PERCEPTION OF VISUAL FORMS IN INTENSELY NOISY TELEVISION IMAGES

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ABSTRACT

This thesis describes the development and application of a novel technique for the investigation of visual perception. A closed-circuit television system was used to display simple shapes, obscured by visual noise, on a television screen under controlled conditions. The noise and the video signals producing the shapes were generated separately. The Signal to Noise ratio of the display on the television screen could then be accurately controlled by varying the proportions of signal and noise combined to form the noisy video signal.

A series of experiments have been performed, using a number of human observers, to determine the relative ease of detection of familiar shapes, in particular straight, curved, bent and broken lines, parallel straight lines and straight lines at different orientations. A shape was shown at low Signal to Noise ratio for a short period and the observer required to decide whether or not it was present in the display. A sequential method was used to determine the Signal to Noise ratio of successive displays in order to improve the efficiency of the tests.

It was found that vertical straight lines could be detected more easily than similar but slightly curved lines.

Increasing the length of a straight line improved its detectability, until visual angles of between 1 degree and 2 degrees were reached, when the improvement became much less marked. This effect was virtually independent of line orientation. Both long and short lines broken at the centre were always less detectable than continuous lines of the same total length. Two identical parallel lines proved no more detectable than one line alone, if they were separated by a viewing angle of more than five minutes. A symmetrically bent line was no more detectable than one of its straight segments when the angle between the two segments exceeded about 10 degrees. The orientation of a straight line made little difference to its detectability, although on average there was a slight reduction in detection threshold for the horizontal and vertical positions.

These results are consistent with the findings of recent neurophysiological research concerning the visual system of the cat, and on this basis a possible detection mechanism in human vision, and its relevance to communication, is discussed.

CONTENTS

GENERAL NOTES

Abbreviations

The following abbreviations are used in the text:

C.F.F. - Critical Flicker Frequency.

L.D.R. - Light - Dark Ratio.

db - Decibel.

Kc/s. - Thousand cycles per second.

Mc/s. - Million cycles per second.

R.M.S. - Root Mean Square.

S/N Ratio - Signal to Noise Ratio.

Figures

In Chapters No. 6 and No. 7, many experimental results are shown graphically. In certain figures, lines are drawn through points representing related measurements. Unless it is otherwise stated in the text, these lines have been introduced solely to clarify this connection, and they do not represent the result of curve-fitting operations.

Where an experimental point represents the mean, $\bar{x}$, of a number of independent observations, the variation of these measurements is indicated by a line between the limits $\bar{x} \pm \delta$, where δ is the standard error of the mean, (Crow, 1960).

Publication

A summary of the experimental technique, and of the earlier results, was presented at the 18th International Congress of Psychology, (Moscow, August 1st - 7th, 1966), under the title "Preliminary Experiments on the Perception of Visual Forms in Noise", by A. H. Marsh and E. C. Cherry.

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CHAPTER 1. VISUAL FORM: ITS MEANING AND IMPORTANCE.

1.1 Introduction.

1.1.1 It is important to realise that the human visual system is not a straightforward communication channel, and that there are many reasons for believing that the fidelity of vision is incomplete. The entire image created by light falling on the retina is not faithfully transmitted to some part of the brain where "perception" takes place. True fidelity of vision would only be possible if the system was capable of sensing the condition of every point in the visual field independently of every other point. All the neurophysiological evidence indicates, however, that in the visual system neural interaction is the rule, rather than the exception. Thus, the image is processed, with the result that those features preferred by the perceptual mechanism can be emphasised at the expense of others. This processing may even introduce wholly spurious effects. The well known geometrical illusions and figural after-effects are obvious examples (Boring, 1942).

The perceptual effect created by a specific amount of light energy striking the retina is therefore related critically to the spatial distribution of the energy. It is the "perceived" spatial organisation of the light that is usually termed the "form" of the image.

1.1.2 It would be convenient to begin any discussion of form, be it tactual, aural or visual, with a precise difinition. Unfortunately, this is not possible. As Stevens (1951) wrote: "In a sense, there is only one problem in psychophysics, namely the definition of the stimulus." While it is possible to assess the light energy differences that produce a visual stimulus, and thereby reproduce it to a given degree of accuracy, those features of stimulus configuration which predominantly influence human perception remain largely a mystery. In 1956 Attneave and Arnoult stated that there was no real psychophysics of form, and nine years later Michels and Zusne (1965) remarked that this was still the case. The immediate objective in this field is therefore not the determination of the precise effects of known form dimensions, but first of isolating them and finding suitable measures for their specification.

1.2 Vision as a Communication System.

1.2.1 Many investigators have approached the problem of form perception by comparing human vision with the process of transmission of information in a Communication System (e.g. Gregory, 1956; Hake, 1957; Tanner, 1957)(Section 2.2.1). Such a system can be represented as in Figure 1.1.

The signal ensemble represents the visual environment, and can be thought of as a large, but finite, number of images which may stimulate the visual system at random, while the

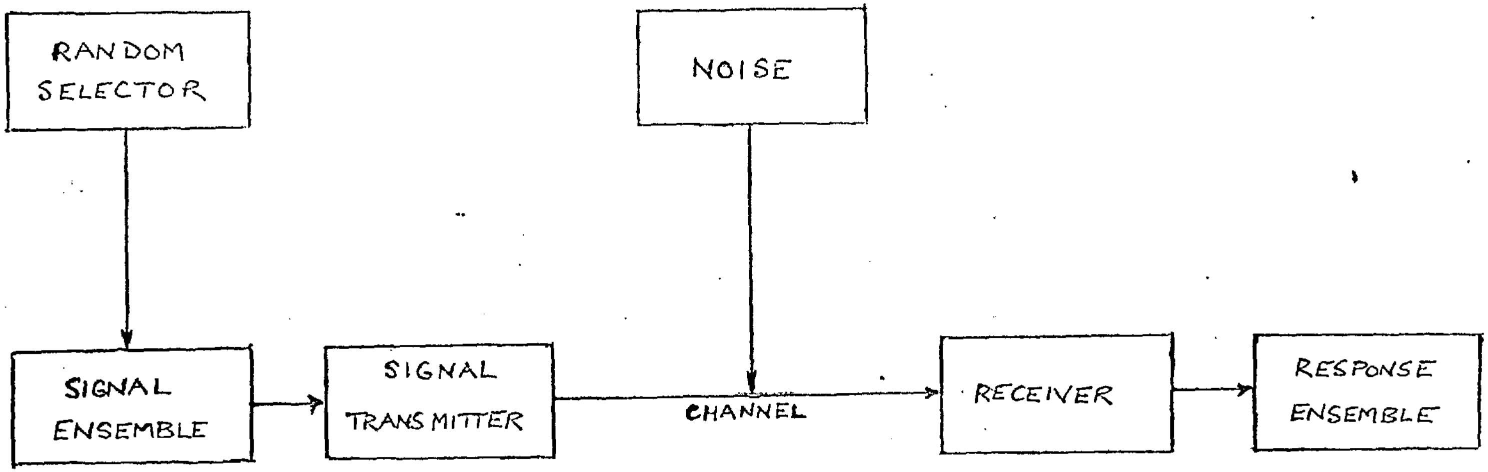

FIG. 1.1. SIMPLE COMMUNICATION SYSTEM (AFTER TANNER, 1957).

transmitter, channel and receiver represent the system from the eye to the brain. The response ensemble is contained within those parts of the brain where the eventual perception occurs.

In any communication system the transmitter section may well introduce reorganisation or "recoding" of the incoming information to adapt it to the properties of the subsequent channel, both for ease of transmission and to combat disruptive influences within the channel. These disturbances are usually referred to as "noise". (The concept of noise will be discussed more fully in Section 1.3.) The receiver must accept this coded information and be capable of making decisions thereon as to the true nature of the original signal, perhaps on the basis of prior information. A sophisticated version of this system may even alter its own parameters to suit overall variations in nature of the signal ensemble. This will necessitate a feedback path (not shown) from the receiver to the transmitter. It is very possible that the human visual system has such a capability, although the nature and extent of such changes, and the speed with which they occur, are very uncertain.

The comparison of the complete visual process with a standard communication system is at best an approximation. It is certainly not possible to divide the visual pathway into such precisely defined compartments with simple labels. It may, however, be more useful to think of a number of transmitter - channel - receiver sections connecting many "staging-posts" in the system. The character of each communication unit, and its intrinsic noise level, may well be of vital importance to the understanding of fundamental aspects of form perception. Recent neurophysiological research which suggests the possible structure of some of these units will be considered in Chapter 3.

1.3 Noise.

1.3.1 In any communication system the passage of information as a message is the essential feature. The transmission channel, however, may be such that disturbances, or "unwanted messages", can occur. These disturbances are generally grouped under the title "noise".

In communication between humans, in particular, the message may be in a number of forms, such as writing or speech. Communication within the system of an individual is also essential in order that sensory information may be conveyed to control regions and motor instructions sent out. These messages are often conveyed through nerve cells or neurons.

The transmission of information through a neuron is usually achieved by the conduction of electrical pulses along its length. The pulses are all similar in shape, and it is the pulse rate, or "firing" rate, which is a measure of the extent of the stimulation of the cell. The important "noise" in this system usually takes the form of a random variation in the mean firing rate (Horn, 1962), in other words spurious pulses may be produced or genuine pulses suppressed. (This behaviour is probably occasioned by fluctuations in the diffusion processes involved in the production of each pulse.) At the junction between the cell and another neuron there is thus uncertainty about the true magnitude of the original stimulation. In the extreme case, if a small variation in the firing rate occurs a decision may be necessary about whether in fact this represents any significant change in stimulation. This type of task, which requires the interpretation of a noisy signal in the most suitable manner, is fundamental to all communication systems, and it is particularly relevant to the problems of visual detection to be discussed in Chapters 7 and 8.

1.4 Vision and the Efficient Design of Communication Systems.

1.4.1 It is a cardinal point in the design of an efficient communication system that its performance should be matched as closely as possible to the characteristics of the users. If this is done, the transmission of unecessary information can be avoided, and the capacity of the channel can be exploited to the full.

The test of a visual communication channel, whatever its complexity, is whether or not it reliably produces the desired effect in the mind of the viewer. A system need transmit "only those data required to set up in the recipient's mind the illusions desired by the sender" (Cherry, 1957). The "illusion" required in a particular case may be that of direct visual communication, or simply the imparting of facts contained in a visual display.

A prominent example of the first case is the domestic "entertainment" television network. Although the image displayed is usually small, of limited resolution, two-dimensional and monochromatic, within these conventions, nonetheless, the illusion of direct communication is possible. This requires conscious acceptance of the image defects by the viewer, and consequently the merit of such a system is usually judged in terms of its acceptability to a suitably large proportion of viewers.

For visual channels which are primarily concerned with the accurate transmission of information, the criterion of "acceptable quality" is insufficient, and, indeed, irrelevant. The important factor is whether observers can extract useful information from a display with an arbitrarily low rate of error. This criterion is not synonymous with high quality in the entertainment sense. For example, it is possible to obtain all the information necessary for picture reconstruction, from a display which would be unacceptable for prolonged domestic "entertainment" viewing (Pearson, 1965).

Of the television systems in existence today, all are adapted to the well-known characteristics of the human visual system, such as visual acuity and critical flicker fusion frequency, but do not deliberately utilise the more subtle aspects of visual perception. While this approach was tolerable thirty years ago, the present shortage and expense of transmission bandwidth requires a reduction in the quantity of unecessary information that is sent.

Seyler (1961), for example, discussed the inefficiency of present television systems, and suggested the exploitation of the inability of the human visual system to follow rapid changes in picture detail. It should be noted that schemes such as this are intended for what Seyler calls "maximum-contingency" systems, where the accepted illusion of direct communication must be maintained. If this requirement is absent, the problem is simplified, for the channel may be designed to transmit pictures which, while obviously not reproductions of the originals, contain all the features needed by the observer. The information used to sustain the illusion of direct communication is redundant in a system concerned solely with the transmission of this kind of message.

It is to assist in the design of such utilitarian communication devices that knowledge of the properties of human vision can most usefully be employed. If the behaviour of the sensory channel can be defined, then an external communication system can be efficiently matched to its properties.

1.5 Form Perception and Visual Communication in Practice.

1.5.1 If the perceptually important features of a visual display are known, then the information required for adequate reproduction of the display can be reduced to a minimum. Such a reduction may be achieved by eliminating the unecessary characteristics and detail from the original display itself, or by arranging for the transmission equipment to perform this function (Cherry et al., 1963). To carry this rationalisation a stage further, if the vision of the viewer is known to be adapted to receive certain stimuli more readily than others, it may be possible to reorganise or "recode" a visual message in a manner more suitable for efficient transmission.

There are many applications of such an approach outside the field of television communication. The design of notices, in particular road signs, should be done to optimise the transmission of information to the observer, especially when viewing conditions are unfavourable, or "noisy". The shape or markings of life rafts and like objects, which must usually be detected against confusing backgrounds, should obviously be determined by information about visual perception. Similarly, the design of display devices for sonar or radar systems must benefit from a greater knowledge of the facets of human vision. Conversely the art of camouflaging objects against visual inspection can only be facilitated by knowing what shapes are seen more easily than others.

1.6 Summary.

1.6.1 In general, any addition to the knowledge of the workings of human vision is of immense value, both as a step towards the solution of the problem of understanding human perception, and also for its immediate practical advantages. The experiments to be described in this thesis have used television displays in a novel manner to investigate how simple shapes are detected by human observers. It is not solely for this reason, however, that this introductory chapter is devoted to the engineering aspects of form perception. The ideas of Communication theory have come to exert an increasing influence on research in vision. With this approach in mind, the chief task becomes that of discovering the way in which visual information is coded in the system, and the succeeding chapters will seek to show how this knowledge may be obtained.

CHAPTER 2. A SURVEY OF THEORIES OF VISUAL FORM PERCEPTION.

2.1 The Gestalt School.

2.1.1 Vision has been of great interest to philosophers for many centuries, and both Kepler and Newton, for example, produced theories to explain properties of vision and light. In succeeding years, however, most research was devoted to the development of optical devices and to the understanding of light itself. The study of visual perception, as such, dates chiefly from the nineteenth century.

At this time, a specific perception was considered to be no more than an "association" of individual sensations, constructed as a building is of bricks. However, by the 1920's the Gestalt school had revolutionised the subject. The Gestaltists recognised the importance of totality of impression, in that a perception could be far more than the sum of its elements. Their observations, obtained by introspection, rather than by objective experimentation, led to the defining of certain principles of stimulus organisation. According to "Gestalttheorie", a particular two-dimensional shape may be, perceptually, more than a set of unrelated elements, and similarly a collection of shapes may be more than a random juxtaposition of structures. If the shapes are seen spontaneously as a group, then the collection is "organised". According to members of the Gestalt school, notably Wertheimer (1923), the chief properties determining the nature and extent of the organisation are proximity, similarity, good continuation, common fate, and closure. These have been summarised by Woodworth (1938) and Dember (1963).

The first two factors are almost self-explanatory. If the other variables are constant, structural elements (in dot patterns, for example) are perceived in groups based on close proximity. Conscious attempts to organise groups of more separated elements are possible but difficult, and the imposed perceptual organisation may spontaneously break up. Alternatively if the separation of dissimilar elements is constant, then the grouping tends to be of elements of similar appearance. If both factors are simultaneously varied under the right circumstances, perceptual antagonism between the two may occur. The effect of the similarity of certain components may be offset by their degree of separation. Similarly, lack of similarity may be counterbalanced by close proximity.

Good continuation is a somewhat more subtle concept. Essentially it embodies the idea that the ordered arrangement of a group of elements must influence the perception of others in the structure. If these do not conform to the pre-imposed pattern then perceptual organisation may not occur. Continuation can be a most powerful feature, outweighing both proximity and similarity.

Common fate is the principle applied to a situation where many stimulus elements share a particular property, such as movement as a whole in a given direction. Dember quotes the example of an animal unseen when stationary against a natural background, but easily visible when moving.

Closure involves one of the most important ideas of Gestalt psychology, that of "completeness". A bounded or closed figure is usually seen as a distinct unit. In general, if a pattern can be seen as a complete closed unit, the effects of this factor will overide the influence of others.

Thus, the importance of the entire perception is one of the fundamental features of Gestalt psychology. The characteristics of this whole are determined in part by the parameters which have been discussed, and it is relatively easy to demonstrate their influence in simple cases. Unfortunately, factors such as good continuation, common fate and closure do not always lend themselves to quantitative analysis. Without precise relations between the factors, it has been found that, in general, it is very difficult to specify the perceptual properties of a particular shape. This weakness does not, however, invalidate the basic premise of the Gestalt school. A perception does not correspond in a point-to-point fashion to the stimulus configuration, but depends on what happens to its elements within the perceptual system.

2.1.2 The attempts of the Gestalt psychologists to explain their indisputable observations in terms of human physiology had only limited success. Hebb (1949) has compared the theories of Kohler (1940) and Lashley (1942). Both these theories recognised the importance of the visual cortex, as suggested by knowledge of the effect of cortical damage on visual perception. Both also agreed that specific perceptual responses, such as recognition, did not require the stimulation of particular neurons. On this hypothesis, it is the pattern of neural responses, not the location, which is important. Kohler suggested that the perceptual mechanism depended on cortical electrical fields, while Lashley proposed the existence of waves of excitation in the cortex, and consequent interference patterns. These were to exist in localised areas, concerned with particular functions, and Zangwill (1963) has noted that a mixture of localised and diffuse activity of this kind, is not incompatible with present ideas of cortical behaviour.

While the theories of Kohler and Lashley could explain some of the Gestalt ideas of perception, at that time the precise mechanisms suggested were not easy to reconcile with the anatomy of the system. In addition, as Hebb pointed out, it is very difficult to account for perceptual learning on either basis. Hebb, therefore, stimulated by the work of Marshall and Talbot (1942), and while accepting parts of Gestalt theory, attempted to establish a perceptual model based on actual neural analysis. He directly contradicted the idea of unlocated patterns of neural excitation, in favour of specific cortical cells responding to specific stimuli. He also emphasised the importance of including an explanation of perceptual learning in any theory. He considered this of prime importance, in view of the apparently rudimentary perceptual abilities of the newly-sighted. Many months may be needed before an unassisted infant or a newly-sighted adult can perform the most simple visual discriminations. Hebb suggested that stimulus analysis was performed by a vast interacting network of cells, and that a particular network, frequently exposed to a particular stimulus, might slowly change physiologically to facilitate the necessary response. The process, the production of a "cell assembly", forms the basis of a long-term learning mechanism, according to Hebb's theory. The theory also includes the possibility of the existence of certain "intrinsic" neural organisations in the immature visual system. Exposure to environment is then supposed to modify or build up aspects of these organisations. This is a most interesting idea in the light of recent additions to knowledge of the neurophysiology of vision (Section 3.5.9).

However, at about the same time that Hebb published his work, the study of communication in general was revolutionised by the introduction of the theory of Communication (Shannon 1949).

2.2 "Information" Measures of Form.

2.2.1 The development of the theory of Communication, and the plausible idea of human vision as a sophisticated communication system, directed considerable interest to the possibility of describing and classifying visual forms by a suitable information measure. It was hoped that it would be possible thereby to analyse the perception of different forms on the basis of a comparison of these information measures.

Hake (1957), in a major survey of the perception of form, considered the analogy between vision and a communication system. He discussed the research work in psychology relevant to pattern vision, including the study of threshold measurements, visual distortion, form discrimination, constancy of form perception and form memory, and concluded that the visual system does not operate to produce "fidelity", the faithful transmission of visual information, but instead "coherent" reconstructions of visual stimulation. He defined "coherence" as a measure of the resemblance of past and present stimulation, and the efficiency of predictions about future stimulation.

To satisfy the needs of such an arrangement, Hake suggested that the visual path might be represented by a communication system of limited capacity incorporating a feedback channel to send back information from the receiver to an adaptive transmitter. By means of this feedback, the posterior end of the channel informs the anterior end of the "coherence" apparent in the transmitted information. The feedback information is then used by the anterior end to make decisions about which aspects of stimulation to sense and transmit.

Tanner (in Wulfeck and Taylor, 1957) also pointed to the resemblance between a perceptual process for form perception and a simple communication system. In the appropriate terminology, a perception becomes a hypothesis selected from an ensemble of possible events, the decision being governed by a set of prior probabilities. This is in fact a formalisation of the basic system suggested by Hake. The ensemble of possible events and the associated prior probabilities are determined by the environment and past experience of the viewer, respectively. The feedback channel put forward by Hake is an added sophistication, and has the effect of adapting the system to meet changes in the source of visual information.

The validity of the analogy between the human visual process and a communication system was discussed in the introductory chapter (Section 1.3). Undoubtedly information about the environment is conveyed to the relevant regions of the brain by the visual system. However, the utility of the comparison depends on whether the "units" of the system (or of the many constituent systems) can be recognised and their properties defined. Since detailed knowledge of the entire visual pathway is not yet available, this is a considerable difficulty. Many workers, nevertheless, have attempted to find the information-bearing features of various shapes by indirect means. This has involved an arbitrary, if well-informed, designation of the perceptually important elements of a figure, and an attempt to relate the deduced information load to the perceptual properties.

2.2.2 Attneave and Arnoult (1956) showed that, in certain cases, information in plane figures might be concentrated at those points in the contour where the change of gradient is most steep. This suggested that curvilinear forms could usefully be approximated by drawing straight lines between such important points of the contour, according to rather arbitrary rules. The number, or the logarithm of the number, of sides (or vertices) of shapes such as polygons (or figures which could be reduced to polygons by approximation), has been used by many workers as a measure of the information content of the shape. Crook (1957) and Brown et al. (1962) investigated the discrimination of pairs of polygons against noisy backgrounds, and related their results to information analyses of the shapes. This proved inconclusive, largely because it was found that 8-sided shapes were more easily discriminated than either 4- or 16-sided shapes, which was not in accordance with the information estimates. Hochberg and McAllister (1953) and Hochberg and Brooks (1960) have also performed experiments on discrimination, using the number of line segments, angles and points of intersection of complex line figures to determine information measures. They found a significant correlation between the ease of identifying a particular shape and its information load. However, this correlation was not nearly large enough to suggest that the information measures were a complete perceptual specification of the figures.

An interesting variation of these methods was proposed by Barskii and Guzeva (1962). This assessed the information content of a figure by considering variations in the contour in terms of polar co-ordinates. The technique gave some success when used to predict the relative ease with which detail could be seen in irregular low contrast images. However, no systematic relation was found between information content and the detection threshold of a shape.

Attneave (1957) compared the judged "complexity" of a figure with the estimated information content, to test the relation between the subjective and theoretical measures. He found some agreement between complexity judgements and the number of turns in the contour of a shape. Coules et al. (1962) performed similar experiments, when investigating the effect of visual noise on complexity judgements. In these experiments, the actual number of sides accounted for a considerable proportion of the variation in the judgements. However, there were distinct differences in judged complexity among the forms with the same number of sides.

The methods mentioned so far have been concerned with line figures, or only the contours of solid shapes. Other workers have considered more solid figures, such as those constructed of dots (French, 1954; Attneave, 1955) or blocks as in the "metric" figures of Fitts et al. (1956) and Rappaport (1957). In these cases, where a random shape is constructed of identical elements, a logical estimate of information load can be made, although the weightings of such factors as symmetry present problems. In general, the experiments have yielded the result that increased information load in a shape leads to deterioration in human performance under test conditions, although this is not invariably so. Once more, no simple quantitative relationship emerged.

The work listed above is merely a small sample of the many attempts that have been made to obtain a measure of the "important" information in a visual display, and many other examples can be found in Michels and Zusne (1965) and Wulfeck and Taylor (1957). One of the principal difficulties besetting the comparison of results is the considerable variation in the measuring methods employed by different workers. For example, the attributes of a figure relevant to its "judged complexity" (Attneave, 1957; Coules et al., 1960) may not necessarily be important to its discriminability from other shapes (Crook, 1957) or its "semantic rating" (Van de Geer and Levelt, 1963).

Despite the considerable ingenuity and plausibility of all these approaches, a systematic dependence of the perceptual properties of a figure on the estimated information content has **not** been revealed. Michels and Zusne summarised the situation by suggesting that the information content of a form obtained by such methods can best be described as a measure of the <u>degree</u> of organisation of the figure, without wholly describing that organisation. To illustrate the point, they cite the case of an eight-sided polygon of which the eight vertices or sides can be infinitely rearranged, without affecting many information measures. Intuitively, it would be most surprising if such rearrangements resulted in no change in the perceptual properties of the shape.

The comparative lack of success of the "information" approach prompts the conclusion that while it is possible to specify some of the visual information contained within a form by these means, such a measure alone is not sufficient to predict the details of human form perception. Alternatively the bases on which the estimates so far have been made are wrong, or, at best, incomplete.

