at each point of the counter-phase modulated pattern is the same, some retinal positions receive constant stimulation whilst others receive temporally modulated stimulation. This inequality of stimulation and the lack of agreement in the literature concerning the effectiveness of counter-phase modulation in removing local adaptation was the basis for the rejection of this technique as a means of reducing local adaptation in this study. Drifting of the stimulus was also rejected because of the danger that subjects may make involuntary "feature-locked" saccades away from the fixation point which would again cause non-uniformity of retinal adaptation.

For the adaptation experiments to be described in this thesis it was decided to reduce local adaptation effects by the use of the "saccade-like" displacements of the adaptation pattern and a single test pattern as in Experiment 2. This method was preferred for the present studies to the use of the stationary adaptation pattern and multiple test pattern technique because of the relative simplicity of describing the single test pattern in terms of the supposed features and relations of a structural theory of pattern recognition.

In summary it has been shown that:

1) Contrast threshold elevation of a single test pattern (e.g. Fig 1.4c) occurs after adaptation to multiple adaptation patterns like those of Fig, 4.1a,b. Periodicity of the test and adaptation patterns is not required therefore to give a

contrast threshold elevation effect.

2) The contrast threshold elevation effect produced with a single test pattern and a multiple adaptation pattern subjected to saccade-like displacements is not a simple consequence of local adaptation.

3) The results of the experiments described in this chapter illustrate that care must be taken in adaptation experiments to reduce local adaptation effects and the saccadic-displacement technique described here fulfills this aim.

In the next chapter the adaptation technique chosen here, that is one using a single test pattern and saccade-like displacement of the multiple adaptation pattern, is used to investigate the specificity of the adapted mechanisms for pattern element shape.

CHAPTER 5. EXPERIMENTS ON STIMULUS SPECIFICITY.

It is known from previous studies that the contrast threshold elevation effect is dependent on both the relative orientation (where defined) and relative size e.g. Maudarbocus and Ruddock (1973) of the adaptation and test patterns. The results of these studies may be summarised briefly as follows.

a) When the test and adaptation patterns have a defined orientation, the maximum contrast threshold elevation occurs when the orientation of the adaptation pattern and the test pattern are the same.

b) When the test and adaptation patterns have a defined "size" (which may be parametrized by, say, fundamental spatial frequency) the maximum contrast threshold elevation occurs when the "sizes" are the same. A more detailed review of these results is given in the Introduction (section 1.4.2.).

If the contrast threshold elevation measured in the present study with the adaptation technique described in Chapter 4 is not simply a result of non-specific adaptation to any spatially structured pattern it might be expected that selectivities similar to those found with other adaptation techniques in the above studies should also be shown here. In particular, the orientation and size selectivity shown in previous studies of the contrast threshold elevation effect should also be shown using stimuli appropriate to the present study. The following experiments examine the specificity of the contrast threshold elevation effect measured by the present adaptation technique (Chapter 4) for stimulus shape (Experiment 1) and also for stimulus size and orientation (Experiments 2 to 5).

5.1. Experiment 1 - Shape specificity.

Evidence was presented in the previous chapter to show that adaptation to a multiple array of copies of a single 'T'-shaped test pattern caused subsequent elevation of the contrast threshold of the test pattern. Random saccade-like displacements of the adaptation pattern were used to reduce any local retinal adaptation effects.

Although the adaptation patterns in the experiments described in the previous chapter gave rise to an elevation of contrast threshold, the results of these experiments did not show that this threshold elevation was specific to the shape of the single pattern elements. For, it could be argued that any spatially non-uniform distribution of light incident on the retina is sufficient in itself to give rise to a contrast threshold elevation of the spatially non-uniform test pattern. It might be further suggested that if two such spatially non-uniform adaptation patterns have the same overall mean luminance they would give rise to equal contrast threshold elevations of the test pattern, For example,if each of the copies of the T-shaped test pattern (Fig.5.1c) in the first adaptation pattern (Fig 5.1a) were replaced by some other spatially structured pattern, such as a disc, to form a second adaptation pattern (Fig.5.1b) and these two adaptation patterns had equal mean luminance the above suggestion would predict equal contrast threshold elevations of the test pattern (Fig.5.1c) after adaptation to any of the two adaptation patterns.

A problem arises in the choice of disc size, however, for if an equal number of discs to that of 'T'-shaped figures are used to form the adaptation patterns (thus preserving the "global" adaptation pattern structure) disc size and local disc luminance become dependent variables. It is likely that local luminance changes would affect measurements of the contrast threshold elevation related to local pattern shape changes. It is therefore desirable to maintain equality of the local luminance of the discs and 'T'-shaped figures used as "subpatterns" to form the two adaptation pattern types. Thus if equality of global pattern structure, mean luminance and local "subpattern" luminance is required for the disc and 'T' adaptation pattern, the disc diameter must be chosen so that the disc area is equal to the area of a single 'T'-shaped subpattern.

The aim of the present experiment was to examine therefore, with the stimulus types described above, whether or not the supposed mechanism detecting the test pattern was adaptationally sensitive to the shape of the "subpatterns" forming the adaptation patterns rather than to any spatial non-uniformity.

Stimuli.

Three types of adaptation pattern were used in this experiment and these are illustrated in Fig. 5.1. The 'T' adaptation pattern of Fig. 5.1a was identical to that used in the experiments of Chapter 4 with its subpatterns made up of two orthogonal bars of dimensions 20' x 3' distributed pseudo-randomly within the 15^{o} diameter field and oriented at 45^{o} to the vertical. The disc adaptation pattern of Fig. 5.1b, consisted of discs of diameter 8.7' (area equal to that of a single T-shaped subpattern) centred at the position of each T-shaped subpattern of the 'T' adaptation pattern. Thus the 'T' and disc adaptation patterns differed only in the shape of their subpatterns. As discussed above, equating the mean luminance of the adaptation patterns ensures equality of the local luminances of disc and T-shaped subpatterns. The third adaptation pattern was a uniform field of diameter 15^{o} with mean luminance equal to that of the two patterned adaptation stimuli. The mean retinal illumination of the adaptation stimuli was 4.0 log trolands and that of each of the elements of each patterned adaptation stimulus was 5.7 log trolands.

The test pattern, Fig. 5.1c, consisted of a 15^{o} diameter uniform field of mean luminance equal to that of the adaptation patterns.

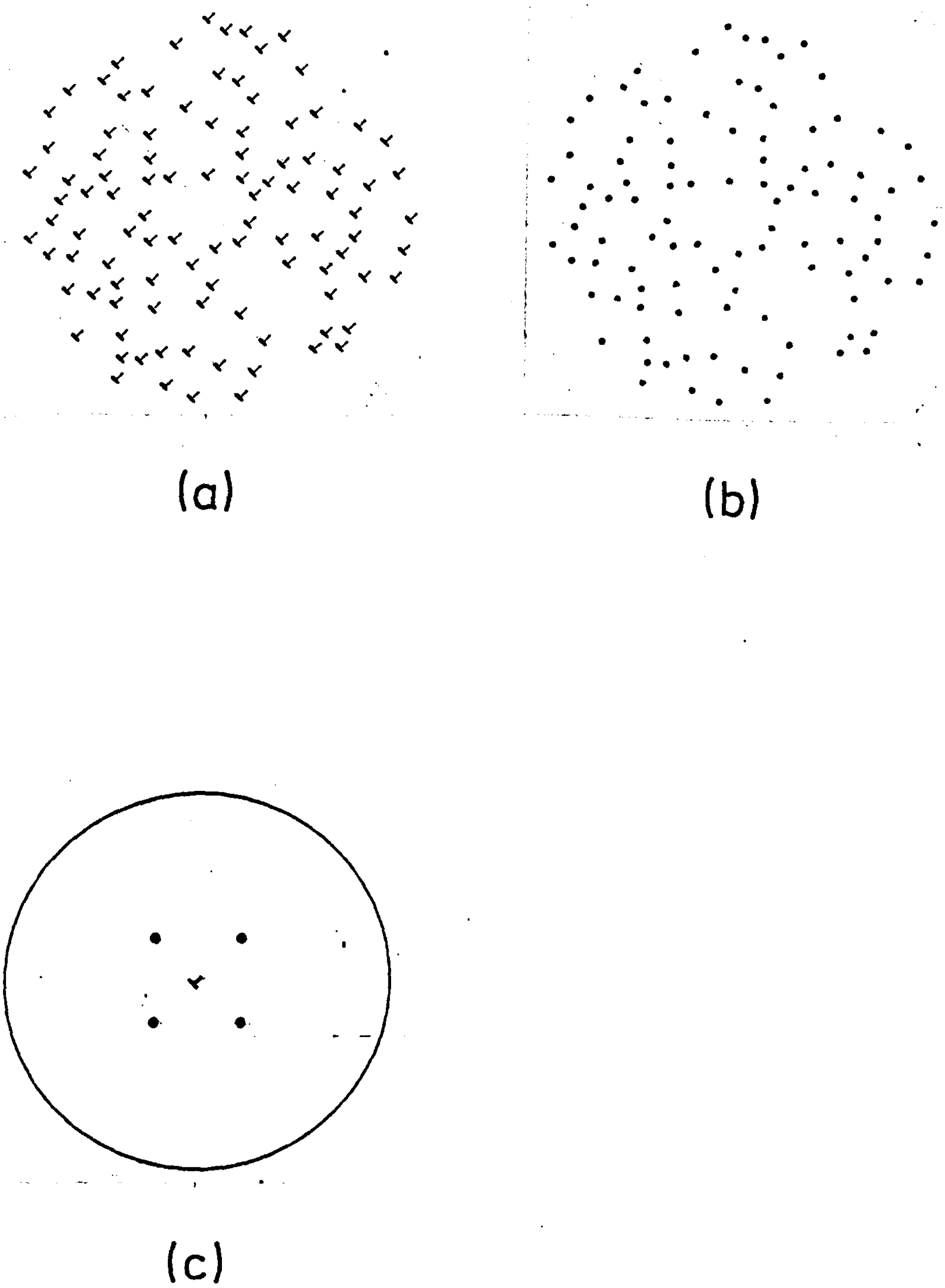


Fig. 5.1. Stimuli for experiment 1. The stimuli were brighter than their backgrounds.

Superimposed and centred within this uniform background field was a single T-shaped figure identical to those forming the 'T' adaptation pattern. As an aid to fixation four black dots formed a square of side 3.5° placed symmetrically within the circle. The luminance of the T-shaped figure was controlled by a neutral density wedge as described in Chapter 3.

Methods.

Stimuli were presented in Maxwellian view (section 3.2.1) with a time course as described previously (section 3.3.). Local retinal adaptation was reduced by the imposition of small saccadic displacements on the adaptation stimuli (section 4.2). The adaptation patterns were presented in the sequential counterbalanced design for two treatments described in section 3.4.1 and each subject performed four runs.

Contrast thresholds were determined using the method of adjustment (section 3.3.).

Subjects.

Three subjects ATS, DHF and RJM all with either normal or corrected-to-normal vision participated in this experiment. For further subject details see section 4.1.

Results.

Fig 5.2 shows, for the 3 subjects, contrast threshold elevation Δ (section 3.3.2.). The error bars indicate ±1 SEM. Each value of Δ is the mean of 12 measurements made in the four runs of the balanced sequence. All subjects show a highly significant ($t > 4.65$, $df=11$, $P < 0.001$) elevation of contrast threshold (typically of magnitude greater than 0.1 log units) for both disc and 'T' adaptation patterns. It can also be seen that adaptation to the disc adaptation pattern elevates the contrast threshold of the single T test pattern less than adaptation to the 'T' adaptation pattern

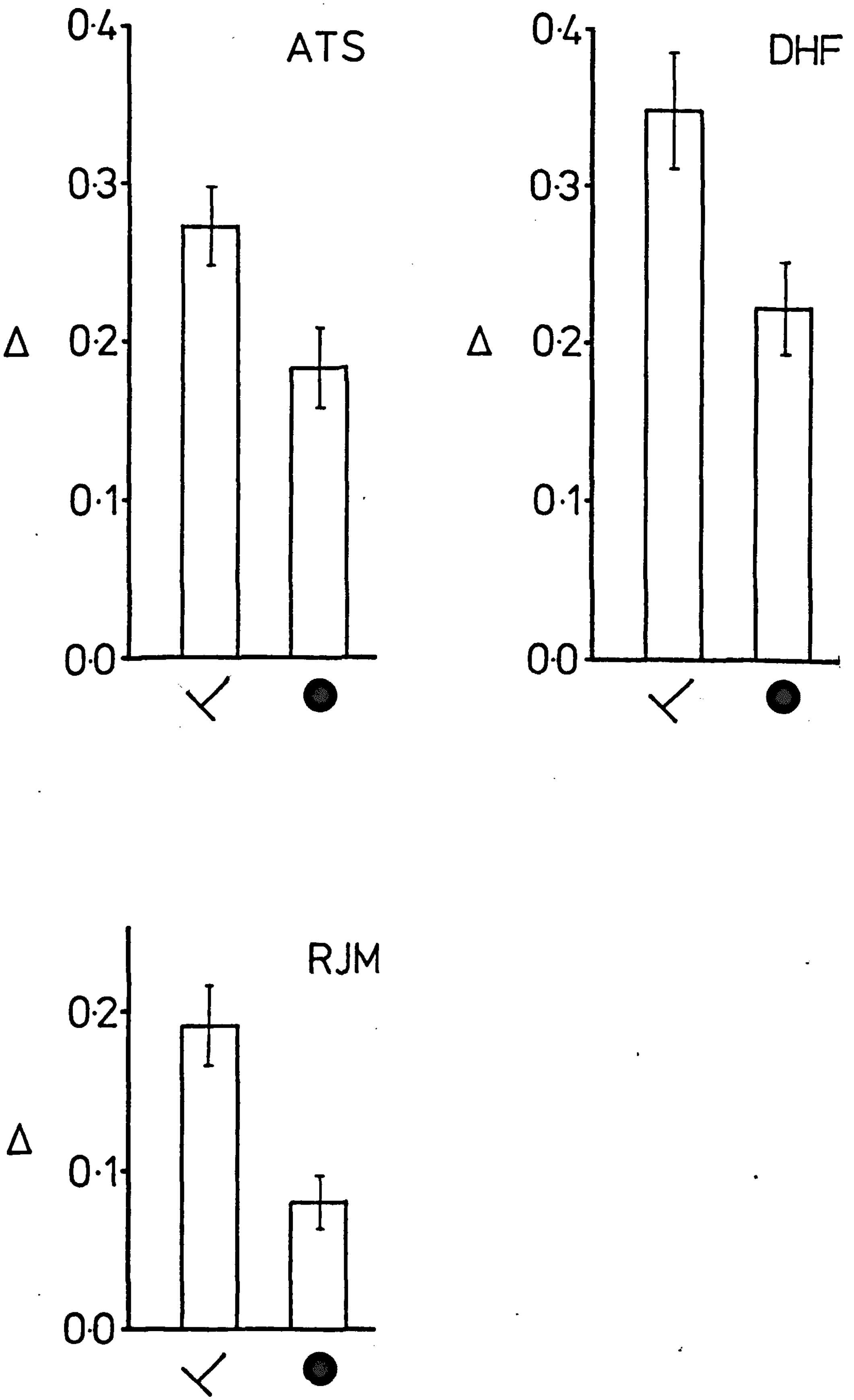


Fig. 5.2. Results of experiment 1. Contrast threshold elevation Δ in log units plotted against adaptation type (indicated by a typical subpattern below the abscissa).

for all subjects. Typical contrast threshold elevations are 0.1 log units and 0.25 log units for adaptation to disc and 'T' adaptation patterns respectively. This difference in contrast threshold elevation is significant ($t > 2.57, df=22, P < 0.01$) for all subjects.

Discussion.

The results show that the elevation of the contrast threshold of a T-shaped test pattern after adapting to a collection of disc-shaped patterns is not as great as that produced by adapting to a collection of copies of the T-shaped test figure.

The notion that the differential contrast threshold elevation observed here is a consequence of differences in "global" structure is rejected for the following reason. In both the disc and T adaptation patterns the subpattern elements are identically placed within the visual field and therefore the "global" structure of the adaptation pattern is the same. The differential contrast threshold elevation effect must, therefore, be attributed to more local pattern differences within individual subpatterns.

The constraints of equal area for the individual disc and individual T subpatterns and equal overall mean luminance ensure equality of the local luminance of a disc subpattern and T subpattern. Local luminance differences therefore cannot be argued as the cause of the differential contrast threshold elevations observed. The remaining conclusion is that the differential adaptation observed is due to the localised spatial distribution of the light, i.e. the differences in shape between the disc and T figures. The suggestion outlined in the introduction that the contrast threshold elevation observed with the present adaptation technique is merely a consequence of some general adaptation effect of spatially non-uniform light distributions is, therefore, unlikely.

The results also show that adapting to the disc adaptation pattern causes a significant contrast threshold elevation of the T test pattern. This finding of a non-zero contrast threshold elevation implies that the supposed mechanism detecting the T test pattern is also adaptationally sensitive to the disc adaptation pattern but to a lesser extent than to the T adaptation pattern. It appears therefore that the supposed mechanism detecting the T test pattern has a fairly broad selectivity for spatial variables. To determine more clearly the limits of this spatial specificity of the supposed detecting mechanism the following experiments were performed.

5.2. Orientation selectivity.

5.2.1. Experiment 2 - Orientation selectivity for single bars.

It is known from the experiments with grating patterns (section 1.4.2.) that the contrast threshold elevation effect is selective for the relative orientation of the test and adaptation patterns. This experiment was designed to investigate the extent of this orientation effect for the small localised bar patterns used in the present adaptation technique.

Stimuli.

Two adaptation patterns were used in the experiment and these were as follows. The spatially structured pattern of Fig. 5.3a consisted of 100 bright bars of dimensions 40' x 3' all with the same orientation placed pseudo-randomly in a 15° diameter limiting circle under a similar regime to that previously described for the T adaptation pattern (section 4.1.). This bar adaptation pattern could be presented with the bars orientated either vertically (0°), horizontally (90°) or at one of the two obliques (45°, -45°). The second adaptation pattern was a 15° diameter uniform field.

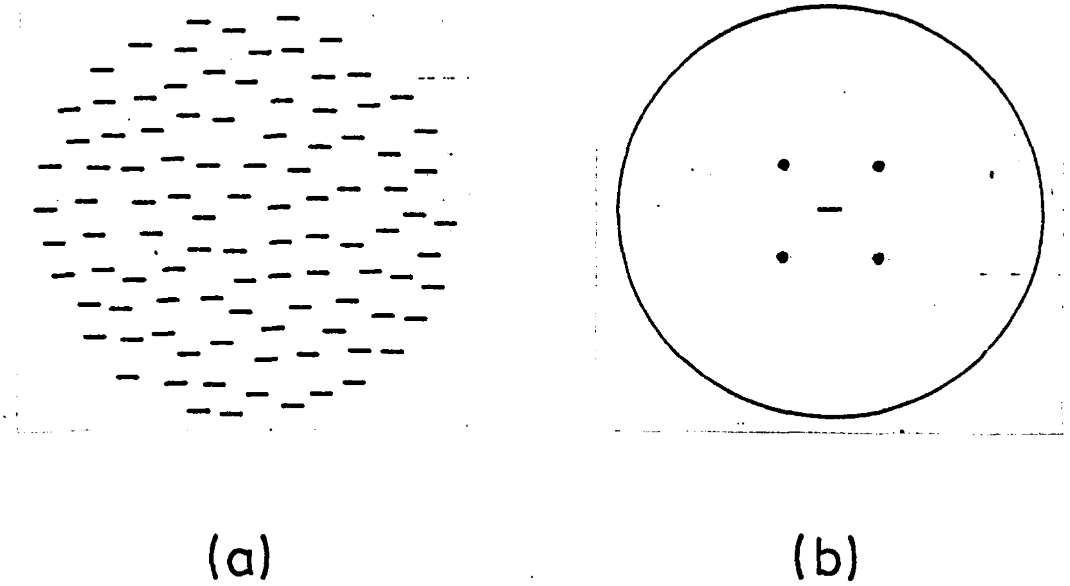


Fig. 5.3. Stimuli for experiment 2. The stimuli were brighter than their backgrounds.

These adaptation patterns were matched for an equal mean retinal illumination of 4.0 log trolands as described previously (section 3.2.6).

The test pattern consisted of a single bar, identical to one of those forming the adaptation pattern, placed at the centre of a white uniform field of equal mean luminance to the adaptation patterns. Four dark fixation dots were provided as before. (Fig. 5.3b). The test pattern was used with two test bar orientations, the one vertical (0°) and the other horizontal (90°) to control for any effects of the vertical saccade-like displacements of the adaptation patterns (section 4.2.).

Methods.

The stimuli were presented in Maxwellian view as before and the only changes from the previous methods (described in Experiment 1) were as follows. The experiment was divided into two main parts; in the first, the test bar pattern had vertical (0°) orientation with the saccadic displacements of the adaptation patterns in the direction parallel to the long dimension of the test bar; in the second, the test bar was horizontal (90°) and therefore orthogonal to the direction of adaptation pattern saccadic displacements.

Each part of the experiment was divided into 8 runs during which the bar adaptation pattern was presented at each of the four possible bar orientations (-45°,0°,45°, and 90°) according to the design for four treatments described in section 3. The same order of adaptation pattern presentation was used for the second part of the experiment where the test bar was horizontal.

Subjects.

One subject RJM participated in this experiment (for further subject details, see section 4.1.).

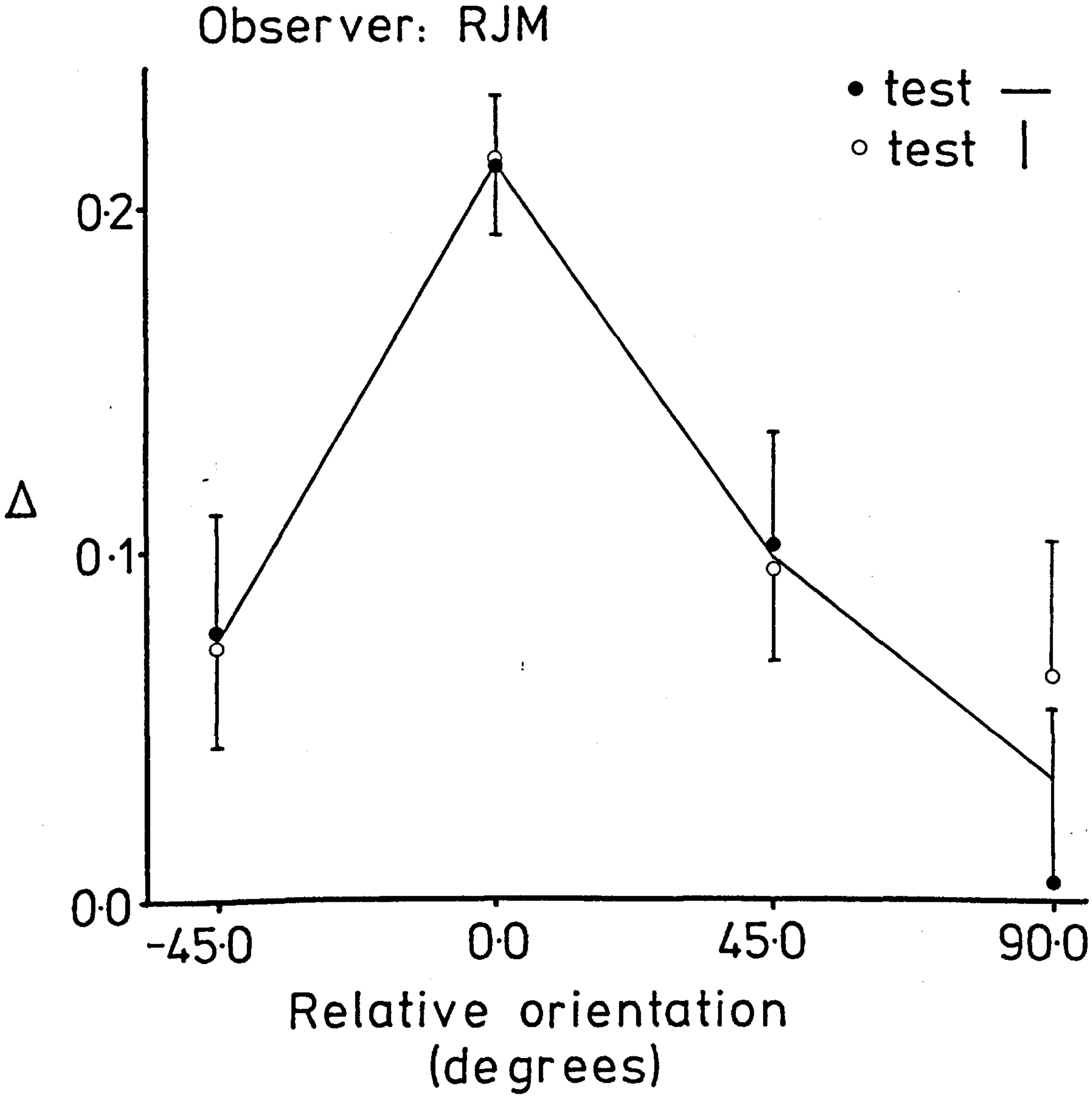


Fig. 5.4. Results of experiment 2. Contrast threshold elevation Δ in log units plotted against adaptation pattern orientation.

Results.

The results are shown in Fig. 5.4. Open symbols represent the contrast threshold elevation of the single bar test pattern when it was vertical (0^{o}) and therefore of the same orientation as the adaptation pattern saccadic displacements. Filled symbols represent the contrast threshold elevation when the bar test pattern was horizontal (90^{o}) and therefore orthogonal to the adaptation pattern saccadic displacements. The ordinate shows contrast threshold elevation, Δ (section 3.3.2.) for the four adaptation pattern orientations (relative to the bar test pattern orientation) shown on the abscissa. The error bars represent ±1 SEM. The values of contrast threshold elevation obtained for the two test bar orientations do not differ significantly from each other at any point ($t < 0.17$, $df=14$, $P > 0.5$) and there is a significant ($t > 2.91$, $df=14$, $P < 0.01$) peak in contrast threshold elevation at 0^{o} when the bar test pattern and bar adaptation pattern are of the same orientation. The continuous line joins points at the mean of the contrast threshold elevation values obtained with the two different bar test pattern orientations.

Discussion.

These results show that the adaptation produced in the present technique is orientation specific in a similar way to the orientation specificity found with grating-pattern stimuli. Moreover, this orientation specificity is not simply a result of the direction of adaptation pattern saccadic displacements as the coincidence of the results for both orientations of the bar test pattern shows. The orientation specificity observed here has an approximate half width, based on the continuous line of Fig. 5.4, of 23^{o}. This value may be an overestimate resulting from the coarse angular sampling interval used in the present experiment and is, therefore, not inconsistent with the results obtained with grating-pattern stimuli giving half widths of 13° to 14° (Blakemore and Nachmias, 1971; Maudarbocus and Ruddock, 1973).

5.2.2. Experiment 3 - Orientation-selectivity for T-shaped patterns.

In the previous experiment it was shown that the threshold elevation effect measured with the present technique showed orientation selectivity for a single bar. It might be suggested, however, that more complex pattern may not show this adaptational orientation-selectivity and that the joining together of bars to form a more complex pattern removes the selectivity of the supposed detecting mechanism for bar orientation. The present experiment investigates the orientation selectivity of the contrast threshold elevation effect for the "complex" T-shaped patterns of Experiment 1. If the contrast threshold elevation effect measured with the present technique remains orientation selective despite pattern complexity we might expect the maximum contrast threshold elevation effect when the adaptation and test sub-patterns are of the same orientation.

Stimuli.

Two adaptation patterns were used in this experiment as follows. The first adaptation pattern was identical to the T adaptation pattern of Experiment 1 and is reproduced here as Fig. 5.5b. This adaptation pattern consisted of 100 copies of a T shaped figure formed from two 20' x 3' orthogonal bars distributed pseudo-randomly within a 15° limiting circle (section 4.1.). This 'T' adaptation pattern was presented in one of two orientations each with the bisected bar of the T on the left of the visual field but with the component bars either vertical and horizontal or both at 45° to the vertical as shown in Fig 5.5b. The second adaptation pattern was a 15° diameter uniform field. These adaptation patterns were

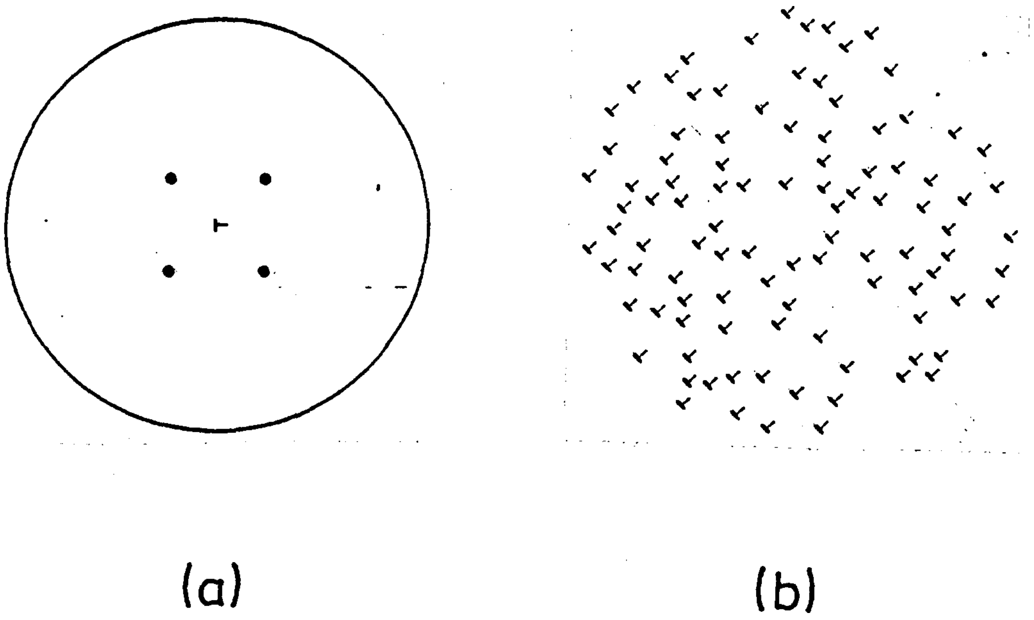


Fig.5.5. Stimuli for experiment 3. The stimuli were brighter than their backgrounds.

matched for an equal mean retinal illumination of 4.0 log trolands as described previously (section 3.2.6.).

The test pattern was identical to that used in Experiment 1 and is reproduced here as Fig. 5.5a. This test pattern consisted of a single T figure, identical to one of those forming the adaptation pattern, placed at the centre of a white uniform field of equal mean luminance to the adaptation patterns. Four dark fixation dots were provided as before. The test pattern was used with two orientations of the T figure in both of which the bisected bar of the T figure was on the left of the visual field. In the one (0°) condition the component bars forming the T test pattern were vertical and horizontal. In the other (45°) condition the component bars forming the T test pattern were both orientated at 45° to the vertical.

Methods.

The stimuli were presented in Maxwellian view (section 3.1.2.) and the only changes from the previous methods (described in Experiment 1) were as follows.

The experiment was divided into two parts. In the first part the T test pattern was orientated with its bar components at 45° to the vertical. In the second part the T test pattern was orientated with its bar components vertical and horizontal. Each part of the experiment was divided into 4 runs during which the T adaptation pattern was presented at each of the two possible orientations according to the design for two treatments described in section 3.4.1. The same order of adaptation pattern presentation was used for the second part of the experiment where the T test pattern bar components were vertical and horizontal.

Subjects.

One subject RJM participated in this experiment. For further subject details see section 4.1.

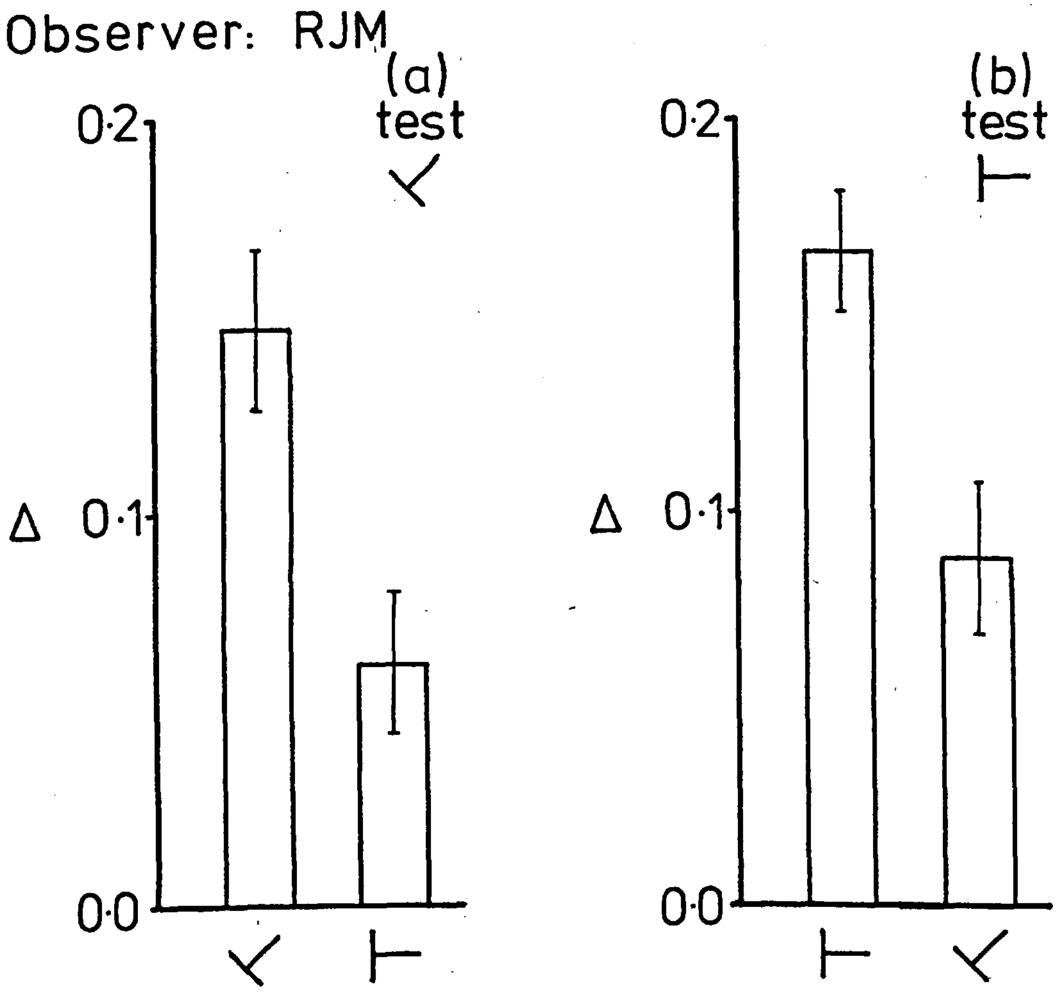


Fig. 5.6. Results of experiment 3. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern on the abscissa). The inset shows test pattern orientation.

Results.

Fig 5.6. shows the results. The ordinates represent contrast threshold elevation Δ (section 3.3.2) of the T shaped test pattern in log units and the abscissae are labelled by a typical element from the adaptation pattern. The results when the T test pattern component bars are orientated at 45° to the vertical are shown in Fig. 5.6a and the results when the test pattern component bars are horizontal and vertical are shown in Fig. 5.6b.

The orientation of the test pattern is shown in the inset. The right hand columns of the bar charts represent the contrast threshold elevation of the test pattern when the adaptation pattern had bar componenets at an orientation of 45° relative to those of the test pattern. The left hand columns of the bar charts represent the contrast threshold elevation of the test pattern when the adaptation pattern had bar components with the same orientation as those of the test pattern.

In both sections of the experiment the contrast threshold elevation of the T test pattern after adaptation to an adaptation pattern with similarly orientated subpatterns is significantly higher than after adaptation to an adaptation pattern with subpatterns at 45° to the test pattern ($t > 3.16, df=22, P < 0.01$). The typical magnitudes of these contrast threshold elevations are 0.15 and 0.08 respectively.

The differences in contrast threshold elevations between similar conditions in the two parts of the experiment are nonsignificant ($t < -0.76, df=22, P > 0.2$).

Discussion.

The maximum contrast threshold elevation of the T test pattern occurs when the orientation of the subpatterns of the adaptation pattern is the same as the orientation of the test pattern.

