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PSYCHOPHYSICAL EVIDENCE CONCERNING THE INTEGRATION OF CURVATURE INFORMATION IN SHORT CONTOURS

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TITLE........PSYCHOPHYSICAL EVIDENCE CONCERNING THE INTEGRATION OF

..........CURVATURE INFORMATION IN SHORT CONTOURS..............

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I certify:

(i) That the greater portion of the work submitted in the above thesis has been done subsequent to my registration for the degree of Ph.D.

(ii) That the above thesis is my own account of my own research.

(iii) That no part of the work incorporated in the above thesis has previously been incorporated in a thesis submitted by me for a Higher Degree at any university.

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Abstract

Performance of curvature discrimination was measured for a wide range of stimulus curvatures and sizes, using an adaptive version of the Method of Constant Stimuli. Performance is expressed both in terms of curvature difference thresholds, and efficiency, where efficiency is defined as the ratio ideal minimum response variance, based on the spatial statistics of the retina, to the observed response variance. The results lead to three major conclusions.

Curved lines may be processed for curvature discrimination decisions with the same efficiency as straight lines, under appropriate conditions.

The results are not consistent with a high degree of common processing for straight and curved lines, but suggest the operation of two parallel processes, one for straight lines and one for curved lines. Each process has strict input limitations. Those for the process concerned with straight lines have already been determined by Andrews, Butcher and Buckley (1973).

The stimulus input limitations for the curved line process are determined in the present study, and suggest that this process is primarily concerned with local slope analysis, and is limited to a range of slopes of 40 degrees. Experiments using broken stimuli throw further light on the working of this process, as does a detailed study of the relationship between efficiency for curvature discrimination and stimulus orientation range (defined as the product of stimulus curvature and length).

The orientation range limit is reduced to 30 degrees when oblique stimuli are used, or a single central gap is added to horizontal stimuli.

The implications of these results are discussed, and suggestions for further research made.

Acknowledgements

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This thesis is dedicated to Helen, who has borne the greatest cost.

Contents

CHAPTER 1. : THE PERCEPTION OF CONTOURS AND CONTOUR SHAPE.

1.1 Introduction.

We live in a world furnished with many spatial continuities. There are continuous surfaces, and continuous edges; there are continuities of texture, colour and brightness; space itself is apparently continuous. With our vision, we may perceive these continuities consistently, and yet our visual system is only equipped to collect light at a discontinuous array of points, since the organ responsible for this collection, the receptor surface of the retina, consists of a mosaic of discrete light sensitive elements of finite size, number and spacing. Even although there is a vast number of these receptor elements, it is perhaps surprising that our visual perception of space is continuous, since this implies that the visual system has to guess or infer the presence of these continuities.

The retina is capable of recording a great deal of information in its response to the pattern of incident light. The number of potential patterns of excitation across the retina is uncountable, far in excess of the number of nerve cells within the cranium. Likewise, the number of possible neural connections between different sets of receptors, making logical combinations of this input, is infinite. It follows that a certain selection of incident light patterns are detected and analysed more directly than others, as individual entities. Particular patterns of input (presumably those that natural selection has found to be the most useful or frequent) are condensed into simpler statements. These simpler statements must reduce the redundancy of the input information, since the visual pathway, which conveys all visual information to the higher centres of the brain, has a strictly limited capacity (input information is redundant in the sense that the visual system is able to use a symbolic code to represent the large amounts of information, contained in continuities of edge, colour, and luminance, for example, by concise descriptions).

It might be supposed that a transmission system which uses a symbolic code, and that infers the presence of continuities from the response of a discontinuous transducer, would be rather inaccurate in judging fine details in its input. In the case of the visual system, this is not so. The simpler statements, used to reduce the redundancy of the input information, must also maintain aspects of this data with a very high degree of accuracy : for example, stereoscopic vision requires precision in the recording and analysis of the position of an object, or a feature of an object. These simpler statements are much more than mere summaries of the input.

A striking example of the parallel operation of these two processes of redundancy reduction and precise analysis of the same object, is provided in the results reported by Ludvigh (1953), who measured the smallest displacement of the central dot in a row of three dots, which his subjects could reliably discriminate. The dots each only subtended 3 sec. arc at the retina, and therefore, even allowing for light spread by the optics of the eye, probably only stimulated a very few receptors at any one instant. The first point to note in his results, is the extremely high accuracy with which the relative positions of these dots can be judged : the smallest displacement threshold (orthogonal to the row of dots) is less than 3 sec. arc, an order of magnitude smaller than the distance separating two adjacent receptors. Secondly, this threshold for relative position was found to vary systematically with the separation of the dots, being smallest when the stimulus array suntended between 10 and 20 min. arc, and increasing rapidly, as the separation between the dots became larger. This finding implies that the three dots are being summarized in some manner, when less than 20 min. arc apart, but not when they are more widely spaced. If this were not the case, increasing separation should have a steadily increasing effect on judgements of relative position, due to the cumulative effects of random distortions in the visual metric, and also arising from the increasing grain size of the retinal mosaic, with the increasing eccentricity of the stimulus.

It is very tempting to conclude that it is by means of the simplification or summarization of the input, which accomplishes a reduction in the redundancy of the input, that this high level of accuracy is achieved. This is paradoxical : when the stimulus array in Ludvigh's experiment can be summarized, information must have been discarded, but judgemental error is low; when the stimulus array cannot be summarized in the same manner, judgemental error is relatively high. The explanation for this paradox is that no information is lost by the process of making a summary, provided that the summary is appropriate, and that the receiving processes are informed of the nature of the summary process : absolute information is replaced by experential information (both inherited and personal experience, but probably mostly that inherited), and ninety nine times out of one hundred, the two are identical.

Patterns of light, collected at discrete points on the retina and corresponding to discrete points in space, are mapped onto the percepts of whole objects and continuous space. The immediate processes of summary must begin this task of perceptual inference, and must therefore, contain all the information necessary for the visual system to identify an object, and to discriminate its size and shape, position and attitude, brightness and colour, and the temporal sequence of events involving that object. A summary which contains some of this information at relatively high levels of accuracy, is of course constrained in a system with a limited transmission capacity, to categorize and generalize much of the information recorded at the retinal surface, by extracting pre-defined features of the pattern of stimulation, which can be interpreted at a later stage.

1.1.1 Features, Especially Contours.

Feature extraction is a fundamental and important step in the overall process of form recognition and analysis, and yet there is little understanding and knowledge of the matter. The problem should not lie in establishing the hypothesis that the visual system does extract features, which it obviously has to, but rather in establishing which features are the ones employed, in what form they are represented, and what additional information is available, within the visual system, concerning that particular feature.

Barlow, Narasimhan and Rosenfeld (1972) argue that common ground between the disciplines of neurophysiology, perceptual psychology, and artificial intelligence, shows that these independent approaches are all highlighting the same difficulties, and then suggest that a joint approach could be profitable. One aspect of common ground that they draw particular attention to, is the importance that all types of pictorial analysis give to edges, lines and the ends of edges and lines.

The potential usefulness of such features cannot be denied. Contours, which are defined as discontinuities of contrast, texture and colour, provide cues which may be used to specify the shape of an object, its attitude and position, and its size. The relative position of two or more objects may, in some cases, be specified by the overlap of their images, which may in turn be specified by the intersection of contours. Attneave (1954) describes a number of principles of redundancy reduction that could be employed to advantage by the visual system, and points out that the consequences of these principles are very similar to the consequences of the principles of Gestalt Psychology (eg. Koffka, 1935). Four of the ten principles concern the use of contours as elements of an economical description of an object or space. He states that areas of texture or colour, either with a regular variation or with none, may be specified by the function of variation, and the boundary of the area. Likewise, the parts of a boundary which show regular variations in direction, can also be defined by a specification of the function of variation, and the loci of the limits of this variation. The important point is that such principles of symbolic encoding require less transmission capacity, than point-for-point descriptions would.

Contours of one sort or another seem to have a physiological importance to the visual system. Ever since the work of Hubel and Wiesel (1959, 1962), it has been clear that the nerve cells of the striate cortex of an anaethetized cat or monkey respond preferentially to patterned stimuli of light, in contrast to the receptors of the retina, which apparently only respond to the photon energy in the light stimulus. It has been repeatedly shown that cells in the various centres in the visual pathway prefer bar-shaped stimuli to unpatterned stimuli (Kuffler, 1953; Hubel and Wiesel, 1962, 1965; Barlow, Blakemore and Pettigrew, 1967; Pettigrew, Nikara and Bishop, 1968). Whilst the precise form of the spatial convolution applied to the input to such cells is still a matter of some controversy, the organization of the striate cortex does lead to the supposition that it may be involved in the extraction of contour-like features, and their subsequent analysis.

Contours have also been shown to play a major role in the development of human visual behaviour. A newborn opens its eyes in light of moderate intensity, and engages in active, vigilant scanning of the environment (Haith, 1968). This scanning is halted when an edge or contour is discovered, and the eye-movemnets then appear to be aimed at crossing and re-crossing it (Kessen, Salapatek, and Haith, 1972). Vertical contours are preferred at first, and then as the infant develops, horizontal and lastly oblique contours are also able to elicit this behaviour. The work of Fantz on the visual preferences of infants also supports the notion that contours are of particular salience in the visual environment to the developing visual system. Fantz has found that the shape of a contour is important : children under about two months of age prefer checker-boards to a bull's eye pattern (that is, they spend more time gazing at checker-boards);

the preference is reversed in older children (Fantz, 1958,1967; Fantz and Nevis, 1967). As the visual system becomes experienced, it apparently becomes more able to analyse complex contour pattern. The important point is that the visual system appears to devote much of the time during a period when it is thought to be plastic and modifiable, to studying contours in the visual environment.

These various considerations, taken together, stress the importance of physical contours in the environment to those processes carried out by the visual system in perceiving this environment. Much effort has been expended in an attempt to discover how such contours are represented within the visual system, and terms such as spatial frequency channels, edge detectors, line detectors, and so on, have been coined and used by numerous authors, to express opinions concerning which description of the critical features of contours or structure in the visual world are the most appropriate to use in discussing the representation of such structure.

However, this is not the problem of interest here. Contours are clearly important in vision, but the question to be asked is as follows. How well does the visual equipment, which infers the presence of contours in the environment, operate, and what information is it able to extract concerning these contours from the discrete array of point samples of the incident light pattern on the retina ? In the terms used above, how much information does that summary, or group of summaries, which indicate contours, convey through the visual system ?

When this question has been fully answered, than the nature of the summary, or the process of simplification, and inference of continuity, will have been defined.

What form should such an answer take ? Why is the data of Ludvigh (1953) which is cited above as evidence concerning such a process of summary and simplification, useful in this respect, when for example, the data of French (1919) is much less useful. Both showed that a spatial judgement task, dot alignment or vernier discrimination, respectively, suffers errors that are a function of the stimulus array size.

The data of French suggest that it is not just information at the discontinuity that is being used by the visual system to perform the task, but that the relative position of the two lines is judged by accumulating information along the whole stimulus. This is certainly interesting, but the data of Ludvigh indicates that something much more interesting than mere counting is happening in the visual system.

The crucial difference is that in the experiment of French, one might expect vernier acuity to improve with increasing stimulus size, if one considered the task to involve relative position, because the visual system is given a more powerful stimulus, but in the experiment of Ludvigh, the stimulus has very nearly the same power to perform the task, at the different sizes, and the results are more surprising.

It is restrictions in the ability of subjects to perform tasks, particularly where none would be indicated by the nature of the stimulus employed, that throw most light on the early processes in the visual system concerned with the reduction of redundancy , and selective feature extraction.

The next section will consider what is known of the processes of contour information extraction by the visual system, and discuss what the implications of this knowledge are for an understanding of the underlying processes.

1.2 Contour Information Processing.

It has been argued above, that the visual system has to infer continuous qualities of space from the discontinuous response of the retina to incident light patterns. At the same time, it has to reduce the redundancy in the neural description of the light pattern, which it can do by using a pre-defined alphabet of features. It seems surprising that while the system logically is making guesses and categorizations (neither process naturally conducive to high fidelity of information recording and transmission), it can still sustain high accuracy in certain spatial judgements. This high eccuracy is not uniform, and it is through the non-uniformities that clues to the nature of these visual processes should be found.

The literature abounds with examples of high spatial accuracy for visual judgements, but little of this data can provide any direct insight, because the non-uniformities in performance are not easily deduced from the sort of functions measured : it is of little use or interest to know that vernier acuity can be as little as 5 sec. arc. There are, however, some studies which show sytematic variations in spatial thresholds which do lead to some insight into the visual processes underlying the perception of visual space.

Contours can provide information concerning the shape of an object; its size; its position; and its attitude. Different judgement tasks can test the ability of the visual system to extract these different types of information from the visual world. Examples of tasks assessing the use of shape information are vernier acuity (discontinuous shape) and curvature acuity; size and position information usage

might be assessed by length and separation judgements; attitude processing might be tested by slope comparison tasks.
These interpretations of what processes the various tasks are testing are subjective, since in a sense they are all tests of relative position. However, if the visual system is to achieve anything in the direction of form analysis and recognition, then it must proceed with analysis beyond the point of relative position, and it therefore seems reasonable to make the above interpretations of the experiments. The question of interpretation is not serious at this stage, and the experiments themselves will be shown to justify these interpretations.

There is a little data in the literature for all of these tasks, rather more for vernier acuity than for the others. This data will now be described, in an attempt to elucidate some of the limitations of the visual system. It is almost impossible to compare directly different sets of results, since the conditions vary widely from experiment to experiment, and as a result, very little quantitative information can be gleaned.

It is important to note that the experiments reported are all concerned with the visual analysis of lines. Whether these results may be generalised to all types of contour or not remains to be seen, although it does seem likely that similar processes must operate.

1.2.1 Vernier Acuity.

Vernier resolution was first measured by Wulfing (1892), and consists of the judgement of the misalignment of two lines, one directly above (or beside) the other,(see Fig. 1.2.1a). He found that the threshold was very small. Hering (1899) attempted to account for the small value, when compared with the diameter of a single retinal receptor, by arguing that, if each receptor had a local sign, or fixed spatial positional value, which could be used by the higher centres, then any process that combined the local signs of a number of receptors responding to aline or contour, woubd lead to a more precise local sign for that line, than that for any one receptor.

It is clear that using several adjacent receptors, rather than just one, could improve perceived spatial positional specificity for an object, provided that the combinations were efficient. That this is the case is suggested by the low value of the measured threshold. That combinations are made along the line, and that the results of these combinations are improvements in acuity, is shown by the data of French (1919-1920), who found that vernier acuity improved with increasing line length. This explanation was elaborated by Weymouth, Anderson and Averill (1923). It does seem likely from these results, that spatial information from a number of different receptors can combined with sufficient efficiency to improve on the positional specificity of a single receptor. However, it is not clear from these results, what the limits of such combinations might be.

Many years later, Baker complained that 'little attention has been paid to the stimulus factors which affect vernier acuity' (Baker, 1949). To a degree, this has subsequently been corrected, but to little avail (until this last decade), since the underlying philosophy motivating this research has been in error. Subsequent workers have generally addressed themselves to the problem of a mechanism for vernier acuity. It might, however, be presumptious to seek a fixed mexhanism for vernier acuity : the visual system could learn a strategy for using processes with rather different purposes and therefore untouched properties, for making vernier judgements. It may be of some interest to discover which cues govern the performance of the task, but the primary interest should lie in discovering what the combination possibilities for this high accuracy are. It is the basic result of vernier acuity, not the task of vernier acuity that is of interest.

For the record, it is worth making a list of those stimulus parameters, which have been found to affect, or have been found not to affect the precision of vernier judgements.

Baker (1949) found that vernier acuity varies with the level of illumination, the colour, and exposure duration of the stimulus.

Berry, Riggs and Richards (1950) found that line width is not a factor influencing the precision of vernier decisions, which they interpreted as evidence suggesting that it is the edges of the target that are important, and provide the cues for the task.

Leibowitz (1954) showed that vernier acuity is the same for light-on-dark and dark-on-light stimuli.

Leibowitz (1953) showed that vernier acuity is a function of stimulus orientation, in the same way that grating resolution is.
Keesey (1960) showed that stabilization of the retinal image does not reduce the precision of vernier judgements, thereby dispelling the notion that the sweep of the critical discontinuity past a receptor provided the cue for the task .
Findlay (1973) showed that the superposition of an oblique sinusoidal grating (contrast modulation 0.6) on a vertical target of low luminance (just visible when combined with a vertical grating) redüced acuity by a greater amount than superposition of similar vertical or horizontal gratings. This result suggests that the task may be affected by the relative contrast (and therefore visibilty) of the contour break and the line elements. This may suggest which cues are important.

The work of the last decade on vernier acuity, especially that of Andrews, and that by Westheimer, has been much more sophisticated, and provides clear insight into the processes behind the high vernier resolution achieved under appropriate conditions. In 1919, French had shown that vernier acuity varied with stimulus size, but it was not until the work of Andrews, Butcher and Buckley (1973), that the significance of this variation in acuity with stimulus length was explored and understood.

Andrews et al. (1973) asked the question : what improvement in the precision of vernier judgements (amongst other judgements - see section 1.2.4) would be expected in an ideal system which lost no information, beyond the sampling of space at the retina, as the size of

the stimulus increased ? The problem is a statistical one : what is the minimum variance of vernier judgements in response to a focused, thin, instantaneous stimulus image ? This quantity can be calculated, using the known statistics of the distribution of the receptor cells on the retina surface, and if then compared with the human psychophysical response error variance, it can be used to calculate visual relative efficiencies (see Chapter 2, Section 2.5 for details). They found that vernier resolution is highly efficient for stimuli up to 30 min. arc in length, but that efficiency drops for longer stimuli. This is very interesting : it suggests that the output from foveal retinal receptors is primarily organized or collected into samples that are about 30 min. arc in length. This is a limitation of the system, of the type sought. The figure of 30 min. arc will assume some importance below.
They also found that adding a gap to a very long stimulus had no effect on performance until the gap was 5 min. arc in length, when increasing gap size leads yo a fall in efficiency.

Westheimer and co-workers have been concerned with both the temporal and the spatial characteristics of vernier acuity. Only the spatial characteristics are of interest here, except to note that they find little effect of stimulus motion on thresholds for vernier resolution (Westheimer and McKee, 1975). This is in agreement with the findings and conclusions of Keesey (1960).
Westheimer and Hauske (1975) have found that the presence of abutting or flanking contours (Fig. 1.2.1b), orthogonal to or parallel with the target respectively, can have a detrimental effect on the precision of vernier judgements. This effect is maximum when the contours are

between 2.5 and 5.0 min. arc either side of the target. These distances for lateral interactions are much larger than the distances over which the light from the contours involved would spread because of optical imperfections in the eye, and so it seems that the interactions are neural in origin.

Westheimer and McKee (1977a) have found evidence for lateral interactions that are facilitory in effect, but are restricted to a region rather closer to the stimulus target. They have made two pairs of comparisons, and find an interesting coincidence between the two comparisons. They compared vernier acuity at a variety of stimulus luminance levels for two conditions : a stationary target, displayed for 90 msec., and a target moving with a speed of 0.9 degrees/second, displayed for an arbitrary long exposure of 190 msec. The two conditions produce the same relationship between vernier acuity and stimulus luminance. They also compared the two conditions : a stationary target, exposed for 45 msec., and a moving target with a speed of 1.8 degrees/second, exposed for 190 msec. Once again, the two conditions produce the same relationship between vernier acuity and stimulus luminance. In each case, it seems that information from the moving target can be collected over a fixed extent of space : threshold could be due to summation over a constant spatial extent of just under 5 min. arc.

Westheimer and McKee (1977b) have also measured the effect of stimulus line length on the threshold for vernier offset. Their results are very similar to the results of Andrews et al. (1973), but they draw attention to the finding that vernier acuity improves as line length increases up to about 5 min. arc, and then remains moderately stable for lengths up to 50 min. arc. Because they do not consider the implications of stimulus length on the task information, they do not realize the significance of the longer lines.

They also measured the effects of a gap between the two line elements of the stimulus. Thresholds were measured as a function of gap size, and component line size (see Fig. 1.2.1c). They find, once again in good agreement with Andrews et al. (1973), that for gaps of up to about 5 min. arc, there is no effect of gap size on vernier acuity. Interestingly, they also find that the same minimum threshold is obtained, regardless of the size of the line elements, even for dot elements. It should be noted, however, that it could be argued that they were not recording vernier judgements. Andrews et al. (1973) have pointed out that vernier discriminations can be made for a stimulus of known orientation, by judging the overall slope of the stimulus array.
Westheimer and McKee (1977b) also found that the line size does not influence vernier acuity for gap sizes greater than the optimum. They conclude that a separation of 5 min. arc between the two features is optimum for vernier resolution.

Westheimer and McKee (1977b) further showed that threshold for vernier resolution is not a function of the relative slopes of the two line elements (see Fig. 1.2.1d), except for a slight increase in threshold for the largest orientation differences, which they interpret as being due to the lateral interference described in Westheimer and Hauske (1975), and above.

Before considering the detailed implications of these definitive experiments by Andrews and co-workers, and Westheimer and co-workers, the results of experiments on other tasks, loosely involving shape discriminations, will be described.

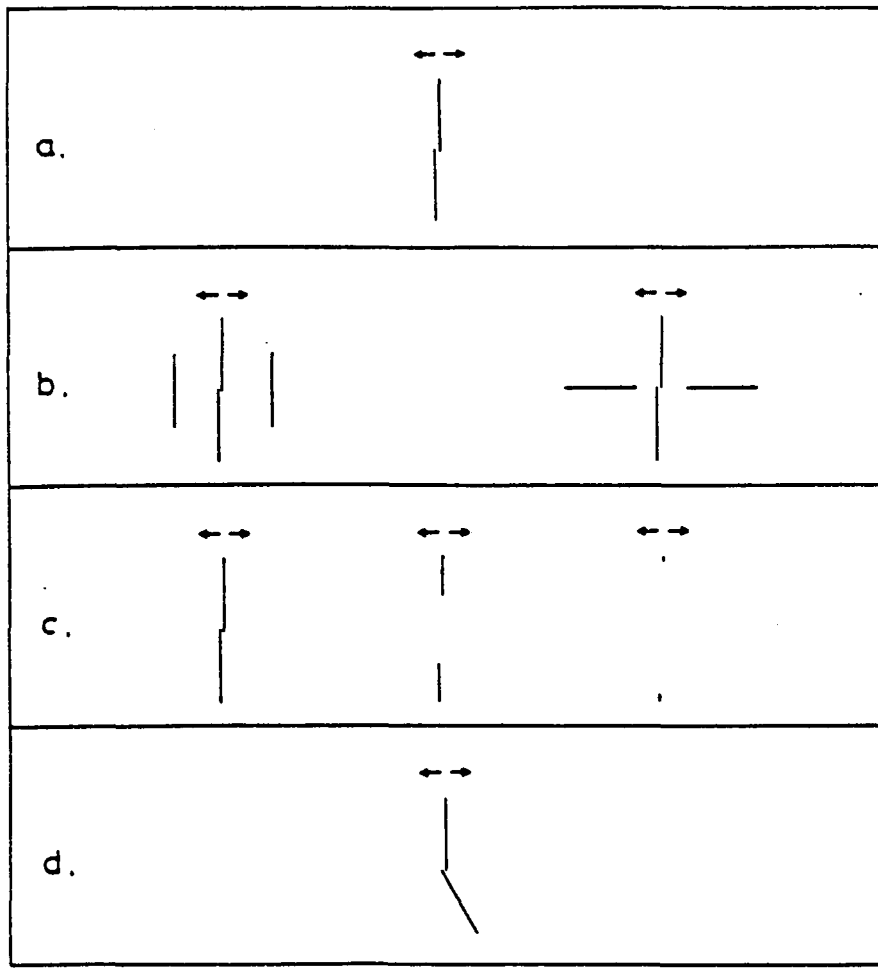


Fig. 1.2.1 Stimulus Configurations used by various investigators of vernier acuity.

1.2.2 Dot Alignment Discrimination Tasks.

In the lowest extreme of line element size, the vernier resolution task becomes a dot alignment discrimination task. A number of studies have measured performance for this task, and related tasks.

The study by Ludvigh (1953) has been described above (in section 1.1). His subjects were desired to judge the position of a dot with reference to two dots, one either side of the test dot (see Fig. 1.2.2a). He found that threshold for dot alignment was as low as 2 to 3 sec. arc, for a stimulus size of between 10 and 30 min. arc. At 30 min. arc, threshold is higher, and remains higher for longer separations of the reference dots. The figure of 30 min. arc suggests that there is a similar limitation operating in both this task, and the vernier resolution task, since this length is also limiting for high efficiency in the study by Andrews et al. (1973). Andrews et al. (1973) measured thresholds for the alignment of three short dashes, each subtending 40 sec. arc, and find a similar function.

Westheimer and McKee (1977b) have also made measurements for dot alignment types of tasks, and they present data for the discrimination of the vertical alignment of two points in space as a function of the separation between the two points (see Fig. 1.2.2b). Whether the points are two dots, or two small breaks, one in each of two parallel horizontal lines, thresholds are very small, being of the order of 5 sec. arc in the smallest cases. Thresholds are smallest for separations of 4 to 5 min. arc, and increase slightly for larger separations of up to 10 min. arc. This data is very similar to the data for vernier acuity under comparable conditions, in the same study.

There is also a study by Beck and Schwartz (1979), which adds nothing to the understanding of the processes of visual analysis, and which reaches the erroneous conclusion that vernier judgements (dot alignment judgements ?) are made from orientation information; they reach this conclusion via a confusing argument. The reasons for the conclusion being erroneous are contained in two studies : Andrews et al. (1973), and Westheimer and McKee (1977b), and will be discussed in the next section, which considers those tasks that involve slope estimation.

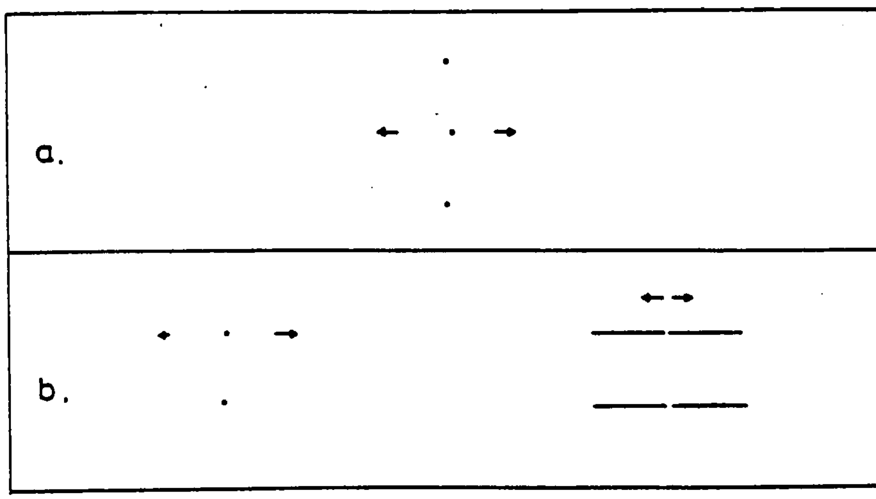


Fig. 1.2.2 Stimulus configurations used in investigations of dot alignment discrimination.

1.2.3 Slope Estimation Tasks.

The discrimination of the relative position of two dots, as in Westheimer and McKee (1977b), described above (in section 1.2.2), could be considered as an absolute judgement of the slope of the (imaginary) line joining the two dots. Beck and Schwartz (1979) conclude that this is the mechanism, not only for the dot task (which they did measure), but also for the vernier resolution task (which they did not measure). Even admitting the former (which would be wrong, except perhaps for very short stimuli), it is hard to understand how this can be generalized to the latter. The reason why the former may not in general be admitted, is contained in the data for the performance of slope estimation tasks.

There have been a number of studies of performance for the estimation or comparison of line slopes. The first was by Jastrow (1893), who found that acuity for line slope judgement is relatively high, being of the same general order as vernier acuity. It seems that the highly accurate processes involved in the relative localization of two contours (and the detection of a discontinuity at the point of their conjunction) are not the only high accuracy processes.

The next study was by Salomon (1947), who measured the precision with which a dot could be placed in the direction implied by a line (see Fig. 1.2.3a). She varied both the length of the reference line, and the distance of the dot from the end of the line, and found that the further the dot from the line, the less accurate the performance, but the longer the line, the more accurate the estimates of perceived direction were.

This result is conformed in a study using a similar task, by Buoma and Andriessen (1968), whose major interests lay elswhere, and are not of interest to the present argument.

A study by Sulzer and Zener (1953) showed that acuity for judgements of the departure from parallelism of two contours also shows that acuity increases with increasing lin length; this result is confirmed in a study by Rochlin (1955). See Fig. 1.2.3b.

Once again, all these early studies have failed to take into account the implications of stimulus length for the information available for the task, and therefore provide little real insight into the processes of visual analysis. As for vernier acuity, the situation is explored and assessed in a study by Andrews (1967b). Work by Westheimer and his co-workers also adds to an understanding of the processes in operation when slope estimations are made.

Andrews (1967b) found that relative efficiency for parallelism judgements (comparison of the slope of one line with that of another reference line) is constant and high for line lengths up to about 10 min. arc, and then falls with further increases in line length. He found that the distance between the two lines to be compared did not affect this efficiency (up to a separation of about 30 min. arc), except for the case of overlapping stimuli, which produced a very large depression in efficiency. This is interesting, in the light of the lateral interactions between parallel contours, as expressed in the performance of a vernier resolution task, and described by Westheimer and Hauske (1975) (see section 1.2.1 above).

Westheimer, Shimamura and McKee (1976) measured the effects of flanking lines on judgements of departure from verticality of a single contour. The flanking stimuli could be parallel, vertical lines of various lengths, and aligned with various parts of the target line (see Fig. 1.2.3c); they could be a vertical column of short horizontal lines (Fig. 1.2.3d), one above the other; they could be a vertical row of dots (see Fig. 1.2.3e); or they could be a random scatter of dots about a given lateral distance from the target line (see Fig. 1.2.3f). It was found necessary to have flanking stimuli on both sides of the target, to obtain a sizable reduction in acuity.(thereby explaining the lack of lateral interaction in the study by Andrews, 1967b).
The results show that the form or orientation of the flanking stimulus is not important, but that its distance from the target must be between 2 and 3 min. arc. This figure compares well with the similar flanking zones of optimum interference for vernier acuity, reported by Westheimer and Hauske (1975), and described in section 1.2.1 above.

Whilst there is this similarity between the processes used for slope estimation and vernier resolution, there is a major difference in the length tolerance of the two tasks, as is shown by the results of Andrews. This difference is large enough to suggest that the neural substrate underlying the two tasks is quite different. This point is illustrated by some data presented by Westheimer and McKee (1977b), who compared threshold for judging the vertical alignment of two dots, and threshold for judging the slope of the line formed by joining two such dots. Threshold in the second case is almost double that in the first case, despite the fact that the full line should allow a far more accurate discrimination of verticality. This also suggests that the slope estimation task is quite different to the task of dot alignment. The process involved in dot alignment judgements, is probably closely related to the process involved in vernier judgements, at least for small stimuli, as is shown by the data of experiment 2 of that paper.

The next section will consider another group of tasks which appear to use the same, or a closely related process, to that used for vernier acuity.

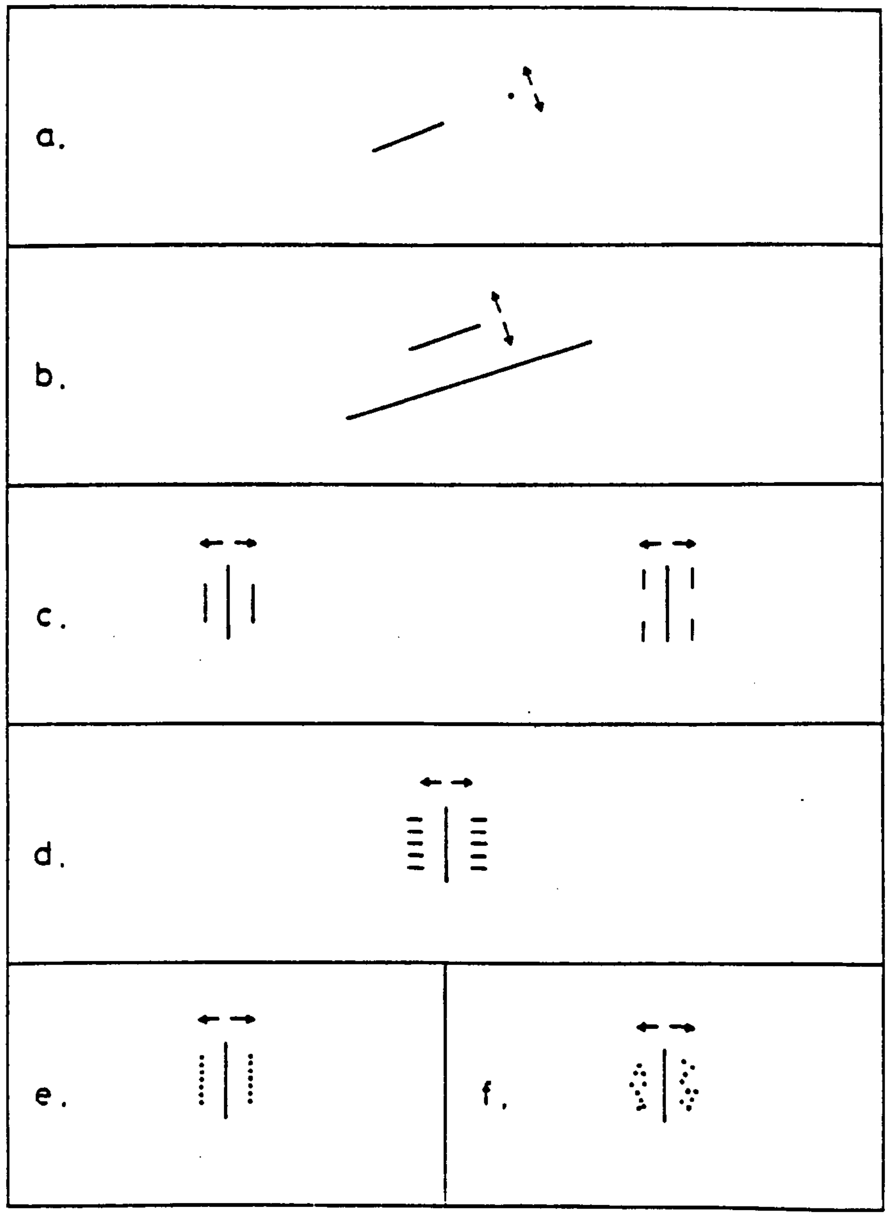


Fig. 1.2.3 Stimulus configurations used in slope estimation tasks.

1.2.4 Curvature Discrimination Tasks.

There has been rather less work on the ability to discriminate curved lines from straight lines.

Della Valle, Andrews, and Ross (1956) measured thresholds for arc curvature (see Fig. 1.2.4a), and chevron curvature (see Fig. 1.2.4b) discrimination as a function of line length. They draw two conclusions: sensitivity to 'off-straightness' is superior for larger length stimuli; and superior for arcs than for chevrons. The latter conclusion is critically dependent upon the geometrical parameter chosen to indicate threshold, and is essentially meaningless. The smallest threshold for 'off-straightness' that they found was 16.1 sec arc (not the 1.61 sec. arc as reported !) and so it is clear that curvature discrimination is another highly accurate spatial task. They do not consider the importance of line lengths, and the smallest length that they used was 32 min. arc, far too long to examine the relationship between the tasks of curvature discrimination, and those of vernier resolution and slope estimation.

Ogilvie and Daicar (1967) made a study of curvature discrimination, but used only six different stimuli : two line lengths of 17.5 and 41.5 min. arc; and only horizontal, oblique and vertical orientations. 'Off-straightness' thresholds of the order of 2 to 5 sec. arc were obtained. On the basis of scant data, they reach the rather strange conclusion that 'an appropriate measure of acuity for tasks like this is the angular area' (area between arc and imaginary chord). Their reasons for this conclusion are obscure.

There is only one other study of curvature discrimination, that by Andrews, Butcher and Buckley (1973). This study considers relative efficiency for the task, as a function of stimulus length, thereby avoiding the traps of endless argument about geometric parameters, and their relative appropriateness, or whatever.
Andrews et al. (1973) measured performance of curvature discrimination for both arc and chevron curvatures, and found that the two tasks are performed at essentially the same efficiencies for the range of line lengths tested. Efficiency is high for lines of length up to 30 min. arc, and then falls with increasing line length, much in the same fashion that efficiency for vernier resolution varied with stimulus size (in the same study, and with the same subjects). The similarity of these results is very suggestive. The suggestion of a relationship between vernier resolution and curvature discrimination is enhanced by their finding that the effects of a central gap on the vernier resolution task, and two gaps on the curvature discrimination task (see Fig. 1.2.4c) are very similar for long lines. For shorter lines, the vernier resolution could be due to the use of stimulus orientation cues, and so the comparison may not be valid.
Efficiency for curvature discrimination in short broken stimuli, of length less than 30 min. arc, is higher than for the corresponding unbroken lines.

These results strongly suggest that curvature discrimination shares processing pathways with vernier resolution and dot alignment tasks, but not with slope estimation tasks. It should be noted from the data of Andrews et al. (1973) that efficiency for curvature discrimination is higher than efficiency for slope comparison for lines of length between 10 and 30 min. arc.

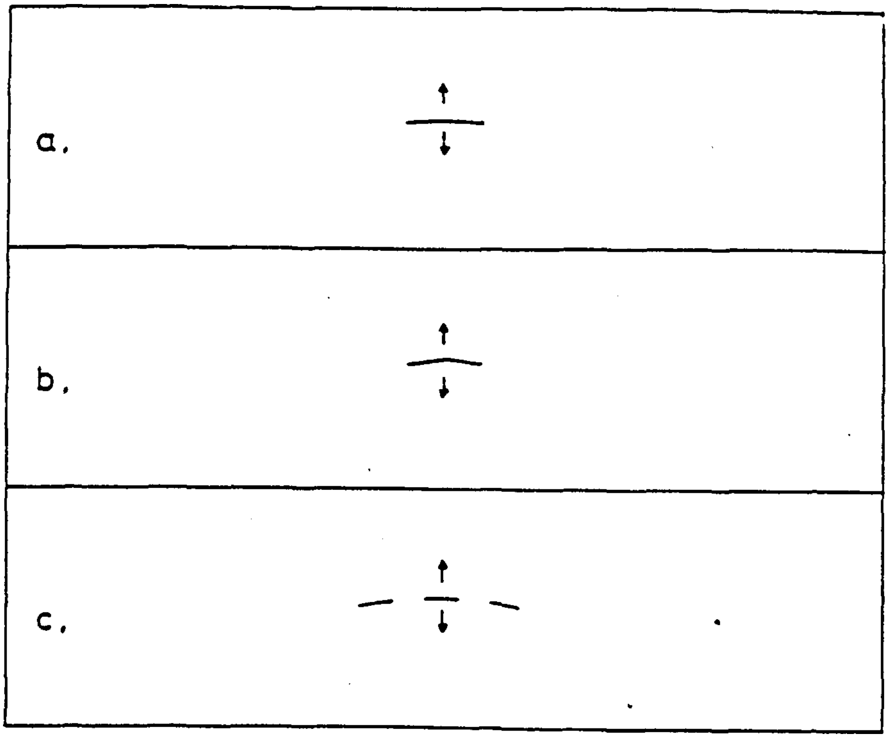


Fig. 1.2.4 Stimulus configurations for investigations of curvature discrimination.

1.2.5 Stereoscopic Depth Discrimination.

Depth distances of the order of 5 sec. arc can be reliably discriminated under appropriate conditions and for line stimuli. Anderson and Weymouth (1923) have shown that the threshold varies with stimulus length : threshold gradually decreases as line length increases from 3 to 30 min. arc.
Berry, Riggs and Richards (1948) have shown that depth discrimination is not a function of stimulus width, the same result as they found for vernier acuity.
Berry (1948) has shown that stereoscopic depth discrimination is more tolerant of target separation than is vernier acuity.
Mitchell and O'Hagan (1972) made measurements of depth discrimination thresholds. Their primary interest was in discovering which inter-ocular stimulus differences led to a decrement in performance, and which differences did not, but as a part of this investigation, they reported data for the effect of stimulus size on stereoscopic acuity for two identical straight lines. They found that a depth of about 18 sec. arc could be reliably discriminated for line lengths up to 30 min. arc.

Butler and Westheimer (1978) have demonstrated the existence of flanking zones, within which lines interfere with the task of depth estimation, or comparison. These zones are 2.5 min. arc away from the target, but the stimuli in them must be at the same depth from the observer as the test stimulus.
Whilst the lateral separation is similar for this effect and the flanking interference with vernier and orientation tasks, this effect on depth

discrimination has a depth restriction which the interference with the vernier resolution does not.

The two tasks of vernier resolution and depth discrimination are quite clearly different. The effect of target separation is different; the effects of stimulus length may be different; and the effects of flanking stimuli are different in detail.

1.2.6 Distance Comparison Tasks.

In 1863 Volkmann showed that two distances can be recognized as different, when they differ by only 12.4 sec. arc. Whilst this is an order of magnitude larger than the thresholds for vernier acuity, it is still an accurate judgement.
Subsequent authors have published the results of similar measurements (Shipley, Nann and Penfield, 1949; Pollock and Chapanis, 1952), and obtained rather larger thresholds for line length comparison (between 4 and 7 min. arc).
Wolfe (1923) has measured performance of a related task, that of mid-point estimation, and found similar results to these.

Such studies have generally been concerned with the constant errors of judgement (illusions of line size), rather than the reliability of such judgements, the precision with which distance can be estimated. It is the latter that is of interest to the present discussion, and so the results of these studies are of no direct relevance. Once again, the work of the last decade, by Andrews and co-workers, and Westheimer and co-workers, is of direct relevance.

Andrews, Webb and Miller (1974) measured the relative efficiency for distance discrimination as a function of stimulus size in four different conditions : the distance to be compared could be defined by two dots or one line, and the distances to be compared could be parallel and above each other (see Fig. 1.2.6a), or parallel and beside each other (end on) (see Fig. 1.2.6b). Efficiencies are much lower than for the tasks described above, but this may, in part, be due to the large stimulus sizes used, which ranged from 3 to 6 degrees of arc. The two different configurations did not appear to have any effect on the thresholds for comparison, other than the expected effect of the eccentricities of the stimuli. Although there is no more absolute distance information in a line than in two dots (the distance is defined by two points in space in each case), efficiency for lines is found to be higher, perhaps indicating that there is a preference in the visual system for continuity of form in large figures.

Andrews and Miller (1978) have measured acuitites for the spatial separation between two lines (see Fig. 1.2.6c), as a function of line length and separation distance. Once again, they found very low efficiencies, even for line lengths of only 10 min. arc (but at a large stimulus separation reference of 82 min. arc). Threshold separations between 1 and 3 min. arc were obtained. Threshold is constant for line lengths up to about 30 min. arc, then gradually falls. Efficiency, therefore, drops quite steeply to this length, and then drops less steeply. The implication of this result, that the position of a 30 min. arc line has the same threshold as that of a 10 min. arc line, is that the position of a line is recorded by processes with a functional grain size of about 30 min. arc. Improvement in position estimation only occurs when the lines are longer than 30 min. arc, and more than one "position estimate" is available.
Threshold for separation increases with increasing reference separation, a fact which is paralleled by the increasing receptor size with increasing eccentricity of the stimuli, which means that the spatial position is recorded by the retina with less fidelity.

The major conclusion of these two studies is that distance and absolute position are not encoded efficiently by the visual system, except perhaps in the case of small stimuli, close together.

Westheimer and McKee (1977b) have considered the latter types of stimuli, and find small thresholds for distance comparison tasks in general. Thresholds of the order of about 6 sec. arc were obtained for judgements of the distance between two lines (even without a physically present reference distance), where the separation was between 1 and 4 min. arc (see Fig. 1.2.6d). Beyond this separation, threshold rises sharply. The length of the stimulus is not important for lengths up to at least 20 min. arc.

Before proceeding to summarize all the data presented in these last few sections, it is worth noting that the two figures of 30 min. arc length and 4 to 5 min. arc width (lateral spread) have once again assumed an importance in the results, although the 30 min. arc length in the experiments of Andrews and co-workers has the significance here, of defining the smallest length for any useful integration, not the largest for any efficient performance, as previously.

