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Early visual detection of oriented line targets

Spatial characteristics, temporal characteristics, and reference frames of early visual orientation-processing

LAURA MARY DOHERTY

Doctor of Philosophy

THE UNIVERSITY OF ASTON IN BIRMINGHAM

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Summary

The orientations of lines and edges are important in defining the structure of the visual environment, and observers can detect differences in line orientation within the first few hundred milliseconds of scene viewing. The present work is a psychophysical investigation of the mechanisms of early visual orientation-processing.

In experiments with briefly presented displays of line elements, observers indicated whether all the elements were uniformly oriented or whether a uniquely oriented *target* was present among uniformly oriented *nontargets*. The minimum difference between nontarget and target orientations that was required for effective target-detection (the *orientation increment threshold*) varied little with the number of elements and their spatial density, but the percentage of correct responses in detection of a large orientation-difference increased with increasing element density. The differing variations with element density of thresholds and percent-correct scores may indicate the operation of more than one mechanism in early visual orientation-processing.

Reducing element length caused threshold to increase with increasing number of elements, showing that the effectiveness of rapid, spatially parallel orientation-processing depends on element length.

Orientational anisotropy in line-target detection has been reported previously: a coarse periodic variation and some finer variations in orientation increment threshold with nontarget orientation have been found. In the present work, the prominence of the coarse variation in relation to finer variations decreased with increasing effective viewing duration, as if the operation of coarse orientation-processing mechanisms precedes the operation of finer ones.

Orientational anisotropy was prominent even when observers lay horizontally and viewed displays by looking upwards through a black cylinder that excluded all possible visual references for orientation. So, gravitational and visual cues are not essential to the definition of an orientational reference frame for early vision, and such a reference can be well defined by retinocentric neural coding, awareness of body-axis orientation, or both.

Keywords: vision psychophysics orientation preattentive search

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Chapter 1. Introduction

1.1 Motivation for the study of early visual detection of oriented line targets

1.1.1 The oriented-line-target detection task

The psychophysical experiments reported in this thesis involved detection of oriented line targets. Observers viewed displays similar to those shown in Figure 1.1. Displays were presented briefly and the observers indicated whether a line element differing in orientation from the others, a *target*, was present.

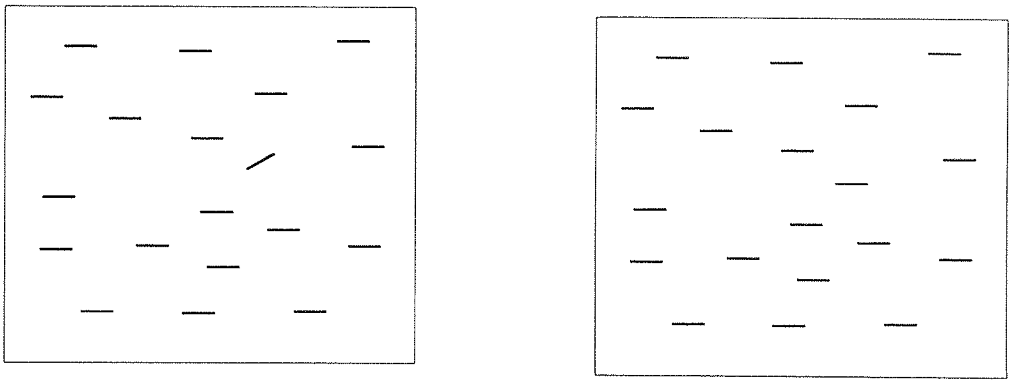

Fig 1.1. Schematic diagrams of displays used in an oriented-line-target detection task. The display on the left contains a line element differing in orientation from the rest, a *target*. The display on the right contains no target.

In the following paragraphs, the motivation for studying performance in such a task is explained.

1.1.2 Motivation for the study of early visual search and detection

Searching for objects in complex visual environments is a common activity in everyday life. It usually requires little effort from the human observer, but the visual processes involved must be extremely complex: no machine-vision system performs the task as well as a human can. Information about many aspects of the visual environment is obtained within the first few hundred milliseconds of scene viewing. The rapid visual processing that provides this information is known as *early visual processing* or *early vision*. Through investigation of this processing, insight can be gained into the way in which construction of the visual percept begins. The study of early vision might also provide useful bases for image-processing algorithms.

1.1.3 Motivation for the study of visual orientation-processing

The orientations of lines and edges define much of the structure of the observer's environment. To interact effectively with the environment, the observer requires a good explicit or implicit understanding of this structure. Line and edge orientations and orientation differences are among the features of the visual environment that are perceived most rapidly. So, studying detection of orientation differences can provide information about processes that are both essential to the observer's understanding of his surroundings and among the first to operate in visual scene analysis.

1.1.4 Understanding how early visual processes may be implemented: physiology and modelling

The study of early visual perception of orientation may provide information not only about the processes producing a visual represention of structure, but also about possible physiological implementations of those processes. There have been many physiological studies of the orientation-processing characteristics of neurones in the mammalian visual system and the interactions between such neurones. Knowledge of these physiological properties alone provides only limited insight into the production of the visual percept from neural signals. Yet if this knowledge is integrated with detailed information from psychophysical studies of orientation processing, greater insight can be gained. Physiological and psychophysical information can be integrated by constructing computational or mathematical models that both are physiologically plausible and predict psychophysical performance accurately. The study of early visual detection of oriented line targets may provide information allowing the further development of such models, thus increasing understanding of the physiological computations underlying the perception of structures in the visual environment.

1.2 Overview of thesis contents

In this thesis, the aspects of early visual orientation-processing considered are its spatial and temporal characteristics and the way in which its orientational reference frame is determined.

Chapters 2 to 6 of this thesis comprise a review of previous work, from the fields of psychophysics, physiology, and computational modelling, that is relevant to the discussion of the experiments presented in later chapters. Chapter 2 concerns the general characteristics of early visual search and detection and how these characteristics have been determined. In Chapter 3, previous work on search and detection with oriented-line displays is presented, in order to indicate what is known about performance in these tasks and which issues are addressed by the experimental work reported in this thesis. Chapter 4 is a brief review of the physiological aspects of visual orientation-processing that are relevant to the discussion of the experimental work. Chapter 5 is a review of psychophysical aspects of visual orientation-processing in general (as opposed to early processing alone) that may be important in understanding the characteristics of performance in oriented-line-target detection tasks. In Chapter 6, there is a brief description of mathematical filter models of early vision that may be used to integrate physiological and psychophysical information about orientation processing. Chapter 6 also includes the description of a model specifically designed to predict the results of oriented-line-target detection experiments.

Chapters 7 to 12 concern experimental work. Chapter 7 contains a description of the methods common to all of the experiments. The experiments reported in Chapter 8 are investigations of the effects on oriented-line-target detection performance of the number and density of elements in the display. In Chapter 9, the effects of line-element length on detectability of oriented line targets are described. The effects of viewing duration on performance in the oriented-line-target detection task are discussed in Chapter 10. The issue addressed in Chapter 11 is the way in which the reference frame for orientation in early vision is determined. In Chapter 12, the conclusions that can be drawn from the experimental results are presented, with suggestions for further experimental work.

Chapter 2. Early visual search and target detection

2.1 Studying early vision

2.1.1 Defining early vision

For the purposes of this thesis, the terms *early vision* and *early visual processes* will be used to refer to visual processes which operate on the visual information captured before the observer makes his first eye movement after stimulus presentation. Since the first eye movement after initial fixation is typically made after about 200 ms (Carpenter, 1988), early visual processes are thus the processes which operate on information obtained within about the first 200 ms of scene viewing. The term *preattentive vision* (Neisser, 1967) has often been used to describe the same set of processes, but has the additional implication that the processes operate before attention is focused at a specific visual-field location. The way in which attention is allocated is unknown in many of the experiments discussed in the present work, so *early* will be used in preference to *preattentive*. In some contexts, the term *early vision* indicates low-level, rather than rapid, visual processes. The term will not be used in this way in the present work.

2.1.2 Visual search and target detection paradigms

Two general paradigms used to study early vision are visual search and target detection. In both paradigms, a display depicting several objects or *elements* is presented. The observer indicates whether an element differing from the others is present. This element is known as a target (see Figure 2.1). The visual attribute defining the target is either indicated to the observer at the start of the experiment or simply defined by the target's uniqueness within the display. The other objects in the display are known as *distractors, background elements*, or *nontargets*. (In this thesis, the term *nontargets* will be used, as it includes no assumption of the distracting or background-forming characteristics of the elements.) In the visual search paradigm, the display remains visible until the observer makes a response. The time interval between the onset of the stimulus and the observer's response is known as the *reaction time or response time*, and is a commonly used measure of performance in these experiments. Another measure that may be used is the interval after stimulus presentation within which 50 per cent of targets are detected (e.g. Javadnia and Ruddock, 1988). In the target detection paradigm, the display to which the observer responds is presented for a fixed duration. It may be followed by a *mask*, an image that limits the observer's processing of the retinal after-image of the target-detection display.

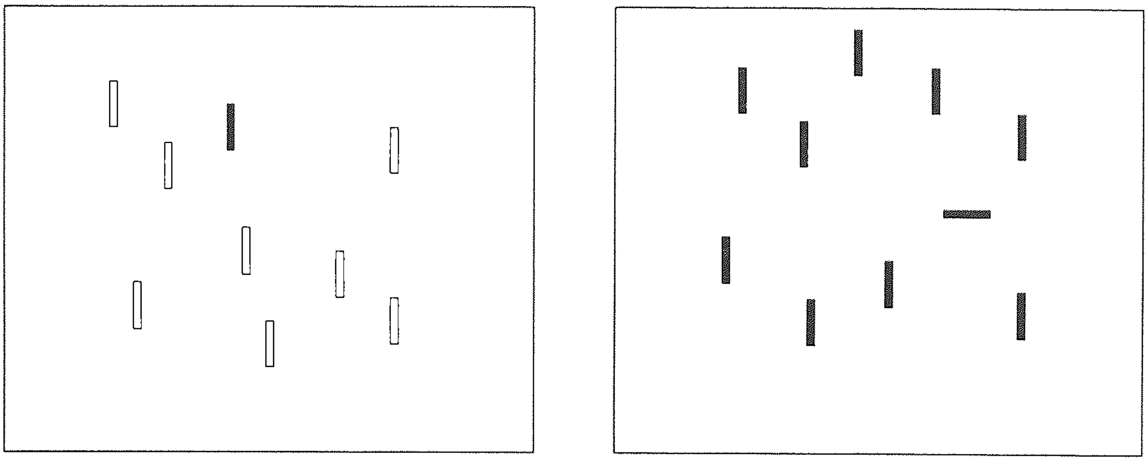

Figure 2.1. Schematic diagrams of displays used in search and detection experiments. In the display on the left, the target is the dark bar and is defined by its lightness. In the display on the right, the target is the horizontal bar and is defined by its orientation.

In a visual search experiment, observers may choose to view the image for as long as they wish, so that not only early but also later processes may be involved in producing the response. Results of such experiments do not necessarily reflect the operation of early visual processes alone, but have nonetheless been important in the study of early vision, the interaction between early and later visual processes, and visual attention. In contrast, target detection paradigms allow the experimenter to control the duration for which the observer has access to the target-detection display, and thus ensure that the results reflect the characteristics of only early processes. So, the target detection paradigm does allow the study of early visual processes in isolation, but provides little information about the operation of later visual processes or visual attention.

The experiments reported later in this thesis involve a target detection paradigm. To set in context the results of these experiments, previous work involving both search and detection paradigms is discussed in Sections 2.2 to 3.5.

2.2 General characteristics of early vision in visual search and target detection

2.2.1 Rapid, spatially parallel processing

There have been many reports that early visual processes operate rapidly and in parallel across the visual field (e.g. Treisman *et al.*, 1977; Bergen and Julesz, 1983). The variation of detection performance with the number of elements in a display, the 'set size', has been taken to indicate whether target detection is achieved by these rapid, spatially parallel processes (Treisman and Gelade, 1980). If detection performance remains stable as set size is increased, then rapid, spatially parallel processes must extract all the required information. If detection performance worsens when set size is increased, then the task must require visual information that these processes cannot extract. In studies of visual search, an increase of reaction time with increasing set size has generally been interpreted as evidence that serial processing of information from different locations is required (e. g. Treisman and Gelade, 1980; Marendaz *et al.*, 1991), but it has been shown that slow parallel processing could produce a similar increase in reaction time with increasing set size (Townsend, 1971). In target-detection paradigms that allow the use of rapid processes only, performance is expected to worsen with increasing set size if the information extracted rapidly and in parallel from many locations is not sufficiently detailed.

2.2.2 Automaticity and popout

Detection of targets through the use of only rapid, parallel processes has been described as "preconscious" (Julesz, 1986), and "automatic' and "effortless", because the observer becomes aware of the target without scrutinizing it (Treisman, 1986). The subjective experience of performing a search task using only rapid, parallel processes is often that the target *pops out* of the display, that is, that it spontaneously attracts the observer's attention. With target detection displays that are masked only a few hundred milliseconds after onset, this *popout* sensation is generally not experienced; neither are detection tasks with these briefly presented displays perceived as effortless.

2.2.3 Search asymmetry

If reversal of target and nontarget roles for a pair of display elements results in a change in search process, from rapid, parallel search to slower search or vice versa, then the pair is said to give rise to *search asymmetry*. For instance, in a search experiment (Treisman and Souther, 1985) with target "Q" and nontargets "O", reaction time data were consistent with rapid, parallel processing (Treisman and Souther, 1985). With target "O" and nontargets "Q", reaction times increased with set size as if slower processing was required.

Search asymmetry has been found with many pairs of elements, and has therefore been proposed as a diagnostic to determine which visual attributes are extracted from the image by early vision (i.e. rapid, parallel processes) alone. For instance, on the basis of the data in the preceding example, it was suggested that some visual feature detectable by early processes was present in "Q" but not in "O" (Treisman and Souther, 1985).

2.2.4 Effectiveness and limitations of rapid, parallel visual processing

Aspects of the visual environment that are perceived rapidly and in parallel have been referred to as *primitive features*, *visual primitives*, or *salient features*. These salient features include colour, motion, luminance, size, curvature, and orientation (Treisman and Gelade, 1980; Treisman and Souther, 1985; Treisman, 1988). Search asymmetry occurs with most salient features, so the salience of a target depends not only on the feature it possesses but also on the characteristics of the nontargets. For example, targets that are greater in size or luminance contrast than the surrounding nontargets appear more salient than targets that differ from the nontargets by the same amount but are smaller, or lower in luminance contrast (Treisman, 1988).

Rapid, parallel processes also allow detection of many types of texture border (e.g. Julesz, 1981; Nothdurft, 1992). This result is unsurprising, as perception of objects as distinct often requires discrimination between textures.

Visual search and target detection experiments have provided information about the limitations as well as the effectiveness of early processes. It was suggested that targets defined by a unique combination or *conjunction* of features rather than a single unique feature could not be detected using early processes alone (Treisman and Gelade, 1980). An example of a *conjunction target* is a dark vertical bar among light vertical bars and dark horizontal bars (see Figure 2.2): the observer must perceive both the orientation and the colour of the target in order to detect it. It was proposed that the observer could not perceive the combination of features as being associated with the same element unless he or she focused attention on it, or scrutinized it, and this could not be done using early vision alone (Treisman and Gelade, 1980).

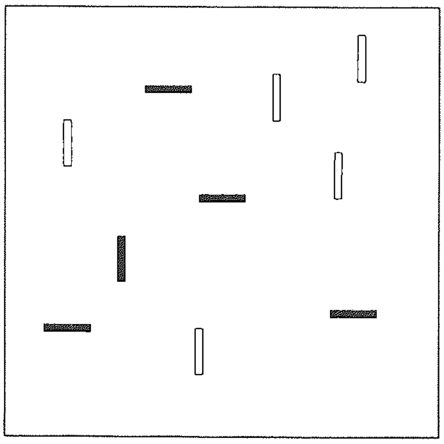

Figure 2.2. Schematic diagram of a search display with a conjunction target. The target, a dark vertical bar, is defined by its combination of orientation and lightness: the nontarget bars are either dark or vertical, but not both.

In some experiments with colour-orientation conjunction targets, parallel search has been found insufficient (Treisman and Gelade, 1980). Other experiments, however, have provided evidence consistent with early detection of various types of conjunction target. Conjunctions of colour with motion or stereoscopic depth (Nakayama and Silverman, 1986), motion with form (McLeod *et al.*, 1988), and some conjunctions of colour with letter-shape (Egeth *et al.*, 1984) can be detected in parallel. Conjunctions of colour and orientation can produce a visual aftereffect (the McCollough Effect) in which certain orientations induce the perception of certain colours. This effect is found even if the adapting gratings inducing the effect are viewed peripherally and therefore not scrutinized. Thus direct scrutiny is not always essential in the detection of a combination of stimulus characteristics (Houck and Hoffman, 1986).

In addition to primitive features and some conjunctions, some information about three-dimensional shape and spatial relations between features is extracted by early processes. In one search experiment, the elements were line drawings representing 3-D objects and the target differed from the nontargets by its 3-D orientation (Enns and Rensink, 1991). Each element contained the same set of oriented line segments, so differing 3-D orientations could be identified only by the spatial relations between segments. Detection of the differences in 3-D orientation was rapid, indicating that the spatial relations between oriented line segments could be processed in early vision (Enns and Rensink, 1991).

Early vision may also facilitate construction of a representation of surface reflectance (Sun and Perona, 1996). In their search experiment, a 3-D percept was created using stereo disparity cues and perspective projection. With shaded display-elements, search for a flat target among 3-D nontargets was easy and appeared parallel, but search for a 3-D target among flat nontargets was harder and appeared serial (Sun and Perona, 1996). The opposite asymmetry was found with wire-frame stimuli. These results would be expected if discrimination were based not on 3-D shape but on apparent reflectance. When a shaded shape is seen as 3-D, luminance differences are generally attributed to shape and therefore not perceived as reflectance changes, but when a shape is perceived as flat, any luminance changes must be due to changes in surface reflectance. So, with many 3-D nontargets and one 2-D target, the only perceived changes in reflectance are in the target and so it is easily detected. With many 2-D shapes and a 3-D target, however, many reflectance changes among the nontargets are perceived, and the target must therefore be detected using weaker cues than reflectance change (Sun and Perona, 1996).

2.2.5. Limitations of a dichotomous description of search and detection processes

Many search and detection results have been interpreted in terms of a rapid, parallel stage and a slower (usually serial) stage without consideration of alternative explanations (Carrasco and Frieder, 1997). Yet there have been challenges to the notion that a visual search or detection process can be strictly classified as either rapid and parallel or slower.

One reason to question the dichotomous description proposed by Treisman and Gelade (1980) is that it was part of a theory of visual search ("Feature Integration Theory") that included no consideration of the physical properties of stimuli (Driver and Macleod, 1992). In a study of search for conjunctions of orientation and motion (Driver and MacLeod, 1992), oriented targets differing by 45 deg from the nontargets were more easily detected among moving than among stationary nontargets. Oriented targets differing by only 9 deg from the nontargets were more easily detected among stationary than among moving nontargets. Thus a search asymmetry could be reversed by a simple manipulation of stimulus properties. This observation could be accounted for by considering the properties of visual subsystems specialized for processing moving or static stimuli (Driver and Macleod, 1992). It could not be accounted for within a general theory of search that predicted parallel or serial processing without reference to specific stimulus attributes (Driver and Macleod, 1992). The stimulus dimension on which elements vary has also been found to have an important influence on the set-size effects thought to indicate whether processing in rapid and parallel, or slower. Verghese and Nakayama (1994) have compared set-size effects with targets defined by colour, spatial frequency, and orientation, and concluded that the results were best considered in terms of early processing characteristics for each stimulus type rather than a single parallel mechanism. The apparent variation in effectiveness of parallel processes for conjunction search (described in Section 2.2.4) might also be better explained using this approach than within a dichotomous description of search and detection processes. A quantitative model of search processes that includes parameters depending on stimulus properties but no assumptions about parallel or serial processing has produced accurate fits to some search data (Bundesen, 1990).

Another reason to question the dichotomous description of search is the difficulty encountered in determining the nature of the process that follows the rapid, parallel stage. It was originally proposed that this process was serial and *self terminating* (Treisman and Gelade, 1980). If a search process is self-terminating, then it terminates either when a target is found or when all the elements have been scrutinized. For a serial, self-terminating search, the increase of reaction time with set size should be twice as great with displays containing no target as with displays containing a target: the observer must scrutinize all of the elements in order to be sure that there is no target, but, on average, only half of the elements in order to find a target if one is present. Some results were found to be consistent with serial, self-terminating search (Treisman and Gelade, 1980), but it has been noted that such results often differ between observers (Duncan and Humphreys, 1989). Also, a linear relationship between reaction time and set size, often taken to indicate serial search, can be found in some data from searches rapid enough to have been classified as parallel (Duncan and Humphreys, 1989). It has been suggested that there might be no strict dichotomy between rapid, parallel, and slower search processes, but rather a continuum of processing speeds in search (Duncan and Humphreys, 1989). Evidence supporting this suggestion has been provided by an analysis of reaction times from over 200 experiments: different tasks have been found to produce different variations in reaction time with set size, but these variations cannot be discretely categorized (Klempen *et al.*, 1997).

Another factor reducing the usefulness of the dichotomous description is the lack of specification of the visual field area over which parallel processes are supposed to operate. A task may appear to be performed using parallel processes when stimuli are foveal, but not when they are peripheral. (See Section 3.4 for a discussion of eccentricity effects on oriented-line-target detection.)

So, processing in search and detection tasks can be rapid and parallel within some area of the visual field (most tasks with transient, masked displays would be impossible otherwise), but it seems likely that processing progresses gradually from rapid, largely parallel, processes, to slower processes that may be parallel or serial. Performance in a particular task is likely to be determined by the speed and effectiveness of visual filtering mechanisms sensitive to the relevant stimulus attributes, and not only by high-level coding of some set of primitive features. In this thesis, new experimental results are interpreted within the context of previous, similar experiments, with the assumption that some of the relevant processing is parallel. In view of the evidence discussed in the present section, however, no strict dichotomy between rapid, parallel, and slower processes is assumed.

Chapter 3. Search and detection with oriented-line stimuli

3.1 Rapid, parallel processing and slower processing

Previous experiments have yielded conflicting evidence concerning the ability of observers to detect oriented line targets using only parallel processes. In visual search for a vertical target among tilted nontargets (oriented at 18 deg to the vertical), reaction time has been found to increase with increasing set size, as if rapid, parallel processes were insufficient (Treisman and Gormican, 1988; Marendaz *et al.*, 1991). In visual search for a tilted target among vertical nontargets, rapid, parallel processes were apparently sufficient (Treisman and Gormican, 1988; Marendaz *et al.*,1991). In some studies of target detection with briefly presented, masked displays, detection performance with vertical targets and oblique nontargets has been found to worsen with increasing set size (Verghese and Nakayama, 1994; Sagi and Julesz, 1987). Yet it has been suggested that although detection performance is better when nontargets are vertical than when they are oblique, parallel processes facilitate visual search (Javadnia and Ruddock, 1988) with any nontarget orientation, provided that the increment between nontarget and target orientations is about 10 deg or more. The amount of prior knowledge observers had about target-detection displays differed between studies, as did the length of the line elements. The experiments described in Chapters 8 and 9 of this thesis provide evidence indicating which of these factors may have given rise to the difference in apparent effectiveness of parallel processes.

3.2 Orientational anisotropy

3.2.1 Characteristics of orientational anisotropy in line-target detection

As mentioned in Section 3.1, asymmetries with respect to orientation have been found in visual search data. Detecting a tilted target among vertical or horizontal nontargets is easier than detecting a vertical or horizontal target among tilted nontargets (Treisman and Gormican, 1988). The variation of target-detection performance with nontarget orientation has been studied in detail by Foster and Ward (1991) and Foster and Westland (1995). The orientation increment threshold, that is, the smallest orientation-difference between nontargets and target for which detection performance reaches a fixed level, has been calculated for a range of nontarget orientations (Foster and Ward, 1991). For almost all observers, the variation of these thresholds with nontarget orientation has been found to be periodic with a period of about 90 deg (Foster and Ward, 1991). This periodicity is a consequence of the fact that performance is best when nontargets are horizontal or vertical and poorer with other nontarget orientations. Periodicities with smaller periods have also been found (Foster and Westland, 1997); these tend to differ between observers. The coarsest periodic variation (with period about 90 deg) can be predicted by a model in which early visual processing of orientation is dominated by two oriented filter mechanisms, one with greatest response to orientations near the vertical and one with greatest response to orientations near the horizontal (Westland and Foster, 1995). The model is described more fully in Section 6.3. It has been suggested (Foster and Westland, 1997) that the finer periodic variations might result from the operation of finer oriented-filter mechanisms than those incorporated in the two-filter model.

3.2.2 Effect of viewing duration on orientational anisotropy in line-target detection

The prominence of the 90-deg periodicity relative to those with smaller periods has been found to decrease when the effective viewing duration of target-detection displays is increased from 100 to 220 ms (Foster and Westland, 1997). An experiment to examine in more detail the variation of oriented-line-target detection performance with effective viewing duration is reported in Chapter 10.

3.3 Effect of line-element configuration

3.3.1 Effect of orientation contrast

The importance in target detection of orientation contrast — rather than absolute orientation — has been studied using displays with with non-uniform nontargets (Nothdurft, 1992). The orientations of the nontargets varied progressively throughout the displays, each nontarget differing in orientation from its neighbour by a fixed amount (see Figure 3.1). If a target was present, it had a greater orientation difference from its neighbour than that fixed amount. Displays were presented for 100 ms and were not masked. Observers performed the task effectively and "targets spontaneously caught their attention" (Nothdurft, 1992), provided that the orientation difference between adjacent nontargets was less than about 30 deg. Nontargets sharing the orientation of the target did not attract attention. It was therefore concluded that popout does not arise simply because a line element has a particular absolute orientation (Nothdurft, 1992).

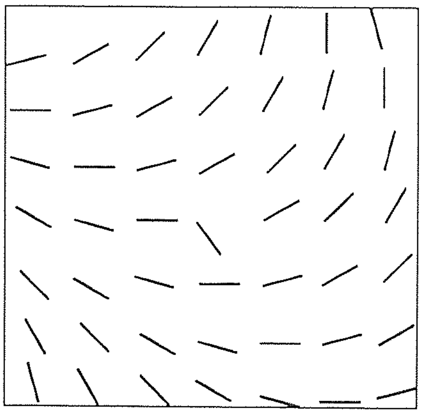

Figure 3.1. Schematic diagram of a target-detection display with progressively varying nontargets. Adjacent nontargets differ in orientation by 15 deg. The target is at the centre of the display.