2.3 A Neural Model of Form Perception.

2.3.1 Blackwell (1957, 1963) pointed out that simple informational analyses of visual stimuli do not account for the distortions that may be introduced by any reorganisation or interaction in the visual system. He emphasised that the <u>neural</u> correlate of a stimulus should be considered in an information analysis. An obvious essential to progress, if this is to be done, is a knowledge of these distortions, and Blackwell has suggested that this could well be obtained by means of psychophysical experiments from which the nature of the physiological system could be inferred.

An application of this approach has been described by Kristofferson (1957). This is an extension of the theory of retinal summation proposed by Graham et al. (1939). Kristofferson asserted that detection of a stimulus occurs whenever the amount of excitation at any point in the pattern of neural excitation produced by the stimulus exceeds a critical value. Each point in the neural pattern receives excitation from every retinal point. Kristofferson postulated that the amount of excitation contribution to a neural locus from any retinal point is a function of retinal distance between that point and the one corresponding to the neural locus. The contribution, as a function of this distance, he termed the element contribution, and the ideas as a whole, the element contribution theory.

Among the expected consequences of the theory are that the stimulus luminance needed for detection will decrease as the size increases, and that the most detectable shape is circular. These aspects of human perception were thoroughly investigated by Kristofferson and his colleagues, and encouraging results were obtained. However, although the general trend of the measurements confirmed the possibility of an element-contribution mechanism existing in the human visual pathway, there were interesting anomalies. In particular, rectangular targets proved generally more detectable than the theory predicts, but compound stimuli, such as crosses and "multi-legged" targets, were less detectable than expected. The significance of these results will be considered again in Chapter 7.

2.4 Summary.

2.4.1 This is by no means an exhaustive survey of the various attempts which research workers have made to assess the process of visual perception. For a detailed account of the history of the subject, the reader is referred to Boring (1942). Of recent work, the writer has given most attention to those theories which appear to promise most for future progress. Many others have, of course, been suggested. In particular, the influence on figure perception of area, perimeter, orientation, symmetry, and combinations of these factors, have all been studied. A review of much of this work can be found in Pierce (1963), Michels and Zusne (1965) and Graham (1966).

It must reluctantly be said, however, that the quantitative study of visual form perception has advanced only gradually in the past forty years. The Gestalt school, while able to describe and specify particular perceptual phenomena, did not provide satisfactory explanations. Similarly, information measures based on the intuitively "important" features of a stimulus, are not always consistent with the perceptual properties of that stimulus. Hebb (1949) suggested that specific neural interactions were the basis of perceptual mechanisms, and Blackwell (1957, 1963) proposed that any information analysis of a visual stimulus should be based on the stimulus patterns resulting from these interactions. Mackay (1960) has justifiably pointed out that specific neural theories are only equipped to describe simple perceptions. Complex perceptual processes, involving many cross-connections among neural pathways, may prove unmanageably elaborate. Under these circumstances, he suggested that it might prove fruitful to treat the electrical and physical behaviour of the system in terms of patterns or waves of activity, with defined laws of motion and interaction. This is an interesting revival, if only as a model, of the ideas of cortical activity suggested by Lashley.

Despite the drawback of complexity, however, it is unlikely that future theories, whatever their basis, will completely ignore the knowledge of the neurophysiology of vision that is becoming available. The experiments to be described in this thesis are, in fact, attempts to infer the nature of parts of the perceptual system from psychophysical tests, as suggested by Blackwell, and hence explain certain simple detection phenomena. Since the tests are based on ideas about the visual system stimulated by recent neurophysiological research, several features of its structure must be reviewed in detail.

CHAPTER 3. THE HUMAN VISUAL PATHWAY: A BRIEF SUMMARY OF PHYSIOLOGICAL KNOWLEDGE RELEVANT TO THE PERCEPTION OF VISUAL FORM.

3.1 The Visual Process.

3.1.1 The visual process begins when light passes into the eyeball, through the eye lens, and affects the light-sensitive rod and cone cells of the retina. These cells are activated by the light and, in turn, stimulate other retinal cells, so that eventually the light signals emerge in the form of electric impulses in the fibres of the "optic nerve". This reaches the brain at the lateral geniculate body, which sends fibres to the visual cortex region of the brain.

Compared with the numbers of retinal receptors in an eye, there are significantly fewer independent nerve fibres in the "optic nerve". This suggests that considerable reorganisation and compression of the original light message occurs in the retina. That the most important image processing **takes place** within the cortex is in no doubt, but the information reaching the cortex must be influenced by the earlier stages of the system. For this reason, the structure of these regions is of great interest, and will now be considered in detail.

3.2 The Eye.

3.2.1 The human eyeball is an irregular spheroid, of about 24 m.m. diameter, set in a socket in the skull and movable within the confines of the socket and the six muscles which control eye movement.

In normal vision, the human eyeball is not still, but in constant "saccadic" motion. Small, involuntary movements, which may shift the retinal image by several minutes of arc, persist even when the eye is "fixed" on a stationary object.[*]

Because of the eyeball movements, the image on the retina is kept in motion. These movements are of three distinct types. One makes the retinal image drift slowly away from the fixation point. This terminates in a "flick" that brings the image back towards the original position. The velocity of the flick can be as high as 5,000 degrees of arc per second. Superimposed on the drift is a tremor of frequency up to 150 c.p.s. and amplitude such that the image moves about half the diameter of a cone receptor cell.

The precise function of these involuntary movements is not wholly understood. They are almost certainly connected with the complex control mechanisms of the eye, and Fender (1964) has shown that the control of eyeball movement is analogous to a complex

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[*] Distances in retinal images are usually expressed in terms of the angle subtended at the centre of the pupil by an object in air whose geometrical image would just cover the retinal distance. One minute of arc corresponds in a typical eye to a retinal distance of 5×10^{-3} m.m..

servo-mechanism. One most interesting phenomenon apparently connected with continuous eye motion, is that of the "disappearance" of stabilised retinal images. It has been found that an image that is fixed on the retina is not perceived continuously but disappears sporadically, in whole or in part (Ditchburn and Fender, 1955; Pritchard, 1961; Bennet-Clark and Evans, 1963). It would seem likely that eye movements are intended, in part, to avoid the occurrence of such stabilised images, and consequent disappearance or fragmentation of what is seen. The possible significance of the experimental results obtained in this field will be referred to in Chapter 8.

3.3 Image Formation.

3.3.1 The retinal image is produced by a relatively simple lens system. Light from external objects passes into the eyeball via transparent protective layers, and the highly refracting cornea, through a circular hole of variable diameter known as the pupil. The function of the pupil is to restrict the aperture of the lens system within the eye in accordance with the strength of the incident light, but it also causes some blurring of the retinal image as a result of Fraunhofer diffraction.

The light after passing through the pupil eventually strikes the crystalline lens. The curvature of the faces of the lens may be altered by ciliary muscles which pull on the ligaments enclosing the lens, thereby changing its shape. By such means, a focused image of an external source is produced on the retinal cells which cover most of the inner eyeball surface.

3.3.2 All lens systems are liable to distort the images that they produce, and that in the eyeball is no exception. Apart from pupil diffraction effects, the slightly irregular lens surfaces cause image aberrations, and further degredations occur because of scattering and diffraction in the layer of blood vessels and cells immediately above the retinal receptors. The problem of chromatic aberration also cannot be ignored, although it is distinctly possible that somewhere in the visual system there is a mechanism to compensate for this defect, (Kohler 1962).

The result of these imperfections in the system is an inevitable deterioration in the quality of the retinal image. This sets a lower limit on the detail which can be clearly seen in the image. There is an extra complication involved in the specification of the degree of detail resolution that is possible. If the image is brightly illuminated, the pupil aperture may be small and diffraction effects will then predominate. At the other extreme, when the pupil size is a maximum, lens imperfections introduce considerable image aberration. An illumination corresponding to a pupil diameter of 3 m.m. has been found to be the optimum for resolution of adjacent parallel lines (Westheimer, 1963). A line separation of 0.6 minutes of arc is necessary for the resolution of a grating under these optimum viewing conditions.

Thus, if the ideal image consists of two such grating lines sufficiently close together, the blurred images of each will overlap to an extent which prevents the discrimination of the two as separate entities. It is the properties of the retinal cells which define this limit.

3.4 The Retina.

3.4.1 The structure of the retina is "inverted" in that retinal cells concerned with visual processing subsequent to the stimulation of the light sensitive receptors, lie above the receptors themselves. Incident light must therefore pass through this layer, with some consequent light loss through absorption and scattering, before a sensitive cell can be stimulated.

There are two basic receptor cell types, namely rods and cones, so called because of their shape. There are about 120 million rods and 7 million cones in the average human retina, but they are not uniformly distributed. The two cell types differ in many ways, particularly in their sensitivity to light and in their response to light wavelength. The cones are concerned with reception of stimuli of fairly high intensity and for the appreciation of differences in the wavelength of incident light. The rods are more sensitive than the cones but are not colour sensitive. However, for the purposes of most of this discussion, rods and cones will be jointly regarded as light receptors and treated as of similar nature.

At the rear of the eyeball, near the main visual axis of the eye, lies a small depressed area, known as the fovea centralis. Within the fovea, cones predominate, and the density of receptors (about 10^5 per square m.m.) is greater than in any other retinal region. The exact extent of the fovea is ill-defined, and angular sizes of between 1 degree and 5 degrees are often quoted. The most common figure seems to be in the region of 2 degrees to 3 degrees.

Because of the great receptor density, the fovea is the region of the retina used for the most detailed analysis of visual images, and the resolution limit in an image is defined by the resolution possible at the fovea. There are two structural factors which may influence this limit. These are the finite size of individual cone cells (about 1 minute of arc) and the cross-connections of the neural outputs from the receptors to the retinal bipolar cells. These bipolar cells are the next link in the neural channel, and in their turn affect or "synapse" with retinal ganglion cells.

It must be emphasised here that many receptor cells may synapse with a bipolar cell; conversely one receptor may synapse with several bipolar cells. Again, the same dispersion of stimulation occurs at the synapse between the bipolar cells and the retinal ganglion cells, the layer of cells which send signals to the brain. The interactions among retinal cells apparently cause a reduction in the amount of information passed from the retinal receptors to the brain. The extent of this reduction is indicated by the fact that although there are 127 million receptors, there are only 1 million fibres in the optic nerve.

The degree of cross-stimulation in the retina has been found to vary according to retinal position, and is believed to be a minimum in the foveal region. It is even possible that each foveal cone has access to an individual fibre in the optic nerve leading to the brain. The fact that there are almost as many ganglion cells in the foveal region as there are receptors encourages this view. Even if this is not the case, it does not necessarily follow that a proportionate loss of image detail will result in all circumstances. To understand this fact, it must be appreciated that all retinal interconnections are not excitatory. The fineness of discrimination associated with a particular cell may be determined by the arrangement of excitatory and inhibitory synapses which drive it.

Such arrangements are the basis of the reorganising process or "recoding" which the visual message undergoes in the nervous system. Since the pattern of interconnections may well favour certain messages at the expense of others, a knowledge of their structure is vital to any model of form perception based on physiology. It is only in comparatively recent years that such knowledge has been forthcoming.

3.5 Neural processes in the visual system.

3.5.1 The actual conversion of incident light patterns into neural firing is thought to involve a photo-chemical process occurring within the retinal cells. Whether this "recoding" of the information takes place in the receptor cells themselves, or subsequently, is uncertain. Without doubt, the information has been transformed into repetitive impulses by the level of the ganglion cells, and this activity has been noted by many workers. Rushton (1962) and Tomita (1963) both remark that similar discharges have not been found in the receptors or the bipolar cells, although this may merely be due to technical difficulties in detection rather than to the absence of firing itself.

The pulses detected in ganglion cells, and in subsequent cells in the system, all have much the same amplitude, and the strength of the stimulus giving rise to them is reflected in their rate of occurence. Some cells, when not stimulated, do not fire. Others, notably those in the lateral geniculate bodies, maintain a fairly uniform firing rate, which may be increased or decreased by suitable stimulation.

Information is passed from one neuron to another across the junction known as a synapse. Synaptic transmission in vertebrates is believed to include a chemical diffusion process. In general, the end of a nerve axon splits into many filaments, and the arrival of neural signals causes the emission of a substance which diffuses to the receiving elements of the next cell in the system. Two types of synapse have been found in vertebrates; the excitatory and the inhibitory synapse. In excitation, the diffusing substance tends to stimulate the firing of a cell; in inhibition, the substance acts to prevent or reduce firing.

The axons of receptor cells which synapse with bipolar cells, the next in the system, do not exhibit splitting, or arborisation, to any great degree. "Horizontal" cells have been identified, however, (Morgan, 1965) which apparently make it possible for individual receptors to interact directly. The bipolars, moreover, having many receiving elements, or dendrites, can receive inputs from several receptors. These bipolars, in their turn, affect the retinal ganglion cells, but because of the arborisation of their axons and the many dendrites of the ganglion cells, it is possible for one bipolar cell to affect many ganglion cells, and for one ganglion cell to receive inputs from many bipolars.

The axons of the retinal ganglion cells are very long (about three inches) and pass over the inner surface of the retina, converging to a point at the back of the eyeball.

Here they become bundled together, and leave the eyeball to form the "optic nerve". There are thus two neural junctions in the array of retinal cells, and it is presumably at these that information reorganisation occurs.

3.5.2 In the past fifteen years, the technique of recording electrical impulses directly from nerve fibres, using micro-electrodes, has advanced immensely. Among those to use these devices, in the exploration of the visual system, was Kuffler (1953), who made a detailed study of the behaviour of retinal ganglion cells in the cat. There is an understandable lack of similar data concerning human subjects, and the majority of this research has been performed on an animal whose visual system is apparently similar to that of man, in particular on the monkey or on the cat.

The approach used by Kuffler was to illuminate specific areas of the retina of an anesthetised cat, while simultaneously recording the effect on the firing rate of a particular ganglion cell. He found that a typical ganglion cell receives its input from receptors in a restricted area of the retina, which he termed the "receptive field" of the cell. These fields are roughly circular with a centre which when stimulated with increased light energy tends either to increase or decrease the firing of the ganglion cell. The centre is surrounded by a larger area of receptors which produce the opposite response when similarly stimulated.

He called such fields "on" centre and "off" centre receptive fields, according to whether the ganglion cell was excited or inhibited by increased light energy.

Typically Kuffler found that illuminating the entire central region of an on-centre field evokes a large increase in neural firing rate. A smaller or larger spot is less effective. Illuminating the whole retina diffusely does not affect a retinal ganglion cell nearly so strongly.

Hubel and Wiesel (1960) have confirmed Kuffler's findings, by similar work on both the monkey and the cat, and also studied the variation of receptive field size with retinal position. Near the fovea, they discovered a tendency for the field centres to be smaller than elsewhere. Indeed, in the fovea of the spider monkey, field centres of the size of a single cone have been found. In the peripheral regions of the retina, however, these centres may be many times larger.

In general, it would appear from these results that retinal ganglion cells respond not simply to the presence or absence of retinal illumination, but receive inputs which equip them for contrast discrimination of a simple kind. Thus the first stage, at least, in the conversion of a light pattern on the retina into a "perception" takes place in the retina itself.

Barlow, Fitzhugh and Kuffler (1957) reported that the annular receptive field structure in the cat retina is modified according to the state of adaptation of the eye. For the light-adapted eye, the typical annular arrangement, with the antagonistic central and peripheral responses, is found. When the eye is dark adapted however, the receptive field structure of each cell degenerates into a zone of one response type only. A typical ganglion cell is then responding simply either to an increase or to a decrease in illumination anywhere in its receptive field. Thus, the simple discriminatory system which at normal retinal illuminations responds to contrast rather than diffuse illumination, is apparently transformed to a detection mechanism when the light level is low.

While this seems a very plausible arrangement, it must be noted here that Spinelli (1966) has recently cast some doubt on the completeness of the results obtained for retinal ganglion cells in the cat. This question will be referred to in Section 3 5.11 and Section 8.5.4.

3.5.3 In comparison with the remainder of the visual nervous system, the "optic nerve" is a comparatively uncomplicated structure. As stated, it consists largely of the axons of retinal ganglion cells, and a few nerve fibres associated with eye control.

As the nerve fibres from each eye reach the brain, the two meet, at the optic chiasma, and some redirection of the fibres occurs. In man, the fibres from the right side of both retinae run to the lateral geniculate body at the right of the brain; the fibres from the left hand side of both retinae go to the lateral geniculate body at the left of the brain. This rearrangement is most probably associated with the processing of retinal images essential to stereoscopic vision. It must be emphasised that synapses between neurons are not known to occur within the "optic nerve". The axons of retinal ganglion cells thus synapse only with the neurons of the appropriate lateral geniculate body.

3.5.4 Again, the principal work on the neural reorganisation which occurs at the geniculate bodies is that of Hubel and Wiesel, on the spider monkey and the cat (1960, 1961). They investigated the receptive field patterns associated with particular geniculate cells. It was found that many of the characteristics of receptive fields of retinal ganglion cells are reproduced in the fields of cells in the geniculate body. Each cell is affected by an approximately circular retinal region with either "on" centre and "off" periphery, or vice-versa. However, it was also found that the ability of peripheral illumination to cancel the effects of central illumination was much enhanced, compared with the situation found for ganglion cells. The geniculate body cells thus have the ability to increase the disparity, already present in ganglion cells, between response to a small spot and to diffuse light.

3.5.5. Each lateral geniculate body sends nerve fibres to the adjacent half of thevisual cortex. The cortex is a structure of tremendous complexity. In the cat, Hubel and Wiesel (1961) have found that retinal receptors project to parts of the visual cortex in a systematic topological manner.

The millions of axons entering each half of the cortex from the appropriate geniculate body, appear to connect with a certain type of cortical cell in the region known as Visual 1. From these cells, visual information is disseminated throughout all layers of the cortex by numerous neural interconnections.

Hubel and Wiesel have investigated cells in several layers of the cortex, and discovered a significant change in the shape of the receptive fields. The first group of cells, apparently stimulated by the geniculate cells, they designated "simple". The function of these appears to be to respond to straight line stimuli, such shapes as bars, slits and edges. Whether or not a given cell responds depends critically both on the orientation of the shape and on its position on the receptive field. Once again, the receptive field is divided into "on" and "off" regions, but circular symmetry is not found. A typical field has a long narrow "on" area adjoined by larger "off" areas on each side. The optimum stimulus for such a cell is a straight slit precisely filling the "on" area. Stimulation with the slit in a different orientation produces a much weaker response.

Diffuse light on the whole retina produces little effect on the firing of such a cortical cell, so it is reasonable to suppose that the neural effects of the "on" and "off" areas balance with considerable precision.

Whatever the nature of the appropriate stimulus for a simple cortical cell, Hubel and Wiesel found that, for all the cells that they investigated, the most efficient stimulus involves a straight line of a particular position and orientation. They discovered nothing to suggest that, among such simple cells, any one orientation is more favoured than another.

It is interesting to speculate at this point, that slit or bar receptive field organisation could arise from a suitable combination of a number of concentric "on" and "off" fields of the type common among geniculate cells. Although there is no direct physiological evidence of such specific interconnections, this theory is very reasonable. The explanation is also in accordance with the greater receptive field size of simple cortical cells (Section 3.5.6) compared with that of geniculate cells.

3.5.6 In addition to discovering cells with the properties described above, Hubel and Wiesel found a separate type, which they termed "complex". In many ways, simple and complex cells have similar properties, with one major exception. A complex cell will respond optimally to a straight edge or slit or bar of a particular orientation. However, this response is not critically dependent on the position of the stimulus on the retina. The response will be maintained over a considerable retinal region, usually the entire receptive field of the cell. The complex cortical cell is sensitive to one aspect of the optimum stimulus, its orientation. It is most tempting to regard this as the first step towards form generalisation in the visual system.

It is difficult to find an explanation of this behaviour of the complex cortical cell, in any arrangement in which geniculate cells feed directly to complex cells. A more likely theory is that each complex cell receives its input from the fibres of several simple cells. These cells must all have the same receptive field type and orientation, and the fields must be appropriately positioned to occupy the receptive field of the complex cell.

An indirect substantiation of the existence of this arrangement is provided by the structure of the visual cortex. Hubel and Wiesel (1963 (a)) found that cells with the same receptive field orientation are arranged in columns in a direction perpendicular to the cortex surface. Both simple and complex cells are present in these columns, and the neural interconnections are far more plentiful along the column length than in side to side directions. In addition, the variation in retinal position of the receptive fields of simple cells in a column is of the same order of magnitude as the size of the field of typical complex cell in the same column.

Because a complex cell probably receives its input from a number of similar, but spatially separated, simple cell receptive fields, it is likely that a suitable moving stimulus may produce sustained firing of a particular cell. Hubel and Wiesel have tested this hypothesis for a number of complex cells. They discovered that movement of an optimally orientated line stimulus, in a direction perpendicular to the orientation, is usually the most powerful way of continuously activating a cell. However, the two directions of movement are not necessarily equally effective, and one direction may produce no response at all. Also the rate of movement is important, the response usually being optimum for speeds between 0.1°/sec and 20°/sec.

3.5.7 It is instructive at this stage to consider in detail the properties of the receptive fields of complex cells. In the cat, while the field of a typical simple cortical cell in or near the fovea may have a diameter of 1° to 2°, a complex field is generally of larger size, ranging from

2° to 3° near the fovea to 10° or more in the periphery. Despite this size, it is generally found that the optimum width of a bar or slit stimulus for these cells is about 10 minutes of arc in width. Thus, the convergence of nerve fibres at each stage of the visual pathway apparently leads to increased receptive field size, without great loss of certain types of detail.

The importance of correct stimulus orientation has been stressed. Hubel and Wiesel record that the orientation of a stimulus is usually critical, in that changing it by more than 10° to 15° produces a marked dimunition in cell response and that a 30° change makes it wholly ineffective.

The response of a complex cell to variation of the length of a stimulus was also studied. A maximum response is obtained when the full length of the receptive field is covered, and making the stimulus any longer has no further effect for that cell. However, although a stimulus is effective wherever it is shone within the receptive field of the complex cell, two parallel stimuli within the field seldom give a more powerful response than either one independently.

3.5.8 Although the question of binocular interaction has not been directly studied by the writer, it is interesting to record here than Hubel and Wiesel (1962) found that the majority of cells in the visual cortex can be stimulated from either of the two eyes. A cell influenced from both eyes always has receptive fields in corresponding positions in the two retinae. These fields are of the same size and arrangement. For a given complex cell, it is found that stimulation in both eyes together does give a more vigorous response than either applied alone. Some cells respond equally well to stimulation of either eye; others favour one or the other. A few respond to one eye only.

3.5.9 Hubel and Wiesel (1965) have also reported investigations into areas of the cat cortex beyond those so far discussed, the so-called Visual II and III areas. In addition to "orthodox" complex cells, they detected what they termed hyper-complex cells, with properties analogous to those of simple and complex cells.

A lower-order hypercomplex cell responds to a slit, bar or edge of appropriate orientation, but the stimulus must be spatially terminated in a suitable manner. The cell has, in effect, a receptive field with an excitatory and inhibitory region, both sensitive to the same stimulus shape. It thus behaves as if receiving an input from two cells, one exciting the cell from a receptive field occupying one area, and the other inhibiting the cell from an adjacent receptive field.

Higher-order hypercomplex cells resemble lower-order hypercomplex cells in that the optimum stimulus is a terminated straight line or edge. However, Hubel and Wiesel discovered, although from the study of only eleven cells, that the higher-order cells respond wherever the termination of the line or edge falls in the receptive field. Furthermore, some cells will respond to a line in either of two orthogonal orientations. In fact these cells behave as if receiving inputs from a number of lower-order hypercomplex cells. Again, a columnar structure was found in Visual II and III, and the constituent cells in a particular column were those expected from the above argument. A column in Visual II and III would contain hypercomplex cells, and those complex cells that might be expected to project to them. In Visual III, in fact, columns were found in which some cells had one receptive field orientation and others had a field orientation at 90° to this direction. Such hypercomplex cells, responding to a terminated line or edge (c.f. a "corner" detector) are apparently designed for detecting discontinuities in simple line or edge stimuli.

3.5.10 The process of stimulus analysis thus progresses systematically from the retina to the visual cortex. Retinal receptors respond basically to input light energy. Ganglion cells, when the eye is light-adapted at least, are more sensitive to small spots of light on the retina than diffuse illumination, and this "contrast" response is heightened when the lateral geniculate cells are reached. At the cortex, the first major development occurs. Simple cortical cells respond best to straight line stimuli of specific position and orientation, while complex cells are sensitive to orientation alone. The hypercomplex cells then appear to detect variations in the structure of these straight stimuli. Beyond this stage, at the time of writing, little or nothing is known.