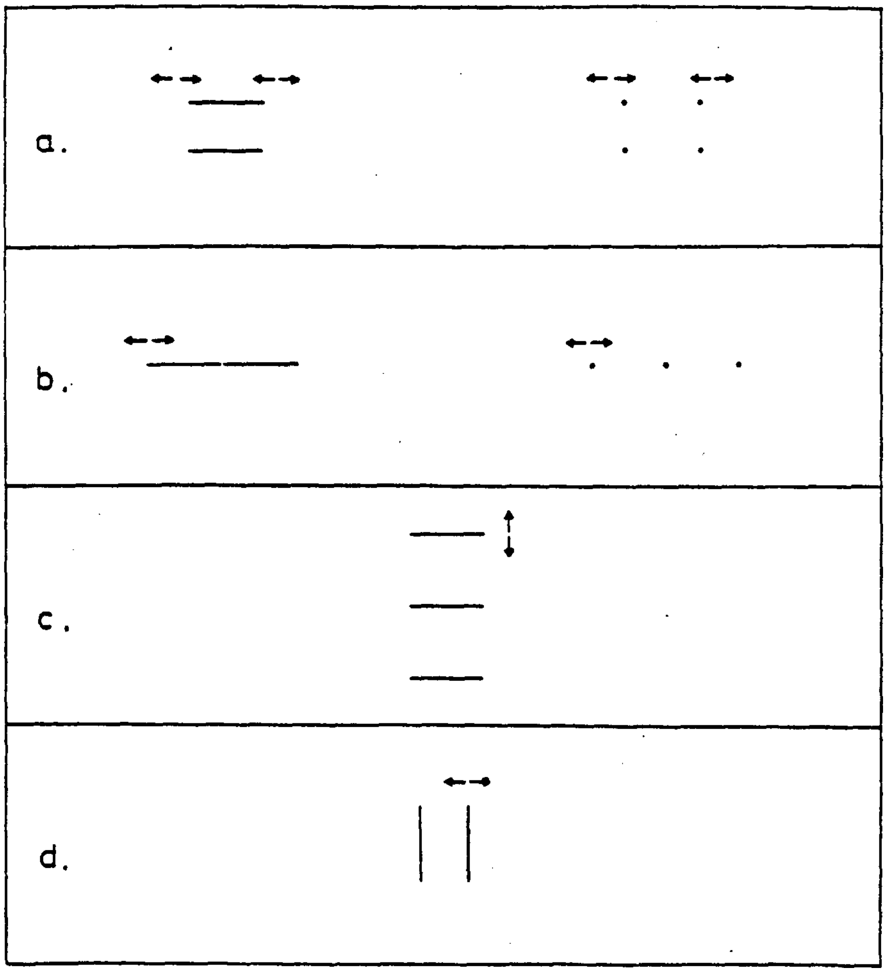


Fig. 1.2.6 Stimulus configurations used in investigations of distance comparison tasks.

1.3 Spatial Tasks and Visual Processing Summarized.

The preceeding sections have listed a number of generic types of spatial comparison or estimation, and described the data for performance of these tasks, under a number of different experimental conditions. The purpose of this present section is to summarize and interpret these results. This interpretation will lead to the questions prompting the experiments to be reported in subsequent chapters.

1.3.1 The Classification of Tasks.

The classification of the tasks employed, is in a sense arbitrary, and is only justified by the results. For example : vernier resolution and stereoscopic depth discrimination are both tasks requiring the judgement of relative position of lines., as is a distance comparison task ; chevron curvature discrimination is a task that involves the comparison of the slopes of two lines, as is the parallelism task; dot alignment tasks can be allied in this manner with almost any of the other tasks.
However, the results obtained for performance of these tasks, especially the data for the effect of stimulus extent, provide a strong basis for a classification of the tasks into groups that appear to share common processing.

Are there any gross differences between performance levels for these tasks described ?
The largest difference is between the tasks of distance estimation,

especially with large stimuli and large distances, and all the other tasks. The distance tasks are performed at much lower efficiencies and accuracies.

Another difference is between the tasks of slope estimation and the remainder. Slope estimation tasks are performed efficiently, but only for very short lines; efficiency falls for longer lines (longer than about 10 min. arc). The remaining tasks are performed efficiently for lines up to 30 min. arc in length, and perhaps longer for the tasks of depth discrimination.

The similarity between the tasks of vernier resolution, arc and chevron curvature discrimination and 3 dash alignment is illustrated in the results of Andrews et al. (1973), who showed that all three tasks are performed at high efficiency for stimulus extents up to about 30 min. arc; efficiency drops for larger stimuli in all cases. The same result was obtained by Ludvigh (1953) for the task of three dot alignment.

Stereoscopic depth discrimination appears to be rather different from these other tasks. There is little data for the task, but it appears to be more tolerant of target separation than the others, and the details of the interfering flanking stimuli are also rather different.

For the sake of argument, each of these three broad categories will be given a name : the category of low efficiency distance tasks will be described as <u>absolute position</u> tasks; the slope and stereoscopic depth discrimination tasks will be named <u>attitude</u> tasks; and the remainder will be named <u>shape</u> tasks.

Each of these three broad categories will be considered separately.

1.3.1.1 Shape Tasks.

The shape tasks comprise vernier resolution, dot and dash alignment, curvature discrimination, and some tasks involving length and relative position comparisons in very small figures. Andrews et al. (1973) suggest a concept that economically describes the first three tasks : they are all examples of collinearity-failure detection and discrimination. They all involve positional differentiation along the contour. The length and relative positional tasks involve differentiation in the orthogonal direction. These are all grouped together, because there are grounds to suspect that they might share some degree of visual processing.

Whilst the forms of departure from collinearity are quite different and discriminable in those first three tasks, the tasks have a number of features in common. From the work of Andrews et al. (1973) and inferences from the data of Ludvigh (1953), it is clear that figures under 30 min. arc in length are processed at high relative efficiency; those larger, at lower efficiency.

From the work of Westheimer and co-workers, it is seen that there is some lateral interaction over a region of space extending about 4 to 5 min. arc on either side of the stimulus. There are two aspects to this.

Firstly, there are interfering flanks, apparent at a distance of about 3 to 4 min. arc from the target stimulus. The presence of irrelevant contours in these zones increases spatial thresholds.

Secondly, there are summation zones, closer to the stimulus : information from a moving stimulus can be collected over a region of just under 5 min. arc. Likewise gaps of up to 5 min. arc between the two line elements of a vernier target do not affect performance. The distance between short lines is also very efficiently judged when the separation is less than about 4 to 5 min. arc, and further, the vertical alignment of one feature (eg. a break in a line, or a dot) with another similar feature, is estimated with a high accuracy for feature separations up to about 5 min. arc. It is by this coincidence of the importance of the distance of 5 min. arc lateral spread, for both vernier tasks, and the tasks of local relative position and separation, that both are included in the same group.

In summary, it seems that the (so-called) shape tasks are performed most efficiently when the stimulus is within a rectangle of space, measuring 30 min. arc in length, and 5 min. arc in width. This high efficiency is reduced when there are irrelevant flanking contours at, or just beyond and parallel to the long edges of this rectangle.

It is interesting to note, in passing, that Thomas (1978) has found that the visibility of a bright bar is a function of the length of the bar up to a limit of 40 min. arc, beyond which, length is not important, and is also a function of the width of the bar, up to a similar width limit of 5 min. arc. This is critical rectangle with dimensions that are very similar to those for the region of space covered by the shape process. Visibility and spatial discrimination of clearly visible targets are not easily compared tasks, and so the possible relationship is not clear.

1.3.1.2 Absolute Position Tasks.

This is a group of low efficiency tasks, generally involving large stimuli, at large separations. The relative position and distance features of small figures, that provide cues for the other types of spatial tasks, are clearly encoded in a different manner, and with much greater precision. There are some clues to what the relationship between absolute position tasks and shape tasks might be, which will now be discussed.

Threshold for separation discrimination is constant at about 1.75 min. arc, for lines up to 30 min. arc in length, and then decreases with increasing line length (Andrews and Miller, 1978). This suggests that absolute position is encoded via a small population of local signs, spaced at 30 min. arc intervals, which may be combined for larger figures (giving a smaller threshold as a result).

This result suggests that the same rectangle of space, which represents the area for the most efficienct shape judgements, represents the area for the least accurate absolute position judgements.
This further suggests an economical explanation for the low efficiency obtained for absolute position tasks. If lines of length up to 30 min. arc had their position specified solely by which rectangle of space they fell within, then the variance of position judgements would be no less than $d^2/12$, where d is the width of the rectangle. This means that the standard deviation of the response error distribution (threshold) in an absolute position task should be constant at between 1.15 and 1.45 min. arc (for d = 4 and 5 min. arc), for lines of length less than 30 min. arc, and should then fall at an unspecified rate with

increasing line length, beyond 30 min. arc.
This is quite close to the values and pattern of threshold obtained by Andrews and Miller (1978), and suggests that the absolute position specificity of the rectangle of space is the basis for the responses in this task, and that this specificity is used efficiently.

This hypothesis is speculative : there is no direct evidence that the local signs of coding units, that are primarily concerned with local shape differentiation, play this role; but the hypothesis is economical and consistent with the data to date. If the shape discrimination processes have a positional specificity, that can be compared from individual process to process, then there would be no requirement for a separate set of processes for the encoding of position information.

1.3.1.3 Attitude Tasks.

The tasks of slope comparison and estimation, and stereoscopic depth discrimination are grouped together on no good grounds, except that they are both tasks that can be performed efficiently, but that do not share the characteristics of the shape tasks.

Stereoscopic depth discrimination appears to be an efficiently performed task, but there is insufficient data to be able to draw any conclusions about relationships between it and the other tasks.
Berry (1948) has shown that a gap in the stimulus disturbs vernier acuity more than it does stereoscopic acuity.
Butler and Westheimer (1978) have shown that the flanking zones for stereoscopic depth discrimination are depth specific, whereas those for vernier resolution are not.
Stereoscopic acuity is not tolerant of motion in depth, but vernier acuity is (Westheimer and McKee (1978). Vernier acuity is also tolerant of motion in the direction of discrimination.
The optimum size of stimulus for stereoscopic depth discrimination has not been established.

Slope comparisons are very efficient for lines up to about 10 min. arc, but efficiency falls steeply for longer lines. This is rather surprising in view of the relative numbers of orientation and curvature selective cells in the visual cortex of cat (eg. Hammond and Andrews, 1978)
There is no ready explanation for the differences between slope and shape tasks. The limit of line length is not imposed by the shape process, with its rectangular region of space, in the way that the

performance of absolute position judgements is limited. If absolute orientation, for the purposes of slope estimation or comparison, were derived from the orientation specificity of this process, then neither the line length limit, nor the level of threshold would be explained. The judgements of slope, based on the orientation specificity of the process with the rectangular collecting region, would have a minimum error variance of $\phi^2/12$, where ϕ is the spread of potential angles ($= 2.\tan^{-1}(d/L)$ where d = width of the rectangle, and L = length of the rectangle). For d = 5 min. arc and L = 30 min. arc, ϕ is found to be 19 degrees, and the slope threshold is found to be 5.5 degrees (corresponding to a threshold displacement of 57 sec. arc for a stimulus of length 10 min. arc).
This is much larger than the threshold obtained by Andrews (1967b), and Andrews et al. (1973), and it is clear that these thresholds are not limited by the rectangle of space served by the shape process, in any simple manner.

It is not clear what does limit performance for slope comparison tasks, and it remains surprising that slope comparisons of lines of lengths greater than 10 min. arc are processed at a much lower efficiency than curvature discrimination tasks.

1.3.2 Levels of Processing.

The results quoted in the preceeding sections are consistent with only two types of process (perhaps three if the results of stereoscopic depth discrimination are included), subserving three generic types of task. There is a process which is capable of highly efficient differential shape tasks (relative position), which can operate over a region of space 30 min. arc long and 5 min. arc wide. The position of whole lines with respect to remote objects (absolute position) is lost within this region of space.
Secondly, there is a process concerned with line slope estimation, which is also highly efficient, but only for lines that are 10 min. arc or less in length.

The data of Andrews for the two types of task (Andrews, Butcher and Buckley, 1973; Andrews and Miller, 1978) also point to second order processes or combinations of information for stimuli that are larger than about 30 min. arc. In the case of absolute position tasks, threshold would be independent of line length, for all line lengths unless combination of position estimates were possible from different points on the line, falling within the rectangles of space corresponding to separate processing devices. Andrews and Miller (1978) have shown that threshold does fall for lines greater than 30 min. arc in length, providing clear evidence for some sort of second order processing. The fall in threshold is not very great however.
In the case of shape tasks, Andrews et al. (1973) have shown that, although efficiency falls for line longer than 30 min. arc, it does not

fall as steeply as it would be expected to, were there no further processing. They argue in favour of second order combination of the outputs from the primary processes, rather than the use of parallel but less efficient larger sized processes.

Experiment V of Andrews et al. (1973), which was concerned with measuring performance of curvature discrimination for stimuli consisting of three short dashes, throws some more light on the process of second order combination of estimates of curvature. The dashes were only 5 min. arc long (in the longest case), and therefore individually provide very little curvature information. Performance is little affected by the presence of gaps for lines up to about 30 min. arc total stimulus extent (threshold is unchanged; efficiency rises as a result). This is for stimuli that may be encompassed by the rectangular collection region for one individual shape process. When the gaps are 25 min. arc each in length, and the total stimulus extent is more than 50 min. arc, efficiency is alnost independent of stimulus extent. This suggests that the efficiency for second order combination is the same whether the processes in use are near neighbours, or quite remote.
Thresholds are all less than 40 sec arc, much less than the thresholds for absolute position judgements, and so there must be a second order or level of curvature processor, which is distinct from the second level of absolute position processing.

Andrews (1967b), and Andrews et al. (1973) present data that clearly shows that orientation information is also available for second order combination. Once again, the efficiencies for stimulus sizes, that are greater than the optimum, do not fall as steeply as they would, were there no second order combination.

Thus it is seen that second order combinations are available and useful. It is not possible to pass much comment on these combinations, and on their relative efficiencies, because there are two unknown parameters : the efficiency of combination; and the density of estimates (ie. what the functional overlap of the collection regions for adjacent processing devices is). Andrews et al. (1973) and Andrews and Miller (1978) suggest that the second order combinations are probably quite efficient.

1.3.3 In Conclusion.

In section 1.1 above, it was demonstrated that there are a number of operations that the visual system has to perform on the response pattern of the retina to incident light. The visual system has to extrapolate from the information in the discontinuous array of receptor cells, to infer the presence of continuities in the visual stimulus. It has to utilize the redundancy of the pattern of stimulated receptor cells, in order to overcome the transmission limits of the visual pathway. This it presumably achieves through the use of some form of predefined alphabet of symbolic features, redundant information thereby being discarded.
These two processes of extrapolation, and redundancy reduction, could be combined, and this would be an economical method of visual analysis. The question is : which features are extrapolated and extracted, which features are discarded, and which features are recorded with high accuracy ?

It has been known for well over a hundred years that the visual system is capable of some very accurate judgements. Recent research on these observations has led to a considerable understanding of the answers to some of the questions.
In summary, the results require that there be two parallel analyses of space underlying these high accuracy judgements (there may well be more, but the data to date only require two).
For shape tasks, and absolute position tasks, there is a process, serving a region of space that measures about 30 min. arc by 5 min. arc.
Certain tasks, loosely involved with the shape of straight or nearly

straight lines, and economically described as collinearity-failure detection tasks (Andrews, Butcher and Buckley, 1973), can use the spatial information within such a region in a differential manner, and with high efficiency.

Absolute position of a line is probably represented only by the gross positional specificity of such a process, and is therefore not recorded with great fidelity.

For slope tasks, some other arrangement or process must be used, although very little can be said about such a process.

These two processes are considered to be parallel, since both operate at the same high efficiencies. They are however, clearly different.

One can speculate as to why the two might be separate. A clue comes from the vast literature on so-called 'channels' in vision (see Braddick, Campbell and Atkinson, 1978 for a review). It is proposed that there are certain channels for information transmission, that are specific to certain features of the stimulus, such as orientation or spatial frequency. Orientation specificities are found to have the following psychophysical properties :

i) Gratings of similar orientation mask each other (ie. raise contrast threshold) eg. Cambell and Kulikowski (1966).

ii) Pre-adaptation to a high contrast grating produces an orientation specific threshold elevation eg. Gilinsky (1968)

iii) Subthreshold summation of similarly oriented gratings is found eg. Kulikowski, Abadi and King-Smith (1973).

iv) Superimposed gratings of different orientations lead to 'monocular rivalry' eg. Campbell, Gilinsky, Howell, Riggs and Atkinson (1973).

v) Orientations exhibit simultaneous contrast. eg. Wallace (1969).

vi) Andrews (1965) has proposed inhibition between orientation selective filters, on the basis of the time course of perceived orientation.

vii) The tilt after-effect shows a successive effect on perceived orientation eg. Vernon (1934), Gibson and Radner (1937).

viii) Orientation-specific chromatic aftereffects have been obtained eg. McCullough (1965).

No-one has proposed 'vernier-offset' selective channels, and after-effects of perceived vernier off-set. Similarly 'absolute-position' channels have not been proposed (size-specific channels have been proposed, but only for smaller sizes). Whilst the following curvature-specific effects have been reported, it is claimed that all are readily explained in terms of local orientation-specific effects (see Blakemore and Over, 1974; MacKay and MacKay, 1974; and Crassini and Over, 1975a; for details of the arguments).

i) Curvature after effects are reported by Gibson (1933), Bales and Folansbee (1935), Carlson (1963), Wilson (1965), Coltheart (1971), Blakemore and Over (1974), Crassini and Over (1975a), Vernoy (1976), and Timney and MacDonald (1978).

ii) Curvature-specific masking is found by Crassini and Over (1975a) and Timney and MacDonald (1978).

iii) Simultaneous curvature contrast was studied by Crassini and Over (1975a). There is a myriad of curvature illusion (see Tolansky, 1964; Robinson, 1972).

iv) Curvature-specific chromatic after-effects were reported by Riggs (1973). But it is thought that they can be explained by orientation-specific chromatic after effects (see MacKay and MacKay, 1974; Stromeyer, 1974; Riggs, 1974; Sigel and Nachmias, 1975; and Crassini and Over, 1975b).

The concensùs of opinion is that all these effects of curvature can be explained in terms of local orientation effects. This is certainly true for the curvature-specific masking, and the curvature-specific chromatic after effect. It is also true for at least most of the simultaneous curvature contrast effects.
The explanation could account for the adaptation and after effect for curvature reported by Gibson (1933), in the case of curved lines, whose chord is vertical. This has been demonstrated by Blakemore and Over (1974). Such an explanation would fail to explain adaptation and after-effect for oblique curves.
However, the evidence does not in general support the notion of curvature selective channels in human vision.

It may be that the visual system uses orientation for internal rescaling and adaptation, in order to keep the metric of visual space normailzed (as proposed by Andrews, 1964, 1965, 1967a). This could mean that, whereas shape and absolute position information is consciously available to the observer, slope information is primarily intended for other purposes, and is only indirectly available to the subject's consciousness, for the purpose of psychophysical slope estimation.

It may be behaviourally adaptive and useful to know precisely what and where an object is, but less useful to know what its attitude is. Conversely, it may be useful to be able to compensate for global changes in the range of orientations experienced (such as could arise from a change in the observer's attitude, and therefore would be relatively frequent), but much less useful to be able to compensate for global changes in shape (which are hard to imagine).

1.4 The Questions Arising, and Research Proposed.

There are a number of potentially interesting gaps in our knowledge of the visual processes underlying the encoding and analysis of form.

The relationship (if any) between the process involved in shape tasks and that involved in slope comparison and estimation tasks, is not understood.
What effect does the shape of the stimulus have : do curved lines stimulate the same processes as straight lines ? Or, are there different processes for curved lines ?
There is as yet, very little understanding of the organization of spatial information within the primary processes proposed. Are there further tasks, like slope comparison. which might be expected to fall within the competence of the processes of high efficiency differentiation, but are found not to do so ?
This would throw some light on the nature of the information collected by these processes actually is.

It is plausible that measurements of visual spatial discrimination, using curved lines rather than straight lines, as has always been the case to date, might illuminate some of these areas of doubt.
One might expect straightness to be an anchor point in the perceptual dimension of curvature, such as vertical and horizontal are in the perceptual dimension of orientation. Then one might wonder, is straightness associated with higher discriminatory powers than are found for the rest of the dimension, as is the case for vertical and horizontal orientations.

The experiments to be described below, set out to begin to answer these questions. They are primarily concerned with the shape task of curvature discrimination; both broken and unbroken stimuli are used, since the comparison has been found to be very powerful in the case of straight lines. Short stimuli are used exclusively (less than $\frac{3}{4}$ degrees arc. in all cases), since it seems very likely that the regions of space that are suscetible to high efficiency performance are small.

The experiments are essentially exploratory in nature. They start with a nearly clean slate, rather than a well formulated hypothesis with predictions to test. For this reason, they sometimes appear to be rather arbitrary in conception : this is usually the case ! However, the results do enter suggestive outlines on the slate, and do not appear arbitrary. They indicate the presence of one, and perhaps two novel processes with high efficiency differential capabilities, but with quite distinct properties. The most important evidence for these is to be found in Chapters 5,6 and 7. The evidence is reviewed and integrated in the final chapter, which concludes with a new list of questions arising.

CHAPTER 2. : EXPERIMENTAL METHOD.

All the experiments to be described have a common method, which will be described in some detail prior to the experiments themselves.

Typically, the subject is presented with two stimuli, test and comparison, and is required to make some binary decision based on his sensation and perception of those stimuli. His individual judgements are not particularly informative : it is the distribution of judgements at different stimulus values that is of interest. The subject is not exactly veridical in his judgements, he makes systematic errors. The subject is also not consistent in his responses to a given stimulus, he makes variable errors. It is possible to define a response error distribution, which statistically describes the probability of a given response to a given stimulus. The mode of this distribution corresponds to the point of subjective equality (PSE), the stimulus level where either response is equally likely. For an unimodal, symmetrical distribution, this coincides with the median and mean.

Assuming the response error distribution to be normal, the two statistics of interest are the mean and standard deviation. Probit analysis of the response counts provides estimates of these. In fact, Probit analysis estimates the median of the response distribution, and the rate of change of error probability at the median (Finney, 1952). These lead to estimates of the mean and standard deviation, for a normal distribution. The mean may be used as the PSE or constant error of a discrimination task, the standard deviation may be used as the threshold difference for that task.

Andrews (personal communication) has calculated that these parameters are estimated with optimum efficiency, when responses are obtained to a stimulus range that is 2.6 to 2.7 times the standard deviation, and centred on the mean of the response error distribution. This is psychologically rather convenient. Senders and Soward (1952) have shown that it is good practice to include some easy judgements in a discrimination task. The range suggested covers probabilities of 0.1 and 0.9 for a given response, and therefore contains some easy judgements.

The appropriate psychophysical procedure to obtain such response counts, is the Method of Constant Stimuli. The traditional technique is very inefficient, but with the advent of fast computers, adaptive versions of the traditional methods have been developed. An adaptive version of the Method of Constant Stimuli has been developed and used by Andrews, Webb and Miller (1974) and by Andrews and Miller (1978). A modified version of this was used in the present experiments, and will now be described in detail.

2.1 An Adaptive Method of Constant Stimuli.

The basic modification to the traditional method is that the stimulus series used, is made to be a function of the subject's response distribution. Should the subject's criterion for response change, or should an inappropriate series of test stimuli be chosen at the outset of the experimental run, then the stimulus ranged is changed to meet the new requirements, and the run is not wasted.

At any one time, four stimulus levels are in use, and are presented to the subject in a psuedo-random sequence. The sequence has two constraints, which are aimed at making the sequence of stimuli and responses appear random to the subject. The same test stimulus is not presented to the subject more than twice in immediate succession. No more than five stimuli on the same side of the centre of the stimulus range are presented in immediate succession. These constraints avoid shifts in the subject's criterion due to the stimulus diet, and avoid the subject's typical preference for distributing his responses equally between the available response options from causing distortions of the response error distribution. No other constraints are applied to the sequence.

Each run is split into a number of response blocks (usually eight), and each block consists of a fixed number of responses (usually fifteen). At the end of the second and every subsequent block, a rapid and slightly approximate Probit analysis is made of the last two blocks of responses. The stimulus series can be corrected, if it is found to be off-centre or or the wrong width. The whole process takes less than 100 msec., and is performed in the idle time between the subject's response, and the presentation of the next stimulus. The subject is therefore unaware that the stimulus series has changed.

A full correction is rarely made, since some lag in the adaptations is present, avoiding making the system too sensitive to transient changes in the subject's criterion, and to inaccuracies in the analysis. It is preferable to follow the responses faithfully for the first few corrections, allowing any gross errors in the estimates that were used to start the procedure to be corrected. Subsequently, it is better to follow with considerable lag, and only to act on relatively large changes. The stimulus range is carried over from run to run in a session based on the same task, along with the current lag, providing the new start estimates for the next run.

The stimulus series is determined from two parameters, the centre and width of the range. These are derived from the mean and standard deviation of the subject's response error distribution, by the following rule :

$$P_{r+1} = k.(E_r + C_r.(E_{r+1} - E_r))$$

where P_{r+1} is the new stimulus range parameter

E_r is the releveant statistic

C_r is the correction factor

and k is a constant relating the statistic to the stimulus range.

For the centre of the stimulus range, the statistic is the mean of the response error distribution, and 'k' is unity; for the width of the stimulus range, the statistic is the standard deviation, and 'k' is 2.7 . The correction factor or constant, determining the lag,

C_r is itself a function of recent response errors, and is calculated thus

$$C_{r+1} = \frac{E_r - E_{r-1}}{E_r + E_{r-1}}$$

As a result of the operation of these rules, if a parameter has remained stable, the correction constant approaches zero; if a parameter changes suddenly, the correction constant increases, but there is not an immediate effect on the stimulus series. In the latter situation a change in that direction is made more likely at the next correction, if the change is a result of a trend; otherwise, the change is ignored.

For the case of the parameter of stimulus width, an asymmetry is introduced into the calculation of the new correction constant. The above expression is used for an increase in the estimated width, but for a decrease, the following is used :

$$C_{r+1} = \frac{E_r - E_{r-1}}{E_r}$$

The reasons for this asymmetry are as follows.
It is arranged that an experiment begins with an overestimate of the standard deviation of the response error distribution, and therefore with a stimulus series that is slightly too wide. This means that the experiment begins with some easy discriminations, to lead the subject into the near threshold judgements. Therefore a decrease in the width of the stimulus series is more likely than an increase.
The effects of the width of the stimulus series being too large or too small are not the same, either. If the task is too easy for the

subject, he will relax and performance will not be quite optimum. If the task is too difficult, the subject becomes baffled, and may forget the task. In such a situation, it is rather more difficult to recover.

In all cases, the correction constants are restricted to values between 0.00 and 1.00. Zero results in no change in the stimulus series; unity leads to full correction. Values of 0.75 are appropriate to start an experiment; after the first run, the correction constants will normally have values less than 0.1.

2.1.1 The Prerun.

The adaptive Method of Constant Stimuli, as described, is aimed at achieving the maximum statistical efficiency for the minimum subject labour. The only requirement is an initial estimate of the appropriate statistics, to be used for determining the starting stimulus series. These can be very approximate, and that of the standard deviation should be an overestimate preferably.

The initial estimates of mean and standard deviation of the error distribution are derived froma brief prerun sequence of trials, based on the staircase Method of Limits. The prerun ends after four reversals of response. A fairly accurate estimate of the mean may be obtained from the mean reversal level. The standard deviation is estimated by the difference between the two extreme reversal levels.

This procedure also has the advantage that it familiarizes the subject with the stimuli, and with the task to be performed.

2.1.2 Problems with the Method of Constant Stimuli.

No psychophysical procedure is without its drawbacks. The Method of Constant Stimuli is the best method for measuring both the mean and standard deviation of the response error distribution. Unlike many methods, it bases the estimates of these statistics on several points on the psychometric function and works on a plausible, and precise hypothesis, relating probabilities of responses to the underlying decision processes. However, it is not without its faults. These are discussed at Length in Guilford (1953) and Laming (1973), but will be summarized here.

The Method of Constant Stimuli may introduce biases into the subject's responses, if used unwisely. These biases are thought to arise from two distinct sources : the process of making judgements, and the generally restricted stimulus diet. How far these two sources are the same is a matter for debate. The process of making a decision is thought to lead to the so-called response effect: the available responses tend to be used equally frequently by the subject, especially when the judgements are difficult.
The stimulus effect is very similar. Any asymmetry of the stimulus series generates a perceptual constant error, which is registered in the subject's responses. The PSE tends towards the weighted mean of the stimulus diet. A related effect is described by Stevens (1957). There is reputed to be an asymmetric discrimination process on prothetic variables (that is variables in which the sensation is quantitative rather than qualitative: intensity rather than colour), whereby one stimulus is identified as the standard by virtue of its position in space or time. This, it is claimed, distorts the continuum, and biases the subject's perception.

Whether these two effects, the response effect and the stimulus effect, are truly separate, or whether they are cause and effect is not clear, however, they are both very small in an appropriately controlled experiment. The adaptive nature of the technique described above, ensures this. For a perceptual dimension that is very labile, such as contour curvature, these drawbacks can mean that the measured PSE is not a very reliable or accurate estimate of the true sensory effect.

2.2 Apparatus.

The experiment was controlled by a CAI Alpha minicomputer, using purpose written software in FORTRAN and BETA assembly-code. FORTRAN was used for the floating point arithmetic subprograms, and assembly-code for everything else (thereby saving memory, and improving efficiency).

Stimuli were generated on a Hewlett Packard CRT screen with a P31 phosphor by a QVEC graphics device, which produces vectors from digital data stored in the computer memory, and accessed by DMA. Very high refresh rates were used. Line widths were less than 1.0 mm. (subtending 35 sec. arc at the retina from a viewing distance of 6m.). Curved lines were drawn from a large number of connected straight line segments, each the same length and less than the width of the line. The QVEC allowed a programmable resolution of 1.75 sec. arc on the screen when viewed froma distance of 6m. The stimuli were timed by a quartz crystal oscillator.

Responses were signalled to the computer on a button box, which activated a digital input interface with the computer. An indicator on the box was subsequently set, to show which response had been recorded.

The subject sat at a distance of 6m. from the screen, which was surrounded by a large grey board of the same colour and brightness as the screen, providing a field of 4 deg. by 6 deg., essentially without high contrast contours. The CRT display subtended 40 min. arc square at the retina. The subject's head was not restrained (comfort is considered to be of paramount importance in a lengthy psychophysical experiment), but marks were provided in the field of view, to enable the subject to check his head elevation periodically. Any change in the position of the eyes relative to the screen would lead to small distortions of the stimuli on the slightly curved screen.

The experiments were carried out in a lecture hall, that was normally lighted providing a comfortable background luminance for the subject. The display screen and background field were placed to avoid any contrast shadows or reflections in the central 4 by 6 deg. arc field of vision. The subject sat in a comfortable high-backed chair. The subject viewed all stimuli binocularly, using a fixation spot on the display screen to aid fixation : the importance of fixation was stressed to each subject. In general, stimulus intensity was not closely controlled, and in practice the brightness of the stimuli was set to the most comfortable level for the particular subject, who was told to set the stimuli bright enough to allow clear vision, but not so bright that any glare was experienced. For experiments involving very small stimuli, brightness was thought to be more important, and in these conditions, a filter was used to set the brightness of the stimuli a fixed quantity above luminance threshold. Andrews, Butcher and Buckley (1973) found that for the type of spatial discrimination task under consideration, the optimum intensity level could be halved or doubled without affecting performance measurably.

2.2.1 Stimuli.

All the stimuli used in the following experiments are small bright lines, drawn under computer control on a CRT with P31 phosphor. The stimuli are defined by five parameters describing stimulus curvature, stimulus length, position relative to the centre of the screen (2 parameters), and overall orientation of the stimulus with respect to the horizontal. A number of different options could be employed to construct these definitions :

1) Curvature. The curvature of the line could be specified directly, or the radius of curvature could be specified, or the height of the apex of the curve above its imaginary chord could be specified.

2) Line Length. The length of the curve could be specified by the length of the arc directly, or by the chord length, or by the angle subtended by the curve at the centre of the circle.

3) Position. The position of the line was specified by the rectangular co-ordinates of the centre of the line, or the centre of the imaginary chord, or the centre of the circle, with respect to an origin at the screen centre (and point of fixation).

4) Stimulus Orientation. The orientation of the chord of the curve could be specified with respect to the horizontal.

With these parameters, it is possible to specify completely any curved (or straight) line anywhere on the CRT screen.

The typical arrangement of stimulus elements, employed in all experiments, except Experiment 2 and 7, is shown in Fig. 2.1. This will be refered to as the standard configuration.

The complete set of stimuli for an experiment constist of an optional comparison stimulus for the subject to base his responses on, and a series of test stimuli, varying linearly in one of the defining parameters. The step size for the linear variation could also be declared, providing the potential to create an easy or a difficult series of stimuli to be judged. In most cases, the spacing of the stimulus series was set so that between four and eight stimuli would be used over the course of a run. This is found to lead to consistent responses.

In the later experiments, a gap or a number of gaps were introduced into the stimuli (test stimuli, and if required, comparison stimulus also). Further parameters were necessary to define the number of gaps, and their sizes and positions.

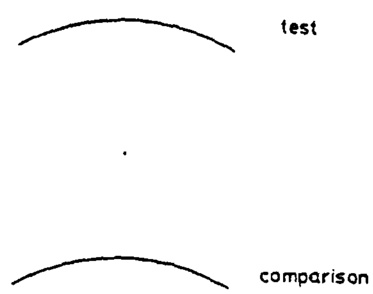


Fig. 2.1 The standard configuration of stimulus elements. The upper curve has avariable curvature; the lower curve is fixed.

2.3 Experimental Procedure.

The following experimental procedure was always carried out.

The subject would set the brightness of the stimuli first. Then the task was described in detail to the subject, including explicit instructions concerning fixation.
The prerun was then carried out, to establish a suitable series of stimuli for the start of the experiment. The subject would next be given the option of resetting the stimulus luminance, and asked whether he understood the task required.
The run proper would follow, lasting about fifteen minutes. At the end of this period, when the last response had been collected, the subject would be informed by a message on the screen, and the computer would store the data on a floppy disc. Whilst the computer performed a full analysis of the run, the subject would be given a five minute break, to relax and recover from the effects of over-enthusiastic fixation. After this break, the next run would be started, with the stimulus series determined at the end of the previous run, and the final correction constants of the previous run. In general, three or four runs would make up a session, lasting for between one hour to one and a half hours.

The various experimental conditions in any experiment were tested in a psuedo-random sequence, with one condition per session. The conditions were all tested twice, with the sequence being reversed for the second set of measurements.

The run consisted of a given number (usually 120) of responses. After each stimulus had been presented, the screen was left blank until a response was recorded. The subject was required to make a two-alternative forced choice decision, but could signal to the computer that his fixation had failed during the stimulus presentation (eg. due to sneezing), in which case the response would be skipped.

After the response, there was a three second delay, during which the subject was required to fixate a spot on the screen, in readiness for the next stimulus. During this period, the subject could change the response just recorded (but not after the next stimulus had appeared on the screen), and the delay would then begin again: after three seconds the last response recorded would be stored. During this delay, the subject could also halt the run for a short break, if required. When he was ready to continue, the computer would start the three seconds delay again, and then proceed with the next stimulus.

The sequence of events, and options, in a single stimulus/response cycle is shown in Fig. 2.2.

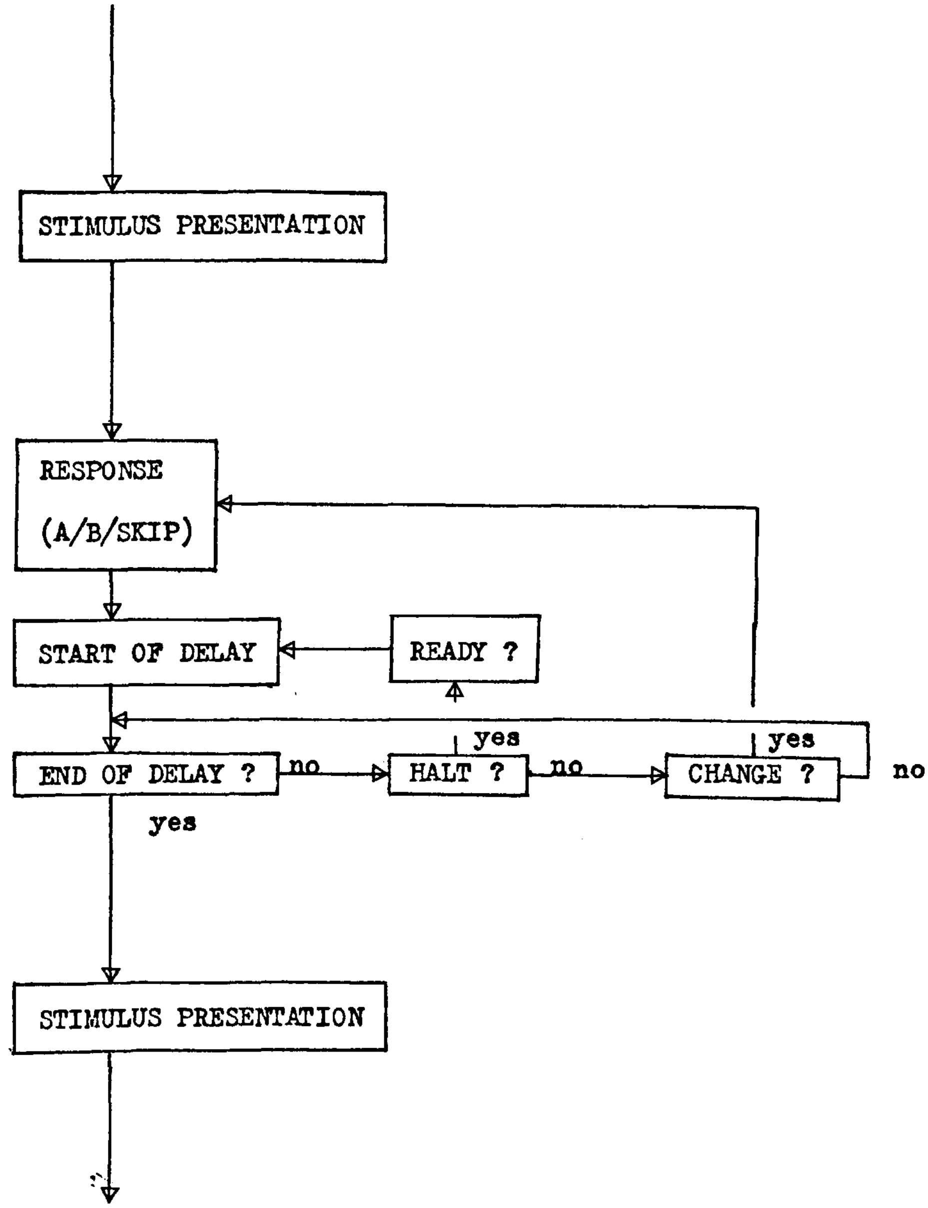


Fig. 2.2

SEQUENCE OF EVENTS DURING A SINGLE STIMULUS/RESPONSE CYCLE.

2.4 Data Analysis.

At the end of each run, when the criterion number of responses had been collected, a full analysis was performed. Probit analysis was used, first on the individual blocks of responses, then on the first and second halves of the run separately, and lastly on the complete run. A chi-square goodness of fit for the Probit regression line was also calculated.

This multiplicity of analyses enabled the experimenter to detect any instabilities in the subject's responses. Such instabilities as a continual drift in the PSE would lead to inhomogeneous data, and the analysis would not be strictly valid. If this led to a large chi-square for the overall fit, for example, the run would have to be discarded. The precise criteria for rejecting a run are set out below. The number of such runs was small.

For each experimental condition, a number of runs would be carried out, in two sessions. Each session would start with a prerun, and then three or four runs would follow. Each run was analysed separately, giving a set of estimates of the mean and standard deviation of the response error distribution. These estimates were then combined to give an overall estimate of the response error statistics. Means are combined by taking the arithmetic average; standard deviations are combined by taking the root-mean-square. These overall estimates are quoted in the results, and used to calculate efficiencies.

2.4.1 Criteria for Rejecting a Run.

An experienced subject, making a simple decision, has a response criterion that is stable, at least in the short term. This is not always the case, and sometimes the subject has a response criterion that is clearly unstable. This leads to inhomogeneous data, and poses intractable statistical problems. Such runs, therefore, have to be discarded.

There have to be objective criteria for judging whether or not to reject a run. The criteria used will now be described : in general they are a matter of common sense, supported by reasonable statistical arguments.

The problem arises primarily since the perception of curvature is a very labile phenomenon, as is witnessed by all the illusions and after-effects.

1). The first rule is based on the chi-square for the goodness-of-fit of the Probit regression line. If the chi-square value showed the data to be significantly non-normal at the 5% probability level, then the run had to be rejected.

2). The second criterion concerns the two half run estimates of the standard deviation of the response error distribution, and the whole run estimate of the same. If the whole run estimate is larger than both half run estimates, then the process of combining the two halves has added extra variance to the data, and this would indicate that the run had to be rejected.

3). The third rule concerns the two half run estimates of the PSE. If there is a difference of one standard deviation between the two estimates, then this is interpreted as indicating that the subject's response criterion changed in the course of the run. Such a run would have to be rejected.

4). The last criterion for run rejection concerns the individual estimates of the standard deviation in each of the 8 blocks of 15 responses. If the variance of these estimates was greater than the response error variance of the whole run, then this was taken as evidence that there had been some fleeting, but large criterion changes, leading to a large inhomogeneity in the subject's responses. Such runs had to be rejected. This amounts to rejecting those runs where, on average, the estimate of the response error standard deviation in each individual block of responses is different from the whole run estimate of the standard deviation of the response error distribution, by one standard deviation.

The process of 'data-cleaning' did not appear to distort any of the major trends in the data.

2.4.2 Standard Errors and the Reliability of the Results.

The standard errors of the estimates of the PSE and standard deviation of the response error distribution, obtained by Probit analysis for a run of 120 responses, are approximately 15 and 25 per cent of the sample estimate standard deviation, respectively. These standard errors will not be quoted in the tables of results.

The standard deviation of the distribution of obtained estimates from individual runs will be quoted. This statistic can be used to gauge the reproducability or reliability of the results, from day to day.

2.5 Relative Efficiencies and Spatial Discrimination Tasks.

Comparison of the performance of different visual spatial tasks is an essential step in the progress towards an understanding of the processes by which our visual sense operates. The comparison of results from different experiments, and from different tasks, is not a trivial matter however.

How can performance in a vernier resolution task, and performance in a curvature discrimination task, be compared ?

What measure of performance would make a valid comparison ?

Threshold measurements, expressed by geometric parameters of the stimulus are unsuitable, since these geometrical descriptions are generally arbitrary.

Efficiency of information processing is the most suitable measure of performance: in principle, performance of vernier resolution, curvature discrimination or any other task may be compared, when performance is expressed in the same terms of efficiency. In practice, certain assumptions have to be made in calculating efficiencies, which restrict the range of tasks that may be compared by reference to this construct.

The concept of an ideal device as a yard-stick, with which to measure human visual efficiency is due originally to Rose (1942), who was considering the sensitivity of the visual system to light energy.

Barlow (1962a,b) refined the concept of quantum efficiency of visual discrimination of light intensities.

Andrews (1967b) devised a rather different type of ideal device, limited by the known spatial statistics of the retinal mosaic, unlike the ideal device of Rose, which is limited by the statistical fluctuations in the number of photons in a given stimulus.

A device with spatial sampling variance can be used to assess the human performance of spatial tasks, and is therefore very useful in studying the nature of the visual processes behind spatial differentiation.
The device of Andrews should be clearly distinguished from the spatial device of Barlow (1978), which works on the spatial variance in the stimulus itself, rather than the spatial variance imposed on the stimulus by the retinal mosaic.
The device of Andrews can be applied to regularly patterned stimuli, such as the targets of vernier resolution, whereas the device of Barlow requires 'random' patterned stimuli.

The concept of an ideal processor of line stimuli overcomes the problem of the interpretation of results of spatial threshold measurements.
The concept, as devised by Andrews (1967b), is used in extension below.

The ideal processor starts with the information available to the visual system at the highest level that can be explicitly defined. In practice at present, this is the receptor surface of the retina. This information is then used without further loss, to perform the same task as the subject in the experiment, resulting in an ideal response.
Since the retina introduces some spatial variance, this response is also variable, and an ideal response distribution can be defined.
The standard deviation of this ideal response distribution can then be determined, and used to represent an ideal threshold for the task and stimulus.

The ideal threshold can then be compared directly with the experimental threshold, to give an efficiency for that task and stimulus. Information is inversely proportional to variance, according to Fisher (1951), and since efficiency can be defined as the ratio of information output to input, the subject's efficiency for a given task is defined as the square of the ratio of ideal threshold to observed threshold, expressed as a percentage :

$$\text{Efficiency} = \frac{\text{Ideal response variance}}{\text{Observed response variance}}$$

This measure may be used to compare directly many different stimuli and tasks without recourse to shaky assumptions of mechanistic or geometric nature, and has three main advantages.