To strengthen the evidence for this conclusion, another experiment was undertaken (Nothdurft, 1992). Observers had to state whether a vertical element was present in a display of progressively varying elements. This task was achieved rapidly only when the vertical element differed in orientation from its neighbour by an amount greater than the orientation difference between nontargets. Thus rapid, parallel processing was insufficient (Nothdurft, 1992) when the target was defined by its absolute orientation alone and not by orientation contrast. The results of an experiment concerning the role of highly localized orientation-contrast in line-target detection are presented in Chapter 8.

The effects of orientation contrast and absolute orientation in displays with uniformly oriented nontargets have also been investigated (Foster and Westland, 1995). Performance with such displays was found to depend both on orientation contrast and on absolute orientation (Foster and Westland, 1995). In view of this result and the finding that absolute orientation has little effect when nontargets vary in orientation (Nothdurft, 1992), it seems likely that detection of targets among uniformly oriented nontargets may depend in part on mechanisms that are sensitive to absolute orientation and are ineffective when nontargets vary in orientation. A mechanism with these characteristics could be formed by lateral interactions between orientation-selective units in the visual system that each give their greatest response for the same orientation (Stemmler *et al.*, 1995). These interactions and their possible relation to popout effects is discussed in Section 4.6.

3.3.2 Effect of element density

The spatial density of elements in oriented-line displays determines how localized the orientation contrast is. The effect of element density on detectability of oriented line targets has been investigated by Sagi and Julesz (1987). In their experiments, line elements of length 1.0 deg and width 0.1 deg had a minimum spacing of 3.4 deg in some displays and 2.0 deg in others. Targets could be vertical among horizontal nontargets, vertical among oblique (45 deg to the vertical) nontargets, or oblique among orthogonal oblique nontargets. Observers knew the orientations of the target and nontargets. Performance was measured by the percentage of correct responses, the effective viewing duration having been adjusted to give somewhat less that 90 per cent correct detection with only two elements in the display (Sagi and Julesz, 1987).

When the minimum inter-element spacing was 3.4 deg, performance worsened as set size increased from 2 to 40. When the minimum inter-element spacing was 2.0 deg, performance worsened as set size increased from 2 to 20 or 30, and then improved as set size increased to 40. In additional trials with larger set sizes, carried out with dense displays only (minimum inter-element spacing 2.0 deg), performance continued to improve as set size increased from 40 to 100 (Sagi and Julesz, 1987).

Because of the way in which the set-size effect depended on element density, it was concluded that orientation differences were detected in parallel only when the distance between elements was short or, more precisely, less than some critical distance, so that some "short-range process" could be used. For elements of length 1.0 deg, this critical distance was found to be 2.0 deg (Sagi and Julesz, 1987).

A neural mechanism that might give rise to the observed variations in performance with element density was identified (Sagi and Julesz, 1987). Some neurones in the visual cortex of the monkey (DeYoe *et al.*, 1986; Knierim and Van Essen, 1992) and of the cat (Kastner *et al.*, 1997) have the property of *surround selectivity* for orientation: a neurone with this property will respond strongly to a line element differing in orientation from a group of uniformly oriented surrounding elements. (Experiments revealing this neural property are described in Section 4.7.). Surround selectivity was proposed as a mechanism that might produce the observed improvements in performance with large set sizes and dense displays (Sagi and Julesz, 1987). It was also suggested that a dichotomy of visual processing corresponding to that between preattentive and attentive processes might be found in the dichotomy between short- and long-range processes (Sagi and Julesz,1987).

There was no systematic effect of target and nontarget orientations in the study by Sagi and Julesz (1987). In view of the results of other experiments, this absence of orientational effects was probably a consequence of the combinations of nontarget and target orientations selected: vertical targets have not been found to be highly salient (Triesman and Gormican, 1988), and targets among oblique nontargets are not so easily detectable as those among vertical or horizontal elements (Foster and Ward, 1991).

In this study of element-density effects (Sagi and Julesz, 1987) as in most search and detection studies, density and set size were confounded: the displays likely to have most elements within a critical distance of one another were also those with the greatest set size. An experiment similar to that of Sagi and Julesz (1987) but in which density and set size are disconfounded is reported in Chapter 8 of this thesis. This experiment allows comparison of percentage-correct data with the increment-threshold data from other experiments reported in this thesis, and verification that the confounding of density and set size in previous studies did not have an important effect on performance.

3.3.3 Effect of spatial regularity

Line-element configurations in target-detection displays can affect detection performance. In particular, the collinearity of nontarget elements has been found to be a strong cue for detection (Meigen *et al.*, 1994). In a study of the effect of nontarget collinearity, the exposure duration required for correct location of the target was used as the performance measure. This exposure duration was significantly shorter with collinear than with non-collinear nontargets (Meigen *et al.*, 1994). Strong configural effects have also been found in studies of texture segmentation: a border defined by elements with the same orientation as the border itself is more salient than a border defined by high orientation-contrast (Wolfson and Landy, 1995).

In some previous target-detection experiments (Foster and Ward, 1991; Foster and Westland, 1995), target-detection displays have been generated by placing elements at the vertices of an invisible square matrix. As the matrix had vertical and horizontal edges, adjacent vertical or horizontal nontargets provided a stronger collinearity cue than tilted nontargets (See Figure 3.2). The distribution of the elements was perhaps too sparse for such cues to have been important with most displays (there were 20 elements placed randomly on a matrix with 100 vertices), but it is possible that, with displays in which elements appeared close together, detection was facilitated by nontarget collinearity. This facilitation would have been greater for vertical or horizontal than for tilted nontargets, and could therefore have increased performance anisotropy. The possibility that performance anisotropy was a consequence of spatial regularity in target-detection displays is investigated in an experiment reported in Chapter 11 of this thesis.

Aston University

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Figure 3.2. Collinearity of nontargets. When elements are placed at vertices of a square matrix, vertical or horizontal elements give a stronger collinearity cue than oblique elements (Meigen *et al.*, 1994).

3.4 Effect of element eccentricity

In visual search for oriented line targets, it has been found that targets at peripheral locations are detected more slowly and less accurately than those near the centre of the display (Carrasco and Katz, 1992; Carrasco *et al.*, 1995). This effect cannot be attributed to eye movements or attentional factors (Carrasco and Katz, 1992; Carrasco *et al.*, 1995). It has been noted (Carrasco and Frieder, 1997) that set size and element eccentricity have been confounded in many studies of visual search and detection. An experiment has been carried out in order to determine whether some effects previously attributed to set size variations could be accounted for by element eccentricity (Carrasco and Frieder, 1997). Observers searched for oriented line targets in displays containing elements of uniform size and in displays containing elements scaled by the cortical magnification factor (as calculated by Rovamo and Virsu (1979) and Virsu and Rovamo (1979)). With displays containing elements of uniform size, there were clear effects of set size and element orientations, but with displays containing scaled elements these effects were much reduced (Carrasco and Frieder, 1997). Thus it has been shown that some effects of set size in search for oriented line targets may be attributable to element eccentricity. Because of the effect of scaling on orientational asymmetry in visual search, it has been suggested that this asymmetry reflects the orientation-processing characteristics of physiological mechanisms rather than the use of different high-level visual codes or qualitatively different search processes for different target orientations (Carrasco and Frieder, 1997).

In the experiments reported in this thesis, the range of possible target positions was the same with all set sizes, so there was no confounding of target eccentricity with set size.

3.5 The reference frame for orientational anisotropy in line-target detection

3.5.1 Effect of visual context

Orientational anistropy in visual search can be affected by the visual context of the search display. This effect has been demonstrated in a search experiment in which observers viewed displays of vertical and tilted elements (Treisman and Gormican, 1988). Each display had a rectangular frame, either with vertical and horizontal edges or with two edges parallel to the tilted elements (at 18 deg to the vertical). When the frame had vertical and horizontal edges, search for a vertical target among tilted nontargets was slower than search for a tilted target among vertical nontargets. When the frame was tilted, this asymmetry was reversed. So, the slower search was always for the target aligned with the frame (Treisman and Gormican, 1988). It was concluded that the "null" or "standard" value for orientation, which is usually vertical, is at least partially determined by the context of the display, and not only by the direction of gravity or the retinal vertical (Treisman and Gormican, 1988).

In some target-detection experiments (Foster and Ward, 1991; Foster and Westland, 1995), observers viewed displays through a rectangular aperture. The need to verify that orientational anisotropy was not simply a consequence of this viewing condition provided part of the motivation for the experiment on visual context and spatial regularity, described in Chapter 11 of this thesis.

3.5.2 Effect of observer posture

Performance asymmetry in visual search for oriented line targets has been found to depend on gravitational cues. This dependence has been demonstrated in an experiment with oriented-line displays known to produce search asymmetry (Marendaz *et al.*, 1993). Observers performed a search task while standing, sitting immobilized (in a "shell mattress"), or supine (lying horizontally and looking upwards at the display). When observers were sitting immobilized, they could use no cues derived from posture maintenance. This condition was included because it has been claimed (Stoffregen and Riccio, 1988) that the orientation perceived as vertical depends on the way in which the observer must counteract gravity in order to balance, rather than the observer's awareness of the gravitational force itself. When observers were supine, the direction of gravity was orthogonal to the plane of the stimulus display and therefore could not be used as a reference for orientation.

With supine observers, no search asymmetry was found: reaction time data were consistent with parallel search for all combinations of target and nontarget orientations presented (Marendaz *et al.*, 1993). With observers sitting immobilized, search for vertical targets among oblique nontargets appeared parallel. Search for horizontal targets among oblique nontargets appeared serial (Marendaz *et al.*, 1993), and search for oblique nontargets among horizontal or vertical nontargets appeared parallel. Thus it seemed that the characteristics of mechanisms underlying search asymmetry were not fixed with respect to a retinocentric reference frame but determined dynamically according to the observer's perception of gravity (Marendaz *et al.*, 1993).

As the reference frame for search asymmetry did not appear fixed with respect to the retina, the possibility that this reference frame was determined by the subjective vertical or horizontal was investigated (Stivalet *et al.*, 1995). Observers searched for oriented line targets while rotating in a centrifuge. Displays were similar to those used by Marendaz *et al.* (1993). The rotation velocity of the centrifuge was adjusted so that the perceived vertical was close to the orientation of the tilted (18 deg to the vertical) elements in the search display. With displays containing horizontal and tilted elements (18 deg to the horizontal, approximately perpendicular to the perceived vertical in the centrifuge condition), rotation in the centrifuge caused a reversal of the search asymmetry found with standing observers: search was slower for tilted targets among horizontal nontargets than for horizontal targets among tilted nontargets. With displays containing vertical and tilted elements, rotation in the centrifuge caused a reduction in the search asymmetry found with standing observers: search appeared parallel whether the target was vertical or tilted (Stivalet *et al.*, 1995).

An explanation for the variation of search asymmetry with observer posture was proposed, as follows (Stivalet *et al.*, 1995). When observers were standing, they extracted strong somatosensory and proprioceptive cues for both horizontal and vertical, so the dominant orientations for early filtering were well determined and there were search asymmetries for both vertical and horizontal axes. When observers were supine, both vestibular and somatosensory cues were irrelevant to the definition of horizontal and vertical in the plane of the search display, so there was little evidence of search asymmetry for either axis. When observers sat immobilized, many vestibular cues for the vertical were suppressed, so there was search asymmetry for the horizontal but not for the vertical axis. When observers were rotating in the centrifuge and the perceived vertical was at about 18 deg to the actual vertical, there was little search asymmetry for the vertical axis, as if the vertical reference were not well defined, and reversed search asymmetry for the horizontal axis, as if the perceived rather than the actual horizontal was a well-defined reference for the mechanisms giving rise to the asymmetry (Stivalet *et al.*, 1995).

The general conclusion from work described in this section is that the reference frame for early visual orientation-processing is not purely retinocentric but is determined by integration of visual, vestibular, somatosensory, proprioceptive and tactile information (Stivalet *et al.*, 1995). It has been suggested (Marendaz *et al.*, 1993) that this information might be used to alter the bandwidths or preferred orientations of low-level oriented-filter mechanisms (a model that is based on such mechanisms and predicts orientational anisotropy in target detection is described in Section 6.3). Previous studies of the effect of observer posture (Marendaz *et al.*, 1993; Stivalet *et al.*, 1995) have included too few stimulus configurations to allow assessment of this suggestion. Chapter 11 includes the description of an experiment in which observers were supine and there was a wide range of nontarget orientations, so that more detailed information could be obtained about the effect of observer posture on early orientation-processing mechanisms.

Chapter 4. Physiology of orientation processing in the mammalian visual system

4.1 Scope of review of physiology

There follows a brief description of the visual physiology that has been incorporated in models of early vision or used as a basis for hypotheses or speculations related to the experiments discussed later in this thesis. This description is somewhat simplified and very limited in scope; for more detailed and comprehensive review of the physiology of visual orientation-processing, see (e.g.) Leventhal (1991) or Zeki (1991).

4.2 Orientation sensitivity of retinal and lateral geniculate neurones

Initial processing of the pattern of light incident on the retina is by neurones in the retina. There are neuronal projections from the retina to the lateral geniculate nucleus and from the lateral geniculate nucleus to the visual cortex. These projections form the main, although not the only, visual pathway. Responses of neurones in the retina and lateral geniculate nucleus (LGN) are typically invariant with respect to orientation. The *classical receptive field* (the visual-field region in which an isolated stimulus must appear in order to evoke a neural response) of a retinal or LGN neurone typically has a *centre-surround* architecture. Centre-surround receptive fields are such that a stimulus of suitable size presented at the centre of the receptive field evokes a response (e.g. an increase in neural firing rate) and the same stimulus presented within an annulus surrounding the centre evokes the opposite response (e.g. a decrease in neural firing rate). Because there is little variation in reponse with orientation in the retina and LGN, visual processing of orientation is generally considered to begin in visual areas beyond these in the visual pathway.

4.3 Orientation sensitivity of cortical neurones

One of the most common types of cell in the mammalian visual cortex is the *simple cell.* Such cells have small receptive fields and are orientation selective. They respond only if the stimulus (for example, a bright bar) is within a particular range of orientations and a particular part of the receptive field. If the stimulus is located in a region flanking this part of the receptive field, the response is suppressed so that an increase in firing rate occurs when the stimulus is removed (this is known as an *OFF* response, whereas an increase in response when a stimulus is presented is an *ON* response). The maximum response is evoked only when a stimulus of the correct orientation in the correct location covers the entire length of the receptive field or goes beyond it; if the stimulus has less than this length then the response is weaker.

Approximate representations of receptive fields of simple cells are Gabor functions, difference-of-Gaussian functions, and difference-of-offset-Gaussian functions (Young, 1987). All of these functions have been used in models of early visual processing, but some may have greater physiological plausibility than others. In particular, support for the use of Gabor functions in modelling has been provided by comparison with actual receptive fields of cat cortical neurones (Daugman, 1985; Jones and Palmer, 1987), and by a mathematical model predicting the form of a receptive field that, like the receptive field of a simple cell, has response linearity and orientation selectivity (Atick and Redlich, 1990).

Other orientation-selective neurones in visual cortex include *complex* and *end-stopped* cells. Complex cells have much larger receptive fields than simple cells, and yield ON and OFF responses from all parts of their receptive fields. They are also much more numerous than simple cells. End-stopped cells respond only to bars shorter than some critical length.

4.4 Influence of nonvisual information on responses of orientation-sensitive cortical neurones

The response of a cortical neurone can be affected by the animal's posture. In particular, the responses of some cortical neurones in cat (Horn and Hill, 1969) and monkey (Sauvan and Peterhans, 1997) may compensate for head tilt. The responses of these neurones appeared to depend on the orientation of the stimulus with respect to gravity and the body axis, rather than with respect to the retina.

4.5 Dependence of orientation discrimination on orientation-sensitive cortical neurones

There is evidence to suggest that orientation discriminations depend on orientation-selective cortical units. If a kitten is reared without visual experience, its cortical cells show no orientation selectivity (Wiesel and Hubel, 1965; Ganz, Fitch, and Satterberg, 1968). Kittens reared with one eye shut, so that the cortical neurones with input from that eye have no orientation selectivity but those with input from the visually experienced eye are normal, can perform orientation discriminations with the visually experienced but not with the other eye (Ganz and Fitch, 1968). In more detailed studies, it has been found that cells in cat cortex respond only to the orientations experienced during rearing (Blakemore and Cooper, 1970; Hirsch and Spinelli, 1970).

4.6 Possible neural bases of anisotropy in orientation processing

The results of visual deprivation experiments are consistent with a dependence of orientation discrimination on orientation-selective cortical neurones, but do not provide evidence linking neural properties and anisotropies in orientation processing.

In cat, more simple cells with receptive fields within 5 deg of the visual axis have been found to prefer vertical or horizontal than oblique orientations (Pettigrew *et al.,* 1968). In several studies of monkey cortex, the proportion of cortical neurones responding most to horizontal and vertical has been found to be higher than that of cortical neurones responding most to oblique orientations (e.g. Mansfield and Ronner, 1978; Orban and Kennedy, 1981). In rabbit, units were found that had responded most to horizontal and vertical borders, but there was no evidence of units responding most to other orientations (Levick, 1965). This evidence concerning neuronal density is suggestive rather than conclusive, but it does indicate one possible neuronal basis for the oblique effect (Appelle, 1972).

Anatomical characteristics of visual processing areas have also been identified as possible substrates of the oblique effect in some species. The number, and more markedly the length, of dendrites (thin prolongations of the neuronal cell body) have been found to be greater in vertically and horizontally than in obliquely oriented receptive fields of cat, rat, and monkey (Colonnier, 1964). This may imply slightly greater connectivity between neurones with vertically or horizontally oriented receptive fields than between other neurones. This anatomical evidence is perhaps the only irrefutable indication of orientational anisotropy in the visual system that is fixed in a retinocentric reference frame: in principle, neural responses studied electrophysiologically could have been influenced by vestibular or visual cues, as it is unclear how the anaesthesia and paralysis used in some electrophysiological experiments affect the low-level integration of these cues.

There is some electrophysiological evidence of anisotropy in orientation processing in the human cortex. In one experiment, the amplitude of the visual evoked potential with oblique stimuli was found to be 0.3 log unit less than that with vertical or horizontal stimuli (Campbell and Maffei, 1970). No corresponding difference was found in the electroretinogram with the same stimuli (Maffei and Campbell, 1970). It was therefore concluded that the oblique effect arose between sites of origin of the electroretinogram and the visual (cortical) evoked potential.

In a rare instance of recording from cortical units in humans (the subjects had intractable seizures) Marg *et al.* (1968), found two receptive fields that were circular, two rectangular and horizontal, and one rectangular and near-vertical. The sample of receptive fields is too small to allow firm conclusions, but the evidence does not contradict the notion that human visual cortex may contain more units that respond most to horizontal or vertical than units that respond most to oblique orientations. In Section 5.4.2, there is a discussion of the possibility that orientational anisotropy in visual processing depends on these variations in neural density with preferred orientation.

In addition to the findings concerning neuronal density, there is some evidence that the orientation bandwidths of cortical neurones responding most to oblique orientations may be greater than those of neurones responding most to vertical or horizontal (Rose and Blakemore, 1974).

4.7 Possible neural mechanisms of line-target detection

If the observer has no prior knowledge of stimulus orientation, performance of tasks such as orientation discrimination or line target detection requires perception of orientation differences. This perception cannot be explained in terms of isolated responses to single line elements. Rather, it requires that responses of neurones are affected by stimuli outside the classical receptive field (described in Section 4.2) or that responses of many neurones are integrated. Information about the effects of stimuli outside the classical receptive field and the interactions between orientation-sensitive neurones is therefore important in understanding early visual orientation-processing.

Popout that is dependent on highly localized orientation contrast has been found in several experiments (e.g. Nothdurft, 1992). As mentioned in Section 3.3.2, it has been suggested that neurones with surround selectivity might be implicated in the production of popout effects (Sagi and Julesz, 1987; Knierim and Van Essen, 1992). The responses of cortical neurones in alert monkeys (Knierim and Van Essen, 1992) and in anaesthetized and paralysed cats (Kastner *et al.*, 1997) have been tested for surround selectivity. The stimuli used were made up of oriented line elements, one at the centre of the neurone's classical receptive field and others surrounding that central element. In both species, twenty to thirty per cent of the neurones tested had the property of surround selectivity: these neurones responded more strongly when the surrounding elements were orthogonal to the central element than when the surrounding elements were parallel to the central element.

It is unclear whether strong evidence for orientation-contrast sensitivity would have been found if the orientation difference between central and surrounding elements had been much smaller than 90 deg, as it is in many target-detection tasks. It is also unclear whether a difference in orientation between the central element and just one or two surrounding elements would have produced a strong response to orientation contrast. Surround selectivity might be an effective mechanism of target detection with displays with uniform nontargets, but might not be so effective with displays of progressively varying nontargets such as those used by Nothdurft (1992).

The responses of many orientation-selective neurones in monkey cortex have been found to be suppressed by the presence of line elements outside the classical receptive field (Knierim and Van Essen, 1992). This effect has been found to be stronger with dense than with sparse elements (Knierim and Van Essen, 1992). If the suppressive mechanism is involved in target detection, then the sensitivity of the mechanism to element density might contribute to the observed improvements in performance with increasing density in some psychophysical tasks (e.g. that used by Sagi and Julesz (1987), discussed in Section 3.3.2).

It has also been proposed that popout with uniform nontargets could be facilitated largely by a suppressive mechanism involving lateral interactions between neurones with the same preferred orientation (Stemmler *et al.*, 1995). It has been proposed that one function of the suppressive mechanism is to reduce the strength of the responses to nontargets and thus improve the signal-to-noise ratio, where the signal is the response to the target and the noise is the sum of responses to nontargets (Stemmler *et al.*, 1995). As the suppressive mechanism is supposed to operate at high but not at low contrasts, it has been predicted (Stemmler *et al.*, 1995) that popout for a uniquely oriented target among uniformly oriented nontargets will be reduced or eliminated at low contrast. This prediction is yet to be tested. One way in which such a test might be performed is described in Section 12.1.3.

The orientation tuning-characteristics of cells are not only affected by signals outside their receptive fields, but they are also dynamically variable (Ringach and Hawken, 1997; Volgushev *et al.*, 1995). In particular, the orientation preferences of some cells in macaque visual cortex have been found to change with time, generally from one orientation to the orthogonal orientation. Such dynamics are difficult to explain on the basis of feedforward neural models alone, but easily explained by models incorporating intra-cortical feedback (Ringach and Hawken, 1997). In view of these temporal variations in neural sensitivity, orientation-processing in the visual system must be regarded as a dynamic operation, rather than one involving units of temporally invariant response characteristics (Ringach and Hawken, 1997). As orientation preferences of individual units can change so markedly with time, it is perhaps unsurprising that orientational anisotropies in line target detection change (Foster and Westland, 1997) as the effective viewing duration is increased.

4.8 Magnocellular and parvocellular pathways

There is evidence for two major parallel visual pathways from the retina to various areas of the visual cortex in primates. These are known as the magnocellular (M) and parvocellular (P) pathways. In the retina (Leventhal, 1979; Perry *et al.*, 1984), M cells respond transiently to low as well as high contrasts, have no wavelength selectivity, and have axons that conduct their responses very rapidly.

Retinal P cells respond to high contrasts and have a sustained response, and many of them are wavelength selective. Retinal M and P cells have axons projecting to the lower two and upper four layers of the LGN respectively. Most cells in the P layers of the LGN are selective for wavelength, whereas most cells in the M layers are not (Wiesel and Hubel, 1966).

The M and P pathways each subdivide. Part of the M pathway has been identified as a motion pathway: direction and orientation selective (Dow, 1974). Another part has been identified as a dynamic form pathway (Shipp and Zeki, 1989). The P pathway divides into a pathway for colour and a pathway for form linked to colour (Shipp and Zeki, 1989).

The functions of M and P pathways have been studied psychophysically in monkeys (Schiller *et al.*, 1990). The monkeys performed psychophysical tasks before and after lesions to either the M or the P layers of the LGN. Lesions of the P layers produced deficits in fine stereopsis, fine shape discrimination, and perception of colour and texture. Lesions of the M layers produced deficits in motion perception and in perception of flicker with frequency greater than 5 Hz (Schiller *et al.*, 1990).

The relation between these visual pathways and the mechanisms giving rise to anisotropy in early orientation-processing is unknown. In Chapter 10, the results of an experiment on detectability of line targets as a function of effective viewing duration are discussed with respect to the characteristics of M and P pathways.

Chapter 5. Psychophysics of visual orientation-processing

5.1 General characteristics of visual orientation-processing and the study of oriented-line-target detection

This chapter concerns psychophysical experiments providing information about the characteristics and possible mechanisms of visual orientation-processing. The tasks used in these experiments, unlike target-detection tasks, generally involve scrutiny and foveation of the stimuli. Conclusions based on the results of these experiments may not all hold for the mechanisms and processes implicated in detection of parafoveal line-targets in brief displays. Nonetheless, some of these conclusions may be relevant in the interpretation of target-detection results, modelling of early visual processes, and guiding further investigation of early visual orientation-processing.

5.2 Channels selective for spatial frequency and orientation

5.2.1 Channels selective for spatial frequency and orientation revealed by adaptation effects

It is widely accepted that the visual system contains different *channels* for processing different spatial frequencies and orientations. Evidence for low-level, spatial-frequency-selective mechanisms has been found in studies of visual adaptation effects. Viewing a sinewave grating of given spatial frequency produces an increase in contrast threshold for gratings of similar spatial frequency but not for gratings of very different spatial frequencies (Campbell and Kulikowski, 1966; Blakemore and Campbell, 1969; Movshon and Blakemore, 1973). In a study of visual adaptation (Blakemore and Campbell, 1969), this change in contrast threshold was found to increase with the length of time for which the observer views the adaptation grating, reaching a plateau with a viewing duration of one minute. In a study in which the effect of longer adaptation durations was considered, it was found that the adaptation effect continued to increase until the observer had viewed the adapting stimulus for between 30 and 60 minutes depending on the individual (Magnussen and Greenlee, 1985). The increase in contrast threshold has also been found to increase as the contrast of the adapting grating is increased (Blakemore and Campbell, 1969). The adaptation effects were orientation-specific.

The bandwidth of individual, spatial-frequency-specific mechanisms has been found to be about one octave at half amplitude (Blakemore and Campbell, 1969). (Bandwidths for adapting frequencies in the high range were narrower than those for lower adapting frequencies.)

These findings in psychophysical studies of adaptation have strong similarities with findings obtained in physiological studies of neurones in cat visual cortex. The shape of the spatial sensitivity functions both of the neurones (Campbell *et al.*, 1969) and of the psychophysical channels (Blakemore and Campbell, 1969) varied little with the preferred spatial frequency. The property of orientation selectivity was also common to the psychophysical channels and many cortical neurones in cat (Hubel and Wiesel, 1962; Campbell *et al.*, 1968) and monkey (Hubel and Wiesel, 1968).