3.5.11 Since Hebb (Section 2.1.2) attached great importance to the mechanism of perceptual learning, it is interesting to note the observations recorded in Hubel and Wiesel (1963 (b)), and Wiesel and Hubel (1962 (a); 1962 (b)), on the physiology of vision in kittens.

In brief, they discovered that, in young kittens, the geniculate and cortical cells have retinal receptive fields structures of the same type as those present in adult cats. This was so even when the kitten had no previous visual experience. Compared with cells in the mature cat, those in young kittens respond more sluggishly to visual stimuli, and their receptive field orientations tend to be less well-defined.

Hubel and Wiesel also found that if one eye of a kitten was deprived of vision for 2 or 3 months from birth, either completely or with a translucent occluder, then marked structural changes, akin to atrophy, occurred in geniculate cells driven from that eye. No such change was observed in retinal cells. In the cortex, again no atrophy was noticed, but it was found that the vast majority of cells were driven from the normal eye, and the few cells driven from the deprived eye had abnormal receptive fields.

If the kitten's eye was not obstructed until 2 months after birth, i.e. after the eyes had opened, the effects described previously were very much reduced. A mature cat, moreover, showed no change from the normal, either in receptive field organisation or cell structure, even when deprived of vision for 3 months.

The conclusion would seem to be that the young kitten, prior to any visual experience, has an innate system of neural interconnections. This becomes more clearly defined when the eyes open and are exposed to form stimulation. If no such stimulation is forthcoming to an eye within a short period, some cells, which cannot be usefully stimulated from the other eye, apparently atrophy.

It should be emphasised again, that it is most speculative to relate observations made on the cat to the visual system of man. However, in the absence of reliable alternative data, it must be considered significant that there exists in the immature cat, a mechanism so similar to that which Hebb considered necessary in human vision.

3.5.12 A substantial review of the experimental work on the neurophysiology of vision is contained in Graham (1966). In particular, notable contributions have been made by Burns and Pritchard (1964), on cortical cells of the conscious cat, Barlow and Hill (1963), on retinal ganglion cells of the rabbit, Maturana, Lettvin, McCulloch and Pitts (1960), on the frog retina, Maturana and Frenk (1963) on the pigeon retina , Hartline et al. (1956, 1959), and Ratliff et al. (1963) on the compound eye of Limulus. Because of the considerable differences in the complexity of the brains and systems studied, it is difficult to make more than a superficial comparison of the various results. It is of interest, however, to note that they all reveal some form of systematic analysis of the incident light information, in a manner similar to that discovered by Hubel and Wiesel.

In addition, the work of J. Z. Young (1962 a; 1962 b; 1964) should not be omitted from any survey of visual physiology. From studies of the common octopus, he has developed a model to describe the working of its brain, and how it can adapt its behaviour to the external conditions. While the simple octopus brain bears only slight resemblance to the sophisticated structures of the higher animals, the concept of cells acting as "switching circuits" in the learning process may well have general relevance.

The majority of this review is devoted to the work of Hubel and Wiesel simply because of the extent and thoroughness of their study, and its great implications for the subject of form perception. Whether their work can be regarded as definitive is another matter. Since the majority of this thesis was prepared, Spinelli (1966) has reported a most elegant experiment in which the receptive fields of ganglion cells in the retina of the cat were mapped. He questions the generally accepted ideas of purely concentric "on-centre" and "off-centre" field distributions, in view of his discovery of line and edge detectors among these cells. If these findings can be reproduced on a larger scale, the concept of receptive fields of cortical cells being a combination of the receptive fields of the preceding neurons in the system may require modification.

3.6 Summary and Discussion

3.6.1 The boundaries of knowledge of the vertebrate visual system have been greatly extended in the last fifteen years. Those aspects which the writer considers of importance to the study of perception have been described in this chapter.

Although the experiments have been performed on animals other than man, it is unlikely that the results are not in some way relevant to the processing that occurs in the human visual channel. Again, the majority of the investigations have been on anaesthetised animals, and it is possible that the neural interactions which have been mapped may be functions of the animals' state of consciousness. Hubel and Wiesel (1965) state that, although deepening the anaesthesia made responses more sluggish, no change in response specificity was noticed. Even if the eye of a conscious cat or monkey does not exhibit such simple receptive field patterns, it cannot be without significance that the organisation exists in the unconscious animal.

It is also interesting to consider the location of the neural networks that have been investigated. The cells concerned have been those associated with the transmission and reception of information through the channel between eye and the major part of the brain. Although the human brain is a far more sophisticated structure than that of the lower animals, it shares that communication "bottleneck" with the cat. It is very possible that similar methods are used to overcome the inevitable transmission problems posed by such a channel.

To conclude, there is evidence now available of a basis for the neural processing that occurs in the early stages of the human visual system. The experiments on visual detection, which will be described in Chapter 7, are intended to test for the presence of some of these structures.

CHAPTER 4. THE USE OF TELEVISION DISPLAYS IN PSYCHOPHYSICAL EXPERIMENTS

4.1 Introduction

4.1.1 The author believes that the experimental work to be described involves a novel use of television displays for the measurement of detection thresholds. Griffiths and Nagaraja (1963) described experiments using television images to simulate the behaviour of Radar displays, and the method independently proposed by Professor E. C. Cherry in 1962 and developed by the writer is similar in some ways. Because of the unusual nature of the approach, the basic features of television displays will now be considered.

4.2 The Nature of Ciné and T.V. Image Construction.

4.2.1 All Ciné and T.V. "moving" pictures are carefully created illusions. The limitations of the human visual system are exploited (albeit with a degree of co-operation on the part of the viewer) to produce these illusions. The systems are generally very successful, although difficulties can arise, such as the well-known "wheels running backwards" effect.

The basis of all systems is the presentation of a series of stationary, or near-stationary, images in rapid succession. The scenes are changed at a rate so fast that the substitution is not noticed by the watcher.

4.2.2 The ciné projector is probably the most effective of the devices that perform this function. A ciné film consists of a series of frames, which are stationary pictures or "stills". Light is shone through the film and a suitable lens system to produce an image on a screen.

It is important to note that the film runs through the projector in a series of jerks, not continuously. A frame arrives before the light source, and stops, while the light is cut off by a shutter. This then opens and the image of the still is seen on the screen. The shutter then closes and the next frame moves into place, and the process is repeated. However, for primarily mechanical reasons, a film speed of 24 frames per second is usually used. If the succession of projected stills occurs at this rate, with high screen brightnesses, a pronounced flickering of the image is noticed. It is therefore arranged that the image is again interrupted by the shutter in the middle of the illumination period, thereby doubling the flicker rate. This flicker rate of 48 images per second is not normally noticed, and the impression of a continuous image is created.

This brief description of the principles of ciné projection illustrates the degree to which the simulation of moving pictures relies on the perceptual properties of human vision.

4,2.3 The construction and presentation of a television image is basically similar to that of a ciné image, but several important differences exist.

The picture is obtained as follows: a scanning spot, produced by an intensity-modulated electron beam, traverses the screen, moving rapidly, horizontally from left to right, and more slowly vertically from top to bottom. The screen is coated with a phosphor which glows when struck by the beam. The beam thus "illuminates" a small area of the screen as it passes, according to the luminance of the image at that point. This area continues to glow after the beam has gone, but the luminance decays to a negligible value by the time the spot reappears at the same point. The decay time of the luminance is usually between 1 and 10 milliseconds, depending on the type of phosphor material, and the spot does not return for 40 milliseconds (in the British system). In fact, although the traverse of the screen from top to bottom takes only 20 milliseconds, the image thus produced is not immediately repeated. Indeed, a second is illuminated, "interlaced" between the scanning lines of the first, before the first path is retraced. The two interlaced "fields" form one complete "frame".

The resulting effect is of an illuminated image occurring with a periodicity of 20 milliseconds. The fact that the spatial location of alternate images is slightly different does not cause a pronounced sensation of flicker, under normal viewing conditions. Only if the screen is inspected closely, can a slight flickering of adjacent lines be discerned.

It is when the process of image construction in the viewer's mind is considered, that uncertainties arise. Undoubtedly, by the time the scanning beam has reached the botton of one field, the lines at the top have faded to a very low luminance, and therefore there must be an intensity gradient across the screen, at any instant. The field is thus progressively constructed and is not presented as a complete display. This situation is further complicated by the interlacing of successive fields in each frame. It is difficult to decide whether interlaced fields should be considered as forming perceptually distinct images, or not, since the screen is normally viewed at such a distance that the adjacent scanning lines cannot quite be resolved.

Thus there is only an indirect parallel between the stationary, once interrupted, ciné frame, and the interlaced, progressively scanned television frame. Although under specific conditions both look similar, the process of image formation in the brain may be very difficult.

4.3. Flicker Perception.

4.3.1 Since the perception of a television image depends so much on the way in which the visual system responds to successive fields and frames, it is advisable to study briefly the relevant aspects of flicker perception. The main variable determining whether temporal variations, or discontinuities, in a light stimulus, are perceived as flickering of the image, is the rate of fluctuation. The transition point between perceived "fused" and perceived "flickering" is usually called the critical flicker frequency, or C.F.F.

Dember (1963) notes that the literature on C.F.F. contains a number of contradictory findings, and attributes this largely to interactions among the many variables studied, and also to the fact that there is wide inter- and intra-individual variability. The main factors and their effects will be summarised below.

4.8.2 With respect to the intensity of the display in its "on" phase, in general, as intensity increases C.F.F. rises. (Eventually, at very high intensities, this effect disappears and the C.F.F. may even decline.) In addition, for a given C.F.F., the area of illumination and intensity are interchangeable within sensible limits.

The relative proportions of illumination and darkness in a cycle, (Light-Dark Ratio, or L.D.R.) are also important. At low intensities, a unity L.D.R. yields the highest C.F.F. At very high luminances, the highest C.F.F. is produced by the smallest L.D.R., i.e. when the cycle is predominantly dark.

There is a pronounced difference in C.F.F. according to where the image falls on the retina. The periphery, which has greater contrast sensitivity as a rule, also has a higher C.F.F. than the fovea. However, at very high intensities this effect is apparently reversed.

It is also uncertain whether C.F.F. is constant throughout the visual system. Lindsley (1953) recorded neural discharges in the visual system of the cat, from the retina to the cortex. He found that the electrical activity at each of the loci tended to reproduce the frequency of a flickering light shone on the retina. However, as the flicker frequency was increased the cortex stopped following, at about 40 cycles/sec, while the retina was still responding appropriately at 100 cycles/sec. Thus the C.F.F. may vary, not only with retinal location, but also within the stages of the visual system.

4.4 C.F.F. and Television Displays.

4.4.1 It is clearly not easy to distinguish any systematic relationships between C.F.F. and the various relevant factors. However, from the viewpoint of ciné and television displays, a few basic rules can be assumed. Because of the nature of the displays, there are few high intensity images, or parts thereof, presented to the human eye. Within this limitation, it can be said that the perceived C.F.F. rises with image intensity, rises with image size and rises if the image impinges on the periphery rather than the fovea.

Fink (1957), without specifying an L.D.R., states that an image repetition frequency of 50 per second is the C.F.F. for a luminance of 29 ft. lamberts. Since this figure is usually above the peak luminance of a television image, and the L.D.R. is high, such displays should not be perceived as flickering. Fink does not quote a corresponding viewing distance and visual fixation, but it is not unreasonable to suppose that his figures correspond to "domestic" viewing conditions, and therefore to predominantly foveal vision.

In practice a television image does not flicker noticeably, unless it is viewed so that the image falls on the extreme retinal periphery. While this is satisfactory from the entertainment point of view, this fact also suggests that the frame repetition rate is not far removed from the C.F.F. For this reason, and because of the other features of the display construction, it is not certain that a television image can be regarded as an exact analogue of a direct visual stimulus.

4.5 Summary.

4.5.1 The purpose of this chapter has been to explain the nature of a television display, and to emphasise the extent to which the simulation of the image depends on the properties of the visual system. The great advantages of using television in a psychophysical experiment, which will appear in the following chapters, are not necessarily obtained without loss of generality in the results. This topic will be discussed again, in the light of the experimental results, in Section 8.2.

CHAPTER 5. THE EXPERIMENTAL APPARATUS AND THE OBSERVERS

5.1 The Principle of the Experiments

5.1.1 Basically, the experiments have involved the detection by observers of simple visual images, presented with a background of visual noise in a television display.

The fundamental concepts of noise have been described in Section 1.4, and the example of disturbances affecting a neural "message" was briefly discussed. There are several varieties of noise effects which commonly occur in a television system, and the manifestations in each case may be different. For example, the disturbance may take the form of false picture information in a stable display, loss of synchronisation in the display construction or both.

Only the first case is of interest here. It can occur, for example, in so called "fringe" reception areas of broadcast transmission. The received signals are weak and the amplification necessary to produce a useful signal introduces noise from within the receiver circuits. However, the synchronisations circuits of modern receivers, using "flywheel" techniques, can produce steady displays from relatively noisy signals, so the resulting image is simply a "noisy" picture. A similar situation exists if a closed-circuit television camera is used to monitor a situation under low lighting conditions. The synchronisation signal can be independent of the camera unit, so that perfect picture stability is obtained. However, the high video signal amplification necessary again introduces electrical noise.

Under particular circumstances, the appearance of the resulting picture may vary widely when the final "noisy" signal reaches the display tube. This depends largely on the noise source or sources in the system (Maurice et al. 1955). In many cases, when several independent sources contribute to the final noise signal, the noise tends to have a Gaussian amplitude distribution and a flat frequency spectrum within the bandwidth of the system (Prosser and Allnatt, 1965). In this instance, it is possible to think of a 405-line display of noise alone as consisting of a matrix of 600 x 400 dots, the intensity of each being independent of its neighbours, described by a Gaussian amplitude distribution, and changing once every twenty-fifth of a second. This concept, of course, is only approximate, since no account is taken of the scanned structure of the display. In addition, the non-linear input voltage versus output luminance relation of the typical television display tube at low luminance cannot always be ignored. This relation follows an approximate square-law (luminance proportional to $(\text{voltage})^2$), and the video signal from the camera unit is usually distorted in advance to compensate for this. Any noise introduced in the channel subsequent to this "gamma correction", as it is called (Fink, 1957), is affected by the display tube characteristic. It has been found in practice that the importance of the non-linearity decreases as the mean screen luminance is increased, (see Section 5.2.4), at least until saturation of the beam current takes place.

In the experiments to be described, the visual noise used was Gaussian and of 3 Mc/s. bandwidth, since this was readily available, was found to make an excellent background for obscuring displays, and was also a good representation of the typical disturbance encountered in television systems. The appearance of a display composed of such noise alone is shown in Figure 5.1.

5.2 Apparatus Arrangement.

5.2.1 A modified closed-circuit television system formed the basis of the test equipment. A camera unit was omitted, since the simple visual patterns employed in the experiments could be produced with great precision for long periods of time (many months, if necessary) by using electronic switching circuits. The video signals produced in this manner were also virtually free from noise. These "synthetic" television signals were linked directly to a high-quality television monitor.

A diagram of the arrangement of the apparatus is shown in Figure 5.2.

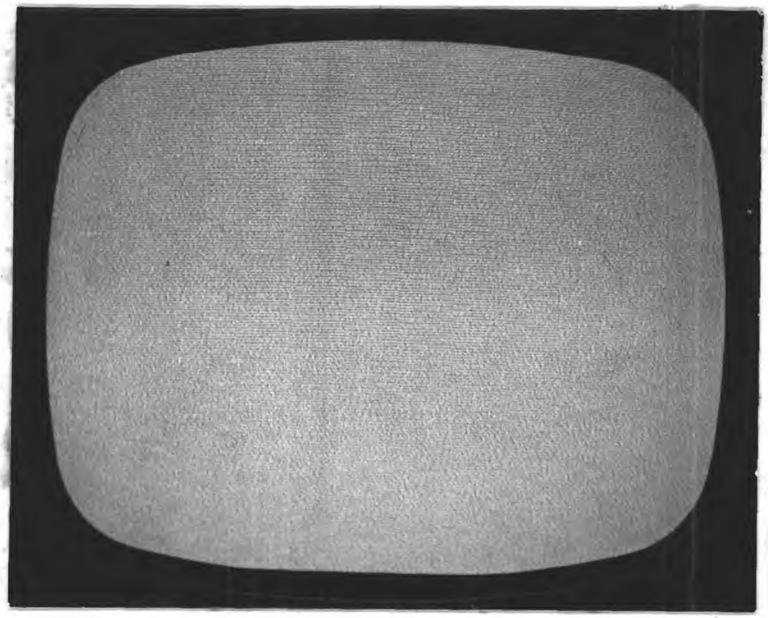


Fig. 5.1.
T.V. display composed of Noise alone.

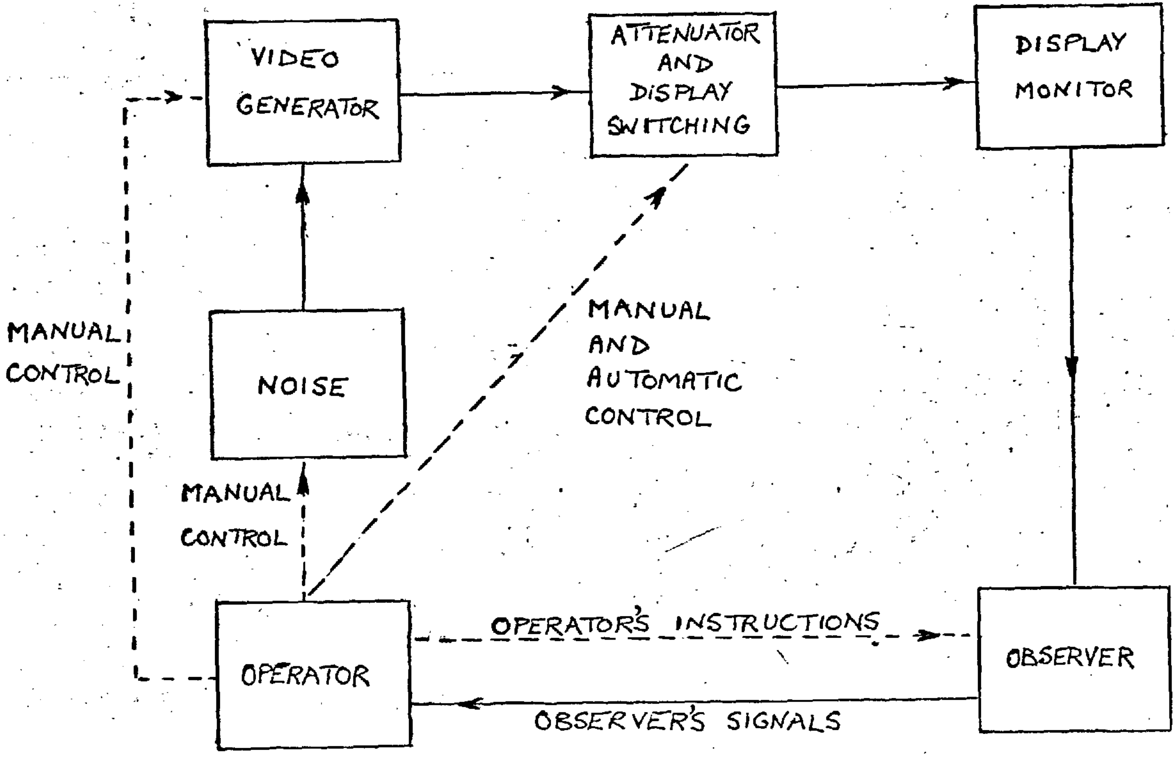


FIG. 5.2. APPARATUS ARRANGEMENT.

5.3 Video Signal Generator (see also Appendix 1).

5.3.1 This provided high precision, simulated video signals of simple television pictures such as straight lines and curves. The signals produced were in the form of a voltage waveform, without blanking pulses, and appropriately synchronised to the display on the monitor. The synchronisation signals for the entire equipment were obtained from a stable independent source.

The magnitude of the video waveform could be varied using a wide- bandwidth Wayne-Kerr, Q251, voltage attenuator. This was calibrated, in steps of 0.5 db, from 0 db. to 61.5 db. attenuation.

The attenuated signal was then passed through a single-stage, resistance-capacitance filter of 3 Mc/s bandwidth, prior to reaching the noise-adding circuits. In addition, a "pedestal" waveform was added to the video signal at this stage to provide flyback blanking and also to set the mean luminance level of the ultimate display. A diagram showing the process of building up the video signal is given in Figure 5.3.

The complete video signal was subsequently selected by the display switching circuits (Section 5.5.1) and then taken by cable to the display monitor. This was an orthodox television-studio type without radio-frequency stages, manufactured by Rank-Cintel Limited (Type 28842). A 17 inch (diagonal) screen size was used, although this choice was determined by factors not connected with the experiments that

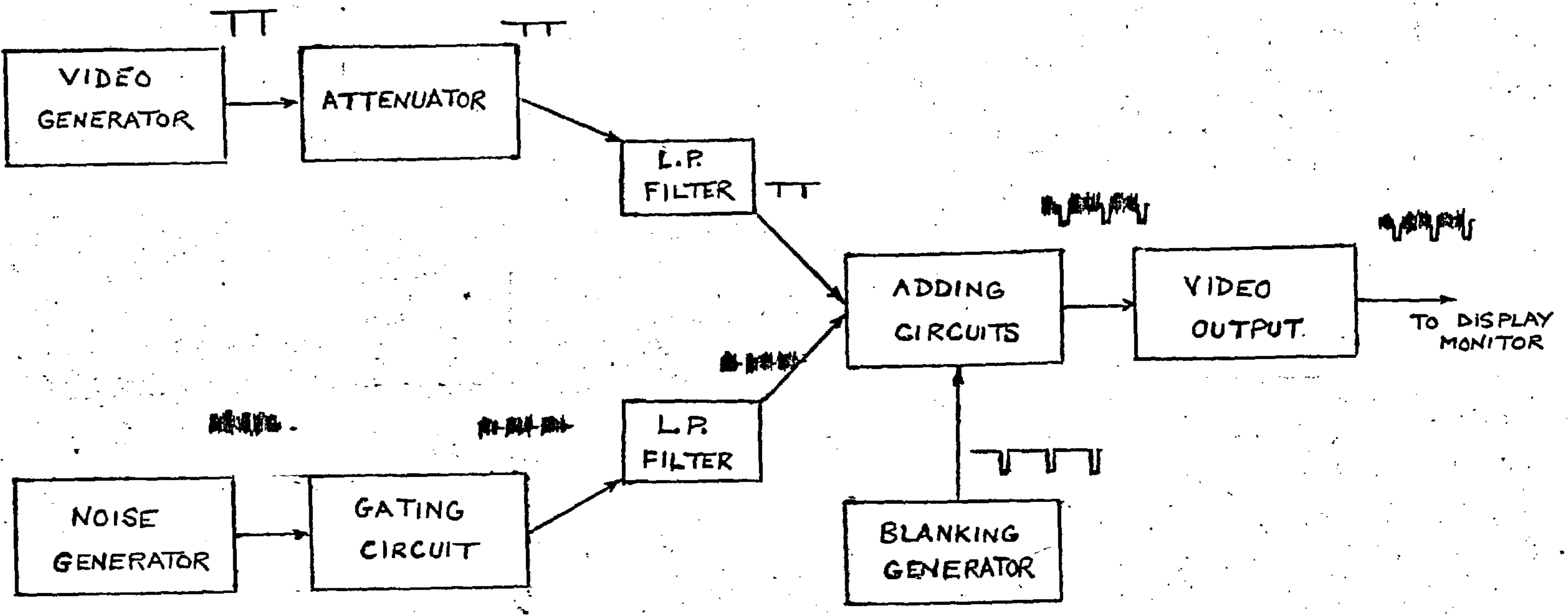


FIG. 5.3. PRODUCTION OF NOISY VIDEO SIGNAL.

were performed. Considerable care was necessary in the selection of the particular unit employed to ensure that no important spurious patterns were visible on a supposedly blank screen. The whole system operated to British television standards, namely 25 frames per second, 2 to 1 interlace, 405 lines per frame, and 3 Mc/s nominal video bandwidth.