It appears therefore that the supposed mechanism being adapted in the present experiment is selective for the orientation of the pattern. It should be noted, however, that the present experiment does not distinguish between selectivity for orientation of the pattern as a whole and selectivity for orientation of the component bars (but see Chapter 6). The results of the experiment do indicate that connecting the component bars together to form a complex pattern does not destroy the orientation selectivity shown for single bars in the previous experiment.

It might be suggested that the orientation selectivity found here is a result of some selective enhancement of the supposed detecting mechanism response in the direction of the saccade-like displacements. The similarity of the results from both parts of the experiment, however, shows that the orientation selectivity is related to the relative orientations of the stimulus patterns and not to their relationship to the saccadic displacement direction.

5.3. Size selectivity.

5.3.1. Experiment 4 - Length selectivity.

The contrast threshold elevation effect has been shown to be selective for the length of the bars in a grating pattern (Nakayama and Roberts, 1972) and other stimuli periodic in two dimensions (Burton and Ruddock, 1978). Burton and Ruddock (1978) also demonstrated with stimuli periodic in two dimensions that this selectivity for bar lengths was shown only when the bar-length to bar-width ratio was less than 3.0. The following experiment examines whether this length selectivity and in particular its dependence on bar length/width ratio is shown with the present technique in which a single test pattern and non-periodic adaptation patterns are used.

Stimuli.

The adaptation patterns used in this experiment each consisted of 200 small bars distributed pseudo-randomly within the 15° adaptation field. All the bars in the adaptation patterns had the same orientation and width (3.0min arc). Fig. 5.7a shows a typical adaptation pattern. The different adaptation patterns are distinguished by the length of the bar subpatterns composing them. A total of ten adaptation patterns with bar length to bar-width ratios of 0.5, 1,2,3,4,5,6,7,8, and 9 were used in the experiments to be described. The eleventh adaptation stimulus was a 15° diameter uniform field.

The test pattern consisted of a single bar of the same orientation as those of the adaptation patterns, superimposed on a 15° diameter uniform field with dark fixation spots as before. Fig. 5.7b shows a typical test pattern.

Four test pattern bar lengths with bar-length to bar-width ratios of 1,3,5, and 7 were used and the experiment was divided into four parts with one length of test bar used in each part. In each part four adaptation patterns were used with bar-length to bar-width ratios two above, one below and one equal to the bar-length to bar-width ratios of the test pattern.

Because equal numbers of bars were used in each of the adaptation patterns in order to preserve global structure, changing bar length also changed the transmission of the stimulus mask. This change in transmission meant that it was not possible to maintain both the mean luminance of the adaptation pattern and the local luminance of each bar for all the adaptation patterns. Because the length selectivity being investigated is dependent on the local properties of the adaptation patterns that is the bar subpattern lengths, the adaptation pattens were equated for local luminance of individual subpatterns.

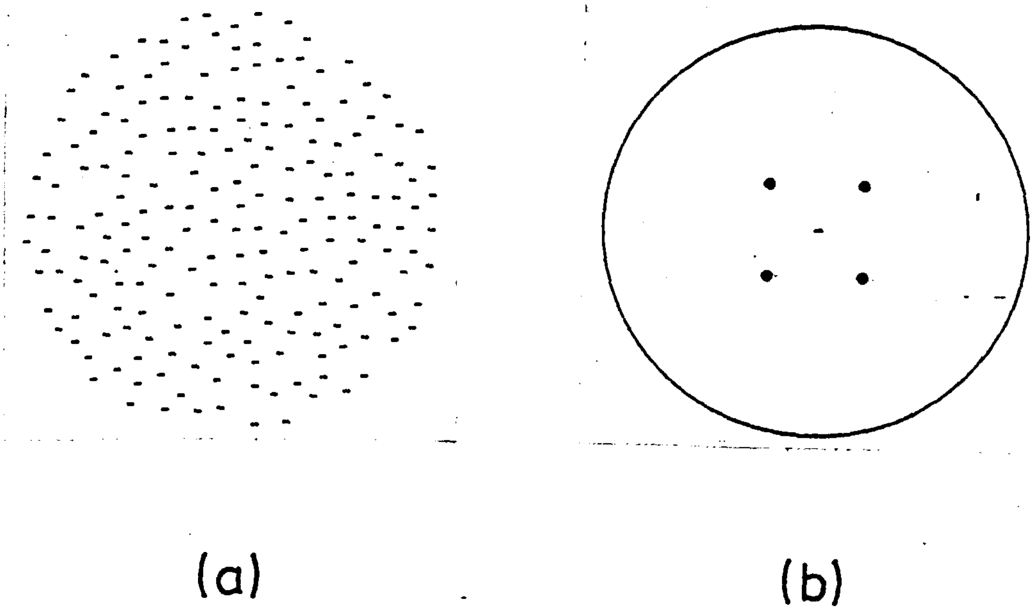


Fig. 5.7. Stimuli for experiment 4. The stimuli were brighter than their background.

The mean luminance of the bar adaptation pattern thus varied as a function of bar length. The uniform adaptation pattern and uniform test background pattern had equal luminances and were chosen to have mean luminance equal to that of the adaptation pattern with bars of length to width ratios of 3. This choice gives the same mean retinal illumination of 4.0 log trolands used in the other experiments described.

The changes in mean luminance which occur when changing from adaptation pattern to test pattern increase monotonically with increasing adaptation pattern bar length. Any length-selective effects because of their non-monotonic variation with adaptation pattern bar length should presumably not be masked by these monotonic changes in mean luminance increment.

Methods.

The stimuli were presented in Maxwellian view as described previously (section 3.1.2.) and contrast thresholds were obtained using the method of adjustment (section 3.3.). The time courses of the adaptation and test periods were as before (section 3.3.) and the adaptation stimulus was subjected to saccade-like motion during the adaptation period (section 4.2.).

As mentioned previously the experiment was divided into four parts in each of which one length of bar test pattern and its four associated bar adaptation patterns were used (see stimuli section).

Each part of the experiment consisted of 8 runs during each of which each of the 4 bar adaptation patterns was presented once. The 8 runs formed two blocks balanced for order and carry-over effects (section 3.4.3.).

Subjects.

One subject RJM participated in this experiment. For further subject details see section 4.1.

Results.

Fig. 5.8 shows the results of this experiment. The ordinate shows the contrast threshold elevation Δ (section 3.3.2) and the abscissa represents the length-to-width ratio of the bars in the adaptation pattern. The symbols on the abscissa represent the length-to-width ratios of the bars in the test patterns. Contrast threshold elevations corresponding to a particular bar test pattern are indicated by plotted symbols the same as those referring to the length-to-width ratio of the bar test pattern. The error bars represent ±1 SEM.

The results for the bar test patterns with length-to-width ratios of 1,3 and 7 show contrast threshold elevations (typically of magnitude 0.1 to 0.2 log units) which indicate some selectivity for bar length. The results for the test pattern with a length-to-width ratio of 5 indicate no significant length selectivity. In detail the results are as follows.

For the bar test pattern with length-to-width ratio of 1, the contrast threshold elevation produced by the bar adaptation pattern with ratio 0.5 was not significantly less than that produced by the bar adaptation pattern with ratio 1 $(t=0.71, df=14, P>0.1)$. A significant decrease of this contrast threshold elevation was observed, however, for the bar adaptation pattern with ratio 3 $(t=2.20, df=14, P<0.05)$. For the bar test pattern with length-to-width ratio of 3, the contrast threshold elevation produced by the bar adaptation pattern with ratio 3 is significantly greater than that produced by bar adaptation patterns with ratios 2 and 5 $(t>2.03, df=14, P<0.05)$. For the bar test pattern with length-to width ratio of 5, the contrast threshold elevation produced by the bar adaptation pattern with ratio 5 is not significantly greater than

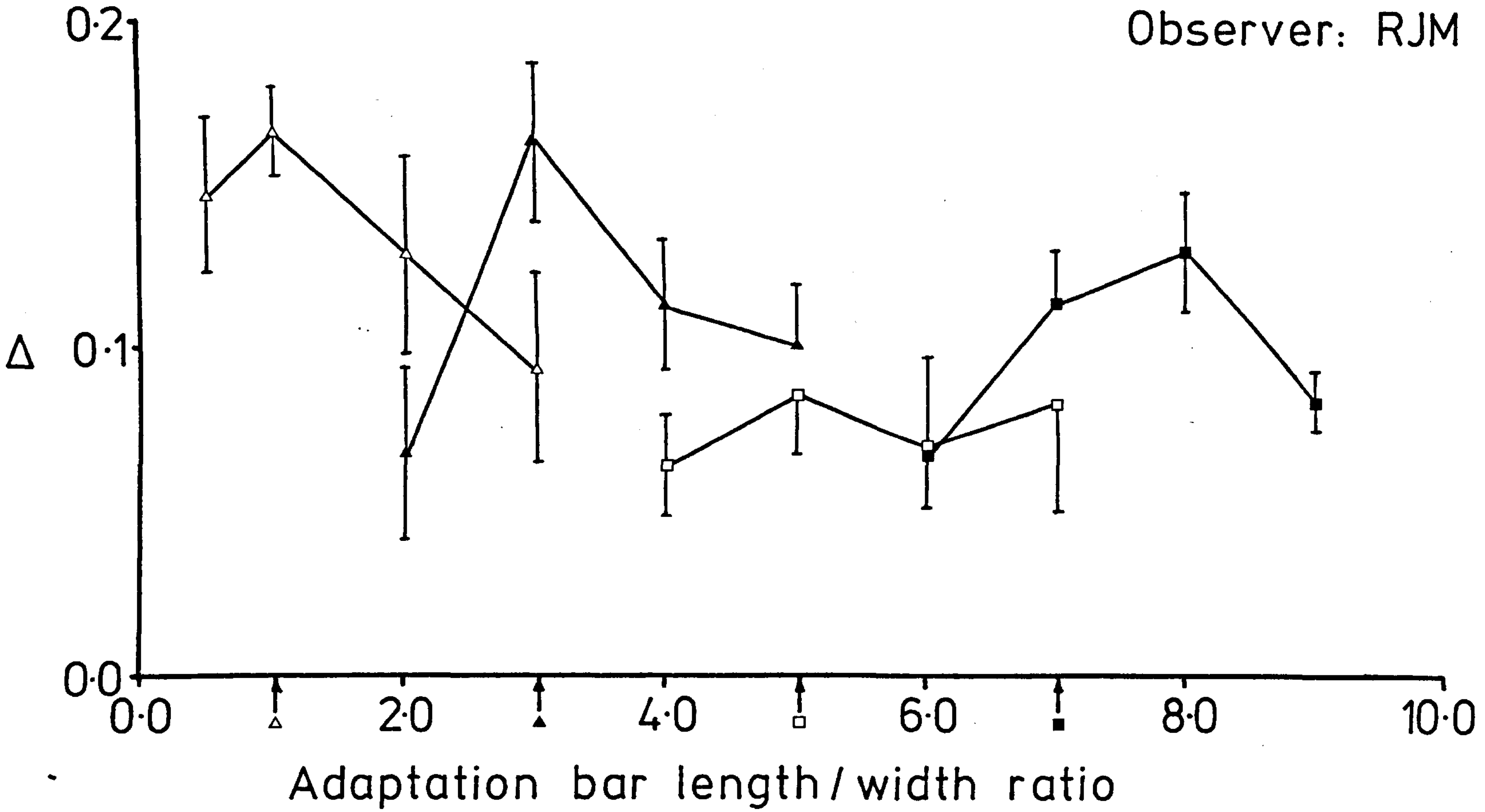


Fig. 5.8. Results of experiment 4. Contrast threshold elevation Δ in log units plotted against length-to-width ratio of adaptation pattern bars.

that produced by bar adaptation patterns with other ratios ($t \leqslant 0.90, df=14, P > 0.1$). For the bar test pattern with length-to-width ratio of 7, the contrast threshold elevation produced by the bar adaptation pattern with ratio 7 is greater than that produced by the bar adaptation patterns with ratios 6 and 9 (significant for ratio 6; $t=2.08, df=14, P < 0.05$; approaches significance for ratio 9; $t=1.69, df=14, P < 0.1$).

Discussion.

The results found here agree with those found by Nakayama and Roberts (1972) and Burton and Ruddock (1978) for the test bar length-to-width ratios up to and including 5. Length selectivity is shown for the test bar length-to-width ratios of 1 and 3 but not for 5. The lack of a reduction in contrast threshold elevation for adaptation pattern bar length-to-width ratios less than 1 may simply be an artefact of the measurement of only one adaptation bar length-to-width ratio at these values, which was insufficient to detect a slow decline. We might expect these latter values of adaptation bar length-to-width ratio to give rise to smaller contrast threshold elevations for they may be considered as bars orientated orthogonally to adaptation bars with length-to-width ratios greater than unity. It should be noted that the test bar in this case was a square with consequently no preference for either of the two orthogonal directions. It seems reasonable to conclude that length selectivity occurs for this length-to-width ratio.

The loss of length selectivity observed in the present study for the test bar length-to-width ratio of 5 is in accordance with the results of Burton and Ruddock (1978) who found loss of length selectivity for ratios greater than about 3. These authors interpreted this as the existence of length selective and length non-selective mechanisms in the visual system. The finding in the present study of length selectivity for a bar length-to-width ratio of 7 is not consistent with these authors findings. The difference in the two sets of results is likely to be due to the differences in technique. Burton and Ruddock (1978) used monochromatic green stimuli matched for overall mean luminance (thus having bars with varying local luminance) with two dimensional periodic structure. Because they used a fixed-size visual field the number of bars in their stimuli also changes. Thus with a fixed mean luminance the changes in local bar luminance need not necessarily have followed a simple scheme. The loss of local bar luminance with increasing bar length in Burton and Ruddocks' experiments may in part explain the loss of length selectivity they observed. Other differences in technique such as the use of periodic rather than non-periodic patterns, multiple rather than single test patterns, and stationary rather than moving adaptation stimuli are also possible sources for these differences in results.

However, it appears from both the study of Burton and Ruddock and the present study that a loss of length selectivity can occur under certain conditions; but these conditions might not simply be defined by length-to-width ratios greater than 3.

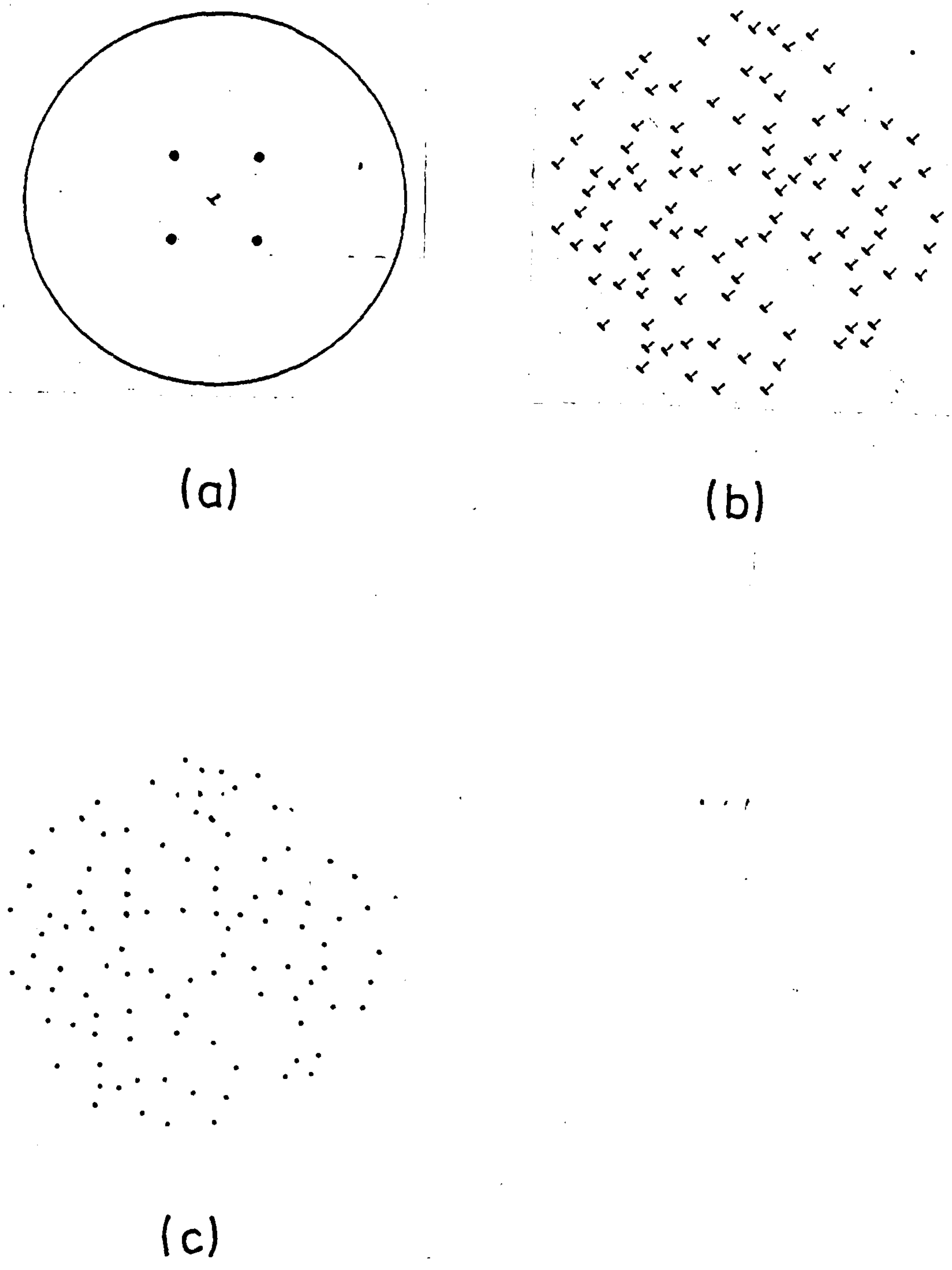
5.3.2. Experiment 5 - Size selectivity - discs and bars.

In experiment 1 the effect of adaptation to a pattern containing dots on the contrast threshold elevation of a T-shaped test pattern was measured. The diameter of the discs was chosen such that their global spatial distribution, pattern mean luminance and local subpattern luminance were the same as those for a T adaptation pattern. The resulting discs had an area equal to that of a T-shaped subpattern. In a study using the contrast threshold elevation effect Naghshineh and Ruddock (1978) found, however, that the contrast threshold of a test grating was elevated after adaptation to either a regular matrix of spots or a random spot pattern. They also found that the maximum contrast threshold elevation occurred when the spot diameter was equal to the width of the grating bars. It might be argued therefore that the disc diameters used in Experiment 1 here were not optimal for producing contrast threshold elevation of the T-shaped test pattern. The present experiment examines this specificity for disc diameter with the present adaptation technique.

Stimuli.

The test pattern used in the present experiment was identical to that used in Experiment 1 and consisted of two bars of dimensions 20' x 3' connected to form a T-shaped figure. This T-shaped figure was superimposed on a uniform background field with four dark fixation dots (section 3.2.5.). The bars in the test pattern were orintated at 45° to the vertical so that the vertical saccade-like displacements of the adaptation patterns did not lie along any of the bars. Fig. 5.9a shows the test pattern.

The adaptation patterns consisted of 100 identical subpatterns distributed pseudo-randomly within a 15° diameter field. Five different adaptation patterns were used as follows. The first four adaptation patterns were distinguished on the basis of their subpatterns. These subpatterns were either copies of the T-shaped test pattern or discs of diameter 0.5, 1 or 2 times the width of a component bar forming the T-shaped test pattern. The fifth adaptation pattern was a 15° diameter uniform field. These adaptation patterns were subjected to saccade-like vertical displacements during the adaptation period (section 4.2.). Fig. 5.9b shows the T adaptation pattern and Fig. 5.9c shows the disc adaptation pattern with discs of diameter equal to bar width. All of the adaptation patterns had their subpatterns located at identical positions to maintain global



(a)

(b)

(c)

Fig. 5.9. Stimuli for experiment 5. The stimuli were brighter than their background.

structure.

The adaptation patterns were matched for an equal mean retinal illumination of 4.0 log trolands (section 3.2.6.) and the test pattern background field was also set at this mean luminance. Because equal numbers of discs are used in each of the disc adaptation patterns the local luminance of individual discs is a monotonic function of disc diameter thus any specificity for disc size (which should be a non-monotonic function of disc diameter) should not be masked by the equating of adaptation pattern mean luminance (c.f. Experiment 4 and see discussion here).

Methods.

The stimuli were presented in Maxwellian view (section 3.1.2.) and contrast threshold measurements were made using the method of adjustment (section 3.3.). Timing of adaptation and test periods were as described previously (section 3.3.).

The experiment was divided into three parts. In each part one disc adaptation pattern of a particular disc diameter and the T adaptation pattern were used. Each part consisted of four runs during which the adaptation patterns were presented according to the sequential counterbalanced sequence described in section 3.4.1.

Subjects.

One subject RJM participated in this experiment. For further subject details see section 4.1.

Results.

The results are shown in Fig 5.10. The contrast threshold elevation of the T test pattern Δ (section 3.3.2.) is shown on the ordinate and adaptation pattern disc diameters are shown on the abscissa. The filled symbols represent the contrast threshold elevation of the T test pattern after adaptation to the T adaptation

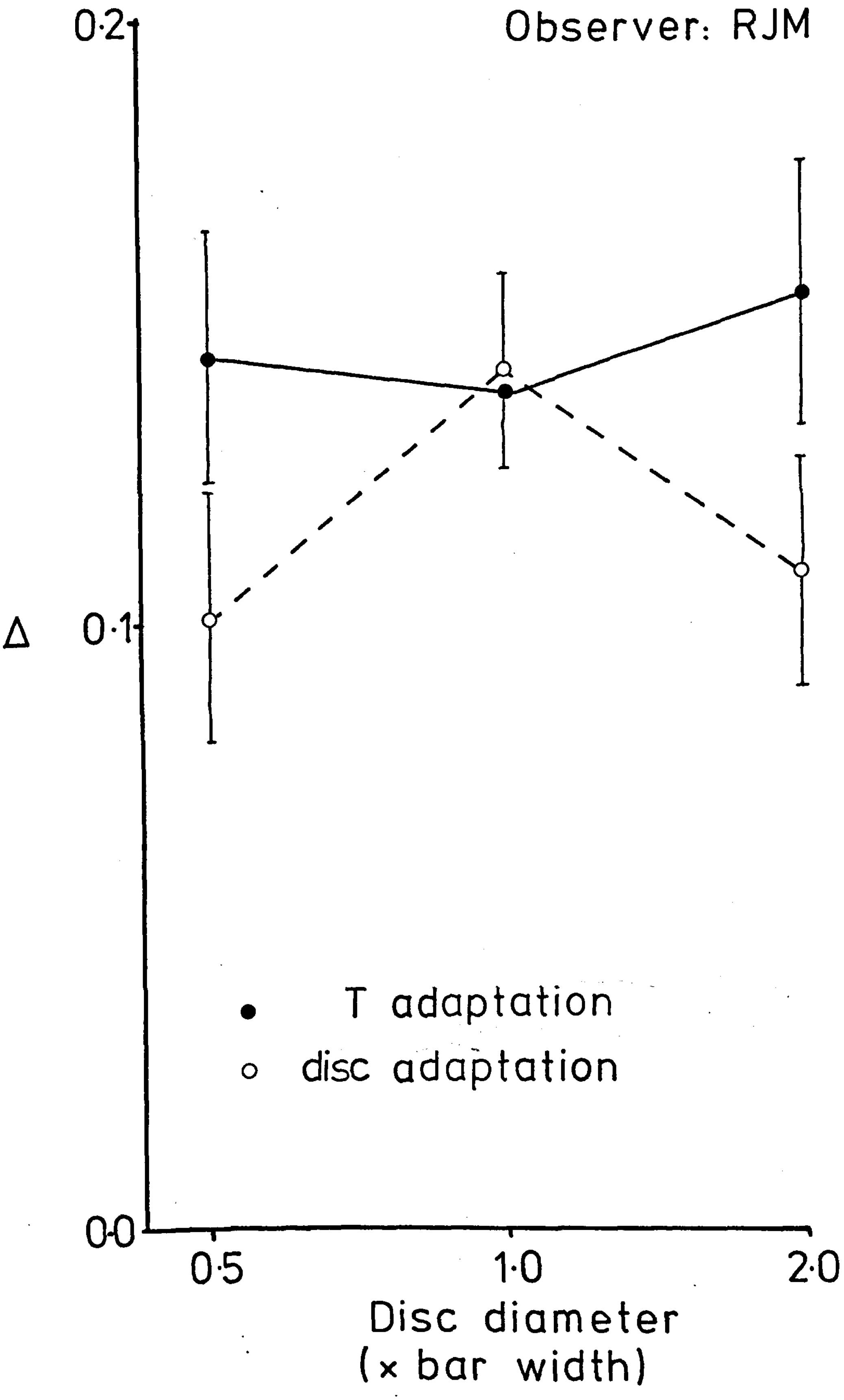


Fig. 5.10. Results of experiment 5. Contrast threshold elevation Δ in log units plotted against adaptation pattern disc diameter expressed as a fraction of bar width.

for the three parts of the experiment. The open symbols represent the contrast threshold elevation of the T test pattern as a function of adaptation pattern disc diameter.

The contrast threshold elevations after adaptation to the T adaptation pattern (typically 0.15 log units) show no significant difference between the three parts of the experiment ($t < 0.67, df=22, P>0.5$). The contrast threshold elevations obtained after adaptation to the disc adaptation patterns with disc diameters of 0.5 and 2 times the bar width are lower than those obtained with the T adaptation pattern and these differences approach significance ($t>1.48, df=22, P< 0.1$). The contrast threshold elevation after adaptation to the disc adaptation pattern with disc diameter equal to bar width is not significantly different from that obtained with the T adaptation pattern ($t=^{-}0.15, df=22, P>0.5$).

All of the contrast threshold elevations measured were significantly greater than zero ($t> 4.86, df=11, P<0.001$).

Discussion.

In agreement with the results of Naghshineh and Ruddock (1978) the present results show that adaptation to disc stimuli causes an elevation of the contrast threshold of bar stimuli. There is also agreement with the finding that the maximum contrast threshold elevation of the bar stimulus occurs after adaptation to discs of diameter equal to the bar width. The "tuning" for disc diameter measured in the present experiment only approaches significance but if the results of Experiment 1 are also considered it is evident that such "tuning" does exist. For, in Experiment 1 the experimental conditions were identical to thoseof the present experiment but a disc adaptation pattern with disc diameter approximately four times the component bar width was used. In Experiment 1 a significant difference was obtained between the contrast threshold elevation of the T test pattern after adaptation to the T adaptation pattern and the "4x" disc adaptation pattern.

The present results therefore extend the findings of Naghshineh and Ruddock (1978) to the case of non-periodic bar patterns and show that this disc size selectivity is not dependent upon the periodic nature of the patterns.

The similarity of the contrast threshold elevations produced by the T adaptation pattern and the disc adaptation pattern with disc diameter equal to bar width is of particular interest. Naghshineh and Ruddock (1978) measured the contrast threshold elevation of a grating test pattern after adaptation either to grating or to disc patterns. Although their measurements of these two threshold elevations were made in separate experiments they are surprisingly similar. We might expect in view of the length tuning data of the previous experiment, that the contrast threshold elevation after adaptation to the disc adaptation pattern would be somewhat less than that after adaptation to the T adaptation pattern. Naghshineh and Ruddock (1978) explain their data in terms of the existence of two mechanisms, the one sensitive to discs and the other to bars, with some form of switching between them. Such a scheme could explain the present results if the sensitivities of the two mechanisms are suitably chosen. In the present experiment the coincidence of the contrast threshold elevations produced by adaptation to disc and T patterns might simply be a result of local luminance differences; the disc local luminance was greater than the T local luminance in order to maintain equality of pattern mean luminance. It is difficult to assess whether this was the case in the study of Naghshineh and Ruddock for their adaptation patterns were presented at "the maximum possible contrast" and the test pattern background was matched to the adaptation pattern mean luminance. Also it is not clear how many discs were contained within their adaptation patterns for varying disc diameters. It is possible, therefore, that the similarity of the contrast threshold elevations after adaptation to grating and disc patterns they observed is also a consequence of local luminance differences.

It was mentioned in the introduction to this experiment that it might be argued that the significant difference in contrast threshold elevation between adaptation to the T adaptation pattern and the same area disc adaptation pattern observed in Experiment 1 might be the result of a non-optimal choice of disc diameter. In view of the present results it is indeed likely that the difference in contrast threshold elevation would be reduced if discs of diameter equal to the bar width were used. For the disc pattern to serve the purpose of a control pattern (as in Experiment 1) for global spatial distribution, mean pattern luminance and local pattern luminance, however, it is necessary for the disc to have an area equal to that of one of the other subpatterns. If a smaller disc with diameter equal to the bar width were used, and equality of adaptation pattern mean luminance and global spatial distribution was maintained, a higher local luminance would be required for the individual discs which could give rise to an artificially elevated threshold. To overcome this increase of local luminance the number of discs in the adaptation pattern might be reduced but this would lose the equality of global spatial distribution with the other adaptation patterns. In conclusion the use of a disc adaptation pattern as a control for global spatial distribution, mean pattern luminance and local pattern luminance is incompatible with the use of discs with diameters equal to bar widths. Conversely, the results of this experiment do not preclude the use of an equal area disc adaptation pattern as a control for the aforementioned factors.

5.4. Summary.

In the present chapter it has been shown that the present adaptation technique, where a moving adaptation pattern consisting of many subpatterns and a stationary single subpattern test pattern is used, reveals spatial selectivities of the contrast threshold elevation effect similar to those found in other studies. It has been demonstrated that the contrast threshold elevation effect measured with the present technique shows specificity for the local spatial properties of the subpatterns. Most previous studies with grating patterns have been concerned with specificities for more global spatial properties of the patterns.

The effect measured here shows specificity for the orientation of bar patterns either singly or when they are formed into a more complex pattern. Selectivity for bar length has also been demonstrated and shows similar properties to those found in other studies for bar length-to-width ratios less than 5. The length selectivity observed with the present technique for bar length-to-width ratios greater than 5 is not consistent with the study of Burton and Ruddock (1978) but this might be attributable to experimental differences.

The contrast threshold elevation of a test pattern consisting of bars after adaptation to disc patterns shows a similar specificity for disc size to that found by other workers (Naghshineh and Ruddock, 1978) with grating and disc patterns.

CHAPTER 6. EXPERIMENTS ON CONNECTIVITY.

The present chapter is divided into two sections. In the first section, the results of the experiments in Chapters 4 and 5 where stimuli composed of T-shaped subpatterns were used are considered within the framework of structural theories of pattern recognition (section 1.2.2.). In the second section, control experiments are described which were designed to test the generality of the conclusions reached in the first section of this chapter.

6.1. Adaptational sensitivity to relational structure.

In the discussion of Experiment 1 of Chapter 4 it was mentioned that the difference in contrast threshold elevation of a single T-shaped test pattern after adaptation to a T adaptation pattern and after adaptation to a disconnected bar adaptation pattern might be interpreted as indicating an adaptational sensitivity to the relational structure of the pattern. That is, an adaptational sensitivity to the relative spatial positions of the supposed bar features forming the T-shaped figures was shown in this experiment. Later experiments described in Chapter 4 demonstrated that the difference in contrast threshold elevation observed in Experiment 1 of Chapter 4 was probably a result of local retinal adaptation. In particular, the results of Experiment 2 of Chapter 4, in which the adaptation technique finally chosen for the present investigations was used, might be interpreted as a lack of adaptational sensitivity to relational structure. To clarify this interpretation and its implications for pattern vision this chapter discusses the results of Experiment 2 of Chapter 4 within the framework of a structural theory of pattern recognition (section 1.2.2.).

Structural descriptions of patterns.

In a structural theory of pattern recognition patterns are described in terms of their local features and the spatial relationships between them (section 1.2.2.). Examples of typical features might be bars and discs; examples of typical relations might be "above", "below", and "left of". The stimuli of Experiment 2 of Chapter 4 (Fig 4.1.) might therefore be described in terms of the above structural components as follows. If we consider the T shaped test pattern of Fig. 4.1c, this might be described as two bar features of orthogonal orientations and a relation specifying the spatial relationship of one bar feature connected at one end to the centre of the other bar feature. The relation might also specify whether one of the bar features is to the "left of" or "right of" the other bar feature. For ease of notation such a relation will be described as specifying "T-connectedness" of two orthogonal bar features.

For the adaptation patterns of Fig. 4.1 we might use a structural description of the following form. In the T and disconnected bar adaptation patterns of Figs. 4.1a,b the "features"(bars of orthogonal orientations) are identical and the difference between these two patterns might be described in terms of the spatial relationships between these features as follows. In the disconnected bar adaptation pattern of Fig. 4.1b the relations specifying the spatial relationships between the bar features may, on average, be considered random. When pairs of bars are formed into T-shaped figures to form the T adaptation pattern of Fig. 4.1a the relational structure may be described as follows. The relations specifying the relative positions of the T-shaped subpatterns are, as in the case of the disconnected bar adaptation pattern, on average random. In addition to these "random" relations, relations specifying the "T-connectedness" (see above) of the bar features are included in the structural description of the T adaptation pattern. The relational structure of the T adaptation pattern might therefore be considered to consist of two components, the one, random relations specifying relative subpattern positions, the other relations specifying "T-connectedness". The single T test pattern might be described as two bar features and the relation specifying "T-connectedness" between these bar features. The structural descriptions of these three patterns may be summarised as in Table I.

TABLE I

	Pattern	Features	Relations
Adaptation		\ , /	Random, T-connected
	Disconnected bars	\ , /	Random
Test		\ , /	T-connected

Interpretation in terms of features and relations.

From a structural theory viewpoint the main difference between the two adaptation patterns summarized in Table I is that the T-adaptation pattern includes relations specifying "T-connectedness" whilst the disconnected bar adaptation pattern does not. Apart from this relational structure difference the two adaptation patterns might be regarded as identical. In these structural terms, the T test pattern has most similarity with the T adaptation pattern.

If we consider the adaptational sensitivity of the mechanisms involved in the detection of the single T test pattern of Experiment 2 of Chapter 4 it is evident that the results of that experiment might be interpreted as an adaptational insensitivity to changes in the relational structure of the adaptation patterns. For, if the mechanism involved in the detection of the single T test pattern were adaptationally sensitive to the spatial relationships of the bar features, specified by a relation of "T-connectedness", then we might expect the T adaptation pattern to be more effective than the disconnected bar adaptation pattern in elevating the T test pattern contrast threshold. This is clearly not the case in the results of Experiment 2 of Chapter 4 which showed similar elevations of the T test pattern contrast threshold after adaptation to either the T adaptation pattern or the disconnected bar adaptation pattern.

Note that although the mechanisms detecting the T test pattern appear to be adaptationally insensitive to the relational structure of the T-shaped figure they do show adaptational sensitivity to the features forming the figure. This conclusion follows from the results of the experiments described in Chapter 5 which demonstrated the specificity of the contrast threshold elevation effect, measured with the present technique, for the shape and orientation of the "local" features. In particular, if we consider Experiment 1 of Chapter 5, the test pattern was the T test pattern (Fig. 4.1c) described above and the adaptation patterns were the T adaptation pattern described above and an "equal area" disc adaptation pattern (Fig. 5. 1b). The latter adaptation pattern might be described in structural terms as consisting of disc features with relations specifying the relative positions of these disc features which are on average random. The only differences between the two adaptation patterns of Experiment 1 of Chapter 6 are therefore, the lack of relations specifying "T-connectedness" in the description of the disc adaptation pattern, and more importantly the different features i.e. discs and bars. The results of Experiment 2 of Chapter 4 indicated that the mechanism detecting the T test stimulus was insensitive to relational structure, thus the differences in contrast threshold elevations observed in Experiment 1 of Chapter 5 might be attributed to "local" feature differences. Thus the greater contrast threshold elevation of the T test pattern after adaptation to the T adaptation pattern than after adaptation to the equal area disc adaptation pattern in Experiment 1 of Chapter 5 might be interpreted as an adaptational sensitivity to feature shape (but see also section 5.3.2.)

In conclusion, these experiments might be interpreted as revealing a lack of adaptational sensitivity to relational structure and adaptational sensitivity to the shape of pattern features. Note that the experiments considered above have only shown this adaptational insensitivity for one particular relation, i.e. that specifying "T-connectedness"; the basis for broadening this to relational structure in general is given in the control experiments of section 6.2.