There is further evidence that the physiological substrate of the psychophysically observed channels is in the visual cortex. When observers viewed an adapting grating monocularly, spatial-frequency-specific adaptation was found in both eyes (Blakemore and Campbell, 1969). This interocular transfer would be likely if the relevant mechanisms were cortical but not if their site was an earlier part of the visual pathway such as the retina or LGN (Blakemore and Campbell, 1969).

5.2.2 Tuning characteristics of orientation-selective mechanisms

The tuning characteristics of orientation-selective mechanisms have been studied by considering summation at threshold (Kulikowski *et al.*, 1973; Thomas, 1978), masking effects (Sekuler, 1965; Campbell and Kulikowski, 1966; Phillips and Wilson, 1984), and adaptation (Blakemore and Nachmias, 1971; Movshon and Blakemore, 1973; Snowden, 1992). Such work indicates that image components differing substantially in orientation are processed with some degree of independence (Thomas and Gille, 1979).

The bandwidths of individual, orientation-selective mechanisms have been estimated using information about the ability of human observers to discriminate between orientations (Thomas and Gille, 1979). Models of possible mechanisms for orientation discrimination have suggested that the orientation bandwidths could be derived from the relation between the probability of detecting an oriented sinewave grating and the probability of correctly identifying its orientation (Thomas and Gille, 1979). This relationship was found psychophysically and then used to determine the orientation bandwidths (Thomas and Gille, 1979). The half-amplitude bandwidths of orientation-selective mechanisms found in this way were in the range 10.5 deg to 20.5 deg, depending on the observer (Thomas and Gille, 1979). Using an adaptation method, Movshon and Blakemore (1973) found smaller bandwidths that also differed between observers (6.5 for one observer and 8.5 for the other). The observer differences in bandwidths of low-level, orientation-processing mechanisms may be one cause of the observer differences found in more complex tasks such as search and detection.

The bandwidths of orientation-selective mechanisms have been found to depend on both the spatial frequency and the temporal frequency of the stimulus (Phillips and Wilson, 1984; Snowden, 1992). For instance, bandwidths of 10 to 15 deg have been reported for spatial frequencies around 10 cycles per degree whereas bandwidths of 30 deg or more have been reported for spatial frequences around 1 cycle per degree (Snowden, 1992). As well as decreasing with increasing spatial frequency, bandwidths have been found to increase with increasing temporal frequency (Phillips and Wilson, 1984; Snowden, 1992). Such effects might explain some of the differences in bandwidths found in studies involving stimuli with differing spatial and temporal characteristics (Snowden, 1992).

For one of two observers who took part in the discrimination experiment of Thomas and Gille, (1979) with stimuli at orientations near to vertical and near to 45 deg to the vertical, orientation bandwidths of mechanisms most sensitive to oblique stimuli appeared greater than those of mechanisms most sensitive to vertical stimuli. As mentioned in Section 4.6, analogous results have been found concerning orientation bandwidths of neurones in cat cortex (Rose and Blakemore, 1974).

5.2.3 A possible mechanism for orientation discrimination

The orientation bandwidths of channels indicated by human psychophysics are about 10 or 20 deg, and those of cortical cells in monkeys and cats may be 30 deg or more (e.g. Schiller, Finlay and Volman, 1976). Yet human observers can discriminate lines or gratings differing in orientation by only 0.3 to 0.5 deg (Regan and Beverley, 1985). A possible explanation is based on a two-phase mechanism:

1. detection of a specific orientation depends on the orientation-sensitive mechanisms which give the strongest response for that orientation, but

2. suprathreshold orientation-discrimination is determined by the difference in signals between orientation-tuned elements (Westheimer, Shimamura, and McKee, 1976).

Thus the detection of a change in orientation could depend on the mechanisms whose response changes most as a result of the change in orientation, rather than the mechanisms that are most sensitive to the orientations of the stimuli (Regan and Beverley, 1985). There is experimental evidence to support this explanation. Adaptation to a high-contrast sinewave grating has been found to impair discrimination of test gratings oriented at 10 to 20 deg with respect to the adapting grating, but have no effect on the detection of the test gratings (Regan and Beverley, 1985). Detection of gratings parallel or near-parallel to the adapting grating was impaired by adaptation, but discrimination of these gratings was actually improved by adaptation (Regan and Beverley, 1985). These results are consistent with the notion that orientation discrimination depends not on the mechanisms giving the greatest responses for the orientations viewed, but on the mechanisms whose reponses are most affected by the difference in the orientations of the stimuli.

A similar principle is incorporated in a line-target detection model in which broad-band oriented filters allow detection of small orientation-differences (Foster and Ward, 1991; Westland and Foster 1995; described in detail in Section 6.3.). According to the model, detection of a target does not depend on the filter response that is greatest for the target orientation but on the filter response that is most affected by the presence or absence of the target.

5.3 The time course of early visual processing

The processing capacity of the visual system is limited and it is important for the observer to gather information rapidly about a complex visual environment. So, an advantageous processing strategy would be one in which a coarse representation of the image is constructed very rapidly to allow perception of the gross structure of the image, then a finer representation is constructed as time progresses. There is some evidence of such a strategy in the spatial-frequency domain.

The variation with time of the spatial-frequency characteristics of visual processing has been investigated by measuring visual sensitivity to length, orientation, curvature, and stereoscopic depth with various effective viewing durations (Watt, 1987). Models of the spatial-frequency processing operations likely to be used were applied to performance in the tasks. To predict the observed variations in performance, the models required large filter scales with short viewing durations and smaller filter scales with longer viewing durations (Watt, 1987).

Two-point resolution acuity has also been studied as a function of effective exposure duration (Watt, 1987). In contrast to the apparent spatial filtering characteristics for other stimuli, the apparent spatial filtering characteristics for two-point resolution remained virtually unchanged as exposure duration varied (Watt, 1987).

On the basis of theoretical arguments (Marr and Poggio, 1979; Watt, 1987) and results on apparent spatial filtering, it has been proposed that low-frequency filters in the visual system are gradually "switched off" as time progresses. It has also been proposed that, for computational reasons (Watt, 1987), the observer has conscious access only to the output of the lowest-frequency filter available at a given stage of processing. This type of processing strategy has been described as "scanning from coarse to fine" (Watt, 1987).

The experiment reported in Chapter 10 of this thesis concerns the variation of detectability of line targets with effective viewing duration. The notion that there might be "scanning from coarse to fine" in the orientation domain as well as in the spatial frequency domain is discussed in relation to the experimental results.

5.4 Orientational anisotropy in psychophysical tasks: the oblique effect

5.4.1 Tasks in which performance is better with vertical or horizontal than with oblique stimuli

There is much evidence to suggest that performance in various visual tasks is better with horizontal or vertical than with oblique stimuli. This phenomenon is known as the *classical oblique effect*. Tasks for which the effect is found include orientation discrimination (Heeley and Timney, 1988; Li and Westheimer, 1997); adjustment of a stimulus to match a known orientation (Jastrow, 1893); estimations of radial position (Smith, 1962; Leibowitz *et al.* 1955); determining the point a line would reach were it extended beyond its existing length (Bouma and Andriessen, 1968) ; Vernier judgements (e.g. Leibowitz, 1955); and perception of parallelism (e.g. Sulzer and Zener, 1953). The highest detectable flicker frequency is also greater for horizontal than for tilted stimuli (Foley, 1962).

Many animals learn to discriminate between horizontal and vertical stimuli faster than they learn to discriminate between obliques. These animals include cats (Parriss, 1964), rats (Lashley, 1938), and rabbits (Van Hof, 1970).

5.4.2 Possible explanations of the oblique effect

Several possible explanations of the oblique effect have been proposed. Optical, neural, vestibular or cognitive factors, or some combination of these, could all conceivably give rise to the effect.

Suggestions that the oblique effect might result from optical factors (e.g. Weymouth, 1959), have been effectively countered: the effect persists even when the optics of the eye are bypassed by projection of stimuli directly on the retina (Campbell *et al.*, 1966; Mitchell *et al.*, 1967). Suggestions that the oblique effect might arise from eye-movement asymmetries (Brown, 1949) or a particularly high density of retinal cells along some meridians (Shlaer, 1937; Hartridge, 1947) can be ruled out by considering results from brief-display paradigms (Higgins and Stultz, 1950) and histology (Polyak, 1941) respectively.

Several neural mechanisms could produce the oblique effect. There is physiological evidence to suggest that visual neurones selective for vertical or horizontal may be more numerous or more narrowly tuned than those selective for oblique orientations (see Section 4.6). It has been suggested that variations in neural density (Bouma and Andriessen, 1968) or orientation-tuning (Andrews, 1967) might give rise to the oblique effect. Alternatively, the way in which neuronal responses are pooled might differ between oblique and vertical or horizontal orientations (Heeley and Buchanan-Smith, 1990). The explanation based on sensitivity has been rejected because the difference in visibility of oblique and vertical Vernier stimuli is insufficient to account for the oblique effect in Vernier acuity (Saarinen and Levi, 1995). Another argument against this explanation is that anisotropy in orientation discrimination is independent of spatial frequency whereas contrast sensitivity depends on stimulus orientation only at high spatial frequencies (Heeley and Timney, 1988). The explanation based on the number of neurones tuned to each orientation is also insufficient to account for the oblique effect (Heeley *et al.*, 1997): when observers discriminated gratings with added 2-D bandpass noise, acuity for orientations near vertical and near 45 deg to the vertical declined with increasing bandwidth in a way that would be expected with near-perfect sampling of the image (Heeley *et al.*, 1997). Thus it has been shown that these neural factors are insufficient to account for the total magnitude of the oblique effect. It has not been shown, however, that these neural factors make no contribution to the psychophysically observed oblique effect.

It has been suggested that higher level processes must be the main source of the oblique effect for orientation acuity (Heeley *et al.*, 1997). One possibility is that oblique orientations are simply less well "labelled" mentally (Heeley and Buchanan-Smith, 1990; see also studies of categorical orientation-perception, e. g. Wolfe, 1993). It is unclear whether the explanations based on neuronal tuning or pooling of neuronal responses can be ruled out.

Most of the neural mechanisms proposed as possible substrates of the oblique effect have been assumed to be fixed in a retinocentric reference frame. Yet it may be possible that even low-level mechanisms operate in some other reference frame, in view of the fact that some neurones in cat V1 have responses that are invariant under head tilt (see Section 4.4). Investigations concerning possible reference frames for the oblique effect are described in the following sections.

5.5 The orientational reference frame for the oblique effect

5.5.1 The effect of visual context on orientation processing

Visual context has been identified as a potential influence on orientation processing in experiments based on a visual task known as the *rod and frame* task (e.g. Cian *et al.*, 1993). Observers in such experiments are required to identify the orientation they perceive as vertical (for example, by tilting a rod until it appears vertical) within a square frame. It has been found that, if the frame is tilted, the rod must be tilted in the same direction as the frame if it is to appear vertical.

This induced change in perception of the vertical might explain the effect of a tilted frame on visual search for oriented line targets. In search experiments with oblique targets among vertical or horizontal nontargets and vertical or horizontal targets among oblique nontargets, performance has been poorest with vertical or horizontal targets (Treisman and Gormican, 1988; Marendaz *et al.*, 1991). If the perception of either the vertical or the horizontal is altered, then it is to be expected that the target orientation giving poorest search and detection performance will also be altered (Stivalet *et al.*, 1995). In a search experiment with a tilted frame (described in Section 3.5.1), it is likely that the perceived vertical will move towards the orientation of the appropriate frame-edges. So, it is to be expected that search performance with a target at the same orientation as the tilted-frame edges will be poorer with the tilted than with the upright frame, as in the experiment of Treisman and Gormican (1988).

5.5.2 The reference for recognition of orientation

Observers can determine whether a test stimulus deviates from vertical or horizontal even when the deviation is only about 0.6 deg (Heeley and Buchanan-Smith, 1990). The orientations of line, edge, and grating stimuli are all recognized equally well (Heeley and Burchanan-Smith, 1990). Deviations from horizontal have been found to be more precisely perceived than those from vertical (Heeley and Buchanan-Smith, 1990). It has been asserted that this ability depends not only on mechanisms operating with a retinocentric reference frame but also on mechanisms for which the orientational reference depends on the observer's awareness of the body axis, gravity, or both (Heeley and Buchanan-Smith, 1990). This assertion has been made because judgements about deviations from vertical or horizontal are as good when there is no visual reference for orientation as when there is a vertical or horizontal stimulus presented before the test stimulus in a two-interval forced-choice paradigm. Thus detecting the deviation does not depend on comparison of retinal images but involves comparison of one retinal image with an internal representation of vertical or horizontal (Heeley and Buchanan-Smith, 1990). It is unclear whether gravity or the body axis is dominant in determining that representation.

5.5.3 The effect of gravitational cues on orientation processing

There have been differing reports about the dependence of orientation discrimination on gravitational cues. In an orientation-discrimination experiment in which observers had their bodies tilted at 20 deg to the vertical and there was no visual reference for orientation, the reference frame for the oblique effect appeared retinocentric (Orban *et al.*, 1984). When observers in a similar experiment had only their heads tilted (Buchanan-Smith and Heeley, 1993), the reference frame for the oblique effect appeared to be determined by gravity or the body axis. It was therefore suggested that the oblique effect could not be based on the variation of low-level neural properties with respect to orientation (Buchanan-Smith and Heeley, 1993). In view of the reports that some cat cortical neurones compensate for head-tilt (Horn and Hill, 1969; Sauvan and Peterhans, 1997), the result of Buchanan-Smith and Heeley (1993) should not be considered as evidence that low-level neural mechanisms make no contribution to the oblique effect. The difference in results concerning reference frames might be explained by the fact that Orban *et al.* (1984) used longer line segments than Buchanan-Smith and Heeley (1993), and therefore provided stronger cues for orientation, especially for simple cells (Chen and Levi, 1996); alternatively, the difference might be explained by the effect of head tilt versus whole-body tilt (Chen and Levi, 1996). In a subsequent experiment, with whole-body tilt of 45 deg, discrimination thresholds for parallelism and perpendicularity were measured (Chen and Levi, 1996). The oblique effect for both discriminations was found to be mapped very accurately to the retinal rather than the gravitational reference frame. This result was considered to provide further support for the suggestion that the oblique effect is associated with a retinal reference-frame and depends on properties of cortical neurones (Chen and Levi, 1996). It is nonetheless possible that the reference frame to which the oblique effect was mapped was determined by the body axis rather than the retinal orientation, as the body-axis and retinocentric reference orientations were confounded.

Chapter 6. Modelling early visual orientation-processing

6.1 Approaches to modelling early vision

Many models of early vision have been based on mathematical filtering operations. Such models have often yielded accurate predictions of visual performance. Most have been models of texture segmentation rather than target detection. Some stimulus types allow effortless texture segmentation but not rapid, parallel visual search (Wolfe, 1992), but as early visual processes are largely automatic (Julesz, 1986; Treisman, 1985), it is likely that many processes operating in the first moments of texture analysis are also involved in target detection. A mathematical-filter model has been shown to predict periodicities in target detection (Foster and Ward, 1991; Westland and Foster, 1995), and the obtention of information relevant to the further development of this model has formed part of the motivation for the experiments reported in this thesis. The main purpose of this short chapter is to provide a description of this model (Section 6.3). To set that description in context, the general form of mathematical-filter models of early vision is outlined in Section 6.2.

Early vision has also been modelled using artificial neural networks (e.g. Schofield, 1993). This approach has provided useful information, particularly about the prenatal development of neural properties of the visual system (e.g. Linsker, 1986a, b, c). It also allows explicit modelling of the operation of individual neurones and the connections between them. To explain visual performance in terms of large ensembles of neurones, however, the mathematical-filter approach may be sufficient. As anisotropy in early visual detection of oriented line targets has been considered in terms of filter rather than network models, the latter are not discussed further in this thesis.

6.2 Mathematical-filter models of early visual processing

Filter-based models of early visual processing generally include the following three stages: convolution of the image with some set of anisotropic spatial filters; nonlinear transformation of filter outputs; and determination of the system's final response. Additional operations used in some models have included spatial smoothing, thresholding, pooling of filter responses, and edge detection.

The initial convolution stage is used as a representation of processing by cortical simple cells, or more generally as processing within an array of channels selective for spatial frequency and orientation (described in Section 5.2). The functions with which the input image is convolved are usually among those that approximate receptive field profiles (described in Section 4.3). The successful operation of the model does not depend critically on which of these functions is chosen (Malik and Perona, 1990). The number of filter classes, each class being defined by the filter response to spatial frequency and orientation, varies between models: some models have predicted segmentation performance effectively with few distinct filter-classes (e.g. Fogel and Sagi, 1989), and others have included as many as 96 filter classes (Malik and Perona, 1990). The modelling of different tasks requires different numbers of filters, as different tasks require processing of different amounts of detail. In addition, a small number of the many oriented-filter mechanisms in the visual system may operate more effectively than the rest in early processing (Foster and Ward, 1991; Westland and Foster, 1995), so modelling very rapid processing of simple stimuli is likely to require fewer filter mechanisms than modelling slightly slower processing of more complex stimuli.

The nonlinearities applied to the filter outputs have included half- or full-wave rectification or energy calculation. It has been argued that the latter operation is less physiologically plausible than the other two (Malik and Perona, 1990), but each of the three operations has been found to predict psychophysical performance adequately.

The appropriate means of determining the model's response to a given stimulus depends both on the other stages of the model and on the type of response required for comparison with human performance. Signal-to-noise measures (e.g. Rubenstein and Sagi, 1990; Westland and Foster, 1995) and cross-correlation (Landy and Bergen, 1991) are among the operations used in models that have successfully predicted performance in texture segmentation or target detection tasks.

6.3 Modelling early visual detection of oriented line targets

As filter-based models have been found to provide useful descriptions of texture segmentation and there are many similarities between texture segmentation and target detection (e.g. Nothdurft, 1991, but see Wolfe, 1992), it seems reasonable to consider a filter-based model as a description of line target detection. Having investigated the variation in target-detection performance with nontarget orientation, Foster and Ward (1991) developed a first-order analysis of this variation that led to the proposal that early visual orientation-processing is dominated by two oriented-filter mechanisms, one preferentially sensitive to orientations close to the vertical and one preferentially sensitive to orientations close to the horizontal. The orientation tuning curves of the filters that best predicted the experimental findings were found (Foster and Ward, 1991). These orientation tuning curves were similar to those of vertical and horizontal components obtained in a principal-components analysis of natural scenes (Baddeley and Hancock, 1991) and had bandwidths within the range of orientation channel bandwidths determined psychophysically. A quantitative model of detection of oriented line targets (Westland and Foster, 1995) has been developed on the basis of the first-order analysis.

Like many texture-segmentation models, the target-detection model (Westland and Foster, 1995) had three stages. These were

1. linear filtering,
2. nonlinear point transformation, and
3. estimation of a signal-to-noise ratio based on responses to images with and without a target.

Linear filtering was by two classes of anisotropic filters, rather than the larger numbers of filter classes generally included in segmentation models. The profiles of these filters were characterized by a long, narrow, excitatory region flanked by inhibitory regions, so that the filter responses were highly orientation-dependent. The orientation giving rise to the maximum response was vertical or near-vertical for one filter class, and horizontal or near-horizontal for the other filter class.

The signal-to-noise measure was calculated separately for each filter class. The final output of the model depended only on the larger of these signal-to-noise values, i.e. on the response from only one filter class. For example, with an oblique target among vertical nontargets, there would be a response from the horizontal filters due to the target but none due to the nontargets, so the signal-to-noise ratio with the horizontal filter class would be high and efficient detection would be predicted. With a vertical target among oblique nontargets, on the other hand, responses to the nontargets would arise with both vertical and horizontal filters, so the signal-to-noise ratio would be low with both filter classes and poorer detection performance would be predicted. Thus the model could account for the orientational asymmetry observed in visual search and target detection while being consistent with the general observation that mammalian visual systems are more sensitive to vertical and horizontal than to oblique orientations.

A version of the model in which all free parameters had been optimized by simulated annealing (a Monte Carlo technique) gave a good fit to psychophysical data (Westland and Foster, 1995): there was no significant difference between the predicted and observed variations in orientation increment threshold with nontarget orientation.

The model involves operations that are physiologically plausible but does not include specification of their physiological implementations. Physiological and psychophysical investigations have provided evidence of several possible mechanisms of orientational anisotropy in vision (see Sections 4.6 and 5.4). It is unclear which mechanism or combination of mechanisms determines the nature of the two-filter system that appears to dominate early visual orientation-processing.

Chapter 7. General experimental methods

7.1 Introduction

This chapter contains a description of the standard experimental methods used in the experiments reported in this thesis. Modifications made to these methods for particular experiments are described in subsequent chapters.

7.2 Apparatus

All stimuli were presented on a cathode-ray tube (Hewlett-Packard, Type 1321A with white P4 sulfide phosphor or Type 1317A with green P31 phosphor, with decay times less than 1 ms) controlled by a vector-graphics generator (Sigma Electronic Systems, QVEC 2150) and additional digital-to-analogue converters, in turn controlled by a laboratory computer. This system allowed specification of 1024 positions along a line of length 1 cm. Points drawn on the cathode-ray tube (CRT) had an approximately Gaussian profile and width about 1 mm at half maximum. The display was refreshed at intervals of 20 ms. (This temporal structure was not visually detectable.)

In all but the experiment on effects of context and spatial regularity (Section 11.1), observers viewed the CRT screen through two horizontally-aligned circular apertures (one for each eye) so that no horizontal or vertical edges were visible. In all but two experiments (described in Sections 11.2 and 11.3), observers were seated and a chinrest was used. A view-tunnel provided a background luminance of about 35 cdm^{-2}. Stimulus luminance was set to about 1 log unit above the observer's luminance-contrast detection threshold at the beginning of each experimental session. To do this, the experimenter placed a 1.0-log-unit neutral density filter between the CRT and the view-tunnel and adjusted the CRT intensity level so that the observer could just detect a flashing line element through the filter.

7.3 Stimuli

In the standard experimental condition, target-detection displays contained 20 line elements of length 1.0 deg visual angle and width 0.1 deg visual angle, presented within a circular field of diameter 20 deg visual angle. All nontargets had the same orientation. A target, placed within an annulus of inner radius 3.0 deg and outer radius 8.0 deg, was present in 50 per cent of trials. When the display contained no target, at least one nontarget appeared within this annulus. The centres of two elements were never closer than 2.0 deg, so the elements did not overlap.

Each masking display comprised clusters of randomly oriented line elements, placed so that the location of each element in the target-detection display was covered by one of these clusters.

7.4 Procedure

At the beginning of each trial, a fixation cross appeared at the centre of the CRT screen. The observer pressed a button on a pushbutton switch box held in the nondominant hand. After a 40-ms interval, the target-detection display was presented for 40 ms. There followed a 60-ms interval during which the screen was blank. The masking display was then presented for 500 ms. The observer indicated whether a target was present in the stimulus display by pressing one of two buttons on a pushbutton switch box held in the dominant hand. In some experiments, the length of the blank interval was adjusted. The procedure for this adjustment in each experiment is given in the section concerning that experiment.

7.5 Experimental sessions

All experimental sessions comprised about 600 trials, 50 of which were practice trials from which no data were recorded. Each session lasted between 30 and 45 min. Most experiments required about 30 sessions from each observer.

7.6 Observers

All observers had normal or corrected-to-normal vision (Snellen acuity 6/6 or greater) and optometrically verified residual astigmatism no greater than 0.25 D. Their ages ranged from 18 to 35 yr. About the same number of male and of female observers took part in the experiments.

The experiments were initially designed to be directly comparable with those of Foster and Westland (1995), so under standard conditions the durations of the stimulus display and blank interval were as used by Foster and Westland (1995). Not all observers performed the task well enough under these conditions to produce reliable thresholds. Therefore, each observer participated in four practice sessions in order to verify that his or her performance of the detection task was adequate. In some experiments, the observer did not continue to participate if he or she scored less than 60 per cent correct during these sessions. In other experiments, the duration of the blank interval was increased until observers reached this performance level.

7.7 Instructions to observers

A set of instructions was read to the observer at the beginning of the first experimental session. In this way the observer was informed that the task was to indicate whether a target was present and learned the functions of the buttons on the pushbutton switch boxes. The observers was asked to respond as quickly as was consistent with accuracy in each trial, and to take several short rests throughout each experimental session. The observer then performed several trials in which both the search display and the mask were presented for 2000 ms so that the observer could examine the displays thoroughly. Several trials were also carried out under standard timing conditions. Throughout this introductory procedure, the experimenter was present and the observer was encouraged to ask questions about any aspect of the task that he or she had not understood.

Observers were given no trial-by-trial feedback about their performance of the task. Occasionally, observers performing the task reliably reported that they were unsure of their ability to perform the task. In such cases, observers were reassured that their detection performance was satisfactory. Observers who did not perform the task reliably did not express uncertainty as to their ability to perform the task.

7.8 Experimental design

In the standard experimental condition, the nontarget orientation for each trial was selected at random from the range 0, 5, ..., 175 deg from the vertical. This fine sampling of nontarget orientation was carried out so that not only coarse but also finer periodic variations in detection performance with nontarget orientation could be examined.

The orientation increment between nontarget and target orientations was varied between 2.5 deg and 40 deg according to the adaptive procedure PEST (Taylor and Creelman, 1967). (A separate PEST procedure was used for each nontarget orientation.) The PEST procedure was generally set to converge at 66 per cent correct: for an unbiased observer, this percentage is equivalent to a value of 0.5

for the discrimination index *d′* from signal detection theory. Occasionally, the convergence value was adjusted by a few per cent for a small number of sessions so that the resulting dataset contained information about a slightly greater range of performance levels. (This increased sampling of performance levels gave an improvement in the fitting of psychometric functions, a procedure described in the next section.)

In each experiment, there were at least 96 trials for each nontarget orientation. Where possible, more trials were carried out in order to reduce noise in the data.

7.9 Data analysis

For each nontarget orientation, the discrimination index *d′* from signal detection theory (Green and Swets, 1966) was calculated for each increment between nontarget and target orientations. For each nontarget orientation, the resulting plots of *d′* as a function of orientation increment were fitted with linear functions. (These functions were constrained so that values of *d′* greater than zero could occur only with orientation increments greater than zero.) In general, the threshold was taken to be the orientation increment for which the fitted functions gave a value of 0.5 for *d′*. The standard deviations of these thresholds were estimated using a bootstrap procedure (Foster and Bischof, 1991).

To test for periodicities in the variation of orientation increment threshold with nontarget orientation, a statistical filtering procedure was applied. This procedure was based on repeated loess (e.g. Cleveland and Devlin, 1988), a method of decomposing a dataset into several components by progressive smoothing and differencing. This method is described in detail in the Appendix.