The frequency response and phase response of the system from 10 Kc/s to 6 Mc/s were measured, using an Advance E1 sine-wave oscillator and a Tektronix Type 551 Dual-Beam Oscilloscope. The sine-wave voltage was fed into the signal attenuator, i.e. the section of the system receiving the signal from the video generator itself, and measured at the anode of the final valve in the display monitor, i.e. at the point immediately prior to the display tube. Care was taken to ensure that the high-frequency compensation circuits in the monitor were not disturbed during the measurements. Since the monitor included a d.c. clamping circuit, to restore the video signal "black" level, operating every 100 microseconds, the actual system frequency response did not need to extend below 10 Kc/s. The results (Figure 5.4) indicate that the voltage gain of the system was constant from 10 Kc/s to 100 Kc/s, and then fell gradually, until at 3 Mc/s it was 3 db down on the level at 10 Kc/s. The phase response (Figure 5.5) was substantially linear over this

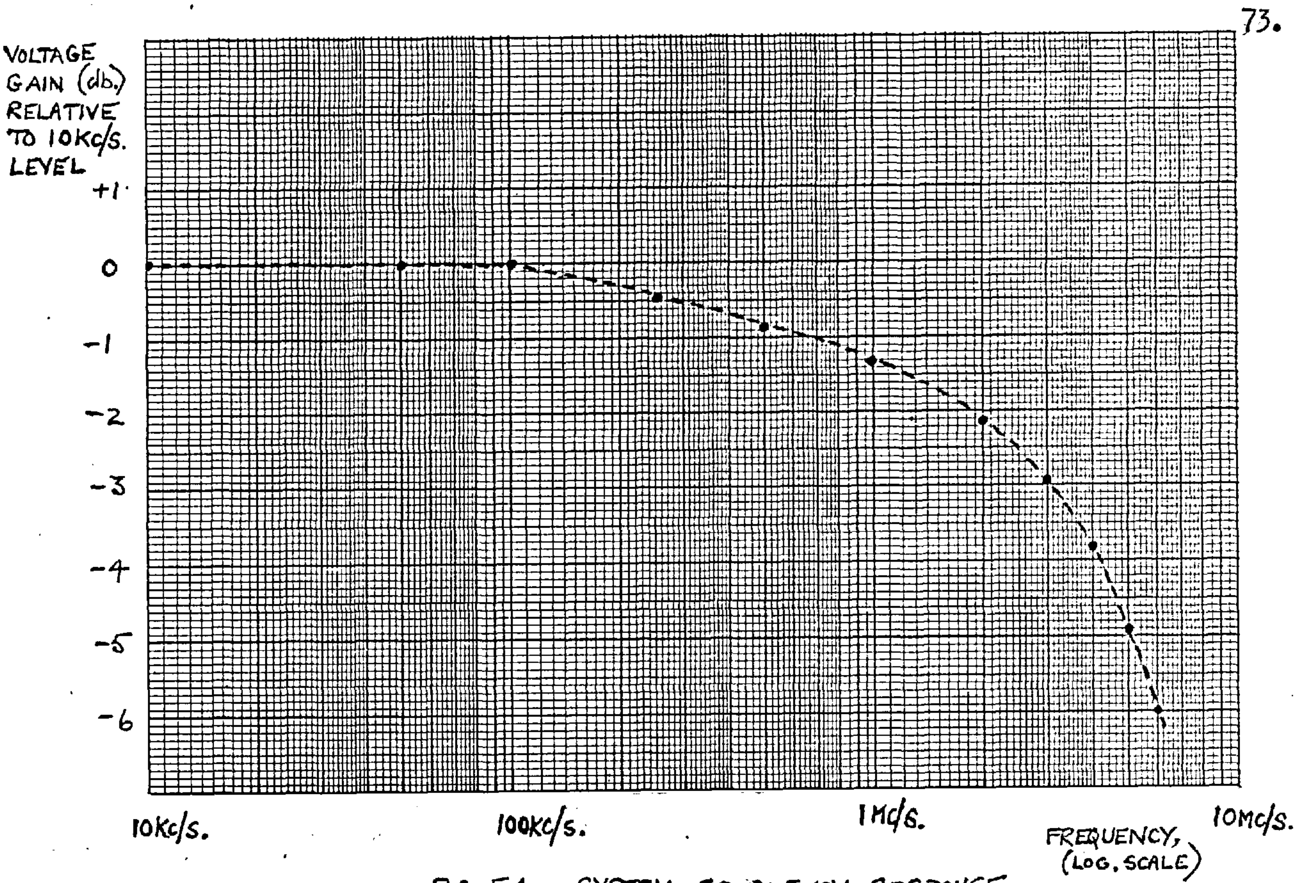


FIG. 5.4. SYSTEM FREQUENCY RESPONSE.

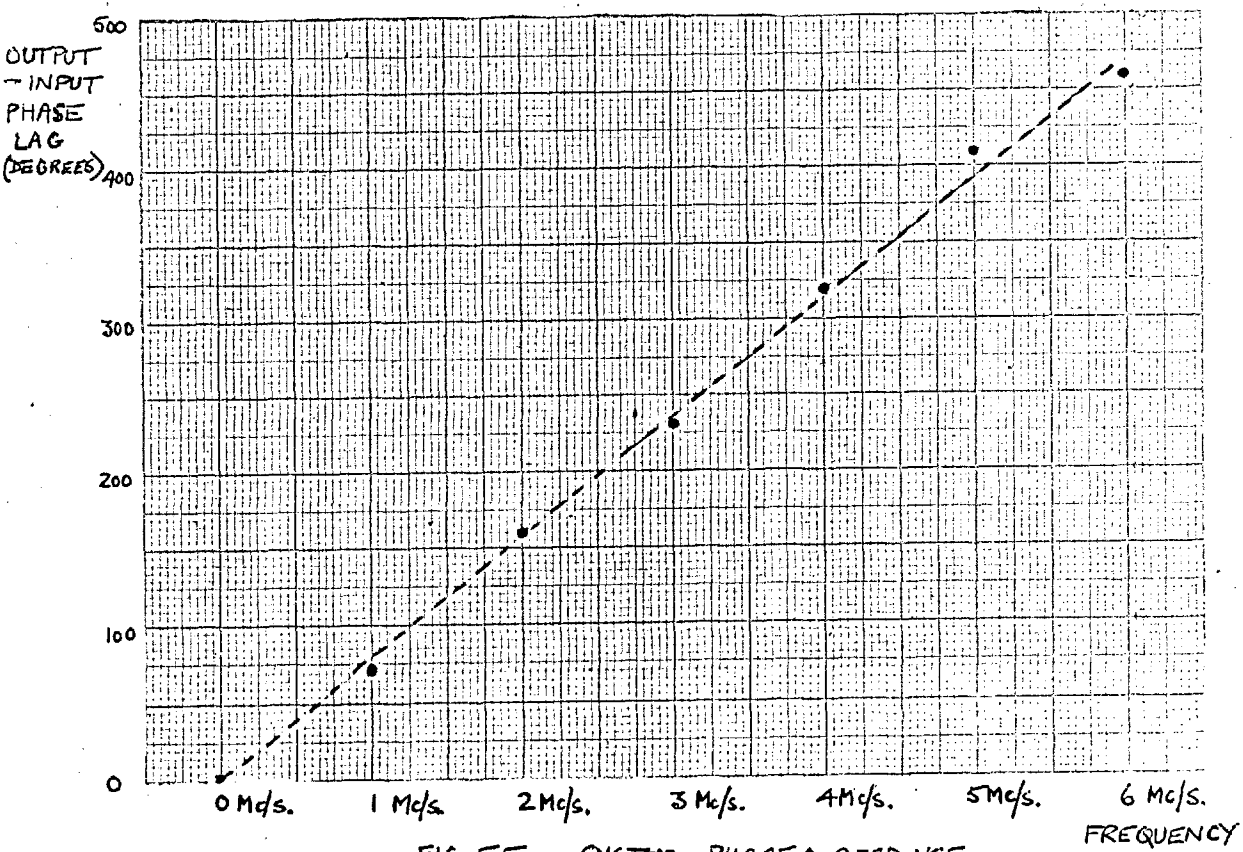


FIG. 5.5. SYSTEM PHASE RESPONSE.

range, indicating that the time delay introduced by the system was independent of signal frequency.

The amplitude distortion of the signal introduced by the system will be discussed in the next section.

5.4 The Noise Generator and Noise Adding Circuits.

5.4.1 The noise voltage was added algebraically to the video signal, via a 3 Mc/s low-pass, resistance capacitance, filter identical to that in the video circuit. The addition was performed using a unity-gain operational-type amplifier.

The noise source was a General Radio, 1390 B, noise generator, specified to provide noise of Gaussian amplitude distribution and flat frequency spectrum to an upper bandwidth limit of 5 Mc/s.

Two precautionary tests were made on the signal output from the noise generator. In the first, a Quan-Tech Level Analyser was used to determine the amplitude distribution of the waveform. The percentage of time in a fixed period that the signal amplitude exceeded a given level is plotted against the level, as shown in Figure 5.6. The abscissa is scaled in units corresponding to a cumulative normal probability distribution. The resulting straight line indicates that the instantaneous noise amplitude was so distributed over a very wide range. Unfortunately, the useful bandwidth of the Quan-Tech Analyser does not extend above 1 Mc/s, and since no alternative instrument was available,

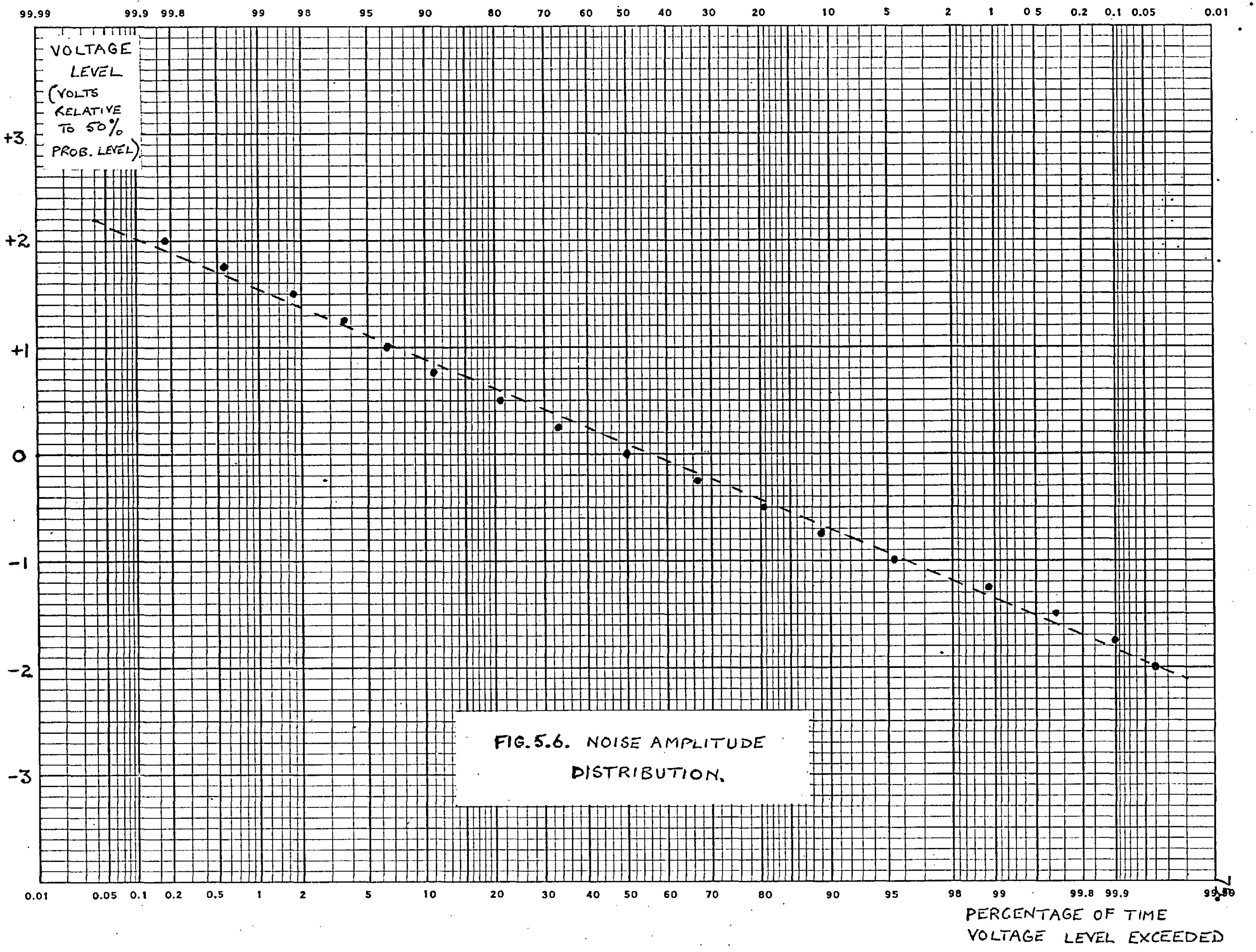


FIG. 5.6. NOISE AMPLITUDE DISTRIBUTION.

the investigation could not cover the full system bandwidth.

Secondly, the frequency distribution of the noise was tested. In the absence of a reliable frequency analyser, the method employed by Pearson (1965) was adopted. This uses the property that the noise power is proportional to the noise bandwidth. The noise power can be expressed as the square of the Root Mean Square noise voltage, $V_{R.M.S.}$, which was measured using a Ballantyne, Type 320 A, True R.M.S. Valve Voltmeter. The noise bandwidth was varied by employing a number of single-stage, low-pass, resistance-capacitance filters. The relation between $(V_{R.M.S.})^2$ and bandwidth is shown in Figure 5.7. The measured points are a good fit to a straight line, indicating that the frequency spectrum of the noise was reasonably uniform from 10 Kc/s to 3 Mc/s.

It must be mentioned that these measurements should be considered as representative of the noise employed in the experiments. It was found in practice that the characteristics of the gas-filled diode employed in the noise generator varied slightly with age, and that it was necessary to replace a particular diode after about 500 hours of use. Considerable care was necessary in selecting replacements so that the accepted amplitude and frequency characteristics could be matched.

It was also necessary to process the noise before it was added to the video signal. The display monitor clamping

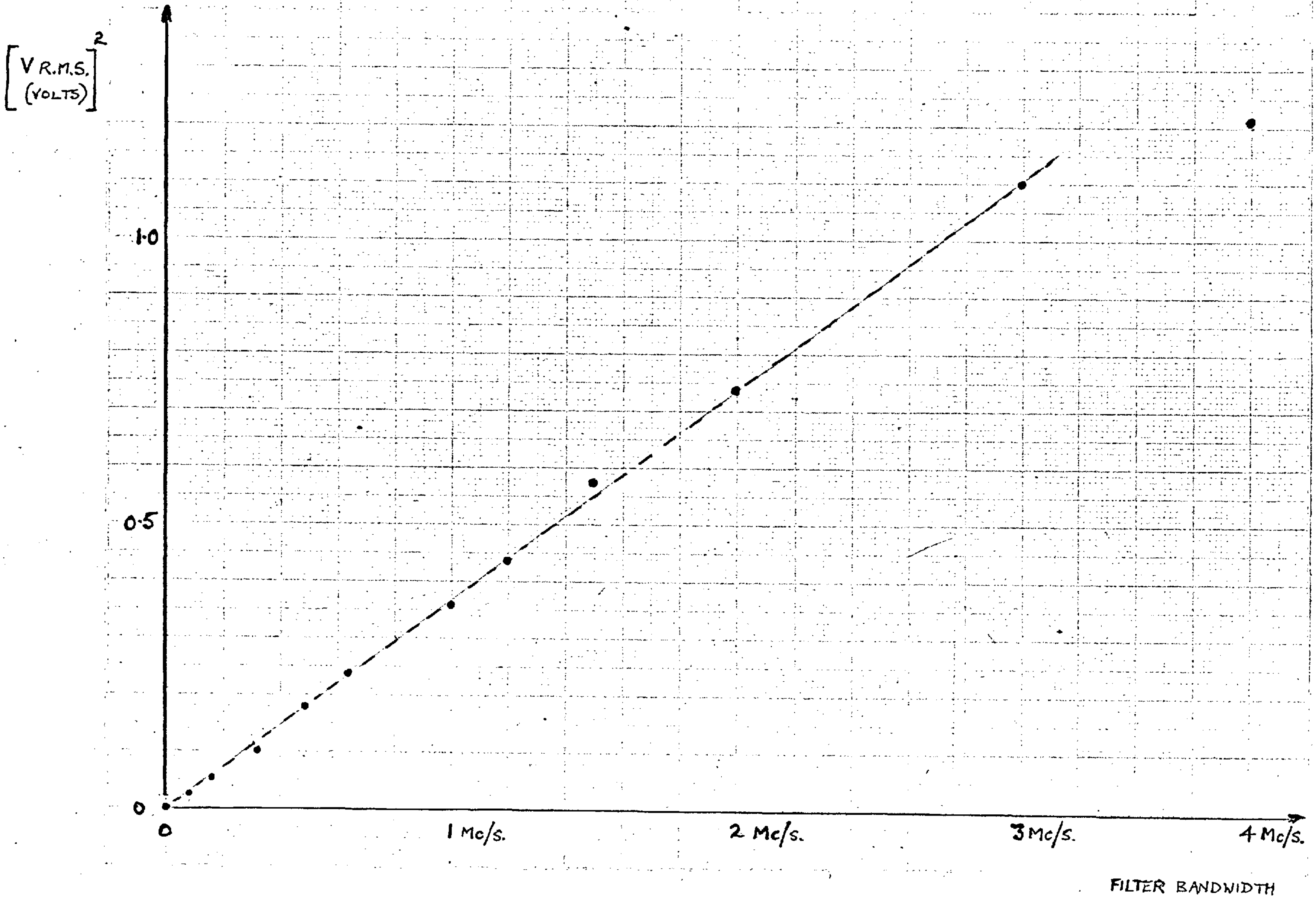


FIG. 5.7. VARIATION OF NOISE POWER WITH BANDWIDTH.

circuit operates during the blanking intervals of the video signal and establishes the black level of the picture on the basis of the signal level in this period. The efficient working of this device was found to be disturbed by high noise levels, so the noise signal was removed during the blanking intervals, using a simple gating circuit. Since this process had no effect on the noise present in the actual display, its effects were disregarded when the measurement of noise level was made.

5.4.2 It is not easy to find a simple but general definition of the relative strengths of signal and noise in a television display. The various methods normally employed have been summarised (Marsh, 1963), and are satisfactory in only limited circumstances. The experiments to be described have all used two-level or "black and white" pictures, in particular dark shapes against a lighter background. With such simple displays, a concise and meaningful definition of Signal to Noise ratio (S/N ratio) is possible.

To make this clear, a simple example will be discussed. Consider a display containing a narrow, vertical, dark line on a light noise-free background. If the line extends over the full picture height, the video signal voltage corresponding to any one line will be of the form shown in Figure 5.8. The black level regions A and C correspond to the flyback intervals when the scanning beam is returning to the left of

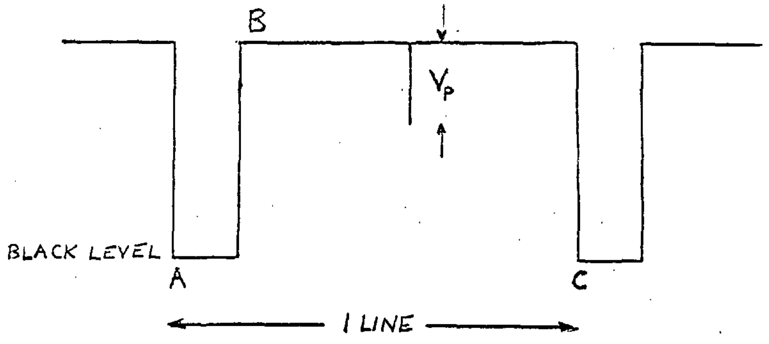


FIG. 5.8.

the screen to begin the line. The region B is at a constant level above black, except where a narrow downward pulse forms part of the dark line in the picture. It is the height of this pulse, V_p , which defines the strength of the picture signal, relative to the uniform background, at least in terms of the signal voltage. This height V_p , can thus be compared with $V_{R.M.S.}$, the Root Mean Square voltage of the noise added to the signal, to describe the S/N ratio of the resulting picture.

5.4.3 There remains the question of whether measurements relating to the video signal applied to the display tube are a direct measure of the luminance S/N ratio of the eventual picture. As mentioned in Section 5.1, the relation between voltage applied to the display tube and output luminance is not always linear. This distortion is most marked in dark regions of the picture, and becomes less significant in brighter areas. The amplitude distribution of a signal, involving luminance excursions over a wide range, such as noise, might well be significantly altered by this characteristic.

To minimise this distortion, the mean screen luminance must be well above the black level. The actual luminance chosen for the experiments was influenced by considerations of subject fatigue (See Section 5.6.2), since a very bright screen proved unpleasant for long periods. A compromise level of 5 ft. lamberts was chosen, and the luminance characteristic of the entire system in this region was investigated by the following method.

A simple video signal corresponding to a uniform blank screen was employed, as shown in Figure 5.9.a. The magnitude of this signal, and therefore the luminance of the screen, was varied at the attenuator. The luminance was monitored using a photo-cell from a G.E.C. 904 illumination meter coupled directly to a Digital Measurements 2001, Mark II digital voltmeter. The photo-cell unit was fixed flush with the centre of the monitor screen. The indicated voltage V_L (which was proportional to the screen luminance) versus input signal voltage V_S is shown in Figure 5.9.b. The effect of the non-linear transfer function can clearly be detected, but over a wide range as indicated by the dotted line, the characteristic is substantially linear. The abscissa of Figure 5.9.b. is marked in steps corresponding to units of $V_{R.M.S.}$, above and below the mean level. This noise level remained constant in all the tests. Over 95% of the noise excursions are contained within the quasi-linear range indicated. It can thus be seen that the noise voltage suffers comparatively little amplitude distortion in the conversion to luminance noise, provided the mean luminance of the screen remains sufficiently high.

This testing method was also employed to check the variation of the picture signal level in response to the settings of the Wayne-Kerr attenuator. A video signal of the type shown in Figure 5.10.a. was employed. The screen

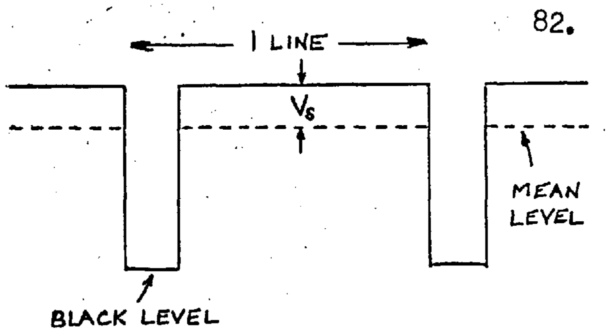


FIG. 5.9.(a).

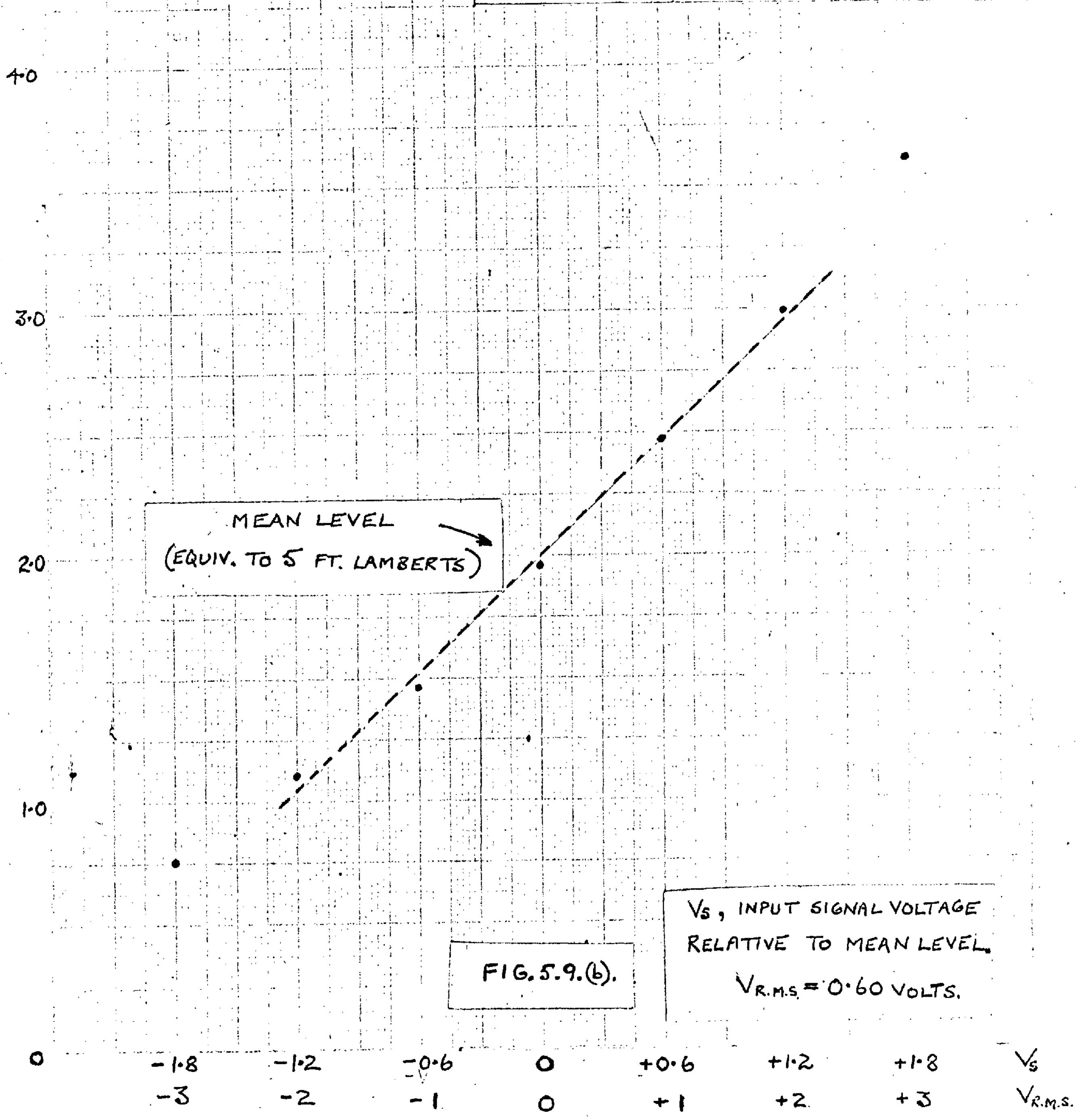


FIG. 5.9.(b).