Interpretation in terms of Fourier analysis.

The conclusion of the preceding paragraph may be equivalently stated (see section 1.5.3.) in terms of a Fourier theory of pattern analysis (section 1.5.1.) as follows. The detecting mechanism in such a Fourier theory might be considered as being adaptationally sensitive to the amplitude of the Fourier (spatial frequency) components of the pattern and adaptationally insensitive to their relative phases. This statement may be illustrated by considering the T test and adaptation patterns. If the detecting mechanism is assumed to be conducting some form of local Fourier analysis of the patterns (section 1.5.1) it is sufficient to ignore the global structure of the adaptation patterns and to consider their local structure only. In this case the T adaptation pattern may be regarded as two orthogonal bars forming a T figure, and the disconnected bar adaptation pattern may be regarded as two orthogonal bars with, on average, random positions relative to each other. Two types of Fourier analysis may then be performed on these two orthogonal bar patterns. In the first case relative spatial phase between the two bars is included in the analysis and in the second case relative spatial phase is excluded from the analysis.

In the first case where spatial phase is included in the analysis of each of the T and disconnected bar adaptation patterns, the Fourier spectrum is modified depending upon the particular juxta position of the two orthogonal bars (see appendix). If the mechanism detecting the T test pattern performed this type of Fourier transform which is sensitive to the relative spatial phase between the two bars, the difference in this information for the two adaptation patterns would elicit a different adaptational response.

In the second case of Fourier analysis where spatial phase is not included in the analysis both the T and disconnected bar adaptation patterns would give rise to identical Fourier transforms (see appendix). Thus a detecting mechanism performing this form of Fourier analysis would not be expected to give a different contrast threshold elevation of the T test pattern in response to the different adaptation patterns.

The latter form of phase insensitive Fourier analysis is consistent with the results of Experiment 2 of Chapter 4 and we might therefore conclude that in a Fourier framework the detecting mechanism is adaptationally insensitive to local relative phase.

Discussion.

Julesz and Caelli (1979) discuss the role of Fourier analysis in studies of texture perception and point out the agreement of early measurements of texture discrimination (Julesz, 1962, 1975, and Julesz, Gilbert, Shepp and Frisch, 1973) and some grating adaptation effects (Graham and Nachmias, 1971). In these cases the visual system appears to show insensitivity to phase (or spatial position) information in the stimulus patterns. Julesz and Caelli, (1979) continue by citing later studies of texture discrimination

(Caelli and Julesz, 1978; Caelli, Julesz, and Gilbert, 1978) which do not support this phase insensitivity.

They conclude that ..."the visual system for the relatively simple task of preattentive texture perception can utilise the phase (position) information, but most likely _not_ in the form of _global_ Fourier phase spectra in which the conspicuous local spatial information is submerged. Instead, it seems more likely that the positional information is evaluated by averaging the output of many local, non-linear analysers tuned to specific geometrical features".

The results of Experiment 2 of Chapter 4 indicate that, in contrast to the finding of Caelli and Julesz, 1978, and Caelli, Julesz, and Gilbert, 1978 for texture discrimination, the visual system is not adaptationally sensitive to _local_ relative-position information. It therefore appears that the nature of the processes underlying texture discrimination and the nature of those underlying the contrast threshold elevation measured with the present adaptation technique are different. It is also worth noting here that Beck has argued that there is a diminished sensitivity to local position information in the peripheral discrimination of line figures (Beck, 1972; Beck and Ambler, 1973).

It may be concluded from the above discussion that each of these different experimental techniques allow examination of either different stages of the pattern analysis process or different aspects of the same process. For example, it might be argued that the contrast threshold elevation effect reveals the properties of some primary feature analysers and texture discrimination reveals the properties of more central analysis. Alternatively, it might be suggested that both experimental techniques allow examination of the same process but the parts of the pattern analysis process concerned with spatial relationships are not adaptationally sensitive. A third possibility is that the process examined with the texture discrimination technique is parallel to the process examined with the contrast threshold elevation effect.

6.2. Control experiments.

In the previous section it was argued that the mechanisms involved in the contrast threshold elevation effect measurements reported here were both adaptationally insensitive to relational structure and adaptationally sensitive to the features of a pattern. The experiments discussed in the previous section (Experiment 2 of Chapter 4 and Experiment 1 of Chapter 5) only considered, however, one particular spatial relationship, that is, a relation specifying "T-connectedness". It might be suggested therefore that the generalization of the conclusions of the previous chapter to relational structure of all types was unfounded, and that these conclusions are only applicable to the particular case of "T-connectedness".

To test the validity of this generalization Experiment 2 of Chapter 4 and Experiment 1 of Chapter 5 were repeated with different stimuli and in particular with patterns having a different relational structure. These control experiments are described in the following sections.

6.2.1. Experiment 1 - Control for subpattern size.

It might be suggested that the lack of a difference in the contrast threshold elevation produced by the T and disconnected bar adaptation patterns of Experiment 2 of Chapter 4 are the result of the particular subpattern sizes chosen. To check that these subpattern sizes were not in some way special the present experiment repeats Experiment 2 of Chapter 4 with twice the size.

Stimuli

The test pattern was a single T-shaped figure consisting of two identical orthogonal bars of dimensions 40' x 6' orientated at 45° to the vertical and horizontal. This T-shaped figure was superimposed on a 15° diameter uniform field with four dark fixation spots (section 3.2.5.). The resulting test stimulus is shown in Fig. 6.1a.

Three adaptation stimuli were used as follows; In the first, 27 copies of the T-shaped test figure were distributed pseudo-randomly within the 15° diameter field under a similar regime to that used to produce the stimuli of Fig. 4.1., this resulted in the T adaptation pattern of Fig. 6.1b. In the second, the bar elements comprising the T adaptation pattern were independently distributed within the 15° diameter field to produce the disconnected bar adaptation pattern of Fig. 6.1c. The third adaptation pattern was a 15° diameter uniform field.

All the adaptation stimuli and the test background field were matched to give a mean retinal illumination of 4.0 log trolands. During the adaptation period the adaptation stimuli were subjected to small saccade-like displacements to reduce local adaptation (section 4.5).

Methods.

Stimuli were presented in Maxwellian view (section 3.1.2.) and contrast thresholds were obtained using the method of adjustment (section 3.3.). The adaptation patterns were presented in a sequentially counterbalanced sequence consisting of four runs as described in section 3.4.1. Timing of the test and adaptation periods was as described in section 3.3.3.

Subjects.

One subject RJM participated in this experiment. For further subject details see section 4.1.

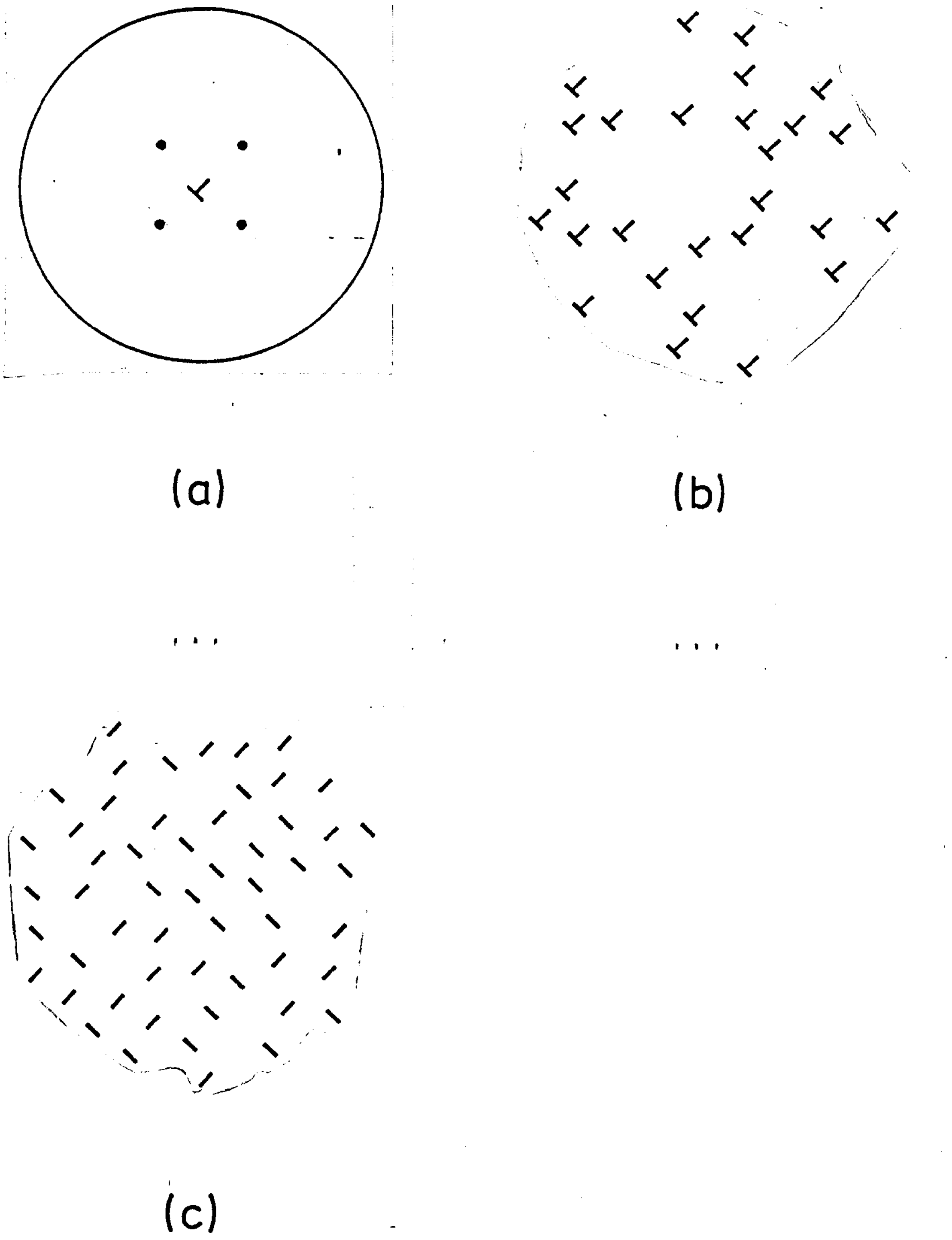


Fig. 6.1. Stimuli for experiment 1. The stimuli were brighter than their backgrounds.

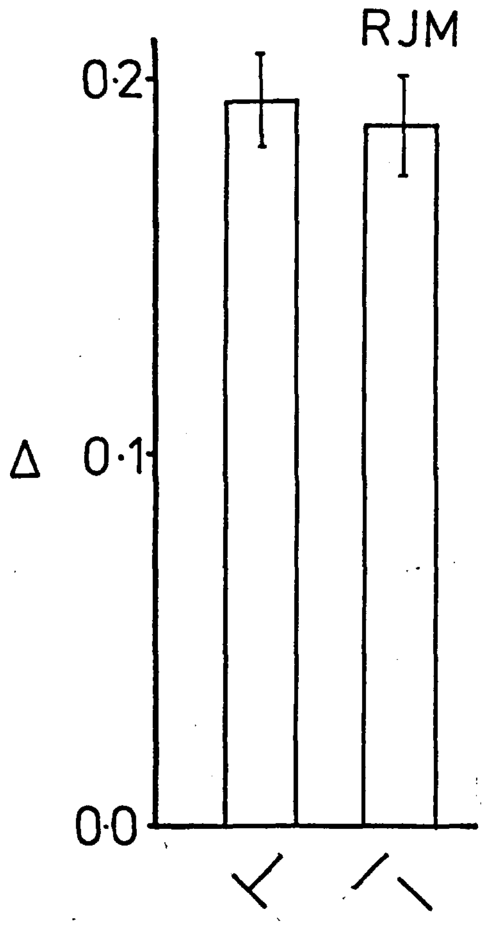


Fig. 6.2. Results of experiment 1. Contrast threshold elevation Δin log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

Results.

The results are shown in Fig. 6.2. Contrast threshold elevation Δ (section 3.3.2.) of the T test pattern is plotted against adaptation pattern type indicated on the abscissa by a typical subpattern. Both the T adaptation pattern and the disconnected bar adaptation pattern cause a highly significant contrast threshold elevation of the T test pattern ($t > 14.38, df=11, P < 0.001$). There is no significant difference between the contrast threshold elevations (typically 0.2. log units) produced by these two adaptation patterns ($t=0.40, df=22, P > 0.25$).

Discussion.

It is evident that the results of the present experiment are in agreement with those obtained in Experiment 2 of Chapter 4 with smaller subpatterns. The suggestion that the results obtained in Experiment 2 of Chapter 4 are an artefact of the particular choice of subpattern size therefore seems unlikely.

6.2.2. Experiment 2 - Control for bar shape.

In Experiment 3 of Chapter 5 it was observed that the ratio of the length to the width of a bar was critical in determining the selectivity of the contrast threshold elevation effect for bar length. In particular, it was noted that Burton and Ruddock (1978) found a lack of length selectivity for bar length-to-width ratios greater than three. The results of Experiment 3 of Chapter 5 also revealed this lack of length selectivity for a bar length-to-width ratio of five, although other ratios showed length selectivity. The bars used in Experiment 2 of Chapter 4 and the previous experiment had a length-to-width ratio of 6.7. For a ratio of 6.7 the results of the present study (Experiment 3 of Chapter 5) and the results of Burton and Ruddock (1978) disagree, and it might be suggested therefore that bars with this length-to-width ratio are not representative of the general case. It might thus be argued that the results of Experiment 2 of Chapter 4 and the previous experiment are a consequence of the particular bar length-to-width ratio chosen. To investigate this possibility Experiment 2 of Chapter 4 was repeated with bars of a length-to-width ratio of 2.2., for which the results of this study (Experiment 3 of Chapter 5) and that of Burton and Ruddock (1978) agree, as follows.

Stimuli

The test pattern of Fig 6.3a consisted of two identical orthogonal bars of dimensions 20' x 9' orientated at 45^{o} to the vertical and horizontal amd connected to form a T-shaped figure. This T-shaped figure was superimposed on a 15^{o} diameter uniform field with four dark fixation spots (section 3.2.5.).

Three adaptation patterns were used. The first, T adaptation pattern of Fig.6.3b consisted of 100 copies of the T-shaped test figure distributed identically to the T-shaped subpatterns forming the T adaptation pattern of Experiment 2,Chapter 4. The second, disconnected bar adaptation pattern of Fig. 6.3c consisted of the individual bar elements forming the T's in Fig. 6.3b distributed at the same pseudo-random positions as the bars in the disconnected bar adaptation pattern of Experiment 2 of Chapter 4. The third adaptation pattern was a 15^{o} diameter uniform field.

The adaptation patterns were subjected to small saccade-like displacements during the adaptation period (section4.5.). The adaptation patterns and the test background field were all set with an equal mean retinal illumination of 4.0 log trolands (section 3.2.6.).

Methods.

The stimuli were presented in Maxwellian view (section 3.1.2 .) and contrast thresholds were obtained using the method of adjustment (section 3.3.). Timing of the test and adaptation periods was as

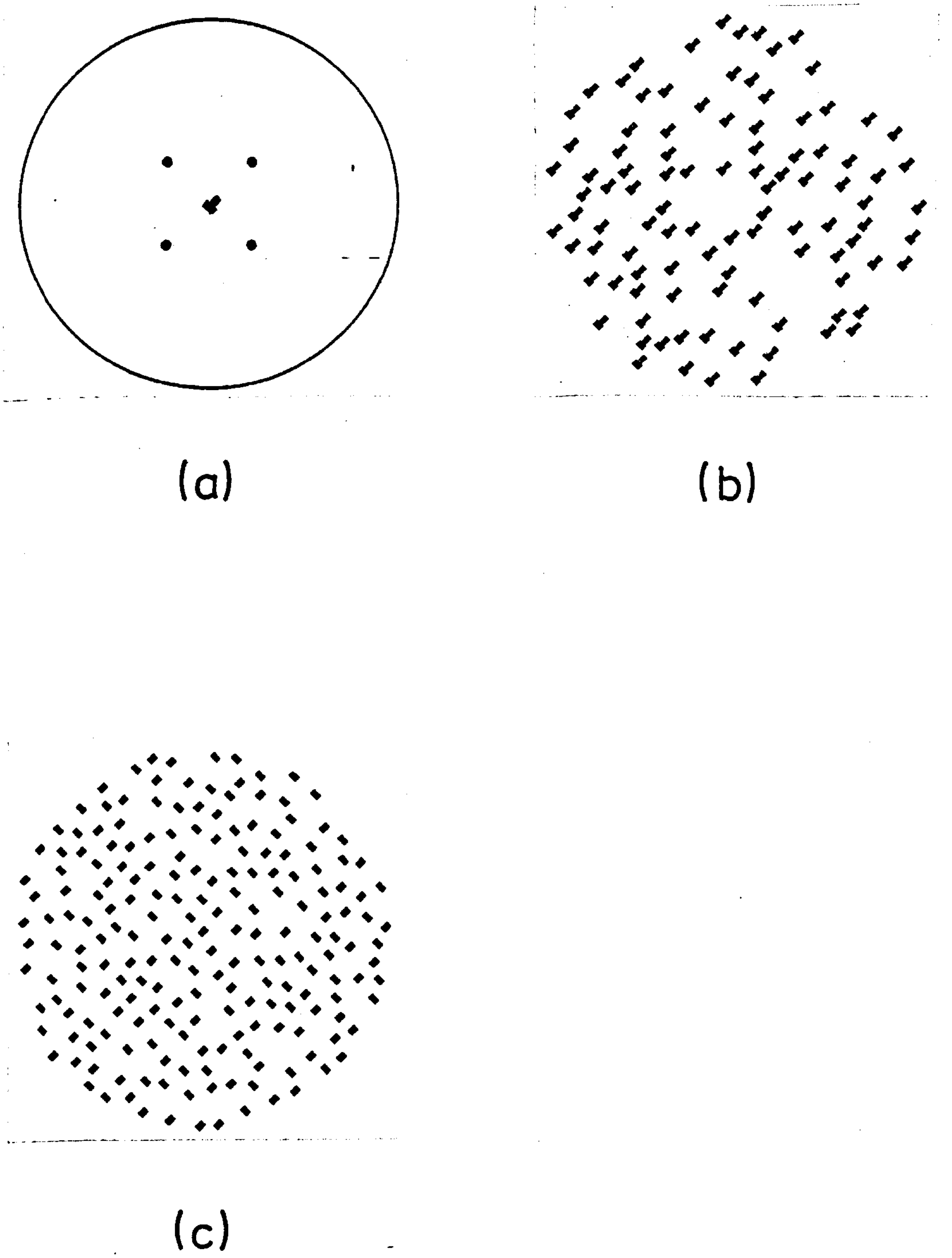


Fig. 6.3. Stimuli for experiment 2. The stimuli were brighter than their backgrounds.

described previously (section 3.3.3.) The adaptation patterns were presented in 4 runs according to the balanced design for two treatments described in section 3.4.1.

Subjects.

One subject RJM participated in this experiment. For further subject details see section 4.1.

Results.

The results are shown in Fig. 6.4. Contrast threshold elevation Δ (section 3.3.2.) is shown on the ordinate and a typical adaptation pattern subpattern is shown on the abscissa. Both T and disconnected bar adaptation patterns give rise to a highly significant non-zero contrast threshold elevation (typically 0.1 log units) of the T test pattern ($t \geqslant 4.50$, $df=11$, $P < 0.001$). The contrast threshold elevation produced by adaptation to the T adaptation pattern is not significantly greater than the contrast threshold elevation produced by adaptation to the disconnected bar adaptation pattern ($t=-0.39$, $df=22$, $P > 0.5$).

Discussion.

The results of the present experiment with patterns consisting of bars with length-to-width ratio of 2.2. agree with the results of Experiment 2 of Chapter 4 where patterns consisting of bars with a 6.7 length-to-width ratio were used. This concurrence of results might be interpreted as evidence indicating that the results of Experiment 2 of Chapter 4 were not simply a consequence of the particular bar length-to-width ratio chosen and that similar results are obtainable with at least one other bar length-to-width ratio.

6.2.3. Experiments 3,4, and 5 - Other connectivity relations.

The results of Experiment 2 of Chapter 4 showed that adaptation to either a T or disconnected bar adaptation pattern elevated

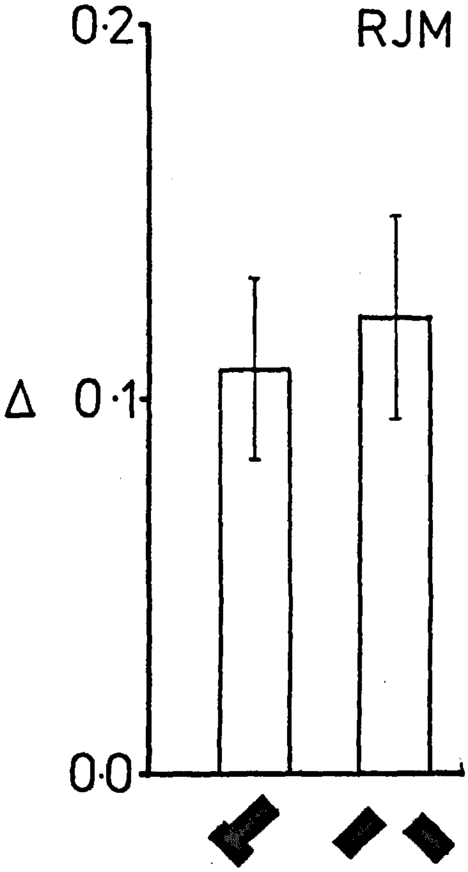


Fig. 6.4. Results of experiment 2. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

the contrast threshold of a single T test pattern by the same amount. This result was interpreted in section 1 of this chapter as an adaptational insensitivity to the relational structure of the patterns and in particular an insensitivity to "T-connectedness". Experiments 1 and 2 described in this chapter showed that the results of Experiment 2 of Chapter 4 were not a consequence of a particular choice of pattern and could be repeated with at least one other subpattern size and component bar length-to-width ratio.

All of the above experiments have used patterns in which the subpattern bars are connected together by a spatial relationship of "T-connectedness". It might be argued therefore that the interpretation that the mechanisms involved in the contrast threshold elevation effect are adaptationally insensitive to relational structure (section 6.1.) is only true for the particular relation specifying "T-connectedness". The present experiments repeat Experiment 2 of Chapter 4, in which T-shaped subpatterns were used, with patterns consisting of bar elements connected together in a spatial relationship other than "T-connectedness".

For each of the spatial relationships considered in the present experiments a control measurement using disc subpatterns is also performed. These control measurements are performed to test whether the contrast threshold elevations measured in the main part of the experiment are simply a result of some general non-shape specific adaptation (see section 5.1). For this purpose disc subpatterns with areas equal to those of the bar subpatterns they replace are used (see section 5.3.2.).

Because of the similarity of the stimuli and methods used in experiments 3,4 and 5 their description is combined in the following sections.

Stimuli.

Each of the experiments described in the present section was performed in two parts. In each part of the experiment three adaptation patterns were used.

The test pattern was the same in both parts of the experiment and consisted of bars with dimensions 20' x 3' related by some connectivity relations to form a simple figure (e.g. the T-shaped figure of Experiment 2 of Chapter 4). This test figure was superimposed on the uniform test background field of diameter 15° with four dark fixation spots (section 3.2.5.).

In the first part of each experiment the first adaptation pattern consisted of 100 copies of the test figure distributed pseudo-randomly within the 15° field (section 4.1.). The second adaptation pattern consisted of the disconnected component bars of the test figure, in equal numbers to those in the first adaptation pattern independently distributed pseudo-randomly within the 15° field (section 4.1.).

In the second part of each experiment, which acted as a control, the first adaptation pattern was the first adaptation pattern described above, that is one consisting of copies of the test figure. The second adaptation pattern consisted of a collection of discs of area equal to that of a single test figure distributed at the same positions as the subpatterns of the first adaptation pattern (section 5.1.). The third adaptation pattern in both parts of each experiment was a 15° diameter uniform field. The adaptation patterns were subjected to saccade-like displacements during adaptation periods. In each experiment the adaptation patterns and test background field were all equated to give a mean retinal illumination of 4.0 log trolands (section 3.2.6.). This luminance equating procedure also

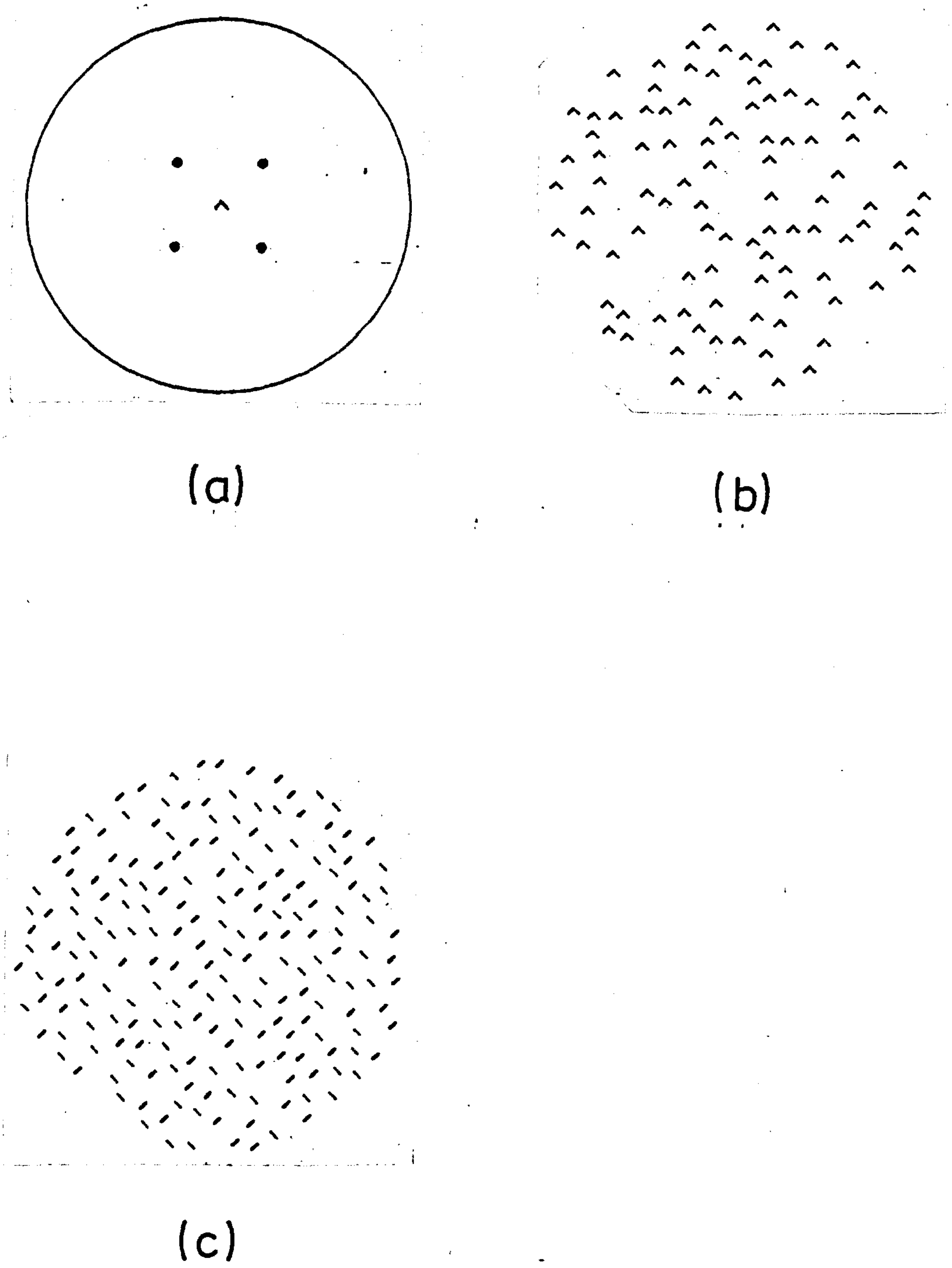


Fig. 6.5. Stimuli for experiment 3. The stimuli were brighter than their backgrounds.

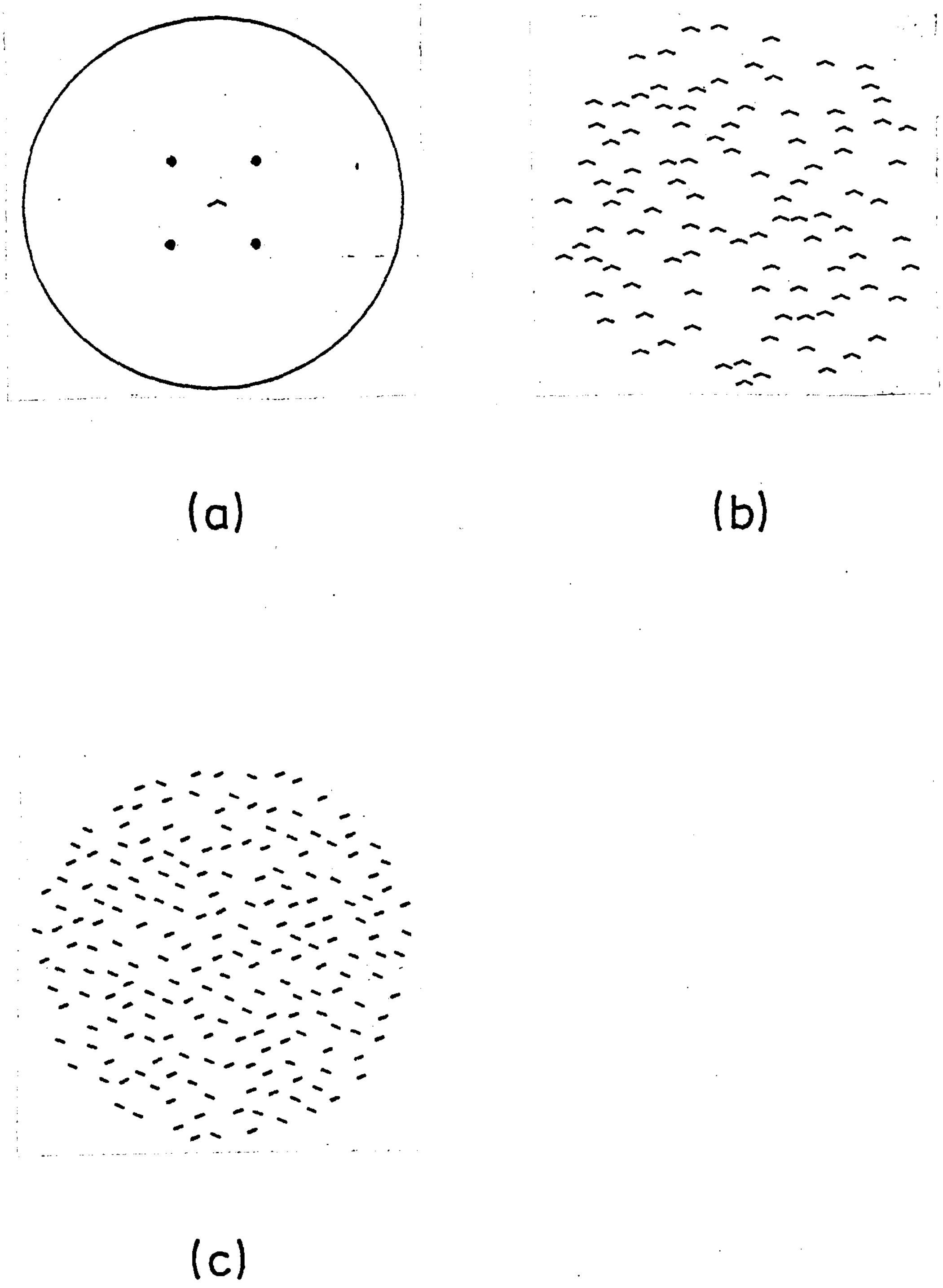
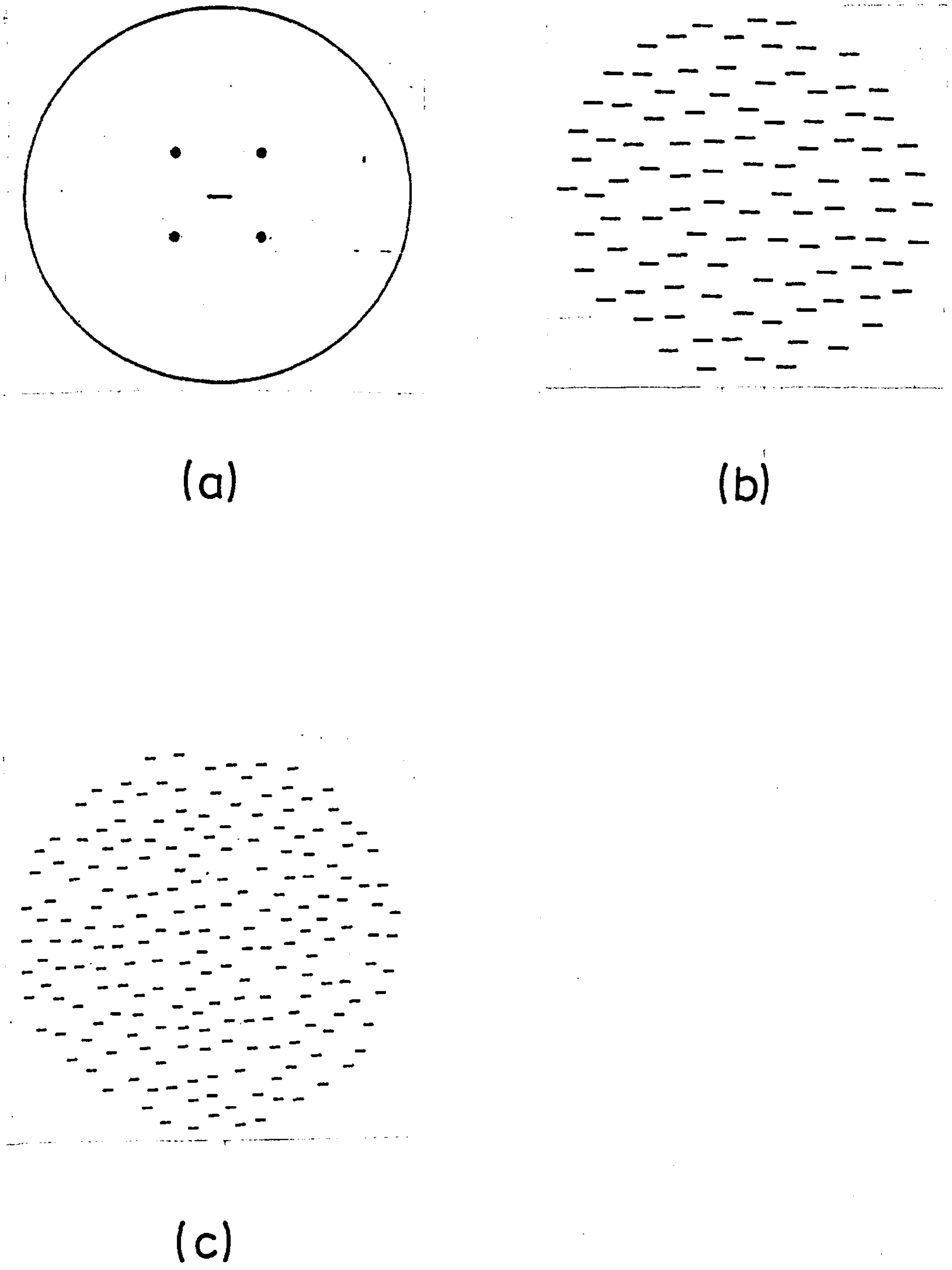


Fig. 6.6 Stimuli for experiment 4. The stimuli were brighter than their backgrounds.



(a)

(b)

(c)

Fig.6.7. Stimuli for experiment 5. The stimuli were brighter than their backgrounds.

results, because of adaptation pattern geometry, in equality of the local subpattern luminances (section 5.1.) . The only differences between Experiments 3,4 and 5 was the spatial relationship between the bar elements forming the test figure. These different spatial relationships were as follows. In Experiment 3 the test figure consisted of two orthogonal bars orientated at +45° and -45° to the vertical and connected together at the ends to form an L-shaped figure. The stimuli derived for this experiment are shown in Fig. 6.5.

In Experiment 4 the test figure consisted of two bars orientated at 67.5° and -67.5° to the vertical and connected together at the ends to form a chevron figure. The stimuli for this experiment are shown in Fig. 6.6.