Firstly, it avoids the arbitrary decision of which geometric parameter to use to represent the results. This is of particular importance for the more complex stimuli, such as curved lines, where any number of such parameters may be devised, each one causing the results to appear quite different. This is a difficulty that many studies have run into; for example, Ogilvie and Daicar (1967) end their report of a study on curvature discrimination with an argument in favour of a psychometrically pleasing, rather than a geometrically pleasing parameter to measure threshold curvature. Such arguments tend to pre-judge the meaning of the psychometric functions obtained.

Secondly, the ideal processor, by working in terms of information and efficiency, allows the study of the micro-structure of a stimulus. The contribution of one part of the stimulus to a given task may be directly assessed by measuring efficiency for that task, with and without the part of interest.

Thirdly, the ideal processor takes into account the varying receptor density on the surface of the retina. Different shaped figures, of necessity, cover different parts of the retina. Different shaped figures, therefore, are subject to different degrees of degradation, before neural analysis begins....

2.5.1 Relative Efficiencies.

The concept of efficiency requires some elaboration. Absolute efficiency is theoretically calculable for a spatial differentiation task, but at present this is impractical, since there is not sufficient knowledge of certain properties of the visual system to enable all the necessary factors to be taken into account.

Relative efficiencies are adequate for comparison purposes, and are used exclusively in the present study. The input to the ideal processor is modelled on the known structure of the retinal surface, and the relative efficiencies must be taken as representing the sum total of neural processing. If detailed knowledge were extended to higher levels of the visual system, then these levels could be used as the basis of the structure of the ideal processor : efficiencies in such a case would represent the remainder of the neural processing.

The retina looses spatial information by virtue of its discrete structure. Each receptor may be regarded as a point sample of the light distribution across the retina, and Barlow (1979) has discussed how such point samples might be combined, pointing out that sampling theory shows that were the position of each sample known, the retina would not in practice loose spatial information. However, it seems unreasonable to presume neural knowledge of this degree, and therefore the problem is now inverted : what information would be lost if the arrangement of receptors were known only in qualitative terms (ie. the order of samples along a given line) and the absolute position of these receptors remained unknown. That is, each point sample is taken to lie within a region of positional uncertainty corresponding to the inter-receptor spacing in any given direction. This sampling uncertainty clearly must loose information, and in essence, it is this loss that is loss that is assessed by the use of the ideal processor.

The concept of the ideal processor and relative efficiencies works as follows :

The processes involved in the visual discrimination of the shape of a line are divided into three types :

a) There are the processes that can be quantitatively defined, such as the finite spacing of the receptors on the retina.

b) There are the processes which cannot be quantitatively defined, but which may be assumed to degrade the information from all stimuli equally, and therefore do not exert a differentail effect on different tasks or stimuli. An example is the time constant for the transduction process.

c). Lastly there are the remaining processes which are the object of the study.

Differences in relative efficiency for different stimuli and tasks, would indicate different processing in the visual system. By systematic exploration of variations in efficiency, the mechanisms involved can become apparent. The effects of removal of certain parts of the stimulus on the efficiency of processing, would indicate which are the most important features of the stimulus, throwing light on those cues used, and on the exact form of the information combined in such mechanisms.

The input to the ideal processor will now be defined, and then its mode of operation will be described.

2.5.1.1 Information Loss in the Ideal Processor.

It is desirable to make the stages in the ideal processor which lose information as close to the actual optical and physiological properties of the human visual system, as possible. The relative efficiencies so determined, can then be said to be governed only by those processes undefined.

Information loss has to be categorized into two types. Firstly, there is the loss that can explicitly be defined as exerting a differential effect on the various stimuli and tasks of interest. Secondly, there is the loss which, as yet, cannot be defined in a quantitative manner, but which is assumed not to exert a differential effect. Other than these, the ideal processor makes no further information loss.

These losses will now be stated, starting with the known or estimable losses of information.

2.5.1.1.1 Differential Information Loss.

a). Each light receptor has a finite size. This means that any location in space has a region of confusion, within which all possible points are indiscriminable. This limits the absolute spatial information. The effective receptor diameter is defined as the distance between the centres of two adjacent receptors.
This effective receptor diameter is a function of eccentricity. Andrews, Butcher and Buckley (1973) found a good fit to the anatomy data of Polyak (1941), and the grating acuity data of Wertheim (1894) and Weymouth, Hines, Raaf, and Wheeler (1928), up to eccentricities of about 4.5 degrees, by the simple rule that each receptor is 0.22 sec. arc greater in effective diameter than its immediately more central neighbour; the central receptor has a diamter of 20 min. arc.
The positional uncertainty within a given receptor is distributed approximately rectangularly, with a range 'd', the diameter of the receptor. This gives a standard deviation for the position uncertainty os $d/\sqrt{12}$.
For convenience, the exact distribution is assumed to belong to the family which allows equation of least squares methods with maximum likelihood methods (eg. normal distribution), and to have the same standard deviation.

b). The packing structure of the receptors on the retinal surface is treated as random. Andrews et al. (1973) quote serial correlations for cone centres. Correlations are negligible beyond a few cones.

c). The light spread function of the optics of the eye also has an effect on the information available in a pattern. This is of some importance for some tasks, involving the estimation of the position of the end of a line, for example. A line of actual (and perceptual) width of 20 sec. arc will be spread out on the retina to cover no less than three receptors, thereby providing rather better position information than if the spread did not occur. When discriminating the curvature of a line, on the other hand, the line still has only two contrast edges, and the light spread is of no importance.

2.5.1.1.2 Information Loss that is Assumed not to act Differentially.

a). The temporal characteristics of the transduction process cannot be stated with sufficient precision to allow for them in calculating relative efficiencies. In particular, there are always slight eye-movements and tremors, which provide a finite number of independent samples of the stimulus information. The ideal processor, and perhaps the human subject, could make use of these samples and reduce response variance. The actual number of samples would be a function of stimulus duration, and so for comparing results at equal stimulus durations, temporal characteristics probably do not exert a differential effect, and may therefore, be treated as an unknown constant.

b). The intensity characteristics of the transduction process, such as the range of response levels available at different intensities of stimulation, might be used to signal how much of a stimulus falls within a given receptive field. Once again, this is assumed not to exert a differential effect on the stimuli and tasks employed, and is treated as an unknown constant.

c). For all but very short lines and dots, blur of the retinal image due to optical imperfections of the eye may be disregarded. An ideal device which knew the form of the light spread function for its own optical system would lose very little information in this way. Note that the system can gain precision for certain spatial judgments (see 'c' p 81).

When all these unknown constants are set to unity, it is possible to calculate the variance of estimates of whatever parameter is required, for an instantaneous, focussed image of the stimulus.

2.5.1.2 The Nature of the Operations of the Ideal Processor.

The input limitations of the ideal processor are now defined. The nature of the operations that it performs will be discussed next.

The ideal processor loses no further information, in making the required estimates for a particular decision. The response distribution can then be inferred, by considering the error probabilities for the estimates. The ideal processor is provided with the same general information as the subject concerning the nature of the stimuli, and the task to be performed. The stimulus to be observed is then input to the device as a geometrical definition. The explicit information transformations which lose information, as defined in the previous section, are then operated on the stimulus. The output of these transformations is a set of receptors which 'responded' to the stimulus, each one providing a mean and a variance of position information for a small segment of the stimulus.

Now the ideal processor performs the task on the resultant data, using statistical decision processes. The Method of Maximum Likelihood is used where available. This ensures that no further information is lost. In general, the Method of Least Squares suffices for line figures and appropriate tasks.

Where the nature of the shape of the stimulus, and the shape distortion, to be judged is known, the task becomes a statistical test for the value of the distortion. The actual test is, of course, dependent upon the task. If the task concerns line slope, then a linear regression test will serve. If the task concerns curvature, then a second order polynomial regression is required.

The variance of the relavant estimate in such tests leads to a measure of the error variance of the ideal processor, and corresponds to the variance of the response distribution of the ideal processor.

This may be directly compared with the variance of the response error distribution for the subject, to provide the relative efficiency for the task and stimulus.

The expression used to calculate the response variance of the ideal processor for the task of curvature estimation is derived in the concluding section of this chapter.

2.5.2 Variance of the Estimates of the Curvature of a Circular Arc.

The co-ordinate function for a circular arc is as follows :

$$(x + c_x)^2 + (y + c_y)^2 = r^2$$

This may be approximated by a polynomial in x. The coefficient of the x^2 term, k_2, is related to the curvature of the arc as follows :

$$k_2 = \frac{c_v}{2} \qquad c_v = \frac{1}{r}$$

Therefore the curvature of a line may be estimated by a polynomial regression analysis of the quartic effect, which is then doubled to give the actual curvature of the line.

In curvilinear analysis by regression, it is convenient to be able to carry the analysis out term by term successively, until a satisfactory fit to the data has been obtained. An expression of the type :

$$Y_i = a + bx + cx^2 + \dots$$

will not meet this requirement, because the partial derivatives with respect to the coefficients, of the sum of squares $(Y_i - y_i)^2$ contain cross terms, producing for each additional term, a new series of simultaneous equations in all coefficients.

Therefore, functions of x_i are defined, $f_0\ f_1\ f_2\ f_3 \dots$ such that

$$Y_i = Af_0 + Bf_1 + Cf_2 + \dots$$

If these functions are orthogonal polynomials, then there are no non-zero cross terms in the partial derivatives, and each coefficient may be estimated independently of the others.

The process of minimising the sum of squares, with respect to each coefficient is then carried out, to provide an expression for the best estimator of that coefficient, and the variance of this estimator.

Starting with the expression

$$E(y_i) = k_0f_0 + k_1f_1 + k_2f_2 + \ldots\ldots k_nf_n \quad .$$

Define $\quad w \quad = \sum_i (y_i - k_0f_0 - k_1f_1 - k_2f_2 - \ldots\ldots k_nf_n)^2$

Take partial derivatives

$$\frac{dw}{df_j} = 2\sum_i ((y_i - k_0f_0 - k_1f_1 - k_2f_2 - \ldots\ldots k_nf_n).f_j)$$

But the f are orthogonal, therefore

$$\sum_i f_r.f_s = 0$$

and $\quad \sum_i f_r.f_r \neq 0$

Therefore

$$\frac{dw}{df_j} = 2\sum_i (y_i.f_j - k_j.f_j^2)$$

Minimise by equation to zero,

$$\frac{dw}{df_j} = 0 \qquad \text{Therefore} \qquad k_j = \frac{\sum y_i.f_j}{\sum_i f_j^2}$$

Therefore, given the estimator for k_j, the variance of this estimator is derived as follows.

$$\text{var}(k_j) = \frac{f_j^2.\text{var}(y_i)}{f_j^2.\ E(f_j^2)} = \frac{\text{var}\ (y_i)}{E(f_j^2)}$$

If enough is known about the distribution of x, one can derive the expected value of f_j^2 . This will be done for a rectangular distribution of mean 0, and standard deviation $d/\sqrt{12}$.

Define the orthogonal polynomial $f_r(x)$:

$$f_r(x) = x^r - \sum_{v=0}^{r-1} \frac{f_v(x)}{c_v} \cdot \sum_{i=1}^{n} x_i^r . f_v(x_i) \qquad \ldots\ldots \underline{1}$$

where $c_r = \sum_{i=1}^{n} f_r^2(x)$

1 may be rewritten as :

$$f_r(x) = x^r - \sum_{v=0}^{r-1} f_v(x). \frac{E(x^r.f_v(x))}{E(f_v^2(x))}$$

Squaring, expanding, and ignoring cross terms

$$\sum_i f_r^2(x) = 2.\sum_i x^r.f_r(x) - \sum_i x^{2r} + \sum_{v=0}^{r-1} n.\ E^2(x^r.f_v(x))$$

Therefore,

$$E(f_r^2(x)) = 2.\ E(X^r.f_r(x)) - E(x^{2r}) + \sum_{v=0}^{r-1} E^2(x^r.f_v(x))$$

Therefore

$$E(f_r^2(x)) = E(x^{2r}) - E^2(x^r).$$

This expression is quite generalfor all 'r', and may be used in the expression for the variance of the estimator for k_j :

$$var(k_j) = \frac{var(y_i)}{E(f_j^2)} = \frac{var(y_i)}{(E(x^{2j}) - E^2(x^j))}$$

Note : $var(y_i)$ is the RMS (weighted mean) of the individual sample position variances.

Now,

$$E(g(x)) = \int g(x).h(x).dx$$

where $h(x)$ is the density function of the sample points.

For a rectangular distribution of sample points,

$h(x) = 1/d$ and the limits are $d/2$ and $-d/2$

$$\text{therefore,}\quad E(g(x)) = 1/d. \int_{-d/2}^{d/2} g(x).\,dx$$

It can be shown that

$$E(x^r) = \frac{d^r + (-d)^r}{2^{r+1}.\,(r+1)}$$

$$\text{and}\qquad E(x^{2r}) = \frac{d^{2r}}{2^{2r}.(2r+1)}$$

Therefore the variance of the estimate of curvature is given by

$$var(f_2) = \frac{var(y_i)}{E(f_2^2)}$$

where $E(f_2^2) = \frac{l^4}{180}$ where l is the stimulus length.

This analysis contains two slight approximations.

Firstly, it is wrong but convenient to analyse the data as if the distribution of sampling were fixed, rather than uncertain. However the density function would be little changed, and the approximation has little effect.

Secondly, the distribution of positional uncertainty, at the sample points is not uniform. Strictly, a weighted regression should be used, but, since the difference in positional uncertainty (effective receptor diameter) is small, the approximation is also small. The effects are alievated by using a mean positional uncertainty, $var(y_i)$.
These two approximations could be avoided, by use of a two dimensional weighted regression analysis. But this would require the calculation of a new set of orthogonal polynomials for each new stimulus.

The expression for $var(f_2)$ is used to calculate efficiencies. The variance of the estimate of stimulus curvature is twice the variance of the estimate of the second degree polynomial coefficient.
A listing of the subprogram used to calculate efficiencies is included in the appendix.

2.5.2.1 Notes on the usage of relative efficiencies below.
In the description of the experiments and results below, the term 'relative efficiency' is abbreviated to 'efficiency'.
Since most experiments involve the use of a comparison stimulus, some assumptions concerning its influence upon performance of the task have to be made. If the ideal processor were informed that the same reference comparison were used throughout a run, it could steadily improve its estimate of the criterion curvature, or it could use an efficient but improper strategy by assessing the reference curvature once only, and then using this estimate as criterion without further variance. It seems probable that such a strategy was used by subjects, and therefore the reference stimulus is considered, in the calculation of efficiencies below, to add no uncertainty, and therefore no response variance to the task.

2.5.3 Appendix.

```
C       MAIN PROGRAM FOR CURVATURE ESTIMATE VARIANCE CALCULATION
        DIMENSION  RVAR(1500)
C       TRACE THE CURVE
        CALL CURVD(CURV,ALEN,SLOPE,XS,YS,IGAPS,PGAPS,RVAR,NCELL)
c       CURV = CURVATURE   (Rad/Min. arc)
C       ALEN = LINE LENGTH (Min. arc)
C       SLOPE = CHORD SLOPE (Radians)
C       XS,YS = LINE STARTING POINT  (Min. arc from centre)
c       IGAPS = NO. GAPS
C       PGAPS = RELATIVE SIZE OF GAPS

        CALL TASK(RVAR,NCELL,ALEN,VERR,BERR,SERR,CERR)
c       OUTPUT  :
C       VERR  =  ERROR OF LENGTH ESTIMATE
C       BERR  =  ERROR OF POSITION ESTIMATE
C       SERR  =  ERROR OF SLOPE ESTIMATE
C       CERR  =  ½ ERROR OF CURVATURE ESTIMATE

        STOP
        END
```

```
      SUBROUTINE CURVD(CURV,ALEN,SLOPE,XS,YS,IGAPS,PGAPS,RVAR,NCELL)

c     OUTPUT :   RVAR(NCELL)      OUTPUT SAMPLE VARIANCES
C                NCELL            NO OF SAMPLES

      DIMENSION RVAR(1500)


      NCELL = 0
      THETA = 3.14159 + SLOPE - ALEN/2.0*CURV
      XW = XS
      YW = YS
      ISECT = IGAPS + 1
      SIZED = ALEN/(FLOAT(ISECT) + FLOAT(IGAPS)*PGAPS
      SIZEG = PGAPS * SIZED
      JSECT = 0

C     LOOP AROUND, TRACING OUT THE CURVE.
30    CONTINUE
      JSECT = JSECT + 1
      WALEN = 0.0
1     NCELL = NCELL + 1
c     GET CURRENT RECEPTOR SIZE + POSITIONAL UNCERTAINTY
      CALL RECP(XW,YW,DIAM,RVAR(NCELL))
      WALEN = WALEN + DIAM
c     MOVE TO NEXT RECEPTOR, AND CHECK IF END OF LINE SEGMENT
      IF(WALEN - SIZED) 2 , 10 , 3
2.    CALL NEXTXY(XW,YW,THETA,CURV,DIAM)
      GO TO 1
```

```
C         FINISH OFF CURRENT LINE SEGMENT (SIZE = ASTEP)
3         ASTEP = SIZED - (WALEN - DIAM)
          CALL NEXTXY(XW,YW,THETA,CURV,ASTEP)
10        NCELL = NCELL + 1
          CALL RECP(XW,YW,DIAM,RVAR(NCELL))

C         END OF STIMULUS ?
          IF(JSECT - ISECT) 20 , 35 , 35
20        CALL NEXTXY(XW,YW,THETA,CURV,SIZEG)
          GO TO 30

35        CONTINUE
          RETURN
          END



          SUBROUTINE  NEXTXY(X,Y,SLOPE,CURV,STEP)
C         FOLLOW A CURVED LINE THROUGH A DISTANCE 'STEP'σ AND
C         CALCULATE THE NEW CO-ORDINATES

          STEPP = STEP
          IF(CURV) 1, 2, 1
1         STEPP = 2.0/CURV * SIN(STEPP/2.0 * CURV)
2         SLOPEP = SLOPE + ASIN(STEPP/2.0 * CURV)
          X = X + STEPP * COS(SLOPEP)
          Y = Y + STEPP * SIN(SLOPEP)
          SLOPE = SLOPE + STEP*CURV

          RETURN
          END
```

```
      SUBROUTINE TASK(RVAR, J , ALEN , VERR , BERR , SERR , CERR )
      DIMENSION RVAR(1500)

      SUMV = 0.0

      DO 11 K = 1,J
      SUMV = SUMV + RVAR(K)
11    CONTINUE

      XVAR = ALEN**2 / 12.0
      XQUART = ALEN**4 / 180.0
      YVAR = SUMV/FLOAT(J)

      VVAR = (RVAR(1) + RVAR(J))/3.0
      BVAR = YVAR/FLOAT(J)
      SVAR = YVAR/(XVAR*FLOAT(J))
      CVAR = YVAR/(XQUART*FLOAT(J))

      VERR = SQRT(VVAR)
      BERR = SQRT(BVAR)
      SERR = SQRT(SVAR)
      CERR = SQRT(CVAR)

      RETURN
      END
```

```
      SUBROUTINE RECP( X,Y,RDIAM,RVAR)

      ECC = SQRT(X**2 + Y**2)  * 60.0

      DIAM = 20.0
      RINC = 0.22
      RLIMIT = DIAM/ 2.0
      RDIAM = DIAM

      IF(ECC- - RLIMIT) 3,1,1
1     CONTINUE
      A = RINC / 2.0
      B = A + DIAM
      C = - (ECC - RLIMIT)
      RANK = ( - B + SQRT(B**2 - 4.0*A*C))/(2.0*A)

      RDIAM = DIAM + RANK*RINC

3     RDIAM = RDIAM / 60.0
      RVAR = RDIAM**2 / 12.0

      RETURN
      END
```

CHAPTER 3. TWO DIFFERENT SPATIAL TASKS COMPARED FOR TWO DIFFERENT STIMULI.

What neural processes are performed on the representation of the retinal image ? In what order are they performed ?

The pattern of connections in the visual system linking the outputs of the receptor cells determines both which neural processes are carried out, and which stimuli are analyzed most faithfully. Therefore, it follows that empirical determination of the power of the visual system for a range of tasks, and a range of stimuli, should throw light on these functional connections. This chapter will consider the two different processes of visual analysis of shape and position, and the two different stimuli, straight contours and curved contours.

It will be argued on mathematical grounds, that the analysis of shape and position are two distinct processes. Results from psychophysical studies by Andrews will be reported to demonstrate that these processes are also neurally distinct, when they are being performed on straight contours. It will then be suggested that the use of a different class of stimulus, namely curved contours, might be expected to lead to further understanding of the neural processes involved.
The results of such a study will then be presented.

A single contour in two dimensional space can be represented mathematically by a function relating all points on that contour to the two co-ordinate axes. A contour can be mapped onto a function in co-ordinate space, and such a function provides all the necessary information to reconstruct that contour; it is an exhaustive description.

Mathematical operatins can be performed on the function to analyze any specific property of the contour. Two formally distinct classes of operation are differentiation and integration: differentiation characterizes the shape of the contour; integration characterizes the position and size of the contour.

The visual system is also capable of representing a contour in two dimensional space. However, the representation is only approximate: the retina samples space selectively, and not all points on the contour are represented. Neural operations are performed on this representation to analyze certain specific properties of the contour.

Both position and size, on the one hand, and shape on the other, can be appreciated by the visual system, and so the neural processes must achieve, amongst others, analogues of the mathematical operations of integration and differentiation.

Neural processes, unlike mathematical operations are imperfect: they lose information, and therefore the results of neural analysis contain further approximations.

Careful assessment and consideration of the information losses incurred in the course of neural processing should provide insight into the nature of these neural processes.

The question of interest is whether the visual system can be shown to attach priority in its neural processing of contours to achieving the analogue of one or other of these operations. Does the visual system extract information for shape judgement and for position judgement, with the same fidelity, or are the losses different ?

Information lost in the course of visual analysis of shape and position can be inferred from estimates of the efficiency with which subjects are able to perform specific visual tasks, involving position or shape judgements of specific stimuli.

Andrews has compared performance of two psychophysical tasks involving these types of judgement with straight line stimuli. The tasks were : discrimination of the direction of curvature (a shape judgement), Andrews, Butcher and Buckley (1973); and discrimination of the distance separating two contours (position judgement), Andrews and Miller (1978). The results of these studies showed that subjects are able to judge relative shape much more efficiently than relative position. Indeed, the difference was so great that it was suggested that the residual positional information, after the analysis of shape could be the sole basis for the position judgements. This constrains the types of candidate neural process considerably.

There is reason to suppose that these results might be specific for straight line stimuli. The majority of cortical units show a preference for collinear stimuli, although there have been a few reports of units that preferred curved stimuli (eg. Heggelund and Hohmann, 1975; Hammond and Andrews, 1978).

Psychophysical studies have also failed to find the same types of response to curved line stimuli as are found to straight line stimuli. There is no good evidence for curvature-specific after-effects (eg. Blakemore and Over, 1974), and for curvature-specific chromatic after-effects (eg. Riggs, 1973; MacKay and MacKay, 1974; Crassini and Over, 1975). This suggests that the study of the efficiency with which the visual system can process curved line stimuli may show further constraints on the types of candidate neural process.

The use of curved contours does present some problems. A psychophysical discrimination task involving curved contours is likely to involve a composite of shape and position judgements. Consider the case where a subject is asked to judge the distance between two contours, both of which are curved. As a result of the shapes of the individual contours, the total stimulus array has different global shapes at different separations. Therefore the subject has the option of using either or both shape and position cues. However, this situation can be turned to advantage. The results of Andrews can be extended by examining whether there are stimulus configurations where shape judgements can facilitate the low efficiency performance of position judgements.

Efficiency for shape judgement will be measured psychophysically by a curvature discrimination task. Performance will be measured as a function of stimulus duration. This will provide useful data, on which to base subsequent stimulus exposure durations.
Efficiency for position judgements will be measured in a separation distance discrimination task, as a function of stimulus separation.

EXPERIMENT 1. : THE EFFECT OF STIMULUS EXPOSURE DURATION ON THE DISCRIMINATION OF CURVATURE IN STRAIGHT AND CURVED CONTOURS.

This preliminary experiment has three basic aims.

Firstly, it will serve to compare performance of curvature discrimination for a curved line, and a straight line. Andrews, Butcher and Buckley (1973) have found a high relative efficiency for the performance of a number of shape discrimination tasks, for straight lines of length less than 30 min. arc. The tasks were vernier resolution, chevron curvature discrimination, and arc curvature discrimination. They suggest that the most economical description of these tasks, which apparently share some degree of visual processing, refers to them as cases of collinearity-failure detection and discrimination. It would be useful to know whether such a summary is adequate in describing all high efficiency shape judgements.

Secondly, this experiment will serve to indicate what the most suitable stimulus exposure duration to use for a full scale study of the effects of curvature on various visual discriminations, might be. This is important since the temporal response of the visual system is not simple, apparently involving considerable integration. It is important to ensure that the stimulus duration chosen allows nearly maximum integration, otherwise the comparison of performances for different stimuli might not be valid.

Thirdly, it would be valuable to know what the efficiency of ,the visual system is for the curvature discrimination of a brief flash stimulus. Such a stimulus rules out involuntary eye-movements, and therefore allows only passive information acquisition strategies. This should provide a base-line efficiency for the case where only one sample of the stimulus data is available. A further benefit from using brief stimuli would be that their appearance is stable, and not subject to the subjective changes in shape that longer duration stimuli are.

In addition, the experiment will serve two useful functions with respect to the subjects.

The data for curvature discrimination in a straight line may be compared directly with the same data in Andrews et al. (1973), thereby providing a link with their results.

The experiment can also be used to train the subjects not to use an eye-movement strategy, by preventing it through the use of very short duration stimuli.

METHODS

The computer controlled Method of Constant Stimuli, as described in Chapter 2, was used.

Two conditions of stimulus curvature were used.
In the zero curvature case, the stimulus array consisted of a fixation spot and a test stimulus. The test stimulus was drawn from a series varying in curvature, centred at a curvature of zero. The length of the stimulus was 20 min. arc. It was situated 2,5 min. arc above the fixation spot.
In this case, the subject was asked to decide whether the stimulus was curved upwards or downwards.
In the curved case, the stimulus array consisted of a fixation spot, a comparison stimulus of curvature 0.05 rad/min. arc and length 20 min. arc, and a test stimulus also of length 20 min. arc, and drawn from a series varying in curvature, centred at a curvature of 0.05 rad/min. arc. All lines were curved upwards. The comparison stimulus was situated 2.5 min. arc below the fixation spot, and the test stimulus was situated 2.5 min. arc above the spot, in the standard configuration.
In this case, the subject was required to decide which line was more curved, top or bottom.

A number of stimulus exposure durations were used, ranging from 10 msec. to 2 sec. The stimulus was presented after a 3 second delay, during which the fixation spot alone was displayed.

Two subjects were tested. One (RJW) made a large number of practice runs, using the curved stimuli, and a stimulus exposure duration of 10 msec. A steady improvement was found over the course of several months in the performance of the curvature discrimination task, finally reaching a plateau. The straight line case did not show a learning effect. This is important.

The second subject (RSS) was tested essentially without practice, although the subject had previous psychophysical experience.

RJW had normal vision, RSS had corrected-to-normal vision.

RESULTS

The thresholds for curvature discrimination are shown in Fig. 3.1.

There is a decrease in threshold for increasing exposure duration. This follows a similar, but not identical time course for the two curvatures used, but there is a difference in the absolute levels of threshold in the two cases. Threshold for straight lines is smaller than for the curved lines. There is also a difference between the two subjects, which is independent of the testing condition, as is presumably related to the different amounts of experience of the two subjects.

Ideal thresholds are 1.667E-5 rad/sec. arc for the straight line case, and 2.498E-5 rad/sec.arc for the curved line case. These are different because of the nature of the two tasks. In the case of the straight lines the task is an absolute one : 'Is the contour curved up or down ?'. In the case of the curved lines, the task is a relative one : 'Which stimulus is more curved, top or bottom ?' This latter case requires analysis of two lines, and therefore has approximately twice the error variance.

Efficiencies are shown in Fig. 3.2. Efficiencies are more nearly the same for the two tasks, and it can be seen that the difference in the obtained thresholds could be accounted for by the nature of the task. This possibility will be discussed below (p.106). Note that this is a special use of the term efficiency, since the temporal requirements (Section 2.5.1.1.2 p81.) are violated in this experiment. The efficiencies quoted only have meaning within the context of this one experiment, as a result.

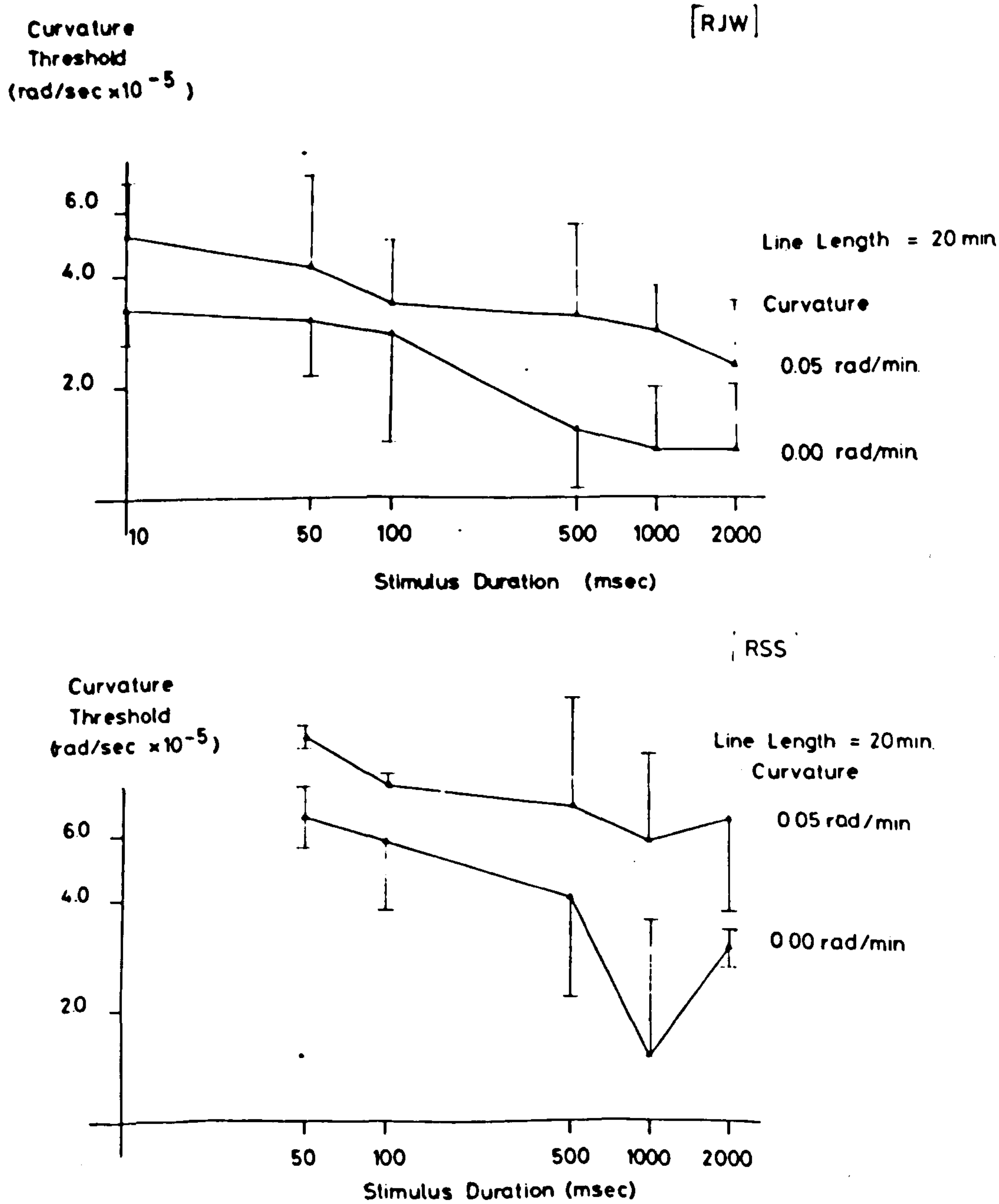
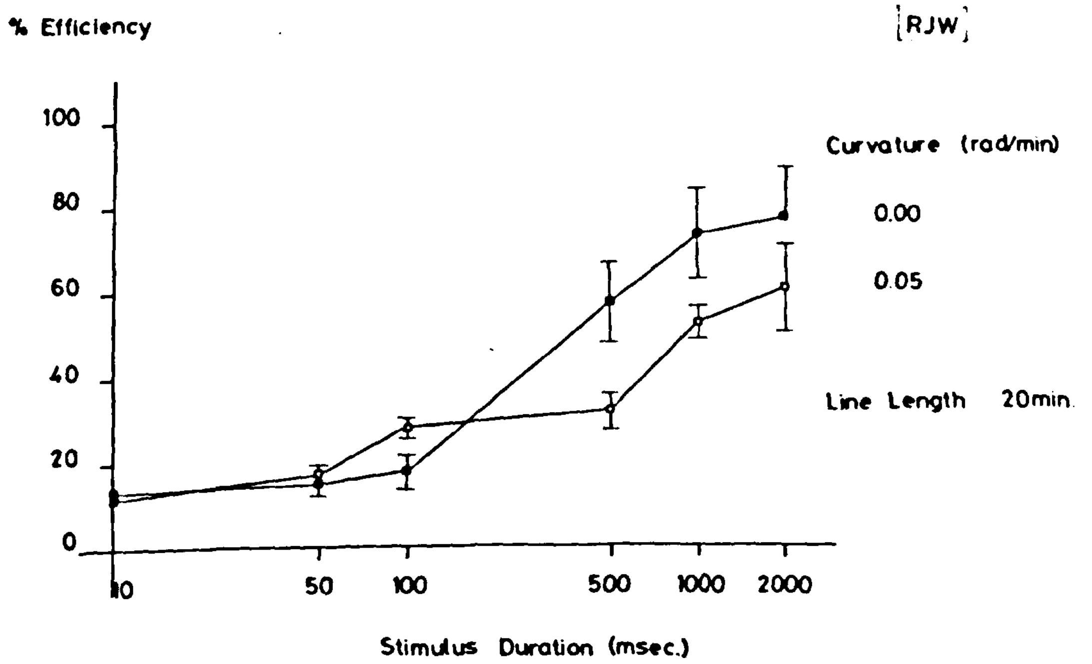


Fig. 3.1 Thresholds for curvature discrimination as a function of stimulus duration and curvature.



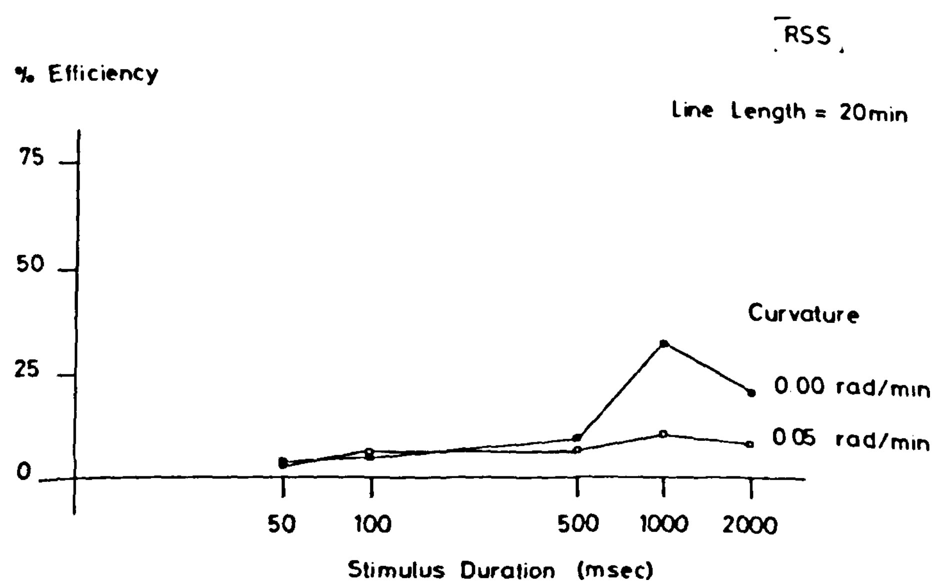


Fig. 3.2 Efficiency for curvature discrimination as a function of stimulus duration and curvature.

DISCUSSION

This experiment had three basic aims, which will now be discussed in the light of the data obtained.

One aim was to measure a base-line efficiency for the discrimination of curvature in a stimulus displayed for only 10 msec. Such a duration rules out eye-movements, and is presumed to allow the visual system only enough time to make one sample of the stimulus data. In practice, such a measurement is precluded, because a brief stimulus appears quite distorted. Similar distortions for brief stimuli are reported in Andrews (1967a).

Another aim was to establish the optimum stimulus duration for future experiments. The data show no minimum stimulus exposure duration, which would allow complete or maximum integration, but the rapid initial summation of information would be avoided by choosing a stimulus duration of 2 seconds.

The major aim of this experiment was to make a comparison of curvature discrimination in straight contours and in curved contours. Whilst thresholds for the two stimuli are rather different, efficiency for the comparison of curvatures of two curved lines, is almost as high as efficiency for the discrimination of curvature direction in a nearly straight line. This is interesting, and suggests that the concept of collinearity-failure detection is inadequate to describe all high efficiency shape discrimination tasks.

There are two problems however, which arise from the use of the comparison stimulus. Both problems may invalidate a comparison of the efficiencies for the two tasks. These problems are: firstly, does the subject have a time invariant strategy in his use of the comparison stimulus, over the course of an experimental run; and secondly, does the presence of a comparison stimulus in the vicinity of the test stimulus alter in any way, the perception of that test stimulus.?

The first problem concerns the weight to be attached to the reference comparison stimulus, when calculating efficiencies. The subject in the comparison task could, in principle, cheat in the following manner. Rather than making a fresh comparison for each stimulus presentation, the subject could estimate the curvature of the test stimulus and compare this with a criterion curvature value. This criterion value would be obtained both from the comparison stimulus, and from a running mean of the test stimuli already seen. It would be subject to an error, but could be used in principle without variance. This would lead to a constant error in the judgements, but a smaller variable error or threshold, since the response variance would be due to the perception of the test stimulus alone. In practice, it is more likely that the subject could use the criterion value with steadily decreasing variance, through the course of a run : the effect of the comparison stimulus would not be time invariant.

The problem has been solved as follows, for this particular case. If the use of the comparison stimulus is time invariant, and a proper comparison between the two lines is made for each judgement, then threshold should not be increased by making the subject uncertain on any one presentation, which stimulus is the test, and which the comparison. The subject in this case would not know which stimulus to judge, were he cheating, and this procedure should raise the threshold. Thresholds were obtained and compared for subject RJW using the two conditions, fixed relative positions of the test and comparison stimuli, and random relative positions.

The results were as follows :

Condition	Threshold	PSE	Efficiency
Fixed pos.	4.372E-5	4.555E-2	16.801
Random pos.	4.841E-5	4.998E-2	13.701
	(rad/sec.)	(rad/min.)	(%)

There is no significant difference between the two thresholds at a 5% probability level (F-test with 12/26 degrees of freedom). The test is not powerful, but clearly, the difference obtained suggests that the use of the comparison stimulus is largely time invariant. It seems reasonable to assert that a fresh comparison between the two stimuli is made for each decision.

The second problem concerns the possibility that closely neighbouring contours (such as the test and comparison stimuli for the curved line case of the present experiment) could generate interactions in the visual system, which might reduce discrimination efficiency. Westheimer and Hauske (1975) have suggested that lateral effects of this kind can disturb vernier resolution judgements. Such an effect might give the straight line case (where only one contour is presented to the subject) an advantage over the curved line case (where two contours, 5 min. arc apart are presented to the subject) in the present experiment.

Even if this were so, efficiency for curvature discrimination of the curved line would be depressed by the presence of the contour. This problem does not upset the principle finding of the experiment, and will not be discussed further here. The problem is returned to in Chapter 5 (Experiment 6), and discussed fully in Chapter 8 (p.234).

The major result of this experiment is therefore that efficiency for curvature discrimination is not reduced very much by a 0.05 rad/min. arc curvature of the stimulus.

EXPERIMENT 2. : THE EFFECT OF STIMULUS CURVATURE ON DISCRIMINATION OF THE DISTANCE SEPARATING TWO CONTOURS.

It has been established that shape judgements are performed at almost equal efficiency for straight lines of length 20 min. arc, and lines of the same length and curvature 0.05 rad/min. arc. In view of the finding of Andrews and Miller (1978), that position judgements are performed at a much lower efficiency, it would be useful to ascertain whether this performance is also independent of the curvature of the stimulus. Whereas it was expected that curvature might reduce the efficiency for shape judgements, it might be expected that curvature could increase efficiency for position judgements. The reason for this, is that any stimulus configuration for such an experiment would allow the subject the option of supplementing position judgements with shape judgements. It would be useful to test whether such an option can be used by subjects to improve performance.

Consider the following task. A stimulus array is presented to the subject consisting of a fixation spot, a comparison stimulus beneath the spot, and curved downwards, and a test stimulus curved upwards, and varying in vertical position (see Fig. 3.3).
The subject is asked to judge whether the stimulus array is flatter than a circle or not. This task strictly requires two independent judgements to be compared. Firstly an explicit curvature judgement is made, to provide the reference separation. Then a position judgement is made, and compared with the reference separation. These judgements could be replaced by an overall shape judgement, since the shape of the total array varies with the separation of the two contours.

Does the option of replacing the shape plus position judgements, by an overall shape judgement improve efficiency ? Is performance limited by the nature of the task, or by the form of the stimuli ? Is the priority processing of shape limited to small, compact, or connected contours ?

METHODS

The computer controlled Method of Constant Stimuli, as described in Chapter 2, was used.

The arrangement of stimulus elements is shown in Fig. 3.3.
The stimulus array consisted of a fixation spot, a comparison stimulus (which does not actually provide a comparison feature, but does serve to define the judgement), and a test stimulus.
Since the spot could arguably interact with the task, providing a cue for response (see p.114 for the way it could do this), a second condition was used, without the fixation spot. In both conditions, the spot was displayed for 3 seconds before stimulus presentation, and the subject was required to fixate at all times.
The comparison stimulus was below the spot, and curved downwards. The position of the comparison stimulus was such that the centre of the imaginary circle, of which the comparison stimulus was a part, coincided with the fixation spot.
The test stimulus was placed above the fixation spot, at a variable distance away (variable in the vertical direction only). The test stimulus was curved upwards, and of the same curvature and length as the comparison stimulus.
The following curvatures were used : 0.04, 0.05, 0.067, 0.08, 0.10, 0.133, 0.20 rad/min. arc.
The two stimuli were always one third of the overall circumference of the circle. This size was chosen so that the distance between the extreme ends (which is the smallest distance between the curves) is the same as the radius of the circle.

Two subjects were used for this experiment. One was tested in both fixation spot conditions (RJW), the other was only tested in the fixation spot present condition. Both had normal vision.

In each condition of fixation spot, the subject was requested to maintain steady fixation at all times. The subject was asked to decide whether the stimulus array he saw was taller or flatter than a true circle.

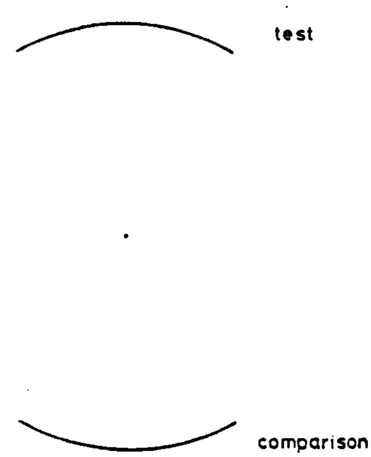


Fig. 3.3 Stimulus configuration for Experiment 2. The upper curve varied in vertical position, the lower curve was fixed.

RESULTS

Thresholds for separation are shown in Fig. 3.4. Ideal thresholds are also shown. The ideal thresholds are based on two judgements : the reference curvature has to be calculated first, using the two arcs independently; then the distance between the arcs has to be calculated. The error variances associated with these two judgements are then combined, to give the overall error variance, leading to the ideal threshold. Note that the subject was not informed of the relationship between the position of the spot and the lower comparison stimulus. The spot therefore provides no further information for the task, and the ideal thresholds for the two conditions are the same.
Thresholds rise with increasing separation (due to the increasing reference curvature), in line with the data of Andrews and Miller (1978).