Chapter 8. Detection of oriented line targets in sparse and dense displays

8.1 Variation of orientation increment threshold for detection of targets in dense and sparse displays

8.1.1 Purpose

Performance in texture segmentation tasks, thought to involve some of the same processes as target detection (e.g. Nothdurft, 1991, but see Wolfe, 1992), has been found to depend on the degree of orientation contrast localized at the texture border (Nothdurft, 1992). One aim of the present experiment was to determine whether highly localized orientation-contrast is required for effective detection of oriented line targets.

Search and detection performance with tilted nontargets has been found to depend on set size in some experiments (Triesman and Gormican, 1988; Marendaz *et al.*, 1991; Sagi and Julesz, 1987) but less so in others (Javadnia and Ruddock, 1988). These differences in results have led to differing conclusions about the effectiveness of parallel processes. So, a further aim of the present experiment was to obtain more information about the effectiveness of parallel processes in target detection.

In previous studies, the effect of set size has been investigated only with a limited number of nontarget orientations. In the present experiment, the dependence of orientational anisotropy on set size was determined in order to provide information for further development of the two-filter model (Westland and Foster, 1995) of oriented-line-target detection.

8.1.2 Methods

The apparatus, instructions to observers, and data analysis were as described in Chapter 7.

Stimuli

The standard element length and field size were used. There were six display configurations defined by set size and sparseness: *sparse* displays had a minimum spacing of 5 deg between element centres and contained 2, 3, 5, or 10 elements; *dense* displays had a minimum spacing of 2 deg between element centres and contained 10 or 20 elements, thus providing a stronger orientation contrast cue than did the sparse displays. Both sparse and dense displays containing 10 elements were included so that set size and element density were not always confounded.

Procedure

The procedure was standard, except that observers MO and ZH performed the task with an ISI of 180 ms, rather than 60 ms. This adjustment was made because these observers responded correctly on less than 66 per cent of trials when the ISI was less than 180 ms.

Design

For each set size, the standard range of nontarget orientations was sampled and PEST was used as described in Chapter 7. Each observer completed six experimental sessions with each set size. In a single experimental session, the set size remained constant. Sessions with various set sizes were ordered randomly, except for those with sparse, 10-element displays, which were carried out after all other sessions.

Observers

There were six observers, three male and three female. Three of them had participated in similar experiments. The others had not, and completed several practice sessions on the task before data were recorded. Only three observers carried out sessions with sparse 10-element displays.

8.1.3 Results

Figure 8.1 shows the variation with set size of orientation increment threshold averaged over all nontarget orientations. The variation of threshold with nontarget orientation is shown with the results of repeated-loess analysis in Figures 8.2(i) to 8.2(xi).

For observers DP, LD, MO, NL, and ZH, threshold averaged over all nontarget orientations was similar or slightly lower with sparse than with dense displays. Only for observer CG was the threshold with sparse displays generally higher than that with dense displays.

For observers DP and NL with 10 elements, threshold was unaffected by display sparseness. For observer LD with 10 elements, threshold was slightly higher with sparse than with dense 10-element displays (18.7 ± 2.1 deg with sparse displays and 15.4 ± 2.0 deg with dense displays). Data obtained with 10-element sparse displays are not shown, as they were very similar to those obtained with 10-element dense displays.

Least-squares linear fits to the plots of threshold against set size were calculated. For observers NL, LD, CG, MO, and ZH, the gradients were not significantly different from zero. For observer DP, the gradient was significantly different from zero ($p < 0.01$) and was shallow (0.14 deg per element with an average threshold of 9.3 ± 1.2 over all set sizes). Examination of the variation of threshold with set size for specific nontarget orientations also indicated no systematic set-size effects.

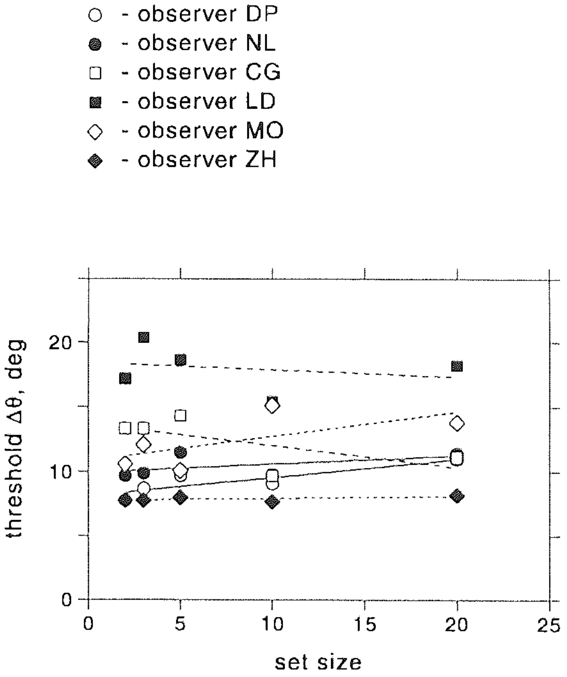
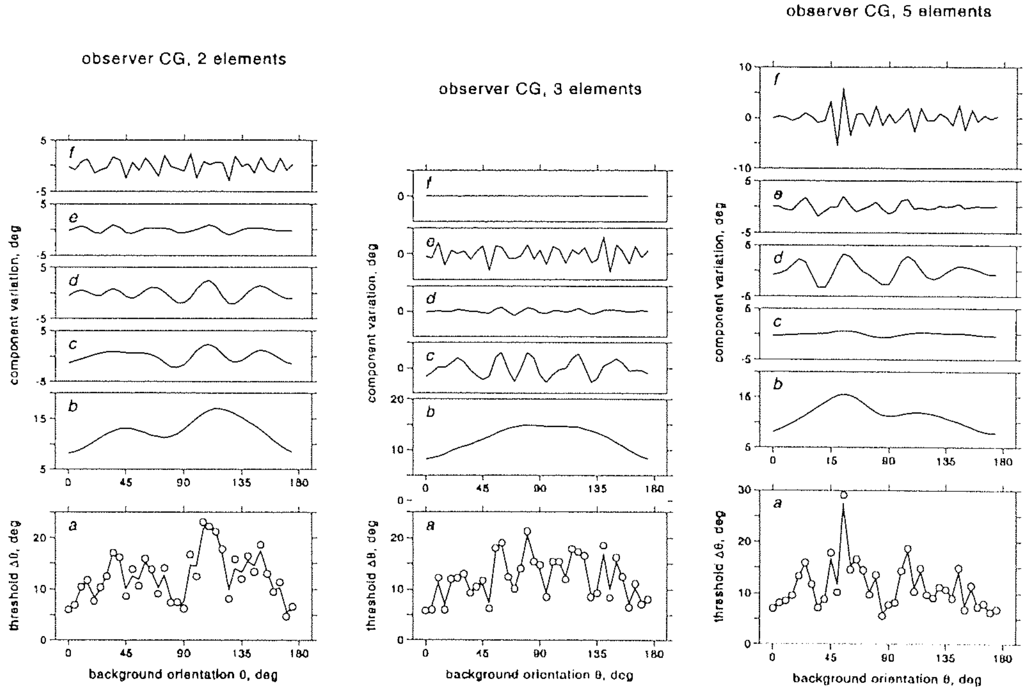


Figure 8.1. Variation of orientation increment threshold with set size. Thresholds averaged over all nontarget orientations. Open circles show data for observer DP, closed circles for observer NL, open squares for observer CG, filled squares for observer LD, open diamonds for observer MO, and filled diamonds for observer ZH. The straight lines show least-squares linear fits.

For observers DP, NL, and LD, there was evidence of a periodicity with period 90 deg with all set sizes and evidence of a periodicity with period 45 deg in some conditions. The 45-deg periodicity did not appear to vary systematically with set size. For observers CG and ZH, the evidence of periodicities was less strong, but nonetheless present in some conditions. Again, there appeared to be no systematic variation in periodicity with set size. For observer MO, there was strong evidence of periodic variation only with 3-element displays.



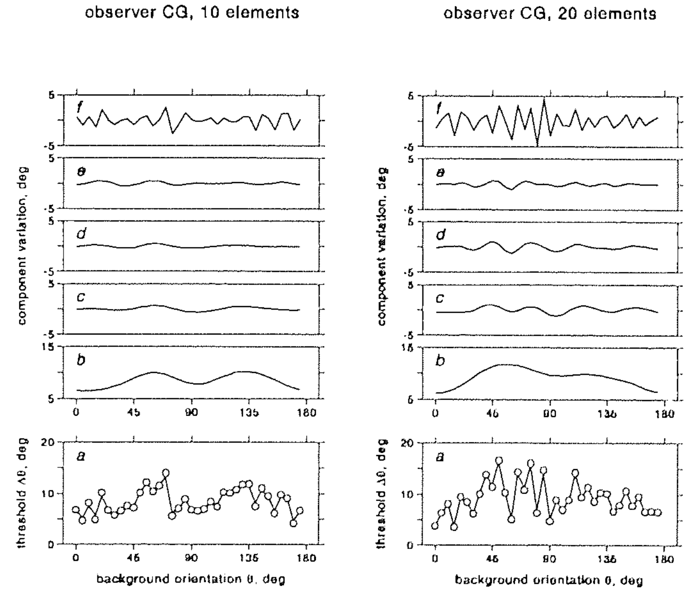
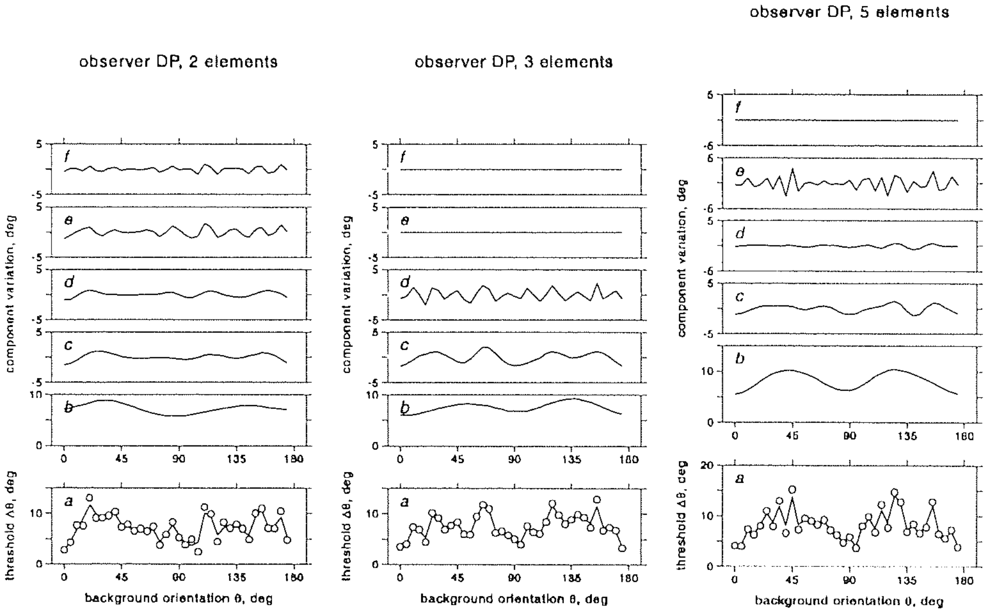
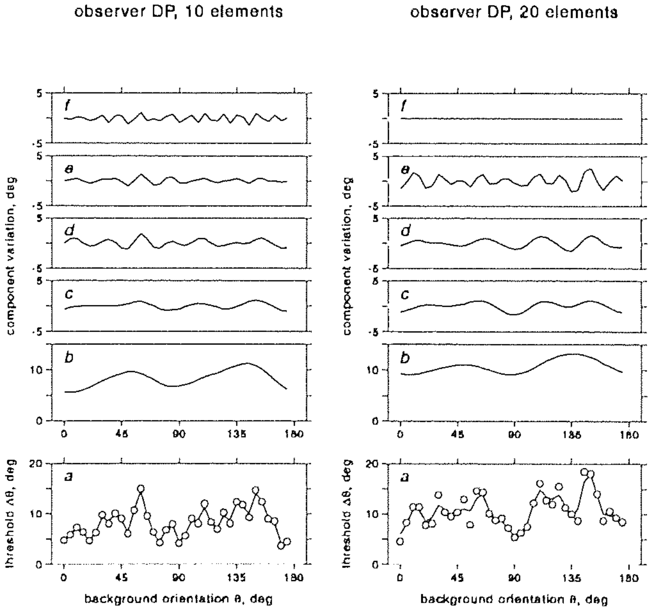


Figure 8.2(i). Variation of orientation increment threshold with nontarget orientation for observer CG with set sizes of 2, 3, 5, 10, and 20. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).


observer DP, 2 elements

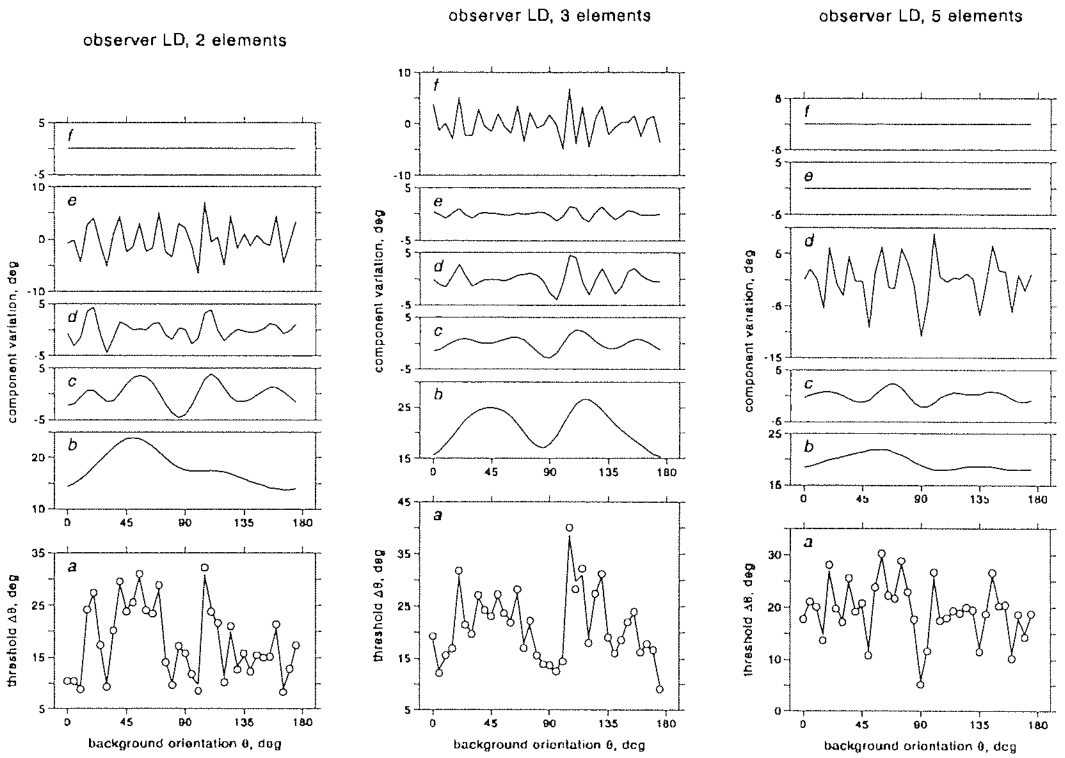
observer DP, 3 elements

observer DP, 5 elements


observer DP, 10 elements

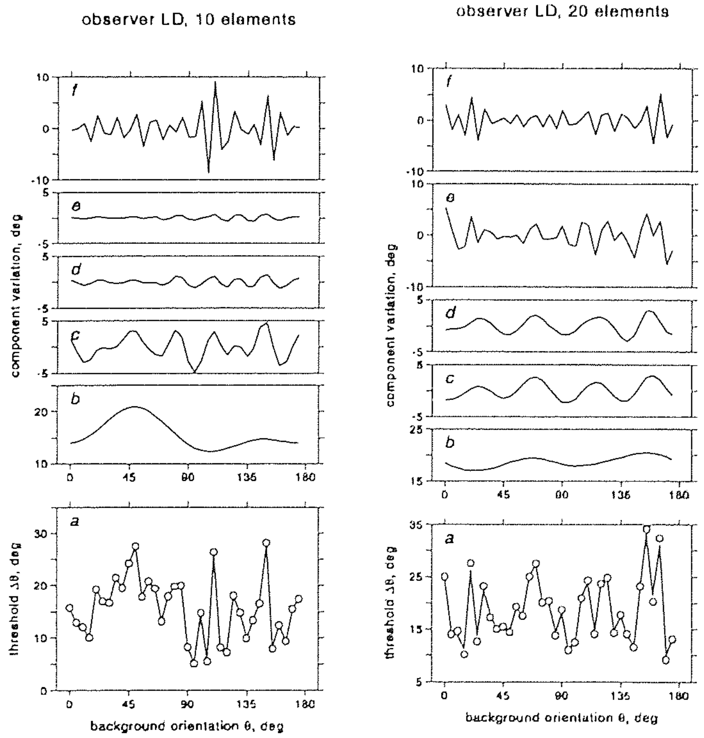
observer DP, 20 elements

Figure 8.2(ii). Variation of orientation increment threshold with nontarget orientation for observer DP with set sizes of 2, 3, 5, 10, and 20. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).


observer LD, 2 elements

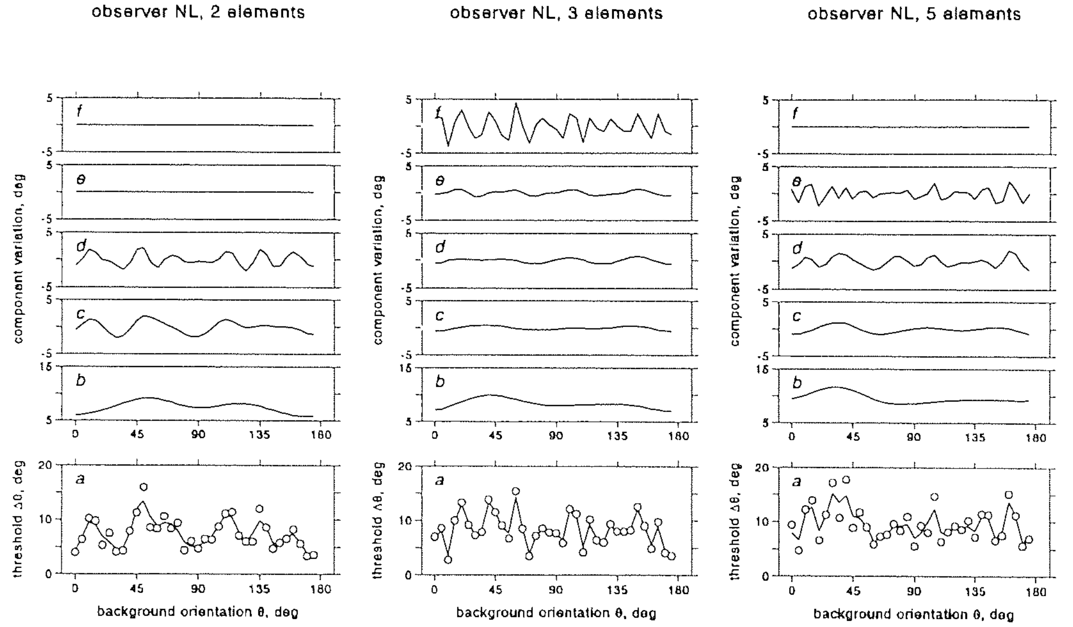
observer LD, 3 elements

observer LD, 5 elements


observer LD, 10 elements

observer LD, 20 elements

Figure 8.2(iii). Variation of orientation increment threshold with nontarget orientation for observer LD with set sizes of 2, 3, 5, 10, and 20. In the plots labelled (a), the thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).



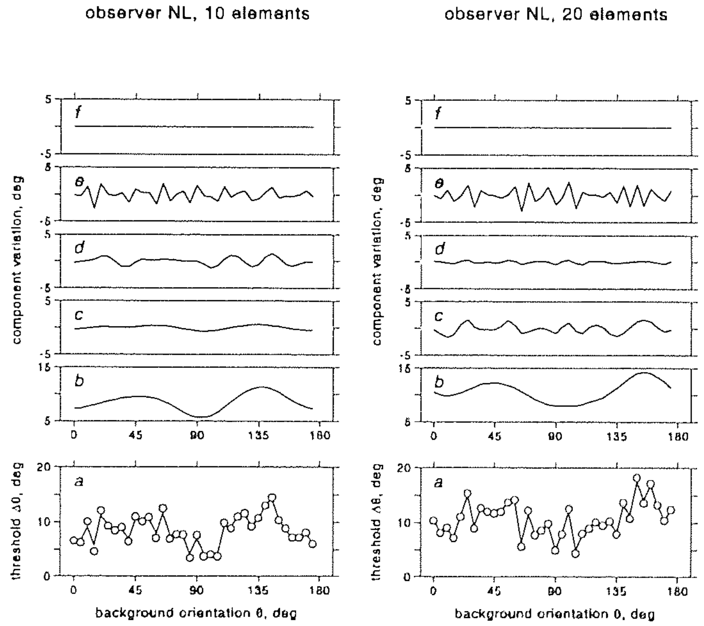
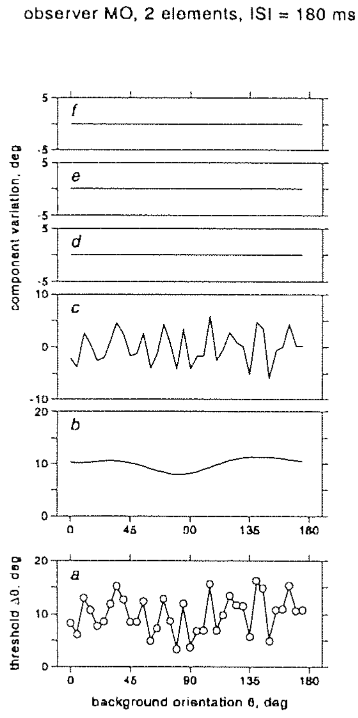
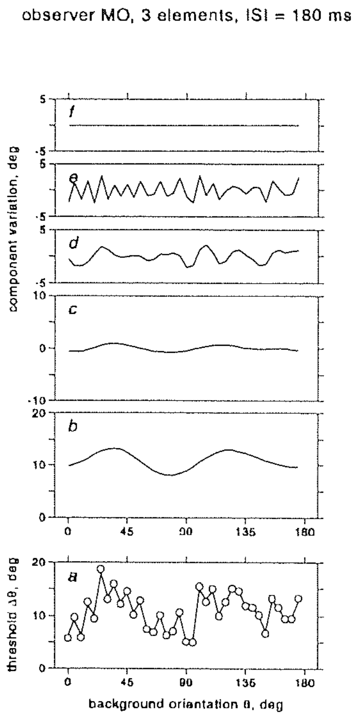
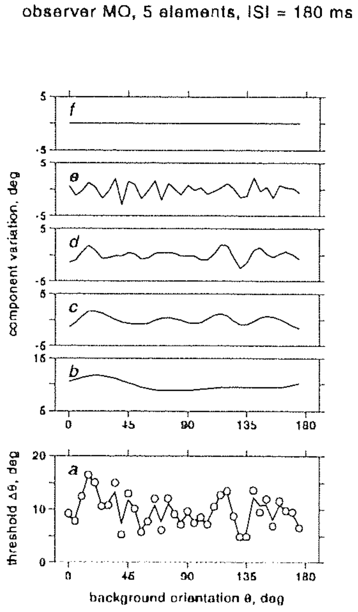
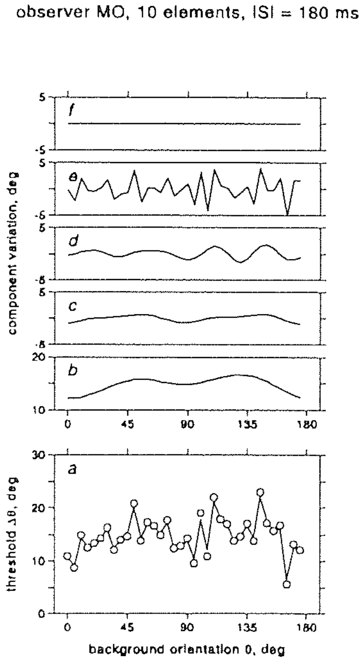


Figure 8.2(iv). Variation of orientation increment threshold with nontarget orientation for observer NL with set sizes of 2, 3, 5, 10, and 20. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).


observer MO, 2 elements, ISI = 180 ms


observer MO, 3 elements, ISI = 180 ms


observer MO, 5 elements, ISI = 180 ms


observer MO, 10 elements, ISI = 180 ms

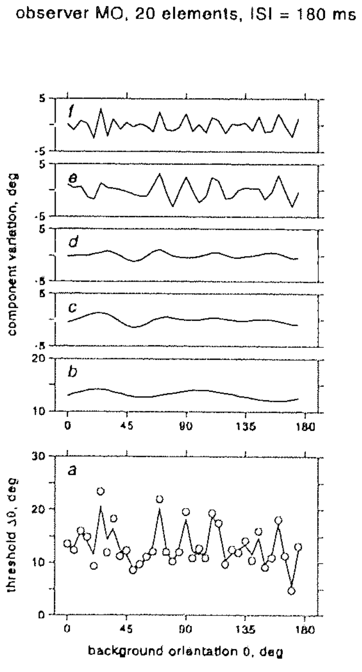
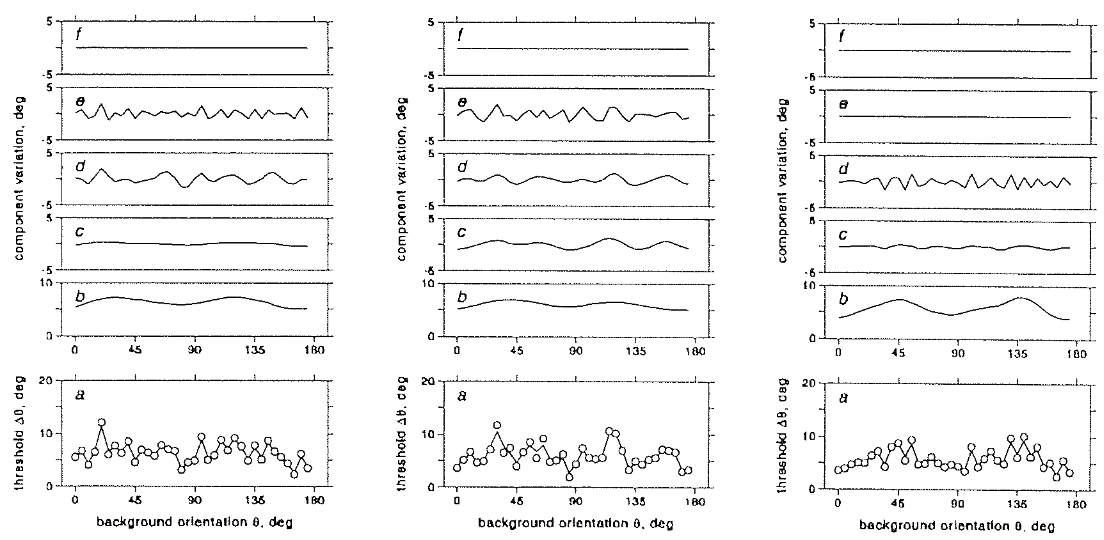

observer MO, 20 elements, ISI = 180 ms

Figure 8.2(v). Variation of orientation increment threshold with nontarget orientation for observer MO with set sizes of 2, 3, 5, 10, and 20. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f). The inter-stimulus interval was 180 ms.

observer ZH, 2 elements, ISI = 180 ms observer ZH, 3 elements, ISI = 180 ms observer ZH, 5 elements, ISI = 180 ms



observer ZH, 10 elements, ISI = 180 ms observer ZH, 20 elements, ISI = 180 ms

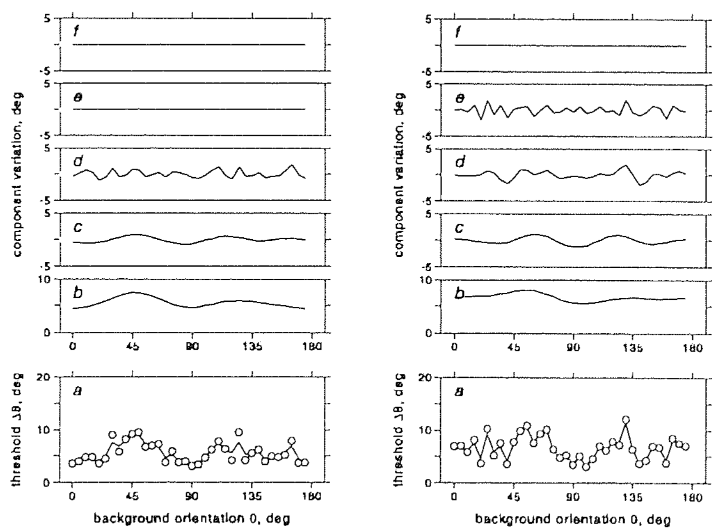


Figure 8.2(vi). Variation of orientation increment threshold with nontarget orientation for observer ZH with set sizes of 2, 3, 5, 10, and 20. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f). The interstimulus interval was 180 ms.