In Experiment 5 the test figure consisted of two identically orientated bars connected together at their ends to form a bar of double length. The stimuli for this experiment are shown in Fig. 6.7.

Methods.

The methods used in each part of each experiment were identical. Stimuli were presented in Maxwellian view (section 3.1.2.) and contrast thresholds were obtained using the method of adjustment (section 3.3.). Timing and procedure were as described previously (section 3.3.3.)

The adaptation patterns were presented according to the experimental design for 2 treatments (section 3.4.1.).

Subjects.

Two subjects RJM and NJL participated in Experiment 3. One subject RJM participated in Experiments 4 and 5. Subject NJL was male, aged 22 years with normal colour vision and visual acuity. Further details of subject RJM are given in section 4.1.

Results.

Figs. 6.8, 6.9 and 6.10 show the results of Experiments 3, 4 and 5 respectively. The ordinate in each case represents the contrast threshold elevation Δ (section 3.3.2.) of the single test pattern after adaptation. On the abscissa a typical subpattern element of the adaptation pattern is shown.

Each set of axes represents the results obtained with the two adaptation patterns indicated by the typical elements on the abscissa. The error bars represent ±1 SEM.

In Experiment 3, the contrast threshold elevation of the L-shaped test pattern (typically 0.2. log units) after adaptation to the L adaptation pattern is not significantly greater than after adaptation to the disconnected bar pattern for both subjects ($t \leqslant 1.30, df=22, P > 0.1$). The contrast threshold elevation of the L-shaped test pattern after adaptation to the disc adaptation pattern is significantly less than that obtained after adaptation to the L-adaptation pattern for both subjects ($t > 2.49, df=22, P < 0.05$). The contrast threshold elevations of the L-shaped test pattern are highly significantly greater than zero in all cases ($t > 9.38, df=11, P < 0.001$).

In Experiment 4, the contrast threshold elevation of the chevron test pattern (typically 0.2 log units) after adaptation to the chevron adaptation pattern is not significantly greater than after adaptation to the disconnected bar pattern ($t=-0.33, df=22, P > 0.5$). The contrast threshold elevation of the chevron test pattern after adaptation to the disc adaptation pattern is significantly less than that obtained after adaptation to the chevron adaptation pattern ($t=2.72, df=22, P < 0.01$). The contrast threshold elevations of the chevron test pattern are highly significantly greater than zero in all cases ($t > 5.33, df=11, P < 0.001$).

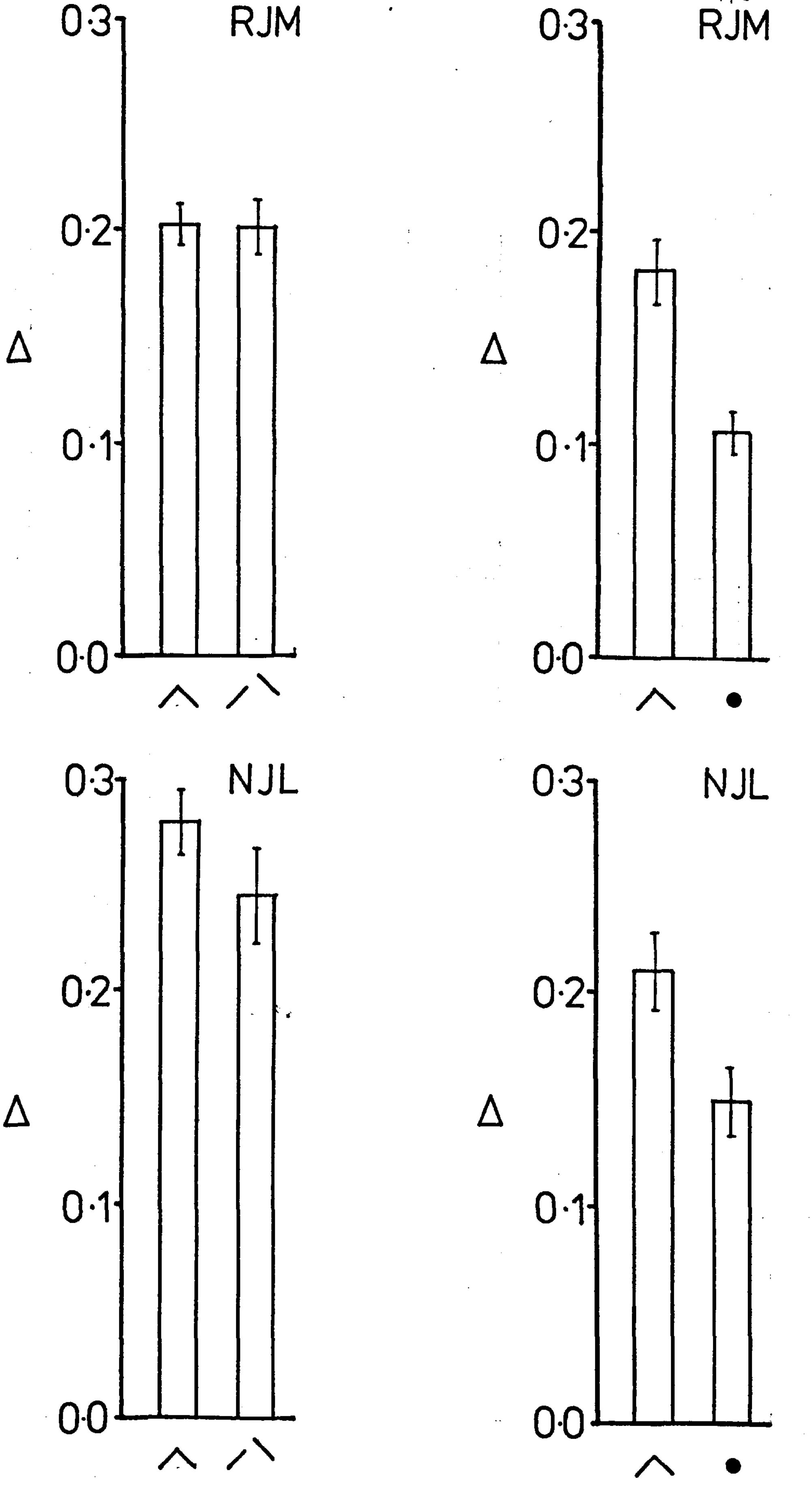


Fig. 6.8. Results of experiment 3. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

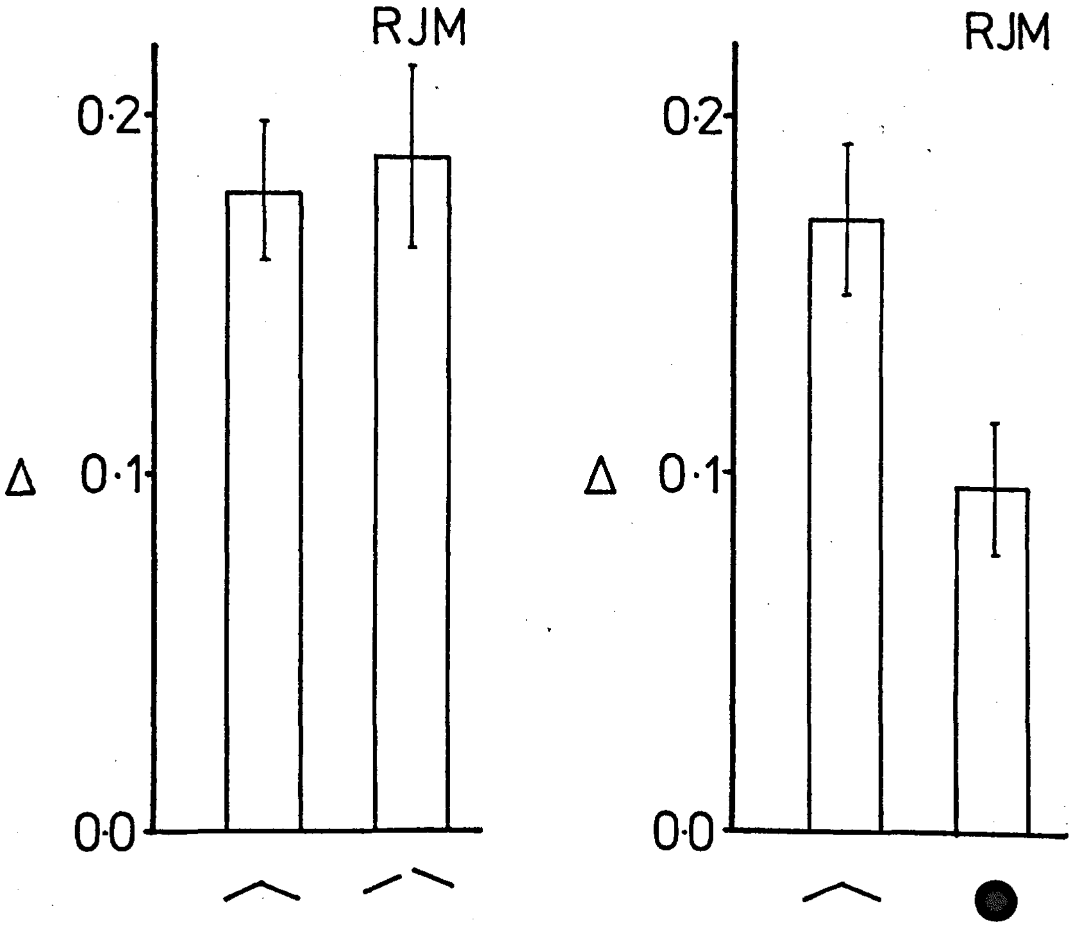


Fig. 6.9. Results of experiment 4. Contrast threshold elevation Δ in log units plotted against adaptation type (indicated by a typical subpattern below the abscissa).

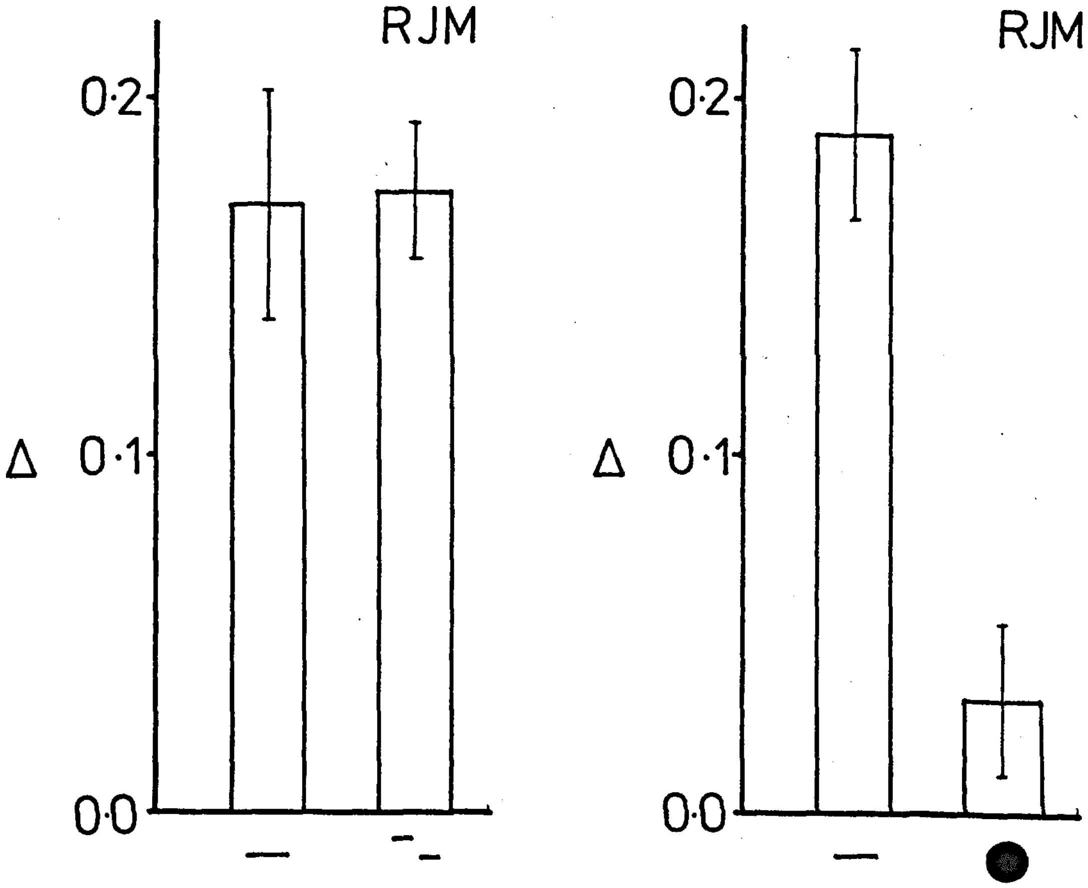


Fig. 6.10 Results of experiment 5. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

In Experiment 5, the contrast threshold elevation of the long bar test pattern (typically 0.2. log units) after adaptation to the long bar adaptation pattern is not significantly greater than after adaptation to the disconnected short bar adaptation pattern ($t=-0.10, df=22, P > 0.5$). The contrast threshold elevation of the long bar test pattern after adaptation to the disc adaptation pattern is significantly less than that obtained after adaptation to the long bar adaptation pattern ($t=5.00, df=22, P < 0.001$). The contrast threshold elevation of the long bar test pattern after adaptation to the long bar and disconnected short bar adaptation patterns are highly significantly greater than zero ($t \geqslant 5.31, df=11, P < 0.001$). After adaptation to the disc adaptation pattern, however, the contrast threshold elevation of the long bar test pattern only approaches significance ($t=1.52, df=11, P < 0.1$).

Discussion.

The patterns used in these experiments might be interpreted in terms of structural theories of pattern recognition (section 1.2.2.) in the same way as the T-shaped patterns of Experiment 2 of Chapter 4 were interpreted in section 1 of this chapter. In these structural terms the patterns of Experiments 3,4, and 5 may be represented by their bar features and the relations specifying the spatial relationships between these bar features. Table II shows such a representation of these stimuli.

In each of the first two experiments the features comprising both the adaptation pattern formed from copies of the test pattern and the disconnected bar adaptation pattern are identical to those of the test pattern. If the mechanism detecting the test pattern was adaptationally sensitive to features and relations, adapting to the pattern with subpatterns identical to the test pattern should give rise to a greater

TABLE II

	Stimulus	Features	Relations
Experiment 3	Single ∧ test	/ , \	Connected at end
	∧ adaptation	/ , \	Random,connected at end
	Disconnected / \ adaptation	/ , \	Random
	Spot adaptation	●	Random
Experiment 4	Single ^ test	⁄ , ⟍	Connected at end
	^ adaptation	⁄ , ⟍	Random,connected at end
	Disconnected ⁄ ⟍ adaptation	⁄ , ⟍	Random
	Spot adaptation	●	Random
Experiment 5	Single — test	- (or —)	Concatenated(or none)
	Long — adaptation	- (or —)	Random,Concatenated(or nor
	Disconnected short ‐ ‐ adaptation	-	Random
	Spot adaptation	●	Random

contrast threshold elevation of the test pattern than adapting to the disconnected bar pattern. This effect is not observed, however, in the results of both of these experiments. That is, no significant difference in test contrast threshold elevation is shown between adaptation to a pattern formed from subpatterns identical to the test pattern and adaptation to disconnected bar patterns. These results agree with those from the previous experiments (Experiment 2 of Chapter 4 and experiments 1 and 2 here) with T-shaped patterns. It appears therefore that the mechanisms detecting the test pattern in

TABLE II

	Stimulus	Features	Relations
	Single ∧ test	/ , \	Connected at end
periment 3	∧ adaptation	/ , \	Random, connected at end
	Disconnected / \ adaptation	/ , \	Random
	Spot adaptation	●	Random
	Single ^ test	/ , \	Connected at end
periment 4	^ adaptation	/ , \	Random, connected at end
	Disconnected / \ adaptation	/ , \	Random
	Spot adaptation	●	Random
	Single — test	- (or —)	Concatenated(or none)
periment 5	Long — adaptation	- (or —)	Random, Concatenated(or none)
	Disconnected short - - adaptation	-	Random
	Spot adaptation	●	Random

contrast threshold elevation of the test pattern than adapting to the disconnected bar pattern. This effect is not observed, however, in the results of both of these experiments. That is, no significant difference in test contrast threshold elevation is shown between adaptation to a pattern formed from subpatterns identical to the test pattern and adaptation to disconnected bar patterns. These results agree with those from the previous experiments (Experiment 2 of Chapter 4 and experiments 1 and 2 here) with T-shaped patterns. It appears therefore that the mechanisms detecting the test pattern in

TABLE II

	Stimulus	Features	Relations
Experiment 3	Single ∧ test	/, \	Connected at end
	∧ adaptation	/, \	Random,connected at end
	Disconnected / \ adaptation	/, \	Random
	Spot adaptation	●	Random
Experiment 4	Single ∧ test	/, \	Connected at end
	∧ adaptation	/, \	Random,connected at end
	Disconnected / \ adaptation	/, \	Random
	Spot adaptation	●	Random
Experiment 5	Single — test	- (or —)	Concatenated(or none)
	Long — adaptation	- (or —)	Random,Concatenated(or none
	Disconnected short - - adaptation	-	Random
	Spot adaptation	●	Random

contrast threshold elevation of the test pattern than adapting to the disconnected bar pattern. This effect is not observed, however, in the results of both of these experiments. That is, no significant difference in test contrast threshold elevation is shown between adaptation to a pattern formed from subpatterns identical to the test pattern and adaptation to disconnected bar patterns. These results agree with those from the previous experiments (Experiment 2 of Chapter 4 and experiments 1 and 2 here) with T-shaped patterns. It appears therefore that the mechanisms detecting the test pattern in

TABLE II

	Stimulus	Features	Relations
Experiment 3	Single ∧ test	/, \	Connected at end
	∧ adaptation	/, \	Random,connected at end
	Disconnected / \ adaptation	/, \	Random
	Spot adaptation	●	Random
Experiment 4	Single ︿ test	⟋, ⟍	Connected at end
	︿ adaptation	⟋, ⟍	Random,connected at end
	Disconnected ⟋ ⟍ adaptation	⟋, ⟍	Random
	Spot adaptation	●	Random
Experiment 5	Single — test	- (or —)	Concatenated(or none)
	Long — adaptation	- (or —)	Random,Concatenated(or none
	Disconnected short - - adaptation	-	Random
	Spot adaptation	●	Random

contrast threshold elevation of the test pattern than adapting to the disconnected bar pattern. This effect is not observed, however, in the results of both of these experiments. That is, no significant difference in test contrast threshold elevation is shown between adaptation to a pattern formed from subpatterns identical to the test pattern and adaptation to disconnected bar patterns. These results agree with those from the previous experiments (Experiment 2 of Chapter 4 and experiments 1 and 2 here) with T-shaped patterns. It appears therefore that the mechanisms detecting the test pattern in

each of these experiments is not adaptationally sensitive to the spatial relationships between the bar features.

It might be suggested that the contrast threshold elevations observed here are the results of some non-specific adaptation to any spatially non-uniform patterns of the same mean luminance (see section 5.1.). The disc adaptation patterns used in the second halves of these experiments were spatially non-uniform patterns with the same mean pattern luminance, global structure and local luminance as the adaptation pattern consisting of copies of the test pattern (see section 5.3.2.). If the contrast threshold elevations in the present experiments were a result of some non-specific adaptation as suggested above then we might expect the contrast threshold elevation of the test figure after adaptation to the disc adaptation pattern to be the same as the contrast threshold elevation after adaptation to the other adaptation patterns.

The significant difference between the contrast threshold elevation observed after adaptation to the pattern formed from copies of the test pattern and the contrast threshold elevation observed after adaptation to the disc pattern in all the present experiments make the above suggestion unlikely (see section 5.1.)

The results of Experiment 5 may appear counterintuitive, for if the test pattern is considered as a single bar it would appear that adaptation to bars of the same length and adaptation to bars of half the length of the test bar give rise to the same test contrast threshold elevation. This result is inconsistent with the findings of Nakayama and Roberts (1972) who found that the contrast threshold elevation measured with grating patterns is selective for the length of the bars of the gratings.

One explanation of the present results may be found in the length selectivity experiments of Chapter 5 (experiment 3). It was observed in these length selectivity experiments that the ratio of bar length to bar width was decisive in determining the presence, or lack, of length selectivity in the contrast threshold elevation effect. The test bar in the present experiment has a length-to-width ratio of 13.3 which is greater than any of those used in Experiment 3 of Chapter 5. Burton and Ruddock (1978) found no length selectivity for test patterns containing bars with length-to-width ratios greater than about 3.0. Although the results in Chapter 5 using the present adaptation technique do not entirely agree with the results of Burton and Ruddock it is possible that the present test bar pattern does not show length selectivity. If this is the case then the results obtained would support this proposition and give support to the notion on non-length selective mechanisms as proposed by Burton and Ruddock (see section 5.3.1.).

An alternative explanation of the non-length selective adaptation observed in the present experiment, taking into account the results of Experiments 3 and 4, might be as follows.

The mechanism detecting the test pattern might be adaptationally sensitive to the short bar features and, as in Experiments 3 and 4, not adaptationally sensitive to their spatial relationship, i.e. concatenation. In this case the results obtained by Burton and Ruddock (1978) might be explained as follows. If the mechanisms involved in the contrast threshold elevation effect are adaptationally sensitive for bars up to a critical length-to-width ratio of three, then the detection of bars with a greater length-to-width ratio might be based upon some more central process sensitive to the concatenation of these short bars. In this way the supposedly more peripheral processes involved in adaptation would only show length selectivity for bars of length-to-width ratios less than three.

In conclusion it may be said that the results of the present experiments indicate that, in agreement with the suggestions of section 1, the visual system is not adaptationally sensitive to the spatial relationships between local pattern features, in particular to those spatial relationships specified by relations involving connectivity. The results of the control experiments using discs show that this lack of adaptational sensitivity to spatial relationships is not simply a result of a general contrast threshold elevating effect of any spatially non-uniform adaptation pattern.

6.3. Conclusions.

In the present chapter it has been argued that the visual system is not adaptationally sensitive to local position information, in particular that information specifying the way in which bar elements are connected to each other to form simple figures. It has been shown that this conclusion may be interpreted in terms of structural theories of pattern recognition as an adaptational insensitivity to relational structure or equivalently relative spatial phase.

This conclusion has been shown to contrast with that from some texture discrimination experiments and it has been suggested that these two experimental techniques (adaptation and texture discrimination) may investigate different aspects of the pattern vision process.

6.4. Appendix.

For a bar of dimensions p and q in the x and y spatial directions (using the usual Cartesian co-ordinates) the Fourier transform is,

$$g(k_x,k_y) = pq \operatorname{sinc} \pi pk_x . \operatorname{sinc} \pi qk_y \qquad 6.1$$

Where k_x, k_y are the spatial frequencies in the x and y directions. Now if the bar is shifted by a displacement denoted by the vector (a,b) from the origin of the Cartesian axes, the new Fourier transform $g'(k_x,k_y)$ of the bar is given by the shifting theorem (Goodyear, 1971) as,

$$g'(k_x,k_y) = g(k_x,k_y)e^{-2\pi i (k_x a + k_y b)} \qquad 6.2$$

Now these bar Fourier transforms may be combined in two main ways, that is either phase-sensitive or phase-insensitive (see section 6.1.). If $g_1(k_x,k_y)$ is the Fourier transform of one of the two bar features forming the T- and disconnected bar patterns and $g_2(k_x,k_y)$ is the Fourier transform of the other orthogonal bar then a phase-sensitive transform is of the form,

$$g_P(k_x,k_y) = \sqrt{\left| g_1'(k_x,k_y) + g_2'(k_x,k_y) \right|^2}$$

and a phase-insensitive transform is of the form,

$$g_I(k_x,k_y) = \sqrt{\left| g_1'(k_x,k_y) \right|^2 + \left| g_2'(k_x,k_y) \right|^2}$$

The important properties of these two types of transform are that the phase-sensitive transform $g_P(k_x,k_y)$ changes with variations in the distance between the bars forming the patterns but $g_I(k_x,k_y)$ is constant with variations in bar separations.

This conclusion follows from the fact that,

$$\left| g'(k_x,k_y) \right| = \left| g(k_x,k_y).e^{-2\pi i(k_x a+k_x b)} \right| \quad \text{(see equation 6.2)}$$

$$\therefore \quad g'(k_x,k_y) = g(k_x,k_y)$$

Thus in a phase-insensitive transform the relative phase information specifying the bar position, that is the term $e^{-2\pi i\ (k_x a+k_y b)}$ in equation 6.2, is not utilized. In contrast, this relative phase information is used in a phase-sensitive transform.

CHAPTER 7. - EXPERIMENTS ON CURVATURE.

Introduction.

Gibson (1933) reported an apparent curvature of a suprathreshold straight line after prolonged viewing of a curved line. The apparent curvature of the straight line was in the opposite sense to that of the inducing curve. Blakemore and Over (1974) reported that this curvature aftereffect could not be induced when the observer scanned along a chord of the curves forming grating pattern but either fixation of the grating or scanning perpendicular to a chord did produce this effect. Riggs (1973, 1974) obtained curvature-specific colour aftereffects which he attributed to selective adaptation of detectors differentially sensitive to wavelength and direction of curvature. He concluded (Riggs, 1973) that these aftereffects could not be accounted for solely on the basis of input from simpler orientation-selective sub-units. This conclusion has attracted some criticism for the aftereffects induced by arcs transfer to straight lines and vice versa (Crassini and Over, 1975). Also no curvature-specific colour aftereffect occurs if the observer scans along the chord of the arcs during adaptation (MacKay and MacKay, 1974; Sigel and Nachmias, 1975).

Blakemore and Over (1974) suggest that the curvature aftereffect may be due to localised adaptation of straight-edge "detectors". Eye movements along the chord of an arc would, therefore, expose the fovea to orientation information with opposite directions and nullify the aftereffect. In contrast, scanning perpendicular to the chord, or steady fixation, provides consistent orientation information and gives rise to the curvature aftereffect.

The studies mentioned above have discussed the detection of curves by either curvature selective mechanisms or mechanisms selectively sensitive to appropriately orientated bar elements. All of these studies have been unable to distinguish between the processing of curves by curvature sensitive mechanisms and the processing of curves in terms of appropriately orientated bar elements.

As an alternative to the use of suprathreshold measurements of induced curvature or curvature-contingent colour effects the contrast threshold elevation effect may be used to investigate the existence of curvature selective mechanisms.

In one such study Timney and Macdonald (1978) investigated the question of curvature selectivity versus orientation selectivity using both a threshold elevation technique and a masking technique. They measured the contrast thresholds of their grating patterns in terms of a critical test pattern duration thus relying on temporal summation to equate test contrast to test duration. These authors reported maximum threshold elevation for the curved test gratings with curvatures close to that of the adaptation grating curvature. They also found that the functions for masking and threshold elevation are very similar. The findings that larger adapting curvatures show a broader spread of test threshold elevations led these authors to conclude that the detection of curvature is in terms of its tangential orientations. However, after further experiments using tilted linear gratings and curved gratings they conclude that their experiments "...do not provide a full answer to whether curves are processed by curvature detectors or by linear-contour detectors which respond to the tangents of curves". Naghshineh (1977) used grating patterns consisting of curves, connected line segments and elliptical segments in measurements of the contrast threshold elevation effects for various combinations of these patterns. The contrast of the test grating was controlled directly, by the method of adjustment, and the test duration was fixed. For a test grating of fixed curvature, Naghshineh (1977) found maximum contrast threshold elevation to occur after adaptation to curvatures similar to that of the test. He also reported that adaptation curves consisting of two or more connected bars tangential to the test curve were each as effective in producing contrast threshold elevation of the test stimulus as a continuous curve identical to the test. He concluded that tuning to curvature exists but may be due to the activity of mechanisms tuned to straight line elements.

The above measurements of the curvature aftereffect and contrast threshold elevation effect were unable to distinguish between whether curves were detected by curvature sensitive mechanisms or by mechanisms sensitive to appropriately orientated bar elements. The stimuli used in these previous studies were either curves of different curvatures, curves composed of bar elements or bar elements of one orientation. The adaptation technique developed in previous chapters, however, allows a direct comparison to be made of the contrast threshold elevation produced by a "curved" pattern with that produced by the bar elements forming the "curved" pattern. The basis of such a measurement is as follows. A curved line may be considered as the head to tail concatenation of line segments of various orientations. In a structural theory of pattern recognition (section 1.2.2.) such a curved line could be described as several bar features of various orientations related to each other by relations specifying head to tail concatenation. If a curve is regarded in this way it is necessary to determine how many line segments are necessary for a curve composed of line segments to behave in the same manner as a continuous curve. In an adaptation paradigm, Naghshineh (1977) found that two or more concatenated line segments gave threshold elevations of a test curve equal to those of a continuous curve. Pomerantz (1978) has suggested that angle detection processes between pairs of line elements may exist in the visual system (see also Foster, 1980b).

In view of the possible existence of such angle detection processes between pairs of lines, "curves" formed from three bar elements were used in the present experiment.

To test the hypothesis that curves are detected as tangential line elements rather than curves the contrast threshold elevation of a single test "curve" formed from three bar elements was determined after adaptation to either copies of the test "curve" or the disconnected bar elements of the "curve" (see Fig. 7.1 a,b,c). The distinguishing feature between the two adaptation patterns was thus the existence in one pattern of spatial relationships specified by the relation defining curvature. It might be supposed, therefore, that if the mechanism detecting the "curve" test pattern is adaptationally sensitive to the relationship of curvature the "curve" adaptation pattern should give a greater contrast threshold elevation than the disconnected bar element pattern. Alternatively, if the detecting mechanism is only adaptationally sensitive to the bar elements composing the "curve" test pattern, both adaptation patterns should give rise to the same contrast threshold elevation.

As in previous experiments (e.g. section 5.1.) the contrast threshold elevation of the test pattern was determined after adaptation to an adaptation pattern consisting of discs each of an equal to that of the "curve" test figure. This control measurement was made, as before (section 5.3.2.), to check that the contrast threshold elevations observed with the "curve" and disconnected bar adaptation patterns were not a consequence of some general adaptation to spatial non-uniformity.

Stimuli.

The test pattern consisted of three bar-elements of dimensions 13.3' x 3' at angles of 22.5°, 0°, and -22.5° to the horizontal and connected to form a "curve" shape. This "curve" was centred in a

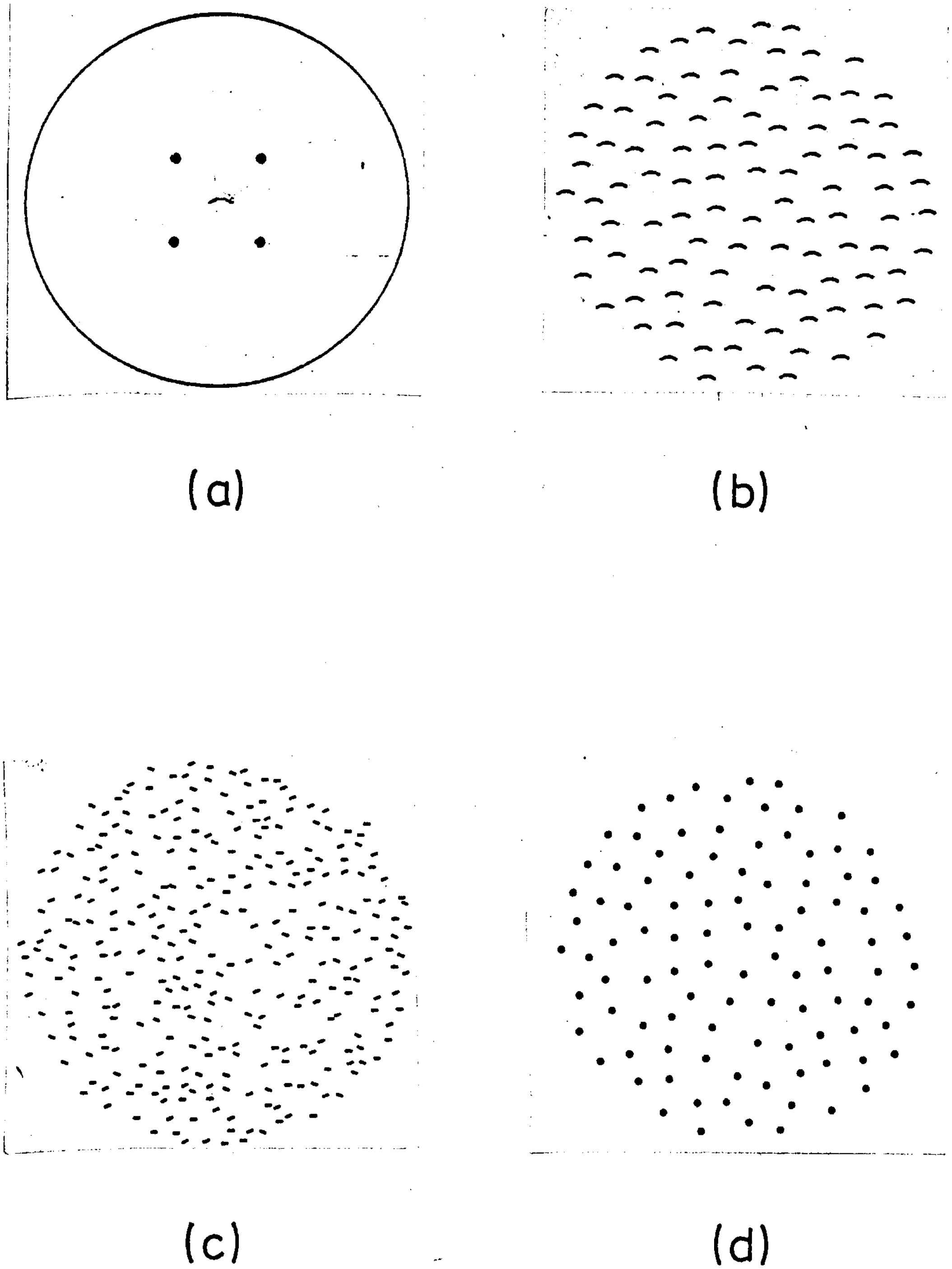


Fig. 7.1. Stimuli. The stimuli were brighter than their backgrounds.

15° diameter uniform test field. Four dark fixation spots were used as before (section 3.2.5.).

Three adaptation patterns were used in the main part of the experiment as follows. The first, "curve" adaptation pattern consisted of 100 copies of the test "curve" figure distributed pseudo-randomly with a 15° field. The second, disconnected bar adaptation pattern consisted of the 300 bar elements of the "curve" adaptation pattern individually distributed within the 15° field. The third adaptation pattern was a 15° diameter uniform field. Fig 7.1a shows the test pattern, Fig.7.1b the "curve" adaptation pattern, Fig 7.1c the disconnected bar adaptation pattern.

For the control part of the experiment the three adaptation patterns were as follows. First, the "curve" adaptation pattern of Fig 7.1b. Second, the disc adaptation shown in Fig 7.1d formed by replacing each of the "curves" if Fig 7.1b by a disc with an area equal to that of one "curve" figure. The third adaptation pattern was a 15° diameter uniform field.

The adaptation patterns and test background field were all equated for a mean retinal illumination of 4.0 log trolands.

During the adaptation period the adaptation stimuli were subjected to vertical saccade-like displacements as described previously (section 4.5.). Note that this saccade-like motion is perpendicular to the chord of the "curves" in the test and adaptation patterns (see introduction to this chapter).

Methods.

The stimuli were presented in Maxwellian view (section 3.1.2) and contrast thresholds were determined using the method of adjustment (section 3.3.). Timing of test and adaptation periods was as described in section 3.3.3. In the main part of the experiment the "curve", disconnected bar and uniform adaptation patterns were presented according to a sequentially balanced order as described previously (section 3.4.1.). This experimental design resulted in a total of four runs. Note that subject IEB only completed the first three runs.

The control part of the experiment followed an identical methodology to the main part of the experiment except the three adaptation patterns comprised the "curve", the disc and the uniform field adaptation patterns.

Subjects.

Two subjects IEB and RJM participated in the main part of the experiment. RJM participated in the control experiment. Both subjects were male, aged 24 years and had normal colour vision and corrected-to-normal visual acuity.

Results.

The results from this experiment are shown in Fig 7.2. Each set of axes represents the results from one part of the experiment and one observer. The contrast threshold elevation of the "curve" test pattern Δ (section 3.3.2.) is indicated on the ordinate. The adaptation pattern used to obtain a particular contrast threshold elevation is indicated by a representative element below the abscissas. The error bars represent ± 1 SEM.