Efficiencies for the task are shown in Fig. 3.5. Efficiencies are quite high for the smallest stimulus, but not as high as those recorded for the shape task in Experiment 1. Efficiency for separation drops very rapidly with increasing separation, up to separations of about 25 min. arc, beyond which, the drop is much less.

There is a difference in the performance obtained for the two conditions, with and without the fixation spot. Clearly, the spot is contributing to the task in some non-veridical manner, for the separations greater than about 25 min. arc. This could be as follows.
The spot is a fixed reference point in space, nearer to the test stimulus than is the comparison stimulus. It could be used to advantage by any

system that lost efficiency as the separation distance increased, provided that some guess about the spatial relationship between the spot and the comparison stimulus was made. Such judgements, of the distance between the test stimulus and the spot, would of course, be strictly non-veridical, but the resultant variance would be lower. It seems likely that the spot was used in this way by the subjects, improving performance for the longer separations.

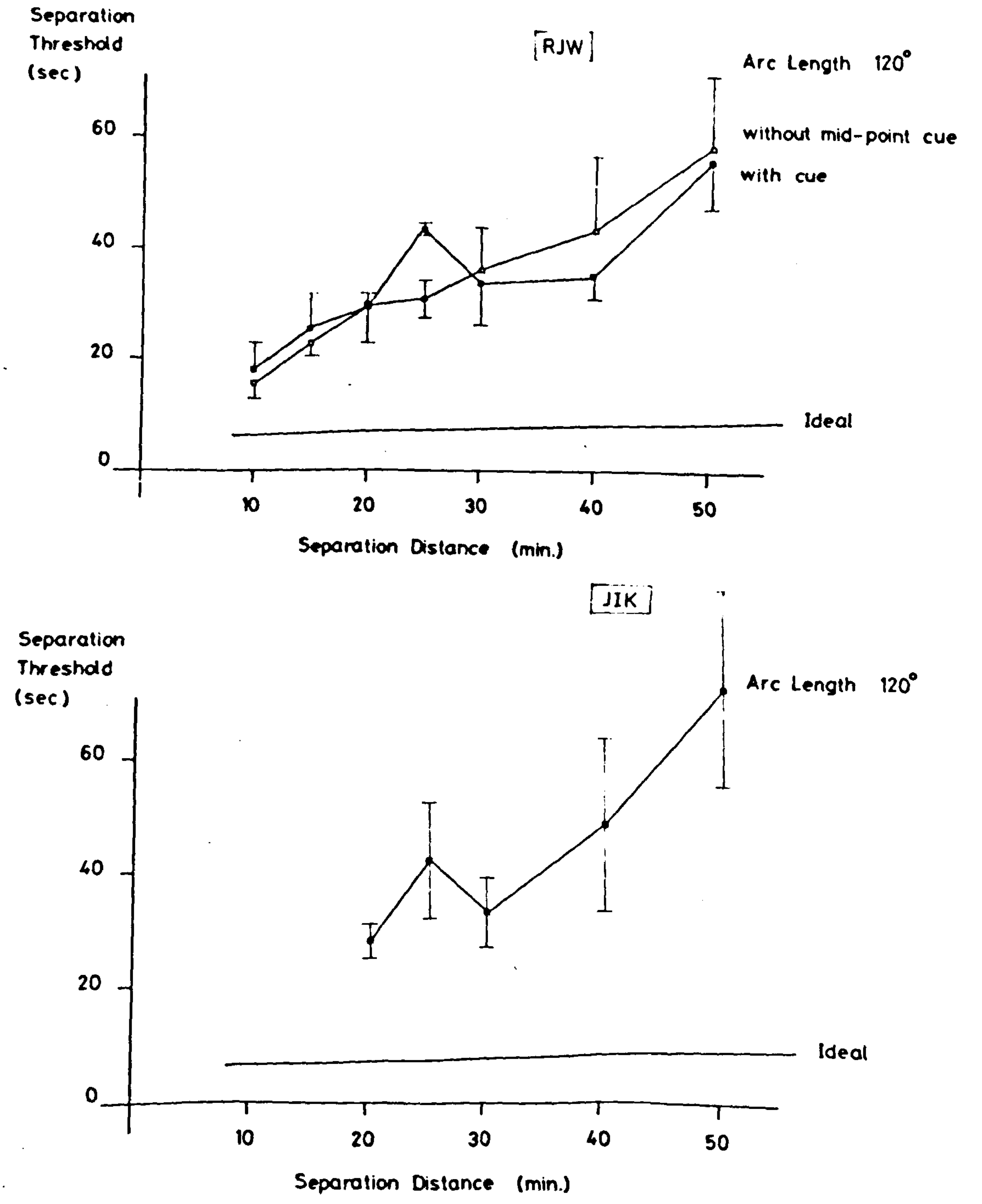


Fig. 3.4 Separation threshold as a function of reference separation.

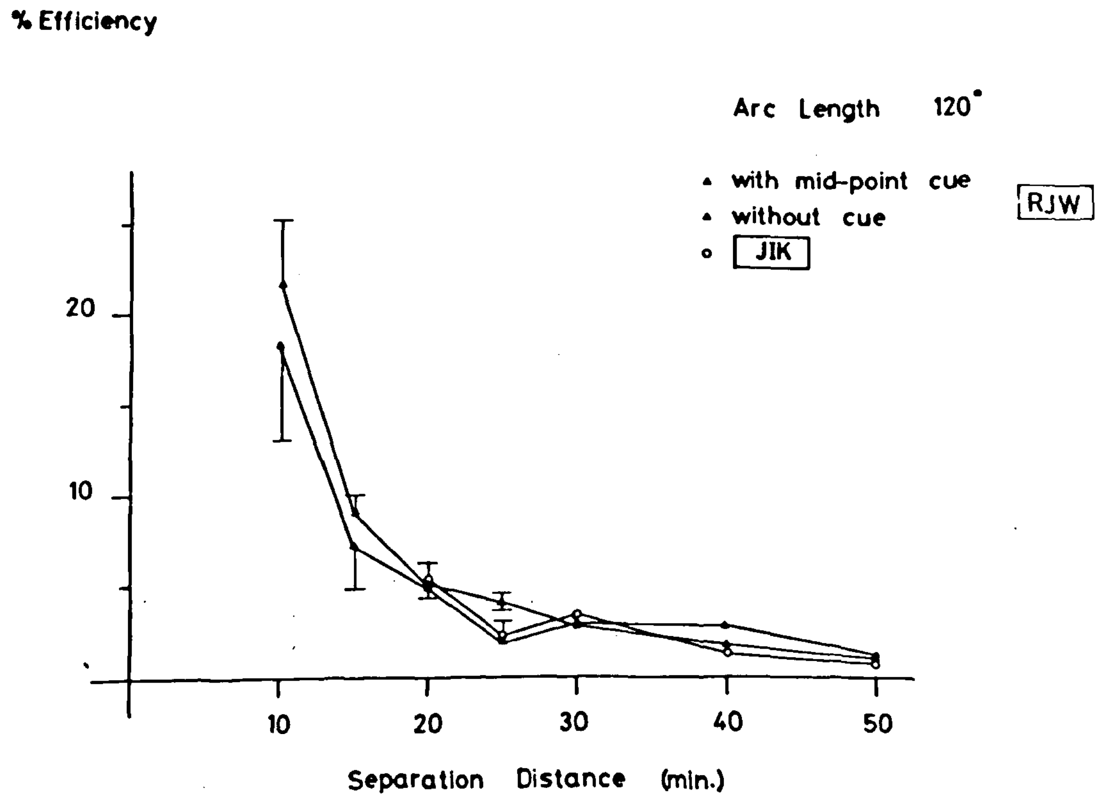


Fig. 3.5 Efficiency for distance judgement, as a function of reference separation. Two subjects.

DISCUSSION

Performance has been measured for a complex task, involving both a shape judgement and a position judgement. The task consists of three operations, which are presumably performed at different efficiencies by the subject. The three operations are as follows : firstly, the curvature must be determined for reference purposes; then the diamèter must be calculated; and lastly, the distance between the stimuli must be compared with this reference diameter.
The two distances to be compared are therefore subject to different types of processing error. In the ideal processor, judgement of the reference diametèr is subject to a much larger error variance, than the second direct distance judgement.

Consideration of the results suggests that this is not true for the subject. The thresholds obtained for both subjects are very close to those for comparable stimulus sizes and separations reported by Andrews and Miller (1978). Since the task that they employed did not include the curvature judgement, the ideal processor makes only a small error variance, and the efficiencies are therefore correspondingly lower.
The efficiencies measured in the present experiment are an order of magnitude higher than those from the simpler task, but are still much lower than those for the basic shape discrimination task of the previous experiment. Therefore it follows that the limiting factor is still the position judgement for the subject; the efficiencies are too low to suggest that the subject ia able to perform a global shape judgement, to by-pass the low efficiency position judgement.

The present data suggest that the low efficiency of performance is due to the nature of the stimulus array (ie. the fact that it consists of two contours, to be judged together, but widely separate in space). The same may apply to the results of Andrews and Miller (1978).

Conclusions about the processing of shape may be unwise from this present data : it is possible that the subjects were using a highly efficient, but technically invalid, strategy to assess the reference diameter. The subjects may not have been making a true comparison between diameter (implied) and distance (observed), but may have been making a comparison between diameter (guessed, and therefore presumably invariant, although subject to a constant error) and distance (observed). The constant errors obtained were large, supporting this possibility.

CONCLUSIONS : TWO DIFFERENT SPATIAL TASKS COMPARED FOR TWO DIFFERENT STIMULI.

What neural processes are performed on the representation of the retinal image ? In what order are they performed ?

It was suggested, in the introduction to this chapter, that the answers to questions such as these could be sought psychophysically by measuring the efficiencies with which the visual system can be used to perform different discriminations on a variety of different stimuli. This chapter has set out to extend the results of Andrews (Andrews, Butcher and Buckley, 1973; Andrews and Miller, 1978) for two differing psychophysical tasks, to a second class of stimulus. It was hoped that the use of curved contours, in replacement of the straight contours used by Andrews, would add further understanding of the neural processes involved.

The two tasks, shape judgement and position judgement, are useful, since they require that the two distinct mathematical operations of differentiation and integration be achieved by analogous processes in the visual system. The results of Andrews suggest that the two tasks use distinct neural processes, when the subject stimulus is a straight line.

Measurement of the performance of the two tasks using curved line stimuli was motivated by the expectations that shape discriminations might be adversely affected by the curvature of the stimulus, but that position discriminations might be improved by curvature of the stimulus (which could imply a shape judgement).

If these expectations had been upheld, the constraints on the bounds of 'shape' and 'position' judgements would have been made more explicit. In practice, neither expectation was upheld. The shape judgement is equally efficient for straight and curved lines. It is also clear that distance discrimination is not facilitated when the subject has the option of interpreting the task as shape judgement.

As an exploratory exercise, this study has been successful in identifying the most interesting problems. These concern the concept of shape, and its judgement.

When the visual system is able to perform an analysis of shape, it apparently processes curved lines no less directly than straight lines. However, it seems that there are situations where an analysis of shape would be mathematically appropriate, but the visual system is unable to perform one.

The concept of collinearity-failure detection and discrimination is now seen to be inadequate as a summary or collective description of all high efficiency shape judgements, although how far it must be modified or extended is not clear. This question will be considered more fully in the following chapters, after a more thorough assessment of the effects of stimulus curvature and size on performance of curvature discrimination has been made.

CHAPTER 4. : PRELIMINARY INVESTIGATIONS OF THE EFFECTS OF STIMULUS CURVATURE AND SIZE ON CURVATURE DISCRIMINATION.

The experiments of Chapter 3 compared the efficiency of judgements of shape and position for straight lines and curved lines. It was discovered that the shape of the stimulus made little difference to performance of these two distinct tasks. In the case of the shape task, there was no evidence that the curved stimulus is processed by the visual system in a way that is less direct than that employed for a straight line stimulus. In the case of the position task, there was no evidence that a layout of the stimuli, which could allow the task to be interpreted as a shape discrimination, improved performance.

These results are interpreted as indicating that the concept of collinearity-failure detection, as proposed by Andrews, Butcher and Buckley (1973), is not sufficient to describe the group of high efficiency shape discrimination tasks.
The concept was introduced to describe collectively the tasks of vernier resolution, chevron discrimination, and curvature discrimination. In each case, the decision reference was an imaginary straight line. Whilst the concept of collinearity-failure detection is too specific, a general concept of shape discrimination is too broad.

In order to determine what modifications have to be made to the concept of collinearity-failure detection, it would be useful to discover the limits of stimulus curvature and size, within which the task of curvature discrimination may be performed at a high level of efficiency.

EXPERIMENT 3. : THE EFFECT OF STIMULUS CURVATURE ON THE DISCRIMINATION OF CURVATURE.

It has been shown that curvature discrimination is performed at almost the same high level of efficiency for straight lines and lines of 0.05 rad/min. arc curvature and length 20 min. arc. This finding suggests that an extension to the concept of collinearity-failure detection is required. If this concept is to be revised, it is important to know the range of stimulus curvatures over which high efficiency curvature discrimination can be performed.
With this aim, the following experiment was carried out to measure the efficiency of curvature discrimination as a function of stimulus curvature.

It is important to avoid confounding the effects of stimulus size, and those of stimulus curvature, and so the stimulus size must be kept constant. This creates a methodological problem, since it is not clear what the appropriate measure of stimulus size might be. As the curvature of a line is changed, so are a number of potential size measures: thus there is no one obvious candidate. Two such measures of stimulus size will be considered: one experimental condition will be concerned with measuring discrimination of curvature in stimuli with a fixed line length of 20 min. arc, as a function of stimulus curvature; the other condition will measure the same function using stimuli with a fixed chord length of 20 min. arc. The differences between the stimuli in these two cases are very small: at the extreme curvature of 0.08 rad/min. arc, the difference in lengths is only 3.18 min. arc.

METHODS

The computer controlled Method of Constant Stimuli, as described in Chapter 2, was used.

The stimulus array consisted of a fixation spot, a comparison stimulus of the curvature to be tested, and a test stimulus of variable curvature, arranged in the standard configuration.
The comparison stimulus was placed below the fixation spot, so that the top of the curve was 2.5 min. arc beneath the spot. The test stimulus was placed above the fixation spot, so that the mid-point of its imaginary chord was 2.5 min. arc above the spot. Both stimuli were curved upwards.
The following values of curvature were tested :
0.0286, 0.0333, 0.04, 0.05, 0.0667, 0.08 rad/min. arc.
The test stimulus was chosen from a series varying in curvature, centred in curvature at the same curvature as the comparison stimulus.
Two conditions of stimulus size were used. One condition used a fixed line length of 20 min. arc, the other used a fixed chord length of 20 min. arc. These lengths were chosen since they were thought to be well within the limits of length for high efficiency curvature discrimination, but beyond the limiting length for high efficiency slope discrimination, as suggested by the data of Andrews et al.(1973).
The stimulus array was displayed after a pre-stimulus delay of three seconds, during which the fixation spot alone was displayed. The stimulus display lasted for two seconds.

Two subjects were tested in each condition, one (RJW) was common to both. The subjects had normal or corrected-to-normal vision. Subjects were instructed to fixate the central spot at all times, and after presentation of the stimulus, to decide which stimulus was more curved, top or bottom.

RESULTS

The two conditions will be considered separately.

i). Fixed Line Length.

The thresholds for curvature discrimination as a function of stimulus curvature at a fixed line length are shown in Fig. 4.1. The ideal thresholds are also shown. Ideal thresholds rise slightly, since net eccentricity of the stimulus increases with increasing curvature.

Measured thresholds also rise, but rather more steeply. This is particularly true of subject JIK.

Efficiencies for the task are shown in Fig. 4.2. The basic trend is a small drop in efficiency as curvature increases. The drop is rather larger for subject JIK. Subject RJW shows a peak in efficiency at a stimulus curvature of 0.0333 rad/min. arc. Peak efficiency for subject JIK is probably at a slightly larger curvature.

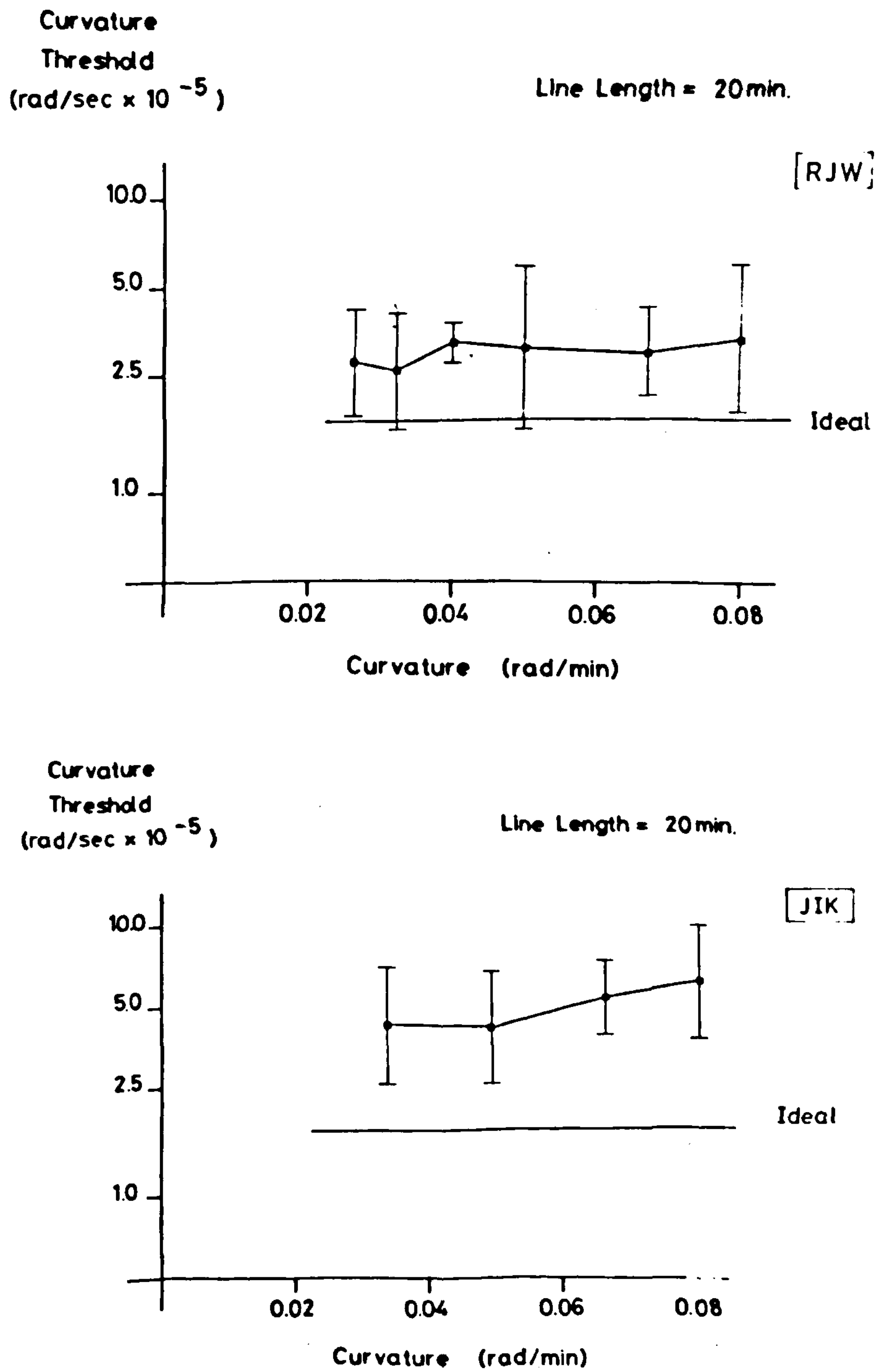


Fig. 4.1 Threshold for curvature discrimination as a function of stimulus curvature, for a fixed length of 20 min. arc.

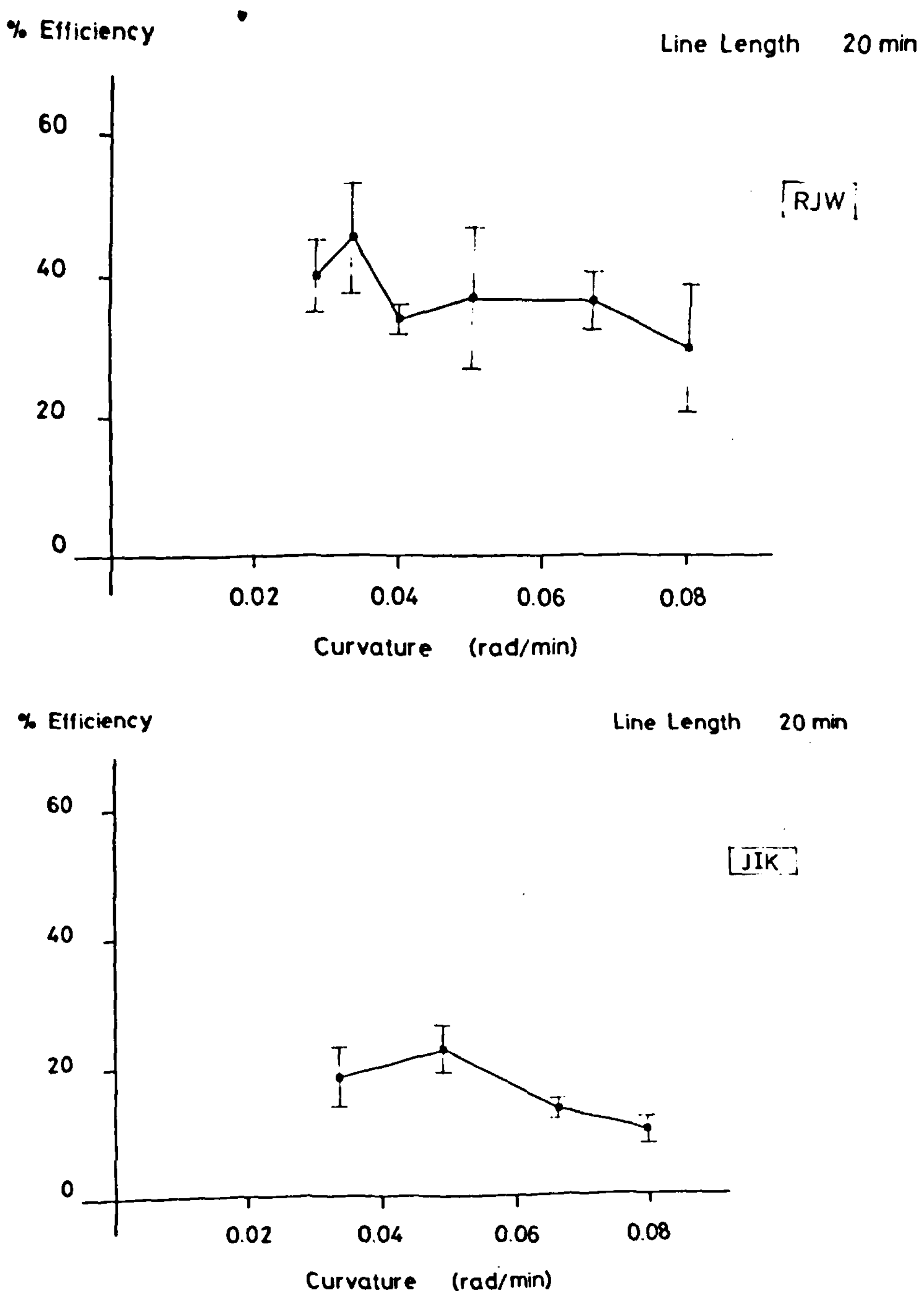


Fig. 4.2 Efficiency for curvature discrimination as a function of stimulus curvature, for a fixed line length of 20 min. arc.

ii). Fixed Chord Length.

Thresholds for curvature discrimination as a function of stimulus curvature at a fixed chord length are shown in Fig. 4.3. Ideal thresholds are also shown. The ideal threshold falls with increasing stimulus curvature, since the lines are longer, and the extra length corresponds to extra information.

The subjects do not seem able to use this extra information efficiently. This is particularly true of subject IEB.

Efficiencies for the same task are shown in Fig. 4.4. Efficiency for curvature discrimination remains high and constant for curvatures up to 0.04 rad/min. arc, but beyond this curvature, falls with increasing curvature. The fall in efficiency is more steep for subject IEB than for RJW.

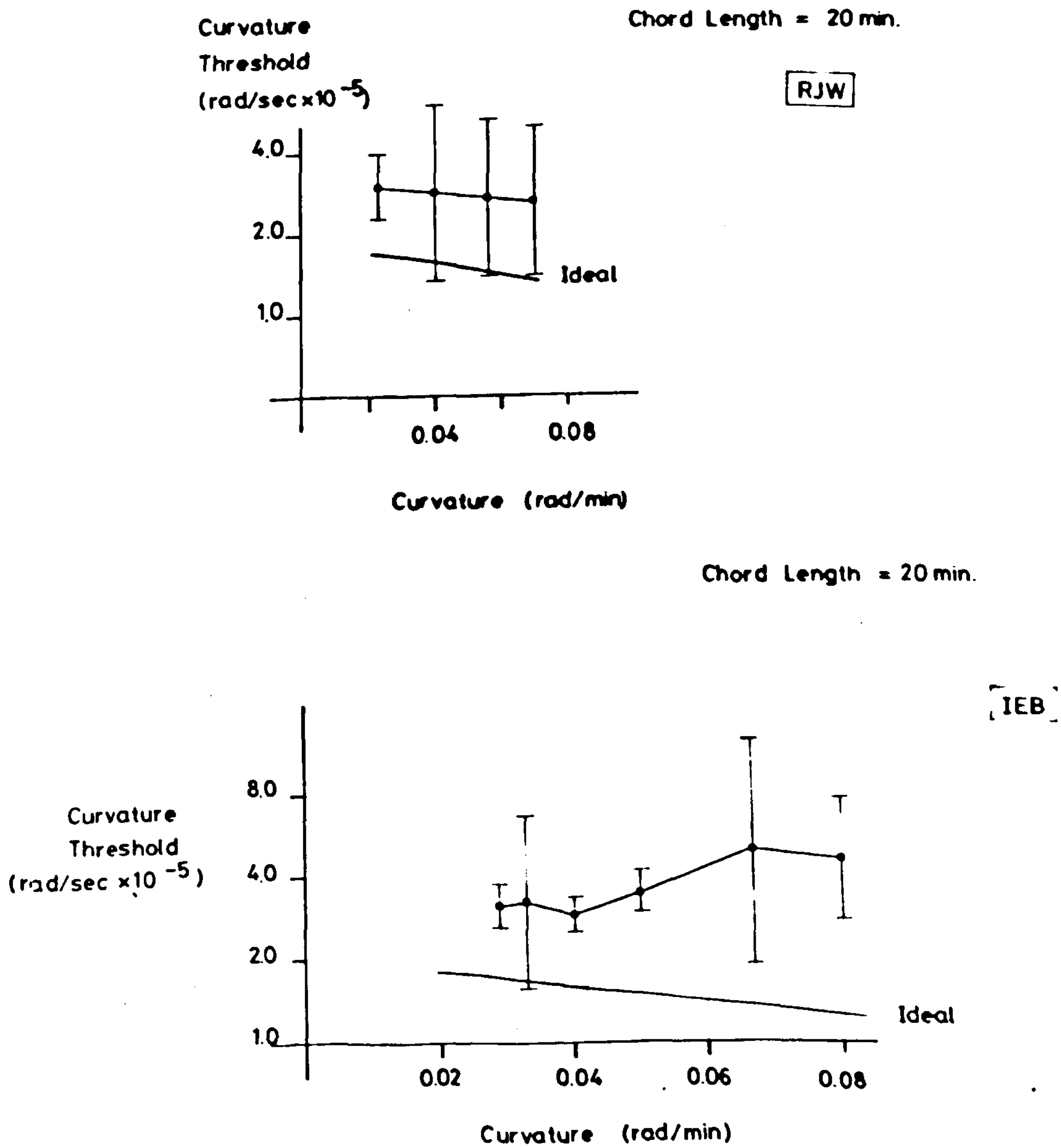
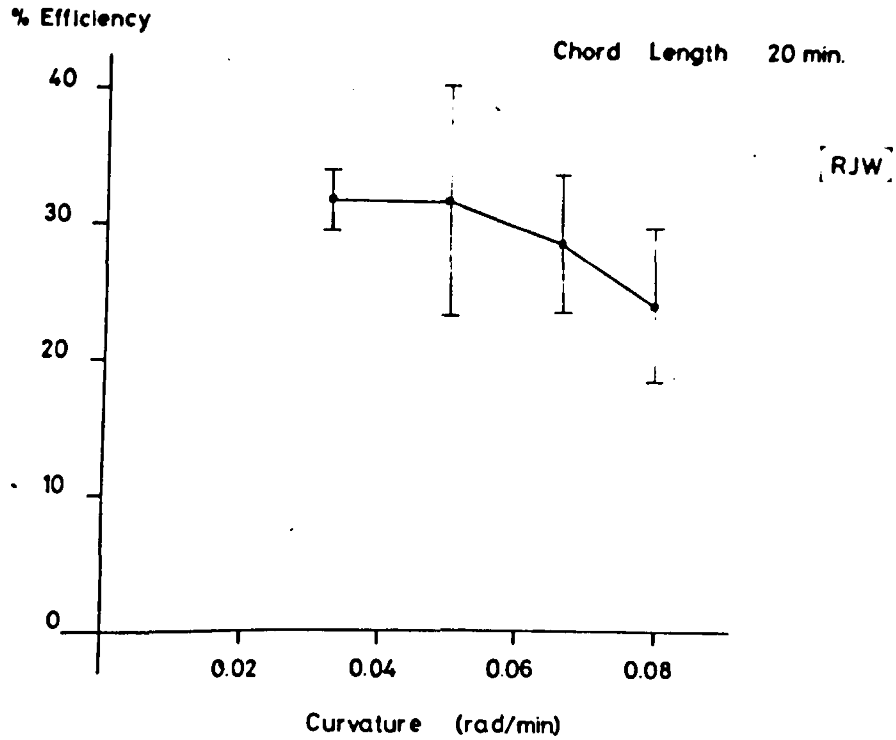


Fig. 4.3 Threshold for curvature discrimination as a function of stimulus curvature, for a fixed chord length of 20 min. arc.



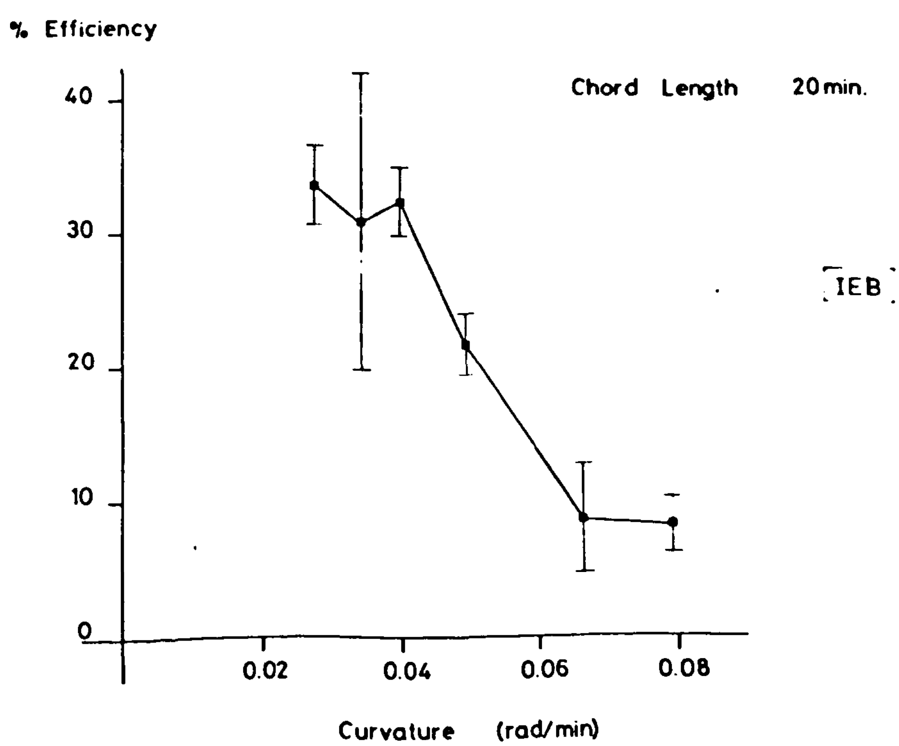


Fig. 4.4 Efficiency for curvature discrimination, as a function of stimulus curvature, for a fixed chord length of 20 min. arc.

DISCUSSION

This study aimed to discover the range of curvatures over which curvature discrimination can be performed at high efficiency. Two conditions of stimulus size were used, since it was not possible to decide a priori which parameter would be appropriate. Testing both the conditions of constant line length and constant chord length proves to have been useful.

The general result obtained is that the efficiency for curvature discrimination is high for stimulus curvatures up to a value between 0.0333 and 0.04 rad/min. arc. Efficiency falls slightly with increased stimulus curvature beyond this peak curvature. Efficiency falls more steeply in the constant chord condition, than in the constant line length condition. This suggests that the length of the lines is very important, at least in the neighbourhood of stimulus lengths of 20 min. arc.

The less practised subjects, JIK and IEB, showed lower efficiencies in general, and the effects of increasing stimulus curvature were more pronounced.

EXPERIMENT 4. : THE EFFECT OF STIMULUS LENGTH ON THE DISCRIMINATION OF CURVATURE AT A FIXED STIMULUS CURVATURE.

The previous experiment has demonstrated that there is a strong effect of stimulus line length on the discrimination, at least for lengths close to 20 min. arc.

Andrews, Butcher and Buckley (1973) measured efficiency for curvature discrimination as a function of line length for straight lines. Their data show that the curvature of nearly straight lines may be discriminated with a high efficiency for lines that are less than 30 min. arc in length. Longer lines are subject to a lower efficiency for curvature discrimination.

The previous study, on the other hand, found that for curvatures greater than 0.04 rad/min. arc, the difference in efficiency for a stimulus of line length 20 min. arc, and a stimulus of chord length 20 min. arc is relatively large (even in the extreme curvature of 0.08 rad/min. arc, the physical difference between the two stimuli is only 3.18 min. arc).

It is clear that the findings of Andrews et al. (1973) for the effect of stimulus length on curvature discrimination in straight lines, are not general far all curvatures.

The present study will attempt to measure the effect of stimulus length on efficiency for curvature discrimination at a fixed curvature of 0.05 rad/min. arc. This stimulus curvature is just beyond the high efficiency region, defined by the previous results, and should show the effect of stimulus length clearly.

It should be noted that two other previous studies have been made of the effects of stimulus size on the discrimination of curvature for nearly straight lines.

Della Valle, Andrews, and Ross (1956) present data for the effect of stimulus size on curvature detection, and conclude 'From the available estimates of sensitivity it is clear that the perception of curvilinearity ... is superior for greater chord lengths.' So what ? Ogilvie and Daicar (1967) extend the argument; after presenting some data of their own, they conclude that one geometric measure of acuity for curvature is better than another. Their argument is nor clear. Neither of these two studies provide any insight into potential mechanisms of information processing in the visual system.

METHODS

The computer controlled Method of Constant Stimuli, as described in Chapter 2, was used.

The stimulus array consisted of a fixation spot, a comparison stimulus, and a test stimulus, in the standard configuration.
The comparison stimulus was placed below the fixation spot, so that the apex of the arc was 2.5 min. arc beneath the fixation spot. The test stimulus was placed 2.5 min. arc above the fixation spot (measured to the centre of the imaginary chord).
The comparison stimulus had a curvature of 0.05 rad/min. arc. The test stimulus was drawn from a series vaying in curvature, and centred at 0.05 rad/min. arc. All stimuli were curved upwards.
The following chord lengths were tested :
7.5, 10, 12.5, 15, 20, 25, 30, 35 min. arc.

The stimulus array was displayed for 2 seconds, after a pre-stimulus delay of 3 seconds, during which the fixation spot alone was displayed.

Two subjects were used. Both had normal vision. Both had taken part previously in the experiment measuring performance of curvature discrimination as a function of stimulus curvature at a fixed line length, and so direct comparison of the results is possible.
The subjects were instructed to fixate the spot at all times, and after presentation of the stimulus array, to decide which line, top or bottom, was more curved.

RESULTS

Thresholds for curvature discrimination as a function of stimulus chord length are shown in Fig. 4.5. Ideal thresholds are also shown. The ideal threshold drops rapidly as stimulus size increases, since the curvature information in a line is proportional to its length raised to the fourth power.

Thresholds for curvature discrimination drop for both subjects. The fall is more steep for subject RJW than for JIK. In each case, the fall is not as steep as that for the ideal thresholds. The fall in threshold for the subjects is quite steep up to a chord length of 20 min. arc, then it becomes less steep.

Efficiencies for the same task are shown in Fig. 4.6. Efficiency is high for chord lengths of less than between 10 and 15 min. arc. For subsequent increases in chord length beyond this length, efficiency falls. The rate of fall is steeper for JIK than for RJW. The rate of fall of efficiency with increasing chord length slows at chord lengths of 20 to 25 min. arc and greater.

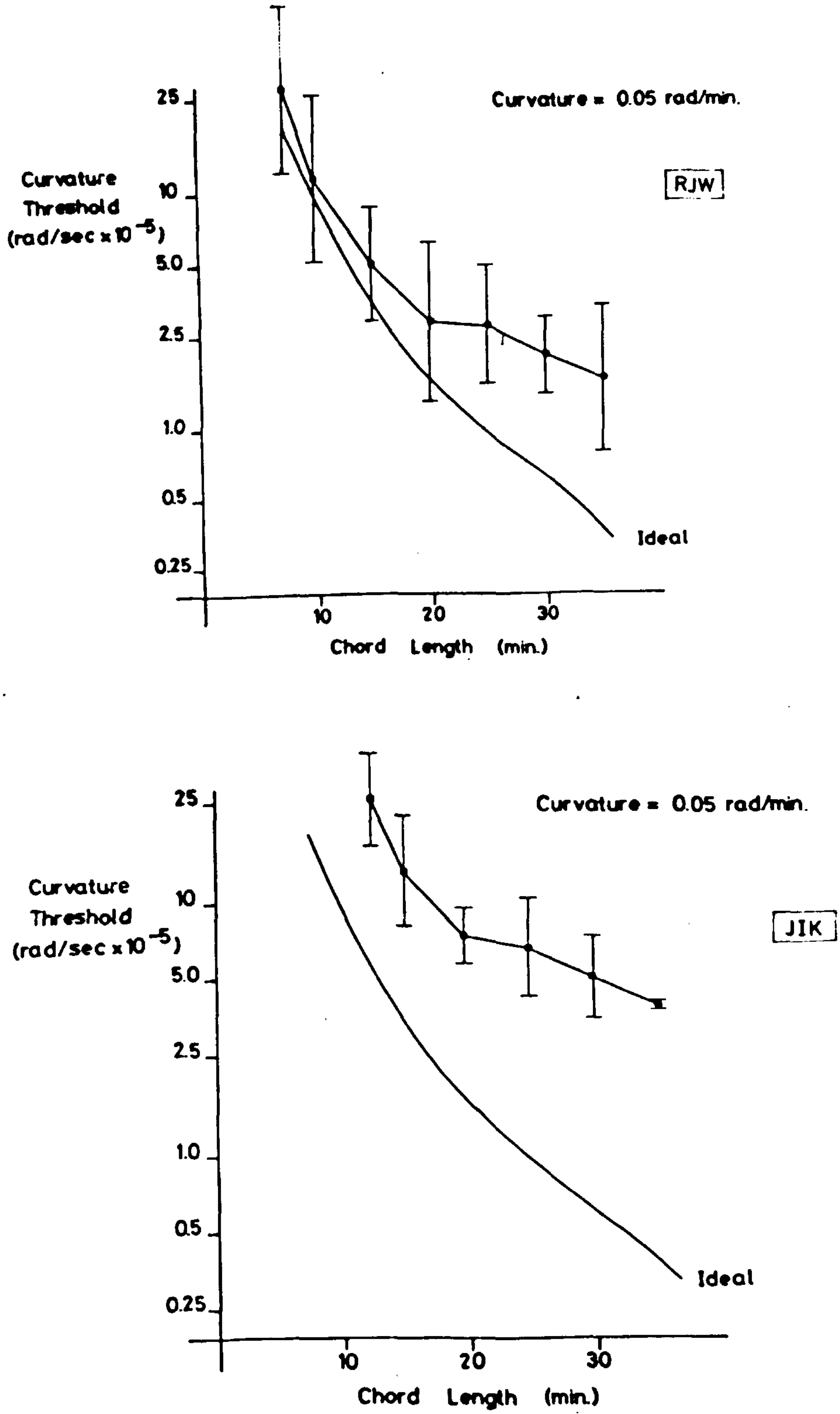
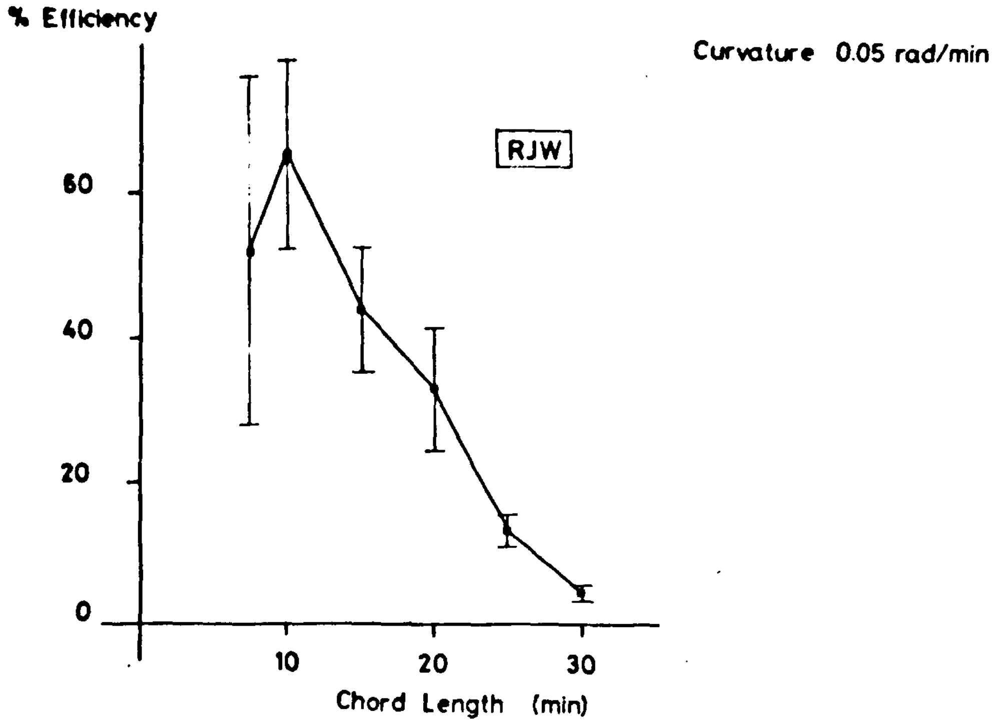


Fig. 4.5 Threshold for curvature discrimination, as a function of stimulus chord length, at a stimulus curvature of 0.05 rad/min.



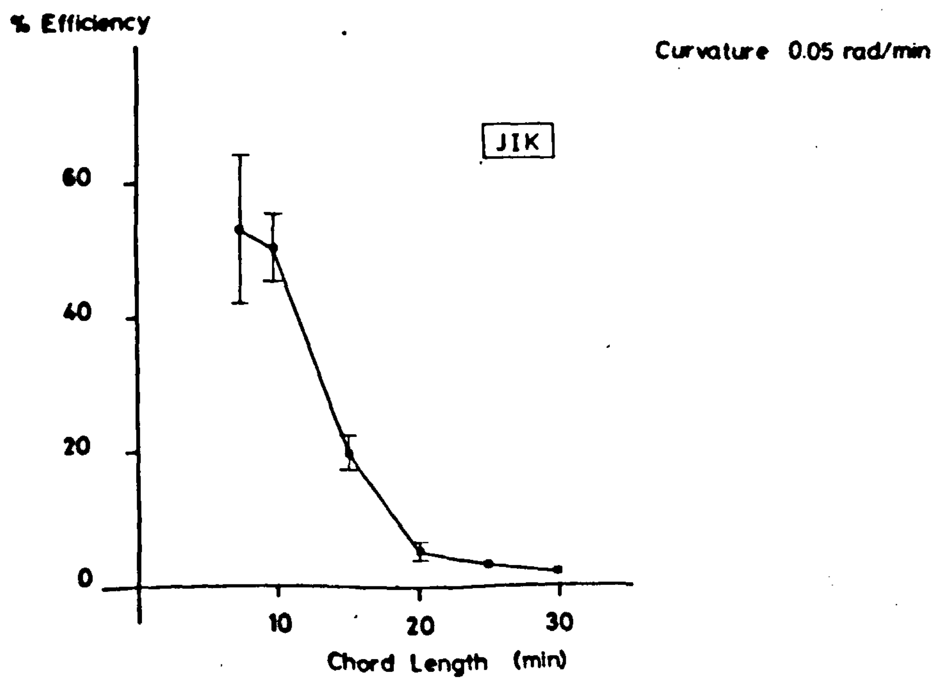


Fig. 4.6 Efficiency for curvature discrimination as a function of stimulus chord length, at a curvature of 0.05 rad/min. arc.