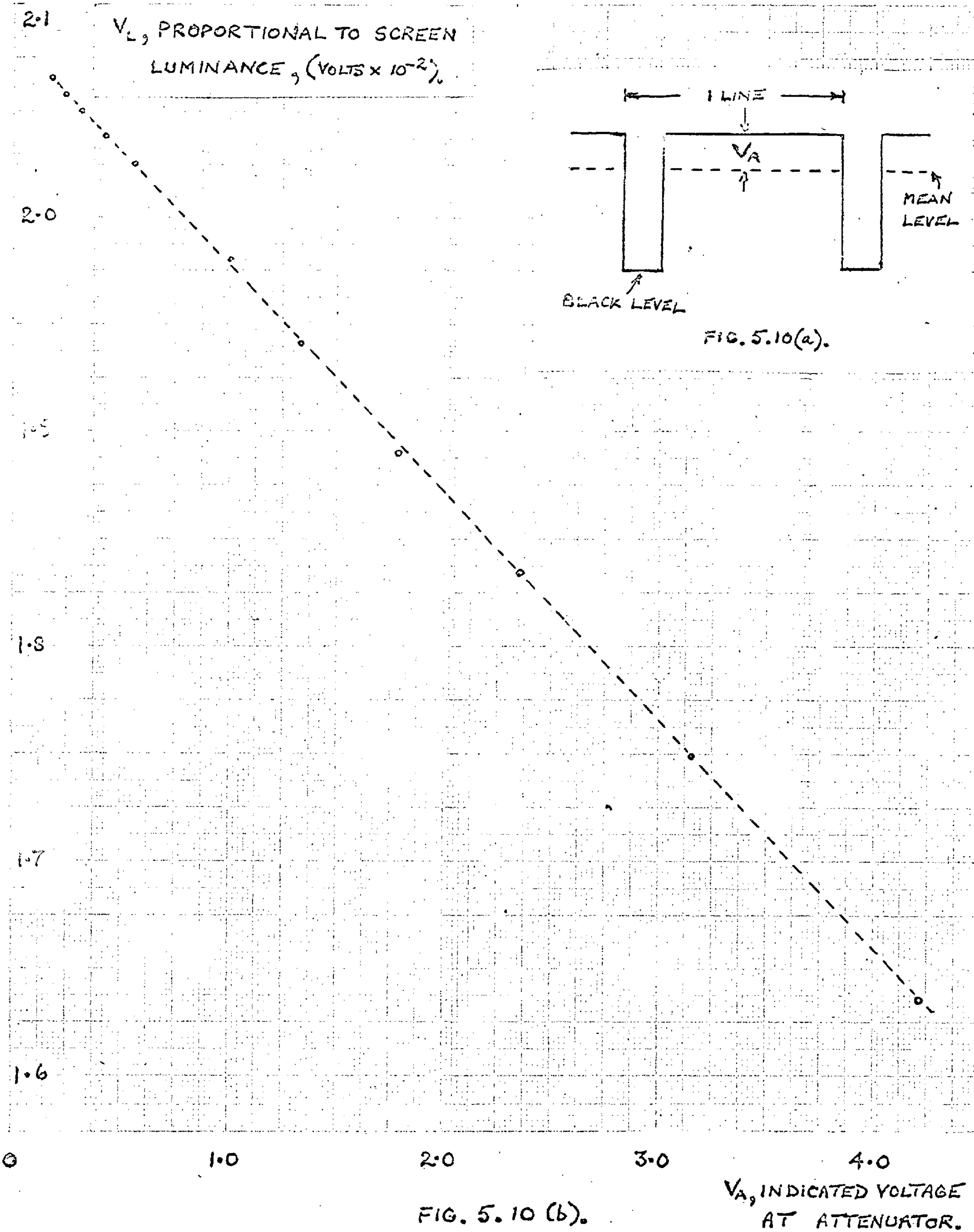


FIG. 5.10(a).

FIG. 5.10 (b).

luminance level, measured again in terms of V_L, is plotted against attenuator setting (on a logarithmic scale) in Figure 5.10.b. Again, it was found that the conversion of the video signal into a luminance signal was linear over the entire range used in the experiments.

In view of these measurements, it was convenient to use the electrical power S/N ratio exclusively to assess the S/N ratio in a display. In practice, both the noise R.M.S. voltage and the signal amplitude were measured at a point immediately before the adding circuits, using the Ballantyne Type 320 A Voltmeter and Tektronix Type 551 Oscilloscope respectively. The noise blanking was removed while the measurements were made.

Using the notation of Figure 5.8, the following definition was used:

$$\text{S/N ratio} = 20 \log_{10} \frac{V_P}{V_{R.M.S.}} \quad \text{db}$$

Typical levels used in the experiments were $V_P = 0.20$ V. and $V_{R.M.S.} = 0.60$ V.

$$\text{i.e.} \quad \text{S/N ratio} = 20 \log_{10} \frac{0.20}{0.60} \quad \text{db.}$$

$$= -9.5 \text{ db.}$$

(If the Luminance S/N Ratio had been specified, a slightly different measure would have been obtained. Within the dynamic range that was used, Screen Luminance, L, is is proportional to input Voltage, V:

$$\text{Luminance S/N Ratio} = 10 \log_{10} \frac{L_P}{L_{R.M.S.}} \quad \text{db}$$

$$= 10 \log_{10} \frac{V_P}{V_{R.M.S.}} \quad \text{db}$$

i.e. S/N Ratio in terms of Luminance = $\frac{1}{2}$ S/N Ratio in terms of Electrical Power.

5.5 Display Switching.

5.5.1 The switching arrangements allowed the operator to present a display to an observer for a precise period of time. It was also possible to immediately substitute a blank display of chosen luminance at the end of this period. Once the process was initiated by the operator pressing a key, the switching was wholly automatic, although provision for occasional manual operation was made.

A typical display sequence would be as follows:-

(i) Operator presses display key. This initiates a half-second delay mechanism (which allows the operation of the random signal selection device, to be described in Appendix 2).

(ii) After the delay, the chosen picture appears before the observer for a given period (usually three seconds).

(iii) The picture disappears abruptly and is replaced immediately by a blank display of pre-determined luminance.

The system has then completed a full cycle, and the display key may be pressed again. If, however, the key is inadvertantly pressed during the cycle, it has no effect.

5.6 Observers and Testing Conditions.

5.6.1 The subjects of the experiments were chosen chiefly from the technical and administrative staff and students of the Electrical Engineering Department of Imperial College. This was necessary because of the lack of an alternative source of supply of continuously available observers. A direct consequence of this limitation was that the majority of the observers were familiar with television techniques. A wide variety of nationalities and backgrounds was included in the group, although more by accident than by design. No evidence was noticed to suggest that such factors might be of importance to the results of the experiments.

Another outcome of the choice of observers from close at hand was that only one female could be employed. This subject was not as technically informed as the others, but no obvious differences were noticed between the results obtained from her and the male observers, although no specific tests for such variations were made.

The observers nominally had normal eyesight, (with spectacles, if usually worn), and their acuity was tested before they were employed, and subsequently at intervals of several months, using a standard optician's chart.

5.6.2 When taking part in an experiment, the observer was seated alone at a constant distance from the display monitor, in an enclosed off-white room, with controlled ambient lighting. This was constant at 0.5 foot-candles, to provide comfortable background illumination, the level being chosen by the majority opinion of the observers. Because of the desire of the writer to operate the display monitor at relatively high luminance (Section 5.4.3), initially a screen luminance of 10 ft. lamberts was employed. However, this level provoked complaints about eye-strain from several observers, so it was reduced to 5 ft. lamberts for the experiments.

The viewing distance was fixed at between eight and nine times the picture height, a length of 108 inches. This was the maximum separation possible between observer and display monitor within the confines of the testing room. Under these conditions, the angular separation of adjacent scanning lines at the observer's eye was 1 minute of arc, and it was found that adjacent lines could not quite be resolved. The total height of the display subtended a viewing angle of 6.3 degrees.

In most of the experiments (Numbers 1, 3, 4 and 5), the observers were not physically constrained in any way, apart from the instruction to watch the screen attentively throughout the test. This situation was modified slightly in the later experiments by the addition of an enclosed "box" around the subject and chair, which allowed only a limited view of the room, but included the display monitor. This was an attempt to help the subject to concentrate and thereby improve the efficiency of the tests. Its success was doubtful, since no obvious improvement was obtained.

Also, in experiments Number 2 and 6, a head clamp was introduced to ensure that the head of the subject remained upright. This was incorporated into the headphones which the subjects normally wore in order to receive instructions from the operator, and to keep out ambient auditory noise. (Figure 5.11).

A light-signal circuit was provided whereby the observers could communicate to the operator their decisions about a particular stimulus. These decisions were normally in the form of "Yes" or "No" replies to simple questions about the display. The way in which the stimuli were presented and the form of the questions are of the greatest importance to the interpretation of the experimental results. The reasons for the eventual choices that were made will be explained in Chapter 6.

5.7 Summary.

5.7.1 The experimental apparatus comprised a high quality closed-circuit television system of orthodox specification, but minus a camera unit. This was replaced by waveform

Fig. 5.11.

Head Clamp.

generator capable of synthesising the signal necessary to display a simple shape on the screen. Gaussian, "white" noise was added to the video signal, and the relative strengths of signal and noise could be varied simply and precisely. The S/N Ratio was specified in terms of the proportions of signal power and noise power in the video signal. This was possible because the display monitor was operated at a sufficiently high mean screen luminance to give a quasi-linear relation between luminance and input signal level.

The display presentation sequence was operated automatically by controlling the output of the waveform generator. The observers, who were tested individually, were seated in an enclosed room under controlled conditions. Their decisions about the displays were communicated to the operator by means of flashing lights.

CHAPTER 6. THE CHOICE OF EXPERIMENTAL METHOD

6.1 The Detection Threshold

6.1.1 The experimental task was that of investigating the perception of simple forms against noisy backgrounds. It was hoped that the measurements would not only provide information directly useful for communication purposes, but would also indicate the possible existence of particular neuro-physiological structures in the visual system. It was therefore necessary to devise an appropriate experimental approach.

At this stage, the meaning of the word perception must be clarified. In the most general sense, perception is defined by stipulating that if the behaviour of an organism can be related to some aspect of an applied stimulus, then the organism has perceived the stimulus (Dember 1963). There are, however, different levels at which perception can occur.

It will be helpful to consider a simple case of a perceptual system. Suppose a light is lit momentarily against a dark background, watched by an observer who is asked to say when he sees the light. When he does so, he is performing the process of detection. If, however, the observer is asked to say whether the light flash is coloured red or green, or what shape it was, he would then be making a choice between alternative stimuli. Since he would presumably need to detect the presence of the image in order to make a decision about its colour or shape, the process of detection would necessarily be essential to the more complicated perceptions such as discrimination and recognition (Dember 1963). The work of Hubel and Wiesel, and others, has indicated that, in the cat, the analysis of a retinal image occurs initially on a stage-by-stage basis, as the signal penetrates from one layer of cells to the next. With such a structure, the accomplishment of a simple perceptual task, such as detection, may involve rather less of the capacity of the system than a higher-order perception. An understanding of a basic human perceptual process may therefore give insight into the more complicated perceptions dependent thereon. It is for this reason and that in the experiments to be described, a detection task has been used as a means of assessing the performance of an observer. The particular importance of the findings of Hubel and Wiesel to this hypothesis will be considered in Section 7.1.

6.1.2 If the example of the light flash and the observer is used again, it might be expected that up to a particular flash intensity, the presence of the light would not be reported, and that above this intensity it would always be detected. This is never the case in practice. Instead, the usual form of a curve relating light intensity to probability of detection is a continuous S-shaped function, not a discontinuous step.

Consequently, no single point satisfies the original definition of a threshold, so it is then necessary to designate as the threshold some stimulus value at which a task is accomplished with an arbitrary probability, often 50%. In the remainder of this thesis, this definition will be adopted, unless otherwise stated.

Several different theories have been put forward to explain the nature and precise shape of the visual detection curve. All include some idea of "noise" affecting the decision threshold, be it caused by random variations in the number of light quanta striking the retinal receptors, or by disturbances within the system itself, or both. Blackwell (1963) examined the theories due to Crozier, Stevens, Blackwell, and Swets and Tanner, and concluded that all predicted realistic threshold functions, with only minor differences in the main. In large scale tests of practical data, obtained by "forced-choice" methods (Section 6.2.2 and 6.3.2), he found that the data could be adequately fitted to normal ogives if the stimulus intensity scale was expressed in logarithmic units. He was slightly less successful with data obtained by the "Yes-No" method (Section 6.2.2 and 6.3.2). The threshold curve in this case was still S-shaped, but was only a marginally good fit to a normal ogive.

6.2 Observer Response Indicator and Stimulus Selection Methods: A Preliminary Experiment.

6.2.1 To obtain experience in testing methods suitable for detection threshold experiments conducted with noisy television displays, a pilot experiment was performed. Four observers were used (R.J., M.M., A.T., R.W.). In this experiment only, the stimuli were presented at constant signal level and the noise power was varied between displays to change the S/N ratio. Two different stimuli were employed:

A. A thin (viewing angle 1.5 minutes of arc), vertical, straight line in the middle of the display, the full height of the screen in length.

B. A line of the same thickness and in the same position, but of sinusoidal curvature, the extent of the horizontal modulation subtending a viewing angle of 25 minutes.

These stimuli are shown at high S/N ratio in Figures 6.1 (a) and 6.1 (b). The choice of these shapes was somewhat arbitrary. Since at the time of the experiment, they could be produced easily, they were used. It was also hoped in view of Hubel and Wiesel's findings concerning straight stimuli, that a significant threshold difference might be found in this case.

At first, the writer thought that the types of noisy display which could be shown to an observer might be contained within three approximate categories. These were:

(i) Those in which he has no reasonable doubt that he has seen the stimulus.

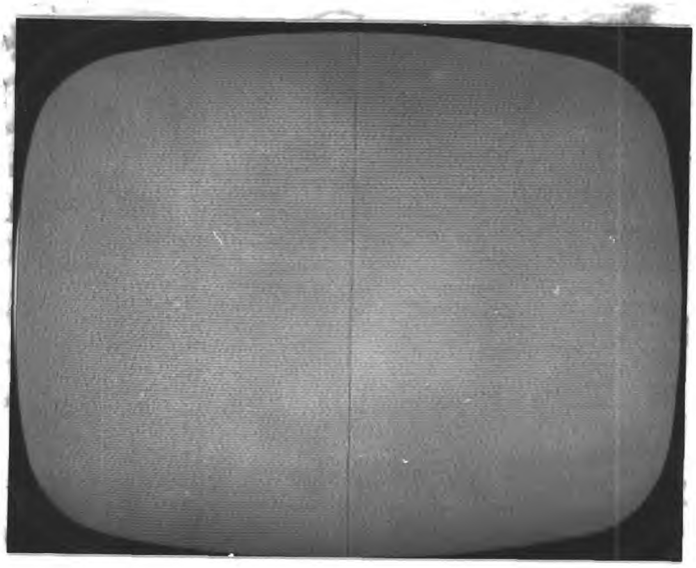


Fig. 6.1(a).

Straight line : Low noise level.

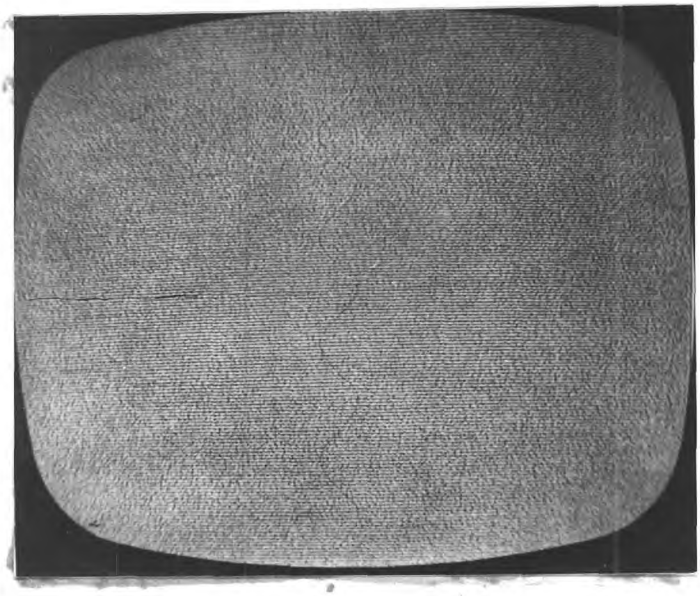


Fig. 6.1(b).

Curved line : High noise level.

(ii) Those in which he suspects from scanty evidence that he has seen it, but is not as sure as in the previous case.

(iii) Those in which he is certain that the stimulus is absent.

On the basis of this assumed behaviour pattern, the following test procedure was adopted. The observer took his seat in the testing room, and a period of some three minutes was allowed to enable any short-term visual adaptation to the conditions to occur. During this time, the stimulus was shown on the display screen at high S/N ratio to ensure that the subject was familiar with its shape and position. He was then told that each noisy display would be shown for three seconds, and that he must then answer the question, "Is the stimulus present in the display?". Only two replies were allowed, "Yes" if he was certain that the stimulus had been shown, "No" if he was certain that it was not present. If he was unsure, he was instructed to reply "Yes" or "No" as randomly as possible. In addition, he was told that on many occasions in one session, the stimulus would be absent from the display. These "blank" displays were used to test for the number of incorrect detections (false-alarms) that were liable to occur under these circumstances. The measurements within a single test were made in equal numbers at six different S/N ratios, separated by 1 db steps. The actual noise level of a particular . presentation, and whether a display would contain the stimulus or not, was decided in a quasi-random manner, using a shuffled pack of cards.

Each test was confined to one stimulus shape only, contained about 100 presentations and lasted about 30 minutes. Including the blanks (about half of this total), nearly 400 individual presentations were made of each stimulus to each observer, in 32 separate testing sessions spread over a period of ten days.

6.2.2 The results of this experiment were illuminating. Three observers (R.J., M.M., R.W.) "detected" the stimulus in very noisy blank displays with probabilities approaching 50%, and even at very low S/N ratios the real stimulus was detected with this probability. This phenomenon, in conjunction with the verbal reports of the three observers, indicated that the more noisy displays "suggested" the presence of the stimulus sufficiently strongly to make a certain "No" decision almost impossible.

The fourth observer (A.T.) had overcome this difficulty by assuming a severe criterion for detection. Whenever he was not absolutely sure of the presence of the stimulus he said "No". As a consequence, he gave a negligible proportion of false alarm detections. The data obtained from A.T. (excluding the blank presentations) are shown graphically in Figure 6.2, on linear versus normal probability axes, and have been fitted, by eye, to a straight line. It would certainly be possible to apply an accurate

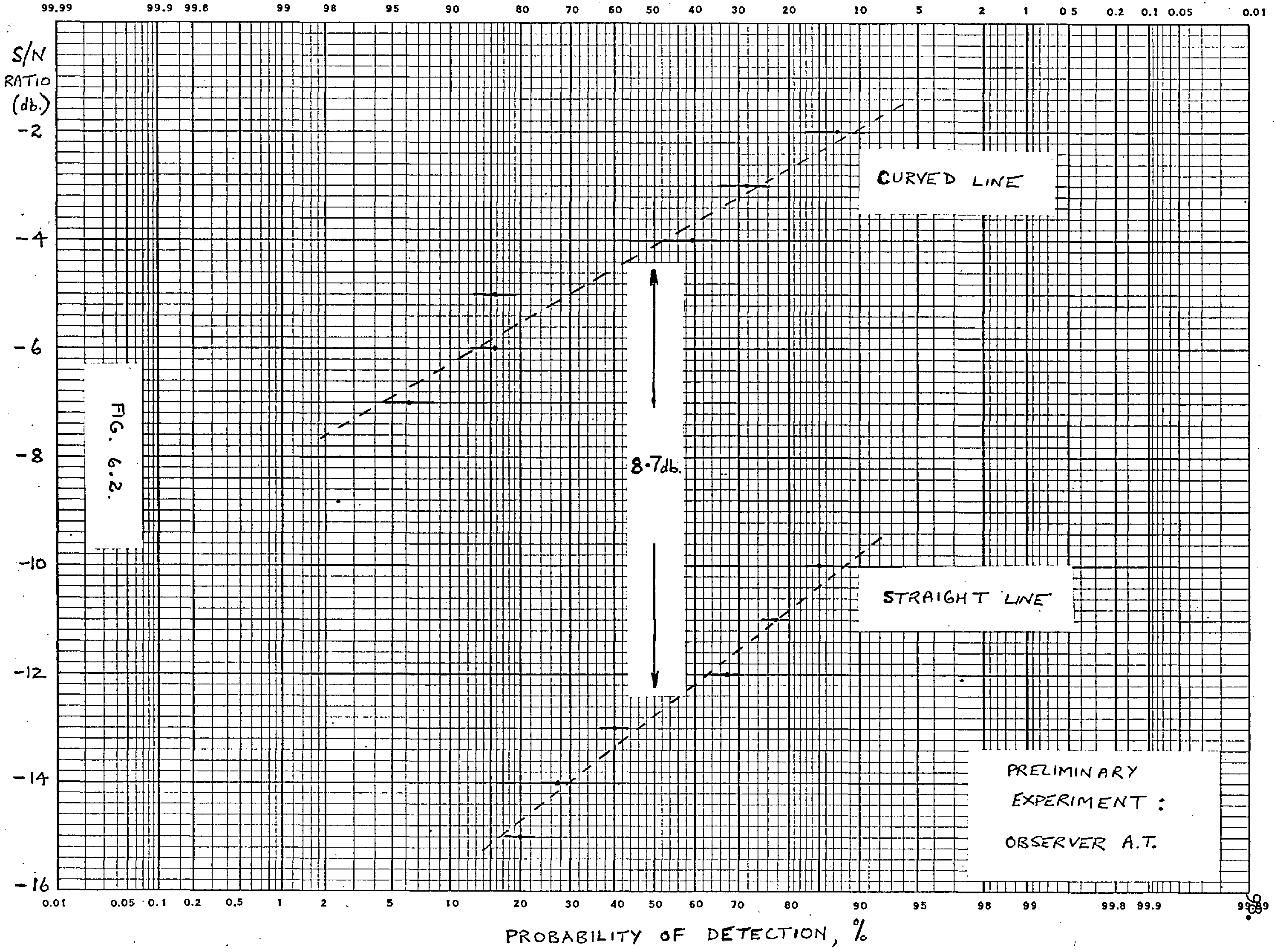


FIG. 6.2.

99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0 5
0.2
0.1
0.05
0.01
S/N RATIO (db.)
-2
-4
-6
-8
-10
-12
-14
-16
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
CURVED LINE
8·7db.
STRAIGHT LINE
PRELIMINARY EXPERIMENT : OBSERVER A.T.
PROBABILITY OF DETECTION, %

curve fitting process, to this data and obtain respectable results. For the purposes of this experiment, this refinement was deemed unnecessary. The probable experimental errors associated with the points indicated on Figure 6.2 were estimated using the technique described by Budrikis (1960).

When the same method of analysis was applied to the data obtained from the other three observers, it was found impossible to fit the points to a similar straight line. Instead it was necessary to consider the probability of a mistake about the stimulus (i.e. stimulus undetected or wrongly "detected") as a function of noise level. These data are shown in Figures 6.3, 6.4 and 6.5, also on linear versus normal probability axes. Since the variation of mistake probability was found to be within the range 0% to 50% the mistake probability was transformed by using the relation:

$$P_t = \frac{(50 - P)100}{50} \ \%$$

where P_t is the transformed mistake probability, and P is the original mistake probability.