Fig 7.2a shows the results from the main experiment using the "curve" and disconnected bar adaptation patterns. For both subjects the contrast threshold elevation of the "curve" test pattern (typically 0.2 to 0.3 log units) is not significantly greater after adaptation to the "curve" adaptation pattern than after adaptation to the disconnected bar adaptation pattern (RJM; $t=-1.63, df=22, P>0.5$; IEB; $t=1.23, df=16, P>0.1$)

Fig 7.2b shows the results from the control experiment on subject RJM. Adaptation to the connected "curve" adaptation pattern

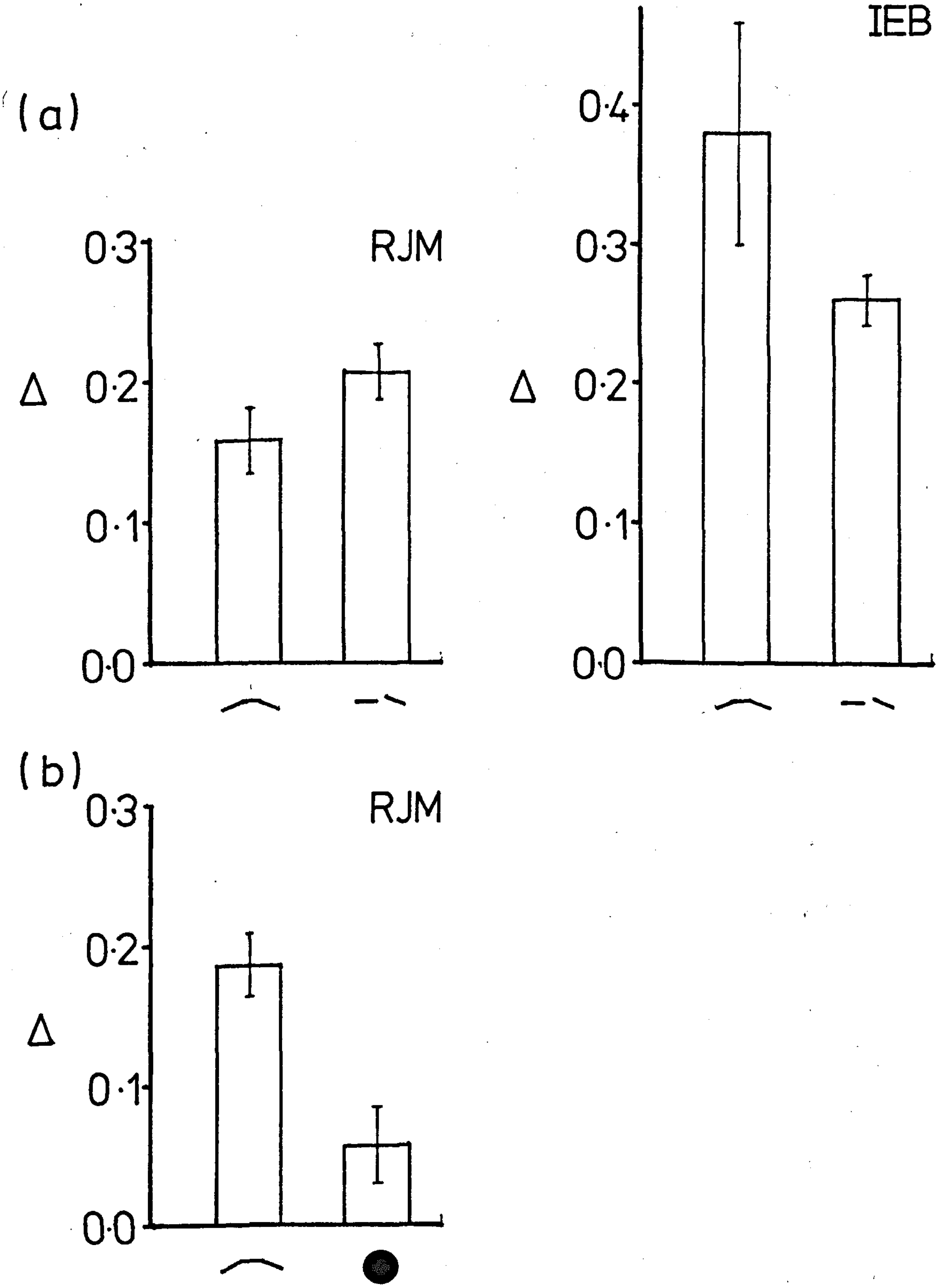


Fig. 7.2. Results. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

gave a highly significantly greater contrast threshold elevation of the "curve" test pattern than adaptation to the disc adaptation pattern ($t=3.78, df=22, P<0.001$). The magnitude of the contrast threshold elevation after adaptation to the "curve" pattern was 0.19 log units compared with a contrast threshold elevation of 0.06 log units after adaptation to the disc pattern.

Discussion.

Adaptation to a pattern consisting of bar elements connected to form curve-shaped figures is no more effective in elevating the contrast threshold of a similar curved figure than adaptation to the individual bar elements comprising the curve-shaped figure. This result is consistent with the hypothesis that the mechanism detecting the curved figure is adaptationally sensitive to the component bars but is not adaptationally sensitive to their connection to form a curved-shaped figure.

This result is also consistent with the previous adaptation studies of Timney and Macdonald (1978) and Naghshineh (1977) who concluded that curves may be detected in terms of appropriately orientated bar elements. These authors were unable to distinguish between the possibility that curves were detected by either curvature sensitive mechanisms or mechanisms sensitive to the appropriately orientated bar elements. This inability to decide between these two possibilities was possibly a result of the patterns used in these studies. For, in each of these studies the effects (either adaptational or masking) of "curved" patterns on "curved" patterns were measured and the selectivity of the mechanisms was inferred from "bandwidths" of curvature tuning curves. In the present experiment, however, the patterns used allow the effects of adaptation to "curves" and adaptation to the appropriately orientated bar elements to be directly measured. The lack of adaptational sensitivity to the spatial relationships defining curvature shown in the present experiment indicates that the existence of mechanisms which are adaptationally sensitive to curvature is unlikely.

The results of the control part of the experiment indicate that the contrast thresholds measured in the main part of the experiment are not simply a result of some general adaptation to spatially non-uniform patterns (section 5.1.). For, the disc adaptation pattern only differed from the "curve" adaptation pattern in the shape of the local subpattern (section 5.3.2.) thus the differences observed between the contrast threshold elevations produced by these two adaptation patterns might be attributed to the local properties of the subpatterns and not to general properties of the whole pattern. The lack of a difference between the contrast threshold elevations of the "curve" test figure after adaptation to the "curve" and the disconnected bar adaptation patterns cannot therefore be attributed to a general adaptation effect as suggested above.

If these results are considered in terms of a structural theory of pattern recognition (section 1.2.2.) the properties of the mechanism detecting the curved test might be summarised as follows. The detecting mechanism exhibits adaptational sensitivity to the bar element features comprising the curve but it is adaptationally insensitive to their joining together in spatial relationships specified by a connectivity relation defining curvature. This conclusion is consistent with the results of Chapter 6 which indicated a lack of adaptational sensitivity to other spatial relationships specified by simple connectivity relations.

It should be stressed that the present results only indicate a lack of adaptational sensitivity to curvature and other visual tasks may reveal sensitivity to curvature.

CHAPTER 8. EXPERIMENTS ON PERIODICITY.

Introduction.

As mentioned in Chapter 1 there have been many studies of the contrast threshold elevation of spatially periodic patterns caused by adaptation to similar spatially periodic patterns. A summary of the findings of these studies is given in the following paragraph (for a more detailed review see section 1.4.).

The contrast threshold elevation effect was first described by Gilinsky (1968), further investigated by Blakemore and Campbell (1968, 1969), and Pantle and Sekuler (1968). These workers found that the threshold contrast of a grating pattern was increased after adaptation to a similar grating pattern. This contrast threshold elevation effect was maximum when the test and adaptation gratings had the same orientations and spatial periodicities (or bar widths). Other investigators have demonstrated that the important parameters of the adaptation and test patterns are the widths of the bright portions of the gratings, the dark portions having little effect on the contrast threshold elevation obtained (Naghshineh and Ruddock, 1978).

Common to all these studies was the use of stimuli consisting of a field completely filled with a spatially periodic pattern.

It is of interest to examine whether this adaptational sensitivity of the visual system to periodic patterns requires the whole stimulus field to be spatially periodic as in the above studies. In particular, can the grating patterns common to these previous studies be modified for use in the present adaptation technique to investigate adaptational sensitivity to localized spatial periodicities?

If the contrast threshold of a small spatially periodic test pattern can be elevated by adaptation to a pattern having local spatial periodicity and this contrast threshold elevation can be shown to be due to the periodicity of the patterns, then we might infer the following. The mechanism detecting the test pattern would, in the above circumstances, be adaptationally sensitive to local periodicity. Such an adaptational sensitivity to local spatial periodicity would show that it is not necessary to have the test and adaptation patterns each consisting of a single periodic pattern as used in the studies discussed above. Adaptational sensitivity to local spatial periodicity would also be consistent with the patch-by-patch Fourier analysis theory of pattern analysis suggested by Robson (1975) (but see also sections 1.5.1. to 1.5.3.). This sensitivity to local spatial periodicity might be interpreted in terms of structural theories of pattern recognition (section 1.2.2.) as a sensitivity to the relational structure defining repetitiveness or periodicity within a pattern.

To investigate these questions the following experiments were performed.

Stimuli.

The stimuli used in this experiment are illustrated in Fig 8.1.

The test pattern of Fig. 8.1a consisted of a single grating comprising five 20' x 3' bars arranged with a mark/space ratio of 1.0. This grating was superimposed at the centre of a 15° diameter uniform field and four dark fixation spots were provided as before (section 3.2.5.).

Three adaptation patterns were used. The first consisted of 40 copies of the small test grating distributed pseudo-randomly within a 15° diameter field (Fig. 8.1b). The second consisted of the 200 bar elements of the grating adaptation pattern individually distributed pseudo-randomly within the 15° diameter field (Fig.8.1c). The first grating adaptation pattern provided the local spatial periodicity discussed in the introduction whilst the second, disconnected bar pattern contained, on average over the visual field, no such local spatial periodicity. The third adaptation pattern was a 15° diameter

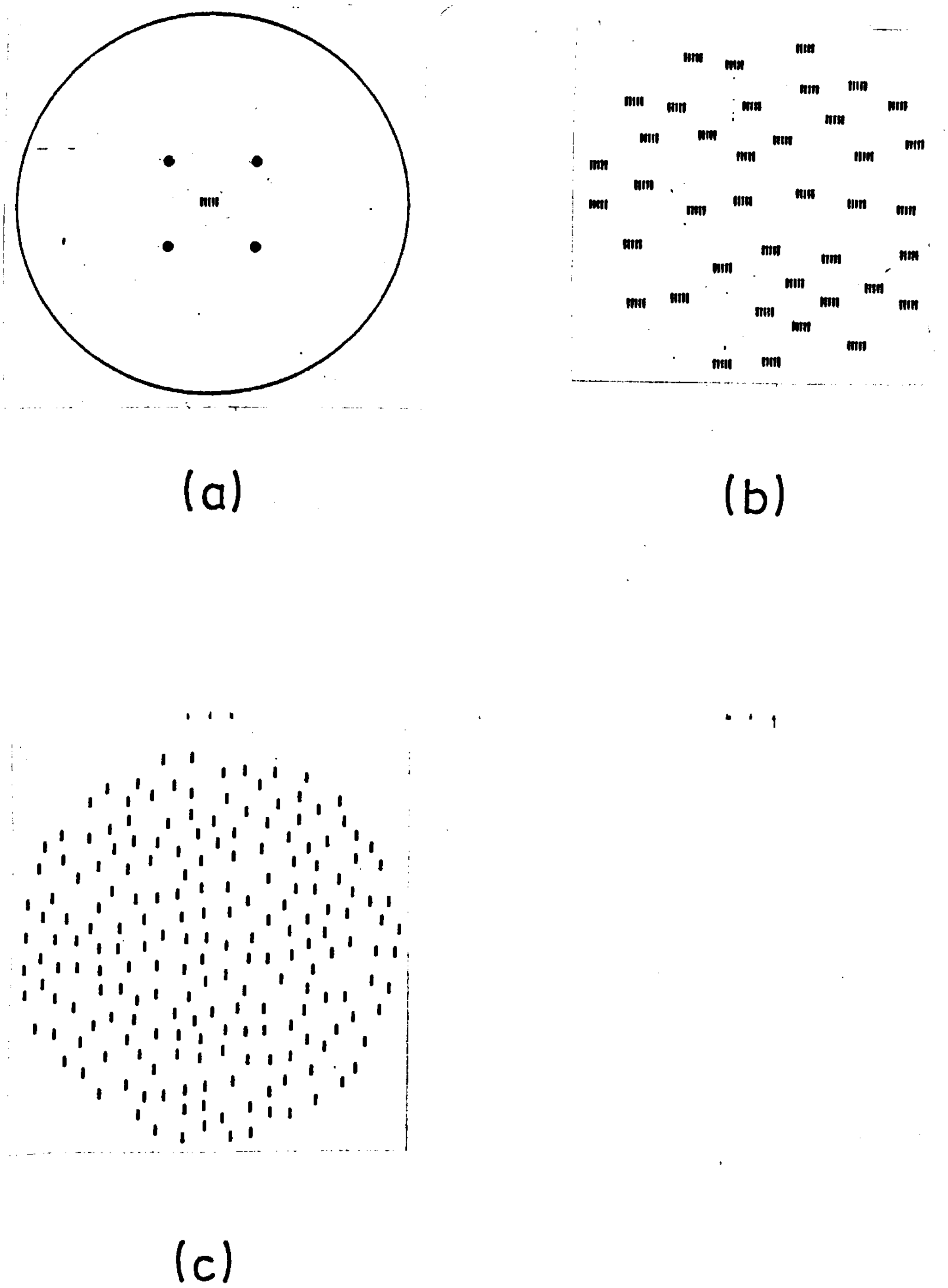


Fig. 8.1. Stimuli. The stimuli were brighter than their backgrounds.

uniform field. During the adaptation period the adaptation patterns were subjected to small saccade-like displacements in a vertical direction (section 4.5.). The orientation of the long dimension of the bars in each of the patterns was the same. This orientation was either vertical or horizontal in each part of the experiment (see below).

The adaptation pattern and test background field were all equated to give an equal mean retinal illumination of 4.0 log trolands (section 2.2.6.).

Methods.

The stimuli were presented in Maxwellian view (section 3.1.2.) and contrast thresholds were determined by the method of adjustment (section 3.3.). The timing of test and adaptation periods was as described in section 3.3.3.

The experiment was divided into two parts. In the one, the orientation of the long dimension of the pattern bars was vertical and therefore parallel to the saccade-like displacements. In the other the orientation of the pattern bars was horizontal and therefore orthogonal to the saccade-like displacements. In this way interaction effects between the saccade-like displacements and any contrast threshold changes may be analysed.

Each part of the experiment consisted of four runs during which the adaptation patterns were presented according to the sequentially balanced design described in section 3.4.1.

Subjects.

One subject RJM participated in this experiment. For further subject details see section 4.1.

Results.

The results for the first part of the experiment where the saccade-like displacements were parallel to the long dimension of the

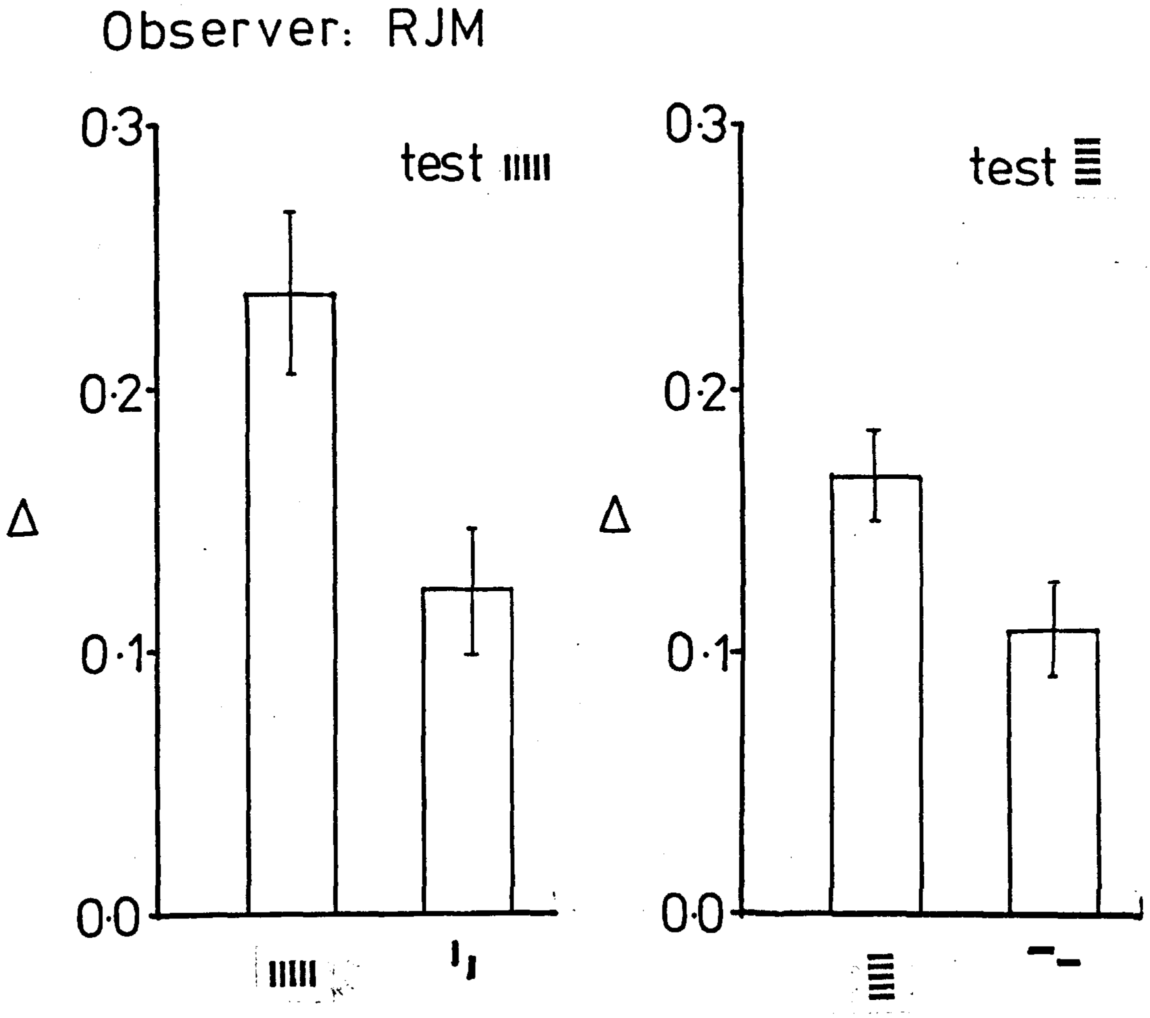


Fig. 8.2. Results. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

bar elements are shown in Fig 8.2a. Elevation of test contrast threshold Δ (section 3.3.2.) is shown on the ordinate and the adaptation pattern type is identified by a typical pattern element on the abscissa. The error bars represent ±1 SEM.

The results for the second part of the experiment where the saccade-like displacements were orthogonal to the long dimension of the bar elements are shown in Fig 8.2b in a similar format to that in Fig 8.2a.

In all cases adaptation to either a grating adaptation pattern or a disconnected bar adaptation pattern produced a contrast threshold elevation of the grating test pattern which was highly significant ($t \geqslant 5.13, df=11, P < 0.001$) and of magnitude between 0.1 and 0.25 log units.

Changing the orientation of the adapting bar elements from orthogonal to parallel to the saccade-like displacements produced an increase in contrast threshold elevation. This increase reached significance ($t=1.99, df=22, P < 0.05$) for the grating adaptation patterns but failed to be significant for the disconnected bar adaptation patterns ($t=0.49, df=22, P > 0.2$).

Both sets of results showed a significantly greater ($t \geqslant 2.28, df=22, P < 0.05$) contrast threshold elevation after adapting to the grating adaptation pattern than after adapting to the disconnected bar adaptation pattern.

Discussion.

From the above results it is evident that adaptation to the grating adaptation pattern produces a greater contrast threshold elevation of the grating test pattern than does adaptation to the disconnected bar pattern. This conclusion does not depend on the orientation of the pattern bars relative to the saccade-like displacements of the adaptation patterns despite changes in the overall magnitude of the effect at these different orientations.

The greater adaptational sensitivity of the mechanism detecting the test grating to the grating adaptation pattern might be interpreted as adaptational sensitivity to the local spatial periodicity of the grating patterns. This finding is in agreement with other psychophysical measurements of contrast threshold elevation where single gratings were used for both the test and adaptation patterns (see introduction to this chapter). These previous findings led to the notion of 'channels' in the human visual system sensitive to spatial periodicity (Blakemore and Campbell, 1969). The present results extend these to a more localised type of pattern and shows that adaptational sensitivity to spatial periodicity exists in small spatially localised areas. This latter suggestion is consistent with the suggestion of Robson (1975) that patterns are Fourier analysed on a patch-by-patch basis by channels selective for local spatial frequency. It was shown in Chapter 1 (section 1.5.), however, that such a local Fourier analysis theory could be regarded as a type of structural theory of pattern recognition.

In terms of a structural theory of pattern recognition the results of the present study might be interpreted as indicating the presence in the human visual system of mechanisms which are adaptationally sensitive to the spatial relationships between bar features specified by a relation defining periodicity or repetitiveness. In Chapters 6 and 7 adaptational insensitivity was found to relational structure specified by various connectivity relations. The findings here of adaptational sensitivity to relational structure of a pattern specified by a relation of periodicity contrasts with these findings of Chapters 6 and 7. Sensitivity to local spatial periodicity might be expected, however, from mechanisms sensitive to bar shaped features, for the two are interrelated. For, a mechanism selective for a certain range of bar feature widths would (unless highly non-linear) also be selective for a limited range of spatial frequencies (MacKay, 1981; see also section 1.5.3. here). Thus the sensitivity for local spatial periodicity might simply be explained by the sensitivity for the size of pattern elements in found Chapter 5 (section 5.3.).

It might be suggested that this sensitivity to local spatial periodicity may be attributed to the cells with periodic sensitivity profiles observed by De Valois, Albrecht and Thorell (1978) in the cortex of cat and monkey. Although the periodic patterns used in the present study might excite such cells it would be incorrect to classify such cells as "local grating detectors". For, many other patterns, including the bar pattern used here would also elicit a response from these cells. The detection of the pattern as a local grating might, however, be attributed to the appropriate combination of the responses from several cells of different sensitivity profiles when their responses are appropriately combined (see section 1.5.2.). The difference in test contrast threshold elevations with orientation of the grating pattern relative to the saccade-like displacements of the adaptation pattern may be attributable to an overall change in adaptational sensitivity between the two parts of the experiment. For, only one orientation of the grating pattern was used in each part of the experiment and therefore any changes in overall sensitivity would affect the comparison of results from the two experimental parts. That this was the case in the present experiment is supported by the fact that the same trend in contrast threshold elevation of the grating test pattern is observed with changing orientation for both the grating adaptation patterns and the disconnected bar adaptation patterns.

An alternative explanation of the change in contrast threshold elevations with orientation of the patterns relative to the saccade-like displacements might be as follows. When the adaptation bars are parallel to the saccade-like displacements the "smearing" effect of the displacements on the retina is reduced in comparison to when the bars are orthogonal to the displacements. The larger threshold elevation observed with bar orientations parallel to the saccade-like displacements may therefore be simply a result of a relatively increased local retinal adaptation. These results concerning orientation effects in no way invalidate the main finding of the experiments that the human visual system is adaptationally sensitive to (a relation of) local periodicity between bar features.

CHAPTER 9. EXPERIMENTS ON FEATURES AND RELATIONS.

9.1. Introduction.

In Chapters 6 to 8 the adaptational sensitivity of mechanisms detecting simple line figures was examined in the context of structural theories of pattern recognition (section 1.2.2.). The results of the experiments described in these chapters support the notion that the mechanism detecting simple connected line figures, e.g. T- or L-shaped figures, is adaptationally insensitive to the relative positions of the bar features forming these line figures. From the results of the control experiments using disc-shaped patterns (Chapters 6 to 8) it might also be inferred that the detecting mechanisms are adaptationally sensitive to the features, e.g. discs and bars, comprising the patterns. This adaptational sensitivity to feature changes was also shown in the results of the stimulus specificity experiments described in Chapter 5. An exception to these conclusions was described in Chapter 8 where the mechanism detecting a small grating pattern was found to be adaptationally sensitive to relative position (relational) information defining periodicity.

These previous chapters have only considered adaptation experiments within the context of structural theories of pattern recognition. Such structural theories were originally proposed as an explanation of the results from experiments based on pattern discrimination and recognition tasks. We might therefore ask, how do the data from adaptation experiments compare with those from discrimination experiments conducted under analogous conditions? Thus in the present chapter an adaptation experiment and a discrimination-under-uncertainty experiment are described. Both of these experiments were conducted with stimuli consisting of simple T- and L- shaped figures similar to those used in previous chapters.

We might expect the results from a discrimination-under-uncertainty experiment to be similar to those from an adaptation experiment in the following circumstances. If there is a limited pattern-encoding capacity for the visual system (Eriksen and Eriksen, 1974; Foster, 1980b) then we might expect the internal representation (section 1.2) of the stimulus pattern formed in a discrimination-under-uncertainty experiment to be restricted to an encoding in terms of attributes analysed in the early stages of visual processing. For, in a discrimination-under-uncertainty technique a target pattern is presented at random positions within a stimulus pattern and therefore we might suppose that the visual system cannot encode the whole stimulus pattern in detail and consequently some of the attributes processed more centrally are not included in the internal representation. Thus if the mechanisms involved in adaptation are only adaptationally sensitive to the attributes that are analysed peripherally then we might expect the results obtained from an adaptation experiment and a discrimination-under-uncertainty experiment to be similar.

The results from a series of studies by Beck (1966a,b, 1967, 1972), Beck and Ambler (1972, 1973) and Olson and Attneave (1970) in which various techniques, including discrimination-under-uncertainty, were used are similar to the results obtained in the present study with an adaptation technique. The similarity of the results from these two different techniques supports the notion that both the adaptation and the discrimination-under-uncertainty techniques reveal the properties of early stages in the pattern analysis process. These authors (Beck, 1966a,b, 1967, 1972; Beck and Ambler, 1972, 1973; Olson and Attneave, 1970) considered the effects of patterns comprising line segments connected in different ways on perceptual grouping and on peripheral and foveal discrimination. The patterns used in these studies were similar to those used in the present adaptation studies described in Chapters 6 - 8 and Experiment 1 of this chapter. For example, the patterns used by Beck and his colleagues consisted of short line segments connected together to form T-, ⊔-, and ┼ - shaped figures of various orientations. When attention was distributed over several spatial locations by presenting a disparate pattern at random positions, these authors found that patterns in which line slope differed (e.g. T, ⊤) were more discriminable from each other than patterns in which line arrangement differed (e.g. T,L). If lines of different orientations are interpreted as different pattern features then these results support the notion that the detecting mechanism in these grouping and discrimination studies is sensitive to feature changes but not to changes in spatial relations. This conclusion is analogous to that arrived at as a consequence of the adaptation experiments described in Chapters 6 - 8 here. In these adaptation experiments the results showed that the mechanisms involved in the contrast threshold elevation effect were adaptationally sensitive to bar orientation (section 5.2.1.) but were not adaptationally sensitive to relational structure (Chapter 6).

Pomerantz (1978) questioned the conclusions of Beck (1966, 1967, 1972), Beck and Ambler (1972), and Olson and Attneave (1970) and proposed that angle and vertex detectors rather than sloped lines are the primitives of human visual pattern recognition. Such a notion of angle or vertex detection would involve sensitivity to the spatial relations defining the connectivity of the angles and vertices. As support for his suggestion Pomerantz cited the results from experiments in which he measured the reaction time of an observer for detection of a disparate pattern quadrant. In his study Pomerantz found that the reaction time for locating a disparate quadrant containing a Δ -shaped pattern from amongst ◹ -shaped patterns was less than that for locating a single differently sloped line (\ )

amongst orthogonal lines (/). He also found that the reaction time for locating a ◹-shaped pattern from amongst ↗ -shaped patterns was insignificantly smaller than for locating a Δ-shaped pattern amongst ↗-shaped patterns. Pomerantz also suggested that the results of Beck and his colleagues, and Olson and Attneave might also be interpreted in terms of angle and vertex detectors that responded to the apparent angles formed between disparate elements and their neighbours.

The results from Pomerantz (1978) are difficult to compare with those of Beck and his colleagues, and Olson and Attneave because the pattern changes in the experiments of Pomerantz are of a different nature from those in other studies. In particular, in the first experiment of Pomerantz the number of bar elements forming each quadrant subpattern changes from one in the first display to three in the second display. Changes in subpattern structure were therefore confounded with changes in subpattern element numbers and make it difficult to determine the cause of the change in reaction time. Beck (1972) noted that his results could be explained by the number of disparate line segments between the two subpattern types. The small change in reaction times found by Pomerantz in his second experiment where the disparate subpattern changes from a Δ -shape to a ◹ -shape may be a reflection of this phenomenon noted by Beck.

Pomerantz also presented results showing how the addition of extra elements to the subpatterns affect their discrimination even if the same additional element is added to each subpattern. The results of these experiments performed by Pomerantz might be interpreted as an indication that addition of feature information to a pattern affects the way in which it is discriminated. Beck (1972) also found that the number of horizontal and vertical line segments in his display was a relevant variable for perceptial grouping. We might conclude, therefore that in order to avoid problems arising from interaction between

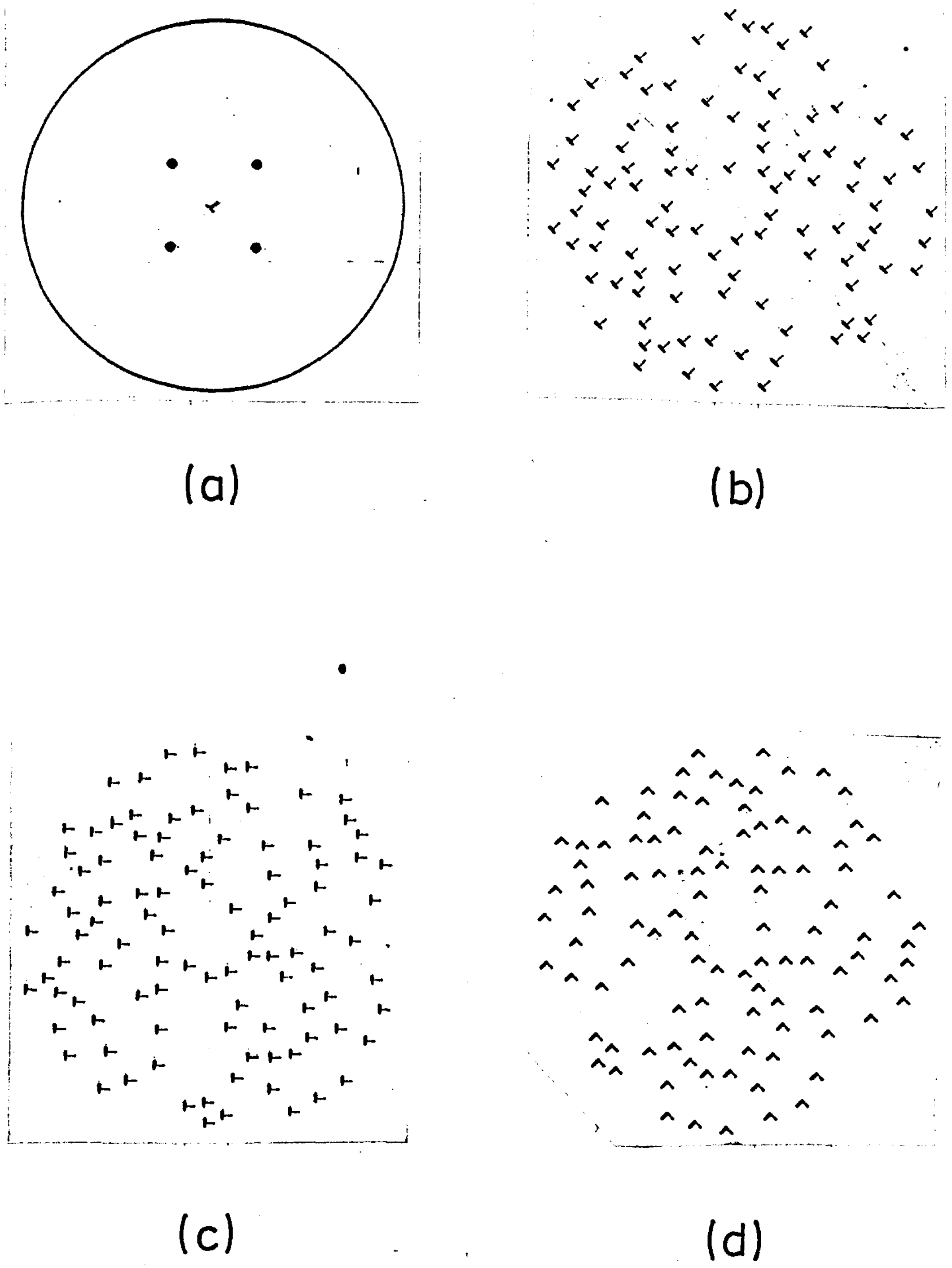


Fig. 9.1. Stimuli for experiment 1. The stimuli were brighter than their backgrounds.

100 copies of the test T-shaped figure distributed pseudo-randomly within the 15° diameter field. The second adaptation pattern of Fig 9.1c was identical to the first except that it was rotated through 45° therefore the bar elements comprising the T-shaped subpatterns were vertical and horizontal. The third adaptation pattern of Fig 9.1d consisted of 100 L-shaped subpatterns, formed from the same bar elements as the T-shaped test figure distributed pseudo-randomly within the 15°field. The orientations of the bars forming each L-shaped subpattern were identical to those forming the T-shaped test figure. A fourth adaptation pattern consisting of a 15° diameter uniform field was also used.

The mean retinal illuminations of the adaptation patterns and the test background field were all set equal to 4.0 log trolands (section 3.2.6.).

During the adaptation period the adaptation pattern was subjected to small vertical saccade-like displacements as before (section 4.5.).

Methods.

The stimuli were presented in Maxwellian view (section 3.1.2.) and contrast thresholds were measured by the method of adjustment (section 3.3.). The timing of adaptation and test periods were as described previously (section 3.3.3.).

Six runs were performed during which the adaptation patterns were presented according to the balanced design described in section 3.4.2.

Subjects.

One subject RJM participated in this experiment. For further subject details see section 4.1.

Results.

The results of this experiment are shown in Fig 9.2. The contrast threshold elevation Δ (section 3.3.2.) is plotted on the ordinate. The adaptation pattern is identified by a typical subpattern

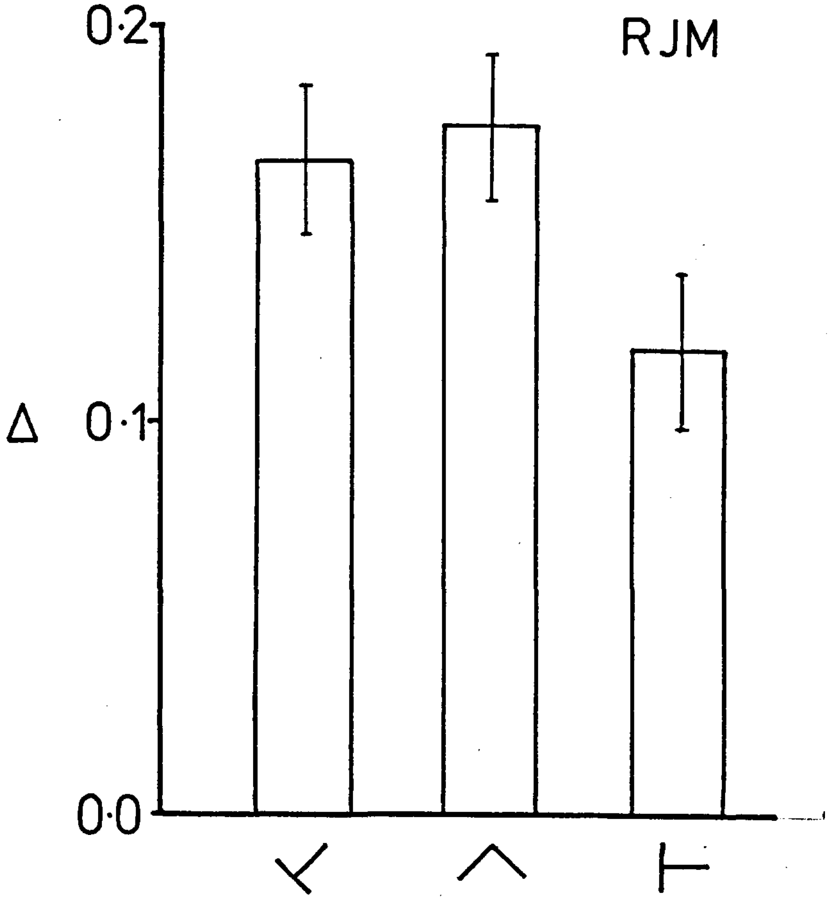


Fig. 9.2. Results of experiment 1. Contrast threshold elevation Δ in log units plotted against adaptation pattern type (indicated by a typical subpattern below the abscissa).

below the abscissa.