8.1.4 Discussion

Effect of localized orientation contrast

Thresholds with sparse displays were often similar to and only occasionally greater than those with dense displays. So, effective detection of line targets among uniform nontargets is possible when orientation contrast is not highly localized. Only the detection performance of observer CG appeared slightly impaired by the absence of highly localized orientation-contrast. The change from dense to sparse spacing with 10 elements had practically no effect on thresholds of NL and DP (a change of less than 3 per cent in each case), also indicating that highly localized orientation contrast was not the dominant cue for detection with these displays. In view of the present results it seems that detection of oriented line targets among uniform nontargets does not require close juxtaposition of differently oriented elements but involves integration of orientation information from locations throughout the visual field.

Effect of set size

A significant increase in threshold with set size was found for only one observer, and even for that observer the increase was small. As set size had so little effect, it is likely that rapid, parallel processes were sufficient to extract the information required for target detection. This result differs from results obtained in visual search experiments. Visual search results have generally provided evidence of slower processing with tilted than with vertical or horizontal nontargets (Treisman and Gormican, 1988; Marendaz *et al.*, 1991).

In the present experiment, performance with tilted nontargets was generally poorer than that with vertical or horizontal nontargets, but was no more strongly affected by set size. It might be that observers can, if required to by the brief-display paradigm, detect targets among tilted nontargets using parallel processes alone, but that they choose to use slower processes to improve accuracy in search experiments. This suggestion might explain differences between the present results and those of search experiments, but it does not explain why parallel processing appeared sufficient in the present experiment but appeared insufficient in previous target-detection experiments (Sagi and Julesz, 1987; Verghese and Nakayama, 1994). An experiment to resolve the difference in findings between the present experiment and those of Verghese and Nakayama (1994) is presented in the next chapter. The following experiment in this chapter is an investigation of the difference between the present results and those of Sagi and Julesz, (1987), who used displays almost identical to those in the present study but measured the percentage of correct responses and informed observers about the target and nontarget orientations in each trial.

Information for model development

The aspect of the present results that is relevant to modelling is the variation of periodicity with set size. On the basis of the present results, the model (Westland and Foster, 1995) should predict that periodic variations in performance with respect to nontarget orientation is largely independent of set size.

8.2. Variation of percentage of correct responses with set size and spatial density of elements

8.2.1 Purpose

In the preceding experiment, it was shown that performance measured in terms of orientation increment thresholds remains stable with increasing set size. This result differs from that of a study in which element length and density were similar to those in the preceding experiment, but the performance measure used was percentage of correct responses (Sagi and Julesz, 1987). In the latter experiment (Sagi and Julesz, 1987), performance worsened with increasing set size. The experiment reported in this section was carried out in order to determine whether the difference in results could be attributed to the performance measure or stimulus configuration, or whether observers simply differ widely in their ability to detect targets in parallel.

In most previous studies of target detection, set size and local element density have been confounded. There has been a greater probability of high local density and therefore high local orientation-contrast with large than with smaller set sizes. The present experiment involved a method of stimulus generation designed to disconfound local orientation-contrast and set size.

8.2.2 Methods

The apparatus was as described in Chapter 7.

Stimuli

There were two display types, low-density and high-density, and four possible set sizes, 2, 5, 10 and 20. In low-density displays, the minimum spacing between elements was 3.4 deg. In high-density displays, the minimum spacing between elements was 2.0 deg and every element was within at 3.4 deg of at least one other element. Thus the local orientation-contrast between target and nontarget elements was similar in all high-density displays, irrespective of set size. All targets were vertical, and all nontargets were oriented at 45 deg clockwise from the vertical.

Procedure

The standard procedure was used, except that for each observer the ISI was such that the percentage of correct responses was between 80 and 90 for a two-element, low-density display. Thus the ISI was determined in the same way as in the study by Sagi and Julesz (1987).

Design

Within each experimental session, trials were grouped into blocks of 25. In each block, the density and set size remained constant. Each session comprised 24 blocks, 3 of each combination of density and set size. Blocks were randomly ordered. Each observer completed 4 experimental sessions (300 trials in total with each combination of density and set size).

Observers

There were three observers. One (the author) had participated in previous experiments. The others had not, and completed four practice sessions on the task before participating in the experiment.

Instructions to observers

Instructions to observers were as in the standard condition, except that the observers were informed of the target and nontarget orientations in sessions in which these orientations remained constant.

Analysis

The percentage score for each block of 25 trials was recorded. For each observer in each condition defined by density and set size, the average of these scores was found.

8.2.3 Results

Figure 8.3 shows the variation of percentage of correct responses with set size. With low-density displays, there were observer differences in the effect of increasing set size from 2 to 5, and there was an overall worsening in performance as set size increased from 5 to 20. With high-density displays, performance worsened as set size increased from 2 to 5, and then was stable or improved slightly as set size increased from 5 to 20.

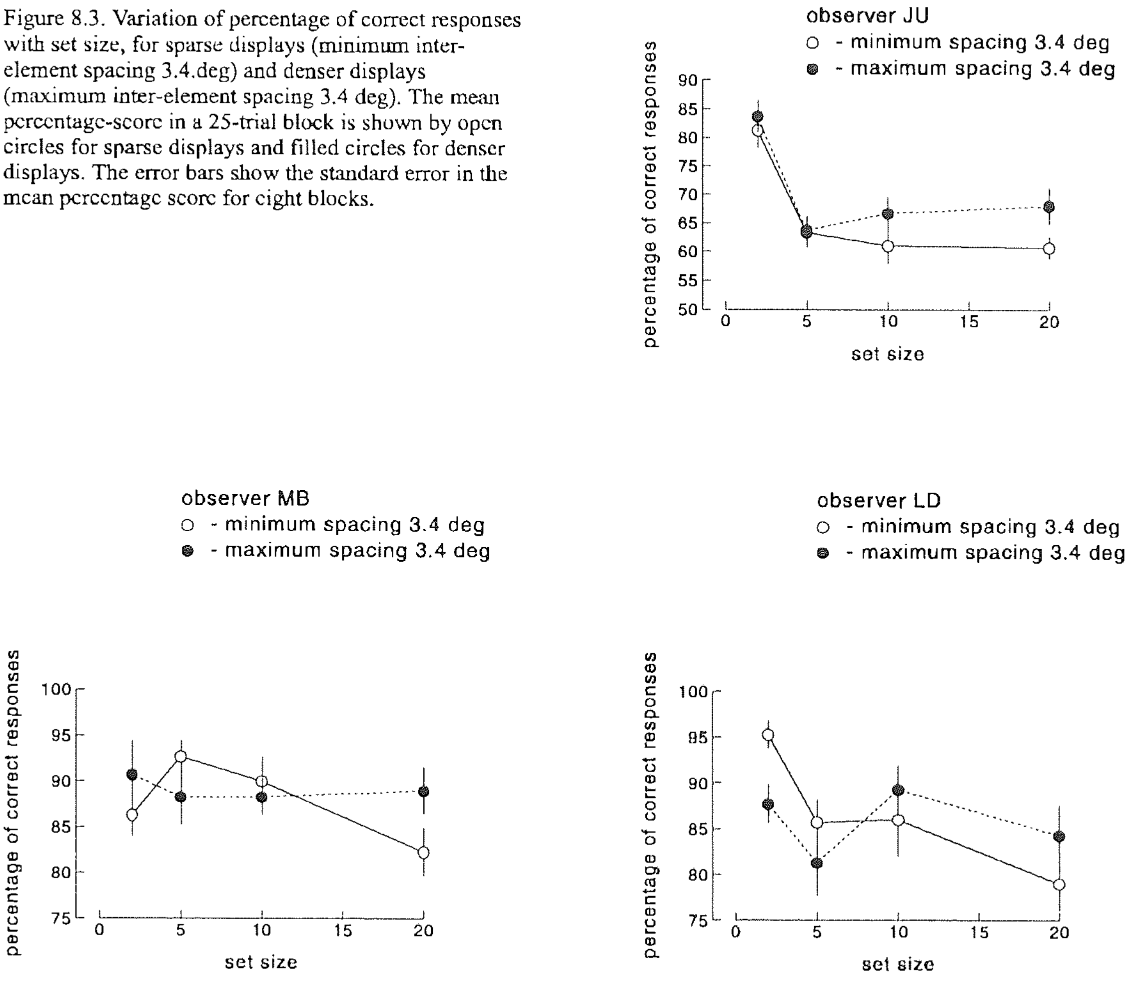


Figure 8.3. Variation of percentage of correct responses with set size, for sparse displays (minimum inter-element spacing 3.4.deg) and denser displays (maximum inter-element spacing 3.4 deg). The mean percentage-score in a 25-trial block is shown by open circles for sparse displays and filled circles for denser displays. The error bars show the standard error in the mean percentage score for eight blocks.

8.2.4 Discussion

The results of the present experiment are consistent with those of Sagi and Julesz (1987): performance worsens with increasing set size when displays have low density, and this worsening is less marked, or even absent, with displays of a higher density.

The present results, like those of Sagi and Julesz (1987), are also in apparent conflict with those of the experiment reported in the earlier part of this chapter. One possible explanation is that the results reported in Section 8.1.3 are orientation increment thresholds and those of the present experiment are percentage-correct scores obtained with a greater orientation increment than the increments in the experiment reported in Section 8.1. If there were a mechanism sensitive to large but not small orientation-differences, and that mechanism were most effective when those differences were highly localized, then a discrepancy between the threshold data reported in Section 8.1 and the present percentage-correct results would be reasonable.

Chapter 9. Detection of long and short oriented-line targets

9.1 Limitations of parallel processing in detection of long and short oriented-line targets

9.1.1 Purpose

As discussed in Section 3.1, previous experiments have yielded conflicting evidence concerning the ability of observers to detect oriented line targets using only parallel processing. The differences in the apparent effectiveness of parallel processing and strength of orientational anisotropy might be attributable to differences in stimulus configuration and information available to the observer. In a study in which displays were presented briefly and then masked and in which performance was found to worsen with increasing set size (Verghese and Nakayama, 1994), the line elements had length 0.24 deg and the observers knew the set of locations at which the target could appear. This knowledge of possible target locations could have encouraged observers to focus attention on one or more of these locations rather than distributing it across the whole display. In investigations suggesting that reliable detection performance requires only parallel processing (Javadnia and Ruddock, 1988; and the first experiment described in the preceding chapter), elements were longer (0.45 or 1.0 deg respectively), and were placed randomly throughout the field, so that the most efficient strategy was to attend to the whole display rather than to a particular subset of locations.

The main purpose of the present experiment was to determine whether the differences in the apparent effectiveness of parallel processing could be explained by differences in line-element lengths, or whether other factors such as observer strategy and individual processing characteristics were important.

9.1.2 Methods

The apparatus and instructions to observers were as described in Chapter 7.

Stimuli

There were two possible line-element sizes, 1.0 deg by 0.1 deg (long) and 0.25 deg by 0.05 deg (short). Each target-detection display contained either all long or all short line elements. Display dimensions for displays with long elements were as described in Chapter 7. Displays containing less than 5 long elements had a minimum element spacing of 5.0 deg and displays containing 10 or more long elements had a minimum element spacing of 2.0 deg. Short elements were presented within a circular field of diameter 10 deg. The target, if present, appeared within an annulus of inner radius 1.5 deg and outer radius 4.0 deg. The length of the short elements was within 0.01 deg of that used by Verghese and Nakayama (1994). The minimum element spacing in all displays containing short elements was 1.0 deg. Masking displays were standard, except that the masking displays for target-detection displays of short elements were generated using short elements.

Design

For each line-element length, there were five possible set sizes (2, 3, 5, 10, and 20) and two possible nontarget orientations (vertical and rotated 45 deg clockwise from the vertical). The nontarget orientation was randomly selected in each trial, and the PEST procedure was used to vary the orientation increment between 2.5 deg and 40 deg (anticlockwise from the nontarget orientation). Within one experimental session, elements were either always long or always short. Sessions with long and short elements were ordered randomly. Within each session, trials were grouped into blocks of 120 trials each. In each block, the set size remained constant. Each session comprised one block of each set size, and blocks were randomly ordered. Each observer completed eight sessions with long and eight sessions with short elements.

Procedure

The standard procedure was used, except that the ISI was set at 60, 120, or 180 ms, whichever was the shortest duration with which the observer scored 66 per cent correct during practice sessions with displays containing 20 long elements.

Observers

There were four observers. Their ages ranged from 20 to 28 yr. Three had participated in similar psychophysical experiments; the fourth had not, and completed four practice sessions on the target-detection task with long elements before participating in the study. The observers had no prior knowledge of target position or target and nontarget orientations.

Analysis

Analysis was as described in Chapter 7.

9.1.3 Results

Figure 9.1 shows the variation of orientation increment threshold for each experimental condition and observer. The straight lines are least-squares linear fits. These functions did not always provide good descriptions of the data, but do indicate whether, overall, there was an increase in threshold with increasing set size.

With long line elements (first two columns, Fig. 1), the gradients of the linear functions were generally close to zero. The only gradients differing significantly from zero were for BF with vertical nontargets (0.16 deg per element for an average threshold of 5.0 deg, $p < 0.05$) and NL with oblique nontargets (0.31 deg per element for an average threshold of 9.1 deg, $p < 0.0001$).

With short elements (third and fourth columns, Fig. 1), all of the gradients were positive and differed significantly from zero ($p < 0.05$ for observer LD with vertical nontargets and observers BF and DP with oblique nontargets; $p < 0.001$ for observers BF and NL with vertical nontargets; $p < 0.0001$ for all other combinations of observer and nontarget orientation). The gradients obtained with short elements and oblique nontargets were either similar to those obtained with short elements and vertical nontargets (observers BF and DP) or greater (observers NL and LD).

9.1.4 Discussion

Effect of line-element length

With long elements, orientation increment thresholds were generally independent of set size; with short line elements, orientation increment thresholds generally increased with increasing set size. This effect would be expected if rapid, parallel processes extracted sufficient information for target detection with many long but not with many short elements. It is uncertain whether observers tried to perform the task by focusing attention on particular locations when elements were short, or whether they continued to distribute attention across the whole display. The latter explanation is perhaps more likely, since performance with few short elements was often as good as that with few long elements, even though the spacing of those few short elements was too great for a focal-attention strategy to be advantageous. When there were many short elements, observers might have used a focal-attention strategy, but, if they did, performance should have improved as set size increased from 10 to 20, as the probability of a nontarget appearing close to the target was also increased. There was little evidence of such an improvement. Whether observers tried to use a spatially parallel or focused-attention strategy, it is clear that rapid, spatially parallel processes could not extract sufficient information for effective detection when displays contained many short elements.

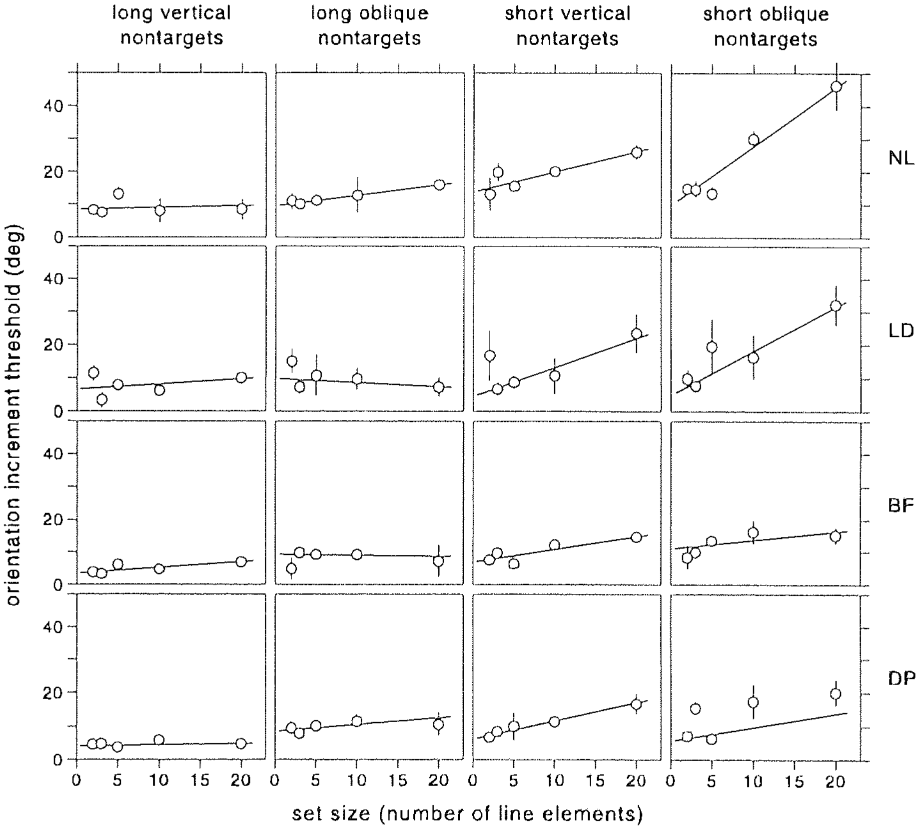


Figure 9.1 Variation of orientation increment threshold with set size, with long (1.0 deg) and short (0.25 deg) line elements. The first column shows data for displays with long vertical nontargets, the second for displays with long oblique nontargets, the third for short vertical nontargets, and the fourth for short oblique nontargets. The top, second, third, and bottom rows show data for observers NL, LD, BF, and DP respectively. Solid lines show least-squares linear fits. Error bars show plus and minus one bootstrap estimate of the sample standard deviation.

Effect of nontarget orientation

With long elements, the expected anisotropy was found. For each observer and set size, the threshold obtained with oblique nontargets was compared with that obtained with vertical nontargets. Of the 20 comparisons made, 12 revealed thresholds differing by more than the greater of the threshold standard deviations; in these 12 instances, the threshold with oblique nontargets was greater than that with vertical nontargets. In only two of the remaining instances was the threshold with oblique nontargets less than that with vertical nontargets. Only for observer NL, however, was the anisotropy strong enough to produce a fairly consistent increase in threshold with increasing set size with oblique nontargets but not with vertical nontargets, consistent with a limitation on the number of elements that could be processed in parallel that is more severe with oblique than with vertical elements.

With short elements there was also evidence of orientational anisotropy: for most observers in most conditions, thresholds were greater with oblique than with vertical nontargets. Moreover, for observers NL, LD, and DP, the increase in threshold with increasing set size was greater with oblique than with vertical nontargets.

Previous work

It seems that reducing line-element length can lead to a reduction in the effectiveness of rapid, parallel processing. This finding may explain why a study in which elements were short (0.25 deg) showed a worsening in performance with increasing set size (Verghese and Nakayama, 1994) and why another study, in which elements were longer (1.0 deg), showed no such effect (Javadnia and Ruddock, 1988). It is unlikely that this worsening in performance with increasing set size resulted from the observers' use of a focused-attention strategy influenced by prior knowledge of the stimuli: observers in the present study knew neither the location nor the orientation of the elements in advance, and their performance with short elements worsened with increasing set size. It is perhaps more likely that early processes cannot extract the amount of detailed orientation-information required for detection from displays with short elements, as the limited spatial extent of elements in these displays gives poor definition of element orientation. The limitations of early visual processes are most evident when elements are short and nontargets are oblique, as they were in the study of Verghese and Nakayama (1994). This result may have implications for some models of early line-orientation coding (e.g. Malik and Perona, 1990), including the two-filter model developed to describe oriented-line-target detection (Foster and Ward, 1991; Westland and Foster, 1995).

Observer differences in effects of line-element length and orientation

The evidence for orientational anisotropy is clear, but the magnitude of the anisotropy varies between observers. For observer NL with long (1.0-deg) line elements, rapid, parallel processes appeared sufficient with vertical nontargets, and slower processes seemed necessary when nontargets were oblique. For observers DP and LD, rapid, parallel processes were sufficient when elements were long, both when nontargets were vertical and when nontargets were oblique. In so far as element length affects task difficulty, it also affects anisotropy: for observers LD and NL, the anisotropy was stronger with short elements than with long elements.

General implication

Since line-target-detection performance is affected by physical stimulus characteristics such as line-element length and orientation, it is important to take these factors into account when making general inferences about early visual orientation-processing. The present findings provide support for the assertion of Verghese and Nakayama (1994) that search and detection data are better explained in terms of stimulus-specific mechanisms than in terms of some general process that operates simultaneously on many stimulus dimensions.

9.2 Effect of line-element length on periodic variations in oriented-line-target detection performance

9.2.1 Purpose

The purpose of the following experiment was to determine whether line-element length affects the strength of periodicities in oriented-line-target detection, and thus indicate the dependence of periodicities on element length that should be predicted by the two-filter model (Westland and Foster, 1995).

9.2.2 Methods

Apart from the following exceptions, methods were as in the preceding experiment.

Stimuli

Elements were always short (0.25 deg by 0.05 deg) and nontarget orientations were drawn from the range 0, 5, ..., 175 deg.

Observers

There were three observers, all of whom had participated in the study on target detection in dense and sparse displays (Section 8.1). Each completed 30 experimental sessions with short line elements.

Analysis

Analysis was as described in Chapter 7, except that thresholds found for observer LD correspond to $d' = 0.2$ rather than $d' = 0.5$.

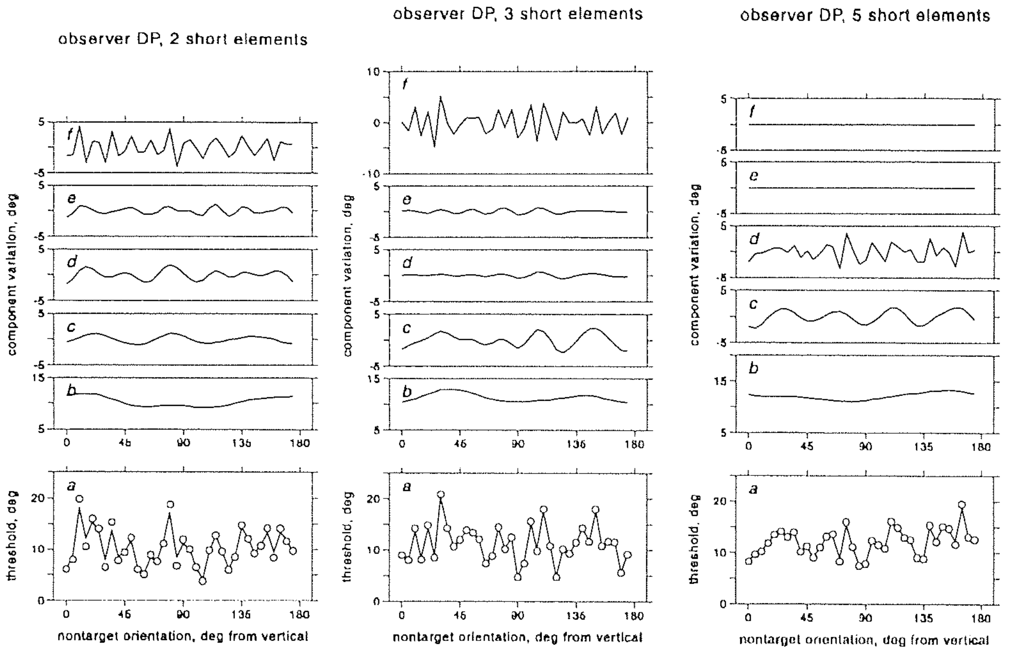
9.2.3 Results

Figures 9.2(i) to 9.2(iii) show the variation of orientation increment threshold with nontarget orientation, and the associated loess decomposition. For observers NL and LD, there was evidence of a periodicity with period 90 deg in most conditions. For these observers, the evidence of a 90-deg periodicity was as strong or stronger than in the experiment with longer elements (reported in Section 8.1). There was little reliable evidence of other periodicities.

For observer DP, the only clear periodic variation in the data had a period of 45 deg and occurred with a set size of 5. Data from this observer in the experiment with longer elements had, in contrast, contained evidence of a 90-deg periodicity in most conditions (see Section 8.1).

9.2.4 Discussion

The data of observers NL and LD, particularly considered in conjunction with the observation from the preceding experiment that there was greater anisotropy with short than with long elements, are consistent with the persistence and possible strengthening of periodicities as element length is reduced. The data of observer DP in the present experiment do not generally show strong periodicities, but even this observer's performance was consistent with an increase in anisotropy with reduction in element length in the preceding experiment (Section 9.1). So, it is likely that anisotropy is, in general, as strong with short as with longer elements, and the predictions of a model of target-detection such as that developed by Westland and Foster (1995) should reflect this.