DISCUSSION

This study completes a preliminary investigation of efficiency for curvature discrimination as a function of stimulus curvature and line length.

The present experiment shows that there is a strong dependence of efficiency for curvature discrimination on stimulus length. Comparison with the data of Andrews et al. (1973) is particularly instructive. They found the length of 30 min. arc to be critical for the high efficiency curvature discrimination of straight lines. The present results show that the length of 15 min. arc is critical for lines with a curvature of 0.05 rad/min. arc.
This difference between the two sets of results leads to several questions. Is the critical length for high efficiency curvature discrimination, a function of stimulus curvature ? Alternatively, are curved lines and straight lines handled by two different types of process, each with its own critical length ?
The latter possibility is interesting, since Andrews et al. (1973) present data which suggests that there is a second type of process for orientation discrimination, which has a critical length of 10 min. arc.

There are no direct conclusions from this experiment, and an exhaustive study of the joint effects of stimulus curvature and length on the efficiency for curvature discrimination is required.

CONCLUSIONS : PRELIMINARY INVESTIGATIONS OF CURVATURE DISCRIMINATION.

Two preliminary experiments have been completed, measuring the effects of stimulus curvature and stimulus length separately on efficiency for curvature discrimination. The results of this exploration of these effects on the task of curvature discrimination suggest that there are some interactions between stimulus curvature and stimulus line length.

It now seems necessary to undertake a large scale investigation of the two domains of stimulus curvature and stimulus length, in order to gain an understanding of the processes underlying these interactions.

CHAPTER 5. : A DETAILED INVESTIGATION OF THE JOINT EFFECTS OF STIMULUS CURVATURE AND LINE LENGTH ON CURVATURE DISCRIMINATION.

The results of Chapter 3 have shown that curved lines can be processed as efficiently as straight lines for two broadly different tasks, by the visual system. It was pointed out that this appears to necessitate a modification to the concept of collinearity-failure detection, as proposed by Andrews, Butcher and Buckley (1973) to describe a group of shape tasks, all of which were performed at a similar high efficiency for lines up to 30 min. arc in length.

The experiments described in Chapter 4 sought limits to the range of stimulus curvature and size within which a similar high efficiency process for curvature discrimination is available.
Two basic results were obtained. For lines of length 20 min. arc, stimulus curvatures up to about 0.04 rad/min. arc can be processed efficiently. Efficiency falls slightly for larger curvatures.
Line length was found to be critical in this experiment.
For stimuli of curvature 0.05 rad/min. arc, lengths of up to about 15 min. arc are processed at high efficiency. Efficiency is much lower for longer lines. This critical line length of 15 min. arc, is very different from the length of 30 min. arc, found by Andrews et al. (1973) as a limit to the high efficiency process for straight lines.

There is an interaction between stimulus curvature and line length on the efficiency for curvature discrimination. Very little else can be said, and a more detailed study is required.

This chapter will present and discuss the results of a major exploratory study in the two dimensions of stimulus curvature and length. The results will suggest a modification to the concept of collinearity-failure detection. Subsequent chapters will examine the implications of the suggested modification.

EXPERIMENT 5. : THE JOINT EFFECTS OF STIMULUS CURVATURE AND LENGTH ON THE DISCRIMINATION OF CURVATURE.

The major finding of the experiments reported in the previous chapter is that there is a curvature-dependent effect of line length on efficiency for the discrimination of curvature. This observation arises from data that merely suggest the presence of such an effect, without providing any insight into its nature. The present experiment is designed to explore this effect thoroughly, in an attempt to define its nature and bounding parameters.

There are several questions which might be asked about this interaction. Is there a parametric effect of stimulus curvature on the maximum length for high efficiency curvature discrimination ? If so, what is the important parameter ?
Alternatively, is it simply the case that a different process is in operation for curved lines, and that process has a different length tolerance ?
It is presumed from the data of Andrews, Butcher and Buckley (1973), for example, that a different process is responsible for slope comparison, with a length tolerance of 10 min. arc. There might be a process responsible for curvature comparison, using curved lines, with a length tolerance of 15 min. arc. If this is found to be correct, it might be asked : what is the critical curvature that determines when a line is processed by the straight line process, and when by the curved line process ?

These questions will only be answered by a full investigation of the joint effects of stimulus curvature and length over a wide range of stimuli. Once the basic data is obtained, rather more precise questions can be asked and answered.
This experiment will undertake a full and wide-ranging exploration of these joint effects of stimulus curvature and length.

The experimenter faces a problem, when exploring simultaneously two new dimensions. Stimuli have to be chosen to efficiently map out the characteristics of the response surface under study. The experimenter can never know if his choice was sufficient, unless an insufficiency is discovered.
The stimuli chosen for this experiment appear to have only one in sufficiency, which will be corrected in Chapter 7.

METHODS

The computer controlled Method of Constant Stimuli, as described in Chapter 2, was used.

The stimulus array consisted of a fixation spot, a comparison stimulus 2.5 min. arc beneath the spot, and a test stimulus 2.5 min. arc above the spot, in the standard configuration.
The stimuli were varied in two dimensions, curvature and line length. Line length was chosen as the parameter of stimulus size, since this is the most direct measure of information content.
The curvatures tested were 0.00, 0.04, 0.05, 0.0667 rad/min. arc.
The line lengths tested were 10, 15, 20, 25, 30, 35 min. arc.
All combinations of these parameters were tested.

Two subjects were used. One subject (RJW) was tested in all conditions. The other subject (NL) was tested in most conditions. Both subjects had normal vision.
Subjects were instructed to fixate the spot at all times, and after presentation of the stimulus, to decide which stimulus, top or bottom, was curved upwards by the greatest amount.

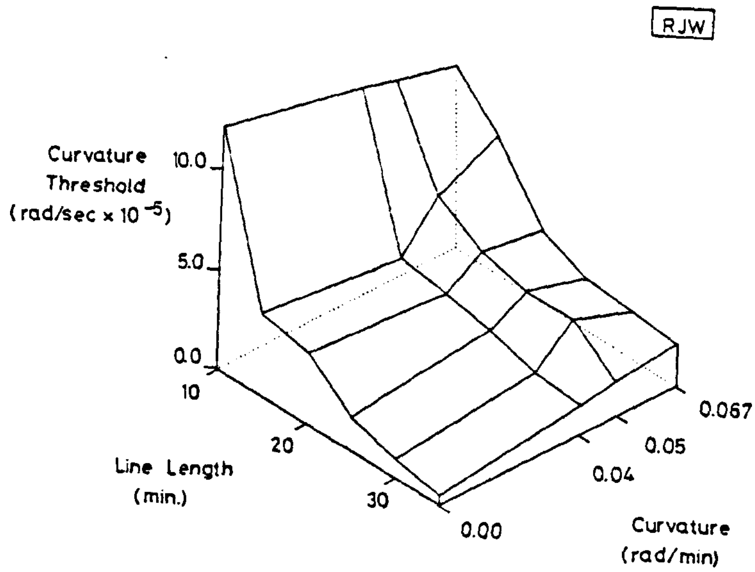
RESULTS

The thresholds for curvature discrimination as a function of stimulus curvature and length are shown in Fig. 5.1. Ideal thresholds for the same task and stimuli are shown in Fig. 5.2.
A number of trends may be discerned in the results.
At short stimulus lengths, the threshold falls with increasing curvature of the stimulus. At long stimulus lengths, the opposite trend is found. Threshold falls more slowly as a function of increasing stimulus length at larger stimulus curvatures, than at smaller stimulus curvatures.
The threshold data for the sero curvature conditions are slightly different from the equivalent data in the results of Andrews et al. (1973). This will be discussed below.

Efficiencies for curvature discrimination as a function of stimulus curvature and length are shown in Fig. 5.3.
The following trends are seen.
At short stimulus lengths, efficiency rises with increasing stimulus curvature.
At long lengths, the opposite is found: efficiency falls with increasing stimulus curvature.
The rate of fall of efficiency as a function of increasing stimulus length, increases as stimulus curvature increases.

Results from the two subjects are in good agreement, except that NL performed at a consistently higher efficiency, especially for the straight lines.

It was noted in the introduction to this experiment, that the range of stimuli chosen for testing was apparently sufficient in all but one respect. The results show that a region of stimulus curvature and length space has been defined and bounded in all but the extreme curvature permissible for the shortest stimulus lengths. This is unfortunate, but will be amended in the data from experiment 9, below.



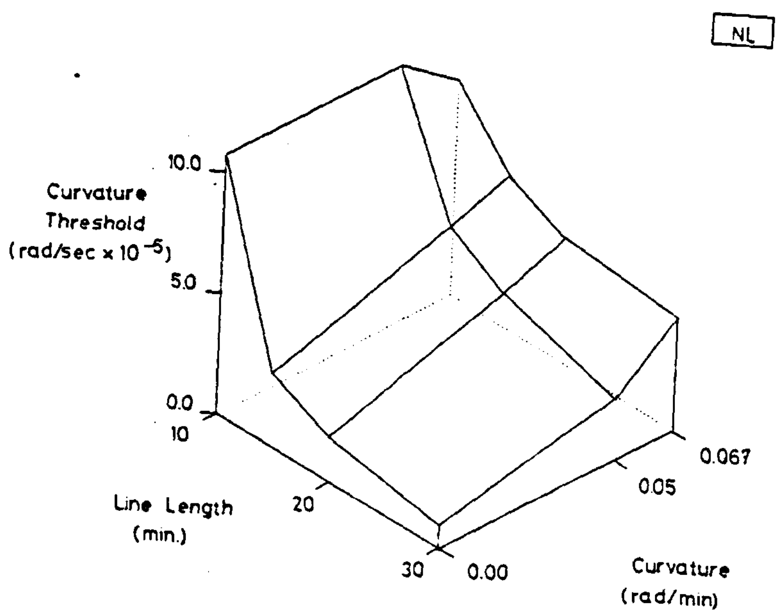


Fig. 5.1 Threshold for curvature discrimination as a function of stimulus curvature and line length.

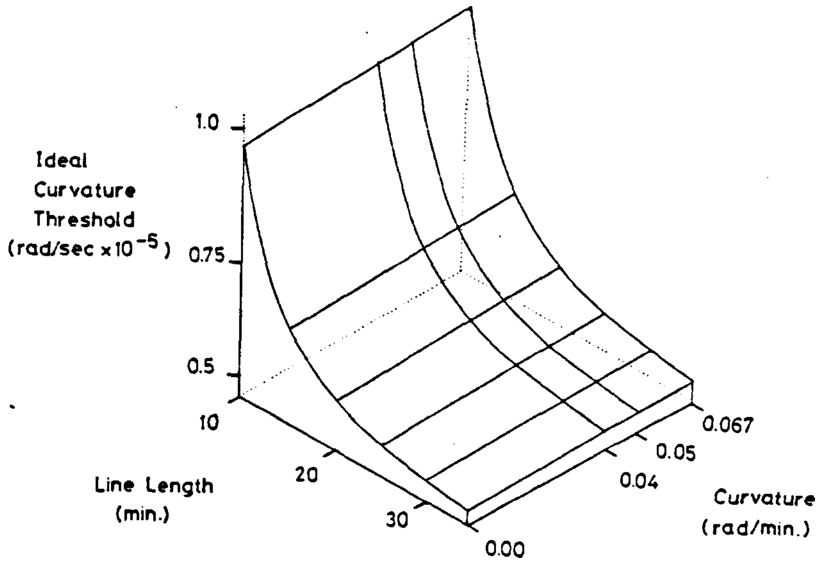
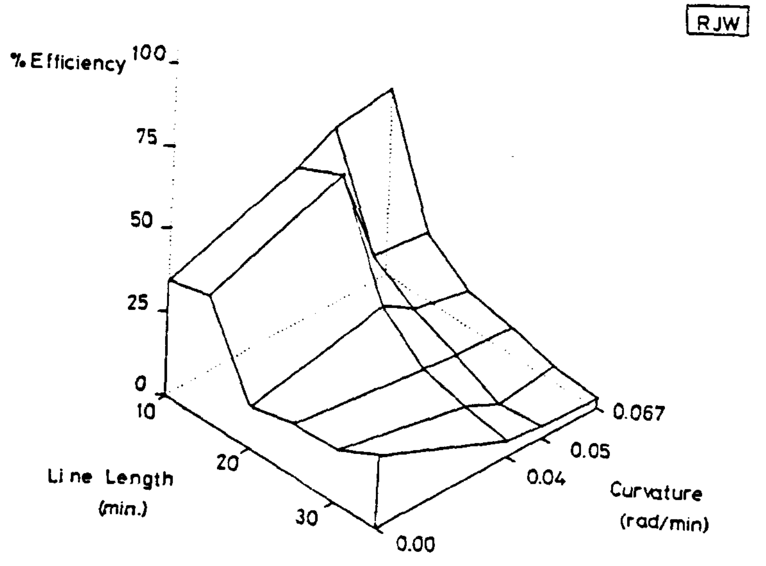


Fig. 5.2 Ideal threshold for curvature discrimination, as a function of stimulus curvature and line length.



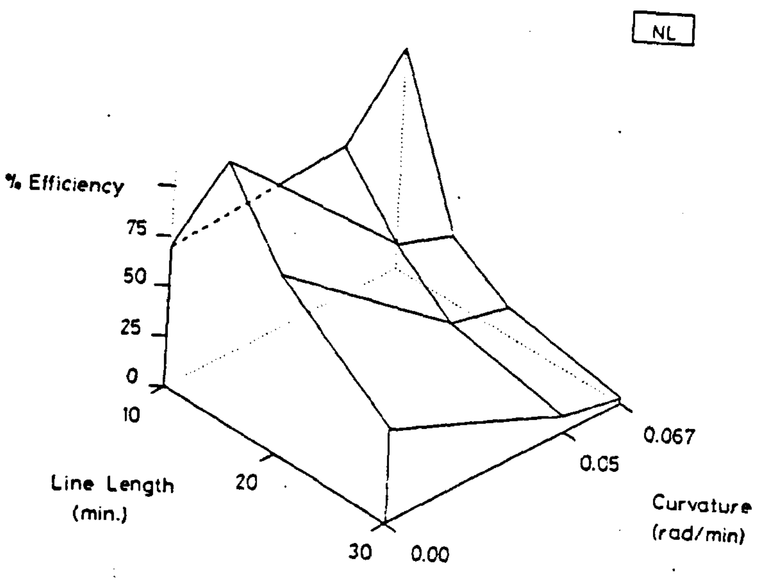


Fig. 5.3 Efficiency for curvature discrimination, as a function of stimulus curvature and line length.

DISCUSSION

There are a number of interesting points to note in the results of this experiment.

The results for the straight line stimuli are not as would be expected. The data of Andrews et al. (1973) show a high efficiency for curvature discrimination up to about 30 min. arc length of lines. In this study, efficiency is high for lines up to about 20 min. arc, and then falls slightly with increasing stimulus length. There is however, one major difference between the two experiments: the present study has a stimulus array consisting of a test stimulus and a comparison stimulus, whereas the study of Andrews et al. (1973) had no comparison stimulus. If the difference between the two sets of results is explained by this, then the possibility that there is some strong interaction between the two stimuli, test and comparison, cannot be ignored. This point will be examined below (p. 159).

The results for the curved lines will now be considered. There are interactions between stimulus curvature and length on the efficiency for curvature discrimination. These interactions can be summarized in three main observed effects, which will be described. These effects will be discussed with reference to the concept of a limiting line length for high efficiency curvature discrimination. This is defined as the greatest line length for a given stimulus curvature for which the subject can discriminate curvature at a high level of efficiency. Limiting curvature is defined similarly for a given stimulus length.

In these terms, a high efficiency region of stimulus curvature and length space may be defined. This would contain the set of stimulus curvature and length combinations that are known to be suitable for the high efficiency curvature discrimination task.
The three observed effects are as follows.

Firstly, it is clear that there is a parametric effect of stimulus curvature on the limiting line length for high efficiency discrimination of curvature. With increasing curvature, the limiting line length decreases: there is a length tolerance cost in processing curved stimuli, which increases as stimulus curvature increases.

Secondly, there is a parametric effect of stimulus curvature on the rate of fall in efficiency as stimulus length increases beyond the limit. The rate of fall in efficiency increases beyond the limit, with the curvature of the stimulus.

Thirdly, there is a rise in efficiency with either stimulus curvature or line length within the region of high efficiency curvature discrimination. This is opposite to the effect of these parameters on stimuli outside the high efficiency region.

Thus, there is a region of the stimulus curvature and length space, within which high efficiency curvature discrimination can be performed. The three observations above concern respectively : the boundary conditions of stimulus curvature and length; the joint effects of stimulus curvature and length beyond the boundary; and the same joint effects within the boundary.

What is the most economical description of these results ? Is there a single stimulus parameter, which can unify the effects of stimulus curvature and length on the efficiency for curvature discrimination ?

Within the boundary of this high efficiency region, efficiency rises as either stimulus curvature or line length increases. Beyond it, efficiency falls as either stimulus curvature or line length increases. The boundary itself is a function of both stimulus curvature and line length.

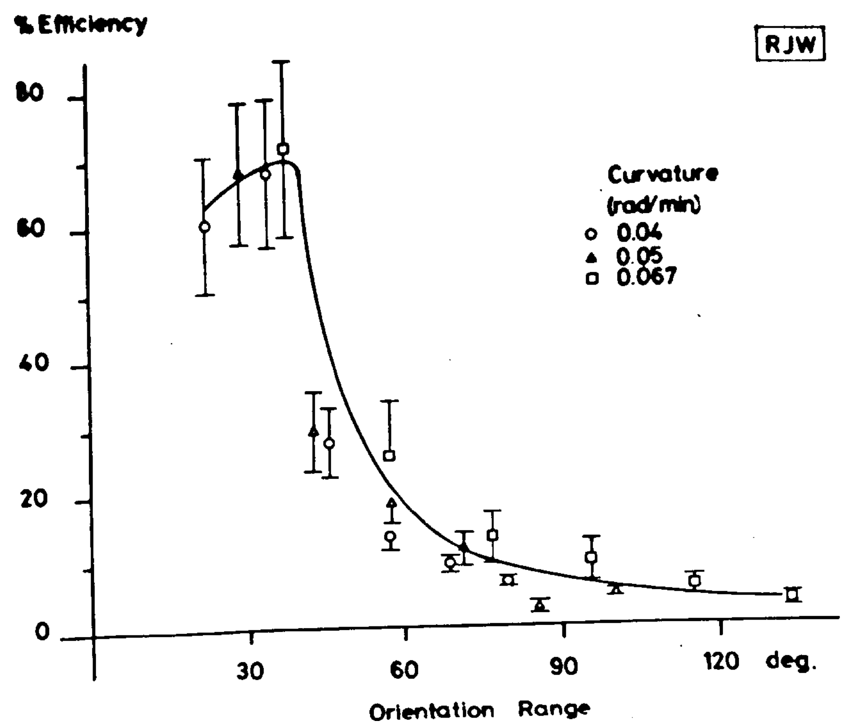
A suitable parameter would be the product of stimulus curvature and line length. Geometrically, this represents the orientation traverse of that particular curvature within the specified line length. It can be described as the orientation range of the stimulus, and corresponds to the difference between the two extreme orientations of the stimulus. A line of curvature 0.05 rad/min. arc and length 20 min. arc has an orientation range of 1 radian, or 57.296 degrees. A straight line has an orientation range of zero, whatever its length.

Fig. 5.4 shows efficiencies for curvature discrimination, plotted as a function of the orientation range of the stimulus. Whilst not perfect, the concept is good is unifying the effects of stimulus curvature and line length on efficiency for curvature discrimination.

The case of straight line stimuli presents a problem, since all such stimuli have the same orientation range of zero. Therefore, either further constraints, on all stimuli, must be introduced to explain the observed performance for straight lines, or such stimuli must be excluded from the scope of the orientation range description on independent grounds.

An example of an additional constraint could involve length limits; an example of independent grounds for excluding straight lines from the orientation range description could be the different effects of practice on performance of curvature discrimination. The discrimination of curvature of straight lines is a task that does not require practice and subjects rarely show any gradual improvement in performance. This is not the case when curved lines are used: there is an initial rapid improvement in performance. There is also a slow, small improvement over the course of several months. The two subjects, RJW and NL had different amounts of experience of curvature discrimination experiments, and this slow learning would account for the apparently superior performance for straight lines in NL, but not in RJW.

It is not clear from the data so far, which course of action is to be prefered, although subsequent experiments will solve this problem.



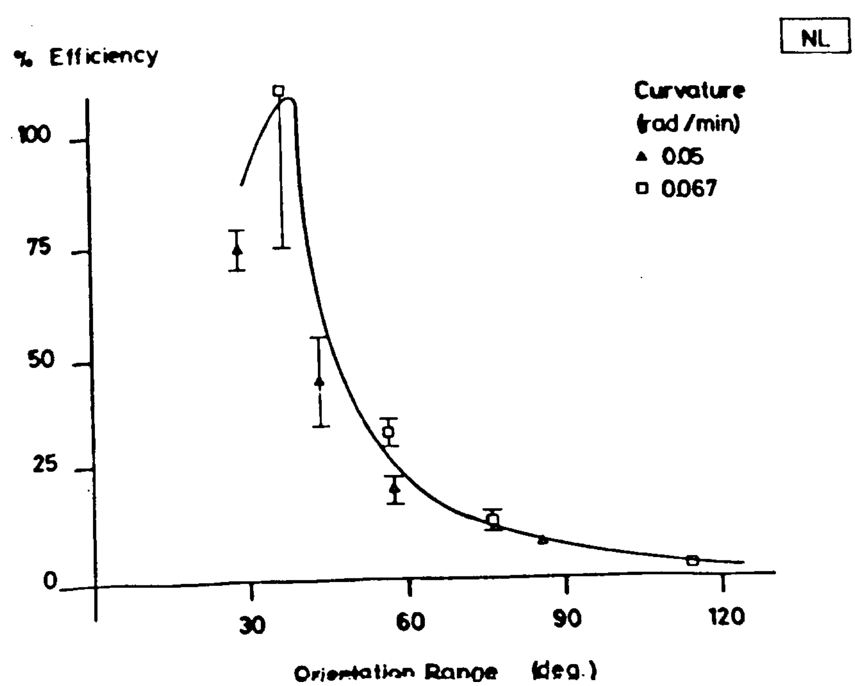


Fig. 5.4 Efficiency for curvature discrimination as a fucntion of stimulus oriehtation range. The line drawn through the data points has no theoretical significance.

CONCLUSIONS

There are a number of conclusions to be drawn from the results of this experiment, but there are rather more questions to be answered, before realistic models can be suggested to account for the data.

It can be concluded that there are parametric effects of stimulus curvature on the critical line length for high efficiency curvature discrimination, and on the rise and fall in efficiency with increasing line length on either side of the critical length. Whilst it is not possible to state exactly which parameter of the stimulus would be the most suitable to describe these effects, several properties of the parameter are clear.
Firstly, it must be a parameter which increases with increasing stimulus curvature at a given line length. This rules out the chord length or horizontal extent of the stimulus as a candidate.
Secondly, it must increase with line length, at a given stimulus curvature.

The simplest parameter, fitting these specifications, is the product of stimulus curvature and line length, described above as the orientation range of the stimulus. This is a concept that would require some elaboration and clarification, if it were to be taken as having any real value in this context.
There are two other parameters that could be considered : the vertical extent of the stimulus; and the area of the segment enclosed by the curve and its (implied) chord.

The former might be suggested by the finding of Westheimer and McKee (1977b) that information for shape judgements (specifically vernier resolution judgements) can be collected from a region that extends for about 2.5 min. arc either side of the stimulus.
The latter parameter, the area of the segment, is the preferred measure of acuity in a study by Ogilvie and Daicar (1967). Their reasons for this preference are obscure, and are based on a coincidence of their measurements of the thresholds for curvature discrimination and slope comparison, when expressed as differences in this parameter. Such a direct comparison of these two sets of results takes no account of the different nature of the information content of the same stimuli with respect to these different tasks, and is therefore invalid. The coincidence is presumably quite fortuitous.

These three candidate parameters each have a corresponding suggested limiting value for high efficiency curvature discrimination. The values are :

orientation range	40.0 degrees
vertical extent	1.5 min. arc
segment area	15.0 $min.^2$ arc.

There is a simple test which can distinguish empirically between the simplest parameter (orientation range) and the other two. This test was carried out, and will now be described.

It was noted above, that the points chosen to sample the space of stimulus curvature and line length were sufficient in all but one respect. The missing point is the limiting curvature for a line length of 10 min. arc, within which the efficiency for curvature discrimination is high. This can now be turned to advantage.

If the line length is kept constant at 10 min. arc, and stimulus curvature is increased, efficiency should rise to some peak value at a critical curvature, and then fall rapidly. The three mooted parameters predict different values for this critical curvature :

orientation range	0.06 to 0.071 rad/min. arc
vertical extent	0.085 to 0.10 rad/min. arc
segment area	0.145 to 0.185 rad/min. arc.

The efficiency for curvature discrimination at a curvature of 0.09 rad/min. arc should distinguish whether the most useful parameter is orientation range or one of the other two. This efficiency was measured for both subjects, and the results were as follows :

Subject	Threshold	PSE	Efficiency
RJW	1.564E-4	0.086	34.412
NL	1.478E-4	0.098	38.528
	(rad/sec.)	(rad/min.)	(%)

These results rule out the parameters of vertical extent of the stimulus and segment area, since the efficiencies obtained are far too low.

Whilst such a test does not prove that the concept of orientation range is the best single parameter to describe the joint effects of stimulus curvature and line length on the efficiency for curvature discrimination, any alternative would have to be very similar.
It seems reasonable to hypothesize that there is a specific limit on the range of orientations that may be efficiently combined to provide curvature information. The limit appears to be about 40 degrees of line slope.

The hypothesis makes a specific prediction, as noted above, concerning the critical curvature for high efficiency performance of a curvature discrimination task involving lines of length 10 min. arc. This prediction will be tested, and the results presented in Chapter 7.

Before proceeding to test this prediction, and to make further investigations of the implications of the concept of stimulus orientation range as a determinant of efficiency for curvature discrimination, there remain two outstanding problems, which will now be solved.

The first problem concerns the possibility of lateral interaction between the two contours in the stimulus array. It has repeatedly been shown that there is some type of lateral interaction between closely spaced contours (eg. Flom, Weymouth and Kahneman, 1963; Sullivan, Oatley and Sutherland, 1972; Westheimer and Hauske, 1975). It was suggested above on p.151 that the difference between the present data for the discrimination of curvature in straight lines, and equivalent data in Andrews et al. (1973) might be due to lateral interaction between the two lines in the stimulus array of the present experiment. The differential effects of such interactions on stimuli of different lengths and curvatures in the present experiment must be considered, since the positions of the two stimuli were fixed relative to each other in a manner dependent on both the stimulus curvature and length.

Could the interactions between stimulus curvature and line length on efficiency for curvature discrimination be due, at least in part, to lateral interactions of this type ?

This possibility will be tested and discounted below in Experiment 6.

The second problem arises from the concept of a limit in the range of orientations that may be used. It is possible that efficiency for curvature discrimination could be determined by a preference for, or a limitation to, the use of certain values of orientation, rather than a certain range of orientations (irrespective of the values of those orientations present within this range).

Strictly, the present data only show that those orientations between +20 and -20 degrees of the horizontal may be efficiently combined for the purposes of curvature discrimination. Other orientations, up to ± 67.5 degrees of the horizontal are not used efficiently. This is equivalent to stating that the oblique orientations are of less information value to the visual system, than those orientations that are close to the horizontal.

This finding could have a similar basis to the well-known oblique effect, which has been shown to exert an effect on vernier judgements (Leibowitz,1955), the three dot alignment task (Ludvigh and McKinnon, 1967), and on curvature discrimination judgements for straight lines (Ogilvie and Daicar, 1967).

An experiment which rules out this possibility, by demonstrating that the relationship between efficiency for curvature discrimination and stimulus orientation range obtains for oblique stimuli, much as it does for horizontal stimuli, will be described below (Experiment 7).

These two experiments will now be described. The general conclusions concerning the effects of stimulus curvature and line length on efficiency for curvature discrimination will then be considered.

EXPERIMENT 6. : THE EFFECT OF SEPARATION DISTANCE ON THE DISCRIMINATION OF CURVATURE IN LINES VARYING IN BOTH CURVATURE AND LINE LENGTH.

The distance separating two curved lines can only be specified in an arbitrary manner, unless the two curves are parallel. Since test and comparison stimuli in the previous experiment were not parallel, the separation had to be specified in a manner which varied with both stimulus curvature and length. The distance quoted, was measured from the apex of the comparison stimulus to the base of the test stimulus, and therefore rperesents a minimum separation. The actual separation between any two corresponding parts of these stimuli is a function of stimulus curvature and length. This variable distance between the two contours could lead to differential neural interactions (the separations are too large for effective optical interaction) between the test and comparison.

The variable distance between test and comparison is too small to act as a cue for the task, since the results require that the separation threshold be of the order of 10 sec. arc, a distance that is almost certainly subliminal (see the results of Experiment 2). However, it has been established that certain shape discrimination tasks are influenced by nearby contours. For example, Westheimer and Hauske (1975) have shown that the presence of flanking contours interferes with performance of a vernier task. This interference is a function of the distance between target and flanks, reaching a maximum at a separation of 3 to 4 min. arc. Westheimer, Shimamura and McKee (1976) have found a similar result for interference with line orientation judgement tasks.

Such interactions could account, at least in part, for the results of the previous experiment, and so in order to examine this possibility, that previous experiment was repeated, using two larger stimulus separations. Fewer points were measured, since the detailed data is not required. If the trends of the previous experimental results are diminished in the larger separations, then there would be a case for suggesting that lateral interactions, related geometrically to the curvature of the stimulus, were influencing those previous experimental results.

The results from this experiment rule out such a possibility, and in addition, suggest that the processes involved in curvature discrimination for straight lines and curved lines might be rather different.

METHODS

The computer controlled Method of Constant Stimuli, as described in Chapter 2, was used.

The stimulus array consisted of a fixation spot, with a comparison stimulus beneath, and a test stimulus above, arranged in the standard configuration.
Two general conditions were used: the test and comparison stimuli could be 10 min. arc or 15 min. arc apart (distances measured from the apex of the comparison stimulus to the base of the test stimulus - see Fig. 5.5). The fixation spot was placed mid-way between the test and comparison stimulus.
The stimulus curvatures tested were : 0.00, 0.05, 0.0667 rad/min. arc.
The line lengths tested were 10, 20, 30 min. arc.
All combinations were tested.
The stimulus array was displayed for 2 seconds, after a 3 seconds delay, during which, the fixation spot alone was displayed.

One subject was used for this experiment (RJW). The subject was instructed to fixate the spot at all times, and after the stimulus presentation, to decide which stimulus, top or bottom, was curved upwards by the greater amount.

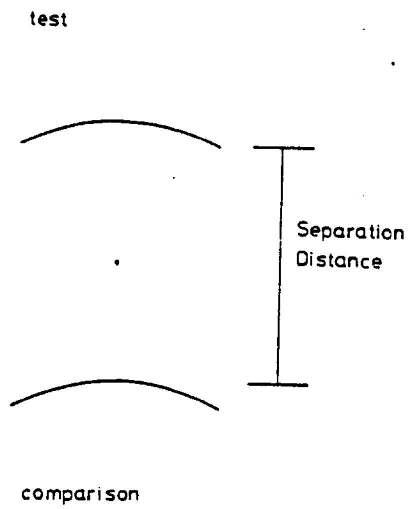


Fig. 5.5 The measure of stimulus separation employed in describing Experiment 6.

RESULTS

Results from the two different separations will be considered separately first, then a comparison between the two sets of results will be made.

Thresholds for curvature discrimination at a separation distance of 10 min. arc are shown if Fig. 5.6. The equivalent efficiencies are shown in Fig. 5.7.
In all cases, threshold falls with increasing line length at a given stimulus curvature.
Thresholds for the straight lines are smaller than the thresholds for curved lines of the same length.
Thresholds for the curved lines follow the same trends as the data of the previous experiment.
Efficiencies for straight lines are correspondingly high. Efficiencies for the curved lines follow the established trend of the previous experiment.

Thresholds for curvature discrimination at a separation distance of 15 min. arc are shown in Fig. 5.8. The corresponding efficiencies are shown in Fig. 5.9.
The data show the same effects as those obtained for the separation distance of 10 min. arc, with one difference. The superiority for discrimination in straight lines is reduced.

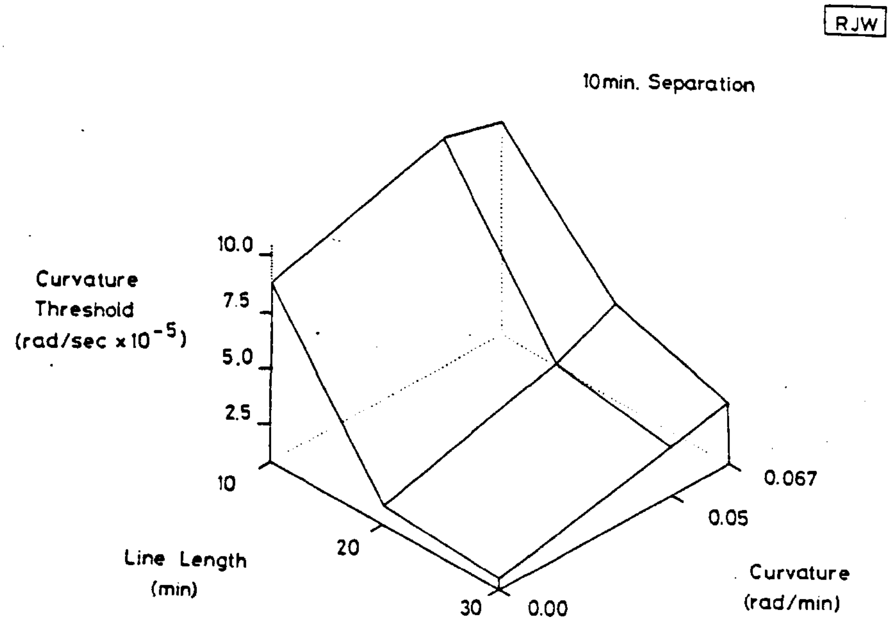


Fig. 5.6 Threshold for curvature discrimination, as a function of stimulus curvature and line length, at a separation of 10 min. arc between test and comparison stimuli.

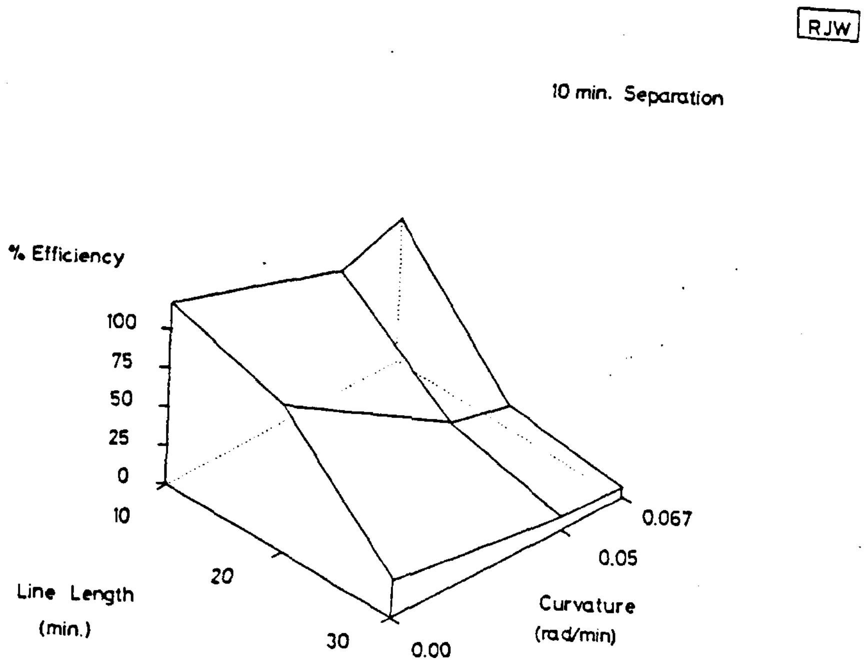


Fig. 5.7 Efficiency for curvature discrimination, as a function of stimulus curvature and line length, at a stimulus separation of 10 min. arc.

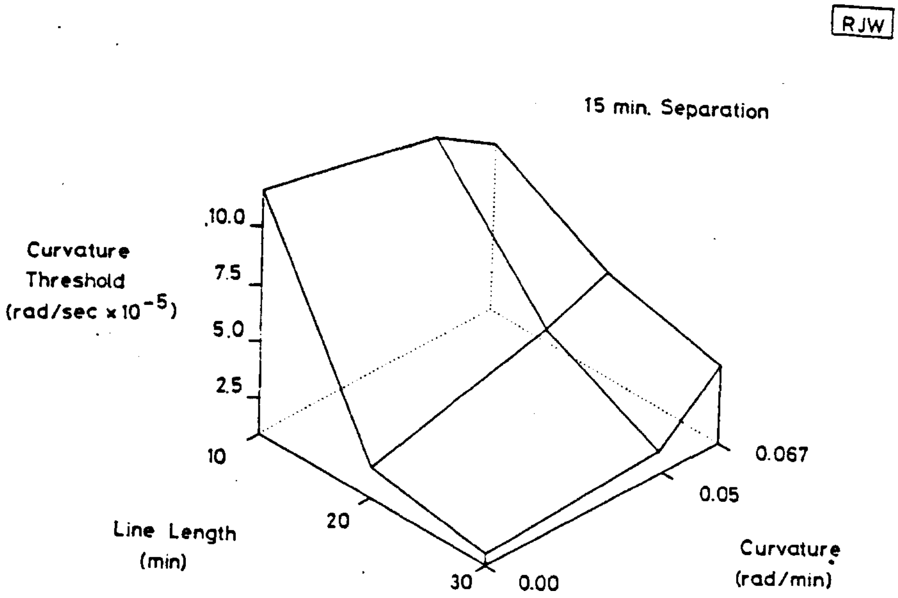


Fig. 5.8 Threshold for curvature discrimination, as a function of stimulus curvature and line length, at a separation of 15 min. arc between test and comparison stimuli.

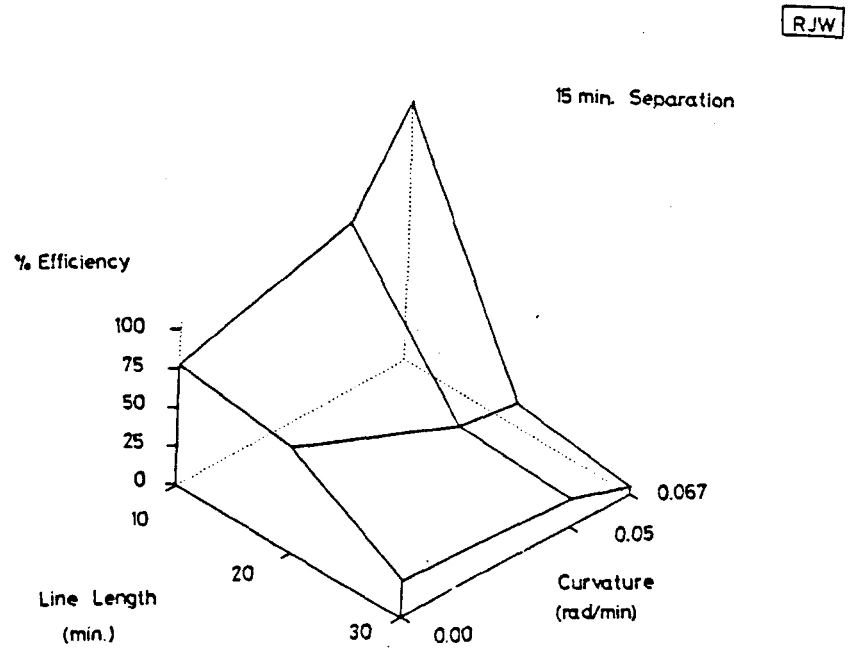


Fig. 5.9 Efficiency for curvature discrimination, as a function of stimulus curvature and line length, at a stimulus separation of 15 min. arc.

Comparing these two sets or results with each other, and with the corresponding data from the previous experiment, shows the following points.

Firstly, efficiencies for straight lines are a non-monotonic function of separation distance (see Fig. 5.10). The intermediate distance of 10 min. arc produces the most efficient performance.

Secondly, the efficiencies for curvature discrimination in curved lines show two basic effects (see Fig. 5.11). Results for lines with an orientation range less than the hypothesized limit of 40 degrees, show a marked increase in efficiency with increased separation between the two contour. It seems that the effects of orientation range are exaggerated at the larger separations. Results for stimuli with an orientation range greater than the hypothesized limit, show no change in efficiency with increasing separation.

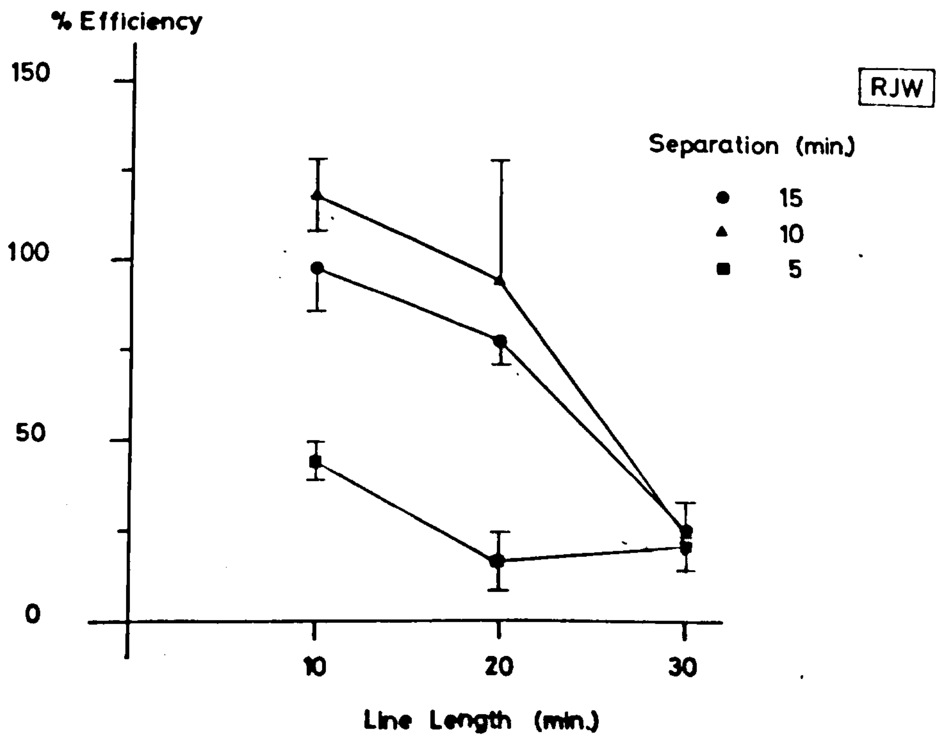


Fig. 5.10 Efficiency for curvature discrimination of straight line stimuli, as a function of stimulus line length and separation.

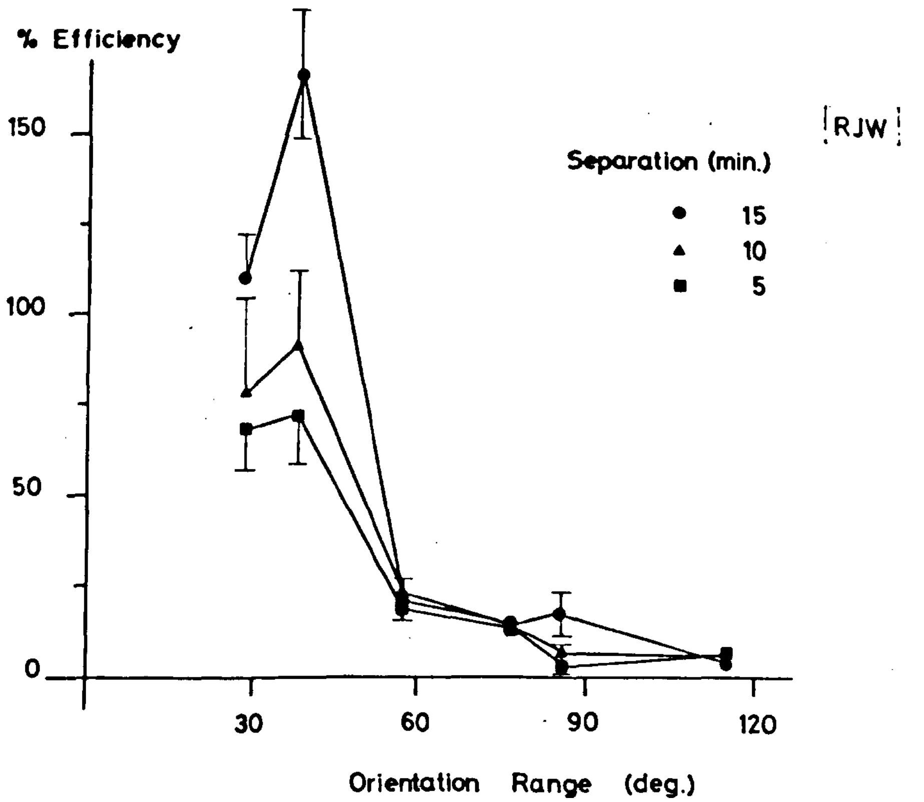


Fig. 5.11 Efficiency for curvature discrimination of curved lines, as a function of stimulus orientation range and separation.