Adaptation to any of the adaptation patterns produced a highly significant contrast threshold elevation of the T test pattern ($t \geqslant 5.90, df=11, P < 0.001$). Critically, the contrast threshold elevation after adaptation to either the L adaptation pattern or the T adaptation pattern in which the bar element orientations are the same as in the T test pattern are not significantly different ($t=-0.33, df=22, P > 0.5$) and typically of magnitude 0.17 log units. The contrast threshold elevations after adaptation to either the L or the T adaptation patterns in which the bar elements were of identical orientations to those in the test pattern are each significantly greater than the contrast threshold elevation after adaptation to the tilted-T adaptation pattern with bars at 45° to those forming the test pattern ($t \geqslant 1.74, df=22, P < 0.05$).

Discussion.

The results of this experiment agree with the findings of the previous adaptation experiments described in Chapters 4 to 8. As in these previous experiments, changing the relational structure of the adaptation pattern had little effect on the contrast threshold of the test pattern used in the present experiment. For, changing the relational structure from one specifying "T-connectedness" to one specifying "L-connectedness" (see section 6.1.) between orthogonal bar features had no significant effect on the contrast threshold elevation of the T test pattern. Changing pattern features by rotating the pattern through 45°, resulted in a change in contrast threshold elevation. This latter result might be interpreted as an adaptational sensitivity to feature changes if differently orientated bars are regarded as different features.

Further discussion of these results is given in section 9.4.

9.3. Experiment 2 - Discrimination-under-uncertainty.

The purpose of the present experiment is to examine, using stimuli analogous to those used in Experiment 1, the effect of changes of either features or relational structure on the discrimination-under-uncertainty of these stimuli. A comparison of the results of this experiment and those of experiment 1, in which an adaptation technique was used, should reveal the properties of the more peripheral stages of pattern processing (see introduction to this chapter).

In the present experiment subjects were required to discriminate the presence of a T- or L-shaped figure in a display consisting of disconnected bars. The T- or L-shaped figure could appear at any one of several random positions, thus providing the uncertainty required to distribute the subject's attention (see introduction to this chapter). The T- or L-shaped figure appeared with its bar elements either parallel to or at 45° to the disconnected bars forming the background field. In the first case, where the bar elements of the T- and L-shaped figures are parallel to the background bars, these figures might be considered as consisting of the same features as the background. Any distinguishability of these figures from the background we might therefore attribute to the spatial relationships between the bars forming these figures.

In the second case, where the bar elements of the T- and L-shaped figures are tilted at 45° with respect to the background bars, these figures might be considered as consisting of different features from the background. Any distinguishability of these figures from the background might therefore be attributed to both feature and spatial relationship differences.

The relative distinguishability of these figures (T,L, tilted T and tilted L) from the background might be supposed to show the relative importance of changes in features and relational structure for the mechanisms involved in discrimination-under-uncertainty. Thus the use of the stimuli described above is analogous to those used in the adaptation experiment of the previous section (Experiment 1).

Apparatus.

The stimulus bar patterns were drawn by an on-line computer controlling a display oscilloscope (Hewlett Packard 1300A with P4 sulphide phospor). The display oscilloscope screen was seen through a viewing system which superimposed a uniform white rectangular 17° x 15.5° background field on the patterns drawn. The background field had a luminance of 140 $cd.m^{-2}$. The bar patterns appeared bright against this background field. The subject set the bar pattern intensity as follows. A 1-log-unit filter was interposed between the oscilloscope screen and the viewing system and the subject adjusted the bar pattern intensity until contrast threshold was obtained. By removing this 1-log-unit filter the bar patterns were, therefore, 1-log-unit above contrast threshold.

Timing, stimulus geometry and order of pattern presentation were all controlled by the computer, which also recorded the subject's response. The subject responded by means of a push-button box connected to the computer which also recorded the response.

Stimuli.

The stimulus patterns were constructed under the following constraints. Two points were chosen randomly within each of the 19 cells shown in Fig 9.3. These points were constrained such that they were at least 40' distant from any other point in the display thus ensuring that the bars of length 20' drawn with their centres at these random points were separated by at least one bar length. One of the points in each of the cells had a bar of +45° orientation with respect to the vertical centred upon it and the other point had a bar of -45° orientation centred upon it. This procedure resulted in the non-target pattern of Fig 9.4a consisting of separated bars pseudo-randomly distributed within a 12° diameter field.

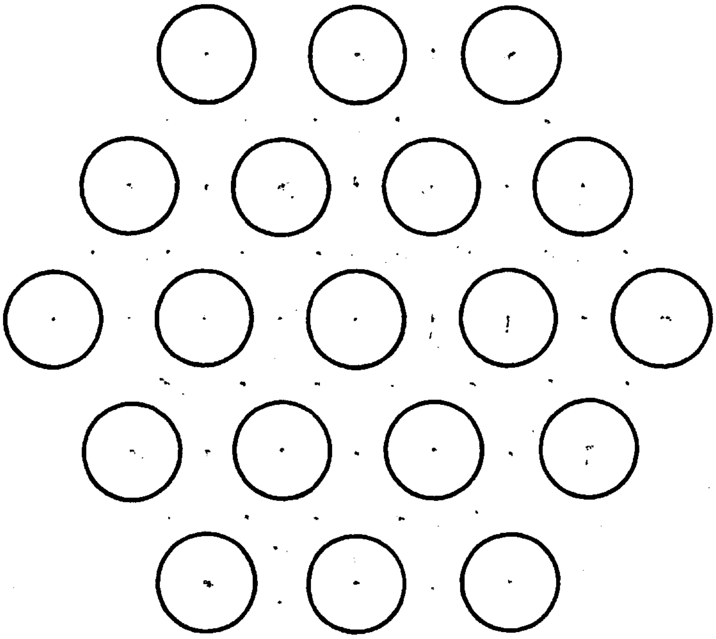


Fig. 9.3. 19 cells within which patterns are distributed in the discrimination experiment.

This non-target pattern was modified in one of the following four ways to produce a background containing a target figure of either a T-,L- tilted-T or tilted-L-shape. One of the 19 cells was selected at random and the two bars within it were replaced by one of the target figures. These target figures were as follows:

T target.

A target figure comprising two component bars of the same length (20') and orientations as the remaining background bars but connected centre to end to form a T-shaped figure. Fig 9.4b shows a typical target pattern containing this target figure.

L target.

A target figure comprising two component bars of the same length and orientations as the remaining background bars but connected at the ends to form an L-shaped figure. Fig 9.4c shows a typical target pattern containing this target figure.

Tilted-T target.

The same as the T-target figure except here the component bars are rotated throught 45° with respect to the background bars. Fig 9.4d shows a typical target pattern containing this target figure.

Tilted-L target.

The same as the L-target figure except here the component bars are rotated through 45° as above. Fig 9.4e shows a typical target pattern containing this target figure.

Subjects.

The subjects used in this experiment were four Psychology and Biology undergraduates aged 20 to 21 years. All had normal or corrected-to-normal vision and were unaware of the aims of the experiment.

The subjects were used in two groups of two, the whole experiment

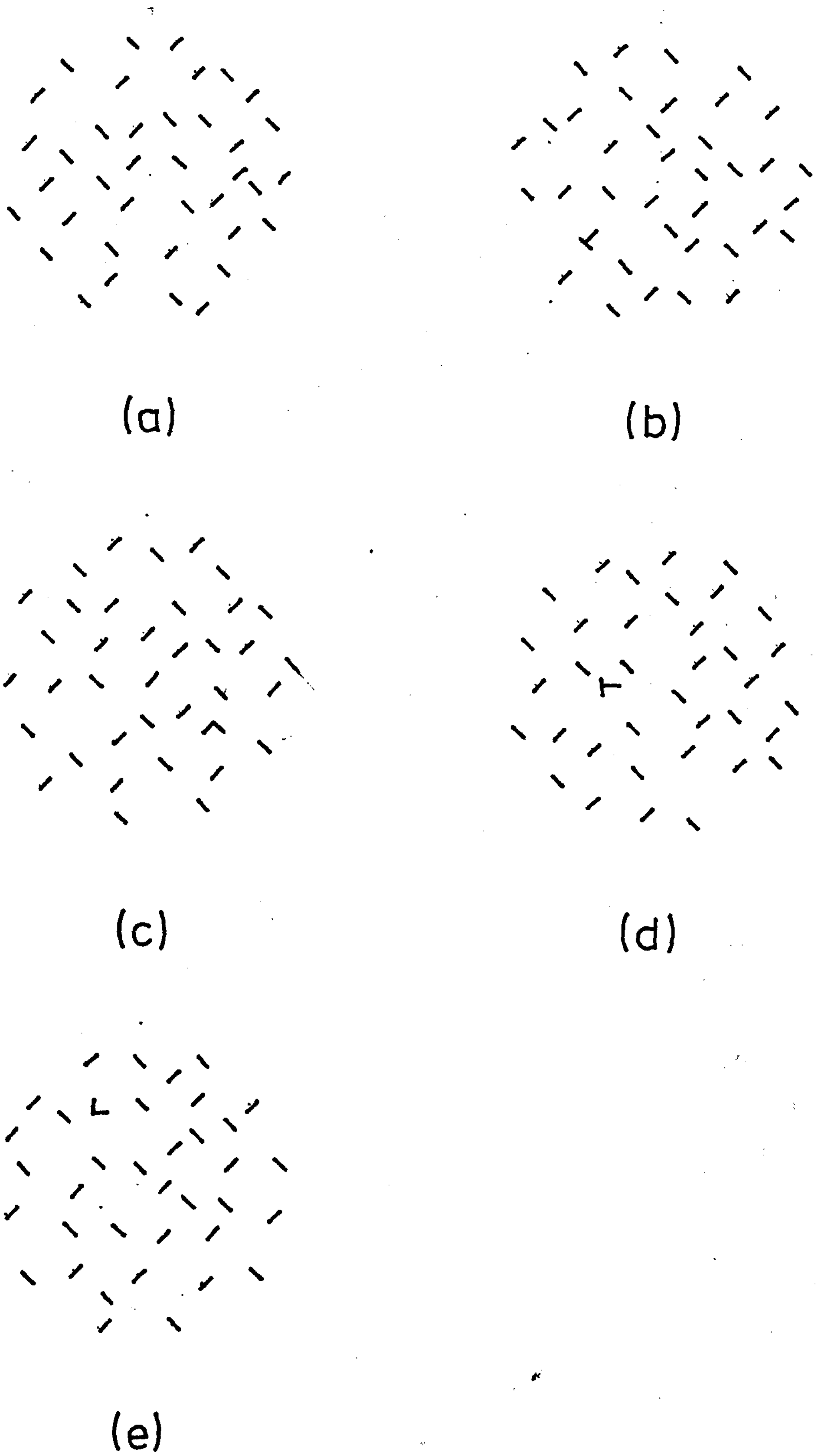


Fig. 9.4. Typical stimuli for experiment 2. The stimuli were brighter than their backgrounds.

on each group being completed in a 2-hour session.

Experimental design.

Each subject took part in 8 runs, each run consisting of 28 presentations of the stimuli. A 2IFC design was used and for each presentation in one interval a non-target pattern (Fig 9.4a) was displayed and in the other interval a target pattern (Fig 9.4b-e) was displayed. The subjects task was to indicate by pressing one of two buttons (forced-choice) in which interval the target pattern appeared.

A typical run is represented in the timing diagram of Fig 9.5. At the beginning of the run a small fixation cross ($1^{\circ} \times 1^{\circ}$) appeared in the screen centre and disappeared when the subject pressed the 'show' button to begin a presentation. 40 ms after the offset of the fixation cross the first stimulus interval of 60ms duration occurred. This was followed by an inter-stimulus interval of 1 second after which the second stimulus interval of 60ms duration occurred. The fixation cross reappeared 10ms after the subject responded. The next presentation was initiated when the subject once again pressed the 'show' button and the end of the run was indicated to the subject by the appearance of "END" on the display screen.

The stimulus duration of 60ms is insufficient to allow the initiation of a saccade in the direction of the target figure thus the uncertainty of the retinal locus of the target figure is maintained (Carpenter, 1977).

Equal numbers of each type of target stimulus appeared in each run and the series of runs was balanced for carry-over and order effects (Finney, 1960). Additionally, in order to reduce response bias the runs were carried out in counterbalanced pairs with a short break between the two runs forming a pair. This counterblancing was of the following form. The interval, first or second, in which the target pattern occurred was changed in all presentations forming a run in the

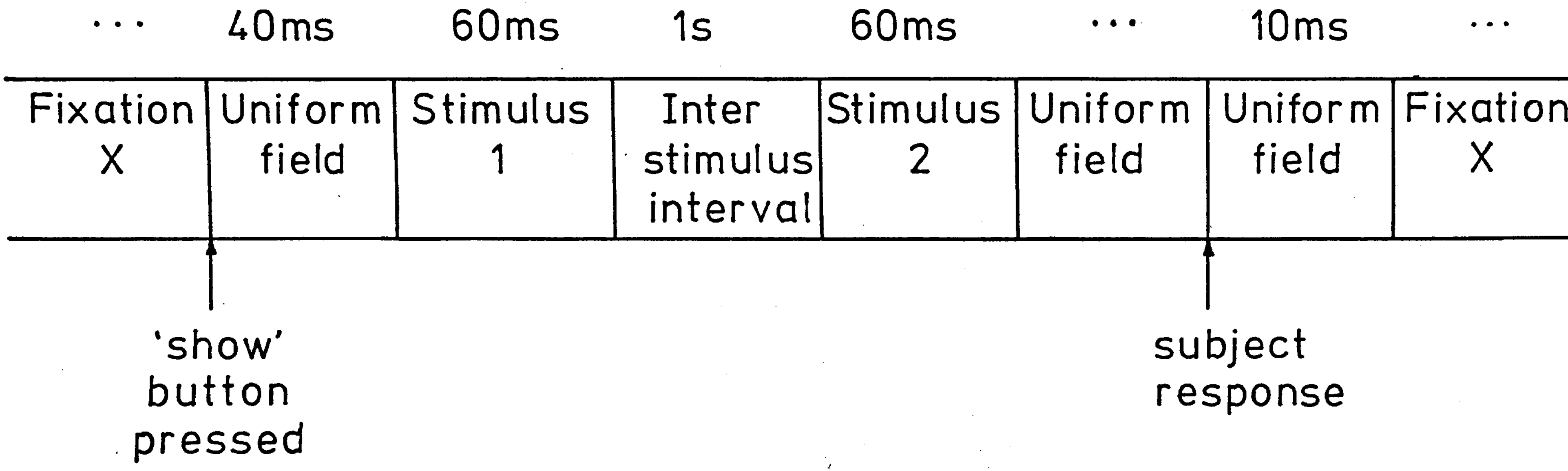


Fig. 9.5. Timing of a presentation sequence.

second of the pair of runs whilst other parameters remained the same. Thus, for example, if in the i^{th} presentation of the first run the target pattern was the first interval then in the i^{th} presentation of the second run the target pattern would appear in the second interval and vice versa. Between pairs of runs the subjects were given a longer rest period (whilst the other subject was completing his pair of runs) to reduce fatigue effects. The whole period for 8 runs was 2 hours with each pair of runs lasting 15 minutes.

The position of the target figure within the field was chosen randomly from the 19 possibilities this giving an equal probability of each retinal site being chosen. A randomization procedure was chosen in preference to a design balanced to give equal numbers of presentations of each type of target figure at each retinal site for the following reasons. A balanced procedure would have increased the number of runs required from each subject. As the aim of the experiment is to investigate the effect of target figure changes rather than retinal location effects the use of the randomization procedure does not affect the conclusions.

Results.

Fig.9.6 shows the pooled results from all runs on all of the observers. The ordinate shows the per cent correct responses for indicating which of the two intervals the target pattern occurred in. The results from each of the different types of target figure are identified by their odd subpattern below the abscissa. The error bars represent the mean of the standard errors from each subjects responses (assuming binomial data).

The subjects responses to the target patterns containing the T- and L-target figures with the same component bar orientations as the background field showed no significant difference ($Z=0.94, P>0.25$) in per cent correct responses although both the T- and L-target

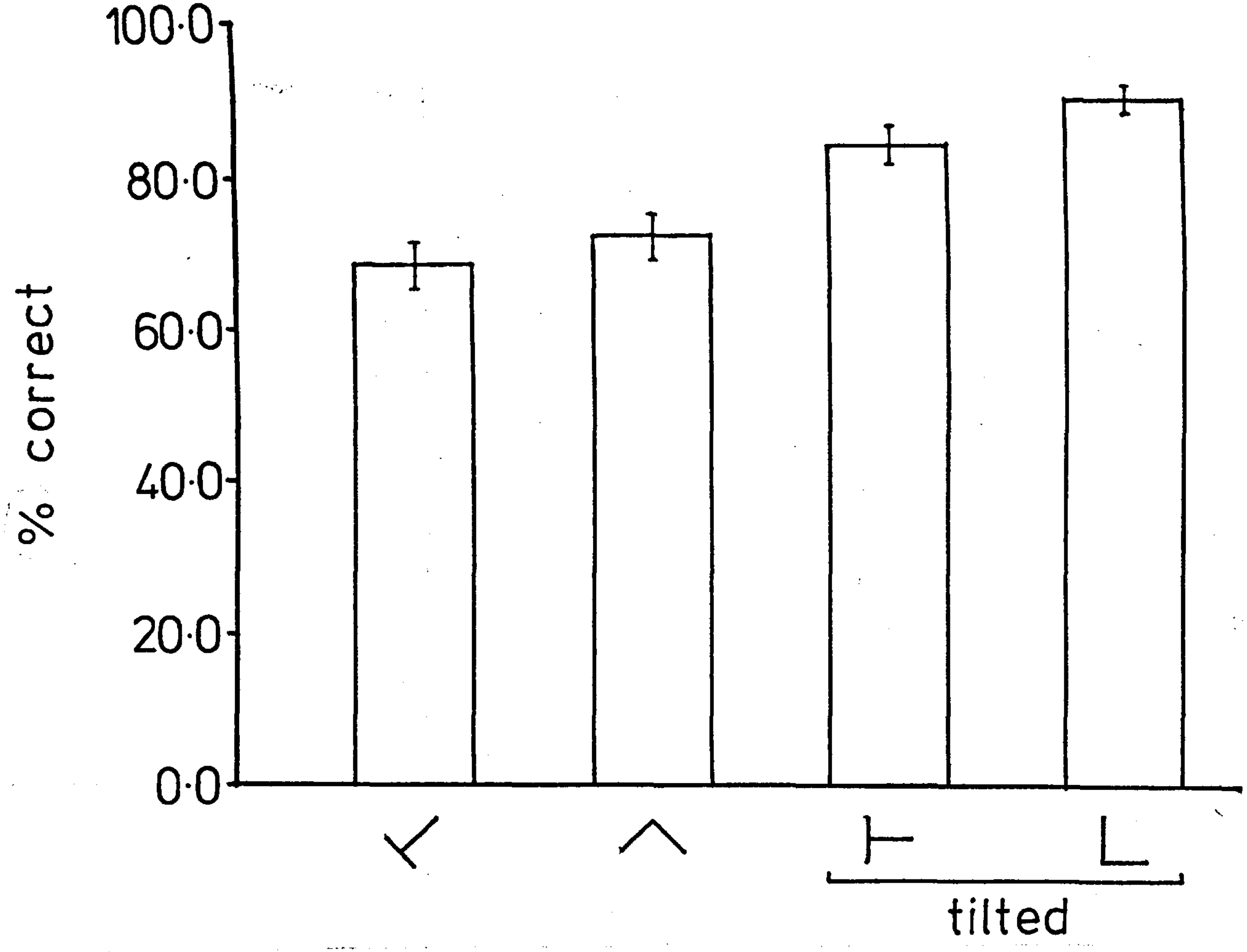


Fig. 9.6. Results of experiment 2. Per cent correct responses plotted against odd subpattern type (indicated on the abscissa).

patterns were detected significatnly ($Z > 6.05, P < 0.001$) above chance level (50%). The tilted-T and tilted-L target patterns containing the target figures with bar components tilted at 45° with respect to the background bars were both detected highly significantly ($Z > 3.15, P < 0.001$) better than the T- and L-target patterns. The tilted L-target pattern was detected significantly better ($Z > 1.89, P < 0.05$) than any of the other three target patterns. These results are qualitatively consistent for all observers as illustrated in Table I which shows the individual per cent correct responses averaged over runs.

TABLE I

Observer	Stimulus			
	T	L	Tilted T	Tilted L
PL	50.0	57.1	80.4	89.4
MT	75.0	87.5	94.6	98.2
PH	80.4	80.4	85.7	91.1
PC	69.6	66.1	78.6	83.9

The significant difference between the untilted and tilted target pattern detection is consistent for all observers. The results concerning significance above chance level of the detection of the two untilted- target patterns and differences between the detection of the two tilted - target patterns show more inconsistency for different observers.

Discussion.

The results of the present discrimination experiment show that orientation of the component bars of the target figures relative to the orientations of the background bar elements is an important factor in determining the ease with which the target figure may be distinguished. When the orientations of the component bars of the target figure are at 45° to those of the background bars, as in the tilted-T and tilted-L target figures, these target figures are more distinguishable from the background than the T- and L-shaped target figures where the bar orientations are the same as the background bar orientations. Note that this difference in distinguishability cannot easily be attributed to changes in local luminance because the target figures involved are of similar spatial luminance distributions. The results of the present experiment agree with the findings of Beck (1966a,b, 1967, 1972), Beck and Ambler (1972, 1973) and Olson and Attneave (1970) who also found that orientation of component bars relative to background bar orientations increases their distinguishability.

The results of the present discrimination experiment might be interpreted also in terms of a structural description involving features and relations as follows. The mechanisms discriminating the target figures appear to be in general more sensitive to the bar feature orientations (or feature type, if differently orientated bars are considered as different features) than their spatial relationships.

The results of the present experiment do reveal some sensitivity of the mechanisms involved in discrimination to the spatial relationships of the bar features forming the patterns as follows. The T- and L-shaped target figures, whose component bars were of the same orientations and dimensions as the background bars, were also distinguishable from the background. This above-chance performance implies that the connectivity of the target figures can be detected in this discrimination paradigm. This effect is, however, relatively small and may simply be a result of the greater local luminance of the relatively compact target attracting the observers attention. Although this result might be interpreted as a sensitivity to the presence of a connected bar pattern it may not be interpreted as a sensitivity to changes of relational structure, for both the T- and L-shaped figures are equally distinguishable from the background field.

The greater distinguishability of the tilted-L-target figure than the tilted-T-target figure may reflect a sensitivity of the visual system to relational structure, for in this case a change of relational structure from "T-connectedness" to "L-connectedness" has had an effect on the distinguishability of the target figure. The greater distinguishability of the tilted-L-target figure than the tilted-T-target figure might show a sensitivity of the visual system to right-angle patterns as suggested by Beck (1967) in an experiment on perceptual grouping. This result might also be indicative of the "angle" detecting mechanisms proposed by Pomerantz(1978) operating parallel to or after mechanisms detecting orientated line segments.

9.4. General discussion.

The results of both the adaptation and discrimination-under-uncertainty experiments show that in general the mechanisms involved in these two paradigms are sensitive to changes of features (or feature orientation)but are relatively insensitive to changes of relational structure. The similarity of the results from these two paradigms is of interest for it might be suggested that the results obtained with either the adaptation or discrimination-under-uncertainty technique reflect the properties of the more peripheral stages of pattern processing (see introduction to this chapter). If this is the case, then the results of the experiments described in this chapter indicate a fundamental difference in the way in which local features and their spatial relationships are processed in the visual system.

The present results support the notion that a pattern is analysed at a peripheral stage in terms of its features and the spatial relationships between these features are analysed by a more central process. Given this notion we might explain the results of the present experiments as follows. Suppose that the mechanisms adapted in the adaptation experiment perform a preliminary feature extraction process and give responses, say, to bars of particular orientations and spots, but pass on relative position information to some more central (non-adaptable) process. Then the results of the adaptation experiment should only reveal the sensitivity of the more central process that analyses relational structure. If we further suppose that the discrimination responses are based on some internal representation of the pattern (section 1.2.) and that this internal representation encodes features and their spatial relations (i.e. a structural theory). Then if pattern encoding capacity is limited in the discrimination-under-uncertainty paradigm (see introduction to this chapter) we might suppose that the internal representation is formed from the more primitive attributes of the pattern (Foster, 1980b) which are extracted at an early stage of processing. In the present case these primitive attributes are the feature specifications. Thus in the discrimination-under-uncertainty paradigm the discrimination process would be limited to discriminations based on feature differences.

It might be conjectured that the greater distinguishability of the tilted-L-target pattern than the tilted-T-target pattern in the discrimination-under-uncertainty experiment reflects the action of the "next" stage of visual processing in terms of bar features connected together to form angles. The equality of the contrast threshold elevations after adaptation to the T- and L-adaptation patterns with bar elements orientated identically to those of the T test pattern does not support the notion that patterns are initially processed in terms of their angle and vertex content (Pomerantz, 1978).

Note, that the present findings are consistent with the notion of pattern analysis in structural terms and, indeed, that the processing of pattern features and their spatial relationships at different stages of pattern analysis fits naturally with such a structural theory. In contrast, other forms of pattern analysis, for example those based on pattern transformation (section 1.2.1) which propose operation on the whole pattern information at each processing stage, do not fit naturally with such a separation of processing.

CHAPTER 10. RELATIONAL-STRUCTURE ENCODING AS A MODEL FOR VISUAL PATTERN RECOGNITION.

In previous chapters both adaptation and discrimination-under-uncertainty experiments have been described and their results have been interpreted in the context of structural theories of pattern recognition (section1.2.2.). The results of the experiments reported in these chapters led to the suggestion in Chapter 9 that the analysis of pattern features occurred at some peripheral stage of pattern processing and the analysis of relationships between these pattern features (relational structure) took place more centrally. Structural theories were proposed initially to explain the results from pattern recognition and discrimination experiments which could not be explained simply on the basis of pattern feature information but required in addition the use of relational structure information (section 1.2.2.). In the present chapter therefore the use of such relational-structure information in predicting the results of a pattern recognition experiment is examined.

The stimuli used in the experiments described in previous chapters consisted of bar features which were connected to each other in various spatial relationships. These stimuli only allowed the comparison of one spatial relationship with another spatial relationship and were therefore only appropriate for examining whether sensitivity to relational structure existed or not. In the present study stimuli which allow the comparison of patterns which differ from each other by some continuously variable and measurable change in relational-structure are used. The use of such a range of stimulus patterns allows the predictions of a model of pattern recognition based on relational-structure encoding to be tested for several, rather than just one, pattern changes.

In the present study random-dot patterns are considered and their relational-structure is varied by subjecting the patterns to rotation through an angle θ . Rotation is used as a means of varying relational-structure for the following reason. If we consider a random-dot pattern we may encode its relational structure in terms of the relative positions of pattern features composed of clusters of dots. For simplicity, only such relative position information as above, below, left of, and right of are considered here. As a pattern is rotated therefore relations specifying "left of" become "above" and "above" became "right of" etc. Thus pattern rotation provides a means of simply changing the relational structure of a pattern in a way which is easily calculable (see 10.3.). An additional reason for the use of rotated patterns is that the variation of pattern recognition performance for such patterns is well documented (Dearborn, 1899; Authorn, 1948; Rock, 1973; Foster, 1978b). Of particular note is the non-monotonic variation of pattern recognition performance with rotation angle. That is, performance is best at 0°, decreases for increasing rotation angles and then increases to a second maximum at a rotation angle of 180°. Because rotation is used as a parameter to vary relational-structure, random-dot rather than random-bar patterns are used. The latter pattern would exhibit some preferred orientations (e.g. 180°) at which the bars forming the rotated pattern would have identical orientations to the bars forming the unrotated pattern. This coincidence of bar orientations could give rise to improved recognition at these preferred orientations.

The plan of the present chapter is therefore as follows. In the first section the general approach used in the formulation of the relational-structure model for the recognition of rotated random-dot patterns is described. In the second section the experimental data against which the model was tested is described.

Also in this section an experiment to determine the importance of certain discrete invariances (section 1.1.1.) in producing the main data is described. In the third section the relational-structure encoding model for the recognition of rotated random-dot patterns is described and its predictions compared with the experimental data. It might be suggested that a relational-structure encoding model is not the only way of predicting the present experimental data. Thus in the fourth section, as a control, a model based on transformational theories of pattern recognition is described and its predictions are also compared with the experimental data. The fifth section is a general discussion of the findings described in the previous sections.

10.1. General.

The experimental data with which the predicted pattern recognition performance was compared is taken from a study by Foster (1978b). In Foster's study the pattern recognition performance for random-dot pattern pairs was recorded and the data expressed in terms of the discrimination index d' (Tanner and Swets, 1954; Green and Swets, 1966). The model output must therefore be expressed in terms of the discrimination index d'. This is achieved in the present model as follows.

If we consider a pattern pair A,B and A is a rotated version of B, $A=\rho_\theta(B)$ then the model provides a deterministic measure of their similarity. This measure may be normalised to range between zero and unity to give a measure of the similarity of the pattern pair, say $c(\rho_\theta(B),B)$. In order for the outputs of the model to be compared with the data of Foster (1978b) it is necessary to express this similarity measure c in terms of the discrimination index d'. Now $d' > 0$ implies that the pattern pair $(\rho_\theta(B),B)$ is generally distinguishable from a randomly paired pattern pair (C,D) and $d'=0$ implies that the two pattern pairs are generally indistinguishable.

Therefore, we may obtain the output of the model in terms of d' simply by a linear scaling of the similarity measure c as follows. If d'^{E}_{Id} represents the experimentally determined value of d' for identical pattern pairs ($\theta=0^{\circ}$) and randomly paired patterns and d'^{T} represents the response required from the model then the scaling required is of the form:

$$d'^{T}(\rho_{\theta}(B),B) = d'^{E}_{Id}\cdot c(\rho_{\theta}(B),B) \qquad 10.1$$

If $\theta = 0^{\circ}$ then $c(\rho_{\theta}(B),B) = 1$ and $d'^{T}(B,B)=d'^{E}_{Id}$ as required. If $c(\rho_{\theta}(B),B) = 0, d'^{T}(\rho_{\theta}(B)B)=0$ which implies that the pattern pair $(\rho_{\theta}(B),B)$ are in general no more distinguishable than a randomly chosen pattern pair (C,D).

It is possible to include in a relational-structure encoding model invariances to certain pattern transformations (section 1.1.1.). For example, if a pattern is encoded in terms of relations specifying "above,"below","left of", and "right of" then the model will show invariance to a certain amount of local pattern distortion or "jitter" and also invariance to pattern translation. If in addition certain simple operations are allowed to be performed on the pattern representation, invariance to certain other discrete pattern transformations may be incorporated into the model. For example, if all relations specifying "left of" are changed to "right of" and vice versa then invariance to pattern reflection in a vertical axis may be incorporated into the model. Similarly changing relations specifying "above" to ones specifying "below" allows invariance to reflection in a horizontal axis μ_x to be incorporated into the model. Finally, if the en bloc reversal of relations specifying "above" for "below" and "left of" for "right of" and vice versa is allowed then invariance to pattern rotation through 180° or inversion ι may be incorporated into the model.

The present relational-structure encoding model was developed therefore in versions which included or excluded these discrete invariances. In this way it was possible to determine whether the inclusion of such discrete invariances was necessary to predict the experimental data. To determine which of the discrete invariances to pattern reflection in a vertical axis μ_y, pattern reflection in a horizontal axis μ_x, and pattern inversion could have been operating in Foster 's (1978b) study, the experiment described in section 10.2.2. was performed.

Note that by the inclusion of an unlimited set of discrete invariances it would be possible to make the model fit the experimental data at all pattern rotation angles. Inclusion of discrete invariances to this extent, however, amounts to the inclusion of the experimental data into the model and is therefore not a test of the predictive power of the model. The basis of the present test of the model is as follows. If the relational-structure model equipped with discrete invariances to a limited number of pattern transformations that allow the model to have invariance to a limited number of pattern rotations then we might suppose the following. A test of the predictive power of such a model with invariance to only a limited number of pattern rotations would be its ability to predict recognition performance for pattern rotations other than those to which the model has inbuilt invariances. Thus by restricting the allowed discrete invariance operations to say invariance to μ_y, μ_x and ι the present relational-structure encoding model may be tested by comparing its predicted pattern recognition performance with the experimental data for a range of rotation angles between 0° and 360°.

In the following section the relevant details of the pattern recognition experiment described by Foster (1978b) from which the experimental data for testing the model was taken, are summarized. Also the experiment to determine which of the discrete invariances to μ_y, μ_x and ι might have been operating in Foster's study is described.

10.2. Visual pattern recognition experiments.

10.2.1. Main data.

The experimental results with which the output from the model was compared were taken from a study by Foster (1978b). The random-dot pattern pairs presented to the model were the same as those used in Foster's study.

In his study Foster (1978b) used briefly-presented pairs of side-by-side random-dot patterns, A and B, related by a clockwise rotation in the plane through the angle θ, ρ_θ such that $A=\rho_\theta(B)$. The angle θ took values in the range 0° to 360° at 15° intervals. In all 24 subjects were used. Fig 10.1 (a) shows a typical pattern pair related by a rotation of 90° (Note that the dots appeared bright against a uniform background).

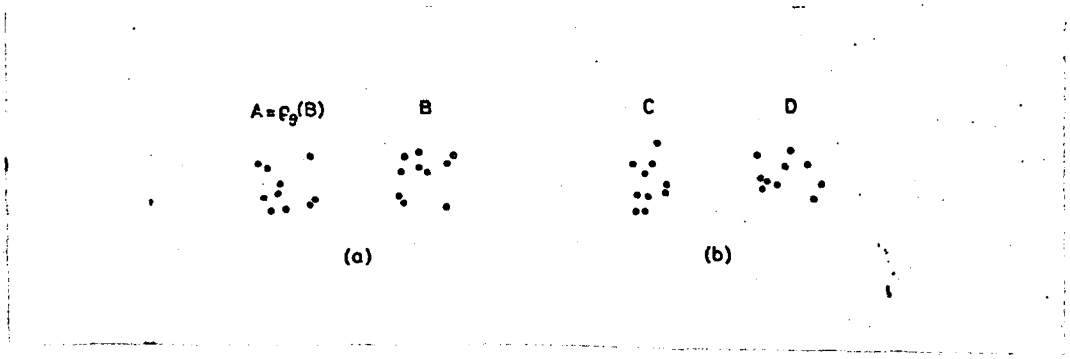


Fig. 10.1 Illustrations of stimulus pattern pairs.

Foster asked each of his subjects to indicate (forced-choice) whether the two patterns had the same shape, in that one pattern could be obtained from the other by some combination of translation and rotation in the plane and reflection about a vertical axis.

As a control patterns paired at random, C and D (Fig. 10.1b), were also presented.

The results of Foster's experiment are given as the filled points in Figs 10.4 and 10.5. Recognition performance at each rotation angle θ is given in terms of Tanner and Swets' (1954) discrimination index d' derived from the simple equal-variance normal-distribution model of signal detection theory (Green and Swets, 1966). This index d' provides a measure of the visual distinguishability of same-shape and different-shape patterns that is relatively insensitive to changes in the subjects' response criterion. For $d' > 0$, the two types of pattern pair are inferred to be visually distinguishable and $d'=0$, they are inferred to be visually indistinguishable.