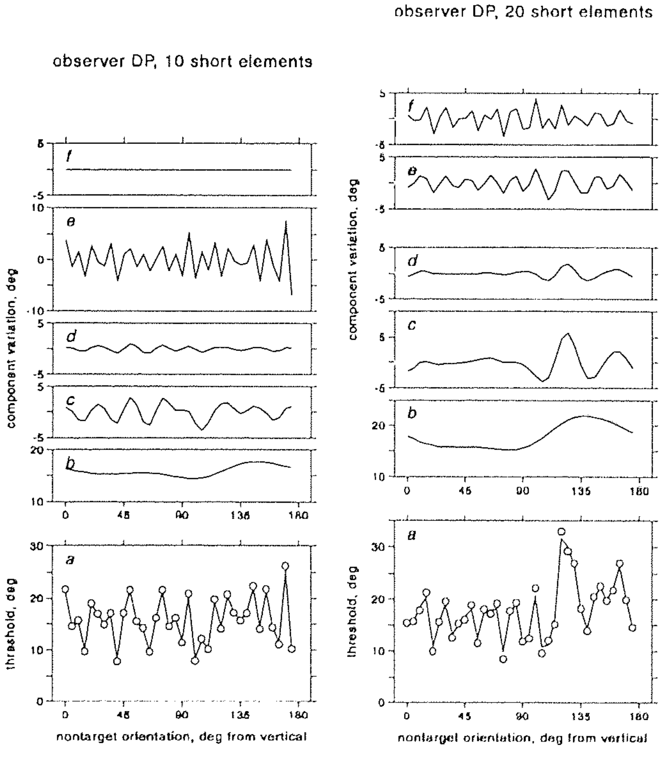
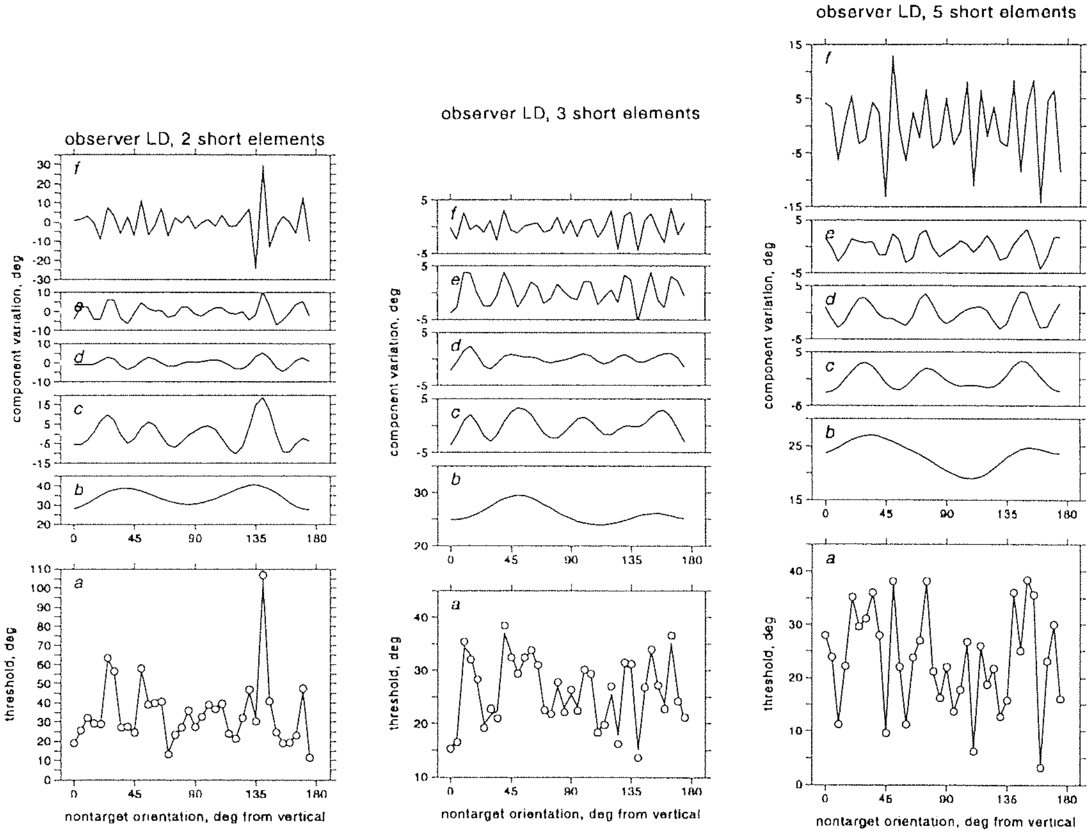
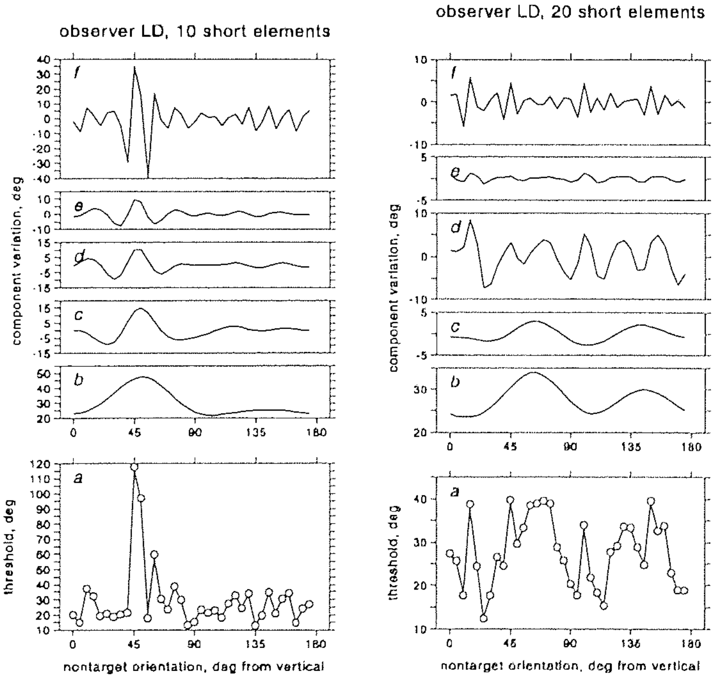


Figure 9.2(i). Variation of orientation increment threshold with nontarget orientation for observer DP with displays of 2, 3, 5, 10, and 20 short line elements. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).


observer LD, 2 short elements

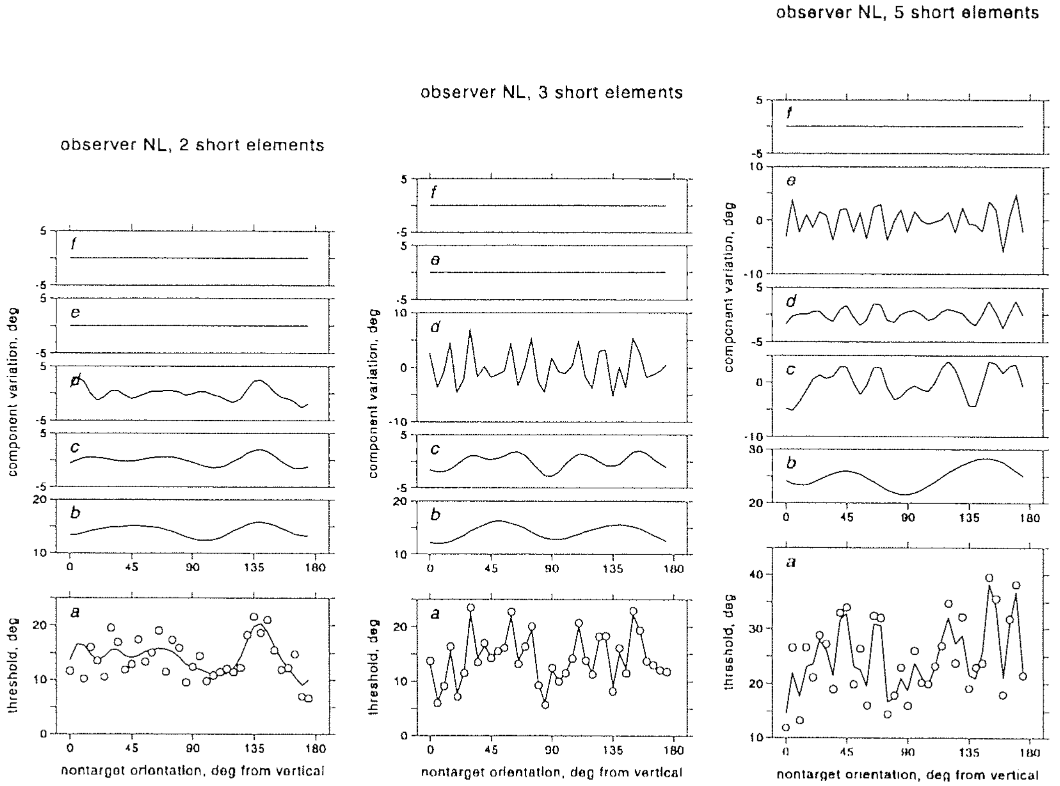
observer LD, 3 short elements

observer LD, 5 short elements


observer LD, 10 short elements

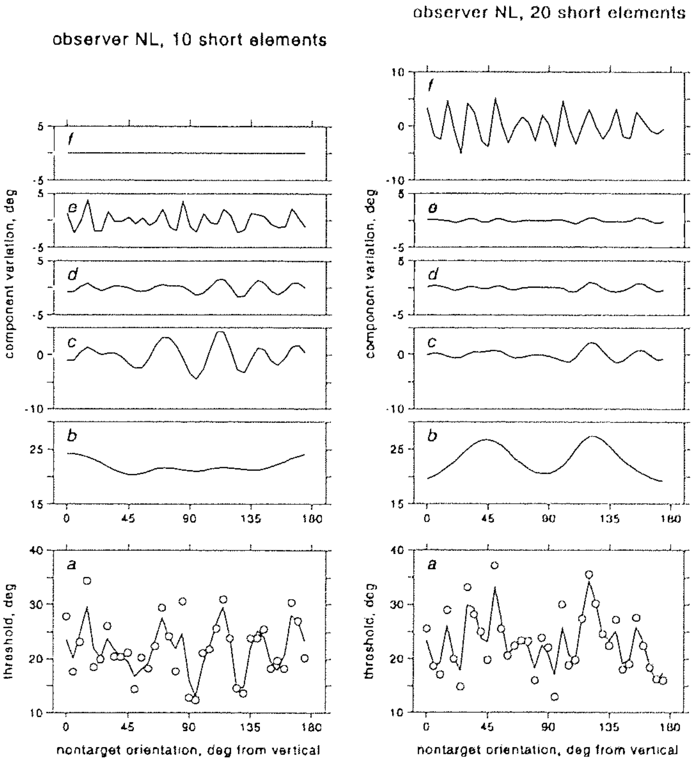
observer LD, 20 short elements

Figure 9.2(ii). Variation of orientation increment threshold with nontarget orientation for observer LD with displays of 2, 3, 5, 10, and 20 short line elements. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).


observer NL, 2 short elements

observer NL, 3 short elements

observer NL, 5 short elements


observer NL, 10 short elements

observer NL, 20 short elements

Figure 9.2(iii). Variation of orientation increment threshold with nontarget orientation for observer NL with displays of 2, 3, 5, 10, and 20 short line elements. Thresholds are shown in the plots labelled (a) and progressively finer components found by repeated loess analysis are shown in plots (b) to (f).

Chapter 10. Variation of line-target detectability with effective viewing duration

10.1.1 Purpose

For most observers, a periodicity with period 90 deg is present in the variation of threshold with nontarget orientation in early visual line-target detection. This periodicity is predicted by the two-filter model of Foster and Ward (1991) and Westland and Foster (1995). Finer variations in threshold with nontarget orientation have also been reported (Foster and Westland, 1997), particularly with increased effective viewing duration (an ISI of 180 ms, rather than 60 ms). It has been suggested that these fine variations might result from the operation of finer oriented-filter mechanisms than those incorporated in the model (Foster and Westland, 1997). One aim of the experiment described in this chapter was to examine the time course of early orientation-processing in greater detail (using a greater number of effective viewing durations than in previous work). Another was to determine whether it would be appropriate to expand the two-filter model to incorporate filter mechanisms tuned to many orientations.

10.1.2 Methods

Stimuli

Standard stimulus displays were used.

Procedure

The standard procedure was used, except for the changes in ISI described in the following paragraph.

Design

There were five masking conditions, each giving a different effective viewing duration. In each condition, the target-detection display was presented for 40 ms. In four of the conditions, it was followed by a blank ISI and then a mask. The ISI lasted 60, 120, 180, or 240 ms. In the fifth condition, no mask was presented.

Observers

There were five observers. One of them (the author) had participated in similar experiments; the others had not, and each completed four practice sessions on the task with the standard condition.

10.1.3 Results

Thresholds averaged over all nontarget orientations decreased as the ISI was increased (see Figure 10.1). For observers SJ, JT, and NP, there was a decrease of 5 to 15 deg in this average threshold as ISI was increased from 60 to 120 ms, then a change of only a few degrees as ISI was increased further. For observers AG and LD, the decrease in threshold with increasing ISI was also greater with short than with longer ISIs.

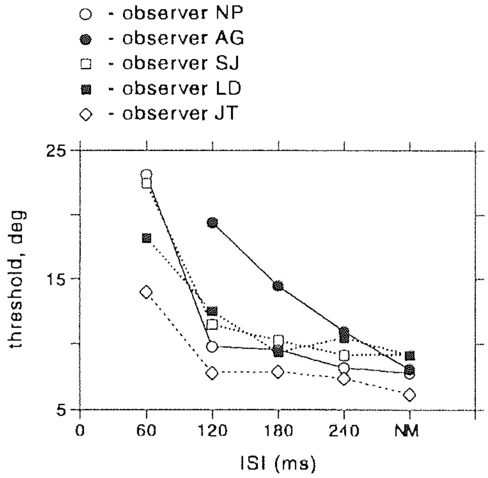
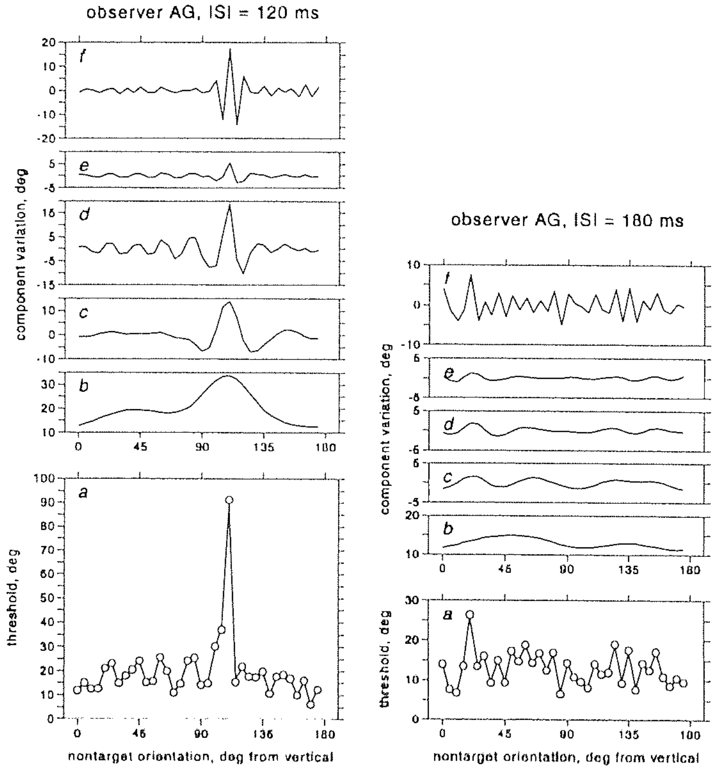


Figure10.1 Variation with respect to ISI of orientation increment threshold averaged over all nontarget orientations. The effective viewing duration was 40 ms greater than the ISI, as the target-detection display was presented for 40 ms. "NM" on the horizontal axis denotes the condition in which no mask was presented. Open circles show data for observer NP, filled circles for observer AG, open squares for observer SJ, filled squares for observer LD, and open diamonds for observer JT.

Figures 10.2(i) to 10.2(v) show the variation in threshold with nontarget orientation for each observer and ISI. (The data of observer AG with an ISI of 60 ms are not shown as this observer did not perform the task reliably with the 60-ms ISI.) There was evidence of a periodicity with period 90 deg in all conditions for all observers, except for observer NP with the 'no mask' condition and observer LD with an ISI of 240 ms. For observers SJ, JT, and NP, the variation in amplitude of the component indicating this periodicity was greatest when the ISI was 60 ms. For observers AG and LD, this variation was affected little by ISI.

The evidence of periodicities with smaller periods was less clear. The prominence of these periodicities varied between observers, and did not appear to vary systematically with ISI.



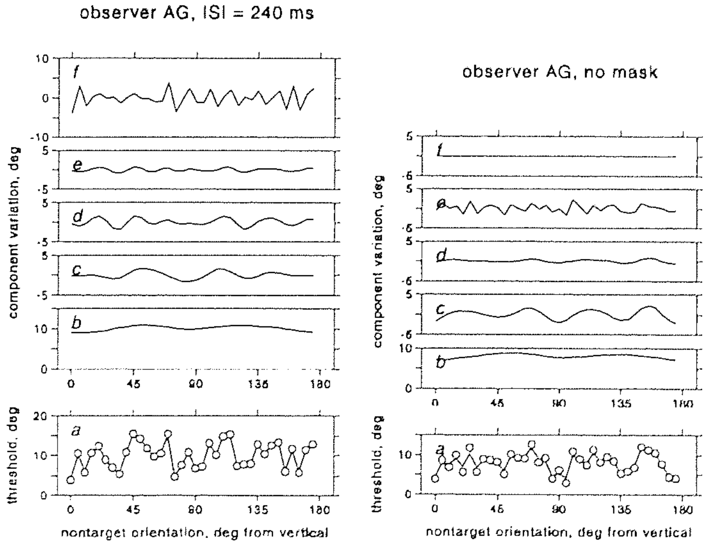
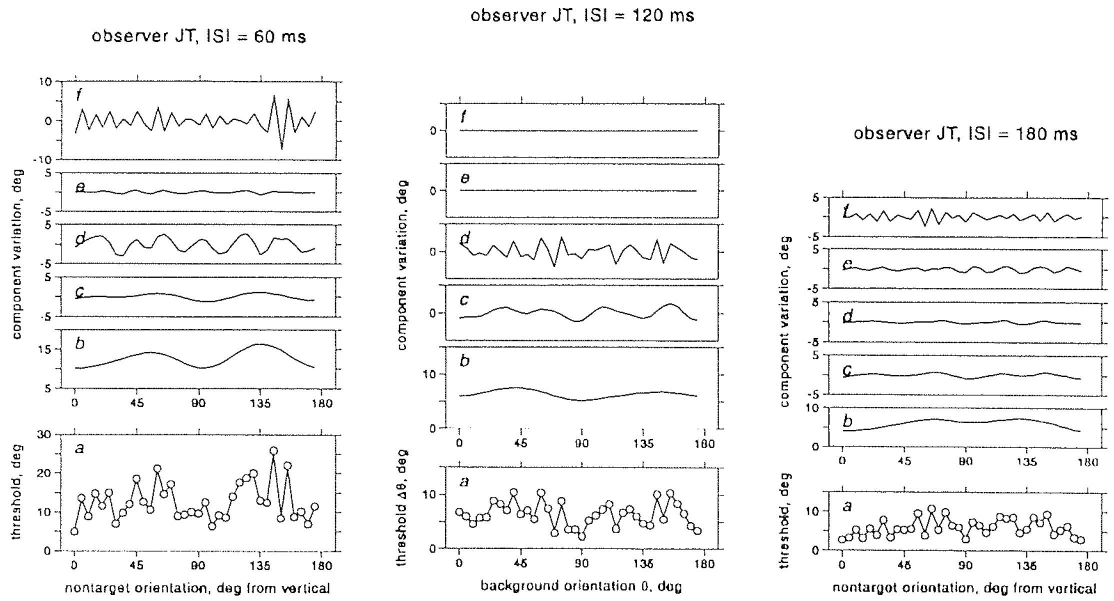


Figure 10.2(*i*). Variation of orientation increment threshold with nontarget orientation for observer AG with an ISI of 120, 180, or 240 ms, or no mask. (The effective viewing duration was 40 ms longer than the ISI as target-detection displays were presented for 40 ms.) In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).



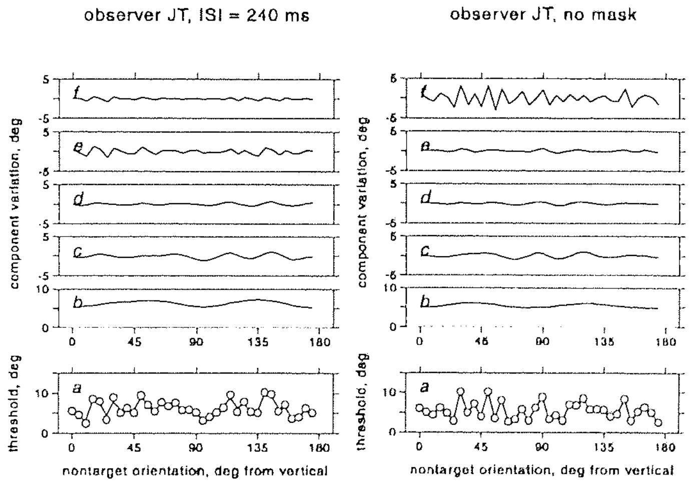
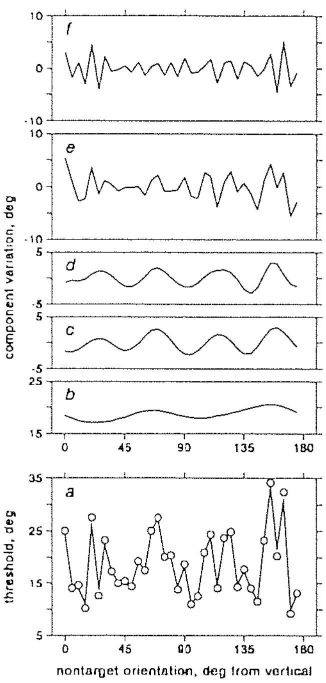
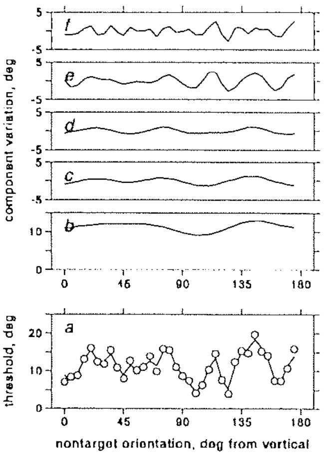


Figure 10.2(ii). Variation of orientation increment threshold with nontarget orientation for observer JT with an ISI of 60, 120, 180, or 240 ms, or no mask. (The effective viewing duration was 40 ms longer than the ISI as target-detection displays were presented for 40 ms.) In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).

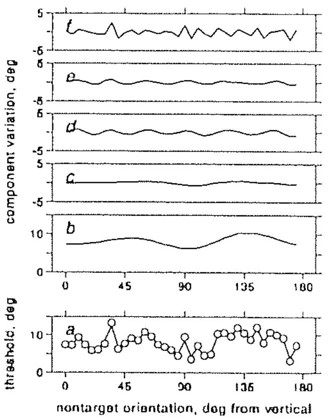
observer LD, ISI = 60 ms



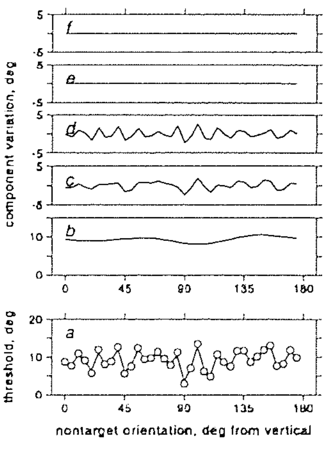
observer LD, ISI = 120 ms



observer LD, ISI = 180 ms



observer LD, ISI = 240 ms



observer LD, no mask

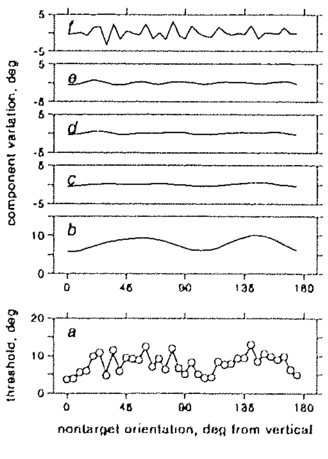
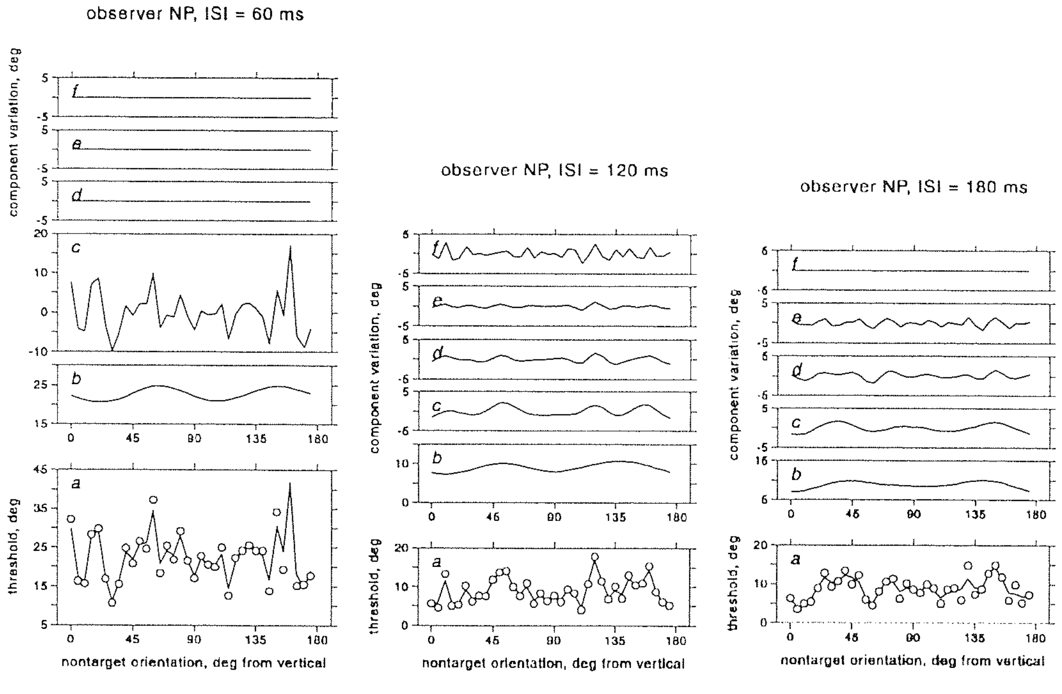


Figure 10.2(iii). Variation of orientation increment threshold with nontarget orientation for observer LD with an ISI of 60, 120, 180, or 240 ms, or no mask. (The effective viewing duration was 40 ms longer than the ISI as target-detection displays were presented for 40 ms.) In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).