DISCUSSION

This experiment was designed to examine the possibility that some distance related interaction between the test and comparison stimuli could account, at least in part, for the trends in efficiency obtained in the previous experiment. Since such interactions would be expected to diminish in their effect on efficiency for curvature discrimination, if they existed, as stimulus separation increased beyond about 5 min. arc, the trends in efficiency, under examination, should also diminish at the larger separations. The results clearly show that the possibility can be discounted: the opposite effect on the trends in efficiency was obtained at the larger separations.

The results show two basic effects of stimulus separation on efficiency for curvature discrimination. One concerns the straight lines, the other concerns curved lines.

Firstly, there is a non-monotonic effect on the efficiencies for straight lines. This suggests that there might be flanking co-operative bands in space, 10 min. arc either side of the target stimulus. More likely is the possibility that this non-monotonic effect represents the actions of two opposing trends. If efficiency for the discrimination of curvature decreases as the stimuli to be compared are increasingly apart, and there is some depression of performance by very close contours (less than 10 min. arc), then the non-monotonic effect would be expected. This latter possibility agrees quite well with the data of Westheimer and Hauske (1975) for the task of vernier resolution.
It should be noted that the data also suggest that the length tolerance of the process is also changed. It would appear that the length limit for high efficiency curvature discrimination lies between 20 and

30 min. arc for the larger separations. This figure agrees rather more closely with the data of Andrews, Butcher and Buckley (1973), who did not use a comparison stimulus (ie, separation is infinite).
Andrews (personal communication) has suggested that a similar process might lead to the low length tolerance of the slope comparison process, which requires a reference stimulus. This idea will be discussed fully in Chapter 8.

Secondly, as separation increases, the basic trends relating efficiency for curvature discrimination and stimulus orientation range are exaggerated in size. Those lines within the hypothesized limit of orientation range are discriminated more efficiently when separation is increased (at least from 5 to 15 min. arc). For those lines beyond the limit of orientation range, efficiency is unchanged by stimulus separation. The relationship between efficiency for curvature discrimination and orientation range of the stimulus, within the limit, is also exaggerated by increasing separation.

These results show that the trends obtained in the previous experiment are not due, even in part, to the slight variations in separation between test and comparison stimulus, arising from the curvatures and line lengths used.
The results also show that there is a difference between the processes involved in discriminating curvature in straight lines and in curved lines. The effects of increasing separation in the two cases are apparently quite different. It is probable that, if further and larger separations were tested, a non-monotonic function would eventually be obtained for the curved lines, but even so, the two sets of results would be quantitatively distinct.

<u>EXPERIMENT 7.</u> : THE JOINT EFFECTS OF STIMULUS CURVATURE AND LENGTH ON EFFICIENCY FOR CURVATURE DISCRIMINATION IN OBLIQUE LINES.

Whilst the concept of orientation range limit seems useful in explaining many aspects of the relationship between efficiency for curvature discrimination and stimulus curvature and length, it may be too general. In particular, the data supporting this concept was obtained by the exclusive use of horizontal stimuli, curved upwards. Therefore the most parsimonious conclusion that should be drawn is that the orientations useful for curvature discrimination are limited to the range ± 20 degrees from the horizontal. Such a finding might be expected on the basis of the classical oblique effect (eg. Appelle, 1972).

Thus there are two candidate conclusions, which make different predictions concerning the relationship between orientation range of the stimulus, and efficiency for curvature discrimination in oblique stimuli.

If there is a limit on the <u>overall range</u> of orientations which may be efficiently combined for curvature discrimination, irrespective of the values comprising such a range, then a similar pattern of rising and subsequently falling efficiency as the stimulus orientation range increases, should also be obtained for oblique stimuli. The actual <u>levels</u> of efficiency may well be lower, but the overall <u>pattern</u> of the relationship should be little changed.

If, however, there is a limit on those <u>values</u> of orientation which may be used efficiently for curvature discrimination, a very different

pattern of efficiencies should be obtained for oblique stimuli.
Fig. 5.12 shows efficiency for curvature discrimination in oblique stimuli, as a function of stimulus orientation range, for a hypothetical situation where only those orientations within ± 25 degrees of horizontal or vertical are available for the task. If performance by subjects is limited by the oblique effect, a similar effect should be obtained.

The efficiency for curvature discrimination as a function of stimulus orientation range will now be measured, in an attempt to decide which potential conclusion is the more correct.
Does efficiency for curvature discrimination fall or rise with increasing stimulus orientation range in oblique stimuli.

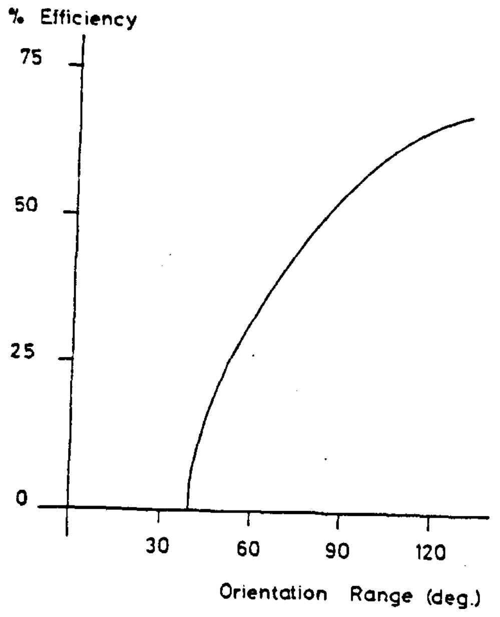


Fig. 5.12 Hypothetical relationship between efficiency for curvature discrimination and stimulus orientation range, for a situation where only those orientations between -25 degrees and +25 degrees of the horizontal and vertical may be used for the task. These orientations are used without information loss.

METHODS

The computer controlled Method of Constant Stimuli, as described in Chapter 2, was used.

The stimulus array consisted of a fixation spot, a comparison stimulus 2.5 min. arc obliquely below and right of the spot, and a test stimulus 2.5 min. arc obliquely above and left of the spot. The array was identical to the standard configuration, but rotated through 45 degrees anti-clockwise (see Fig. 5.13).

Three curvatures were tested : 0.04, 0.05, 0.0667 rad/min. arc.

Four line lengths were tested : 10, 15, 20, 30 min. arc.

All combinations were tested.

The stimulus array was displayed for 2 seconds, after a 3 seconds delay, during which the fixation spot alone was displayed.

One subject was used for this experiment (RJW). The subject was instructed to fixate the spot at all times, and after stimulus presentation, to decide which stimulus was the more curved.

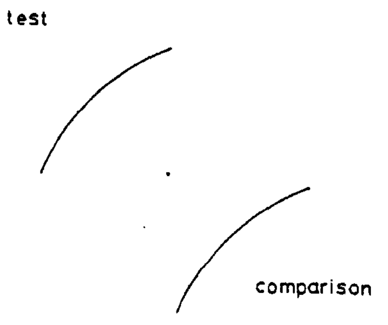


Fig. 5.13 Stimulus configuration for Experiment 7. The test stimulus varied in curvature.

RESULTS

Efficiencies for curvature discrimination in oblique stimuli, as a function of stimulus orientation range, are shown in Fig. 5.14.

There is a very steep fall in efficiency between orientation ranges of 20 degrees and 40 degrees. For increasing orientation range, the subsequent fall is much slower.

Peak efficiency is very high; higher, actually than the peak efficiency obtained for horizontal stimuli. The difference may not be reliable, since several months separated the two experiments. However, the difference in the efficiencies for the stimulus with a curvature of 0.04 rad/min. arc and line length of 10 min. arc, when oriented obliquely or horizontally, is much larger, and is probably much more reliable. The two respective efficiencies are 88.12% for the oblique stimulus, and 60.18% for the horizontal stimulus.

The lowest level of efficiency is very close to that obtained for horizontal stimuli.

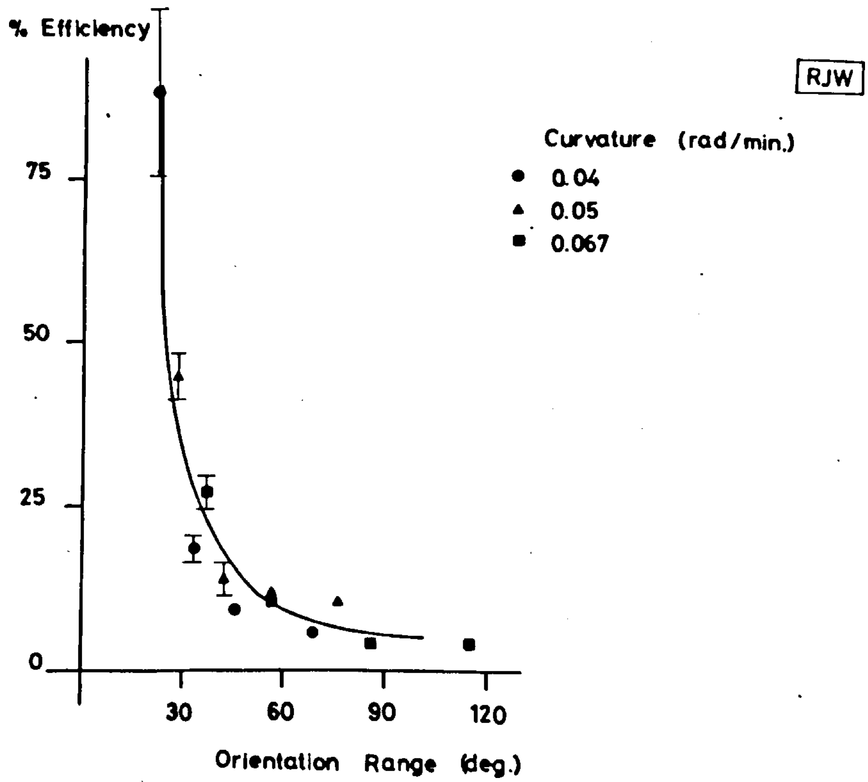


Fig. 5.14 Efficiency for curvature discrimination in oblique stimuli, as a function of stimulus orientation range, at a variety of line lengths and stimulus curvatures.

DISCUSSION

The results of this experiment are clear. The conclusion to be drawn is that there is a specific limit on the range of orientations which may be used for high efficiency curvature discrimination. This limit cannot be explained by reference to the classical oblique effect.

However, it is interesting to note that the orientation range limit is reduced in oblique stimuli. In the introduction to this experiment it was suggested that a generally lower level of efficiency might be expected, as a result of the oblique effect, if it did not have the overall effect on the form of the relationship between efficiency and orientation range. This is also seen not to be the case. The peak efficiency for subject RJW in the main experiment (Experiment 5) is slightly lower than the peak efficiency in this present experiment. The implications of this observation will be considered at length in Chapter 8, when the present data will be compared with other data, which shows another stimulus modification that has an effect of reducing the orientation range limit.

CONCLUSIONS : A DETAILED INVESTIGATION OF THE EFFECTS OF STIMULUS CURVATURE AND LENGTH ON CURVATURE DISCRIMINATION.

This detailed study of the joint effects of stimulus curvature and length on the efficiency for curvature discrimination leads to one major conclusion, and a number of points for further consideration.

It is concluded that there is a region of stimulus curvature and length space, within which all stimuli are processed for curvature discrimination at a high efficiency, and outside which all stimuli are processed at a much lower efficiency.
The most useful parameter to describe the boundary of this region, and the associated effects, has been shown to be that of stimulus orientation range: the product of stimulus curvature and length.
Fig. 5.15 shows some sample orientation ranges.
It has been shown that this parameter is not confounded with specific near horizontal orientation values, which are already widely known to be of particular salience for the visual system.

An orientation range of 40 degrees bounds the high efficiency region for all horizontal, curved stimuli. It seems likely that a smaller value, between 25 and 30 degrees would be the boundary for oblique stimuli, although this point cannot be considered fully proven.
Within this high efficiency region, efficiency rises with increasing orientation range. Beyond the boundary, efficiency falls steeply with increasing orientation range,

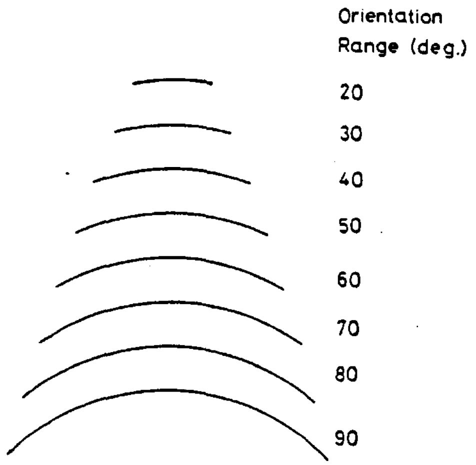


Fig. 5.15 Sample orientation ranges. The lines all have the same curvature. Note that orientation range is a distance-invariant quantity.

Separation of the stimuli does not influence the limit of orientation range for high efficiency curvature discrimination, but it does have an effect on the value of the peak efficiency. Efficiency, within the orientation range limit, is increased with increasing separation of test and comparison stimuli.
The value of peak efficiency is higher also for oblique stimuli, than for horizontal stimuli.

The concept of orientation range and orientation range limits has one drawback, in that certain stimuli cannot easily be accomodated into its framework. All straight lines have the same orientation range of zero, but are not all processed at the same efficiency for curvature discrimination. It is important to consider whether it is possible to find acceptable grounds for excluding straight lines from the scope of the hypothesis of limiting orientation range. This is equivalent to enquiring whether there are any properties of the response of the visual system to straight lines, that are different from its response to curved lines.

One such property is the requirement of a comparison stimulus, for the discrimination of the curvature of curved lines. Straight lines are a powerful anchor point on the dimension of contour curvature.

Another is the different amount of practice required by subjects to reach a performance plateau when discriminating curved and straight lines, reported in Chapter 3 (p.101).

Another such property could be the time constant for the discrimination process, which was shown in Experiment 1 to be rather different for straight and curved lines.

Another such property is the effect of stimulus separation on the discrimination of curvature, which was shown in Experiment 6 to be very different in the two cases.

It is possible that the effects of making a break in the stimulus, may also serve to distinguish between curved and straight lines. Andrews, Butcher and Buckley (1973) present data showing the effect on the efficiency for curvature discrimination in straight lines, of adding two gaps to the stimulus.
In that study, the critical length for high efficiency curvature discrimination was 30 min. arc. The length of 30 min. arc was also critical for the effect of the gaps. In lines less than 30 min. arc in length, the gaps led to a rise in efficiency; for lines longer than 30 min. arc, the gaps led to a decrease in efficiency. The apparent relationship between these two findings, both critically dependent on the length of the stimulus, and both having a critical length of 30 min. arc, suggests that, if there is a difference in the way in which curved and straight lines are processed by the visual system, then breaking the stimulus might show it.
The effects of breaking the stimulus will be considered in the next two chapters.
The use of broken stimuli should also throw some light on the implications of the relationship between stimulus orientation range and measured efficiency for curvature discrimination.

CHAPTER 6. DISCRIMINATION OF THE CURVATURE OF BROKEN STIMULI.

Most of the data presented in the preceding chapters may be described economically by relating efficiency for curvature discrimination to the concept of stimulus orientation range, where the orientation range of a given stimulus is defined as the product of its curvature and length. The concept has been extended to define an orientation range limit, which may be used to partition the space of stimulus curvature and length into two hypothetical sub-spaces or regions: a region of high efficiency curvature discrimination; and a region of low efficiency curvature discrimination. The limit on orientation range for horizontal stimuli is found to be about 40 degrees, and that for oblique stimuli, somewhat less.

The effects of increasing stimulus orientation range within these two hypothetical regions are different. Efficiency increases with increasing orientation range, for stimuli within the high efficiency region; efficiency decreases with increasing orientation range for stimuli within the low efficiency region of stimulus curvature and length space.

Orientation range is a mathematical parameter of the stimulus, which has been found to be powerful in describing certain measurements of efficiency for curvature discrimination. It can be interpreted in a number of ways, each of which suggests a different set of constraints on the types of mechanism which could underlie the process of curvature discrimination.

For example, orientation range may be interpreted as being the difference between the two extreme orientations of the stimulus, or it may be interpreted as a function of the total amount of continuous orientation change.

The former suggests that the intermediate orientations are unimportant, whereas the latter places great stress on the value of these orientations.

This ambiguity of interpretation arises from the simplistic nature of the definition of orientation range. The different interpretations can be distinguished by the addition of further clauses to the mathematical definition of the concept, and empirical evidence is required to suggest which additions to make.

The concept of orientation range, defined as the product of stimulus curvature and length, is unambiguous mathematically, when applied to unbroken stimuli: the two terms, curvature and line length can each only be taken as refering to one quantity.

There are at least two ways in which the concept can be defined for application to broken stimuli, and it is therefore vague. The length term could be defined as the total expanse of the stimulus, including gaps, or it could be defined as the quantity of contour physically present (excluding gaps). There is an effective length for broken stimuli that can be used to derive the stimulus orientation range, and thereby predict or describe the efficiency for curvature discrimination for a given stimulus curvature.

Take a line of length 20 min. arc; make a 5 min. arc long gap: is the resultant effective length 15 or 20 min. arc ? (Or something completely different ?) To which length does efficiency for curvature discrimination more closely result ?

The following experiment will attempt to measure the effect of breaks in the stimulus, on curvature discrimination.

Andrews, Butcher and Buckley (1973) have studied the effect of two breaks in the stimulus on curvature discrimination in straight lines. For broken lines up to 30 min. arc in length, efficiency for curvature discrimination was higher than for unbroken lines; for longer lines, efficiency was lower. Since the region of high efficiency curvature discrimination in their data is also bounded by a line length of 30 min. arc, there seems to be an intimate relationship between the effect of the gaps and the efficiency of the process.

This suggests that the present experiment, which includes both straight and curved lines, may also provide further evidence to support the hypothetical distinction between the response of the visual system to these two types of stimuli.

EXPERIMENT 8. : THE EFFECTS OF BREAKS IN THE STIMULUS ON DISCRIMINATION OF CURVATURE IN LINES VARYING IN BOTH STIMULUS CURVATURE AND LINE LENGTH.

A previous study has suggested that the joint effects of stimulus curvature and length on the efficiency of curvature discrimination may be economically described by reference to the concept of orientation range. The present study is concerned with a close examination of the character of this concept, and will seek the most appropriate interpretation of it.
This will be achieved by measuring performance of curvature discrimination using stimuli with breaks of specific sizes and at specific points in the stimulus. Gaps in the stimulus do not alter the difference between the two extreme orientations, but do change the distribution of orientations within the stimulus. The results should show something of the relative importance of the different parts of the stimulus to the visual system.

The present experiment will consider two conditions.
The first condition has two breaks in the stimulus, one either side of the centre, effectively leaving three lines of equal size, each one fifth of the overall length of the stimulus, separated by two equal gaps, also one fifth of the overall stimulus length.
The second condition has one central gap, one third of the overall stimulus length.
In both conditions the gaps are a fixed proportion of the stimulus, and therefore the information content of the stimulus series, with respect to the task of curvature discrimination, is reduced by a fixed proportion of two fifths and one third respectively for the first and second condition.

This makes comparisons between the two conditions, and between the data for unbroken stimuli of Chapter 5, and the present data for broken stimuli, particularly easy.

METHODS

The computer controlled Method of Constant Stimuli, as described in Chapter 2, was used.

The stimulus array consisted of a fixation spot, an unbroken comparison stimulus 2.5 min. arc beneath the spot, and a broken test stimulus 2.5 min. arc above the spot. This is the standard configuration.
The curvatures tested were : 0.00, 0.05, 0.0667 rad/min. arc.
The lengths tested were : 10, 20, 30 min. arc.
All combinations were tested.
Two general conditions were used : a set of stimuli with two gaps, and a set with one gap, were tested at a selection of stimulus curvatures and line lengths specified above.
In the two gap condition, the gaps separated three segments of equal length, one fifth of the total stimulus length, as were the gaps. (See Fig. 6.1).
In the one gap condition, the gap separated two segments, each one third of the total stimulus length, the gap also being one third of the total stimulus length. (See Fig. 6.2).
The stimulus array was displayed for 2 seconds, after a delay of 3 seconds during which the spot alone was displayed.

Two subjects were used; both had normal vision. One subject was tested in both gap conditions (RJW), the other was tested in only the single gap condition (NL). The subjects were instructed to fixate the spot at all times, and after presentation of the stimulus, to decide which stimulus was curved upwards more, top or bottom.

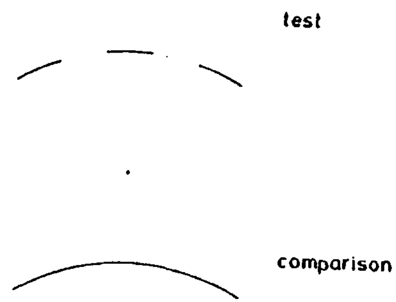


Fig. 6.1 Stimulus configuration for the two gap condition of Experiment 8.

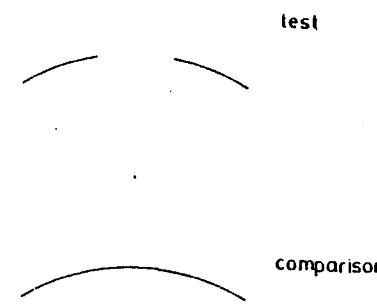


Fig. 6.2 Stimulus configuration for the one gap condition of Experiment 8.

RESULTS

The results from the two conditions will be considered separately first, and then the two sets of results will be compared. In each case a comparison with the corresponding data for unbroken stimuli, from Experiment 5 will be made. The two experiments were performed in immediate succession for RJW, and so the comparison is valid (although weaker than if the data from Experiment 5 had been repeated during the same preiod of time). The two experiments were interleaved for subject NL, and so the comparison is valid and strong.

Thresholds for curvature discrimination are shown in Fig. 6.3 for the case of lines with two gaps. There are several points to note. The thresholds for curvature discrimination in straight broken lines are all lower than the equivalent thresholds for unbroken lines (see Experiment 5).
Thresholds for curvature discrimination for all curved lines are higher than the equivalent results for unbroken lines.
Efficiencies for curvature discrimination of lines with two gaps are shown in Fig. 6.4.
Efficiencies for the straight lines are improved when two gaps are added.
Efficiencies for short curved lines are reduced by adding two gaps, but those for longer lines are slightly improved. The advantage of short lines over long lines is reduced. In general however, the data for the curved lines follow the established trends.

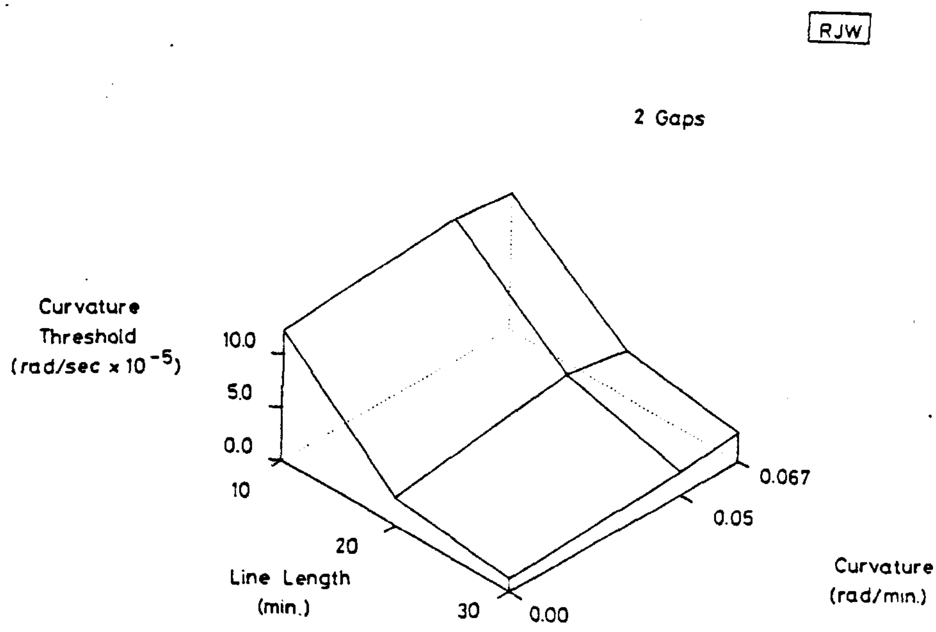


Fig. 6.3 Threshold for curvature discrimination of lines broken in two places, as a function of stimulus curvature and line length.

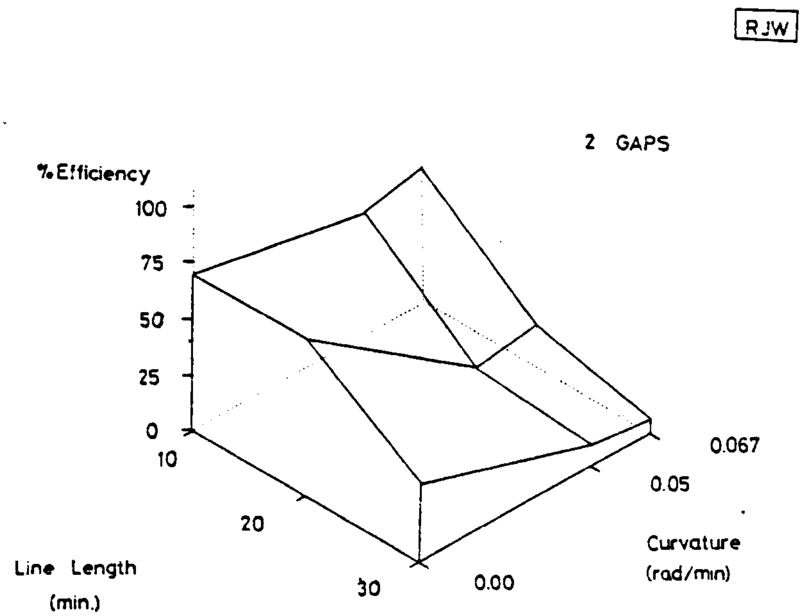


Fig. 6.4 Efficiency for curvature discrimination of lines broken in two places, as a function of stimulus curvature and line length.

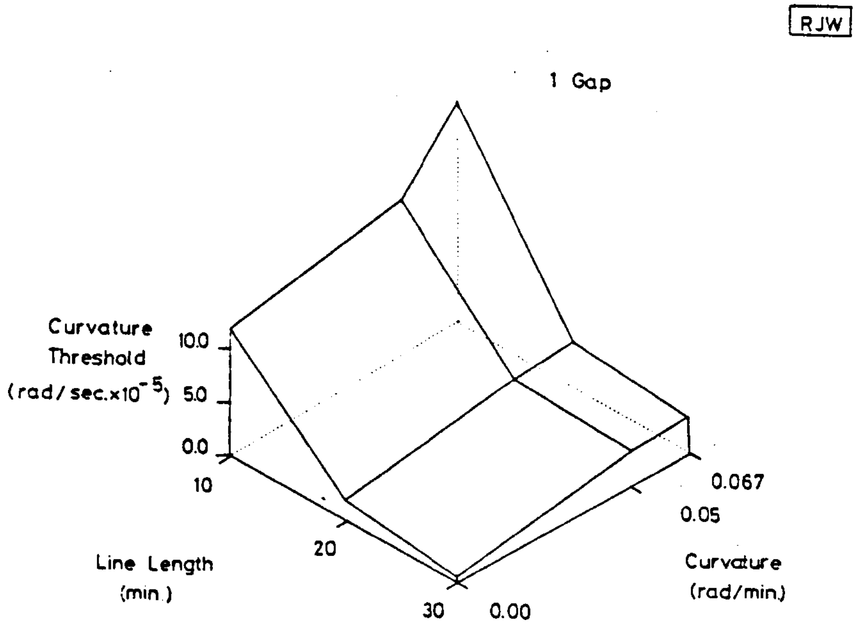
Thresholds for curvature discrimination for lines broken by one central gap are shown in Fig. 6.5. There are several points to note.
As for two gaps, one gap reduces the threshold (this is especially true for subject NL), for straight lines only.
For curved lines, the results are not so simple. Thresholds are generally higher for curved lines broken by a single central gap than for unbroken lines (in all cases for subject NL, and in all cases except (0.05,20) and (0.05,30) for RJW).
Efficiencies for curvature discrimination in lines with a single central gap are shown in Fig. 6.6.
There is a marked increase in efficiency for the straight lines, compared with the efficiendies for unbroken lines (especially for subject NL).
The longest curved lines show a slight increase in efficiency, also, but the short lines show a marked drop in efficiency.
Unlike the two gap condition, the overall form of the trends in efficiency appear to be radically altered by the addition of a single central gap. For the shortest lines, efficiency falls with increasing curvature, instead of rising.

Data from the two subjects is in good agreement, although subject NL shows much higher levels of efficiency in the straight line cases, as before (in Experiment 5). This is once again, presumably due to the relative experience of the two subjects.

Comparing the two sets of data for two gaps and one gap, some interesting points emerge.
In the case of the straight lines, two gaps results in less of an improvement in efficiency for curvature discrimination than does one gap.

Both the two gaps condition and the single gap condition seem to increase the range of lengths for high efficiency curvature discrimination of straight lines.

There is a marked difference between the effect of two gaps and one gap on efficiency for curvature discrimination on the stimulus with a curvature of 0.0667 rad/min. arc, and length 10 min. arc.



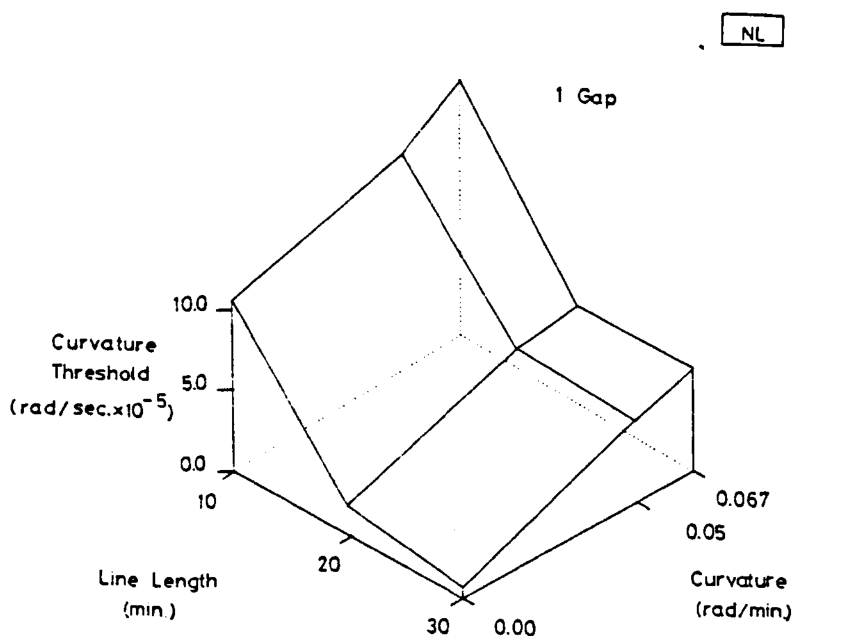
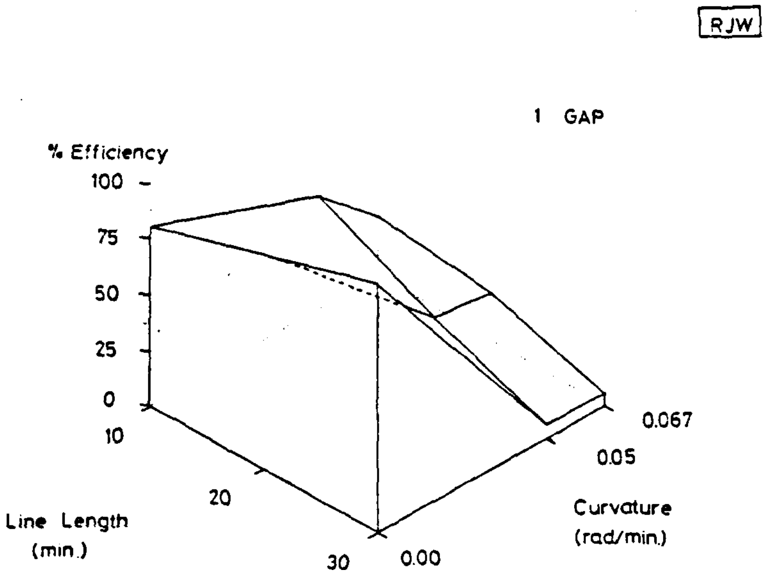


Fig. 6.5 Threshold for curvature discrimination of lines broken by a single gap, as a function of stimulus curvature and line length.



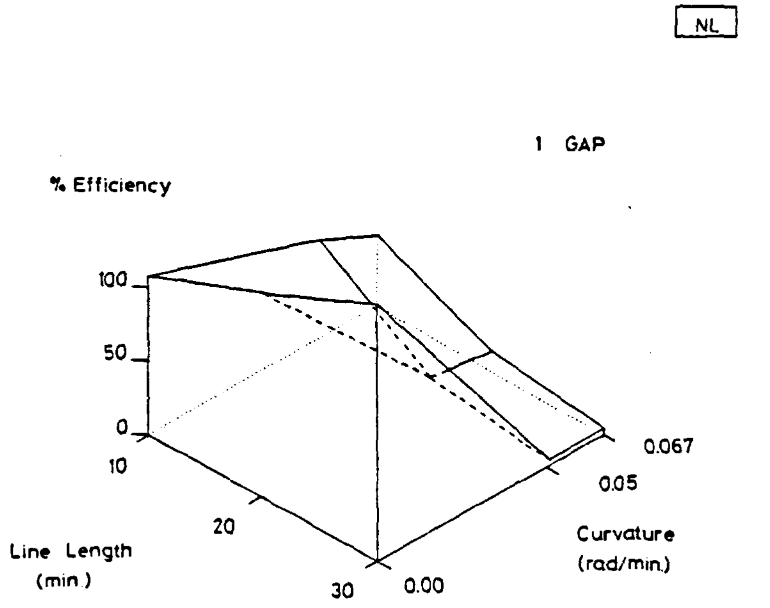


Fig. 6.6 Efficiency for curvature discrimination of lines broken by a single gap, as a function of stimulus curvature and line length.

DISCUSSION

This experiment set out to examine the concept of orientation range and the relationship between it and the efficiency for curvature discrimination. A number of findings emerge.

The data for the effect of adding two gaps to the stimulus show two main points.
Firstly, there is seen to be a difference between the effect of adding two gaps to a straight line and adding two gaps to a curved line. Straight lines are processed much more efficiently with two gaps present, whereas curved lines are not. Further the present results for the effect of line length on efficiency for curvature discrimination, are much more consistent with the data of Andrews et al. (1973). The maximum length for high efficiency curvature discrimination, in the data from unbroken lines from Experiment 5, is between 15 and 20 min. arc. The same maximum length in this present experiment, for lines with two gaps, is between 20 and 30 min. arc, a figure much closer to the figure of 30 min. arc obtained by Andrews et al. (1973) for broken and unbroken lines. There are a number of differences in the stimuli employed that could account for this difference. The present stimuli have larger dashes, which could account for the higher levels of efficiency, than those of the broken stimuli in the studies of Andrews et al. (1973). There is also a comparison stimulus present, which may or may not have an effect on performance. That the form of the relationship between efficiency and line length is altered suggests that this may be the case; the problem will be discussed at length in Chapter 8 (p.234). See Fig. 6.7.

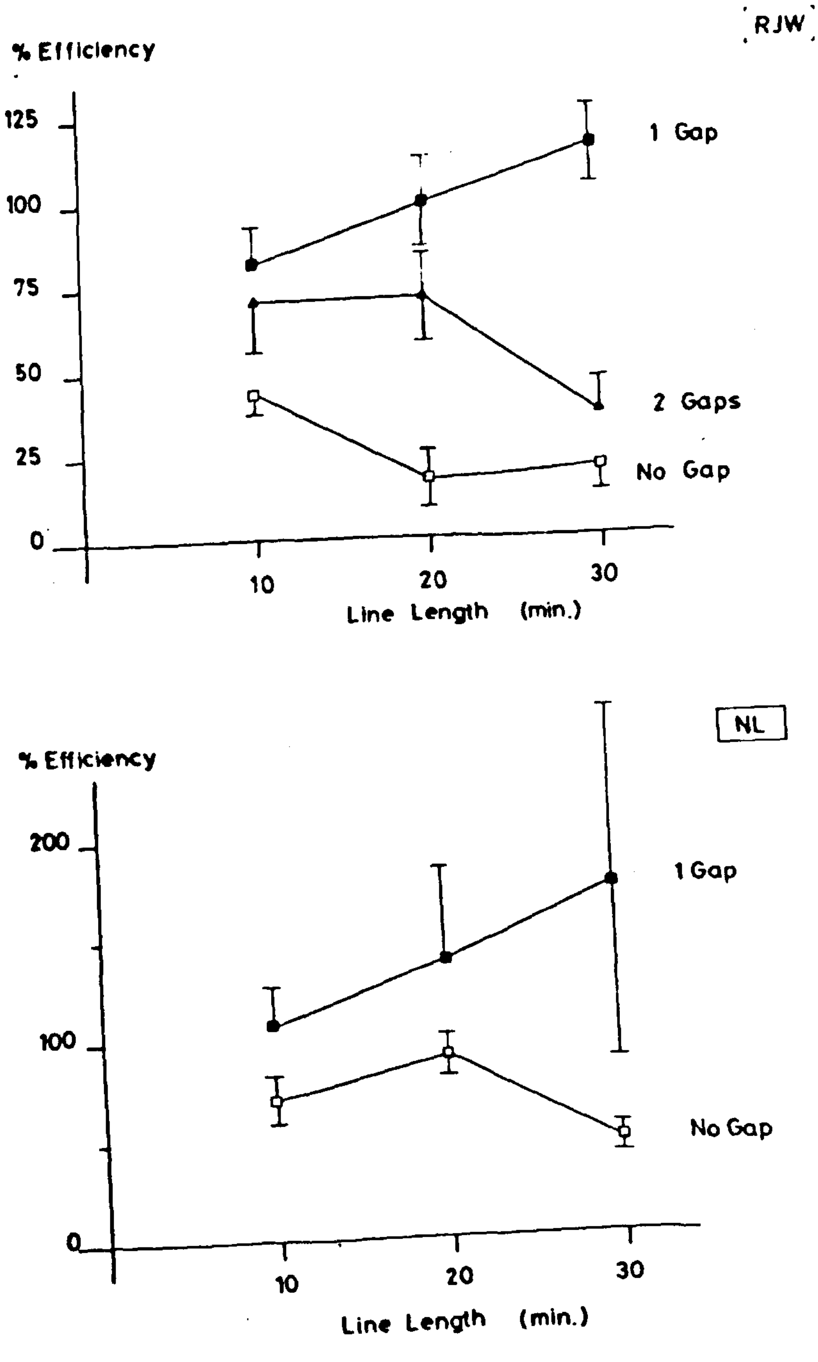


Fig. 6.7 Efficiency for curvature discrimination of straight lines, as a function of line length and gap condition.

Seoondly, there is a difference between the effect of adding two gaps to those curved lines which are normally processed at a high efficiency, and the effect of adding two gaps to those curved lines which are not. Curved lines which are processed at a high efficiency for curvature discrimination, are processed at a lower efficiency when two gaps are added; in contrast, those curved lines that are usually processed at a low efficiency, are processed at much the same efficiency when two gaps are present.

The orientation range limit appears unchanged.

The data for the effects of adding a single gap to the stimulus are interesting. There are two main points.

Firstly, adding one central gap to a straight line improves performance of curvature discrimination: the improvement is much greater than that caused by the presence of two gaps. This may be due to either the relative quantities of line missing, or to the relative position of the missing information.

Seoondly, unlike the effect of adding two gaps to a curved line, adding one central gap appears to alter the trends in efficiency for curvature discrimination.

In particular, there is a strong interference with curvature discrimination when a gap is added to the short, highly curved lines. The trends in efficiency are disturbed by the addition of a single gap, primarily at this one point, at a stimulus curvature of 0.0667 rad/min. arc and a length of 10 min. arc.

How far the concept of orientation range, and limit of orientation range require modification is not clear. Fig. 6.8 shows the efficiencies for curvature discrimination of curved lines, as a function of stimulus orientation range, for the three cases: no gap, one central gap, and two gaps either side of the centre. It seems possible that the single gap has reduced the orientation range limit (orientation range is calculated using the overall dimensions of the stimulus in all cases).

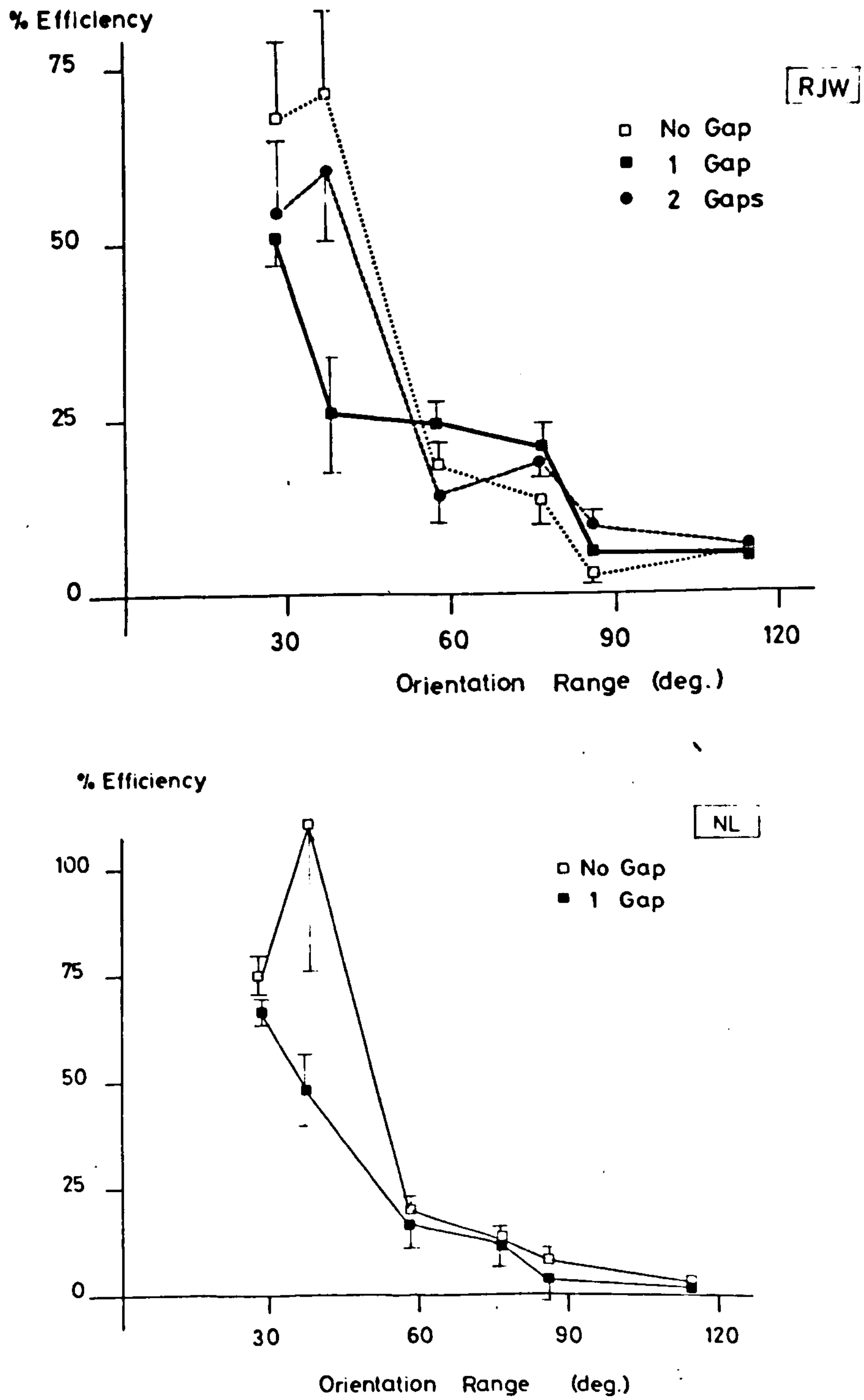


Fig. 6.8 Efficiency for curvature discrimination of curved lines, as a function of stimulus orientation range and gap condition.