Full details of this experiment can be found in Foster (1978b).

10.2.2. <u>Data for invariance weighting</u>.

It was mentioned in the introduction to this chapter that performance at recognizing pairs of rotated patterns shows an upturn at 180° (Dearborn, 1899; Aulhorn, 1948; Rock, 1973; Foster, 1978b). It might be suggested that this improvement in performance at 180° is attributable to transformational invariances within the visual system. In particular, this performance elevation may be attributable to the independent operation of processes invariant to a pattern reflection μ_y about a vertical axis, a pattern reflection μ_x about a horizontal axis, and a pattern inversion ι (i.e. rotation in the plane through 180°). If the first two invariance processes μ_y and μ_x may be jointly effected then the inversion operation is redundant for $\mu_x \circ \mu_y = \iota$.

In order to determine which of these invariances were likely to be important in the experiment of Foster (1978b) the following short experiment using similar conditions to Foster's was performed.

Apparatus and Stimuli.

The stimuli were produced on the face of a cathode-ray display oscilloscope (Hewlett Packard 1300A with P4 sulphide phosphor) by an on line-computer. The face of the oscilloscope was visible through a viewing system which superimposed a 7° diameter 3.1 log trolands white uniform field on the stimulus pattern. The stimuli were viewed monocularly with the right eye at a distance of 1.7 metres. The stimulus patterns appeared as bright dots against a uniform background field.

Fig 10.2 shows the resulting stimulus configuration. Two ten-dot random-dot patterns were presented within two 0.75° limiting circles whose centres were separated by a horizontal distance of 1.25°. Two dark 0.1° diameter fixation spots separated by a distance of 7° were provided as illustrated. The diameter of the individual dots comprising a pattern was 0.03°. Each of the random-dot patterns used consisted of ten dots distributed pseudo-randomly within the 0.75° limiting circle such that they were always separated by a minimum distance of 0.05°.

Methods and Procedure.

Each subject participated in a single run as follows. Before the start of a run the experimenter adjusted the intensity of the patterns on the display oscilloscope until they were at approximately 1-log-unit above the subjects increment threshold. This adjustment was achieved by interposing a 1 log unit neutral density filter between the display oscilloscope and the viewing system, adjusting the pattern intensity to the subjects increment threshold and then removing the neutral density filter. After this luminance setting procedure the subject was given a short practice run consisting of 20 presentations of random-dot pattern pairs of the type and format used in the main run. Before each presentation of a pattern pair

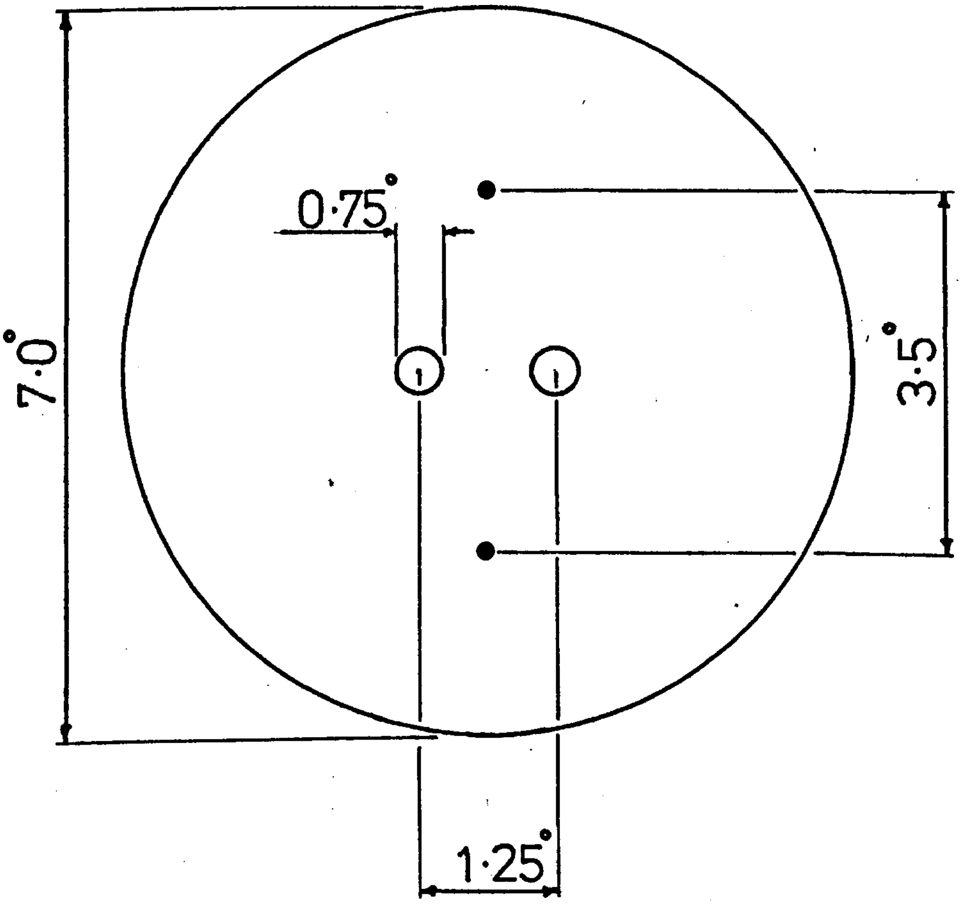


Fig. 10.2 Stimulus parameters for invariance weighting experiment.

the observer informed the experimenter that he was ready and the experimenter then initiated the 200ms pattern presentation period. After such a presentation period the observer informed the experimenter of his response and the experimenter entered the response into the computer. This procedure was repeated for each pattern presentation and was similar to that used by Foster (1978b). The main run consisted of 96 such pattern pair presentations.

The subject was instructed to report the patterns as being the same if one could be obtained from the other by some combination of translation and rotation in the plane and relection about the vertical axis.

Experimental design.

The pattern pairs used in this experiment were of five types as follows:

(i) The same. Both of the patterns in the presentation were identical. That is, if the two patterns were A and B then.

$A = \mathrm{Id}(B)$ where Id is the identity transformation.

(ii) Vertical reflection. One pattern was reflected about a vertical line to form the second pattern i.e.

$A = \mu_y(B)$ where μ_y is the vertical reflection transformation.

(iii) Horizontal reflection. One pattern was reflected about a horizontal line to form the second pattern. i.e.

$A = \mu_x(B)$ where μ_x is the horizontal reflection transformation.

(iv) Inversion. One pattern was an inverted (rotated through 180°) version of the other i.e.

$A = \iota(B)$ where ι is the inversion transformation which rotates pattern B through 180°.

(v) Different. One pattern was a different collection of ten random dots from the other pattern and was not related to it by any simple transformation i.e.

$$A \neq B$$

Of the 96 pattern pair presentations, 48 were presentations of different patterns (type(v)) the remaining 48 being divided equally amongst the remaining pattern pair types. Thus in each run 12 presentations of each of the "same apart from a transformation" pattern pair types (types (i) to (iv)) occurred.

The order of pattern pair presentation was such that it was balanced for order and carry-over effects.

Subjects.

Four male subjects DHF, JIK, BA and RJW of ages between 21 and 35 participated in this experiment. All had normal or corrected-to-normal visual acuity.

Results.

The results pooled over observers are shown in Fig 10.3. The ordinate shows the discrimination index d' for discriminating same pattern pairs (or related by some transform) from different pattern pairs. On the abscissa the various pattern pair transformations are shown. The error bars represent the standard deviations of the respective discrimination index values.

The value of d' for the pattern transformation μ_y (reflection in a vertical axis) is not significantly different from the value of d' for the Id (the same) pattern transformation ($Z = 0.43, P > 0.25$). In contrast the value of d' for the pattern transformation μ_x (reflection in the horizontal axis) is highly significantly less than that for the Id (the same) pattern transformation ($Z = 3.25, P < 0.001$). The value of d' for the inversion transformation (rotation through 180°) is significantly less than the d' value for the Id (the same)

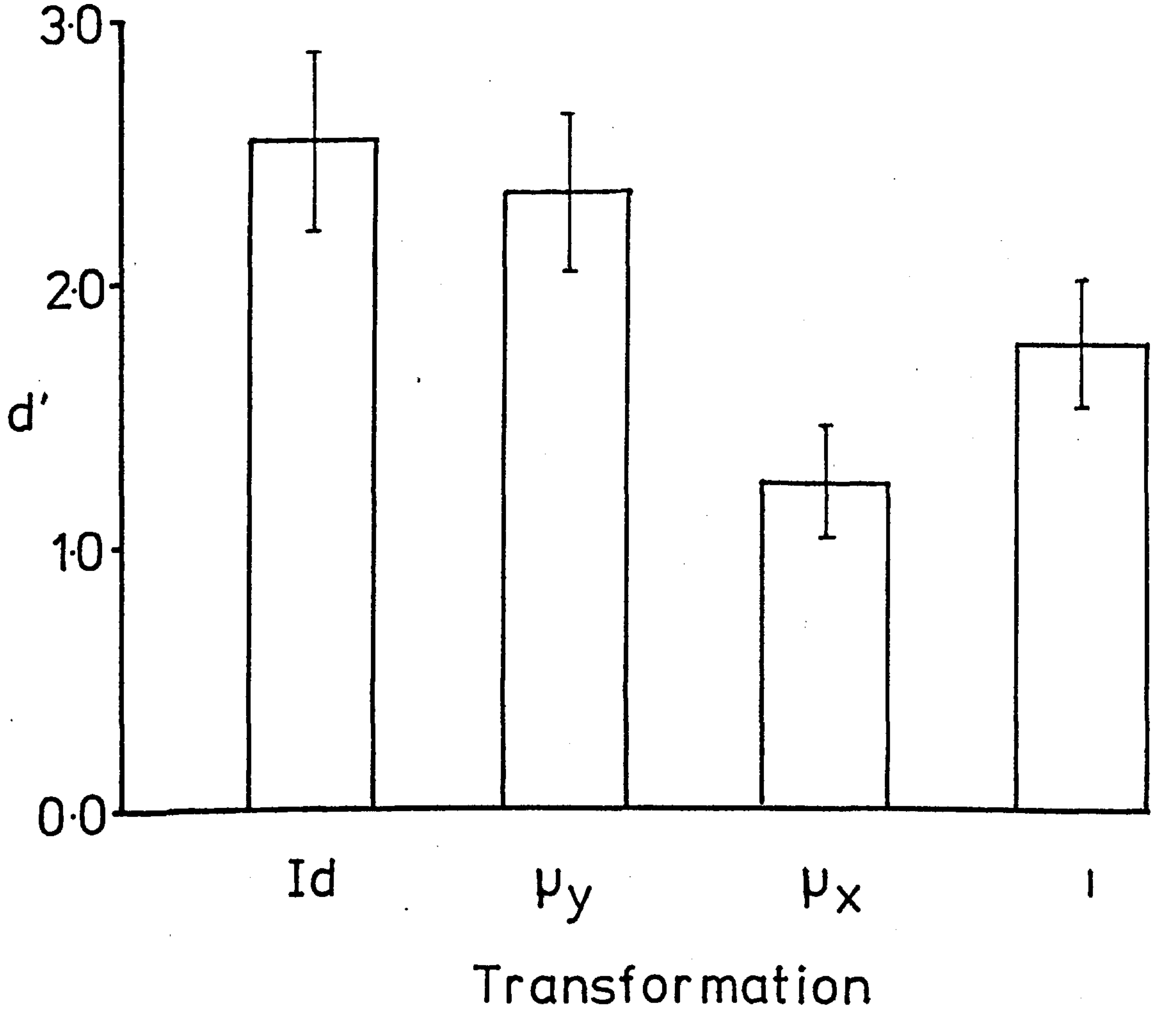


Fig. 10.3 Results of invariance weighting experiment. Recognition performance in terms of the discrimination index d' plotted against the transformation relating pattern pairs.

pattern transformation ($Z = 1.84, P < 0.05$).

Discussion.

The results above indicate that pattern pairs which are related by reflection in a vertical axis are just as discriminable as pattern pairs which are the same. It appears, therefore, that in the present configuration the visual system is exhibiting an invariance to the pattern transformation μ_y (reflection in a vertical axis). Conversely, it appears that reflection in a horizontal axis greatly reduces the discriminability of the pattern pairs relative to the discriminability of "same" pattern pairs. It might be concluded therefore that the visual system exhibits a relative non-invariance to the pattern transformation μ_x (reflection in a horizontal axis). Pattern inversion (rotation through 180°) causes a decrement in discriminability of the pattern pairs relative to the discriminability of same pattern pairs. This decrement of recognition performance is only just significant, however, and it might be concluded that the visual system exhibits a relative invariance to pattern inversion in the present experimental configuration. These conclusions are consistent with the findings of Sekuler and Rosenblith (1964) using different stimulus patterns but a similar stimulus arrangement.

It follows from the above that the elevation in recognition performance at 180° cannot be attributed to the joint operation of two independent processes, the one invariant to μ_y and the other invariant to μ_x. The argument might be as follows. If $P(S \mid Y)$ is the probability of recognising a pattern pair related by the transformation μ_y as "the same", and $P(S \mid X)$ is the probability of a "same" response given a pattern pair related by the transformation μ_x. Then, if $P(S \mid XY)$ is the joint probability of a same response to a pattern pair related by the pattern transformations μ_y and μ_x acting jointly,

$$P(S \mid XY) = P(S \mid X).P(S \mid Y) \text{ for independent operation of } \mu_x, \mu_y.$$

Now the pattern transformation $\mu_x \circ \mu_y$ is equvalent to the inversion operation ι. If $P(S \mid I)$ is the probability of a "same" response given a pattern pair related by the inversion transformation, and if the inversion operation was attributable to the joint operation of μ_x and μ_y, then.

$$P(S \mid I) \quad = \quad P(S \mid XY)$$

Now from the results, $P(S \mid X) < P(S \mid I)$
and because $P(S \mid Y) \leqslant 1$ this implies

$$P(S \mid I) > P(S \mid XY)$$

This result is clearly in contradiction to the above proposal that the recognition performance for pattern pairs related by an inversion transformation is attributable to the joint operation of two invariances to pattern reflections μ_y and μ_x.

Therefore, the only additional discrete invariances which may have been operating in Foster's (1978b) experiment and require testing in the relational-structure encoding model are the reflection in the vertical axis μ_y and the inversion ι.

For the incorporation of the additional invariances to pattern reflection in a vertical axis, μ_y and pattern inversion ι into the model it is necessary for scaling equations similar to equation 10.1. to be used to convert from the model similarity measure to discrimination index d'. The scaling factors (d'^{E}_{Id} in equation 10.1) are taken from the results of Foster (1978b) as the values of d' obtained for identical pattern pairs ($\theta = 0^{\circ}$) for the scaling factor d'^{E}_{Id} and inverted pattern pairs ($\theta = 180^{\circ}$) for the scaling factor d'^{E}_{ι}. From the results of this experiment it was concluded that the recognition performance for pattern pairs related by the pattern transformation μ_y was equal to that for identical pattern pairs, thus for the purposes of the model the third scaling factor $d'^{E}_{\mu_y}$

is chosen equal to d'^{E}_{Id}. The resulting values are given in Table I.

TABLE I

Identity,	Id	d'^{E}_{Id}	=	1.513
Inversion, ι		d'^{E}_{ι}	=	1.326
Reflection, μ_y		$d'^{E}_{\mu_y}$	=	1.513

In appendix A (section 10.6.) the ways in which these scaling equations are used to form the output of the relational-structure encoding model are described.

10.3. Relational-structure encoding model.

If A and B are two patterns in the plane then we may assume that each pattern is encoded in terms of its features and spatial relations between these features. In the present model the only spatial relations considered are of the form left of, right of, above, below. Although other relations of the form connected-to and within may be included in the pattern representation the present analysis does not use these additional spatial relations. Thus, for example, a pattern B is assigned a pattern representation consisting of a set F(B) of local features

$$\left\{ f_i \;\middle|\; 1 \leqslant i \leqslant n \right\} \qquad \text{For n pattern features.}$$

and a set R(B) of spatial relations.

$$\left\{ r_x(f_i,f_j),\ r_y(f_i,f_j)' \;\middle|\; 1 \leqslant i < j \leqslant n \right\}$$

where $r_x(f_i,f_j)$ is the relation indicating whether feature f_i is to the left or right of feature f_j and $r_y\ (f_i,f_j)$ is the relation indicating whether feature f_i is above or below feature f_j. The pattern A may be given a similar pattern representation.

Using the above spatial relations of left of, right of, above and below the pattern representation formed is naturally invariant for pattern position and local pattern distortion or "jitter". The local features f_i formed by various clusterings of the dots in the patterns used in the study of Foster (1978b) are unknown. In the present analysis, therefore, the set R'(B) of spatial relations between individual dots p_i, of the pattern B are used.

$$R'(B) = \left\{ r_x(p_i, p_j), r_y(p_i, p_j) \;\middle|\; 1 \leqslant i < j \leqslant n \right\}$$

For n dots in the pattern B

Similarly, for pattern A where A is the rotated version of pattern B. i.e. $A = \rho_\theta(B)$.

$$\text{Thus} \quad R'(A) = R'(\rho_\theta(B))$$

$$= \left\{ r_x(q_i, q_j), r_y(q_i, q_j) \quad 1 \leqslant i < j \leqslant n \right\}$$

where $q_i = \rho_\theta(p_i)$, $1 \leqslant i \leqslant n$

Because the features of the two patterns are identical (i.e. dots) in the present analysis, comparison of the two patterns A and B is reduced to a comparison of the sets R'(B) with R'(A) and is equivalent to comparison of patterns A and B. This comparison process is accomplished by measuring the number of vertical and horizontal relations left unchanged as the same-shape patterns are rotated relative to each other (Appendix A, section 10.6.).

The incorporation of discrete invariances to reflection in a vertical axis μ_y and pattern inversion ι into the relational-structure encoding model is straightforward. If all relations "left-of" are replaced by "right-of" and vice versa then this is equivalent to the reflection μ_y in terms of its effect on the relational-structure representation. Similarly the replacement of all relations "left of" by "right of" and vice versa and the replacement of all relations "above" by "below" and vice versa is equivalent to the effect of pattern inversion. For each of the discrete invariances Id, μ_y and ι the predicted recognition performance may be calculated on the basis of the number of vertical and horizontal relations left unchanged as the pattern is rotated (Appendix A, section 10.6.). Each of these calculations gives rise to a predicted discrimination index d'^T_α for each of the invariances $\alpha =$ Id, μ_y and ι. Thus, for example, $d'^T_{\mu_y}$ is the predicted recognition performance for comparison of a pattern B with its rotated <u>and</u> reflected version $\mu_y o \rho_\theta$ (B).

In its present form the relational-structure encoding model is not capable of comparing randomly paired pattern pairs and is designed only to respond to patterns having identical features. The calculations of predicted discrimination performance assume that when all the relations of a pattern A are changed (excepting the cases covered by the invariance operations. i.e. reversal of all vertical and horizontal relations) to produce some pattern B, the two patterns A and B are in general no more recognisable than randomly paired patterns.

It is assumed that when several discrete invariances are incorporated in the model the final response of the model is the maximum of the possible recognition performances.

Given the above assumption we may assess four versions of the relational-structure encoding model.

I. $d'^T_1(\theta) = d'^T_{Id}(\theta)$

This version considers only the total number of relations unchanged by pattern rotation. Thus only invariances to pattern position and jitter are included in this version.

II. $d'^T_2(\theta) = \max \left\{ d'^T_{Id}(\theta), d'^T_{\mu_y}(\theta) \right\}$

This version of the model includes reversal of all horizontal relations as well as the consideration of total numbers of relations unchanged as in model I. Thus in addition to invariances to pattern position and jitter a discrete invariance to pattern reflection in a vertical axis is included in this version.

III. $d'^{T}_{3}(\theta) \quad = \quad \max \left\{ d'^{T}_{Id}(\theta),\ d'^{T}_{\iota}(\theta) \right\}$

This version as well as the consideration of the total number of relations unchanged includes the joint reversal of all horizontal and vertical relations. Thus in addition to the invariances of version I this version also incorporates invariance to pattern inversion.

IV. $d'^{T}_{4}(\theta) \quad = \quad \max \left\{ d'^{T}_{Id}(\theta),\ d'^{T}_{\mu_y}(\theta),\ d'^{T}_{i}(\theta) \right\}$

This final version of the model incorporates the reversal of all horizontal relations, the joint reversal of all horizontal and vertical relations and consideration of the total number of unchanged relations. Thus this version incorporates in addition to the invariances of version I, invariance to pattern reflection in a vertical axis and invariance to pattern inversion.

Each of these versions of the model were evaluated by computer for the 21 same-shaped patterns used in the study of Foster (1978b) at angles of $\theta = 0^\circ, 15^\circ, \ldots, 345^\circ$. Fig 10.4. shows the predicted discrimination performance in terms of the discrimination index d' on the ordinate as a function of rotation angle θ on the abscissa for each version of the model. Experimental data from Foster (1978b) pooled over intervals of 45° are plotted as the filled circles. Both theoretical and experimental data are averaged over all pattern pairs. Version III and IV with invariances to either ι alone or μ_y and ι both give good fits to the experimental data. For both of these versions deviations from the experimental data are not significant ($\chi^2 = 2.6$ for version III and 1.7 for version IV, df=6, $P > 0.5$ for both). Versions I and II give inadequate fits to

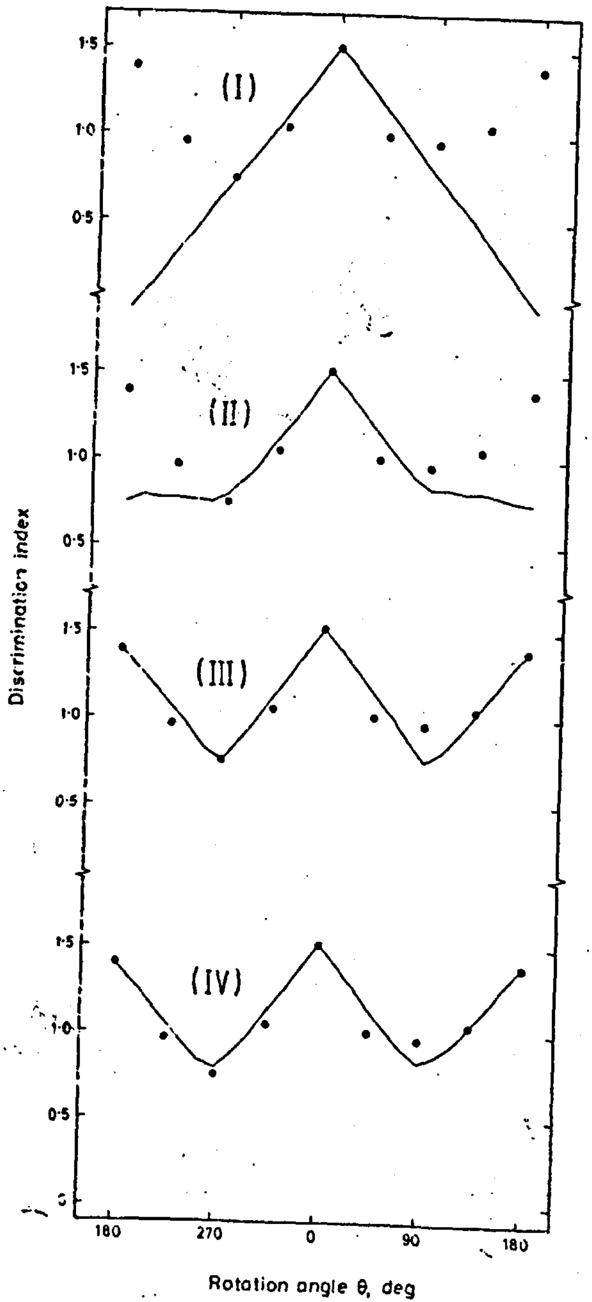


Fig. 10.4 Recognition performance of the relational-structure model. The continuous lines show predicted discrimination performance of same-shape patterns from different-shape patterns as a function of pattern rotation angle for four versions I, II, III, and IV of the model. The experimental data, pooled over 45° invervals, are indicated by the solid points.

the experimental data ($\chi^2 = 84.6$, df = 7, $P < 0.001$ and $\chi^2 = 16.2$, df = 7, $P < 0.05$ respectively.

10.4. Transformational model.

It might be suggested that the relational-structure model based on structural theories of pattern recognition (section 1.2.2.) is not the only way of predicting the data from pattern recognition experiments and that a model based on transformational theories (section 1.2.1) would also suffice.

To examine this suggestion, as a control, a transformational model, equipped with the same properties as the relational-structure model described above, was developed and tested as follows.
For a transformational model, if A and B are two patterns in the plane we may assume that each of the patterns is assigned an internal representation that, within the limits of visual acuity, is in one-to-one correspondence with the original pattern. This assumption implies that a given internal representation does not correspond to two or more visually distinguishable patterns. As a corollary to this assumption the supposed compensatory transformations and correlation operations which are applied to these representations internally may (provided the patterns and operations are defined only to within visual acuity) be considered as acting directly on the patterns A and B. Within the limits of the above assumption this external process is equivalent to the internal process.

In section 10.1 the various invariance properties with which the relational-structure encoding model was equipped were outlined. The present transformational model was also equipped with the same invariance properties as follows. In the present transformational model each of these invariances corresponds to the incorporation of a suitable compensatory transformation into the model. Position invariance is supplied by the use of planar translations $\tau_{(x,y)}$ through x,y where the plane is equipped with the usual co-ordinate system. Invariance to pattern jitter is supplied by the use of non-linear transformations $\sigma^{r}_{(x_i,y_i)}$ described below. Invariance to pattern reflection in a vertical axis and pattern inversion are supplied by reflection in the y-axis μ_y and inversion ι respectively.

Thus the compensatory action of some combinations of these pattern transformations may be applied to the pattern A to give the pattern A'. The correlation between this transformed pattern and the other pattern B forming the pattern pair (A,B) is here measured by a modification of the overlap integral.

$$\iint A'(\xi,\eta)B(\xi,\eta)\,d\xi\,d\eta$$

where $A'(\xi,\eta)$ and $B(\xi,\eta)$ are the planar luminance distributions of A' and B respectively.

The model outlined so far is applicable to any pattern pair A, B and not just dot patterns. The modification to the overlap integral is, however, specific to the particular dot patterns considered here and consists of a replacement of the rectangular functions describing the luminance distribution of single dots by delta functions at the dot centres. This replacement procedure means that a dot in one pattern is either completely overlapped or not overlapped at all by a dot in the other pattern. The overlap integral thus formed is equivalent to a comparison of the two patterns on a dot to dot basis and is the sum of the pairs of dots that overlap. In order to allow for invariance to pattern jitter the delta functions comprising one pattern of the pair being compared are "allowed to move" within a limiting circle of radius r thus allowing local distortion. These local movements are produced by the non-linear transformations $\sigma^{r}_{(x_i,y_i)}$ which shift the centre of each dot p_i through (x_i,y_i), where $x_i^2 + y_i^2 < r^2, i=1, 2, \ldots, n$ (for n points forming a pattern). The radius of the limiting circle r is here referred to as the "jitter parameter". The compensatory translations τ, and jitter σ are adjusted to maximise the overlap or correlation coefficient in each of three conditions corresponding to the three discrete pattern invariances considered i.e. Id, μ_y and ι. This maximisation process might be visualized as follows. If we consider two random-dot patterns then the second pattern is placed over the first pattern and the whole second pattern is translated to give a maximum number of coincident dot pairs. In addition to this translation of the whole pattern the centres of individual dots in the second pattern are independently moved within circles of radius r to give a maximum number of dots coincident in the two patterns. Each of these processes is repeated until the maximum possible number of coincident dot pairs obtainable within these constraints has been found.

From these correlation coefficients (or overlaps) it is possible to compute, as in the relational structure encoding model, predicted pattern recognition performance for each of the discrete invariances, Id, μ_y and ι, to give as before d'^{T}_{α}, α = Id, μ_y, ι (see Appendix B, Section 10.7).

Four versions of the transformational model are considered which are equipped with identical invariances to the four versions of the relational-structure encoding model. These four versions are derived from the theoretical values of pattern recognition performance for each invariance d'^{T}_{α}, α = Id, μ_y, ι, as follows.

I. $d'^{T}_{1}(\theta) = d'^{T}_{Id}(\theta)$

Here the model output $d'^{T}_{1}(\theta)$ is determined solely by the fixed invariances of pattern translation τ and jitter σ .

II. $d'^{T}_{2}(\theta) = \max\left\{d'^{T}_{Id}(\theta),\ d'^{T}_{\mu_y}(\theta)\right\}$

As well as the fixed invariances to pattern translation and jitter, this version also includes invariance to pattern reflection in a vertical axis.

III. $d'^{T}_{3}(\theta) = \max\left\{d'^{T}_{Id}(\theta),\ d'^{T}_{\mu_y}(\theta)\right\}$

This version of the model incorporates invariance to pattern inversion as well as the fixed invariances of version I.

IV. $d'^{T}_{4}(\theta) = \max\left\{d'^{T}_{Id}(\theta),\ d'^{T}_{\mu_y}(\theta),\ d'^{T}_{\iota}(\theta)\right\}$

This final version of the model incorporates invariance both to pattern reflection in a vertical axis and to pattern inversion in addition to the fixed invariances of version I.

Note that the use of the maximum here assumes that the performance of the model is the best of these available from the comparisons made with each of the discrete invariances.

Each of these versions of the model were evaluated by computer for the 21 same-shape pattern pairs and 24 different-shape pattern pairs used by Foster (1978b) at angles $\theta = 0^{\circ}, 15^{\circ}, \ldots, 345^{\circ}$. Each version of the model was also evaluated for four values of, the only free parameter, the jitter parameter r.

The output of the various versions of the transformational model are shown in Fig 10.5.

On the oridinate the predicted recognition performance is shown in terms of the discrimination d' as a function of the rotation angle θ. The results from each version of the model are shown for

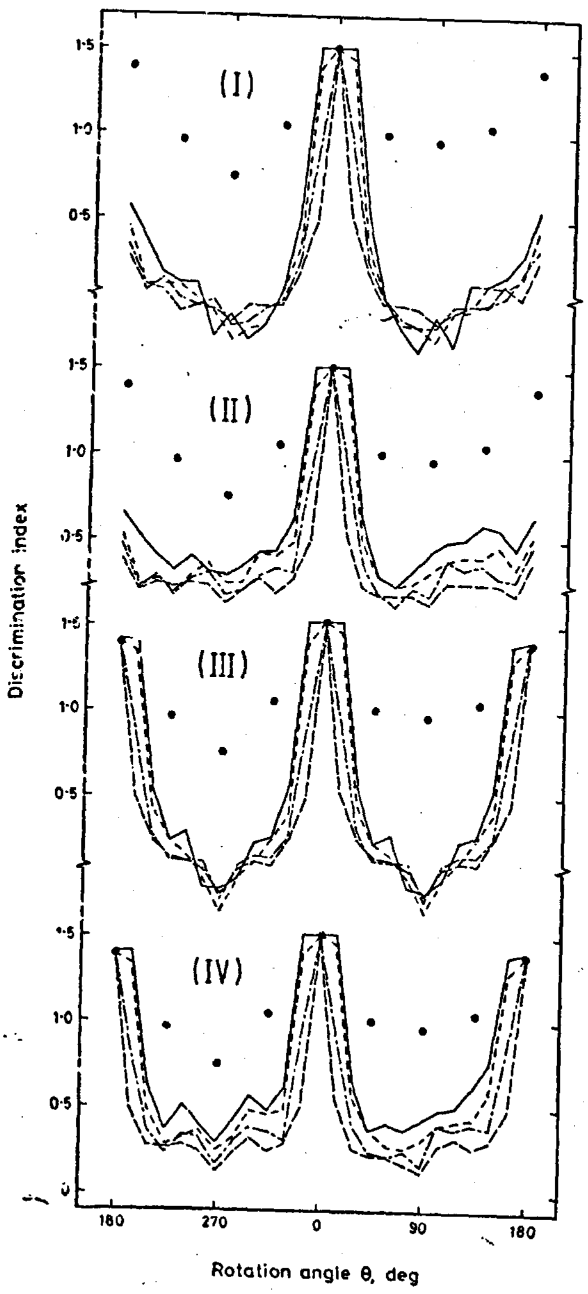


Fig. 10.5. Recognition performance of the transformation model. Predicted discrimination performance of same-shape patterns from different-shape patterns is plotted as a function of pattern rotation angle for four versions I, II, III, and IV of the model. The continuous and various interrupted lines are for different values of the jitter parameter r, which in terms of dot-diameters are thus: --- 1.0, -.-. 1.5, —-—2.0, ——2.5. The experimental data, pooled over 45° intervals, are indicated by solid points.

various values of the jitter parameter r expressed in terms of dot diameters. The filled points indicate the experimental data from Foster (1978b) pooled over 45° intervals. Both the theoretical and experimental data is averaged over pattern pairs.

As can be seen from Fig 10.5 the fit of the theoretical to the experimental data is poor for all cases of every version of the model. The best fit is obtained for version IV where both invariance to pattern reflection in the vertical axis and invariance to pattern inversion are included in the model. Even this best fit fails to predict values of recognition performance at intermediate angles between 0° and 180°. Analysis of the deviations of the version IV, $r = 2.5$ model from the experimental data indicate that the lack of fit is highly significant ($\chi^2=59$, $df=6$, $P< 0.001$, based on formulae from Gourevitch and Galanter, 1977).

10.5. Discussion.

A structural theory of pattern recognition achieves the recognition of one pattern being the same as another on the basis of internal representations in terms of pattern features and relations. In the present chapter a model based on relational-structure encoding was developed and used to predict the experimental data of Foster (1978b) for rotated random-dot patterns. This relational-structure encoding model was equipped with fixed invariances to pattern translation and jitter and different versions of the model were equipped with various additional discrete transformations. It was found that in order for the relational-structure encoding model to be able to predict the upturn in pattern recognition performance for pattern rotations of 180° a discrete invariance to pattern inversion had to be incorporated into the model. Once equipped with this invariance to pattern inversion, however, the relational-structure encoding model provided a good fit to the experimental data at all pattern rotation angles. Note that the incorporation of invariance to pattern inversion into the relational-structure encoding model was relatively simple. For, given the ability to reverse relations specifying "left of", "right of", "above" and "below" en bloc this invariance to pattern inversion is accomplished.

The relational-structure encoding model shows, therefore, the power of structural theories in predicting pattern recognition performance and illustrates how such a model might be used in the interpretation of pattern recognition experiments. In previous chapters it has been shown how adaptation and discrimination-under-uncertainty techniques may be used to investigate the feature part of a supposed structural description. We might suppose that the present pattern recognition technique may be used to investigate the restrictions placed on the relational-structure part of the supposed structural description. For example, the present findings indicate that certain operations, such as relation reversals, may be carried out on the pattern encoding.

Kahn and Foster (1981) have examined the pattern recognition performance for random-dot patterns presented to various parts of the visual field and concluded that relations may be defined with respect to the fixation point. In addition they conclude that both discrete, e.g. relation reversal, and continuous, e.g. pattern translation, operations may be carried out on the pattern encoding. The present study has shown that for at least one of these operations, i.e. relation reversal, a structural theory produces a good quantitative fit to experimental data.

It was suggested that a transformational model might also be able to predict the present data. Thus in section 10.4 a transformational model equipped with the same invariances as the relational-structure encoding model was developed. In order to predict the upturn in pattern recognition performance at 180° this model also required the incorporation of a discrete invariance to pattern inversion. All the versions of the transformational model, however, failed to adequately fit the experimental data at all pattern rotation angles.

The inadequacy of the transformational model may be illustrated by considering a pattern B consisting of a line of ten dots. If A is pattern B rotated through 90° and the dots in the pattern are sufficiently separated then the maximum pattern overlap is one dot pair for any of the discrete invariances; this corresponds to a correlation coefficient of 0.1. The mean correlation coefficent for randomly paired patterns is found to be not less than 0.3, thus the discrimination performance for such a linear dot pattern predicted from versions I, II, III and IV of the transformational model is negative (see Appendix B, section 10.7, equation 10.5). This result would imply that the linear pattern pair are less recognisable than randomly paired patterns and clearly causes difficulty for the transformational model.