The experimental points thus obtained are an approximate fit to a straight line for all three observers, and again a line has been drawn by eye. The differences in threshold S/N ratio between the two shapes have been estimates for each subject and are tabulated in Table 6.1.

It is important to note that while the threshold S/N

Observer.	Absolute Threshold S/N Ratio (db)		Threshold Difference (db)
	Straight line.	Curved line.	
A.T.*	-12.8	-4.1	8.7
R.W.	-13.9	-7.1	6.8
R.J.	-13.3	-4.3	9.0
M.M.	-10.6	-4.9	5.7
Average.	-12.7	-5.1	7.6

* Results for observer A.T. are for 50% detection probability. Others are for 25% mistake probability.

(No errors have been quoted since no formal analysis of the results was made. By inspection, the probable error associated with each absolute threshold measurement is of the order of ± 1 db.. Hence the probable error of each threshold difference is > ± 1db..)

Table 6.1

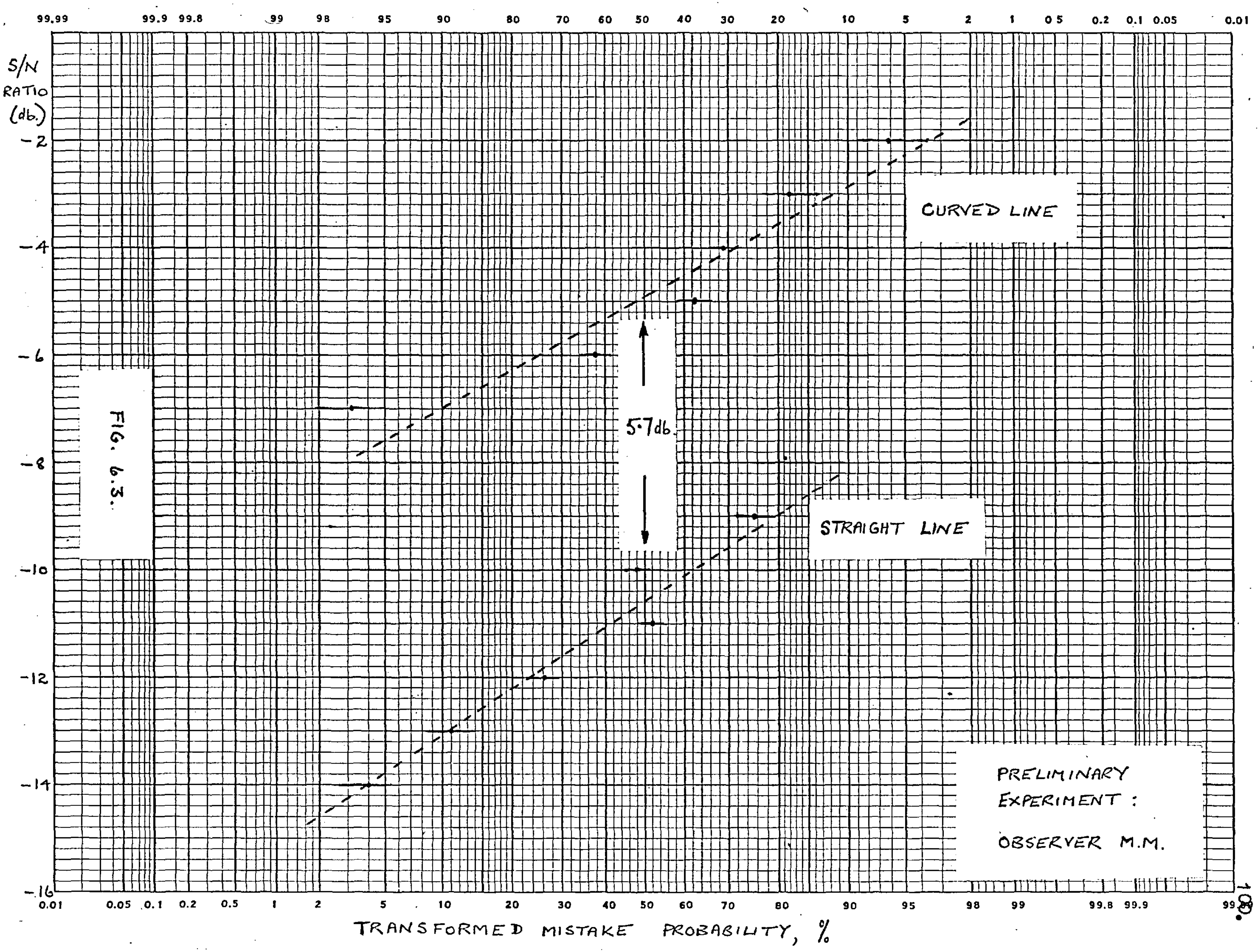
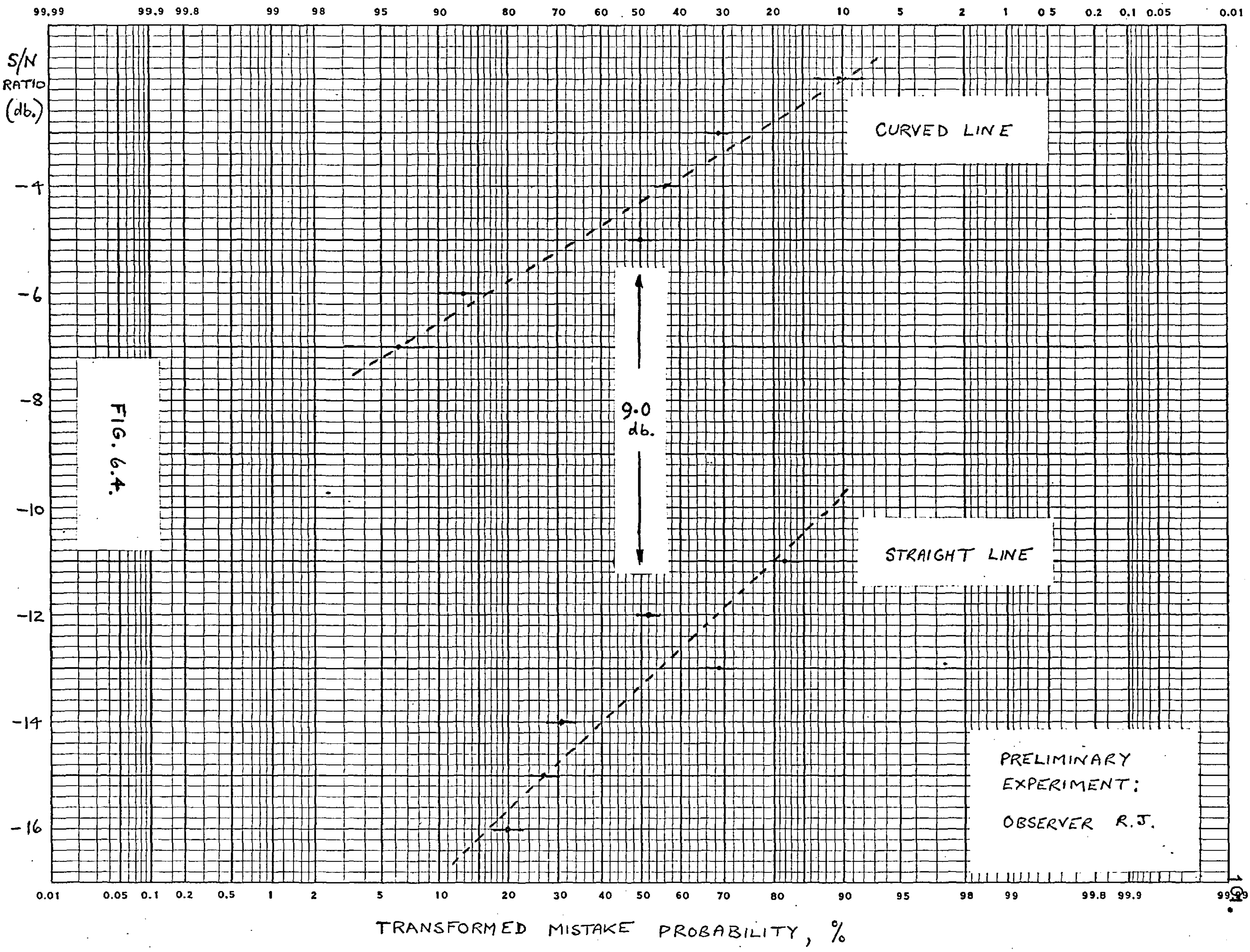

99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0 5
0.2
0.1
0.05
0.01
S/N RATIO (db.)
-2
-4
-6
-8
-10
-12
-14
-16
CURVED LINE
5·7db.
STRAIGHT LINE
PRELIMINARY EXPERIMENT :
OBSERVER M.M.
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
TRANSFORMED MISTAKE PROBABILITY, %

FIG. 6.3.



99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
S/N RATIO (db.)
-4
-6
-8
-10
-12
-14
-16
CURVED LINE
9.0 db.
STRAIGHT LINE
PRELIMINARY EXPERIMENT: OBSERVER R.J.
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
TRANSFORMED MISTAKE PROBABILITY, %

FIG. 6.4.

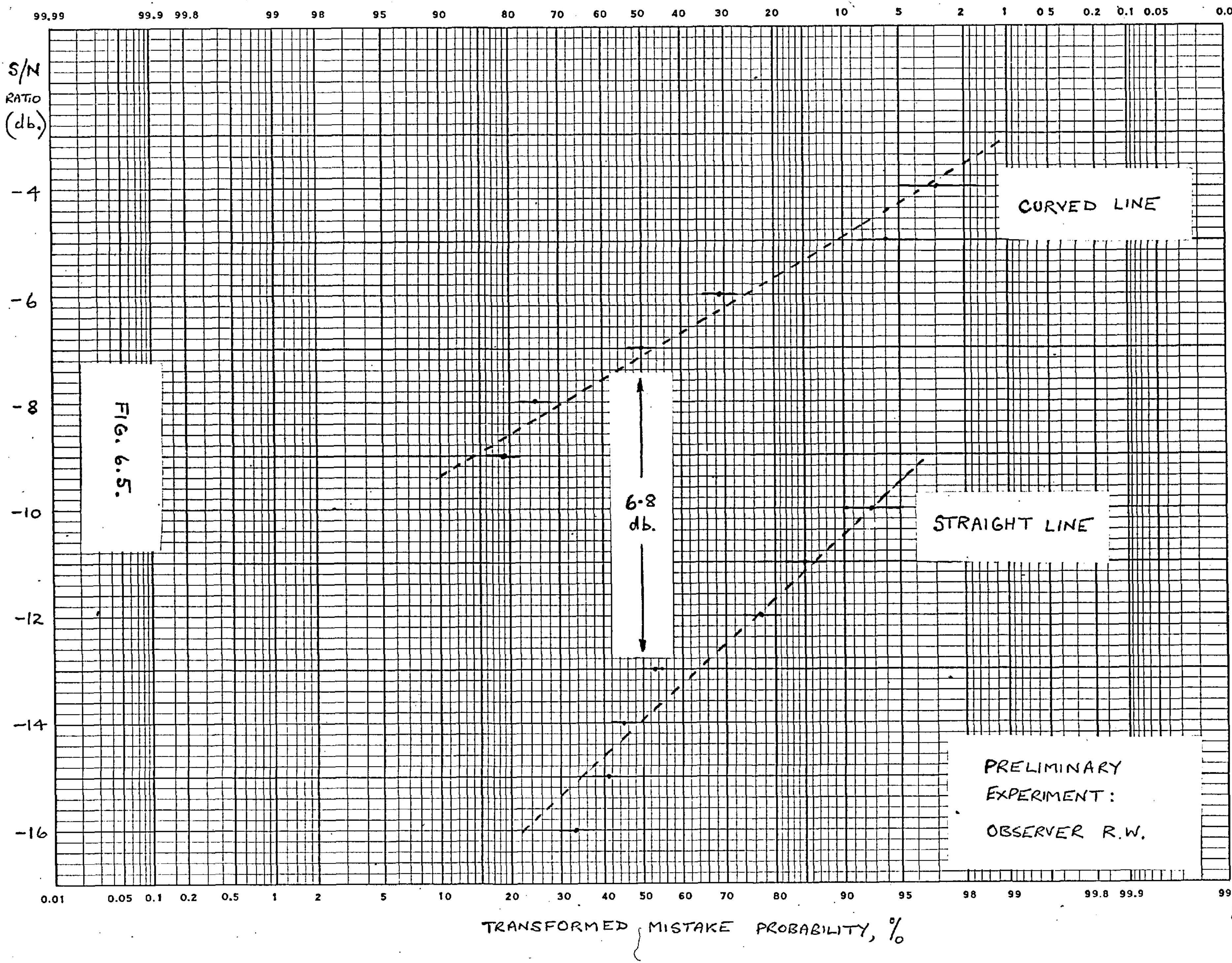


FIG. 6.5.

S/N RATIO (db.)
-4
-6
-8
-10
-12
-14
-16
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
0.01
0.05
0.1
0.2
0.5
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2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
CURVED LINE
STRAIGHT LINE
6·8 db.
PRELIMINARY EXPERIMENT: OBSERVER R.W.
TRANSFORMED MISTAKE PROBABILITY, %

ratio defined for observer A.T. is that at which the detection probability is 50%, it was necessary to use the 25% mistake probability level to obtain a comparable measure in the other cases. Furthermore, the result obtained from A.T., who used a "pessimistic" detection criterion, was calculated on the basis of only half of the measurements used in the other cases, since the blank displays could be ignored. Thus if the number of blanks used in a test could be safely reduced, the modified response criterion would seem to offer a more efficient way of determining such thresholds.

However, before a final choice of method was made, other means of obtaining the observers' judgement were considered. The preliminary experiment involved the so-called "Yes-No" response in which the experimenter takes the decision of the observer at face value. An alternative type of response is the "forced-choice". In this case, the observer must demonstrate his detection of the stimulus by locating it, spatially or temporally. The stimulus might be presented in one of several alternative locations, or during one of several time intervals. On each trial, the observer must always indicate which alternative contained the stimulus, guessing at random if necessary. The differences between the two methods are illustrated by the detection experiments of Blackwell (1953). He decided that as regards the apparent variability of an observer's threshold between sessions, estimates using forced-choice data were slightly more reliable than those using "Yes-No" data. However, the latter method is usually less time-consuming than the former. This is a major advantage in that the importance of any systematic changes of an observer's threshold with time, in a single session, are reduced. For example, if a session is short, the effects of the onset of observer fatigue can be avoided.

To conclude, the preliminary experiment clearly indicated a difference of over 5 db between the detection thresholds of the two stimuli, although the actual magnitude of this difference may vary considerably among observers. Of greater importance, perhaps, at this stage, was the indication that the method of obtaining observer response was inefficient and required further investigation. The eventual decision about which technique to use was influenced not only by the factors outlined above, but also by the method employed for selecting the order of displays in a test.

6.3 Display Duration Experiment, (including the use of Sequential Presentation Techniques)

6.3.1 In the previous experiment, the selection of display parameters (S/N ratio, stimulus present or absent) was determined in a quasi-random manner. Apart from the fact that the S/N ratios were selected from a restricted set grouped around the expected threshold level, each presentation was independent of its predecessors and of the observer's response. This method is well-tried and yields reliable results (Dember, 1963). It is questionable, however, whether it is the most efficient way of obtaining threshold data.

While performing the first experiment, the writer was introduced to sequential presentation techniques. These require that the level of the stimulus in a display is determined by the observer's response to the preceding display or set of displays. In its most simple form, the method was proposed by Dixon and Mood (1948) as a way of testing explosives without undue waste. It is popularly known as the "Up and Down" method, and its application enables the experimenter to obtain an efficient estimate of the 50% probability level of a distribution. This method is a specific application of the more general sequential testing techniques described by Wetherill (1963). By the appropriate grouping of presentations and responses within a test, and basing subsequent displays on the nature of these groups, it is possible to determine the stimulus level corresponding to any one of a finite set of probabilities.

For example, if the threshold function is quite unknown, the parameter values corresponding to, say, the 16%, 20%, 30%, 50% 70%, 80%, 84% probability levels can be found, to give a good estimate of the curve type and position. If the type is known already, the determination of two suitable levels, say 30% and 70%, will determine it completely. If only the 50% level is required, the simple "Up and Down" technique is ideal. The strategies and their use in psychophysical testing have been thoroughly described by Wetherill and Levitt (1965). It must be stressed at this point that these techniques were originally designed for the efficient testing of inanimate objects and structures. They cannot be applied to psychophysical measurement without great care being exercised. It is a fundamental requirement of the theory on which the methods are based that the results of successive presentations should be independent. This condition is most difficult to satisfy when human subjects are tested. However well-trained they may be, they are likely to be influenced in their decisions by what has gone before. For example, since the presentations follow a definite sequence, the subject may detect a pattern, and inadvertantly adjust his responses accordingly. This disadvantage can be avoided by introducing a random element into the technique. The sequence of interdependent presentations may be broken up by unrelated displays, or two independent strategies to determine different percentage points may be randomly interlaced in one test. This idea was recommended by Cornsweet (1962).

Levitt (1964) and White (1966) have compared quasi-random and sequential testing methods, with particular reference to auditory discrimination experiments. They concluded that, provided suitable precautions were taken to avoid inducing spurious effects in the subjects' responses, sequential strategies could be used with success. The advantages and pitfalls inherent in the wider application of the method in psychophysical measurement, as revealed by the writer's subsequent experience, will be discussed in Section 8.3.

6.3.2 Although sequential strategies exist for the independent estimation of several points in a probability distribution they are not all of equal complexity. For a given reliability of result, far more measurements must be made in one test to estimate 16% or 84% probability levels, than 30% or 70% levels, for example. The technique for finding the 50% level is the shortest of all. Alternatively, if a given number of detection measurements can be made in a limited time, they can be used to greatest advantage in the estimation of the S/N ratio corresponding to a 50% probability of stimulus detection.

The latter situation did exist in practice. In the preliminary experiment, each testing session lasted nearly thirty minutes, in which time an observer would be required to make 100 decisions. Some complaints were received from the observers about the onset of fatigue, usually in the form of loss of concentration, after about twenty minutes of the test. Although subjective reports of this nature are notoriously unreliable, it was thought better to avoid any possibility of overworking the observers. It was therefore desirable to keep the tests short, and one way of doing this was the use of a 50% sequential strategy. The decision to use the shortest sequential strategy critically influenced the choice of response indicator. If a forced-choice approach, involving two alternatives, is employed, the probability of correct stimulus location will vary between 50% and 100%. An "Up and Down" method will not give a sensible result in this case. If more alternatives are introduced to lower the "guesswork" probability level ($33\frac{1}{3}$% for three alternatives, 25% for four and so on), the 50% strategy can be used, but this is achieved only at the cost of making the tests more complicated and prolonged, or reducing their accuracy. If a two-alternative system is used and the threshold is re-defined (at say 70% correct location), the longer strategy must again extend the test.

If a meaningful 50% detection probability threshold is to be measured, the use of a "pessimistic Yes-No" response indicator seems appropriate. Preparatory to each test the observer was therefore told that following each display the question to be answered was: "Is the stimulus present in the display?". The qualification was added that he must answer "Yes" only when certain of his decision. Otherwise the reply was to be "No". Such instructions necessarily placed on the observer the onus of establishing a criterion of certainty, and the success of this approach could only be verified by experiment.

6.3.3 In the first experiment, a display duration of three seconds was used, on the advice of other workers and the subjective opinions of the subjects themselves. It would normally seem desirable to give a subject as much time as possible to make a detection decision, if stable and repeatable results are required. On the other hand, the longer a complete session becomes, the greater are the chances of the results being disturbed by factors such as observer fatigue or learning. It was thought advisable to determine what effect, if any, changing the duration had on the visual threshold. At the same time, it would be possible to test the sequential strategy.

The display of Figure 6.1(a) was used exclusively as the test stimulus. In this experiment, and all subsequent experiments, the noise level was maintained constant and the signal level was changed to alter the S/N ratio. This was done to preserve the character of the noise which was affected by the display system non-linearity at high levels, (Section 5.2.4 and Figures 6.1.a. and 6.1.b), and because the false-alarm rate in the previous experiment apparently varied slightly with noise level.

Four display durations were used, namely 12 seconds, 6 seconds, 1.5 seconds and 0.75 seconds. Four observers were tested (S.K., M.M., H.R., R.W.), each on four occasions separated by at least twenty-four hours. One testing session, lasting no more than twenty minutes, was divided into four sections. Each section involved a different display duration, and each duration appeared once in each section during the four tests. This procedure was followed in order to compensate for systematic threshold changes that might occur during a test, due to learning or fatigue for example. Within the limitations of this system, the order of succession of the different durations was randomised among observers and test sessions, although there were no grounds for believing this factor might be of importance. As a further precaution, to ensure that the response instructions were obeyed so that the false-alarm rate was indeed negligible, a small number of the displays contained no stimulus. These were chosen at random automatically, with a probability of one in eight.

6.3.4 The procedure in a typical session was as follows. As before, a three-minute adaptation period was allowed, during which the stimulus was shown at high S/N ratio. Then the observer was informed that the first section of the test would involve a display duration of "X" seconds, and this would then be demonstrated. The test section would follow at once.

The first requirement was a knowledge of the approximate threshold level (which is also a necessity when using the quasi-random method). A display was then presented at this S/N ratio, and at the end of the period the observer signalled his decision. No advance warning of the onset of the display was given, and the observer was required to watch the screen throughout the test. Depending on the response to the first display, the S/N ratio was altered up or down by a step of 1 db for the next. The simple "Up and Down" procedure was followed until several "runs" were complete, and a stable pattern emerged. At this point the process was continued using a reduced step-size of 0.5 db., until five "runs" had been obtained. A typical test result is shown in Figure 6.6.

The initial procedure, using a large step size, was carried out to reduce the possibility of causing bias in the final result by starting at a level considerably distant from the actual threshold. This technique was termed Routine II by Wetherill and Chen (1965), and its use as a precaution was recommended by Wetherill ahd Levitt (1965).

The observer was then told that the display time was henceforth altered, and this would be demonstrated as before. The entire process for the threshold determination was then repeated, and, in all, this was done four times in one test session, once for each different display duration.

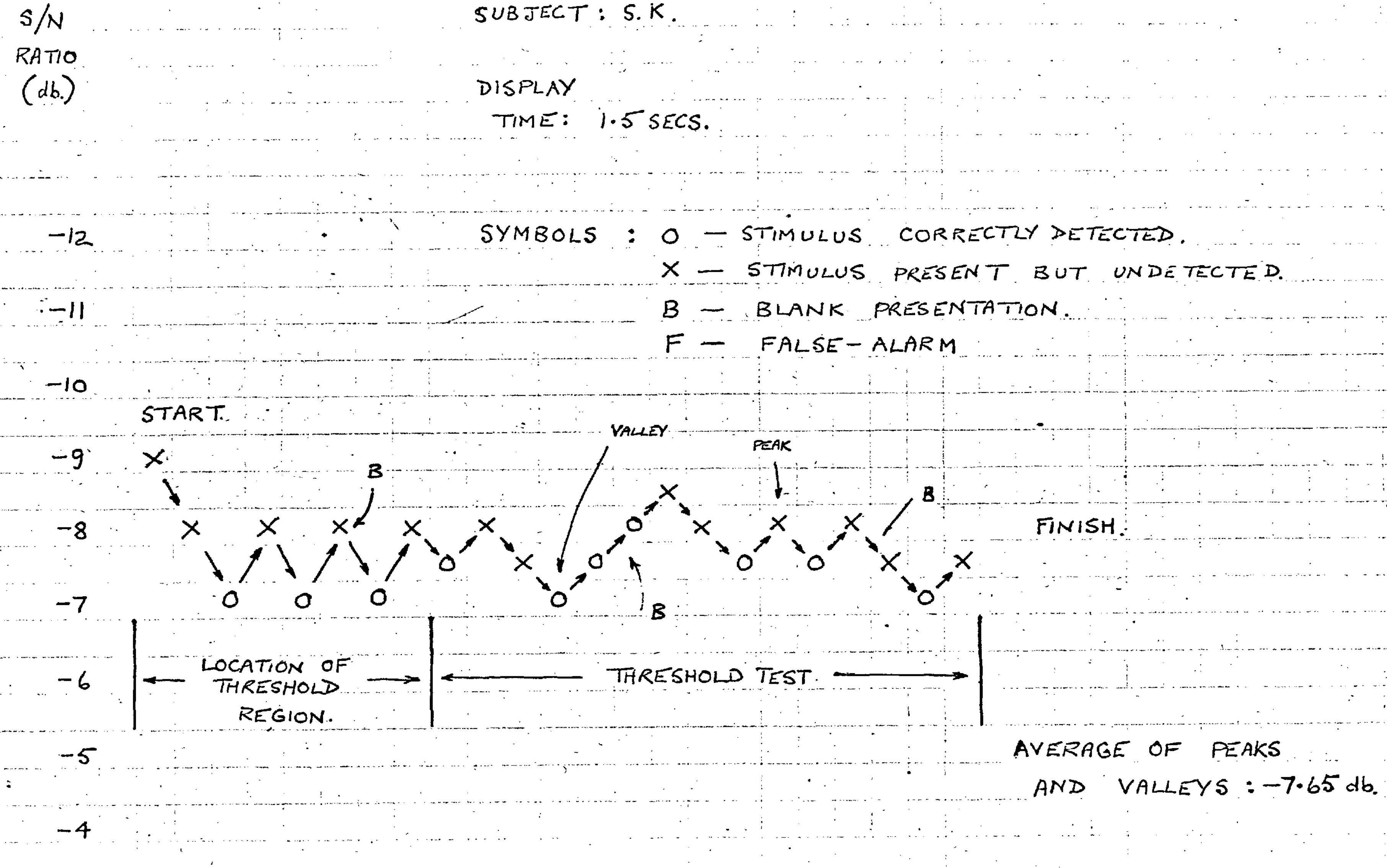


FIG. 6.6.