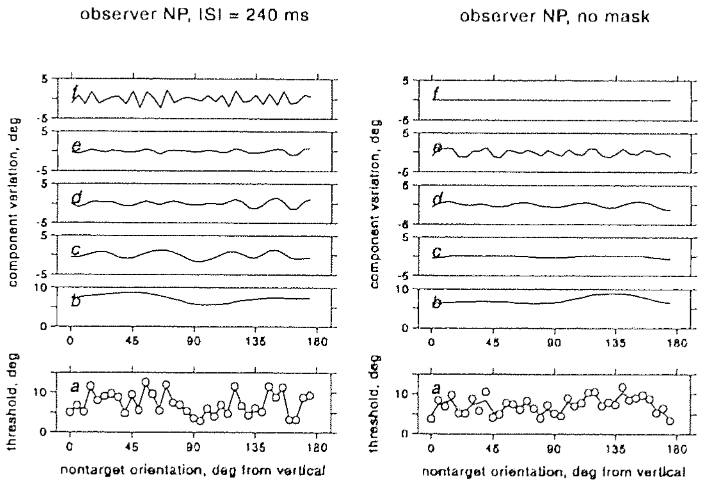
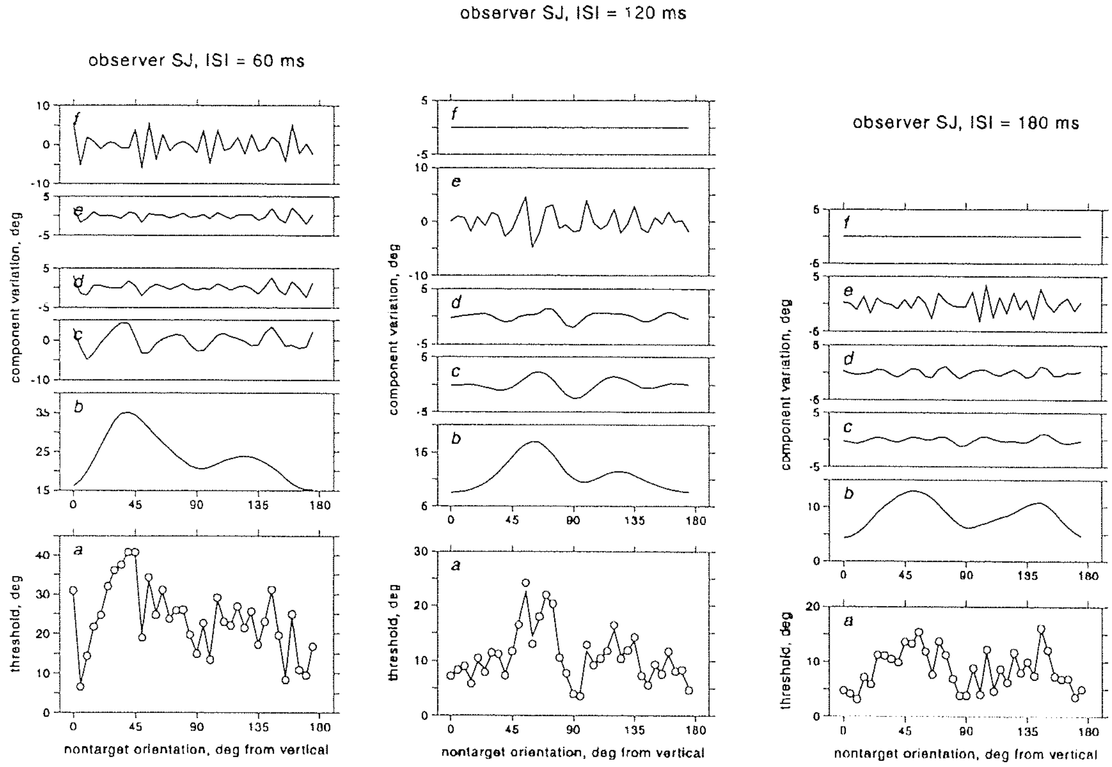


Figure 10.2(iv). Variation of orientation increment threshold with nontarget orientation for observer NP with an ISI of 60, 120, 180, or 240 ms, or no mask. (The effective viewing duration was 40 ms longer than the ISI as target-detection displays were presented for 40 ms.) In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).



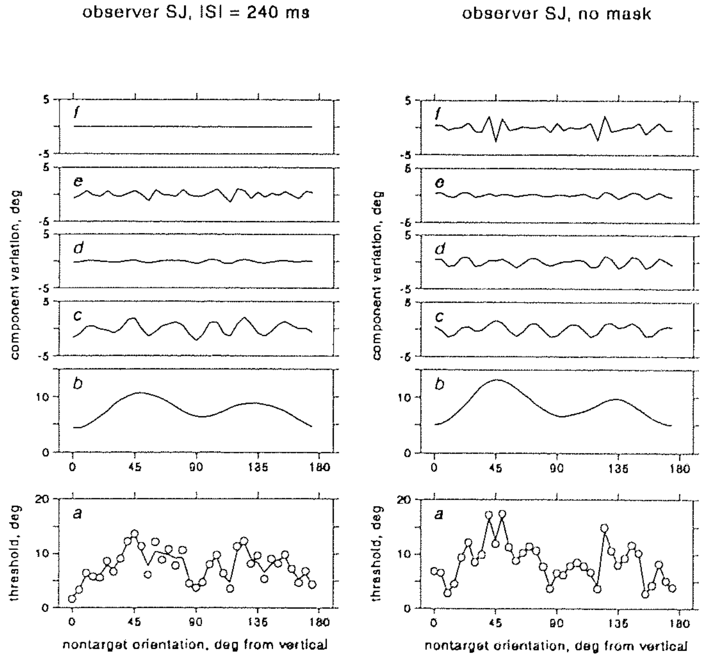


Figure 10.2(v). Variation of orientation increment threshold with nontarget orientation for observer SJ with an ISI of 60, 120, 180, or 240 ms, or no mask. (The effective viewing duration was 40 ms longer than the ISI as target-detection displays were presented for 40 ms.) In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).

10.1.4 Discussion

For observers whose data were consistent with a systematic effect of ISI on the 90-deg periodicity (observers SJ, NP, and JT), the prominence of this periodicity decreased as ISI was increased. This decrease is consistent with the suggestion of Foster and Westland (1997) that the operation of coarse orientation-sensitive mechanisms precedes the operation of finer orientation-sensitive mechanisms. Inclusion of these finer mechanisms in the model of target detection (Westland and Foster, 1995) might not be appropriate, however, since fine orientation-filtering characteristics differ between observers.

Perception of orientation becomes more precise within the first few hundred milliseconds of viewing. For observers SJ, JT, and NP, and to a lesser extent for observers AG and LD, the most marked decrease in average threshold occurred when the ISI was increased from 60 to 120 ms, to give an effective viewing duration of 160 rather than 100 ms.

It is possible that this result is related to the operation of the parvocellular system. There is evidence from experiments on monkeys (see Section 4.8) that the effectiveness of this system for flicker detection drops rapidly as flicker rate increases from 5 to 10 Hz (Schiller *et al.*, 1990). If the parvocellular system responds poorly to stimuli with a frequency of 10 Hz, but supports some processing of stimuli with frequencies between 5 and 10 Hz, then it might be expected that detailed orientation-processing of high-spatial-frequency stimuli with an effective duration of 160 ms would be considerably better than that of stimuli with an effective duration of only 100 ms. The data of the present experiment are consistent with this suggestion.

Each observer's general ability to perceive briefly presented stimuli must also influence the variation of detection performance with effective viewing duration. This influence could account for the apparent observer differences in temporal orientation-processing characteristics, found both in the present experiment and in others reported in this thesis (for example, observers MO and ZH in the first experiment of Chapter 8 could not perform the detection task with an effective viewing-duration of 60 ms but only with effective viewing durations of 180 ms or more). It is unclear whether observer differences in the dependence of target-detection performance on effective viewing duration reflect differences in general perceptual ability, low-level visual mechanisms such as those implicated in the two-filter system modelled by Westland and Foster (1995), or a combination of these factors.

Chapter 11. Determining the reference frame for early visual orientation-processing

11.1. Effects of context and spatial regularity on oriented-line-target detection

11.1.1 Purpose

Early visual detection of oriented line targets can be influenced both by the visual context (Treisman and Gormican, 1988, discussed in Section 3.5.1) and by the spatial regularity of displays (Meigen *et al.*, 1994, discussed in Section 3.3.3). The purpose of the present experiment was to show whether the previously reported orientational anisotropies arose because of these visual cues defining vertical and horizontal, or whether the orientational reference frame for the mechanisms giving rise to anisotropies is defined by other cues such as gravitational information, awareness of the body axis, or retinocentric neural coding.

11.1.2 Methods

Stimuli

Stimulus displays were as in the standard condition, except for the following variations.

There were three types of target-detection stimulus defining three experimental conditions. In the *matrix* condition, elements were placed at randomly selected vertices of an invisible square matrix and displays were viewed through a rectangular aperture with horizontal and vertical edges. In this condition, as in the experiments of Foster and Ward (1991) and Foster and Westland (1995), cues defining horizontal and vertical could in principle be provided by both context and regularity. In the *random placement* condition, the viewing aperture was rectangular and the elements were at random positions, not matrix vertices. In this condition, vertical and horizontal orientations were still defined by the aperture, but not by the placement of lines within the display. In the *circle* condition, elements were randomly placed in a circular field and viewed through two circular apertures, one for each eye. Observers could extract no cue defining vertical or horizontal from the context or regularity in this last condition.

Procedure

The standard procedure was used.

Design

The nontarget orientation for each trial was randomly selected from the range 0, 5, ..., 175 deg. The increment between nontarget and target orientations was randomly selected from the range 10, 20, 30, 40 deg.

Each experimental session involved only one condition defined by context and regularity. Each observer completed 30 sessions, 10 with each of these conditions.

Observers

Two observers participated in this experiment. One (the author) had participated in similar experiments. The other had not, and completed several practice sessions on the task, under standard conditions except that the ISI was 120 ms.

Analysis

The data were analysed as described in Chapter 7, except that the value of d' used to find orientation increment thresholds was 0.2 rather than 0.5.

11.1.3 Results

The variation of orientation increment threshold with nontarget orientation is shown in Figure 11.1, with the associated repeated-loess decomposition. Evidence of anisotropy was found with all conditions, and was as strong with the circle condition as with the matrix and random-placement conditions.

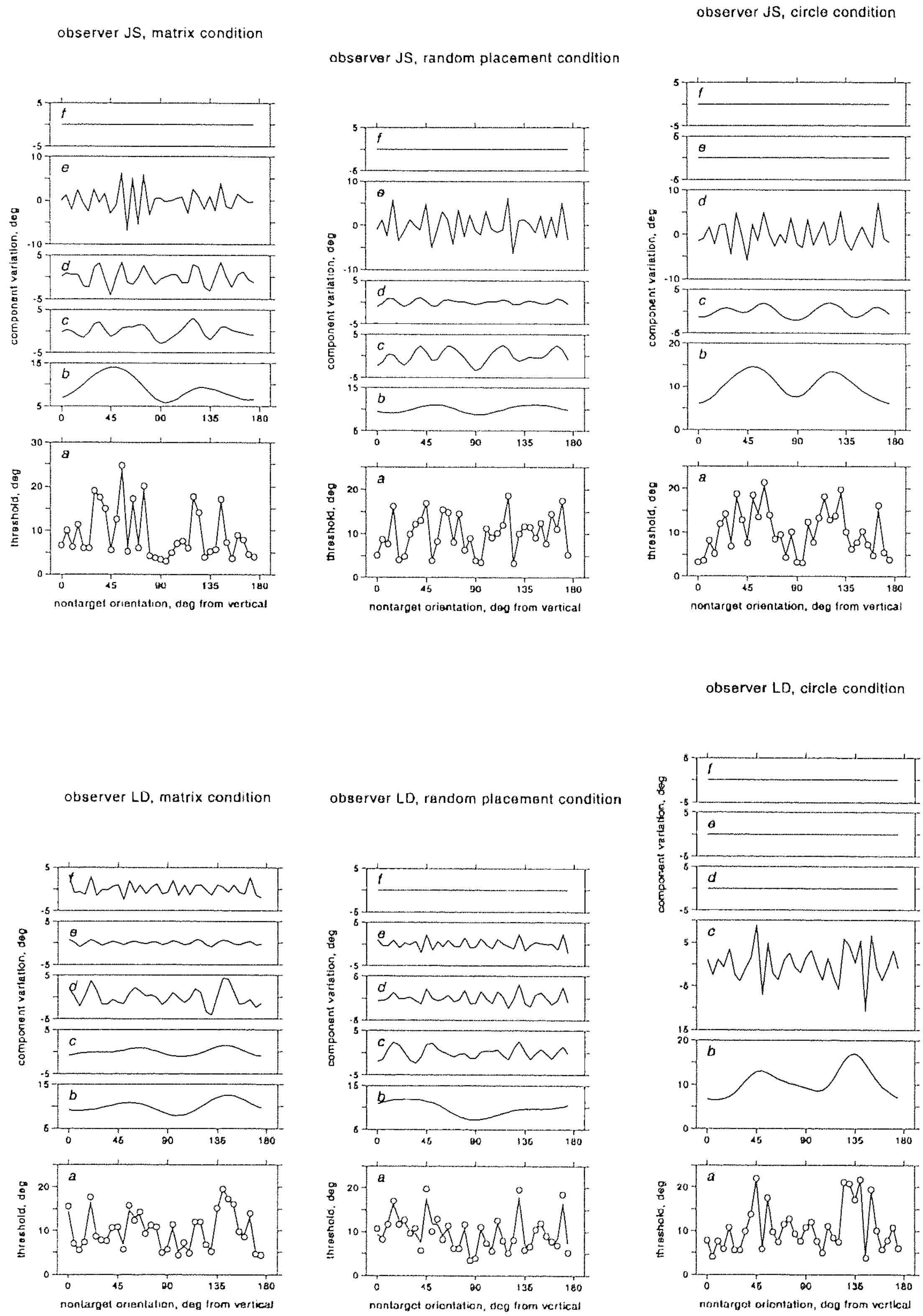


Figure 11.1. Variation of orientation increment threshold with nontarget orientation, in the *matrix*, *random-placement*, and *circle* conditions (first, second, and third columns respectively). Plots in the top row show the data of observer JS, and those in the bottom row show the data of observer LD. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).

11.1.4 Discussion

Orientational anisotropy in line-target detection was found even when aperture edges and element positions provided no explicit visual reference for horizontal and vertical. Therefore, it seems likely that the anisotropy reflects a fundamental characteristic of early orientation-processing rather than a bias introduced by visual cues.

As the anisotropy was found even when no explicit visual cues defined the principal orientations, it appeared that the orientational reference for mechanisms giving rise to anisotropies could be well defined without visual cues. It remained unclear, however, whether the reference was defined by retinocentric or body-axis-dependent cues, or by gravitational cues. To determine in detail how detection performance depends on gravitational information, the following experiment was undertaken.

11.2. The dependence of oriented-line-target detection on gravitational information

11.2.1 Purpose

Visual search for oriented line targets can be affected by information about the direction of gravity (Marendaz *et al.*, 1993). It has been suggested that nonvisual cues might affect the preferred directions or bandwidths of oriented-filter mechanisms operating in early vision (Marendaz *et al.*, 1993), but because few target and nontarget orientations were used in the study of visual search with supine observers, there was insufficient psychophysical information to develop this suggestion in detail. The experiment described in this section, an investigation of target detection with supine observers and a fine sampling of nontarget orientations, was undertaken to provide this information.

11.2.2 Methods

Apparatus

Apparatus was standard, except for the following modifications to allow observers to view displays while supine: a bed was placed in front of the CRT; the view-tunnel was mounted above the observer's head; and a front-silvered mirror oriented at 45 deg to the vertical was placed above the view-tunnel to reflect the stimuli without distortion. Both when sitting and when supine, observers viewed stimulus displays through two circular apertures (one for each eye) aligned perpendicularly to the body axis, so that there was no explicit visual reference defining vertical or horizontal.

Stimuli

Standard stimuli were used.

Procedure

The standard procedure was used, except that the ISI was set at 60, 120, or 180 ms, whichever was the shortest duration that gave about 66 per cent correct detection during practice sessions with the observer sitting.

Design

The standard PEST procedure and range of nontarget orientations was used. There were two conditions defined by observer posture. The *sitting* condition was the standard condition described in Chapter 7. In the *supine* condition, the observer lay on the bed and looked upwards through the view-tunnel to the mirror to view the reflections of the images from the CRT.

Each experimental session involved only one condition defined by posture. Each observer completed 24 sessions, 12 with each of these conditions.

Observers

Five observers participated in this experiment. One (the author) had participated in similar experiments. The others had not, and completed several practice sessions on the task, both sitting and supine.

Analysis

The data were analysed as described in Chapter 7.

11.2.3 Results

For all observers, orientation-increment threshold averaged over all nontarget orientations was affected little or not at all by posture.

The variation of threshold with nontarget orientation was also affected little by posture. This absence of postural effects is evident both in the plots of threshold against nontarget orientation, and in the repeated-loess decomposition of the threshold functions (See Figure 11.2, which shows data obtained with observers sitting, and Figure 11.3, which shows data obtained with observers supine.)

For observers AW, DN, and LD, evidence of a periodicity with period about 90 deg is provided by the coarsest component in the decomposition (plots labelled (b) in Figures 11.2 and 11.3), and this periodicity appears equally strong in both postural conditions. For observer JB, the evidence for a 90-deg periodicity provided by the coarsest component is greater in the supine than in the sitting condition, but inspection of the second component in the sitting condition reveals that there are threshold minima around horizontal and vertical nontarget orientations, so there is little overall effect of posture on anisotropy. For observer JM, there is little evidence of a 90-deg periodicity in either condition.

Figure 11.4 shows the residuals for the data with sitting and supine observers. If gravitational cues had strongly affected orientational anisotropy in detection performance, then these residuals should show some periodic structure. Little periodic structure is evident.

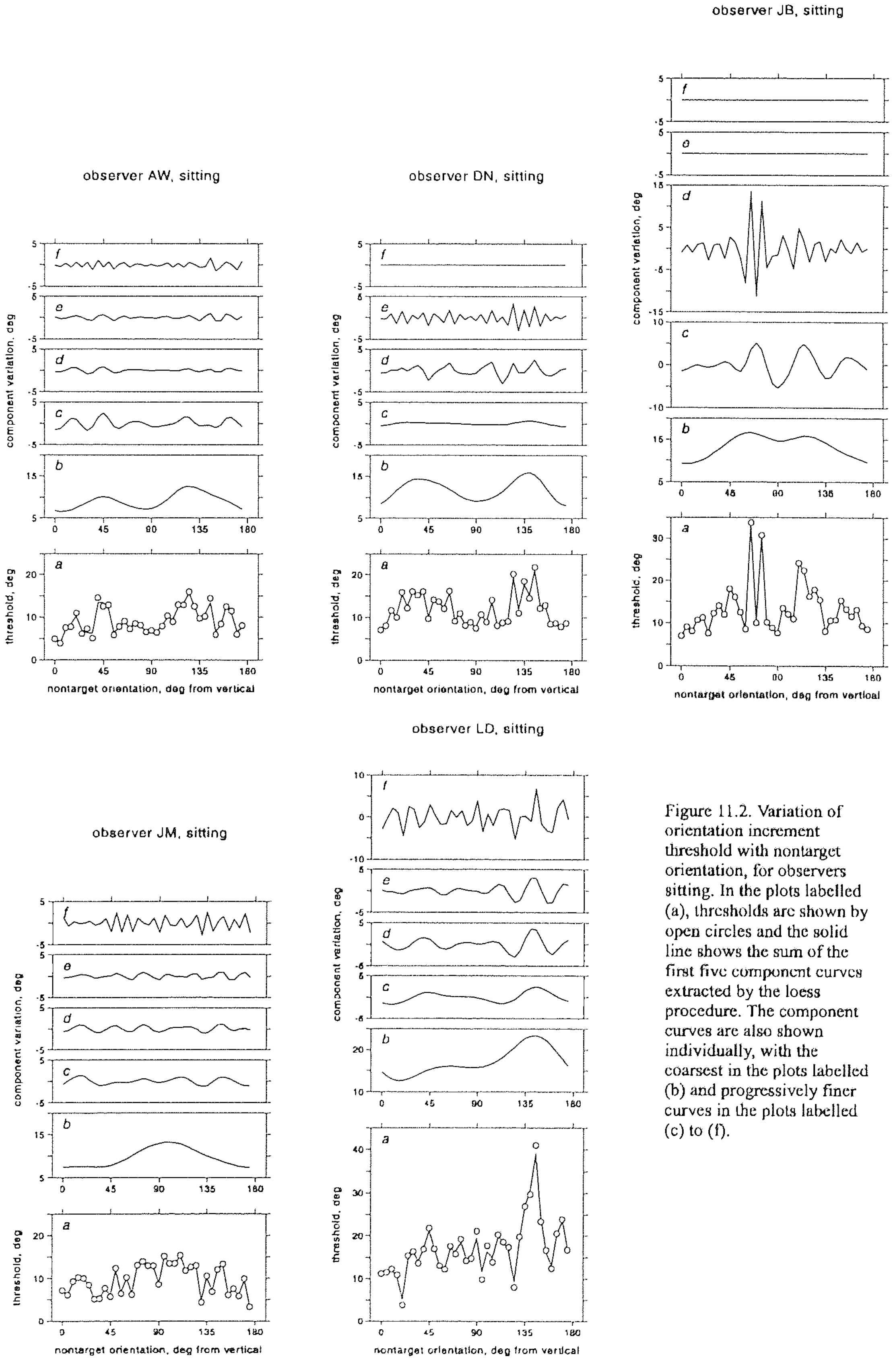


Figure 11.2. Variation of orientation increment threshold with nontarget orientation, for observers sitting. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).

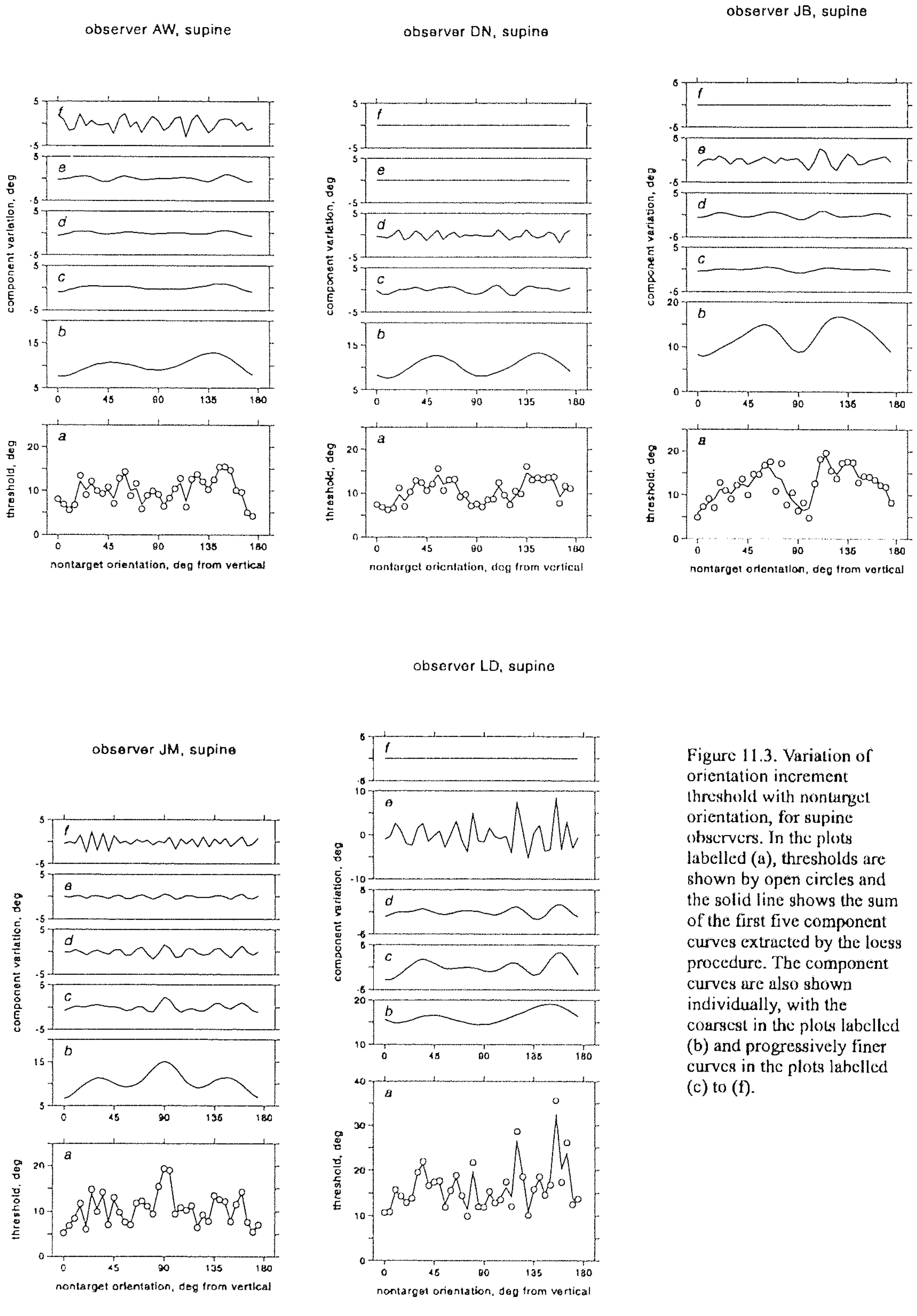


Figure 11.3. Variation of orientation increment threshold with nontarget orientation, for supine observers. In the plots labelled (a), thresholds are shown by open circles and the solid line shows the sum of the first five component curves extracted by the loess procedure. The component curves are also shown individually, with the coarsest in the plots labelled (b) and progressively finer curves in the plots labelled (c) to (f).