CONCLUSIONS : DISCRIMINATION OF CURVATURE WITH BROKEN STIMULI.

A number of conclusions may be drawn from the results of this experiment.

Firstly, it is clear that straight lines and curved lines are processed differently by the visual system. The effect of adding one central gap and the effect of adding two gaps, one either side of the centre, are quite different in straight lines and in curved lines. In all straight lines, threshold is smaller for broken lines than for unbroken lines. The only decrease in threshold for the curved lines obtained are small, and in general, threshold rises when a gap is added to the stimulus. Taking this in conjunction with the data of the previous chapter, which showed a similar distinction between the effects of separation distance on straight lines and on curved lines, it seems reasonable to suppose that curved lines and straight lines are to be considered as separate and different stimuli, rather than points on the same dimension, so far as the visual system is concerned, at least for the purpose of curvature discrimination.

Secondly, the addition of two gaps to curved lines does not seem to change the manner in which the stimulus is processed. The relationship between stimulus orientation range and efficiency for curvature discrimination is diminished in magnitude, but the overall trends seem unchanged. The limiting orientation range is still about 40 degrees; within this limit, efficiency still rises with increasing orientation range; and beyond this limit, efficiency still falls with increasing orientation range.

Lastly, the effect of adding a single gap to a curved line is found to have an unexpected effect. The basic trend of the effects of stimulus curvature and length on the efficiency for curvature discrimination seems to be changed. In particular, the most curved and shortest line, which normally leads to the highest efficiency obtained, is processed at a much lower efficiency when it is broken by a single central gap.

Whilst the explanation for this is not clear, it seems possible that the orientation range limit is reduced by the presence of a single gap (but not by two gaps).

It is obvious that a simple description of the stimulus in terms of its orientation range, where orientation range is interpreted as the difference between the two extreme orientations, is inadequate to determine the efficiency with which the curvature of both unbroken and broken stimuli may be discriminated.

The interaction between the effect of the single central gap, and the effects of stimulus curvature and length, on the efficiency for curvature discrimination shows that some account must be made of the orientations within the two extremes. In particular, the failure of two gaps, one either side of the centre of the stimulus, to elicit the same strong effect may be taken as evidence that the central orientations or positions on the line, are of considerable importance in the processing of curvature.

How this might be best described is unclear, and further exploration of the effects of a single gap is required. The next experiment will measure the effects of gap size and stimulus curvature on curvature discrimination in short lines, in an attempt to determine the region of stimulus curvature and length space within which the central gap has its singular effect on efficiency.

CHAPTER 7. CURVATURE DISCRIMINATION IN SHORT UNBROKEN AND BROKEN LINES.

The results of the previous experiment show that there must be some strong interactions between the different parts of a curved line, within the limiting orientation range of 40 degrees. These interactions are manifest when short stimuli (10 min. arc long) of high curvature (0.0667 rad/min. arc) are broken by a centrally placed gap of substantial size (3.33 min. arc). It is interesting that the stimulus which, when unbroken, is processed at the highest efficiency, should, when broken be processed at a much lower efficiency. It was suggested in the previous chapter that this may be due to a reduction in in the limiting orientation range. Closer examination is required to establish whether this is ths case, and will be provided by the following experiment.

The results of this examination are quite clear, and the effect of a single central gap on performance of curvature discrimination can be accurately and economically described. The detailed implication of the results will be discussed in conjunction with all the previous results in the final chapter. For the present, only the immediate conclusions will be mentioned.

The present study also offers the opportunity to test a prediction of the hypothesis of limited orientation range. In Chapter 5 (p.158) it was noted that for lines of length 10 min. arc, the limiting curvature for high efficiency curvature discrimination should be between about 0.06 and 0.07 rad/min. arc. This prediction is upheld, and the hypothesis is therefore considered to be sufficient and useful.

EXPERIMENT 9. : THE JOINT EFFECTS OF STIMULUS CURVATURE AND GAP SIZE ON DISCRIMINATION OF THE CURVATURE OF SHORT UNBROKEN AND BROKEN LINES.

The results of the previous experiment show that there is a strong interaction between curvature and the presence of a 3.33 min. arc gap on the efficiency for curvature discrimination on lines of length 10 min. arc. With the gap present, efficiency falls with increasing stimulus curvature; with the gap absent, efficiency rises with increasing stimulus curvature. It is clear from this result that the concept oforientation range, defined as the product of stimulus curvature and length, may not be interpreted as the difference between the two extreme orientations of the stimulus : meddling with the distribution of orientations within this range has a strong effect, at least in this case. The data of the previous experiment are not detailed enough to support any particular hypothesis or description of the process involved, but do suggest that the interactions are worthy of further study.

Such a study can be combined with a test of the specific prediction made by the hypothesis of orientation range limits, noted in Chapter 5 (p. 158). If the limit or boundary for high efficiency curvature discrimination is set by an orientation range limit of 40 degrees, then were efficiency for curvature discrimination measured for a series of stimuli of fixed length of 10 min. arc, and with a linear variation in curvature, efficiency should rise to a peak at a curvature between 0.06 and 0.07 rad/min. arc, and should then fall.

Since such a series of stimuli have an almost constant information content with respect to the task of curvature discrimination, the test is suitable for examining the usefulnes of the concept of orientation range.

These two aims are served by one large study, where the independent variables are stimulus curvature, and gap size.
The results fulfil both these aims, and as a bonus, reveal further unexpected effects that are very interesting.
As a result of the data obtained, the effect of a single central gap in short curved lines, on the efficiency for curvature discrimination is now clear, and the hypothesis concerning orientation range limit is found to be useful and sufficient.
A detailed analysis of the results will be deferred until the next chapter.

METHODS

The computer controlled Method of Constant Stimuli, as described in Chapter 2, was used.

The stimulus array consisted of a fixation spot, a comparison stimulus, 2.5 min. arc beneath the spot, and a test stimulus 2.5 min. arc above the spot, in the standard configuration. All stimuli were 10 min. arc in length, and curved upwards.
The stimuli were varied in two domains, stimulus curvature and the size of the single central gap.
The values of curvature tested were : 0.00, 0.02, 0.04, 0.06, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14 rad/min. arc.
The values of gap size tested were : 0.00, 1.67, 3.33, 5.00 min. arc.
The test stimulus was drawn from a series varying in curvature,centred at the curvature of the comparison, and increasing in steps of 0.004 rad/min. arc.
The stimulus array was displayed for 2 seconds, after a pre-stimulus delay of 3 seconds, during which the fixation spot alone was displayed.
The brightness of the stimulus array was very carefully controlled, and set to a predetermined level before each run. The actual level is not important, but variations in the level from stimulus condition to condition might well be.

Two subjects were used; both had normal vision. One subject (RJW) was exhaustively tested in all combinations of stimulus curvature and gap size; the other subject (NL) was tested in rather fewer conditions. The data for subject RJW represents a total of 31240 responses: it proved impractical to record this number of responses from the other subject.

The subjects were instructed to fixate the spot at all times, and after stimulus presentation, to decide which stimulus, top or bottom, was curved upwards by the greater amount.

RESULTS

Thresholds for curvature discrimination as a function of stimulus curvature and gap size are shown in Fig. 7.1.
It seems reasonable to consider the data as belonging to three sets of no gap, moderate gap, and gap too large, rather than the four sets recorded: the coincidence of the thresholds for the two gap sizes of 1.67 min. arc and 3.33 min. arc is high. The only exception to this is the data at a stimulus curvature of 0.12 rad/min. arc. This coincidence suggests that threshold is only affected by the size of the gap at the extremes of unresolved gap, and poorly resolved line segments. In the intermediate range, it seems likely that gap size has no effect on threshold.

Efficiencies for curvature discrimination are shown in Fig. 7.2.
The data is clearer if presented as efficiencies, and the rest of the results will be discussed in terms of efficiency for curvature discrimination. For convenience, the results will be presented in three groups. Firstly, the data from unbroken lines will be described; then the data from the broken lines will be described; and lastly, these two sets of data will be compared.

Note that, in general, the data from subject NL conforms to the same pattern as that of subject RJW. Where there is a discrepancy, this will be pointed out.

Further note that no account of differential light spread effects has been taken in calculating efficiencies. This means that the efficiencies for curvature discrimination at the largest gap size are almost certainly underestimates. Efficiencies for the 3.33 min. arc gap size are also probably underestimates. However, this omission will not affect the argument.

1). Unbroken Lines.

a). There is a steady rise in efficiency with increasing stimulus curvature up to a curvature of 0.06 rad/min. arc. The efficiency for the zero curvature line is slightly higher than the next point on the curvature dimension.

b). This rise in efficiency is followed by a rather more steep fall in efficiency with increasing stimulus curvature, to a minimum at a curvature of 0.09 rad/min. arc. (The minimum is at a curvature of 0.10 rad/min. arc for NL).

c). This is followed in turn by a rapid rise in efficiency as stimulus curvature increases further. There is a second peak efficiency at a curvature of 0.12 rad/min. arc.
The second peak appears to be broader than the first, but this could be due to sampling interval: the true peak could be sharp and at a curvature of 0.125 rad/min. arc.

d). The second peak is followed by a rapid fall in efficiency as stimulus curvature increases further.

e). The efficiency for curvature discrimination at the two peaks identified, is approximately the same (less so for NL). This is important. For RJW, the difference is only four percent, and could be due to sampling (eg. if the true peak is at a curvature of 0.125 rad/min. arc).

2). Broken Lines.

a). Gap size has a non-monotonic effect on the efficiency for curvature discrimination.

b). There is no difference between the trends of efficiency as a function of stimulus curvature in the different gap conditions, and the trends are at the same locations in the curvature dimension. There is no interaction between gap size and stimulus curvature on efficiency for curvature discrimination.

c). There is a relatively steep rise in efficiency with increasing stimulus curvature to a peak at a curvature of 0.05 rad/min. arc. The data for subject NL, although incomplete, probably support this.

d). There is a very steep fall in efficiency as curvature increases further, to a minimum at a curvature of 0.09 rad/min. arc (0.10 rad/min. arc in subject NL).

e). There is a subsequent rapid rise in efficiency to a maximum at a curvature of 0.10 rad/min. arc (the exact position of this peak is obviously unclear, since the sampling is too coarse). The second peak for subject NL is at a stimulus curvature of 0.11 rad/min. arc.

f). This is followed in turn by a rapid fall in efficiency, to a second minimum at a curvature of 0.12 rad/min. arc (0.13 rad/min. arc in subject NL).

g). For subject RJW, there is a last small peak in efficiency at a stimulus curvature of 0.13 rad/min. arc.

h). The data for the 1.67 min. arc gap size depart slightly from this pattern at a stimulus curvature of 0.12 rad/min. arc. There is an extra peak in efficiency for curvature discrimination at this gap size and stimulus curvature.

i). Note that the above trends and effects are only weakly seen for the large gap size. This gap size clearly has a considerable detrimantal effect on discrimination performance. This is not surprising: indeed it is surprising that the subject can make any discrimination of curvature from two small dashes, each only 2.5 min. arc long.

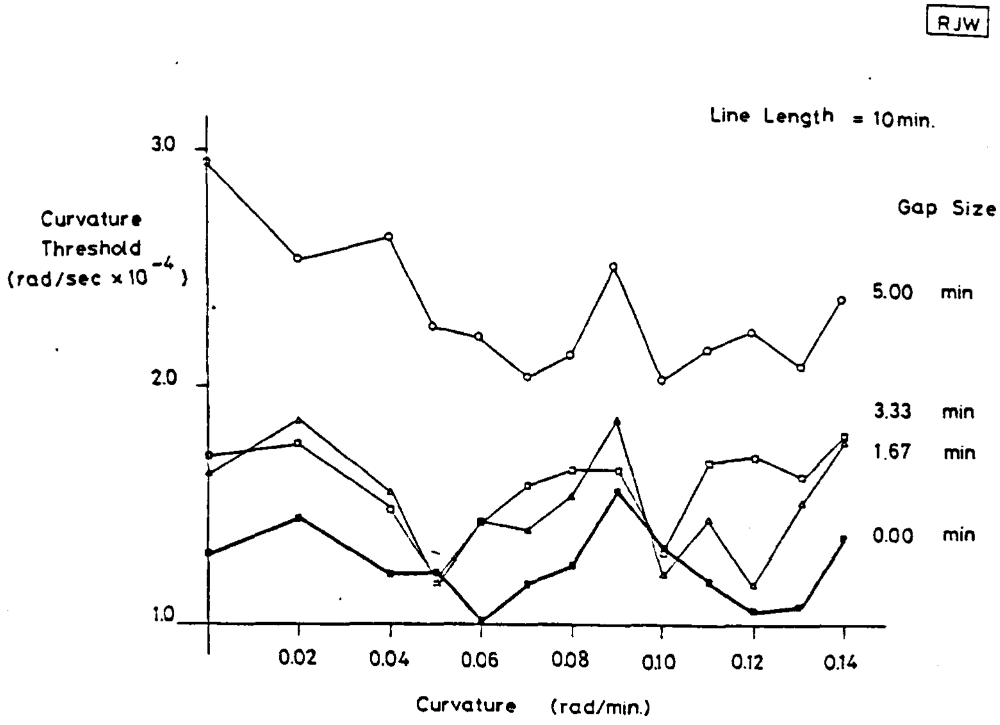
3). Broken Lines and Unbroken Lines Compared.

a). The two main peaks in efficiency appear at different stimulus curvature for unbroken and broken lines.

b). The slopes of rising and falling efficiency either side of these two peaks are different in the two categories of stimulus, unbroken and unbroken.

c). The peaks attain slightly different levels of efficiency in the two cases. No real significance can be attached to this, since peak efficiency is a function of gap size, and that obtained for gap size 3.33 min. arc may not be optimal. Further, the efficiencies for the larger gap sizes are almost certainly underestimates, since the light-spread due to the optics of the eye will have a considerable degrading effect on the information in the stimulus, when the dashes are short. The important point is that efficiency for lines with a gap is not much <u>less</u> than that for unbroken lines.

d). There is a common minimum efficiency for curvature discrimination at a stimulus curvature of 0.09 rad/min. arc (0.10 rad/min. arc for subject NL), despite the fact that the peaks do not have similarly common positions on the curvature dimension.



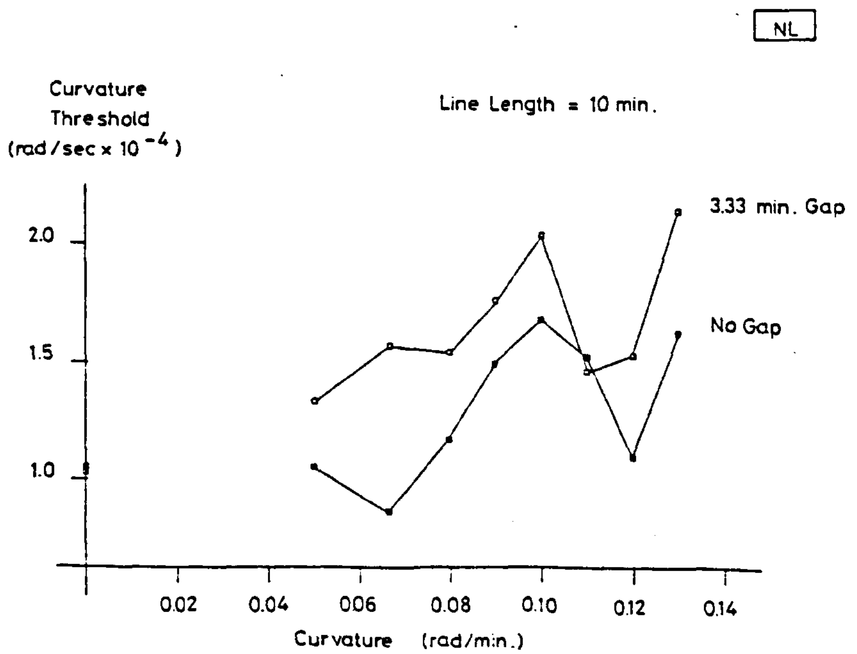
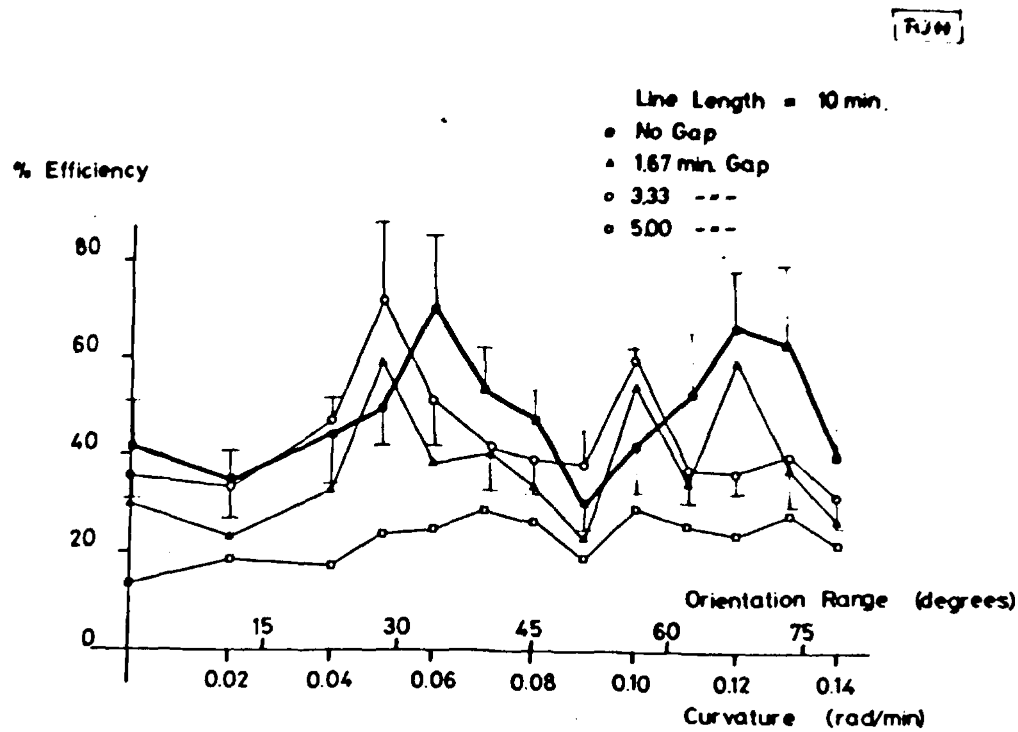


Fig. 7.1 Threshold for curvature discrimination as a function of stimulus curvature, and gap size, in lines of length 10 min. arc.



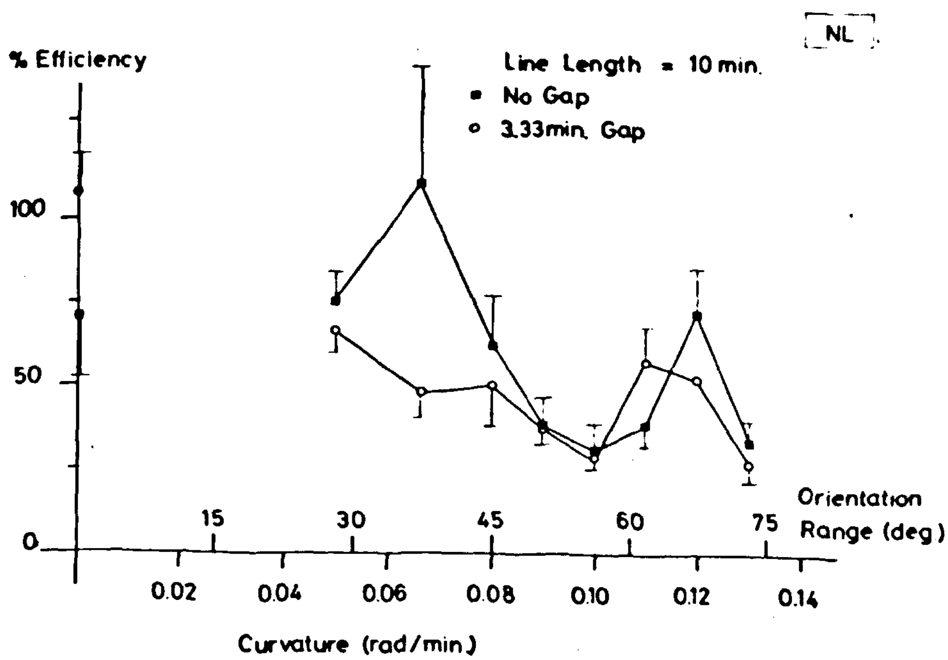


Fig. 7.2 Efficiency for curvature discrimination as a function of stimulus curvature and gap size, in lines of length 10 min.

DISCUSSION

The introduction to this experiment described two main aims. These were, to test a specific prediction concerning the hypothesis of an orientation range limit on high efficiency curvature discrimination, and to clarify the effects of a single central gap on the efficiency for curvature discrimination in short lines. The results will be discussed in the light of these two aims, and then the further implications will be considered.

In Chapter 5 (p.158) it was hypothesized that there is a limit on the range of orientations which can be combined with high efficiency for curvature discrimination. The limit was thought to be between orientation ranges of 35 and 40 degrees. This hypothesis was formulated on the basis of data from studies where there is some potential for confusion between the orientation range description of a stimulus, and other similar measures of stimulus size: an undesirable situation.

The present data, taken alone, could support two possible hypotheses : either there is a single process, with a critical curvature of 0.12 or 0.13 rad/min. arc, which suffers some interference for stimuli of curvature between 0.07 and 0.11 rad/min. arc; or, there could be two processes with critical curvatures of 0.065 and 0.125 rad/min. arc, respectively. Up to a curvature of 0.09 rad/min. arc, the present data agree very well with the data from Experiment 5, if presented in terms of orientation range of the stimulus and efficiency for curvature discrimination.

Beyond this, there is considerable divergence, and the second peak in efficiency has no correlate in the data from Experiment 5. There is a difference in the length of the lines at these high orientation ranges, in the two experiments, and the second peak may be due to a novel system, that only operates for small stimuli.
No such easy agreement between the present data and that of Experiment 5 is found if some other parameter is used, in order that the first of the above two hypotheses may be generalized to all the results. Given such anew parameter, there would still have to be explanations for the interference at curvatures between 0.07 and 0.11 rad/min. arc and its restriction to short lines, and for the high efficiency for curvature discrimination at a stimulus curvature of 0.06 rad/min. arc, for short lines.
It is clear that the orientation range hypothesis is the simplest option, with the qualification that there is a second system for high efficiency curvature discrimination of short, highly curved lines.

The present data, therefore, provide strong support for this hypothesis. The prediction made in Chapter 5, and described above, has been upheld (at least in part), and as a result, the concept of limiting orientation range is found to be useful for describing all conditions of stimulus curvature and length boundary on the high efficiency process, with certain qualifications.

In addition to the limit on orientation range, there also appears to be a strict relationship between orientation range of the stimulus and efficiency for curvature discrimination. Previous data has shown an increase in efficiency as orientation range increases to the limit, and a subsequent fall in efficiency for further increases in orientation range. The present data also confirm this strict relationship: once again, the pattern of rising efficiency with increasing orientation range within the limit, and falling efficiency beyond the limit, has been obtained.

This pattern of efficiency for performance is therefore, an established feature of the curvature discrimination of curved lines, and provides some useful insight into the nature of the processes involved in curvature discrimination. This will be considered at length, in the next chapter.

The second aim of this study was an examination of the effects of a single central gap on efficiency for curvature discrimination, in greater detail than in the previous experiment. This previous experiment had shown that a single central gap in the test stimulus caused a very strong depression in efficiency for curvature discrimination in short, highly curved lines, but much less effect in the other lines that were used. By making a finely detailed study of the parameters of this effect, it was hoped that some understanding of the mechanisms involved might be gained.

The results obtained show that the effect of a single central gap is to reduce the limit on orientation range from about 40 degrees to around 30 to 35 degrees. The previous study had not sampled enough points to show this effect, although as was noted, the data obtained did suggest this conclusion.

There appear to be three possible gap conditions: unresolved gap (ie. no gap); resolved gap; and an extreme which may be a gap that is too large, or it may be the size of the remaining line segments that is too small. Within the extremes, the reduction in orientation range limit does not appear to be a function of gap size: if a gap is present and not too large, then the function relating efficiency to orientation range follows the same course as the equivalent function for unbroken lines, but behaves as if the orientation range of the stimulus were increased by the gap. The amount of the apparent effective increase in orientation range is not a function of gap size.

The present study has also brought to light some other interesting findings. In particular, there is a second high efficiency system, at the much higher curvature of between 0.10 and 0.14 rad/min. arc. This system is entirely novel, and there is no previous evidence of such a system in the data resulting from longer lines. The system does not appear for longer lines of the same orientation range, (see the data of Experiment 5), and informal measurements of efficiency for curvature discrimination in longer lines with the same curvature of 0.12 rad/min. arc suggest that these are also beyond the scope of this second system.

There are several interesting points to note about this system.

Firstly, the peak efficiency obtained for one of the subjects is very close to that for the first system at a curvature of 0.06 rad/min. arc (RJW).

Secondly, the rise and fall in efficiency as curvature increases is steeper than for the first system.

These observations suggest that this system is truly independent of the first system, but the data may reflect a combination of two estimates from the first, lower orientation range system. This point will be considered and compared with other known and potential examples of secondary integration of curvature information, in the next chapter.

This second system does appear to have some similar characteristics to those of the first system.
The optimum curvatures for this system are approximately twice those for the first system (with and without gaps). The gap has a similar effect in the two systems, although the effect is quantitatively twice that of the first system, in the second system.
It is intersting to note that the smallest gap size appears to have an ambivalent effect on efficiency for curvature discrimination in the region of this second system. It causes the established effect of a single gap, in displacing the peak efficiency to lower curvatures, but it also seems to be treated as an unresolved gap by the system. If this were to be the case, then this gap size might be very close to some critical value for this second system.

CONCLUSIONS : CURVATURE DISCRIMINATION IN SHORT UNBROKEN AND BROKEN LINES.

The following conclusions may be drawn from the results of this experiment.

Firstly, the hypothesis that the range of orientations that may be combined with high efficiency to provide curvature information is limited to between 35 and 40 degrees, is supported by the present results. This remains the most economical and sufficient description of the results for unbroken lines (and for lines broken by two gaps, one either side of the centre). However, this description requires two qualifications, which form the second and third conclusions to this study.

Secondly, the effect of a single central gap in a line of length 10 min. arc has been carefully determined. Provided that the gap is not too large or too small (the exact limits are not known, but gaps between 1.67 and 3.33 min. arc are suitable), the relationship between efficiency for curvature discrimination and orientation range of the stimulus is altered. Such a gap physically reduces the sum range of continuous orientation change in the stimulus (one potential interpretation of the concept of orientation range), but has an effect that is equivalent to ADDING a fixed amount of orientation range to the stimulus. The amount is apparently independent of gap size, within the limits.

Thirdly, a wholly unexpected second high efficiency system for curvature discrimination has been discovered. This system appears to be useful for very short, highly curved lines. It has some of the characteristics of the first system (the orientation range limited system). The effect of a 3.33 min. arc gap in the stimulus is the same. The rise in efficiency and subsequent fall as stimulus curvature increases are very similar to those found for the lower curvature system. However, the higher curvature system seems to be limited in its application to short lines only. It is certainly not limited by any simple manner, in orientation range: a stimulus of length 20 min. arc and curvature 0.067 rad/min. arc has an orientation range of 76.5 degrees, much the same as a stimulus of length 10 min. arc and curvature 0.13 rad/min. arc, but it does not share the same high efficiency for curvature discrimination. The limits for this system remain unclear.

The possibility exists that this system could arise from parallel analysis of the two halves of the stimulus by the orientation range limited system, with a highly efficient secondary integration of the results. This will be discussed in the next chapter.

The next chapter will consider the implications of these results, in conjunction with the results of the previous experiments.

CHAPTER 8. : THE VISUAL ANALYSIS OF STRAIGHT AND CURVED LINES.

8.1 Introduction.

The visual system has been known to be very sensitive to small features and differences in line figures, for the last hundred years. It is however, only recently that the significance of these sensitivities to contour shape, size, position and attitude has begun to be appreciated.

Chapter 1 contains a detailed description of the results of the recent experiments, which have led to some understanding of how visual space is differentiated. It was suggested that the results of these recent investigations are in sum consistent with the action of only two parallel types of process : one concerned with line shape differentiation over a region of space measuring approximately 30 min. arc by 5 min. arc; the other concerned with slope estimation, and involving a smaller region, probably 10 min. arc long. Further, it was pointed out that the obtained variable error for tasks of absolute position judgement was consistent with the use of the former process for this purpose, despite a total loss of absolute position information within the region of space served by it.

All the stimuli used in these experiments were straight lines. It was suggested that it would be useful to know whether curved lines excite, and are analysed by the same types of process, or whether the visual system has alternative processes for curved line stimuli.

8.2 The Results of the Present Experiments Summarized.

The major results and findings of this study will now be collected and summarized into two broad categories. Firstly, responses to straight and curved lines will be compared and contrasted. Then the findings on curvature discrimination in curved lines will be described.

8.2.1 Straight vs. Curved Lines.

The present data show that there is one basic similarity and five differences between the responses of the visual system to straight lines and to curved lines.

Curved lines and straight lines are similar, in that each can support a high efficiency discrimination of curvature, under appropriate conditions. The determinants of these conditions are rather different however, and add up to a considerable difference in the manner in which curved lines and straight lines are analysed by the visual system.

i). Curvature discrimination for curved lines requires considerable practice to reach plateau performance. This is not found to be the case for straight lines. (See p. 101).
ii). The discrimination of curvature in curved lines requires a reference to be physically present. This is not so for straight lines.
iii). There are differences, albeit small, in the effects of stimulus duration on curvature discrimination in curved and straight lines. (See Experiment 1).

iv). When a reference stimulus is present, the effects of the distance separating it from the test stimulus are quite different for the discrimination of curvature in straight and curved lines. (See Experiment 6).

v). The effects of gaps in the test stimulus on the performance of curvature discrimination in curved and straight lines are also quite distinct. (See Experiment 8).

On the basis of these results, it is proposed that the visual analysis of curved lines and straight lines must use processes that are, at least in part, different and distinct.

8.2.2 Curvature Discrimination in Curved Lines.

The discrimination of curvature in curved lines, under optimum conditions, is as efficient as (if not more efficient than) the optimum curvature discrimination for straight lines. This is a surprising result.

8.2.2.1 Orientation Range.

There are found to be two basic parameters which affect the efficiency with which curvature discrimination judgements of curved lines are made, namely, stimulus curvature and stimulus length. It is further found that their joint effects are most economically described by reference to their algebraic product. This quantity can be interpreted, conceptually, as a function of the distribution of orientations within the stimulus. The orientation range, or spread of this distribution, is found to be a useful concept to describe the important parameters determining efficiency for curvature discrimination in unbroken stimuli.

8.2.2.2 Orientation Range Limit.

There appears to be a limit to the orientation range which may be used for high efficiency curvature discrimination. The limit in the two subjects extensively tested (RJW and NL, see Experiment 5) is at 40 degrees of slope.

Efficiency rises with increasing orientation range of the stimulus, up to the limiting value, and then falls more steeply with further increases in orientation range. This relationship is illustrated in Fig. 8.1, which shows the combined results of Experiment 5 and the zero gap size results of Experiment 9. The continuous lines drawn on the data have a theoretical basis, and will be described below.

8.2.2.3 Modifications to the Relationship Between Orientation Range and Performance Measured.

The relationship between efficiency for curvature discrimination, and stimulus orientation range has two factors which may be modified by appropriate conditions : the orientation range limit, and the peak level of efficiency.

Orientation range limit is reduced to about 25 to 30 degrees by using oblique stimuli, and reduced to about 35 degrees by adding one central gap to the test stimulus.

Peak efficiency is not altered by these two procedures.

The size of the gap is not important : smaller gaps do not lead to intermediate orientation range limits. It is not known whether intermediate orientation range limits might result from using intermediate stimulus slants.

Peak efficiency is reduced by adding two gaps to the test stimulus, one either side of the centre, and peak efficiency is raised by increasing the separation between the test and comparison stimuli from 5 min. arc to 15 min. arc. Neither of these two procedures changes the orientation range limit.

None of these procedures which affect orientation range limit or peak efficiency appear to change the obtained efficiencies beyond the limit.

8.2.2.4 Secondary Integration of Curvature Information.

Fig. 8.1 shows the obtained relationship between orientation range and efficiency. The continuous lines also show a hypothetical relationship that would be obtained if only the central 40 degrees of orientations and none others were used for curvature discrimination : that is, the relationship between orientation range of the stimulus and efficiency for curvature discrimination, were the information for the task governed by an absolute limit on the orientation range. Clearly there is some further integration of curvature information in the visual system, beyond the limit.

The data in Fig. 8.1 suggests that the higher curvatures in Experiment 5 have a more efficient secondary integration of curvature information than the lower curvatures. This is surprising : smaller stimuli at a given orientation range are subject to a more efficient secondary integration.

8.2.2.5 A Second Process for Curvature Analysis.

Finally, there appears to be another system for curvature analysis, that is restricted to small stimuli of high curvature. Very little else is known about this system. Peak efficiency in RJW is comparable to that for the first curvature system (that limited by orientation range); but is slightly lower in NL. The effect of adding a gap to the stimulus is to reduce the optimum curvature (or whatever turns out to be the appropriate parameter) for the discrimination of curvature.

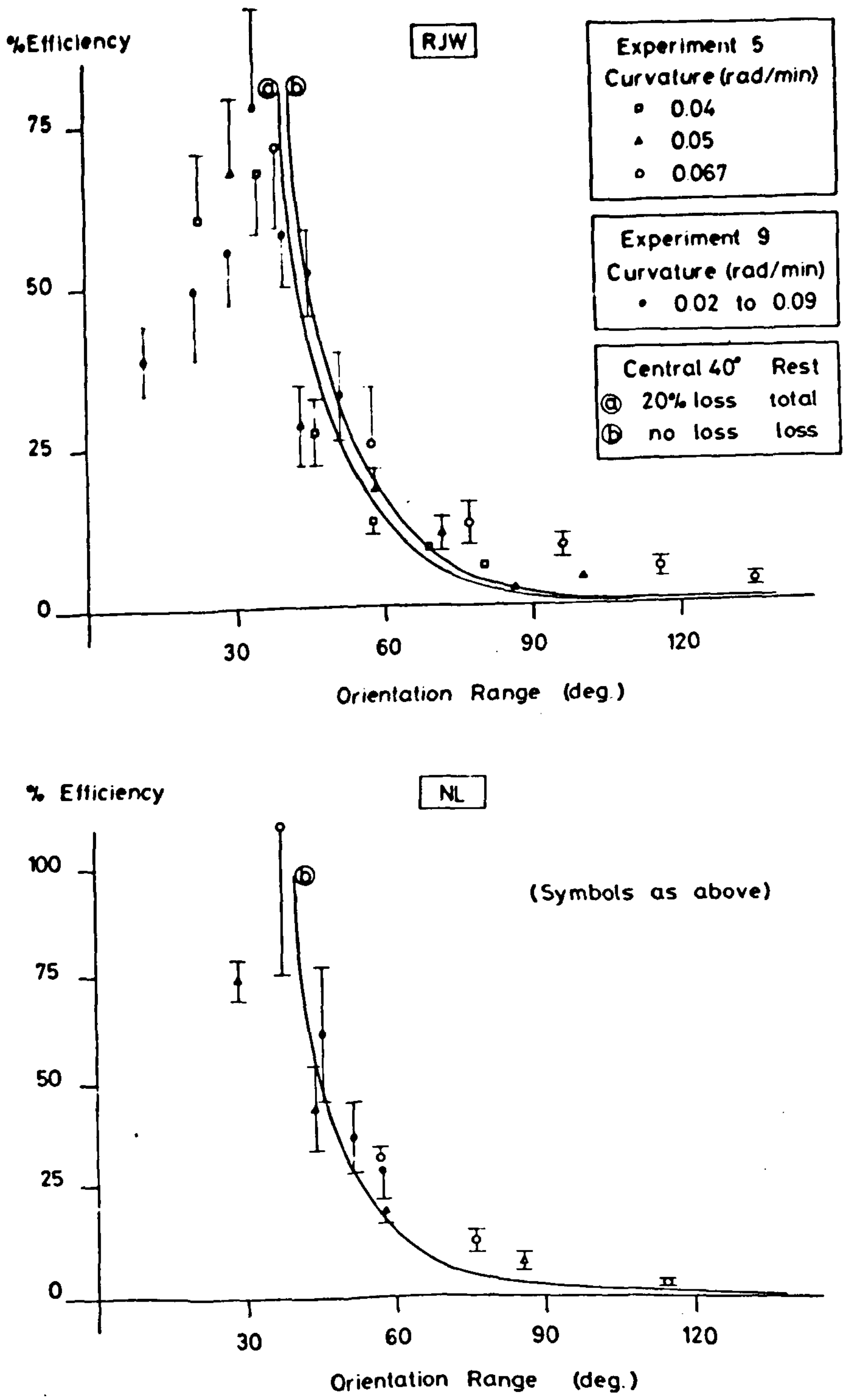


Fig. 8.1 Efficiency for curvature discrimination as a function of stimulus orientation range: the results of Expt. 5 and the unbroken stimulus condition of Expt. 9. The significance of the functions 'a' and 'b' is described in section 8.2.2.4.

8.3 General Conclusions.

The basic findings of this study are :

i) Curved lines may be processed by the visual system, for curvature discrimination, as efficiently as straight lines.

ii) There are, however, considerable differences between the detailed performance of curvature discrimination for curved lines and for straight lines.

iii) The efficiency for curvature discrimination of curved lines is economically described by one parameter, the stimulus orientation range.

iv) The relationship between efficiency and orientation range may be modified by certain alterations to the stimulus array.

v) There appears to be a further process for analysing highly curved short lines.

These lead to a number a general conclusions.
It now seems likely that curved lines and straight lines excite different, but parallel processes. At present there is no simple way to unify the two sets of results : such a way may be found on the basis of further experiments, but at present it seems more useful and preferable to consider them as distinct.
The conclusions may, therefore, be divided into three groups : those concerning straight lines; those concerning curved lines; and those concerning highly curved short lines that seem to excite a different curvature process.

8.3.1 The Visual Analysis of Straight Lines.

In Chapter 1, a process was described, that is concerned with spatial differentiation, over a region of space measuring approximately 30 min. arc by 5 min. arc. Andrews, Butcher and Buckley (1973) found that several different spatial shape tasks shared common properties of high efficiency performance and length tolerance. They described these tasks collectively by the embracing term of 'collinearity-failure detection'.
The present results suggest that this concept is still valid and useful, but not so general. Such a concept cannot describe all highly accurate shape tasks, but instead, it may be used to describe all the tasks that may be performed at high efficiency by use of that shape process described in Chapter 1. Curved lines seem to be beyond the competence of this process.

The present data add a little to the understanding of this process. There is a difference between the results for the discrimination of curvature using straight lines, obtained in Experiment 5 of the present study, and those of Andrews, Butcher and Buckley (1973).
In the present Experiment 5, high efficiency for curvature discrimination was only obtained for lines of length less than about 15 or 20 min. arc. Andrews et al. (1973) found that efficiency for curvature discrimination is high for stimuli up to about 30 min. arc in length.

There is one major difference between the two experiments : the test stimulus was alone in the experiment of Andrews et al. (1973), whereas in the present study, it was accompanied by a reference stimulus of the same length, and 5 min. arc apart. If this is the cause of the difference in the two sets of results, then it has some interesting implications. It may be that the effect of flanking stimuli (on vernier resolution), reported by Westheimer and Hauske (1975) interacts with the length tolerance of the process. The results of Westheimer and Hauske (1975) were obtained by using a 20 min. arc long target, and show a rise in threshold when a flanking stimulus is present 5 min. arc to the side of the target stimulus. Such result could be accounted for by a drop in the length tolerance of the process from 30 min. arc to about 15 min. arc, as is suggested would occur, by the results of the present Experiment 5. Further evidence to support this idea is provided by the results of Experiment 6. For separations between test and comparison stimulus that are greater than 5 min. arc, the length tolerance is increased to between 25 and 30 min. arc, and the resultant data is consistent with that of Andrews et al. (1973). Westheimer and Hauske (1975) also find that the interaction between target and flanking stimulus drops for separations that are greater than 5 min. arc. Some insight into the operation of the flanks might be suggested by the finding in Experiment 8 of the present study, that adding one or two gaps to the test stimulus appears to prevent this lateral interaction. This may be important, at present the implications are obscure.

This argument suggests that the differences between the length tolerances of the shape tasks, on the one hand, and the slope estimation and comparison tasks on the other, might also be attributable to the operation of interference between the test and reference in the latter.

Andrews (1967b) has found that the separation between test and comparison stimuli does not affect performance, for separations up to at least 30 min. arc. Andrews (personal communication) has suggested that a more likely candidate explanation could be the fact that the slope comparison task uses the comparison stimulus as a reference for judgements, unlike the present experiments involving straight lines, where the so-called comparison stimulus is probably passive. This suggestion requires careful testing.

8.3.2 The Visual Analysis of Curved Lines.

The relationship between the orientation range of a stimulus, and the efficiency measured for the discrimination of the curvature of that stimulus, has been described in detail above in section 8.2 ; it now remains to draw some tentative conclusions concerning the process behind this relationship.

8.3.2.1 A Limit on the Range of Orientations that may be Combined Efficiently.

There apparently exists a strict limit on the range of orientations that may be combined with high efficiency for curvature discrimination. The effects of this limit on efficiency are quite abrupt, and stimulus curvature and length space is partitioned into two distinct regions, one subject to high efficiency curvature discrimination, the other subject to very much lower efficiency.
This partition of stimulus curvature and length space into regions of high efficiency or low efficiency processing, is taken as indicating the existence of a separate visual analysis process, concerned with the spatial differentiation of curved lines of orientation range not greater than 40 degrees.

It is difficult to imagine any natural way that a process that is not concerned with some form of slope analysis, can be limited by stimulus orientation range. That such a process is involved in curvature discrimination shows that the slope analysis results are combined to determine the more complex types of contour shape, such as curvature.

It is suggested that there is a high efficiency process that is concerned with the determination and analytical combination of local contour orientations. The process has two stages : a contour is represented by its first derivative (or some similar function), which is then in turn used to extract curvature information.

The orientation range limit can be altered by two modifications to the stimulus : the use of oblique stimuli reduces the orientation range limit to about 25 to 30 degrees; the addition of a single central gap reduces it to about 30 to 35 degrees. In the case of the gap there are two further interesting features.
Firstly, the orientation range limit is independent of gap size, within limits of resolution, as is the threshold for curvature discrimination in a broken stimulus.
Secondly, the position of the gap is clearly important, since adding two gaps, one either side of the centre, does not reduce the orientation range limit.

There are two conclusions that are suggested by these results.
Firstly, it seems reasonable to conclude that, within the orientation range limit, the single central gap does not split the stimulus into two halves for the purposes of processing. If the orientation range limit were increased by the addition of a gap, it would be feasible that the two halves were being processed separately by two obliquely oriented processes (such as happens in the case of very short lines that are broken or unbroken : see the results of Experiment 9, and the discussion on p.248). This possibility is ruled out by the finding that orientation range is, in general, decreased by a single central gap.

Secondly, the two findings concerning the effects of the size and the position of the gap, and the effects of using oblique stimuli, taken together, suggest that the near horizontal orientations might be the most important in determining the orientation range limit. If the near horizontal orientations are present, the limit is 40 degrees; if they are absent, orientation range limit is 30 degrees. This can be expressed alternatively as follows. It could be those orientations nearest to the point of fixation that determine the limit: if they are horizontal, 40 degrees is the limit; if not, 30 degrees is the limit.

This argument presupposes that the two different findings may be taken together. This may not be valid, in which case quite different conclusions could be reached. Further experiments are suggested to decide the point.

A result of this conclusion is that the more extreme orientations cannot be regarded as being recorded more accurately than the central orientations : efficiency for curvature discrimination reaches the same levels when the most extreme orientations are no longer acceptable to the process.

8.3.2.2 Changes in Efficiency Within the Orientation Range Limit.

Within the limit of orientation range, efficiency rises with increasing orientation range of the stimulus. The relationship is approximately linear (see Fig. 8.1). This is a very important clue to lead to an understanding of the organization of information within this process.