DISPLAY DURATION EXPT. — TYPICAL TEST RESULT.

6.3.5 The estimate of the detection threshold was obtained from each section, using the Wetherill method of averaging the peaks and valleys of the five "runs". In general, it was found that the shorter was the display time, the higher was the threshold S/N ratio. This effect is shown for each observer in Figure 6.7(a). There were slight variations between observers in the absolute threshold levels, so in order to illustrate the average effect, the <u>difference</u> in threshold between that for the longest display and for each of the shorter durations was averaged over the four subjects. The result is shown in Figure 6.7(b), and in Table 6.2.

One important feature of the experimental result does not appear in the graphs or the table. This was the fact that when the 0.75 seconds display duration was used, not only did the threshold rise slightly, but also the false-alarm rate increased markedly for all the observers. For the three longer durations, the rate was less than 1%, but rose to over 5% when the period was reduced to 0.75 seconds.

To summarise these results, it can be said that the effect of reducing the display duration on both the detection threshold of the straight line stimulus and the experimental method was slight, until the display time was less than 1 second. The use of the sequential "Up and Down" strategy presented no obvious problems, and no observer reported noticing a pattern in the order of the presentations.

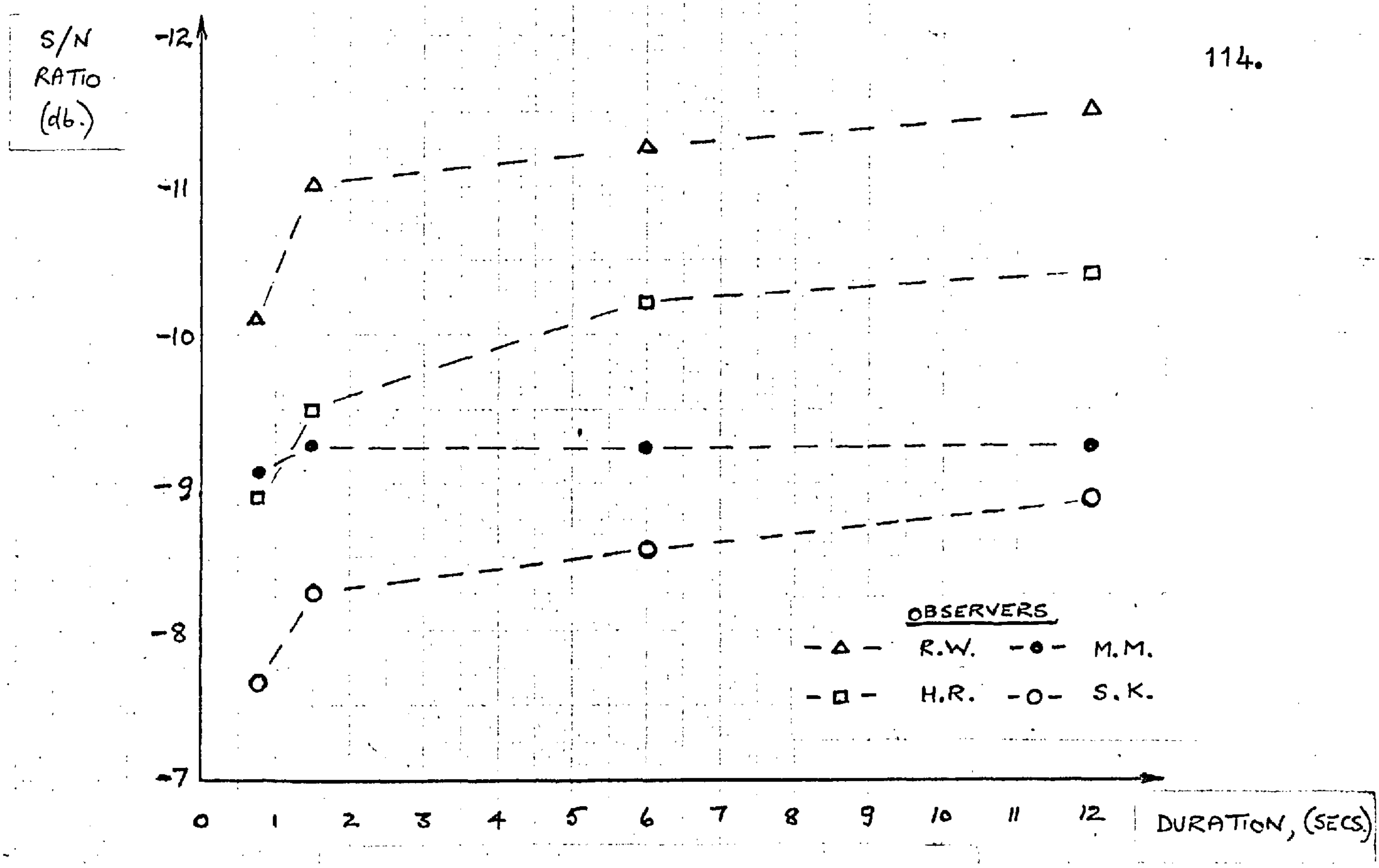


FIG. 6.7. (a) : DISPLAY DURATION EXPERIMENT. INDIVIDUAL RESULTS.

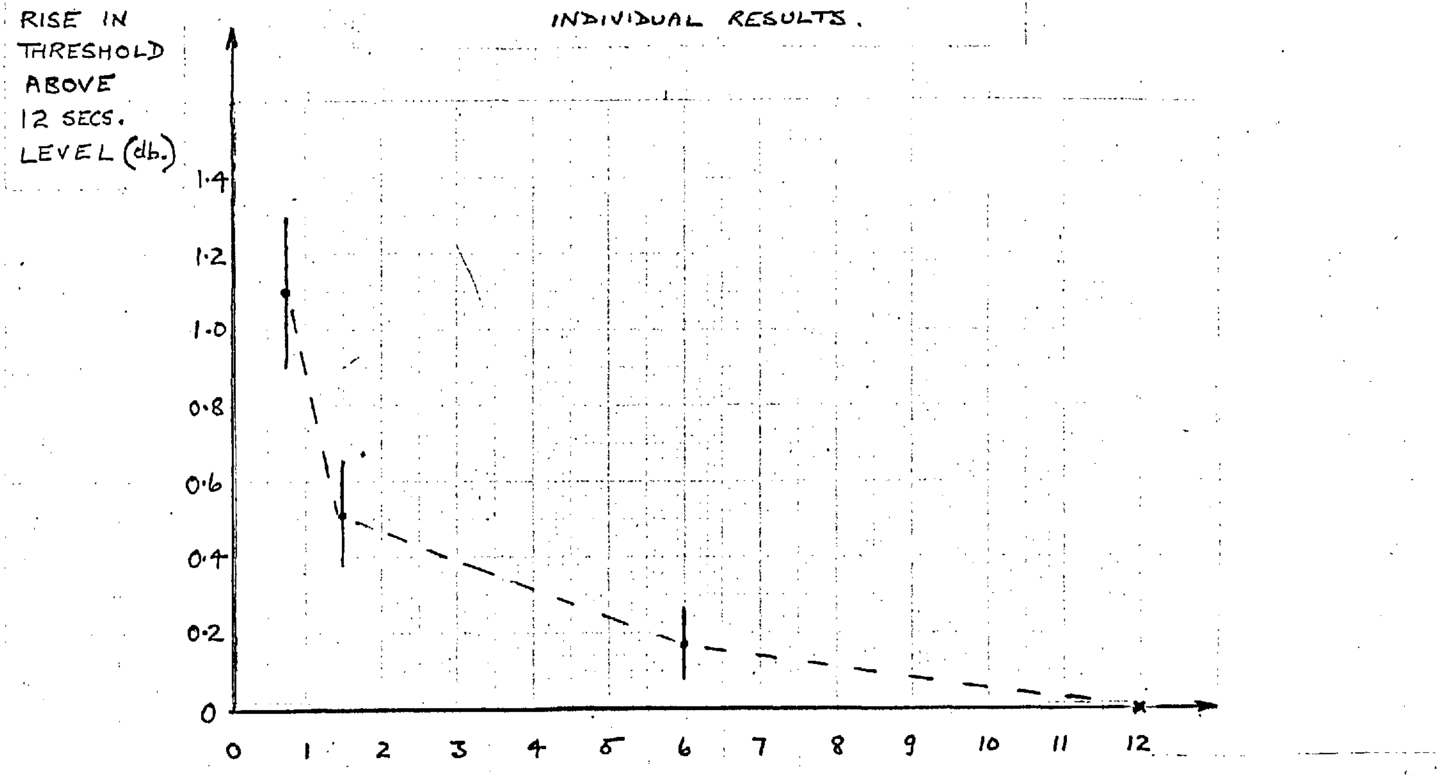


FIG. 6.7.(b) : DISPLAY DURATION EXPERIMENT. AVERAGED RESULTS.

Display Duration.	Av. Threshold Difference.	s/√n	t	Significance Level(t-test)
12 sec.	- db.	-	-	-
6 "	0.17 "	0.12	1.42	0.76
1.5 "	0.51 "	0.14	3.65	0.97
0.75 "	1.10 "	0.20	5.50	0.98

Threshold differences expressed relative to the 12 second level.

Table 6.2

Two practical benefits of using the sequential techniques were found. One advantage was that it became possible to reduce slightly the interval between display presentations. Only minimal adjustments to the equipment, one step up or down in S/N ratio, were required at each change. The other advantage appeared when, owing to a fault in the picture-generating apparatus, no stimulus appeared in the presentations at any time. This was quickly noticed from the pattern of results, and very little time was wasted. It is doubtful whether the defect would have been discovered so rapidly had a quasi-random method been in use.

The "pessimistic Yes-No" response indication also proved successful in that the observers were capable of maintaining a stable detection criterion without giving false-alarms, except when the display duration was reduced to 0.75 seconds.

On the basis of this evidence, it was decided to persevere with the sequential estimation strategy, and a compromise display period of 3 seconds was adopted for the main series of experiments. This duration was well received by all the subjects, and no complaints were made about lack of decision time.

In retrospect, the writer feels that it would have been advisable to test the effect of display duration on the threshold of different forms, at least in some cases. When the experiments were performed, however, there was no reason to suppose that time might be an especially relevant factor. Its possible influence, and suggestions for research on this topic, will be referred to in Section 8.5.

6.4 Summary.

6.4.1 Two preliminary experiments were performed, chiefly to gain experience in the efficient estimation of detection thresholds using television equipment. In the first, a considerable threshold difference between a straight line and a very curved line was discovered. However, the testing method, in which displays were selected from around the threshold region in a quasi-random manner, was found to be inefficient. In addition, the instructions given to the observers about the detection task, were apparently based on a false premise. In the second experiment, to determine a suitable duration for the displays, a sequential method of stimulus selection was used andthe observers were instructed to apply a "pessimistic" detection criterion. This technique was found to give stable results in a reasonably short time, and it was decided to use it in the main series of experiments. A display time of 3 seconds was chosen as a compromise between allowing the observers unrestricted decision time and curtailing each display so much that the detection criterion became unreliable.

CHAPTER 7. THE EXPERIMENTS

7.1 Experiment No. 1.

7.1.1 The neurophysiological structure found in the cat by Hubel and Wiesel (Chapter 3), suggests that some systematic analysis of the retinal image occurs in the early stages of the visual path. Once the existence of detail or contrast has been established, in the retina itself and in the geniculate body, the information is passed to the visual cortex. Here, a large proportion of simple cortical cells respond most vigorously to straight-line stimuli. A curved or bent line cannot stimulate a single cell as efficiently as a straight line, and instead will partially stimulate two different cells. If the stimulation of these cells can be suitably combined no information need be lost. If this combination does not occur, at least under adverse viewing conditions, then a straight stimulus will, in general, produce more neural activity at this level of the system than any other. In noisy displays, consequently, a straight line is the stimulus most likely to cause a significant change in the firing of a simple cell. Whatever else may happen to a weak visual signal on its way into the brain, it is reasonable to suppose that the greater the activity it produces at some early stage, the better may be its eventual chance of detection.

The succeeding experiments were performed to test the general hypothesis that there exists in the human brain a neurophysiological structure, similar to that found in the cat, which favours the detection of line stimuli. A preliminary experiment (Section 6.2), had indicated that a straight line could be detected more easily than a sinusoidally curved line. Experiment No. 1 was designed to continue this investigation. The test stimuli used were:

A. A vertical dark line on a light background. The angle subtended at the observer's eye by the width of the line was 1.5 minutes of arc, and by the length 3.5 degrees.

B. A predominantly vertical line of the same width and length, but slightly curved (equivalent approximately to a 40 degree arc of a circle of radius 9.25 inches).

C. A line similar to B, but of greater curvature (equivalent approximately to a 74 degree arc of a circle of radius 5 inches).

Both B and C were also used with the direction of the curvature reversed. The shapes are shown at high S/N ratio in Figures 7.1(a), (b) and (c).

7.1.2 The choice and production of these shapes presented an interesting problem. While straightness is a comparatively easy property to define, curvature, apart from the rigid mathematical definition, is a much more complex concept. A straight line of a given length can be reshaped into an infinite variety of forms. However, the technical considerations associated with the use of television images

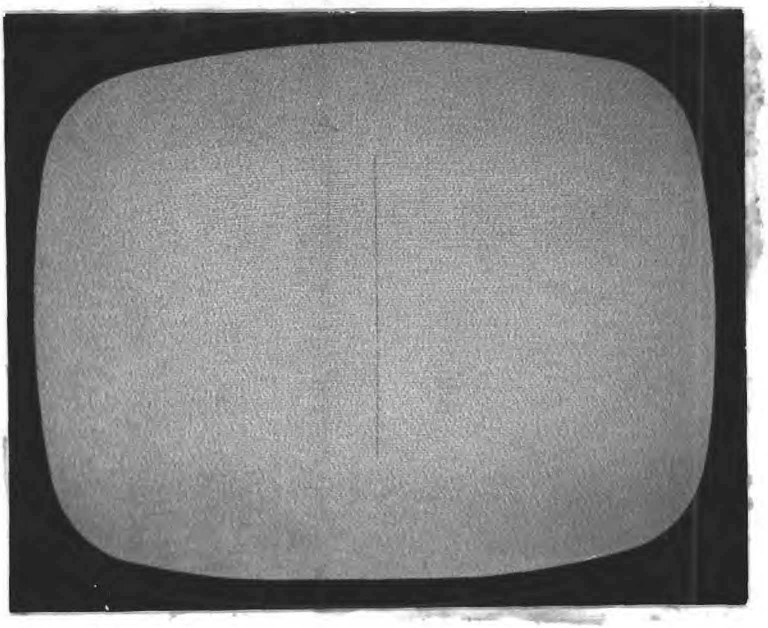


Fig. 7.1(a).
3.5° Straight line.

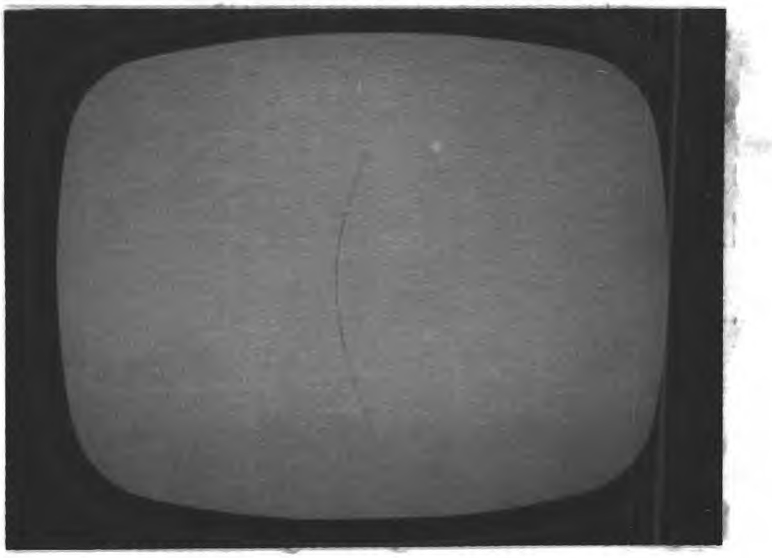


Fig. 7.1(b).

Same line, 9.25" radius curve.

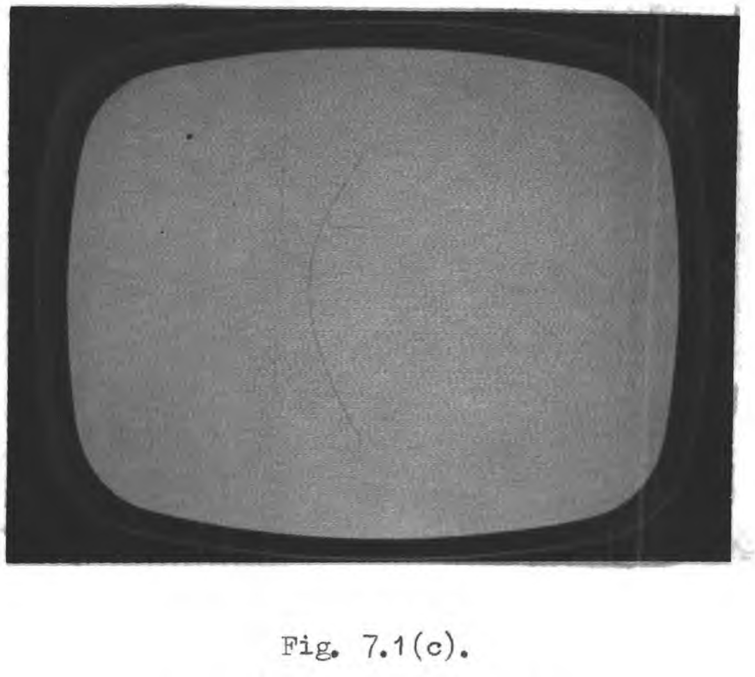


Fig. 7.1(c).

Same line, 5" radius curve.

limited the range of shapes which could be presented.

Because a television picture is constructed on a line scan basis, lines or edges at an oblique angle to the direction of the scanning lines are less faithfully reproduced than those normal to the scanning lines. Instead the observer is presented with a piecewise approximation of the shape. This effect was discernable in the curved line of Figure 6.1.b. used in the preliminary experiment, and could conceivably have influenced the result.

Since the writer felt, therefore, that only slightly curved shapes could be used with confidence, the obvious experiment to perform was to test the effect of slight curvature on the detection threshold of an originally straight line. The nature of the curvature was also decided by practical considerations. Although, in theory, almost any shape could have been shown, using a television camera or slide-scanner, this was not possible in practice. With the limited equipment available at the time the experiments were performed, pictures of acceptable "domestic" standard could be produced, but these were not of uniform quality nor sufficiently stable for use in precise experiments. Therefore the choice of curves was restricted to shapes which could be produced artificially with ease. The "circular" arcs were in fact obtained from sinusoidal waveforms, which gave a good approximation to the correct shape (Appendix 1).

It is arguable, of course, that the exact geometrical shape of the curved line is not important, at least as far as detection is concerned. This raises the problem of familiarity, or how much past experience of shapes influences low-order perceptual processes. Because of the difficulties outlined above, the writer was unable to investigate this topic, but given more sophisticated means of picture generation and control, this would be a most interesting avenue of research.

7.1.3 In this experiment, it was required to find the difference, if any, between the detection thresholds of the straight line stimulus A and the curved shapes, B and C. This was done using observers E.B., E.M., M.M., H.R., A.W., and R.W.,

In the three minute adaptation period allowed before each experiment, the three shapes were shown at high S/N ratio for 60 seconds each. Each test was divided into two parts, of two sections each. The first part involved the estimation of the threshold of stimulus A and one of the curved shapes, and the second part was a repetition of the first except that the direction of the curvature was reversed. Before each section of the test, the stimulus shape to be used was shown at high S/N ratio in a 6-second display, so that the observer would be familiar with its shape and position. The testing method within each section was very similar to that used in the Display Duration Experiment (Section 6.3), and the "pessimistic Yes-No" response was used. The order of the presentation of the shapes (straight or curve first), and also which direction of curvature was shown first, was varied at random between observers.

Each experiment was thus a "running" threshold comparison between the straight line, used as a reference, and one of the curves. Originally each experiment was intended to be of three sections only, with a different stimulus in each section, but pilot tests indicated that a slight improvement in an observer's threshold level (about 0.5 db) regularly occurred during each test, regardless of stimulus shape. This had the effect of biasing the results in favour of the stimulus presented last. While such effects were reduced on average by the random variation of the presentation order between the observers, the writer decided that it was of greater practical advantage to obtain a genuine estimate of the threshold differences for each observer from each test. This was first attempted by changing the stimulus shape frequently from straight line to either curve during the test, but the necessary changeover procedures extended the test duration prohibitively. Of more importance, perhaps, was the fact that the observers sometimes became confused as to which stimulus they were seeking and were forced to stop the test to enquire. The four section method of presentation was found to be a satisfactory compromise. The randomising of presentation order (within this framework) was retained as a precaution against any other ordering effects that might arise.

From each test session, therefore, two estimates were obtained, namely, the threshold differences between the straight line and one of the curves, bent both to the left and to the right. These results are shown in Table 7.1.

In addition, using only stimulus C curved to the right, Figure 7.1(c), a series of three extra tests were performed with observers M.M., H.R., and R.W. spread over a period of one week. This was done to test the stability of the experimental technique, in particular to see if the repeated exposure of the reference stimulus, A, might effect the relative thresholds. The tests also provided a means of assessing the variations between observers for the particular threshold difference which was measured. The results are shown in Table 7.2.

7.1.4 This experiment was reasonably successful, although the scope of the findings was inevitably restricted by the limited range of stimuli used. With this qualification, it can be said that the effect of slightly curving a straight line is to raise its detection threshold. This result was found with all the subjects tested, and, on average, the smaller the radius of the curve the higher the threshold became. There was no indication from the results that this effect depended on the direction of the curvature, although there were slight variations among individual observers.

	Threshold Rise of Curve relative to Straight line. (db.) S/N Ratio.						
	Curve left.	Curve right.	Average.	$s/\sqrt{n}$	Sig. of Rise.	L/R Diff.	Sig. of Diff. t-test. (5%)
Radius 9.25"	1.05	0.94	0.99	0.10	>.995	0.11	Not Sig.
Radius 5"	1.63	1.50	1.56	0.14	>.995	0.13	Not Sig.

Table 7.1

Occasion	Threshold Rise for 5" radius curve, to Right.				
	M.M.	H.R.	R.W.	Average.	$s/\sqrt{n_s}$
1	1.43	2.10	1.00	1.51	0.32
2	1.35	1.25	1.00	1.20	0.10
3	1.00	2.10	1.60	1.57	0.32
4	1.30	2.22	0.70	1.41	0.44
Average.	1.27	1.92	1.08	1.42	0.26
$s/\sqrt{n_o}$	0.10	0.22	0.26	0.08	

No significant difference between average results on different occasions.
No significant difference between average results of M.M. and R.W.

Average result of H.R. significantly different from those of M.M. and R.W.

(t-test at 0.95 rejection level.)

Table 7.2

These findings are in accordance with the idea of simple cortical cells, with straight-line receptive fields, acting as "line detection units". The writer has also made a brief investigation of the detection of edges, in an experiment similar to Experiment No. 1, using observers R.J., S.K., M.M., H.R. and R. W. (Marsh, 1964). The stimuli were a straight vertical edge between dark and light areas on the screen, and a sinusoidally curved version of the same, Figs. 7.2(a) and (b). Both edges extended over the full screen height. A threshold difference of about 3db was found, once more in favour of the straight stimulus.