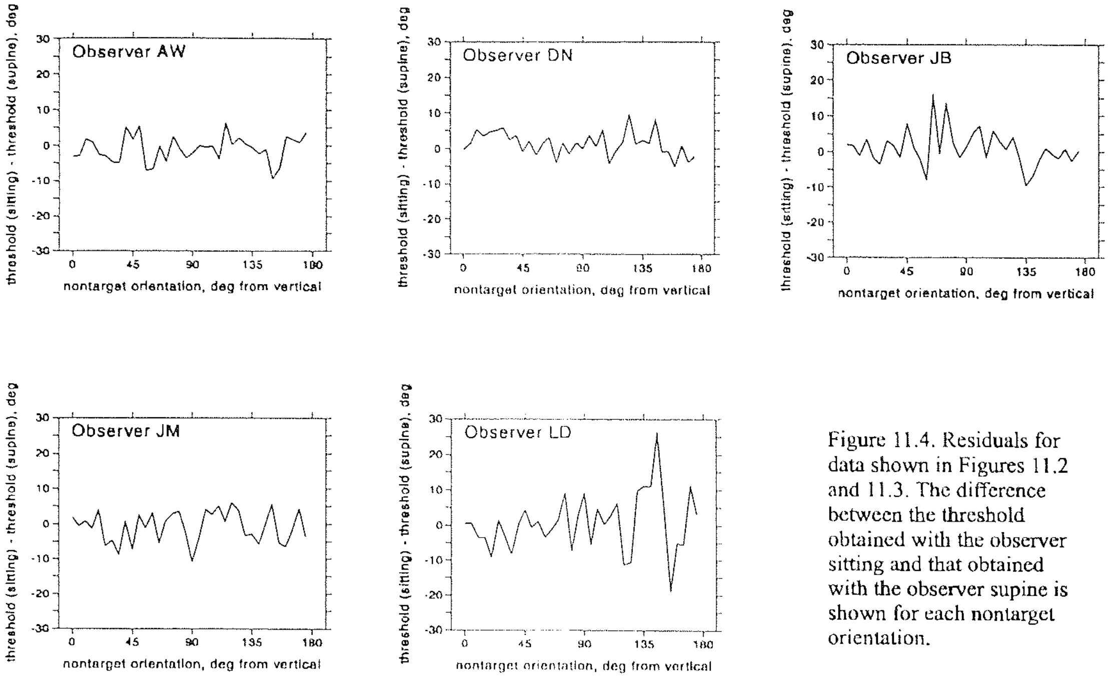


Figure 11.4. Residuals for data shown in Figures 11.2 and 11.3. The difference between the threshold obtained with the observer sitting and that obtained with the observer supine is shown for each nontarget orientation.

11.2.4 Discussion

Orientational anisotropy was as strong in the supine as in the sitting condition. Thus the data from this experiment provide no evidence corroborating the earlier finding that there was little or no orientational anisotropy with supine observers (Marendaz *et al.*, 1993). The anisotropy found in the present experiment did not depend on the presence of an orientational reference defined by gravitational cues.

The difference between the present findings and those of the previous study (Marendaz *et al.*, 1993) might have arisen because the previous study was of visual search, with observers viewing displays for as long as they chose, and the present study was of target detection, with transient, masked, displays. Studies of postural effects on 'attentive' orientation processing have similarly yielded conflicting results, which have sometimes been attributed to small changes in paradigm (e.g. Chen and Levi, 1996). It has been asserted that the determination of a reference frame for orientation in vision is a process involving many factors, and the influence of each factor is task dependent (Heeley *et al.*, 1997). It is possible that in the search task, observers take sufficient time to use information from sensory modalities other than vision and so their awareness of gravity has an effect, whereas in the target-detection task, they cannot do this and must rely solely on low-level, retinocentric, visual processes. If this were the case, then the difference in the results of the present experiment and those reported by Marendaz *et al.* (1991) would be expected. The possibility that this difference is a consequence of the experimental paradigms used (target detection and visual search) is investigated in the following experiment in this chapter.

With respect to the original purpose of the present experiment — to determine how the bandwidths or preferred orientations of early oriented-filter mechanisms are affected by observer posture — no conclusion can be drawn: there was no evidence to suggest that observer posture had any effect on these filter characteristics.

11.3 Control experiment: Reaction times of sitting and supine observers

11.3.1 Purpose

The results of the preceding experiment were unexpected given the findings by Marendaz *et al.* (1993). Aspects of the experimental paradigm that differed between the present work and that of Marendaz *et al.* (1993) included the performance measure and the viewing conditions. The performance measure used in the previous study (Marendaz *et al.*, 1993) was reaction time, whereas the measure used in the experiment described in Section 11.2 was orientation increment threshold. Observers in the previous study (Marendaz *et al.*, 1993) viewed stimuli through a black cardboard cone, wheareas observers in the preceding experiment in this chapter viewed stimuli through two circular apertures, one for each eye. It is possible that the reaction-time data provided information that threshold data did not, or that the alignment of the apertures provided an implicit reference for orientation whereas the cone did not. A control experiment was therefore carried out in order to determine whether the orientational anistropy found in data from supine observers (Section 11.2) could be attributed to the performance measure or viewing conditions rather than taken as evidence of a well defined retinocentric or body-axis-dependent reference for early visual orientation-processing.

11.3.2 Methods

Apparatus

The apparatus was as in the preceding experiment, except that a substitute for the view-tunnel was made in order for the circular apertures to be eliminated in one experimental condition. In this condition, the mirror reflecting images from the CRT was viewed through a black cardboard cylinder so that there were no visual cues, explicit or implicit, that could define an orientational reference.

Stimuli

Stimuli were as in the preceding experiment, except that the fixation cross was replaced by a fixation dot to eliminate any cue to horizontal or vertical that the cross might provide.

Procedure

The standard procedure was used, except that there was no mask.

Instructions to observers

Observers were not only instructed to respond as quickly as was consistent with accuracy but also informed that their reaction times were being measured.

Design

There were three viewing conditions. The *sitting* and *supine* conditions were as in the preceding experiment. In the *cylinder* condition, observers were supine and viewed the CRT through the black cylinder rather than through two circular apertures. Displays could contain an oblique (45 deg to the vertical) target among nontargets that were all vertical or all horizontal, a vertical target among uniform oblique nontargets, or a horizontal target among uniform oblique nontargets.

Analysis

For each observer and combination of orientations, the mean reaction time for correct responses was calculated. Reaction times more than three standard deviations from the mean were excluded from the analysis. Data were pooled across conditions with left and right obliques.

11.3.3 Results

For all observers with all viewing conditions, reaction time was greater when the target was horizontal or vertical among oblique nontargets than when the nontargets were horizontal or vertical and the target was oblique. Search asymmetry as indicated by reaction times was as great or greater in the cylinder condition as in other conditions.

Sitting

Observer	RW	LD	MB
Vertical nontargets	447.1 ± 2.2	397.1 ± 2.1	529.1 ±4.3
Horizontal nontargets	436.6 ± 2.0	400.7 ± 2.4	536.6 ±4.5
Vertical target	451.1 ± 2.2	402.4 ± 2.3	547.0 ± 4.9
Horizontal target	451.9 ± 2.3	405.3 ± 2.4	539.1 ±4.5

Supine

Observer	RW	LD	MB
Vertical nontargets	423.0 ±1.9	394.6 ± 2.3	605.7 ± 5.4
Horizontal nontargets	421.8 ± 1.8	392.4 ±2.2	604.2 ± 5.6
Vertical target	435.1 ± 2.4	399.4 ± 2.3	620.5 ± 6.4
Horizontal target	436.6 ± 2.4	396.4 ± 2.4	623.8 ± 6.2

Cylinder

Observer	RW	LD	MB
Horizontal nontargets	489.7 ± 2.3	425.8 ±2.6	633.6 ± 6.6
Vertical nontargets	484.6 ± 2.2	428.0 ± 2.6	637.0 ± 6.2
Horizontal target	504.6 ± 2.5	432.1 ± 2.7	658.5 ± 7.3
Vertical target	505.4 ± 3.0	434.7 ± 2.7	648.7 ± 6.4

Table 11.1. Reaction times in milliseconds for line-target detection by observers sitting, supine and viewing displays through circular apertures, and supine and viewing displays through a black cylinder. Standard errors in the mean reaction time are shown.

11.3.4 Discussion

It appears that the orientational anisotropy found with supine observers (Section 11.2.3) cannot be attributed to the use of a particular performance measure or type of apparatus. The persistence of search asymmetry in the absence of visual or gravitational cues defining an orientational reference is consistent with definition of such a reference by awareness of the body axis or by retinocentric neural coding. Previous experiments have shown that gravitational (Marendaz *et al.*, 1993) and visual contextual (Treisman and Gormican, 1988) information may influence the reference frame for early visual orientation-processing, but in view of the present results it appears that gravitational and visual cues are not essential to the definition of that reference frame.

Chapter 12. General discussion

12.1 Spatial characteristics of oriented-line-target detection in early vision

12.1.1 Summary of results and conclusions

1. With displays of line elements 1.0 deg long, orientation increment thresholds were largely independent of element density and therefore independent of localization of orientation differences. On the basis of this observation, detecting oriented line targets among uniform nontargets does not appear to require close juxtaposition of differently oriented elements, but involves integration of orientation information from locations throughout the visual field.
2. With displays of line elements 1.0 deg long, orientation increment thresholds with all nontarget orientations were largely independent of set size, and performance anisotropies similar to those reported previously (Foster and Ward, 1991; Foster and Westland, 1995) were found. As thresholds varied little with set size, it is likely that rapid, parallel processes are sufficient to extract the information required for target detection with all nontarget orientations. Detection performance was better with some nontarget orientations than with others, but a qualitative difference (e. g. parallel versus serial) in the type of processing used with different nontarget orientations appears improbable (cf. Carrasco and Frieder, 1997).
3. With displays of line elements 1.0 deg long and an orientation difference of 45 deg between nontarget and target orientations, the percentage of correct responses depended both on set size and on element density. This result appears to contradict (1) and (2), if it is assumed that a single mechanism determines performance with small orientation-increments between the nontargets and the target (e.g. 5 to 30 deg, as in most of the trials used to determine orientation-increment thresholds) and with larger increments (e.g. 45 deg, as in the experiment in which percent-correct scores were found). Therefore, it appears that line-target detection thresholds might be determined by a different mechanism to that determining percent-correct scores with 45-deg orientation increments. The existence of a mechanism sensitive to high but not to low orientation contrasts, and most

effective with localized orientation-contrast, might explain the apparent contradiction between data from experiments in which orientation-increment thresholds were measured and data from experiments in which the percentage correct was measured. Such a mechanism might determine percentage-correct scores with 45-deg increments, but have little influence on performance when the orientation increment between the nontargets and the target is small.

4. With line elements 0.25 deg long, orientation increment thresholds increased with set size. So, it appears that rapid, spatially parallel processes could not extract sufficient information for effective detection when displays contained many short elements. This finding may explain why the results of a study with short elements differed from those of a study with longer elements. It also provides support for the notion that the physical characteristics of stimuli should be taken into account before general conclusions are drawn about the nature of search and detection processes (cf. Verghese and Nakayama, 1994; Carrasco and Frieder, 1997).
5. With line elements 1.0 deg long, orientational anisotropy in target detection varied very little with set size. Therefore, any model of oriented-line-target detection should predict little variation in set size under these conditions.
6. Orientational anisotropy in target detection was found with both long (1.0 deg) and short (0.25 deg) elements. Therefore, any model of oriented-line-target detection should predict little dependence of anisotropy on element length within the range bounded by the lengths of the long and short elements in the experiments.

12.1.2. Comment

It appears that more than one mechanism contributes to performance in target detection. There is physiological evidence for at least two such mechanisms, surround selectivity and suppressive lateral interactions between neurones preferring like orientations. A neural network model (Schofield, 1993) incorporating these two mechanisms has been found to predict performance in some texture-segmentation tasks.

The present work on spatial characteristics of oriented-line-target detection adds to the increasing body of evidence that physical stimulus characteristics of elements in search and detection displays should be taken into account before general conclusions about the nature of search processes are drawn.

12.1.3. Further experiments

It has been asserted (Stemmler *et al.*, 1995) that suppression of responses to like orientations is effective at high but not at low luminance contrast (see Section 4.7). It has therefore been predicted that popout should be weaker at low than at high luminance contrast (Stemmler *et al.*, 1995). As the suppressive mechanism depends on interactions between neurones selective for like orientations, it should be more effective in detection with uniform nontargets than with progressively varying nontargets. To determine whether the suppressive mechanism suggested by Stemmler *et al.* (1995) is important in line-target detection, an experiment could be undertaken with displays presented at various luminance contrasts and containing nontargets of either uniform or progressively varying orientation. If the suppressive mechanism were important for target-detection, then performance with uniform nontargets would be expected to deteriorate more than performance with progressively varying nontargets as luminance contrast were reduced.

12.2 Temporal characteristics of oriented-line-target detection in early vision

12.2.1 Summary of experimental results and conclusions

1. Orientation increment thresholds for oriented-line-target detection decreased as effective viewing duration was increased. For most observers, there was a much greater decrease in threshold when effective viewing duration was increased from 100 to 160 or 220 ms than when effective viewing duration was increased further. It seems reasonable to speculate that this variation in orientation increment thresholds with effective viewing duration might reflect the operation of parvocellular processing-mechanisms: These mechanisms, known to be important in tasks requiring the processing of detail, are likely to be effective after about 200 ms of viewing but not after only 100 ms of viewing.

2. For most observers, the prominence of the 90-deg periodicity relative to finer variations in orientation increment threshold with nontarget orientation decreased as effective viewing duration increased. This observation is consistent with that of Foster and Westland (1997) concerning the variation in periodicities with effective viewing duration. It also provides evidence that "scanning from coarse to fine" occurs in the orientation domain, as well as in the space domain as suggested by Watt (1987).
3. The effective viewing duration required for a given orientation increment threshold differed between observers. The nature and prominence of fine variations also differed between observers. The differences in apparent processing speed could arise because of differences in general perceptual ability rather than low-level factors, but the variations in finer periodicities may reflect that low-level visual orientation-filtering differs between observers.

12.2.2 Comment

The next logical step in development of the two-filter model of target detection would have been addition of filters tuned to orientations other than vertical and horizontal. Observer differences, however, are too great to allow this development of the model to provide further insight into the nature of early orientation-processing in general, rather than for a particular observer.

12.3 Determination of the orientational reference frame for early visual processing

12.3.1 Summary of experimental results and conclusions

1. The 90-deg periodicity in the variation of target-detection performance with nontarget orientation was as strong with displays of randomly placed elements viewed through circular apertures as with displays of elements at matrix positions viewed through a rectangular aperture. Therefore, it seems that this periodic anisotropy reflects a fundamental characteristic of early orientation-processing rather than a bias introduced by spatial regularity of displays or contextual cues giving an explicit visual reference for orientation.

2. The periodicity with period 90 deg in the variation of target detection performance with nontarget orientation was as strong when observers were supine and viewing displays through circular apertures as when they were sitting and viewing displays through circular apertures. As Marendaz *et al.* (1993) found orientational search asymmetry with standing but not with supine observers, the present finding appears difficult to explain unless the orientation-processing mechanisms implicated in target-detection differ from those implicated in visual search, or if the view-tunnel with circular apertures provided a cue that observers could have used as a reference for orientation.

3. With brief, unmasked displays viewed through a black cylinder that eliminated visual cues defining orientation, anisotropy with respect to nontarget orientation was evident in the reaction times of supine observers. So, the results reported in (2) could be attributed neither to the use of a target-detection paradigm rather than a visual-search paradigm, nor to the design of the view-tunnel. The present results with supine observers, unlike those of Marendaz *et al.* (1993), provide evidence that in the absence of visual and gravitational cues there remains a reference for orientation in early vision. This reference must be provided by retinocentric neural coding, awareness of the body axis, or both. It is unclear why the present study has yielded results supporting a conclusion differing from that of Marendaz *et al.* (1993). One possible explanation is that in the work of Marendaz *et al.* (1993) the conclusion concerning anisotropy was based on the variation of reaction time with set size: with oblique nontargets, the nature of this variation depended on observer posture, so it was concluded that gravitational cues were required to define a reference for early orientation-processing. In the present study, on the other hand, the evidence of anisotropy is provided by the reaction times themselves: with oblique nontargets, reaction times were greater than those with vertical or horizontal nontargets whether the observers were sitting or supine, so it appears that the reference for early orientation-processing can be well defined without gravitational information.

12.3.2 Comment

There is physiological and anatomical evidence of meridional anisotropy in the visual system (see Section 4.6), and there is also physiological evidence that information from the vestibular system is integrated in low-level visual processing (see Section 4.4). The results of the present study and those of Marendaz *et al.* (1993) and Stivalet *et al.* (1995) provide psychophysical observations analogous to those from physiology, indicating that various cues may determine the orientational reference in early vision. In view of these results, it seems most probable that this reference is determined by visual cues, gravitational cues, *and* awareness of the body axis or neural coding in retinocentric co-ordinates (the last two types of cue producing the same orientational reference in most situations). So, the results of the present study add to the growing body of evidence (Marendaz *et al.*, 1993; Stivalet *et al.*, 1995; Heeley *et al.*, 1997) of multifactorial determination of the orientational reference in vision.

12.3.3 Further experiments

In many experiments, there has been confounding of the references provided by gravity, the body axis, the retinal vertical, or some combination of these. In order to determine whether the anisotropy found without visual or gravitational cues (see Section 11.3) is dependent on the retinal vertical or the body axis, the variation of target detection performance with nontarget orientation could be measured for supine observers with their heads tilted with respect to the body axis.

It has been found that the dependence on vestibular cues of search asymmetry with tilted and horizontal elements may differ from that with tilted and vertical elements (Marendaz *et al.*, 1993; Stivalet *et al.*, 1995). It is unclear whether visual contextual cues affect the orientational reference frame as a whole, or whether they may affect the search asymmetry for only the horizontal axis or only the vertical axis. This issue could be investigated in an experiment similar to that performed by Triesman and Gormican (1988), in which observers detected targets in displays with either an upright or a tilted frame (at 18 deg to the vertical). In order to determine whether the presence of a tilted frame alters the entire visual reference frame for orientation or only the vertical reference, the experiment could be carried out with displays of horizontal and tilted elements, as well as displays of vertical and tilted elements as presented by Treisman and Gormican (1988).

12.4 Conclusion

The perception of orientation is important in understanding the structure of the visual environment. The present work has provided insight into several aspects of this perception.

It has been shown that rapid, spatially parallel detection of orientation differences does not require those differences to be highly localized within the visual field, but if the orientation differences are large enough (e.g. 45 deg) then they are detected particularly well if they are highly localized. The complex nature of the variation of detection performance with orientation-contrast localization may be an indication that more than one mechanism is involved in target-detection.

Orientational anisotropy in target detection performance has been found in the present work as in previous studies. Experimental results reported in this thesis have provided evidence that this performance anisotropy is a consequence of anisotropic, low-level, visual filtering rather than an indication of qualitative differences in the processing of different orientations.

Performance in a line-target detection task has been found to depend on the length of the stimulus line elements, so this factor should be taken into account when making comparisons between target-detection results in different studies or using such results to draw conclusions about the nature of early processes in general. Any further development of the model of oriented-line-target detection (Westland and Foster, 1995) should include verification that the model predicts the dependence of performance on line-element length and the stability of performance with respect to set size.

The variation of target detection performance with effective viewing duration has been found to be consistent with very rapid, coarse orientation-processing followed by more detailed orientation-processing. For several observers, the most marked increase in the precision of orientation-processing with effective viewing duration occurs as effective viewing duration increases from about 100 to about 200 ms. A speculative explanation of this finding is that the increase in precision is a consequence of the onset of parvocellular processing.

Anisotropy in target-detection performance is found in the absence of gravitational cues defining an orientational reference, showing that a gravitational reference is not essential to the operation of the mechanisms that give rise to orientational anisotropy. It has also been shown that even if all visual and gravitational references are removed then there remains a reliable orientational anisotropy in detection performance. So, it seems that the orientational reference frame of the mechanisms giving rise to orientational anisotropy in early visual processing is well defined by retinocentric neural coding, awareness of the body axis, or some combination of these factors.

Appendix: Decomposition based on repeated loess.

An adaptation of the repeated-loess fitting procedure (Cleveland, 1993, Section 3.11) was used to decompose each increment-threshold function into component curves according to the different numbers of minima revealed at different levels of smoothing of the function. Smoothing was by a nonparametric, locally weighted, quadratic-regression smoother (Cleveland, 1979; Fan and Gijbels, 1996). A quadratic polynomial was used because it produced less bias at the maxima and minima of increment-threshold functions (e.g. Cleveland *et al.*, 1990, p. 8). The weight function was a wrapped Gaussian with bandwidth h.

There were three steps to the repeated-loess procedure.

(1) *Order numbers of minima in components.* The increment-threshold function was first oversmoothed by setting the smoother bandwidth h to 24 deg so that the smoothed curve had 2 or fewer minima. Smoothing was then progressively reduced by decrementing h in steps of 0.3 deg until a value h_1 was reached at which on the next iteration the number of minima in the curve increased from n_1 equal to 2 to a larger number (there was never a decrease). For this value h_1, the curve was undersmoothed in the sense that one or more of the new minima were almost visible; smoothing was therefore increased by incrementing h_1 to $h_1 + kh_1$, where k is the largest value between 0 and 0.5 for which the number of minima in the curve was still n_1. The limit of 0.5 was found optimal in test applications of the procedure to sums of sawtooth functions and sums of sinewave functions. The resulting 'optimally' smoothed curve s_1 with n_1 minima was then subtracted from the original increment-threshold function to produce a residual. The residual was then subjected to the same iterative smoothing process that had been applied to the increment-threshold function. Thus it was first oversmoothed, and the smoothing was then reduced in 0.3-deg steps until h reached a value h_2 at which on the next interation the number of minima in the curve increased from n_1 to a larger number, say n_2; smoothing was then increased by incrementing h_2 to $h_2 + kh_2$,where, as before, k is the largest value between 0 and 0.5 for which the number of minima in the curve was still n_2. The new optimally smoothed curve s_2 with n_2 minima was then subtracted from the original increment-threshold function to produce a new

residual. This process of smoothing and differencing was repeated until no smoothed residual could be extracted with more minima than the last. For each observer, a collection of 9–14 smoothed curves was extracted. The curves were ranked in descending order of amplitude, and the numbers of minima $n_1, \ldots, n_5$ in the 5 largest-amplitude curves were then used as inputs to the next step (a limit of 5 was found to be sufficient in practice).

(2) *Estimate components*. The smoothing and differencing process used in (1) was applied afresh to the increment-threshold function except that optimally smoothed curves $s_1, \ldots, s_5$ were extracted only where the numbers of minima $n_1, \ldots, n_5$ coincided with the selected values $n_{i1}, \ldots, n_{i5}$. If the sum S of the curves s_j, $j = 1, \ldots, 5$, $S(\theta_i) = \sum_{j=1}^{5} s_j(\theta_i)$, where $i = 1, \ldots, 35$, did not adequately fit the increment-threshold function ($p \geq 0.5$), the smoothing of s_5 was reduced until it did. The p-value was calculated from a χ^2 statistic based on $\hat{\sigma}(\Delta\theta_i)$, the parametric bootstrap estimate of the standard deviation of the increment threshold $\Delta\theta_i$ (Efron and Tibshirani, 1993; Foster and Bischof, 1991), and on the degrees of freedom of the smoother (Hastie and Tibshirani, 1990, Section 3.5). If for any m, with $1 \leq m < 5$, the partial sum $\sum_{j=1}^{m} s_j$ provided an adequate fit to the increment-threshold function, the remaining curves s_j, with $m < j \leq 5$, were set to zero.

(3) *Permute extraction order*. Step (2) could be repeated with the component curves extracted in different orders until they stabilized; for example, the partial sum $S_{(m)}$ of the s_j with s_m removed, that is, $S_{(m)}(\theta_i) = \sum_{j=1, j \neq m}^{5} s_j(\theta_i)$, $i = 1, \ldots, 35$, can be subtracted from the increment-threshold function and the residual optimally smoothed to extract a new estimate of s_m. In fact, additional passes beyond the first produced little improvement (Cleveland, 1993, p.155).

The whole procedure was fully automated.

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Aston University

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Canonical Solution Groups of a Homomorphism

Manipulator Kinematics, Nonparametric Regression and Distributed Object Systems

CONOR JEREMIAH DOHERTY

Doctor Of Philosophy

THE UNIVERSITY OF ASTON IN BIRMINGHAM

July 1997

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Thesis Summary

The kinematic mapping of a rigid open-link manipulator is a homomorphism between Lie groups. The homomorphism has solution groups that act on an inverse kinematic solution element. A canonical representation of solution group operators that act on a solution element of three and seven degree-of-freedom (*dof*) dextrous manipulators is determined by geometric analysis. Seven canonical solution groups are determined for the seven *dof* Robotics Research K-1207 and Hollerbach arms. The solution element of a dextrous manipulator is a collection of trivial fibre bundles with solution fibres homotopic to the Torus. If fibre solutions are parameterised by a scalar, a direct inverse function that maps the scalar and Cartesian base space coordinates to solution element fibre coordinates may be defined. A direct inverse parameterisation of a solution element may be approximated by a local linear map generated by an inverse augmented Jacobian correction of a linear interpolation. The action of canonical solution group operators on a local linear approximation of the solution element of inverse kinematics of dextrous manipulators generates cyclical solutions. The solution representation is proposed as a model of inverse kinematic transformations in primate nervous systems.

Simultaneous calibration of a composition of stereo-camera and manipulator kinematic models is under-determined by equi-output parameter groups in the composition of stereo-camera and Denavit Hartenberg (DH) models. An error measure for simultaneous calibration of a composition of models is derived and parameter subsets with no equi-output groups are determined by numerical experiments to simultaneously calibrate the composition of homogeneous or pan-tilt stereo-camera with DH models.

For acceleration of exact Newton second-order re-calibration of DH parameters after a sequential calibration of stereo-camera and DH parameters, an optimal numerical evaluation of DH matrix first order and second order error derivatives with respect to a re-calibration error function is derived, implemented and tested.

A distributed object environment for point and click image-based tele-command of manipulators and stereo-cameras is specified and implemented that supports rapid prototyping of numerical experiments in distributed system control. The environment is validated by a hierarchical k-fold cross validated calibration to Cartesian space of a radial basis function regression correction of an affine stereo model.

Basic design and performance requirements are defined for scalable virtual micro-kernels that broker inter-Java-virtual-machine remote method invocations between components of secure manageable fault-tolerant open distributed agile Total Quality Managed ISO 9000+ conformant Just in Time manufacturing systems.

Keywords: Solution Groups, Manipulator Inverse Kinematics, Model Calibration, Nonparametric Regression, Distributed Object Software Engineering, Sensorimotor Coordination

And pluck till time and times are done
The silver apples of the moon,
The golden apples of the sun.

W.B. Yeats. *The Song of Wandering Aengus*

TO DOREEN

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Conor Doherty

Dublin
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