Consider two ways in which orientation range of the stimulus might be increased : by increasing curvature at a given line length; or by increasing line length at a given stimulus curvature. In both cases efficiency for curvature discrimination rises.

That <u>efficiency</u> should increase with increasing stimulus curvature at a given line length, implies that more information is being extracted and analysed, despite the fact that no more information is physically present.

That <u>efficiency</u> should rise with increasing line length at a given stimulus curvature, implies that not only is more information being analysed (which of itself would lead to no more than an unchanged efficiency), but that the overall accuracy of analysis is improved.

The effect of increasing stimulus curvature, at a constant line length seems to indicate that the process is able to make more samples at the higher curvatures. This is plausible, if the process is sampling local slope information. At the same time, it is important to note that the accuracy of the samples does not decrease. An increase in the accuracy of the samples alone could explain the rising efficiency, but this seems implausible.

That efficiency also rises with increasing line length at a fixed stimulus curvature indicates that the overall accuracy of the samples must increase, or that there is a preferential weighting for the more extreme orientations. It has already been concluded that the extreme orientations cannot be regarded as being recorded more accurately than the central orientations (p.239), and therefore, the first of these alternatives is preferred. It seems plausible that under these conditions, the accuracy of the samples would increase.

The level of efficiency for curvature discrimination for stimuli of orientation range less than the limit can be modified by two alterations to the stimulus array. Efficiency is raised by increasing the distance separating test and comparison stimuli, or it can be lowered by adding two gaps to the test stimulus, one either side of the centre. Increasing the separation between test and comparison stimuli from 5 min. arc to 15 min. arc doubles peak efficiency. Adding two gaps reduces efficiency by a smaller amount.

The effect of stimulus separation is curious. It does not suggest flanking zones capable of interference, such as are found for the straight line process, and reported by Westheimer and Hauske (1975). It is clear that efficiency cannot rise indefinitely, with increasing stimulus separation, but the range of lateral interaction appears to be different from that for straight lines. There is another difference. It has been suggested, on the basis of the data for straight lines in the present study, that the effect of contours in the flanking zones is to reduce the length tolerance of the process. The lateral interactions on curved lines do not appear to modify the orientation range tolerance of this process. This is a strong contrast.

The effect of adding two gaps to a curved stimulus is also quite different from the equivalent effect on efficiency for curvature discrimination in straight lines. For curved lines, peak efficiency drops, but the orientation range limit is unchanged. For straight lines, peak efficiency rises, and the length limit is increased. This is another strong contrast.

That peak efficiency for the curved line process should drop indicates that the addition of the gaps does more than just remove useful or even redundant information (in which case, efficiency should be unchanged or even rise). Either the overall accuracy of the samples of slope information is reduced, or the number of such samples covering those parts of the lines remaining is reduced.

8.3.2.3 The Limited Orientation Range Curvature System.

In summary, the findings relating to stimuli that fall within the orientation range limit lead to the following tentative conclusions and speculations.

i) There is a primary sampling of some slope function of the contour over a limited range of orientations of 40 degrees of slope. This function is likely to be of local slope differences and changes.

ii) These samples are combined to provide estimates of line curvature.

There are two ways in which <u>efficiency</u> for curvature discrimination (not precision) could, in theory, be altered. Either the number of samples for a given portion of the stimulus could change, or the accuracy of the samples could change. It should be noted that the latter does not draw a distinction between the accuracy of sampling, and the accuracy of using, or combining these samples (these two possibilities cannot be directly distinguished by psychophysical data).

iii) The evidence suggests that the number of samples is a direct function of the stimulus orientation range. Increasing orientation range, at a constant line length leads to an improvement in the efficiency for curvature discrimination (ie. greater information uptake). Samples are taken, therefore, at fixed points on the slope distribution, and not in space.

iv) Accuracy of sampling improves with increased orientation range. Increasing line length at a fixed stimulus curvature leads to an improved <u>efficiency</u> (as well as precision) : the addition of extra stimulus information to a curved line results in more efficient use of the information already present in that given line, as well as more efficient use of the information in the portion added.

v) The presence or absence of near horizontal slopes within the stimulus (or alternatively, the orientation of those slopes nearest to the fixation point, or the centre of the curve, horizontal or not), determines the orientation range limit. Both oblique unbroken stimuli and horizontal stimuli with a central gap are subject to curvature discrimination with an orientation range limit of about 30 degrees.

vi) Peak efficiency for such stimuli, with the optimum orientation range of 30 degrees, is higher than the efficiency for unbroken horizontal stimuli with an orientation range of 30 degrees. It is unlikley that these two modifications result in an increased density of sampling, and therefore, it seems more likely that the accuracy of sampling is changed.

Accuracy of sampling appears to be a function of the proximity of the actual stimulus orientation range to the limiting orientation range in operation.

It is as if the process has a set range of slopes which it invariably uses to estimate curvature, whether they are physically present or not, in the stimulus. When the more extreme orientations are not present, this part of the working range adds noise to the process, and reduces its efficiency.

This would also explain why two gaps (non-central) reduce efficiency. The 'active' orientation range of the stimulus (that portion of the overall orientation range which has contour present) is 3/5 of the overall stimulus orientation range : efficiency obtained corresponds to this 'active' orientation range, not the overall range.
For example, efficiency for a stimulus of curvature 0.067 rad/min. arc and length of 10 min. arc is 60.5% when the line has two gaps present. This stimulus has an overall orientation range of 38.4 degrees, and an active orientation range of 23 degrees. Compare this efficiency with the following data for unbroken stimuli : a stimulus of curvature 0.04 rad/min. arc and length 10 min. arc has an orientation range (overall and active) of 23 degrees, and is processed for curvature discrimination with an efficiency of 60.25%; a stimulus of curvature 0.067 rad/min. arc and length of 10 min. arc has an orientation range of 38.4 degrees and is processed with an efficiency of 71.5%.
Clearly it is the active orientation range that determines efficiency for curvature discrimination.

That efficiency is not affected by one central gap in the same manner, is awkward. It seems that the operation of changing the orientation range limit must cause less weight to be placed on the horizontal orientations. Perhaps there exists a process which specialises in the analysis of non-horizontal orientations, with slightly different characteristics.

8.3.2.4 Secondary Integration of Curvature Information from Stimuli that Exceed the Orientation Range Limit.

The data of Experiment 5 clearly shows that there is some secondary integration of curvature information from stimuli that exceed the orientation range limit : the fall in efficiency is not as steep as would be expected were there none. The difference is small, but significant. That it is small and regular suggests that the difference is not due to the operation of further processes, parallel to the orientation range limited process, and with larger stimulus tolerances. Therefore, it seems much more likely that the difference is due to some sort of secondary combination of curvature estimates from a number of primary orientation range limited processes.

The data appears to suggest that the integration of curvature estimates from different primary processes is more efficient for lines of higher curvature and shorter length. In such a case, the processes providing estimates for combination, would be closer together, than when the stimulus had lower curvature and longer length. This suggests that the actions of secondary integration of curvature information are restricted in spatial extent.

As an aside, it is worth noting that all subjects reported that the larger stimuli appeared distorted, since this may also throw some light on the processes of secondary integration. The distortions were all identical : subjects reported that the ends of the larger curves appeared 'droopy', or were 'bent downwards'. These distortions were intermittent, and not necessarily apparent in both test and comparison at the same time. They appeared to take about one second to build up to maximum strength.

A similar effect has been observed by Andrews (personal communication). If a heavy outline of a circle is fixated, then after a short time the circle appears to be distorted, and takes on the shape of a smoothed polygon with about ten edges.

In each case, it could be that there is no overlap between adjacent curvature analysers, and the 'joints' become apparent perceptually. It would be very surprising, if it turned out that there was no overlap between these orientation range limited curvature analysers. The effects require detailed study, but may provide useful information about the processes of curvature analysis in large curves.

8.3.3 High Curvature System.

The data of Experiment 9 show that there is another system for curvature discrimination, operating at much higher curvatures. Informal experiments have suggested that its operation is limited to short lines, or short ranges of high curvature.
This high curvature system shares several properties with the lower curvature orientation range limited system, described in section 8.3.2. Efficiency for curvature discrimination rises, and then falls with increasing stimulus curvature. The effect of adding a single central gap to the stimulus is also similar.

Very little can be said about this high curvature system. It reaches a similar peak efficiency to that of the first system, in one of the two subjects. The intervening curvatures are processed at much lower efficiencies. This suggests that it might be an independent process.
It is, however, also possible that this high curvature system represents highly efficient integration of the ouput estimates given by the lower curvature system. These estimates would be from very close parts of space, and it has already been suggested that this situation leads to a higher efficiency for secondary integration.
The question remains unanswered.

It is worth noting that such a system could have great value for the general operation of pictorial analysis. Attneave (1954) drew attention to the information value of the points of high curvature in contours. He presents a schematic picture of a sleeping cat, that is quite recognisable, formed from only the 38 points of maximum curvature, and the straight lines joining them. All that is needed for a complete description of this figure is a specification of the positions of the points, and the orientation change at these points (see Fig. 8.2). Might not this high curvature system be useful in providing such an analysis ?

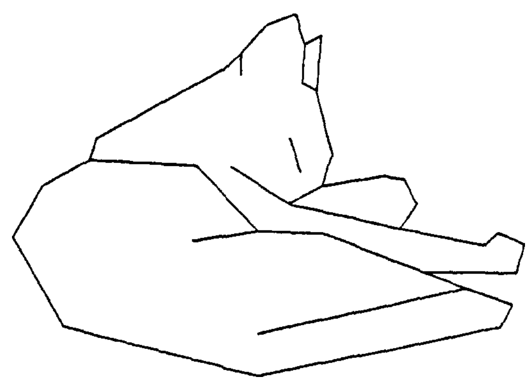


Fig. 8.2 Drawing made by abstracting 38 points of maximum curvature from the contours of a sleeping cat, and connecting these points appropriately. (After Attneave, 1954 fig. 3).

8.4 Questions Arising, and Research Suggested.

The least surprising result of this study is that there now exist more rather than fewer interesting questions, than did before the study was begun. The questions are more specific, but given perhaps three or four processes for the analysis of line information, the general question of 'What else ?' still remains.

There are a number of points concerning the straight line process, that require clearing up. The effect of flanking stimuli has been suggested, and could be easily verified. The possibility of a direct relationship between this shape process and that for slope comparisons has also been hinted at, and would suggest further research.

There are also a number of points concerning the primary, orientation range limited process for curved lines, that would suggest useful experiments. The first point to establish is whether this process can also support tasks such as vernier resolution (of curved stimuli), in addition to that of curvature discrimination. The suggestion as to the mechanism for the combination of slope information requires close investigation, as does the mechanism for the changes in orientation range limit. This latter problem should be examined to establish whether there are only two (or some other small number) of orientation range limits, or whether there is a continuum. The position of a single gap in the test stimulus would be a useful experimental parameter. Likewise, the orientation of the stimulus array should be varied in small steps, to establish the role of near horizontal orientations. The properties of secondary integration of curvature information are also suggestive of many experiments.

The high curvature system is almost completely a mystery. There is a great deal of information to be gathered before the system can be understood.

It is with great pleasure, that I finish this thesis on a note of mystery.

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ADDENDA

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APPENDIX : TABLES OF EXPERIMENTAL RESULTS.

For each experiment the following data is quoted :

i) Grand mean PSE.

ii) Overall RMS standard deviation.

iii) Overall efficiency.

iv) & v) & vi) Standard deviations of the distribution of the estimates of these statistics.

Table numbers and experiment numbers correspond.

TABLE 1. : CURVATURE DISCRIMINATION AS A FUNCTION OF STIMULUS DURATION.

1). Stimulus curvature = 0.00 rad/min. arc.

length = 20.0 min. arc

Duration(ms.)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
10	3.205E-5	5.130E-3	13.690	RJW
50	3.043E-5	5.636E-3	15.186	
100	2.785E-5	5.721E-3	18.132	
500	1.551E-5	4.236E-3	58.489	
1000	1.375E-5	3.241E-3	74.404	
2000	1.343E-5	3.747E-3	77.968	
50	6.568E-5	-1.601E-3	3.461	RSS
100	5.621E-5	-3.247E-3	4.736	
500	4.047E-5	-1.346E-3	9.128	
1000	1.529E-5	-1.690E-3	31.973	
2000	2.694E-5	-0.805E-3	20.595	

2). Stimulus curvature = 0.05 rad/min. arc.

length = 20.0 min. arc.

Duration(ms.)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
10	5.150E-5	5.019E-2	12.33	RJW
50	4.273E-5	4.826E-2	17.31	
100	3.362E-5	4.934E-2	28.89	
500	3.170E-5	4.896E-2	32.33	
1000	2.863E-5	4.833E-2	53.30	
2000	2.275E-5	4.727E-2	61.07	
50	1.086E-4	4.989E-2	2.725	RSS
100	8.014E-5	5.298E-2	5.000	
500	7.096E-5	5.483E-2	6.454	
1000	5.725E-5	5.577E-2	9.798	
2000	6.636E-5	5.649E-2	7.488	

TABLE 1a. : SD. OF DISTRIBUTION OF INDIVIDUAL ESTIMATES.

1). Stimulus curvature = 0.00 rad/min. arc.

length = 20.0 min. arc.

Duration(ms.)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
10	0.306E-5	0.118E-3	1.069	RJW
50	0.476E-5	0.190E-3	1.941	
100	0.835E-5	0.203E-3	4.437	
500	0.251E-5	0.314E-3	9.842	
1000	0.246E-5	0.211E-3	10.885	
2000	0.243E-5	0.265E-3	11.535	
50	0.556E-5	0.435E-3	0.286	RSS
100	1.068E-5	0.859E-3	0.389	
500	1.148E-5	0.644E-3	0.160	
1000	0.583E-5	0.165E-3	0.043	
2000	0.148E-5	0.102E-3	0.015	

2). Stimulus curvature = 0.05 rad/min. arc.

length = 20.0 min. arc.

Duration(ms.)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
10	0.890E-5	0.130E-2	0.916	RJW
50	1.082E-5	0.155E-2	2.264	
100	0.588E-5	0.079E-2	2.530	
500	0.799E-5	0.104E-2	4.091	
1000	0.354E-5	0.116E-2	3.756	
2000	0.396E-5	0.050E-2	10.644	
50	0.286E-5	0.175E-2	0.132	RSS
100	0.289E-5	0.189E-2	0.535	
500	2.183E-5	0.078E-2	1.716	
1000	1.345E-5	0.110E-2	1.879	
2000	1.765E-5	0.177E-2	1.848	

TABLE 2. : THE EFFECT OF STIMULUS CURVATURE ON DISCRIMINATION OF THE DISTANCE SEPARATING TWO CONTOURS.

Target separation distance = circle diameter.

Stimulus size = 120 degrees of the circle circumference.

1). With central fixation spot.

Diameter(r/m)	Threshold(s.)	PSE(m.)	Efficiency(%)	
10.0	18.095	1.054	18.230	RJW
15.0	25.688	1.104	7.375	
20.0	29.688	1.843	4.926	
25.0	43.962	0.072	2.052	
30.0	34.108	1.599	3.224	
40.0	35.349	1.470	2.883	
50.0	55.324	2.652	1.153	
20.0	28.138	-0.291	5.463	JIK
25.0	41.203	-9.950	2.336	
30.0	32.715	-1.463	3.504	
40.0	48.563	-2.168	1.527	
50.0	71.733	-2.219	0.686	

2). Without central fixation spot.

Diameter(r/m)	Threshold(s.)	PSE(m.)	Efficiency(%)	
10.0	15.888	0.874	23.646	RJW
15.0	23.104	0.303	9.117	
20.0	29.266	-0.431	5.050	
25.0	30.935	0.408	4.153	
30.0	36.612	-1.263	2.798	
40.0	43.890	-0.916	1.870	
50.0	58.037	-0.610	1.048	

TABLE 1a. : SD. OF DISTRIBUTION OF INDIVIDUAL ESTIMATES.

Target separation distance = circle diameter.

Stimulus size = 120 degrees of the circle circumference.

1). With central fixation spot.

Diameter(r/m)	Threshold(s.)	PSE(m.)	Efficiency(%)	
10.0	5.141	0.224	5.179	RJW
15.0	6.774	0.292	2.245	
20.0	2.045	0.076	0.482	
25.0	0.883	0.242	0.058	
30.0	7.500	0.388	0.819	
40.0	4.128	0.410	0.389	
50.0	8.369	0.751	0.156	
20.0	3.258	0.006	0.895	
25.0	10.426	0.216	0.836	
30.0	5.867	0.060	0.726	
40.0	14.829	0.153	0.539	
50.0	17.312	0.363	0.191	

2). Without central fixation spot.

Diameter(r/m)	Threshold(s.)	PSE(m.)	Efficiency(%)
10.0	2.725	0.369	3.628
15.0	2.069	0.506	0.943
20.0	6.695	1.382	1.334
25.0	3.251	1.390	0.378
30.0	7.452	0.034	0.658
40.0	12.916	0.400	0.635
50.0	12.441	0.743	0.201

TABLE 3. : THE EFFECT OF STIMULUS CURVATURE ON THE DISCRIMINATION OF CURVATURE.

1). Fixed Line Length = 20.0 min. arc.

Curvature(r/m)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
0.0286	2.857E-5	3.003E-2	39.090	RJW
0.0333	2.675E-5	3.537E-2	44.821	
0.04	3.283E-5	4.016E-2	33.203	
0.05	3.139E-5	4.810	36.704	
0.0667	3.067E-5	6.593E-2	35.857	
0.08	3.389E-5	7.867E-2	29.682	
0.0333	4.183E-5	3.552E-2	18.334	JIK
0.05	4.058E-5	5.097E-2	21.960	
0.0667	5.332E-5	6.865E-2	11.863	
0.08	6.175E-5	8.526E-2	8.938	

2). Fixed Chord Length = 20.0 min. arc.

Curvature(r/m)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
0.0333	3.010E-5	3.273E-2	31.818	RJW
0.05	2.862E-5	4.912E-2	31.813	
0.0667	2.771E-5	6.606E-2	28.711	
0.08	2.683E-5	8.207E-2	24.223	
0.0286	3.118E-5	2.611E-2	33.823	IEB
0.0333	3.266E-5	2.861E-2	30.358	
0.04	2.967E-5	3.579E-2	32.358	
0.05	3.479E-5	4.203E-2	21.533	
0.0667	5.043E-5	6.038E-2	8.668	
0.08	4.740E-5	7.115E-2	7.762	

TABLE 3a. : SD. OF DISTRIBUTION OF INDIVIDUAL ESTIMATES.

1). Fixed Line Length = 20.0 min. arc.

Curvature(r/m)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
0.0286	0.514E-5	0.099E-2	5.317	RJW
0.0333	0.512E-5	0.086E-2	7.675	
0.04	0.217E-5	0.020E-2	2.197	
0.05	0.869E-5	0.051E-2	10.161	
0.0667	0.466E-5	0.173E-2	4.114	
0.08	0.881E-5	0.024E-2	8.908	
0.0333	0.917E-5	0.158E-2	4.608	JIK
0.05	0.820E-5	0.047E-2	3.623	
0.0667	0.735E-5	0.106E-2	1.236	
0.08	1.300E-5	0.235E-2	2.172	

2). Fixed Chord Length = 20.0 min. arc.

Curvature(r/m)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
0.0333	0.378E-5	0.036E-2	2.308	RJW
0.05	0.955E-5	0.120E-2	8.666	
0.0667	0.790E-5	0.078E-2	5.178	
0.08	0.737E-5	0.114E-2	5.962	
0.0286	0.241E-5	0.019E-2	3.017	IEB
0.0333	1.025E-5	0.050E-2	11.003	
0.04	0.171E-5	0.057E-2	2.638	
0.05	0.258E-5	0.056E-2	2.258	
0.0667	2.077E-5	0.038E-2	4.124	
0.08	1.075E-5	0.179E-2	2.034	

TABLE 4. : THE EFFECT OF STIMULUS LENGTH ON THE DISCRIMINATION OF CURVATURE AT A FIXED STIMULUS CURVATURE.

Stimulus curvature = 0.05 rad/min. arc.

Chord L.(m.)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
7.5	2.722E-4	6.443E-2	50.088	RJW
10.0	1.188E-4	5.589E-2	64.972	
15.0	5.041E-5	4.932E-2	42.942	
20.0	2.862E-5	4.912E-2	31.813	
25.0	2.711E-5	4.882E-2	11.410	
30.0	2.055E-5	4.901E-2	8.916	
35.0	1.621E-5	4.994E-2	4.531	
7.5	2.657E-4	9.612E-2	52.600	JIK
10.0	1.364E-4	7.450E-2	49.256	
15.0	7.530E-5	6.847E-2	19.250	
20.0	6.903E-5	6.024E-2	5.467	
25.0	5.115E-5	5.649E-2	3.160	
30.0	4.048E-5	5.340E-2	2.300	

TABLE 4a. : SD. OF DISTRIBUTION OF INDIVIDUAL ESTIMATES.

Stimulus curvature = 0.05 rad/min. arc.

Chord L.(m.)	Threshold(r/s)	PSE(r/m)	Efficiency(%)	
7.5	9.520E-5	0.023E-2	24.770	RJW
10.0	4.120E-5	0.325E-2	13.015	
15.0	1.237E-5	0.084E-2	8.607	
20.0	0.955E-5	0.120E-2	8.666	
25.0	0.683E-5	0.060E-2	2.034	
30.0	0.333E-5	0.053E-2	1.021	
35.0	0.515E-5	0.039E-2	1.287	
7.5	4.860E-5	0.500E-2	11.079	JIK
10.0	2.990E-5	0.270E-2	5.618	
15.0	0.809E-5	0.104E-2	2.387	
20.0	1.338E-5	0.123E-2	0.948	
25.0	0.777E-5	0.156E-2	0.562	
30.0	0.067E-5	0.069E-2	0.044	

TABLE 5. : THE JOINT EFFECT OF STIMULUS CURVATURE AND LENGTH ON THE DISCRIMINATION OF CURVATURE.

1). Thresholds (rad/sec. arc).

Line Length (m).	Curvature (rad/min. arc) 0.00	0.04	0.05	0.067	
10	1.409E-4	1.225E-4	1.155E-4	1.067E-4	RJW
15	5.105E-5	4.064E-5	6.614E-5	8.219E-5	
20	4.386E-5	3.669E-5	5.023E-5	4.543E-5	
25	2.635E-5	3.221E-5	4.366E-5	3.365E-5	
30	1.523E-5	2.351E-5	4.344E-5	3.081E-5	
35	9.075E-6	2.010E-5	2.381E-5	2.732E-5	
10	1.059E-4		1.055E-4	8.648E-5	NL
15	3.087E-5		5.365E-5	6.217E-5	
20	1.858E-5		4.047E-5	5.050E-5	
30	9.865E-6		2.593E-5	4.663E-5	

2). PSE's (rad/min. arc).

Line Length (m.)	Curvature (rad/min. arc)				
	0.00	0.04	0.05	0.067	
10	4.478E-3	4.477E-2	4.590E-2	6.358E-2	RJW
15	1.702E-3	3.969E-2	4.483E-2	6.740E-2	
20	1.911E-3	3.844E-2	4.820E-2	6.568E-2	
25	5.313E-4	3.938E-2	4.785E-2	6.614E-2	
30	-6.131E-5	4.229E-2	5.048E-2	6.538E-2	
35	-2.692E-4	4.245E-2	5.063E-2	6.588E-2	
10	-6.122E-3		3.670E-2	4.370E-2	NL
15	3.786E-3		4.265E-2	5.667E-2	
20	-1.562E-3		4.376E-2	6.258E-2	
30	-8.676E-4		4.657E-2	6.442E-2	

3). Efficiencies (%).

Line Length (m.)	Curvature (rad/min. arc)				
	0.00	0.04	0.05	0.067	
10	43.825	60.177	67.472	71.513	RJW
15	48.037	68.019	28.567	25.506	
20	16.560	27.332	18.322	13.488	
25	20.112	13.601	11.701	9.880	
30	20.812	9.357	2.824	5.740	
35	29.036	6.545	4.759	3.743	
10	70.555		74.740	110.91	
15	131.367		42.685	32.112	
20	90.544		19.609	12.959	
30	47.181		7.790	2.499	

TABLE 5a. : SD. OF DISTRIBUTION OF INDIVIDUAL ESTIMATES.

1). Thresholds (rad/sec. arc).

Line Length (m.)	Curvature (rad/min. arc)				
	0.00	0.04	0.05	0.067	
10	2.456E-5	2.535E-5	1.824E-5	1.879E-5	RJW
15	1.233E-5	0.601E-5	1.559E-5	4.702E-5	
20	2.125E-5	1.060E-5	1.638E-5	1.339E-5	
25	0.999E-5	0.774E-5	1.781E-5	1.0[illegible]5E-5	
30	0.669E-5	0.274E-5	1.297E-5	0.850E-5	
35	0.263E-5	0.239E-5	0.154E-5	0.593E-5	
10	1.669E-5		0.515E-5	2.388E-5	NL
15	0.701E-5		1.070E-5	0.426E-5	
20	0.258E-5		0.654E-5	0.841E-5	
30	1.014E-5		0.499E-5	1.086E-5	

2). PSE's (rad/min. arc).

Line Length (m.)	Curvature (rad/min. arc) 0.00	0.04	0.05	0.067	
10	0.066E-2	0.281E-2	0.708E-2	0.630E-2	RJW
15	0.197E-2	0.098E-2	0.176E-2	0.446E-2	
20	0.176E-2	0.203E-2	0.311E-2	0.476E-2	
25	0.094E-2	0.088E-2	0.104E-2	0.229E-2	
30	0.098E-2	0.075E-2	0.123E-2	0.037E-2	
35	0.057E-2	0.024E-2	0.042E-2	0.035E-2	
10	0.108E-2		0.217E-2	0.011E-2	NL
15	0.081E-2		0.029E-2	0.117E-2	
20	0.052E-2		0.348E-2	0.122E-2	
30	0.005E-2		0.070E-2	0.084E-2	

3). Efficiencies (%).

Line Length (m.)	Curvature (rad/min. arc)				
	0.00	0.04	0.05	0.067	
10	5.776	10.310	11.347	12.927	RJW
15	11.600	9.282	5.924	8.585	
20	8.022	5.244	3.382	3.349	
25	6.940	2.181	2.538	3.002	
30	6.915	0.824	0.744	1.582	
35	6.360	0.553	0.434	1.148	
10	12.841		4.564	35.367	NL
15	30.936		9.830	2.544	
20	9.804		2.658	2.491	
30	7.579		1.742	0.672	

TABLE 6. : THE EFFECT OF SEPARATION DISTANCE ON THE DISCRIMINATION OF CURVATURE IN LINES VARYING IN BOTH CURVATURE AND LINE LENGTH.

1). Separation = 10 min. arc. RJW

Line Length (min. arc)	Curvature (rad/min. arc)		
	0.00	0.05	0.067
i) Thresholds (rad/sec. arc).			
10	8.917E-5	1.109E-4	1.031E-4
20	1.883E-5	3.996E-5	5.164E-5
30	1.440E-5	3.083E-5	3.609E-5
ii) PSE's (rad/min. arc)			
10	3.625E-3	4.524E-2	5.994E-2
20	1.361E-3	4.882E-2	6.832E-2
30	4.194E-4	5.044E-2	6.848E-2
iii) Efficiencies (%)			
10	118.133	77.770	90.348
20	94.558	22.642	14.037
30	24.206	6.172	5.707

2). Separation = 15 min. arc. **RJW**

Line Length (min. arc)	Curvature (rad/min. arc)		
	0.00	0.05	0.067
i) Thresholds (rad/sec. arc).			
10	1.178E-4	9.994E-5	8.145E-5
20	2.366E-5	4.432E-5	5.493E-5
30	1.489E-5	1.911E-5	4.365E-5
ii) PSE's (rad/min. arc).			
10	-5.727E-3	4.745E-2	6.241E-2
20	1.126E-3	5.004E-2	6.929E-2
30	4.177E-4	5.077E-2	6.884E-2
iii) Efficiencies (%).			
10	77.997	110.132	166.634
20	67.741	20.826	14.050
30	25.233	17.736	4.747

2). Separation = 15 min. arc.

Line Length (min. arc)	Curvature (rad/min. arc)		
	0.00	0.05	0.067
i) Thresholds (rad/sec. arc).			
10	1.290E-5	1.128E-5	1.466E-5
20	0.170E-5	0.209E-5	1.363E-5
30	0.143E-5	0.412E-5	1.357E-5
ii) PSE's (rad/min. arc).			
10	0.111E-2	0.115E-2	0.291E-2
20	0.017E-2	0.034E-2	0.117E-2
30	0.145E-2	0.056E-2	0.017E-2
iii) Efficiencies (%).			
10	12.068	12.565	18.068
20	5.622	1.386	2.466
30	2.427	5.400	1.205

TABLE 6a. : SD. OF DISTRIBUTION OF INDIVIDUAL ESTIMATES.

1). Separation = 10 min. arc. RJW

Line Length (min. arc)	Curvature (rad/min. arc)		
	0.00	0.05	0.067
i) Thresholds (rad/sec. arc)			
10	0.677E-5	3.791E-5	3.790E-5
20	0.616E-5	0.815E-5	1.134E-5
30	0.455E-5	0.661E-5	0.561E-5
ii) PSE's (rad/min. arc).			
10	0.109E-2	0.283E-2	0.100E-2
20	0.020E-2	0.068E-2	0.106E-2
30	0.008E-2	0.045E-2	0.046E-2
iii) Efficiencies (%).			
10	10.362	37.609	20.020
20	33.517	5.335	2.181
30	7.643	1.528	0.724

TABLE 7. : THE JOINT EFFECTS OF STIMULUS CURVATURE AND LENGTH ON CURVATURE DISCRIMINATION IN OBLIQUE LINES.

Chord Orientation = 45 deg. RJW

Line Length (min. arc)	Curvature (rad/min. arc) 0.04	0.05	0.067
i) Thresholds (rad/sec. arc).			
10	9.695E-5	1.373E-4	1.753E-4
15	8.073E-5	9.473E-5	1.090E-4
20	5.898E-5	5.228E-5	5.727E-5
30	3.020E-5	3.738E-5	3.564E-5
ii) PSE's (rad/min. arc).			
10	3.874E-2	5.285E-2	5.977E-2
15	3.605E-2	4.270E-2	6.652E-2
20	3.387E-2	4.656E-2	6.256E-2
30	3.585E-2	4.561E-2	6.076E-2
iii) Efficiencies (%).			
10	88.118	44.086	27.192
15	18.319	13.768	10.448
20	9.104	11.764	10.108
30	5.669	4.016	4.289

TABLE 7a. : SD. OF DISTRIBUTION OF INDIVIDUAL ESTIMATES.

Chord Orientation = 45 deg. RJW

Line Length (min. arc)	Curvature (rad/min. arc)		
	0.04	0.05	0.067
i) Thresholds (rad/sec. arc).			
10	1.416E-5	0.969E-5	0.892E-5
15	1.738E-5	1.667E-5	2.684E-5
20	0.636E-5	0.958E-5	0.625E-5
30	0.876E-5	1.101E-5	0.991E-5
ii) PSE's (rad/min. arc).			
10	0.106E-2	0.125E-2	0.577E-2
15	0.171E-2	0.130E-2	0.066E-2
20	0.102E-2	0.088E-2	0.020E-2
30	0.040E-2	0.078E-2	0.097E-2
iii) Efficiencies (%).			
10	12.869	3.594	2.628
15	2.042	2.410	2.573
20	0.985	1.687	1.104
30	1.644	0.683	1.192

TABLE 8. : THE EFFECTS OF BREAKS IN THE STIMULUS ON DISCRIMINATION OF CURVATURE IN LINES VARYING IN BOTH STIMULUS CURVATURE AND LINE LENGTH.

1). Two Gaps. RJW

Line Length (min. arc)	Curvature (rad/min. arc)		
	0.00	0.05	0.067
i) Thresholds (rad/sec. arc).			
10	1.289E-4	1.434E-4	1.364E-4
20	3.069E-5	5.890E-5	5.130E-5
30	1.489E-5	2.926E-5	3.586E-5
ii) PSE's (rad/min. arc).			
10	-1.275E-3	3.507E-2	4.975E-2
20	-1.484E-3	4.101E-2	6.424E-2
30	-9.873E-4	4.537E-2	6.120E-2
iii) Efficiencies (%).			
10	70.683	54.442	60.474
20	71.861	14.401	19.185
30	36.301	9.814	6.616

2) One Gap.

Line Length (min. arc)	Curvature (rad/min. arc)			
	0.00	0.05	0.067	
i) Thresholds (rad/sec. arc)				
10	1.233E-4	1.526E-4	2.138E-4	RJW
20	2.247E-5	4.392E-5	4.801E-5	
30	8.196E-6	3.676E-5	3.878E-5	
10	1.041E-4	1.335E-4	1.573E-4	NL
20	1.835E-5	5.464E-5	6.064E-5	
30	6.582E-6	5.040E-5	6.224E-5	

Line Length (min. arc)	Curvature (rad/min. arc)			
	0.00	0.05	0.067	
ii) PSE's (rad/min. arc)				
10	3.345E-3	4.481E-2	6.508E-2	RJW
20	-5.967E-4	4.191E-2	6.179E-2	
30	-4.004E-4	4.592E-2	6.185E-2	
10	6.036E-4	3.193E-2	3.631E-2	NL
20	-7.206E-4	4.142E-2	5.885E-2	
30	-5.464E-4	4.446E-2	6.271E-2	

Line Length (min. arc).	Curvature (rad/min. arc)			
	0.00	0.05	0.067	
iii) Efficiencies.(%).				
10	81.657	50.878	25.996	RJW
20	99.133	24.848	20.932	
30	115.202	6.051	5.465	
10	107.736	66.448	47.686	NL
20	138.895	16.048	13.079	
30	174.846	3.209	2.120	

TABLE 8a. : SD. OF DISTRIBUTION OF INDIVIDUAL ESTIMATES.

1). Two Gaps. RJW

Line Length (min. arc)	Curvature (rad/min. arc)		
	0.00	0.05	0.067
i) Thresholds (rad/sec. arc).			
10	3.073E-5	2.964E-5	2.530E-5
20	0.930E-5	2.039E-5	0.425E-5
30	0.605E-5	0.599E-5	0.509E-5
ii) PSE's (rad/min. arc).			
10	0.166E-2	0.225E-2	0.203E-2
20	0.080E-2	0.376E-2	0.270E-2
30	0.023E-2	0.069E-2	0.069E-2
iii) Efficiencies (%).			
10	15.014	10.054	10.812
20	13.105	4.070	1.424
30	10.215	2.007	0.767

2). One Gap.

Line Length (min. arc)	Curvature (rad/min. arc)			
	0.00	0.05	0.067	
i) Thresholds (rad/sec. arc).				
10	1.672E-5	5.444E-5	5.101E-5	RJW
20	0.380E-5	0.655E-5	0.911E-5	
30	0.111E-5	1.018E-5	1.138E-5	
10	3.188E-5	0.715E-5	2.114E-5	NL
20	0.493E-5	2.370E-5	1.609E-5	
30	0.287E-5	0.582E-5	2.555E-5	

Line Length (min. arc)	Curvature (rad/min. arc)			
	0.00	0.05	0.067	
ii) PSE's (rad/min. arc).				
10	0.151E-2	0.220E-2	0.122E-2	RJW
20	0.060E-2	0.265E-2	0.333E-2	
30	0.043E-2	0.026E-2	0.034E-2	
10	0.429E-2	1.031E-2	0.337E-2	NL
20	0.038E-2	0.570E-2	0.204E-2	
30	0.014E-2	0.204E-2	0.137E-2	

Line Length (min. arc)	Curvature (rad/min. arc)			
	0.00	0.05	0.067	
iii) Efficiencies (%).				
10	10.182	14.814	5.063	RJW
20	13.191	3.313	3.234	
30	11.077	1.499	0.899	
10	18.814	2.862	8.406	NL
20	45.090	5.683	5.612	
30	87.998	0.429	1.862	

TABLE 9. : THE JOINT EFFECTS OF STIMULUS CURVATURE AND GAP SIZE ON DISCRIMINATION OF THE CURVATURE OF SHORT UNBROKEN AND BROKEN LINES.

Line Length = 10 min. arc.

Curvature (rad/min. arc)	Gap Size (min. arc)				
	0.00	1.67	3.33	5.00	
i) Thresholds (rad/sec. arc).					RJW
0.00	1.306	1.638	1.713	2.947	*E-4
0.02	1.457	1.868	1.773	2.539	*E-4
0.04	1.225	1.573	1.497	2.627	*E-4
0.05	1.227	1.174	1.218	2.248	*E-4
0.06	1.034	1.450	1.441	2.200	*E-4
0.07	1.192	1.417	1.603	2.037	*E-4
0.08	1.268	1.554	1.653	2.125	*E-4
0.09	1.579	1.887	1.671	2.501	*E-4
0.10	1.338	1.229	1.345	2.105	*E-4
0.11	1.202	1.467	1.698	2.148	*E-4
0.12	1.078	1.186	1.729	2.232	*E-4
0.13	1.107	1.526	1.642	2.084	*E-4
0.14	1.395	1.798	1.832	2.355	*E-4

Curvature (rad/min. arc)	Gap Size (min. arc)					
	0.00	1.67	3.33	5.00		
i) Thresholds (rad/sec. arc)						NL
0.00	1.059		1.042		*E-4	
0.05	1.055		1.335		*E-4	
0.067	8.648E-5		1.573		*E-4	
0.08	1.164		1.542		*E-4	
0.09	1.489		1.762		*E-4	
0.10	1.675		2.035		*E-4	
0.11	1.511		1.452		*E-4	
0.12	1.095		1.519		*E-4	
0.13	1.621		2.141		*E-4	

Curvature (rad/min. arc)	Gap Size (min. arc)				
	0.00	1.67	3.33	5.00	
ii) PSE's (rad/min. arc).					RJW
0.00	-9.664E-3	-6.874E-3	-8.967E-3	-6.889E-3	
0.02	9.017E-3	2.082E-2	1.455E-2	1.186E-2	
0.04	4.477	3.690	3.310	3.211	*E-2
0.05	4.345	4.609	4.137	4.889	*E-2
0.06	5.585	5.634	5.304	6.634	*E-2
0.07	6.222	6.403	6.630	6.477	*E-2
0.08	7.614	7.499	7.771	7.705	*E-2
0.09	8.604	8.162	8.270	8.590	*E-2
0.10	9.086	8.995	9.008	10.100	*E-2
0.11	0.100	0.103	0.104	0.114	
0.12	0.108	0.11	0.113	0.126	
0.13	0.115	0.119	0.126	0.133	
0.14	0.127	0.130	0.136	0.147	

Curvature (rad/min. arc)	Gap Size (min. arc)					
	0.00	1.67	3.33	5.00		
ii) PSE's (rad/min. arc).						
0.00	-6.122E-3		6.036E-4			NL
0.05	3.670		3.193		*E-2	
0.067	4.370		3.631		*E-2	
0.08	6.577		6.259		*E-2	
0.09	7.777		7.657		*E-2	
0.10	8.797		7.268		*E-2	
0.11	8.849		7.984		*E-2	
0.12	0.100		8.518E-2			
0.13	0.109		0.104			

Curvature (rad/min. arc)	Gap Size (min. arc)			
	0.00	1.67	3.33	5.00
iii) Efficiencies (%).				
0.00	46.367	33.113	39.912	15.124
0.02	38.726	25.621	37.447	20.448
0.04	49.251	36.338	52.750	19.167
0.05	55.222	65.447	79.778	26.217
0.06	77.789	42.982	57.122	27.428
0.07	58.907	45.131	46.296	32.036
0.08	52.229	37.642	43.624	29.511
0.09	33.764	25.596	42.767	21.323
0.10	47.163	60.484	66.110	32.875
0.11	58.625	38.329	41.537	28.969
0.12	72.999	65.179	40.148	26.859
0.13	69.487	41.085	44.568	30.857
0.14	43.834	29.675	35.864	24.184

RJW

Curvature (rad/min. arc)	Gap Size (min. arc)			
	0.00	1.67	3.33	5.00
iii) Efficiencies (%).				NL
0.00	70.555		107.736	
0.05	74.740		66.448	
0.067	110.910		47.686	
0.08	61.902		50.087	
0.09	37.977		38.464	
0.10	30.034		28.843	
0.11	37.066		56.793	
0.12	70.863		51.947	
0.13	32.401		26.204	

TABLE 9a. : SD. OF DISTRIBUTION OF INDIVIDUAL ESTIMATES.

Line Length = 10 min. arc.

Curvature (rad/min. arc)	Gap Size (min. arc) 0.00	1.67	3.33	5.00	
i) Thresholds (rad/sec. arc)					
0.00	3.745	3.124	2.328	15.104	*E-5
0.02	2.269	3.723	4.597	5.824	*E-5
0.04	2.535	2.378	.1.58	5.827	*E-5
0.05	1.525	3.161	2.449	0.807	*E-5
0.06	2.439	4.023	3.853	2.603	*E-5
0.07	1.829	3.272	3.900	2.484	*E-5
0.08	2.079	3.327	2.954	3.271	*E-5
0.09	3.868	4.185	3.962	4.719	*E-5
0.10	4.144	3.263	0.911	2.152	*E-5
0.11	3.359	2.341	3.108	1.045	*E-5
0.12	1.693	1.726	2.674	7.828	*E-5
0.13	2.881	3.015	4.282	6.478	*E-5
0.14	2.321	5.830	2.667	8.912	*E-5

RJW

Curvature (rad/min. arc)	Gap Size (min. arc)				
	0.00	1.67	3.33	5.00	
i) Thresholds (rad/sec. arc)					NL
0.00	1.669		3.188		*E-5
0.05	2.439		3.752		*E-5
0.067	2.388		2.114		*E-5
0.08	2.568		3.183		*E-5
0.09	2.224		1.559		*E-5
0.10	3.454		2.696		*E-5
0.11	2.225		2.321		*E-5
0.12	3.102		0.135		*E-5
0.13	2.970		3.433		*E-5

Curvature (rad/min. arc)	Gap Size (min. arc)				
	0.00	1.67	3.33	5.00	
ii) PSE's (rad/min. arc)					RJW
0.00	0.387	0.834	0.331	1.085	*E-2
0.02	0.884	0.122	0.548	1.203	*E-2
0.04	0.281	0.233	0.169	0.617	*E-2
0.05	0.089	0.389	0.253	0.599	*E-2
0.06	0.140	0.631	0.339	0.343	*E-2
0.07	0.242	1.721	0.422	0.270	*E-2
0.08	0.383	0.489	0.383	0.855	*E-2
0.09	0.133	0.203	0.241	0.326	*E-2
0.10	0.206	0.155	0.343	0.125	*E-2
0.11	0.210	0.423	0.732	0.900	*E-2
0.12	0.150	0.406	0.860	0.450	*E-2
0.13	0.214	0.232	0.933	0.442	*E-2
0.14	0.195	0.137	0.566	0.250	*E-2

Curvature (rad/min. arc)	Gap Size (min. arc)					
	0.00	1.67	3.33	5.00		NL
ii) PSE's (rad/min. arc)						
0.00	0.108		0.429		*E-2	
0.05	0.207		1.460		*E-2	
0.067	0.011		0.337		*E-2	
0.08	0.147		0.387		*E-2	
0.09	0.075		0.164		*E-2	
0.10	0.271		0.380		*E-2	
0.11	0.161		0.132		*E-2	
0.12	0.223		0.276		*E-2	
0.13	0.205		0.082		*E-2	

Curvature (rad/min. arc)	Gap Size (min. arc)			
	0.00	1.67	3.33	5.00
iii) Efficiencies (%).				
0.00	9.399	5.157	4.849	6.327
0.02	5.392	4.568	6.467	3.543
0.04	10.614	3.885	4.713	4.906
0.05	7.925	15.765	16.029	1.086
0.06	15.038	9.757	10.172	4.217
0.07	8.088	7.369	9.189	3.494
0.08	6.473	6.092	6.981	3.214
0.09	6.753	4.636	7.674	4.649
0.10	9.738	14.363	2.984	4.050
0.11	12.385	4.289	6.794	1.993
0.12	11.461	8.478	4.389	9.424
0.13	16.178	7.257	10.394	9.588
0.14	5.952	7.858	6.032	8.188

RJW

Curvature (rad/min. arc)	Gap Size (min. arc) 0.00	1.67	3.33	5.00
iii) Efficiencies (%).				
0.00	12.841		18.814	
0.05	8.904		7.242	
0.067	35.367		8.406	
0.08	15.777		11.965	
0.09	8.707		3.935	
0.10	7.162		3.303	
0.11	6.299		10.486	
0.12	13.318		0.942	
0.13	6.063		4.852	

NL