Within the context of the present models, therefore, the relational-structure encoding model appears to be the more economical and powerful of the two types. For, given pattern encoding in terms of relations "left of", "right of","above", "below" and the possibility of the en bloc reversal of all such relations the model is able to correctly predict pattern recognition performance for rotated random-dot patterns.

The disadvantage of the relational-structure encoding model, in its present form, is its inability to deal with patterns in which some, but not all pattern features and relations are changed, To resolve this problem it would be necessary to know in what way the local features are appropriately assigned. This problem does not arise, however, for the same-shape patterns studied here.

10.6 Appendix A

Using the notation of section 10.3. the concurrence of the relational-structure representations of patterns A and B, $R'(A)$ and $R'(B)$ may be measured as follows.

Recall that $$R'(A) = \left\{ r_x(q_i,q_j), r_y(q_i,q_j) \;\middle|\; 1 \leqslant i < j \leqslant n \right\}$$

where $$q_i = \rho_\theta(p_i), \qquad 1 \leqslant i \leqslant n$$

and $$R'(B) = \left\{ r_x(p_i,p_j), r_y(p_i,p_j) \;\middle|\; 1 \leqslant i < j \leqslant n \right\}$$

Then if we let

$$\begin{aligned} m^x_{i,j}(\theta) &= 1 \text{ if } r_x(p_i,p_j) = r_x(q_i,q_j) \\ &= 0 \text{ otherwise} \end{aligned}$$

and let $$\begin{aligned} m^y_{i,j}(\theta) &= 1 \text{ if } r_y(p_i,p_j) = r_y(q_i,q_j) \\ &= 0 \text{ otherwise} \end{aligned}$$

A measure of the concurrence of these relational-structure representations is given by the two sums.

$$m^x(\theta) = \sum_{i<j} m^x_{i,j}(\theta) \qquad m^y(\theta) = \sum_{i<j} m^y_{i,j}(\theta)$$

Thus if $\theta = 0^\circ$ the two patterns are identical and $m^x(\theta) = m^y(\theta) = n(n-1)/2$

and if $\theta = 180^\circ$, $m^x(\theta) = m^y(\theta) = 0$.

The two measures $m^x(\theta)$ and $m^y(\theta)$ of relational changes between individual dots in the pattern include unnecessary information concerning changes in the true pattern features which consist of dot clusters. The effect of this unnecessary information is to smooth changes in $m^x(\theta)$ and $m^y(\theta)$ with the angle θ. This smoothing effect may be neglected in the present analysis as a subsequent general smoothing occurs when the responses are averaged over individual patterns.

Note that the above derivations of $m^x(\theta)$ and $m^y(\theta)$ assume that individual dots in the patterns may be labelled, that is, distinguished from one another on the basis of their relative positions. If this labelling assumption was untrue then at least two different dots p_1 and p_2 could be found in a pattern which by some non-zero rotation and translation the pattern could be brought into coincidence with itself and the dots p_1 and p_2 superimposed. The fact that on average the same-shape patterns used in this study only coincide at $\theta = 0^\circ$ (Appendix C, Section 10.8) supports the assumption that individual dots in the patterns are labelled as a consequence of their relative positions.

The incorporation of discrete invariances to reflection in a vertical axis μ_y and pattern inversion ι into the relational-structure model is accomplished as follows. If all relations "left of" are replaced by "right of" and vice versa this is equivalent to the reflection μ_y in terms of its effect on the relational-structure representation. This is equivalent to replacing $m^x(\theta)$ by $n(n-1)/2-m^x(\theta)$. Similarly the joint exchange of all relations "left of" by "right of" and "above" by "below" is equivalent to the inversion ι. In the above notation this corresponds to replacement of $m^x(\theta)$ by $n(n-1)/2 - m^x(\theta)$ and the replacement of $m^y(\theta)$ by $n(n-1)/2 - m^y(\theta)$. In order to convert the outputsof the model in terms of $m^x(\theta)$ and $m^y(\theta)$ into discrimination indices for each of the discrete invariances the $m^x(\theta)$ and $m^y(\theta)$ are each normalised at 0.5 ($m^x(0) = m^y(0) = 0.5$). Thus corresponding to each invariance property we have the predicted discrimination index $d'^T(\theta)$ for the same shape pattern pair $(\rho_\theta(B), B)$ as follows.

$$d'^{T}_{Id}\ (\theta) \quad = \quad d'^{E}_{Id} \cdot (m^{x}(\theta) + m^{y}(\theta))$$

$$d'^{T}_{\mu_y}\ (\theta) \quad = \quad d'^{E}_{\mu_y} \cdot (1 - m^{x}(\theta) + m^{y}(\theta))$$

$$d'^{T}_{\iota}\ (\theta) \quad = \quad d'^{E}_{\iota} \cdot (1 - m^{x}(\theta) + 1 - m^{y}(\theta))$$

where d'^{E}_{α} are given in table I.

10.7. Appendix B

Using the notation of section 10.4, let A (x,y) and B (x,y) be the planar luminance distributions of the two random-dot patterns A and B to be compared. Let A* (x,y) and B* (x,y) be the planar luminance distributions of the patterns A and B after the rectangular functions representing the luminance distribution of single dots have been replaced by delta functions placed at the dot centres (section 10.4.) Then the correlation coefficient c_{Id}, for comparison of A' with B where the comparison pattern A' = Id(A) is given by.

$$c_{Id} = \max_{(x,y)} \max_{[(xi,y_i)]} \iint \tau_{(x,y)} \circ \sigma^{r}_{[(x_i,y_i)]} (A^*)(\xi , \eta) . \; B^*(\xi , \eta)\, d\xi \, d\eta \tag{10.2}$$

The corresponding correlation coefficient when the comparison pattern A' is reflected in the vertical (y) axis, i.e. A' $= \mu_y(A)$ is given by.

$$c_{\mu_y} = \max_{(x,y)} \max_{[(x_i,y_i)]} \iint \tau_{(x,y)} \circ \sigma^{r}_{[(x_i,y_i)]} \circ \mu_y (A^*)(\xi , \eta) . \; B^*(\xi , \eta)\, d\xi \, d\eta \tag{10.3}$$

The third correlation coefficient when the comparison pattern A' is inverted (i.e. rotated through 180°) i.e. A' = ι (A) is similarly given by.

$$c_{\iota} = \max_{(x,y)} \max_{[(x_i,y_i)]} \iint \tau_{(x,y)} \circ \sigma^{r}_{[(x_i,y_i)]} \circ \iota (A^*)(\xi , \eta) . \; B^*(\xi , \eta)\, d\xi \, d\eta \tag{10.4}$$

All integrations are over the plane.

The maximisation of overlap process was accomplished here by calculating the value of the various coefficients <u>c</u> for a range of values of (x,y) and (x_i, y_i), arranged to cover all possibilities, and then taking the maximum. Note that the "brute force" method employed for the computations here may be replaced by a computationally less demanding relaxation method (Rosenfeld, 1977). Each of these correlation coefficients is normalized to unity such that for all the possible pattern pairs A,B

$$\max_{A,B} \left\{ c_\alpha \right\} = 1 \qquad \alpha = \mathrm{Id}, \mu y, \iota$$

Now if the pattern A is a rotated version of the pattern B such that $A = \rho_\theta$ (B) where θ is the angle of rotation we may determine each of the above correlation coefficients for the pattern pair A, B. We may denote these correlation coefficients as $c_\alpha(\theta)$ for $\alpha = \mathrm{Id}$, μy, ι. Note that the $c_\alpha(\theta)$ also depend upon the pattern B but the notation is shortened here as the model output is eventually averaged over all patterns. The correlation coefficients from randomly paired patterns C,D may be averaged over all pattern pairs C, D and denoted by $\tilde{c}_\alpha$ for $\alpha = \mathrm{Id}, \mu y, \iota$.

The conversion of the same-shape correlation coefficient $c_\alpha(\theta)$ to discrimination index d' by a suitable linear scaling may be accomplished in two ways. One method is to compute the discrimination index directly using $c_\alpha(\theta)$ and $\tilde{c}_\alpha$ as theoretical "hit" and "false alarm" rates respectively and then scale the result if necessary. A second method is to subtract from $c_\alpha(\theta)$ the corresponding averaged random pair coefficient $\tilde{c}_\alpha$ and then to normalize. Thus the predicted discrimination index $d'^{T}_{\alpha}(\theta)$ for the same shape pattern pair (ρ_θ (B),B) for discrete invariance property α is given by.

$$d'^{T}_{\alpha}(\theta) = d'^{E}_{\alpha} \cdot \frac{c_\alpha(\theta) - \tilde{c}_\alpha}{1 - \tilde{c}_\alpha} \qquad \alpha = \mathrm{Id}, \mu_y, \iota \qquad 10.5$$

Where d'^{E}_{α} are the experimentally determined discrimination indices for each discrete invariance given in Table I.

The latter form of linear scaling was chosen here (choice of the former method does not materially effect the result) for it is then of the same form as the scaling used in the relational structure model.

10.8. Appendix C.

The mean rotation autocorrelogram for the 21 same-shape patterns used in the present analysis was calculated as follows.

Using the notation of the transformational model described in section 10.4 if we consider equation 10.2 reproduced below.

$$c_{Id} = \max_{(x,y)} \max_{[(x_i,y_i)]} \iint \tau_{(x,y)} \circ \sigma^{r}_{[(x_i,y_i)]} (A^*)(\xi , \eta). B^*(\xi , \eta) d\xi \, d \eta$$

If B is an arbitary dot pattern then the substitution of A = $\rho_\theta(B)$ and use of jitter parameter equal to one dot radius gives the autocorrelation equation.

$$c_{Id}(\theta) = \max_{(x,y)} \max_{[(x_i,y_i)]} \iint \tau_{(x,y)} \circ \sigma^{r}_{[(x_i,y_i)]} \circ \rho_\theta (B^*)(\xi , \eta). B^*(\xi , \eta) d\xi \, d\eta$$

Fig 10.6. shows the average of these autocorrelations for the 21 same-shape patterns. On the ordinate is plotted the correlation coefficient against the angle θ on the abscissa. As can be seen a low correlation exists at all points except when the patterns are coincident at $\theta = 0^{\circ}$.

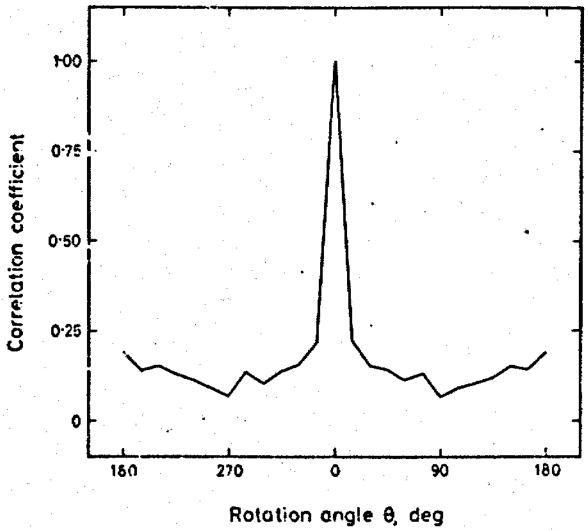


Fig. 10.6 Mean rotation autocorrelogram of the 21 dot patterns.

CHAPTER 11. SUMMARY AND CONCLUSIONS.

In structural theories of pattern recognition the internal representation of a pattern may be considered as consisting of two types of component, the one features, e.g. spots, lines and edges, the other spatial relations between these local features, e.g. above, connected to, and within. This thesis has examined the results from experiments in which both adaptation and pattern recognition techniques were used within the framework of structural theories.

In particular, the effects of changes of pattern relational-structure on the results of contrast threshold elevation effect and pattern recognition experiments have been considered. To investigate structural theories it is natural to use stimulus patterns which can be described simply in terms of their features and relations. Thus in the experiments described in this thesis patterns formed from simple bar and spot features with certain spatial relationships between these features were used, e.g. T- and L-shaped patterns.

In the following section a summary of the main findings of each chapter is given.

11.1. Summary.

Chapter 3 described the Maxwellian view apparatus developed for the measurement of contrast threshold and the general methodology used for these measurements was discussed. In particular it was noted that periodic fluctuations can occur in the contrast threshold which could give rise to errors if the more common practice of measuring baseline contrast thresholds before and after an experimental run is used. To partially compensate for these periodic fluctuations of threshold a method was proposed in which contrast threshold measurement after adaptation to a structured pattern is preceded and followed by a contrast threshold measurement after adaptation to a uniform field. This "bracketing" procedure places the baseline contrast threshold measurements in closer proximity to the measurements concerned with adaptation effects of the structured patterns and therefore any effects of periodic fluctuations of the contrast threshold are reduced. This procedure was used in all of the contrast threshold elevation measurements described in succeeding chapters.

Chapter 4, the first of the experimental chapters, was concerned with the development of the adaptation technique used to investigate the adaptational sensitivity of putative detecting mechanisms in the visual system to the feature and relation components suggested by structural theories. The technique developed here differs from that of earlier studies in the use of a single test figure which may be simply described in terms of a collection of features and some spatial relationships between them. The present technique also differs from previous studies in that the adaptation patterns used here consisted of many copies of the "features" comprising the test pattern distributed within the visual field in a manner that did or did not preserve local relational structure.

Because of the novelty of the present technique it was necessary to establish whether the adaptation and test patterns used would give rise to a contrast threshold elevation effect similar to that found with, for example, grating patterns. The results of the experiments described in Chapter 4 indicated that the patterns used did give rise to a contrast threshold elevation effect and in addition that this effect was unlikely to be a result of local retinal adaptation.

Adaptation to a pattern which contained the same local features in the same spatial relationships as in the test pattern was found to elevate the test contrast threshold more than adaptation to a pattern containing only the same local features as the test pattern (section 4.1.). On further investigation this differential effect on contrast threshold was found to be dependent on local retinal adaptation effects. This dependency was revealed by the use of either a test pattern consisting of multiple copies of the single test pattern (section 4.3.) or by subjecting the adaptation patterns to small saccade-like displacements which could not be visually tracked (section 4.2.). Both of these methods it was argued should have significantly reduced any effects of local retinal adaptation which may have artefactually elevated the contrast threshold of the single test pattern. The use of any of these local adaptation reduction procedures removed the difference in contrast threshold produced with a single test pattern and stationary adaptation patterns. The notion that the use of a moving adaptation pattern differentially affected the contrast threshold elevating ability of the two adaptation pattern types was shown to be unlikely because the combination of multiple test pattern and saccade-like displacements of the adaptation patterns failed to restore any differential contrast threshold elevation of the test pattern (section 4.4.).

The adaptation technique finally chosen for use in the experiments described in subsequent chapters was, therefore, one in which local adaptation was reduced by the imposition of saccade-like displacements on the adaptation patterns. A single test pattern was also chosen since its description in terms of structural components is simple compared with a description in such terms of the multiple test pattern.

Chapter 5 was concerned with the spatial specificities of the patterns used in the adaptation experiments described in this thesis. The experiments of Chapter 4 had established that the present adaptation technique gave rise to a contrast threshold elevation effect.

The experiments described in Chapter 4 had not established, however, whether the effect showed any specificity for pattern shape. The first experiment described in Chapter 5 therefore was performed to measure the contrast threshold elevating effect of adaptation patterns consisting of subpatterns either with the same shape as the single T test figure or with a different shape from the T test figure (i.e. of area equal to that of the test figure). The result of this experiment revealed a greater adaptational sensitivity of the mechanism detecting the T test pattern to the T adaptation pattern than to the disc adaptation pattern. This result was interpreted as showing that the contrast threshold elevation effect measured here exhibited specificity for pattern shape. (section 5.1.). Other measurements of the contrast threshold elevation effect using either periodic or repetitive random patterns have shown that the contrast threshold elevation effect shows specificity for line orientation, pattern size, and line length. The other experiments described in Chapter 5 examined these spatial specificities using the present adaptation technique. The effect measured here was shown to exhibit specificity for the orientation of single lines and also for the orientation of more complex T-shaped figures. Line length selectivity was examined using single line test figures and length specificity was found for lines with length-to-width ratios of 1, 3 and 7 but no significant length selectivity was found for lines with a length-to-width ratio of 5. It was suggested that the difference of this result from that of Burton and Ruddock (1978), who found loss of length selectivity for bar length-to-width ratios greater than about 3, might be due to differences in the stimulus luminance-equating procedures used. It was concluded that line length specificity was shown in certain circumstances but that the presence of such specificity was not simply related to the length-to-width ratios of the line pattern used.

The final experiment described in Chapter 5 examined the effect of varying the size of subpatterns discs forming the adaptation pattern on the contrast threshold of a T test pattern. In agreement with the findings of Naghshineh and Ruddock (1978) using grating and disc patterns the results of this final experiment revealed the greatest contrast threshold elevation when the adaptation discs had diameters equal to the bar width of the elements forming the T test pattern. This result is consistent with the existence of two mechanisms, the one sensitive to disc patterns and the other sensitive to bar patterns as suggested by Naghshineh and Ruddock (1978). It was argued that the equality of the contrast threshold elevation after adaptation either to a T adaptation pattern or a disc adaptation pattern consisting of discs of diameter equal to bar element widths might be attributable to local luminance differences between T- and disc-shaped subpatterns. It was argued that adaptation patterns consisting of discs of area equal to that of a subpattern may be used as a control to ensure that the contrast threshold elevations measured in a particular experiment are not a result of some general adaptation to any spatially non-uniform pattern. In particular, the use of an adaptation pattern consisting of equal area discs ensures that contrast threshold elevation changes measured in an experiment cannot be attributed to changes in global pattern structure, pattern mean luminance and subpattern local luminance.

From the results of experiments described in Chapter 5 it was concluded that in general the contrast threshold elevation effect measured with the adaptation technique used in this thesis showed similar spatial specificities to those measured with other techniques and patterns.

Chapter 6 contained a discussion of some of the experimental findings of Chapters 4 and 5 from the viewpoint of structural theories of pattern recognition and in addition experiments to investigate the adaptational sensitivity of the visual system to various pattern connectivity relations were described.

The findings of Chapter 5 that the contrast threshold elevation of a single T test pattern was the same after adaptation to a pattern containing multiple copies of the test pattern and after adaptation to a pattern containing the disconnected bar elements comprising the T-shaped subpattern was argued in Chapter 6 to be indicative of a lack of adaptational sensitivity to relative spatial position. In particular, it was argued that the results of the above experiment might be interpreted as an adaptational insensitivity to the spatial relation specifying "T-connectedness". It was also argued that these results could be equivalently interpreted as an insensitivity to relative spatial phase if the patterns were considered to be subjected to some form of Fourier analysis in the encoding process. To test the generality of the conclusion that the detecting mechanism is insensitive to the spatial relation defining "connectedness", experiments were conducted in which the T-shaped figures were replaced by line figures with different connectivity relations, i.e. L-, chevron- and bar-shaped figures. In all these configurations no adaptational sensitivity to spatial relationships defined by the relation specifying "connectedness" was revealed. As a control, in each of the above cases the contrast threshold elevation of the test pattern was measured after adaptation to a pattern consisting of discs with area equal to the test figure area. The contrast threshold elevation of the test pattern was found to be smaller after adaptation to the disc adaptation pattern than after adaptation to the adaptation pattern consisting of copies of the test pattern for all of the connectivity relations considered. This finding was interpreted as showing that the results of the main experiments with L-,chevron-,bar-shaped and disconnected bar patterns were not a result of a general adaptation to any spatially non-uniform pattern.

Chapter 7 contained a description of an experiment to examine the notion that curves are detected as the concatenation of their tangential line segments. The adaptation technique described in earlier chapters was used to test this conjecture directly with a single test pattern consisting of three orientated line segments to form a curve-shaped figure. The adaptation pattern used was either one consisting of multiple copies of the curve-shaped figure or one consisting of the independently distributed and appropriately orientated line segments comprising the curve-shaped figure. No difference was found in the contrast threshold elevations of the curve test pattern after adaptation to either the curve adaptation pattern or the disconnected pattern. This result was interpreted as an indication that the mechanisms detecting the curve pattern were only adaptationally sensitive to the line segments forming the curve. These results were also discussed from the viewpoint of structural theories of pattern recognition and it was concluded that the detecting mechanism was not adaptationally sensitive to the spatial relationships defined by a relation or relations specifying curvature.

A control experiment was performed as in Chapter 6 with the same test pattern as above, the curve adaptation pattern, and an adaptation pattern consisting of discs each with an area equal to that of a single curve subpattern. As in previous experiments (section 5.1.) this disc adaptation pattern was used to check that the present technique was revealing sensitivity to local structure and not just sensitivity to either global pattern structure or general pattern non-uniformity.

The results of this control experiment showed a greater test contrast threshold elevation after adaptation to the curve adaptation pattern than after adaptation to the disc adaptation pattern and therefore confirm that the results from the experiment with curve and disconnected bar adaptation patterns are not simply a consequence of a general adaptation to any spatially non-uniform pattern.

Chapter 8 contained a description of experiments to investigate the adaptational sensitivity of mechanisms detecting small localised grating patterns. A test pattern consisting of small bars arranged to form a grating was used. The contrast threshold elevation of this test pattern was measured after adaptation to an adaptation pattern consisting of copies of the test grating and after adaptation to an adaptation pattern consisting of pseudo-randomly distributed copies of the component bars of the grating. The results of the experiments described in this chapter revealed a greater contrast threshold elevation of the single test grating after adaptation to the pattern containing multiple copies of the test grating than after adaptation to the patterns containing the randomly distributed component bars of the gratings. These results were discussed from the viewpoint of structural theories of pattern recognition and it was concluded that the mechanism detecting the test grating was adaptationally sensitive to spatial relationships defined by the relation or relations specifying local periodicity or repetitiveness in the patterns. It was also noted that the present results agree with those found with larger global grating patterns and in addition indicate adaptational sensitivity to local periodicity. The latter finding is consistent with the suggestion that the visual system performs a Fourier analysis of patterns on a patch-by-patch basis (Robson 1975) and that the analysis of larger grating patterns is performed by a combination of these patch-by-patch analyses. It was argued in section 1.5.5., however, that such a patch-by-patch scheme was equivalent to a structural theory of pattern analysis. In chapter 8 it was also noted that we would expect sensitivity to local periodicity to be shown by mechanisms sensitive to a limited range of sizes. Thus in view of the size selectivity of the mechanisms involved in the contrast threshold elevation effect (section 5.3.) it is not surprising that these mechanisms also show adaptational sensitivity to local periodicity.

The experiments described above were carried out with the grating bars orientated either parallel to or orthogonal to the direction of the saccade-like displacements imposed on the adaptation patterns. Changing the orientation in this way did not affect the difference between the contrast threshold elevation after adaptation to the grating pattern and that after adaptation to the disconnected bar pattern. Thus the changes of contrast threshold elevation that did occur with pattern orientation changes do not affect the previous discussion of sensitivity to local periodicity. Some changes in absolute contrast threshold elevations did, however, occur. It was reasoned that these changes in contrast threshold elevation might be attributable either to a general change of adaptability between the two sets of experiments or to a change in the amount of local retinal adaptation at the two orthogonal orientations. The latter effect was thought to occur as a consequence of the tendency of the vertical saccade-like displacements to be more effective at "smearing" the retinal image of a grating with horizontally orientated bars than one with vertically orientated bars.

Chapter 9 describes experiments using both the adaptation technique developed here and a discrimination-under-uncertainty grating patterns is performed by a combination of these patch-by-patch analyses. It was argued in section 1.5.5., however, that such a patch-by-patch scheme was equivalent to a structural theory of pattern analysis. In chapter 8 it was also noted that we would expect sensitivity to local periodicity to be shown by mechanisms sensitive to a limited range of sizes. Thus in view of the size selectivity of the mechanisms involved in the contrast threshold elevation effect (section 5.3.) it is not surprising that these mechanisms also show adaptational sensitivity to local periodicity.

The experiments described above were carried out with the grating bars orientated either parallel to or orthogonal to the direction of the saccade-like displacements imposed on the adaptation patterns. Changing the orientation in this way did not affect the difference between the contrast threshold elevation after adaptation to the grating pattern and that after adaptation to the disconnected bar pattern. Thus the changes of contrast threshold elevation that did occur with pattern orientation changes do not affect the previous discussion of sensitivity to local periodicity. Some changes in absolute contrast threshold elevations did, however, occur. It was reasoned that these changes in contrast threshold elevation might be attributable either to a general change of adaptability between the two sets of experiments or to a change in the amount of local retinal adaptation at the two orthogonal orientations. The latter effect was thought to occur as a consequence of the tendency of the vertical saccade-like displacements to be more effective at "smearing " the retinal image of a grating with horizontally orientated bars than one with vertically orientated bars.

Chapter 9 describes experiments using both the adaptation technique developed here and a discrimination-under-uncertainty technique to investigate the relative importance of the features and relations of a structural theory of pattern recognition in producing the results obtained with these techniques. It was argued that the adaptation technique reveals the properties of peripheral stages of pattern analysis and that the supposed internal representation on which the discrimination-under-uncertainty judgements were based was composed from information obtained at an early stage of pattern analysis. Thus it was suggested that these two techniques should provide similar results if analogous conditions were used.

In the adaptation experiment a single T test pattern and adaptation patterns consisting of randomly distributed subpatterns were used. The adaptation patterns had either features or relations, or both, in common with the test pattern. Bars of different orientations were assumed to be different features. The adaptation pattern subpatterns were therefore T-shaped figures with bar element orientations the same as those of the test, T-shaped figures with bar element orientations at 45° to those of the test, and L-shaped figures with bar element orientations the same as those of the test. The results of the adaptation experiment indicated that adaptation patterns with the same bar element orientations as those of the test figure gave the same contrast threshold elevation despite differences in subpattern connectivity. Changing the adaptation pattern so that its bar element orientations were at 45° to those of the test pattern, however, reduced the contrast threshold elevation of the test pattern. These results were interpreted in terms of a structural theory of pattern recognition and it was concluded that the mechanisms involved in the contrast threshold elevation effect were adaptationally more sensitive to the pattern features than the spatial relationship between these features.

The discrimination-under-uncertainty technique used here required the subject to detect the presence of an odd subpattern embedded in a field of disconnected bar elements. The odd subpattern was presented using a two-interval forced-choice procedure and appeared in any one of 19 random positions within the field of disconnected bar elements. The odd subpattern was composed of two bar elements with orientations either parallel to or at 45° to the background bar-element orientations. These two bar elements comprising a sub pattern were connected together to form either a T-shaped or an L-shaped figure. Four possible odd subpatterns occurred: L, T, tilted -L and tilted-T (where tilted means at 45° to the background bars).

The most significant result of this discrimination-under-uncertainty experiment was that the distinguishability of the tilted odd subpatterns from the background bars was greater than the distinguishability of the untilted odd subpatterns from the background bars. This result was interpreted as a greater sensitivity of the detecting mechanism to changes in line slope than to changes in line arrangement, because the differences between the discriminabilities of odd subpatterns which only differed in line arrangement were small compared with the differences between the discriminabilities of odd subpatterns which differed in line slope.

In terms of a structural theory of pattern recognition these results of the discrimination-under-uncertainty experiment were interpreted as showing a greater sensitivity to pattern feature changes than to changes in relational-structure. This conclusion was identical with the conclusion from the adaptation experiment. This similarity of the results from the adaptation and discrimination-under-uncertainty experiments supports the suggestion that both of these techniques reveal the properties of the more peripheral stages of pattern processing.

The results of the discrimination-under-uncertainty experiment also showed that in general all of the odd subpatterns were detected at an above chance level, although this might have been attributable to local luminance changes. This result might be interpreted as a general discriminability of connected from disconnected patterns and from a structural theory viewpoint might be interpreted as a general sensitivity to the relations defining connectivity. Note, however, that this result did not indicate a sensitivity to changes of connectivity relations. In the discrimination-under-uncertainty experiment a greater discriminability from the background bars was found for the tilted-L than for the tilted-T patterns and this was interpreted as evidence for the possible existence of mechanisms sensitive to "right-angles" or alternatively sensitive to a relation specifying L-connectedness.

Chapter 10 described a model for the recognition of rotated random-dot patterns which was based on structural theories of pattern recognition. This model was used to investigate how structural theories may be used to predict visual pattern recognition performance and also what properties such a model must possess. The model described in Chapter 10 used the encoding of relational-structure in terms of the relations "above", "below,""left of" and "right of" to predict the recognition performance for comparison of random-dot pattern pairs which were related to each other by rotation. The predictions of this model were tested by comparison with the experimental data from Foster (1978b). It was found that in order to successfully predict the upturn in pattern recognition performance for pattern pairs related by a 180° rotation (inversion) it was necessary to equip the model with a discrete invariance to pattern inversion. **It was noted that this discrete invariance to pattern inversion could be simply incorporated into the model by allowing** en bloc reversal of the relations "above", "below","left of" and "right of" to be carried out on the relational-structure encoding. Once equipped with this invariance to pattern inversion the relational-structure encoding model gave a good quantitative fit to the experimental data of Foster (1978b) for all pattern rotation angles.

The suggestion that the data could also be predicted by a model based on transformational theories of pattern recognition was examined by constructing such a transformational model. The latter model was equipped with the same invariances as the relational-structure encoding model and was also tested by comparison with the experimental data of Foster (1978b). This transformational model failed in all of its versions to give an adequate fit to the experimental data. It was concluded therefore that the relational-structure encoding model was the most powerful and economical of the two models.

It was suggested that the findings of Chapter 10 implied that if the visual system did encode patterns in structural terms then the comparison of internal representations that is supposed to take place during pattern recognition allowed certain operations (e.g. en bloc reversal of relations) to be performed on the pattern encodings. These operations might take place before or at the same time as the comparison of the supposed internal representations.

It was noted that the relational-structure encoding model in its present form is unable to predict the recognition performance for randomly chosen pattern pairs. To be able to include this ability in the model we would require a knowledge of the way in which the visual system assigns features to a given pattern.

11.2. General conclusions.

If the findings summarised in the previous section are considered within a framework of structural theories of pattern recognition then the following model of the pattern analysis process might be proposed. If a pattern is considered to be encoded in terms of "features" and their spatial "relations" then we might suppose that the features are analysed at a peripheral stage of pattern processing and their spatial relationships are preserved for analysis at some more central site. In addition we might suppose that the internal representation formed of a pattern may be subjected to certain operations (such as reversal of relations) during the pattern recognition process. Such a model is similar to that proposed by Marr (1976) in which an initial stage of feature extraction is followed by grouping operations.

The present experiments are consistent with the model proposed above for the following reasons. The adaptation experiments described in Chapters 4 to 9 showed that in general the contrast threshold elevation effect measured with the present adaptation technique was adaptationally sensitive to pattern features and adaptationally insensitive to their spatial relationships. An exception to the latter conclusion was described in Chapter 8 where the results of an experiment to examine adaptational sensitivity to local periodicity indicated that such sensitivity did exist. It was argued in the discussion of Chapter 8, however, that this sensitivity to local periodicity was a consequence of the size selectivity shown by the contrast threshold elevation effect. In the latter case, no special mechanism sensitive to spatial relationships specified by a relation defining periodicity need exist. In fact the sensitivity to local periodicity shown in Chapter 8 may be an indication of a lack of sharp selectivity for feature size by the mechanisms involved in the contrast threshold elevation effect. This latter suggestion is consistent with the findings that the contrast threshold elevation effect shows a response to a range of feature sizes rather than to a single feature size (see Chapter 5). In conclusion it is probable that the mechanisms involved in the contrast threshold elevation effect are concerned with some peripheral feature extraction process.

The agreement of the results from the adaptation experiment and discrimination-under-uncertainty experiment described in Chapter 9 indicate that the internal representation formed when processing is limited is based mainly on the feature part of a pattern representation. The sensitivity to right-angle patterns observed in the discrimination-under-uncertainty experiment could reflect the operation either of mechanisms selective for angle (Pomerantz, 1978; Foster, 1980b) or of one of the grouping operations described by Marr (1976). Thus this selectivity for right-angle patterns may show the first stages of the inclusion of relational-structure into the internal representation.

All of the experiments described in Chapters 4 to 9 show that features and relations are evidently processed in different ways (e.g. at different sites) before their use for pattern recognition. This division of processing fits naturally with a structural theory of pattern recognition for such a theory is based on this division of pattern attributes. Such a separation of the processing of feature and relational-structure information is difficult to explain in terms of a transformational theory of pattern recognition, for in the latter theory operations are considered to be executed on a wholistic pattern representation. In view of the present results indicating the division of pattern processing at an early stage a transformational theory would, in the present context, either operate with some recombination of the feature and relation information or consist of two parallel operations on features and relations. In conclusion, the present experimental evidence favours a theory of pattern recognition based on structural descriptions.

The relational-structure encoding model described in Chapter 10 showed how a structural theory of pattern recognition may be used to predict pattern recognition performance. The close agreement of the predicted and the experimental recognition performance for a model based on the use of just four relations (above, below, left of and right of) indicates the potential power of such structural descriptions. Critically, it was necessary to allow certain operations to be performed on the relational-structure representations of the patterns to obtain this fit to the experimental data. The operations required, however, were simple and only involved reversal of the relations specifying feature relative positions. If the features and relations are processed in a different way as was suggested earlier, then operations such as relation reversal might be simply accomodated for these operations could act independently on the relational-structure of a pattern. Note that the need to incorporate the possibility of operations on relational-structure into the model for it to fit the experimental data implies that the visual system must also be able to perform such operations on a supposed internal representation in terms of pattern features and relations. Kahn and Foster (1981) have suggested that these operations on relational-structure also include ones of a transformational nature, e.g. a continuous transformation of a relation specifying "5^{o} to the left of" to a relation specifying "4^{o} to the left of". Such a suggestion is consistent with the present discussion.

In conclusion, the model of pattern analysis suggested by the present study is as follows. The analysis of a pattern is divided into the analysis of its pattern features and their spatial relations. The feature analysis process probably occurs at a peripheral stage of the visual system which is able to be adapted. The analysis of relational-structure probably occurs more centrally in the visual system. For pattern recognition purposes the relational-structure encodings of patterns may be subjected to various operations both discrete and continuous before they are compared. If processing is limited by the use of a discrimination-under-uncertainty technique then the internal representations on which discrimination judgments are based are limited to an encoding in terms of pattern features.

The adaptation technique used in the experiments described in this thesis and the discrimination-under-uncertainty technique thus provide powerful methods for the investigation of the pattern features which are encoded by the visual system. By a combination of these techniques and pattern recognition techniques it should therefore be possible to clarify how features and relations may be encoded for pattern analysis in the visual system.

In addition to the major conclusions discussed above several important points were discussed in the present thesis and these are summarized as follows.

It was demonstrated in Chapter 4 that local retinal adaptation could influence and even change the conclusions of adaptation experiments. It is therefore worth emphasising that care must be taken in any adaptation experiment to either reduce or assess the effects of local adaptation. Similarly, care must be taken to take into account any effects of the periodic fluctuations of contrast threshold in measurements of the contrast threshold elevation effect (see section 3.3).

The adaptation technique developed for the present study (Chapters 3 and 4) allows the examination of local pattern structure in contrast to earlier techniques which only allowed the examination of pattern structure as a whole. The present novel technique is therefore suited to studies based on a theoretical framework of structural pattern descriptions.

The findings of the present adaptation experiments indicate an adaptational insensitivity to local phase (Chapter 6). This finding does not support the notion that the visual system performs a patch-by-patch Fourier analysis as suggested by Robson (1975) which required phase sensitivity within a single local patch. The adaptation sensitivity to local periodicity observed in the experiments of Chapter 8 may seem to contradict this conclusion. Sensitivity to periodicity, however, may occur without sensitivity to relative phase, for the latter is a measure of the phase relationships between the sinusoidal components of periodic patterns. Thus in order to test for sensitivity to local relative phase with grating patterns it would be necessary to compare the contrast threshold elevations produced by adaptation to local gratings consisting of sinusoidal components related to each other in various phase relationships. Additionally, it has been argued that the sensitivity to periodicity observed here may be attributable to the size selectivity shown by the contrast threshold elevation effect (see Chapter 8).

The present adaptation technique allowed the direct examination of the suggestion that curves were detectedin terms of appropriately orientated line segments (Chapter 7). Although the experiments described in Chapter 7 only examined one particular curvature no evidence was found to indicate that adaptationally sensitive curvature specific mechanisms existed. Indeed, the contrast threshold elevation of a curve test pattern could be entirely attributed to adaptation of mechanisms sensitive to the component bars forming the curve.

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