The research reported by Fry (1947) is of considerable interest here. He investigated the variation in contrast detection threshold with the shape of the boundary between two areas, and found that a straight line boundary was perceived more readily than either a curved or "sawtooth" division. In addition, a slightly curved boundary was perceived as straight under threshold conditions.

Kristofferson (1957) measured detection thresholds for simple shapes at low contrast with short display times, (0.01 secs.), to test the element contribution theory (Section 2.3.1). This assumed that patterns of neural activity with radial symmetry determine the detectability of a shape. The theory therefore predicts that shapes with circular boundaries will be the most easily detected. He

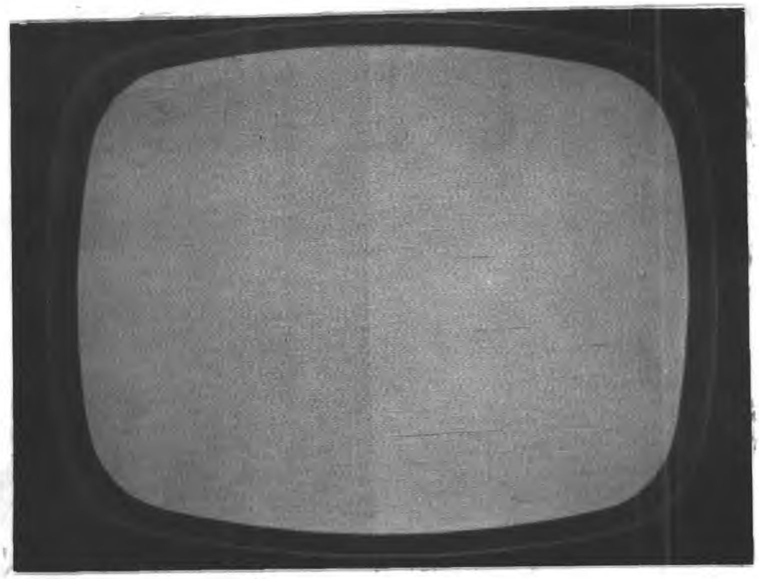


Fig. 7.2(a).

Straight edge.

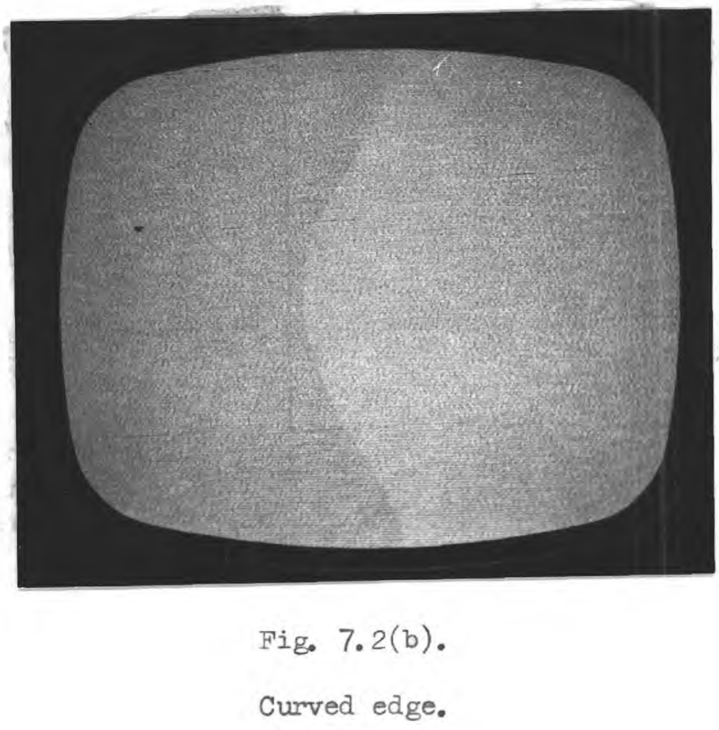


Fig. 7.2(b).

Curved edge.

found in practice that shapes with straight-line edges, such as triangles and rectangles consistently proved more detectable than expected. This deviation was more marked when the background intensity was raised from zero to 10 Ft. Lamberts. In addition, the longer a rectangular stimulus became in relation to its width, the more did its detectability exceed the theoretical prediction. With crosses and "multiple-leg" targets, consisting of straight lines at various angles, the reverse appeared to be true, in that their detectability was less than expected. This curious feature of his results is apparently confirmed by the experiments to be described later in this chapter.

7.1.5 The extended tests on three of the observers indicated the stability of the method chosen for finding the threshold differences, and, within the period of the four tests, no "familiarity" bias in favour of the reference stimulus was discernable. These tests also showed small, but statistically significant, differences between observers in the estimates of threshold difference. While it would be convenient to suppose that all mature humans have identical visual systems, this is rather unlikely. Nonetheless, the variations found were of degree only and not of fundamental behaviour. In these circumstances it can be meaningful to use results averaged over a small group to indicate the probable behaviour of the population as a whole. A measurement on an individual is thereby considered as a random sample from this population. The assumption remains tenable, of course, only if the variance of the mean remains within reasonable limits.

The sequential measuring technique combined with the "pessimistic Yes-No" indicator response, proved successful for estimating the threshold differences. The estimates of absolute threshold level from day to day were more irregular, and this erratic behaviour was probably caused in part by the observer adopting a different detection criterion on different occasions. The method would therefore appear to be more suited for threshold comparisons than such absolute measurements.

To conclude, the results of the experiment, although applicable only to a small range of curves, did nothing to contradict the basic assumptions. Consequently further investigations were made.

7.2 Experiment No. 2.

7.2.1 This experiment was intended to study the effect of varying the length of a vertical straight line.

Hubel and Wiesel (Section 3.5.7) measured the sizes of the receptive fields of a number of simple and complex cells in the visual cortex of the cat. They found that the most common diameter of a simple cell receptive field was between 1 degree and 2 degrees of arc. If the detection of a straight line stimulus depends in some way on the activity of such cells, then it is possible that the detectability of a line stimulus may be simply related to the size and distribution of these receptive fields.

For this reason, in this experiment six different line lengths were used ranging from a 6.3 degrees viewing angle down to 0.2 degrees. The detection threshold of each was found, using observers H.R., A.W., S.K., K.P., and R.W. Two typical stimuli are shown in Figure 7.3(a) and (b). The testing technique was the same as that employed in Experiment No. 1, and each result was again measured relative to that of a reference stimulus. This was the longest line employed, the full screen height in length and subtending an angle of 6.3 degrees at the eye of the observer. At each length the results of all the observers were averaged, and are shown in Table 7.3 and Figure 7.4.

Since Hubel and Wiesel discovered no change in field size with orientation among the receptive fields that they investigated, a further series of tests was later performed, using observers E.B., S.K., E.M., K.P., H.R., and R.W. The display monitor was rotated, using a specially designed cradle, (Fig. 7.14), so that the line stimulus could be presented at an angle to its original vertical position. Three positions were used, at 30 degrees, 60 degrees and 90 degrees to the vertical. The effect of varying the line

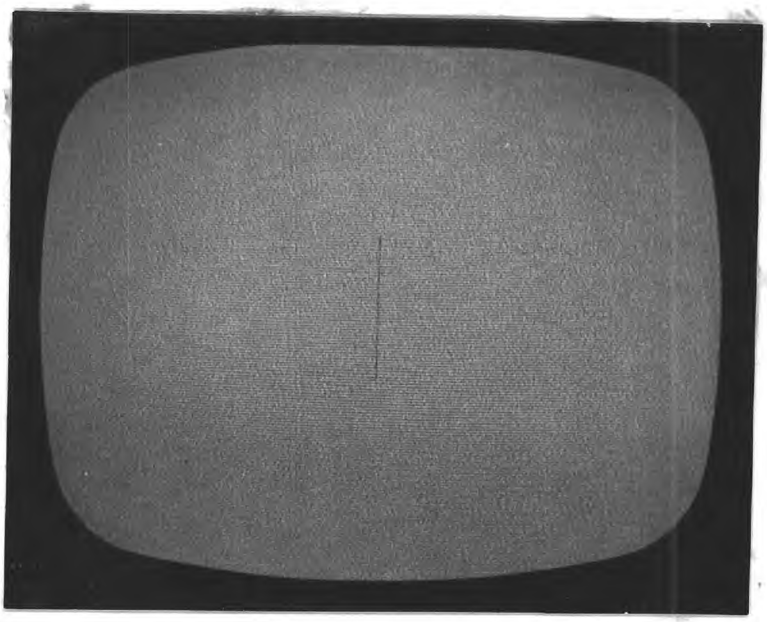


Fig. 7.3(a).

1.6° Straight line.

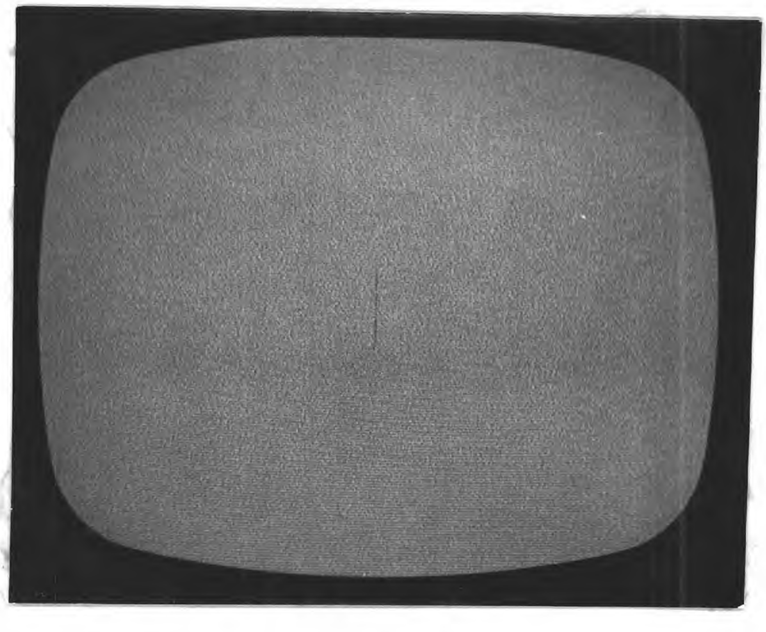


Fig. 7.3(b).

0.9° Straight line.

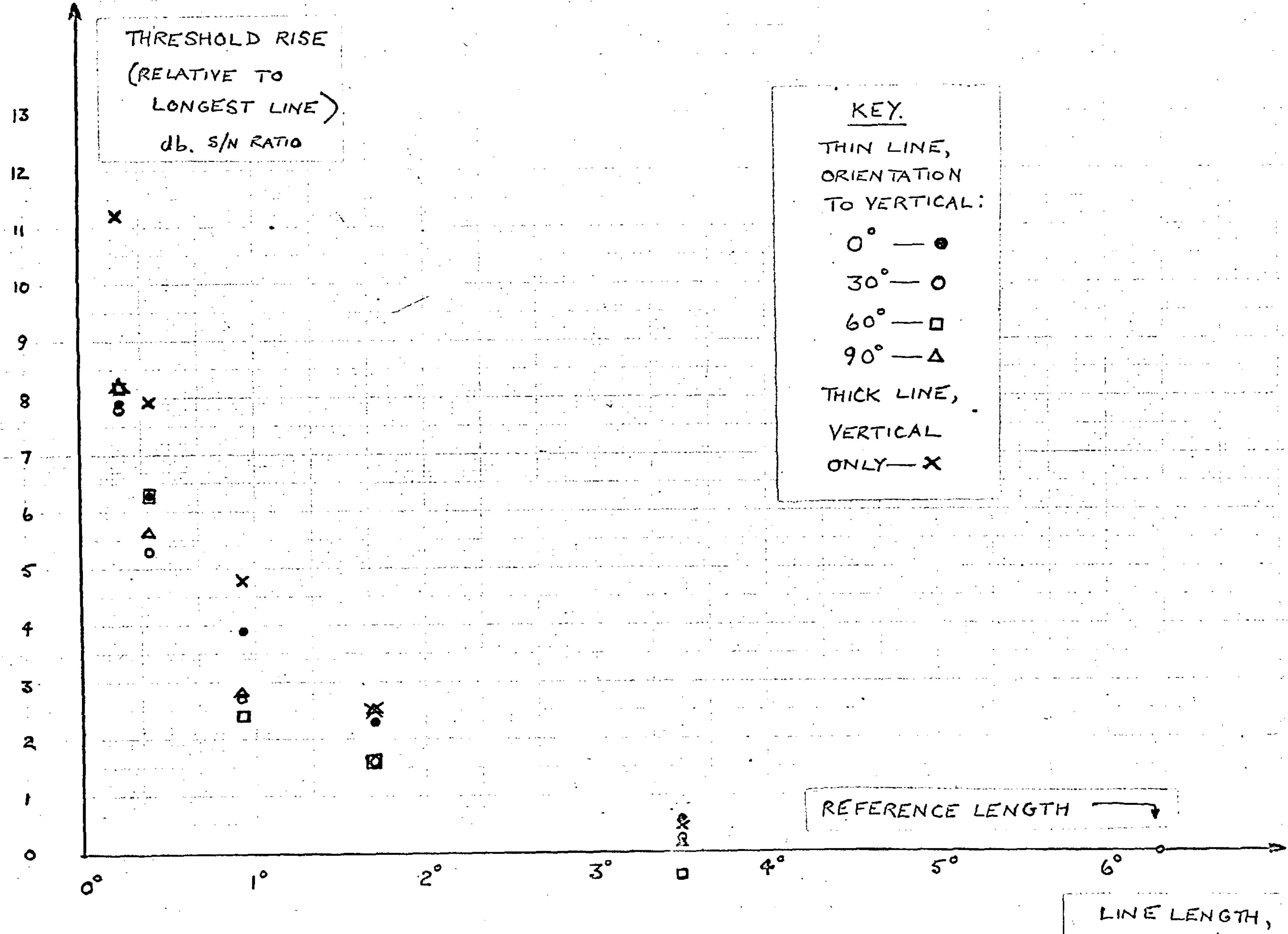


FIG. 7.4. EFFECT OF LINE LENGTH

Orientation to Vertical. / Line Length.	Thin line (1.5'). Threshold rise (db)(Rel. to 6.3° line)				Average of all Orientations	s/√n	Thick line (15').	
	0°	30°	60°	90°			Threshold rise (db).	s/√n
3.5°	0.62	0.22	-0.38	-0.08	0.17	0.20	0.48	0.59
1.6°	2.32	1.52	1.60	2.55	2.19	0.20	2.50	0.48
0.9°	3.90	2.73	2.43	2.78	3.09	0.34	4.80	0.33
0.35°	6.29	5.28	6.29	5.64	5.93	0.45	7.95	1.50
0.2°	7.90	7.83	8.19	8.22	7.97	0.34	11.23	1.70

Results for thin lines of same length at different orientations not significantly different. (t-test:5% level)
Averaged results for thin line and results for vertical thick line significantly different at lengths of 0.90° & 0.20°. (t-test:5% level)

Table 7.3

length was tested, using three of the six observers at each orientation. For this extension of the experiment, the observer's head was clamped (comfortably) in an upright position throughout each test.

These results are also shown in Figure 7.4. In Figure 7.5(a), the data have been averaged over all orientations. They are again reproduced in Figure 7.5(b) but with a logarithmic scale for the line length dimension.

7.2.3 The most interesting discovery made in this experiment is the pronounced bend in the threshold variation curve in the region of 1 degree to 2 degrees of arc when it is displayed using a linear length axis. Increase in line length above this size produces little improvement in detectability. The effect also appears to be virtually independent of line orientation. It is instructive again to compare these results with those of Kristofferson (1957) who measured contrast thresholds for vertical dark lines, of width 1 minute of arc, against a light background. He found just such a variation of threshold with length, including a marked "saturation" effect above a length of about 50 minutes of arc.

7.2.2 In all the experiments described so far, the breadth of the line subtended an angle of 1.5 minutes at the observer's eye. This size was originally chosen because it is comparable with the smallest detail to be found in a normal

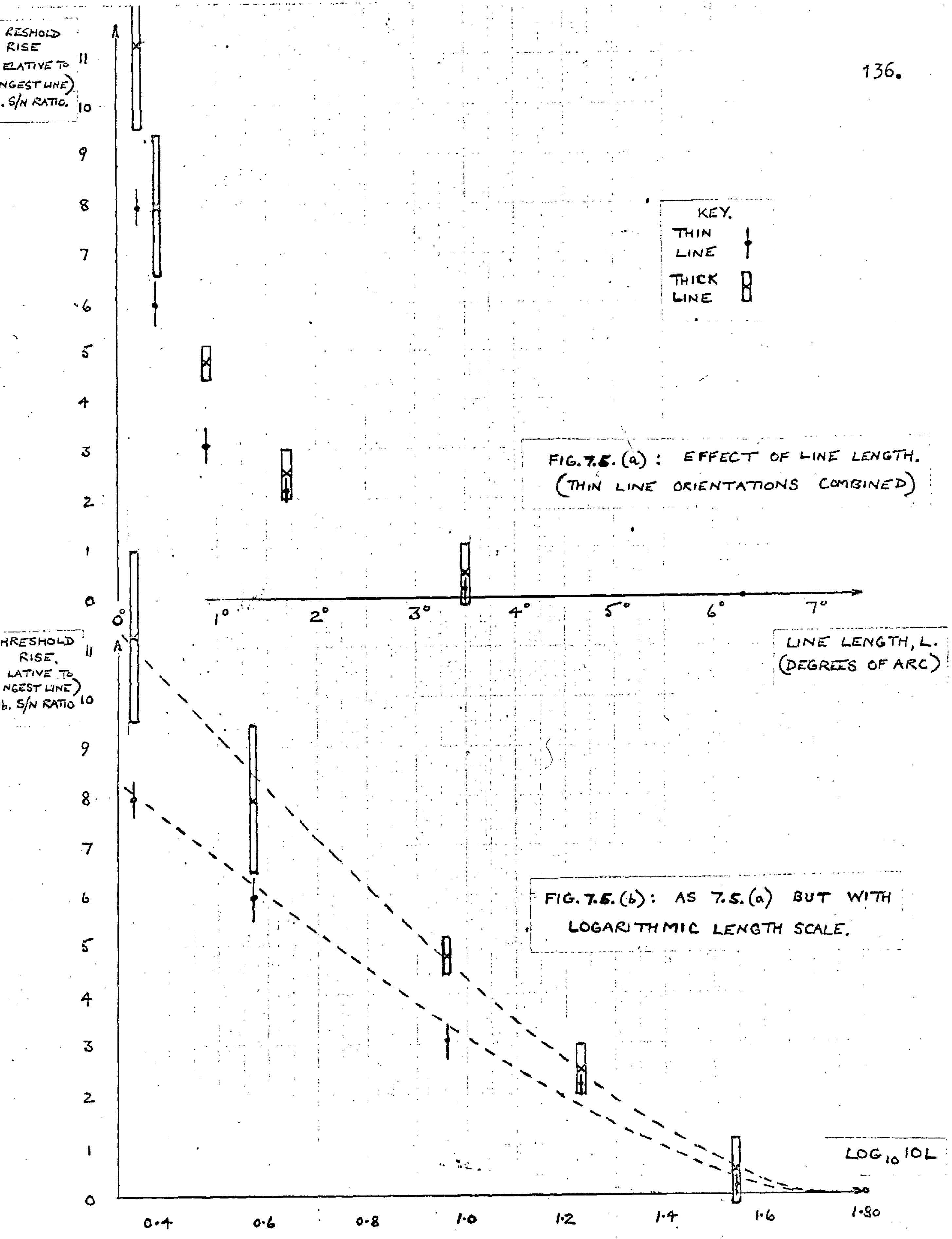


FIG. 7.5. (a): EFFECT OF LINE LENGTH. (THIN LINE ORIENTATIONS COMBINED)

FIG. 7.5. (b): AS 7.5. (a) BUT WITH LOGARITHMIC LENGTH SCALE.

television picture in a system of 3 Mc/s bandwidth, and was therefore of particular interest from the viewpoint of television communication. However, it is very possible that the combined effect of retinal structure and line thickness might influence the form of the detection threshold curve. For example, the retinal mosaic is considerably more coarse outside the foveal region than within it, and neural interaction is believed to occur on a greater scale outside the fovea. If the extremities of a long thin line extend beyond the boundaries of the high-resolution area, some of the neural effect of the line might be lost for these reasons. Indeed, the size of the fovea corresponds very well to the limiting line length found in this experiment. To test whether the thickness of a line materially affects the shape of the threshold/length curve, the experiment was partially repeated, using observers E.M., H.R., and R.W., and a line thickness of 15 minutes of arc,(Fig. 7.6). Only the vertical orientation was considered. The average results at each length are also shown in Table 7.3 and Figures 7.4 , 7.5(a) and 7.5(b).

As might be expected, the thicker line proved more detectable than a thin line of the same length, although no direct comparison between the two was made (see Section 8.2.2) Nonetheless, a similar curve relating detection threshold to line length was found, although for the shorter lengths of

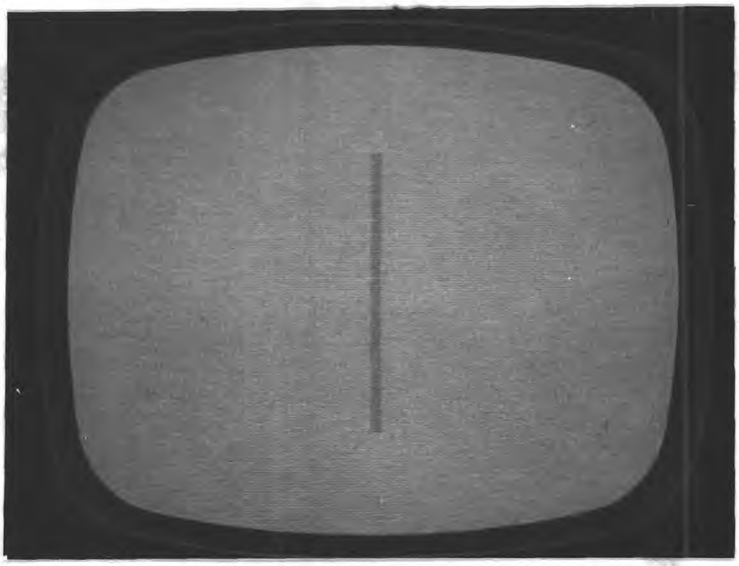


Fig. 7.6.

Thick line.

line the rise in threshold was rather more marked than before. (The shape, in fact, ceases to be a line in the usual sense at these dimensions and is more like a rectangle. The shortest "line" is virtually a square).

7.2.4 Since this experiment, (and also Experiment No. 1), was stimulated by the work of Hubel and Wiesel, it is desirable at this point to suggest how the results might be explained on the basis of neural interactions. For this purpose, some hypotheses concerning the detection process are necessary.

It was noted that, when questioned after a test, the observers all reported that the stimulus was never seen continuously throughout the display period. Instead, the shape would appear and disappear sporadically, sometimes as a whole, or sometimes in parts. The setting of a judgement criterion under these circumstances became a matter of deciding when these shapes were seen frequently enough to be more than the chance configurations of a noisy display. If it is supposed that individual cells in the cortex are acting as "line detection units", then when the line in the retinal image falls on the receptive field of a particular cell, its firing will fluctuate as the noise obscures the line. The "sightings" of a stimulus in a display may be attributable, directly or indirectly, to the behaviour of such a cell, when its firing rate rises momentarily above the threshold level.

In these circumstances, the optimum size of a line stimulus, thick or thin, will depend on the most common size of the relevant receptive fields. According to Hubel and Wiesel, if the stimulus does not fill the receptive field, the resulting neural activity will be less than the maximum possible. At the other extreme, a stimulus larger than the receptive field on which it falls will have no more effect on the cell than one of just the right size. The probability of a very large stimulus impinging on a field of suitable magnitude goes down as the length exceeds the optimum. Thus, as the length of a line is increased, its detectability, in terms of the firing of a cortical cell, should improve until the optimum length is reached. Above this size, the detectability will improve very little. In view of the dimensions quoted by Hubel and Wiesel, this argument implies that simple cortical cells may play a dominant role in the detection process, since the most common receptive field diameter of these cells (in the cat) is between 1 and 2 degrees.

The question of eye movement has been avoided in this discussion, although even a fixated eye is in saccadic motion. Because of this, a stimulus may affect many different cells during the 3 second display period. This movement will certainly complicate the way the visual system analyses the image, but it is difficult to imagine any way in which it might alter the critical stimulus size.

By far the most important supposition in this possible detection scheme is that each cortical cell is acting as an independent unit. A long line stimulus may affect the receptive fields of more than one cell, but this apparently has little influence on the ease with which the stimulus is detected. In other words, the outputs of two, (or perhaps more), simple cells, firing momentarily, and randomly, above their threshold rates, do not create a significant joint effect elsewhere in the system. This rather surprising assumption may seem more acceptable in the light of the experiments to be described later in this chapter.

7.3 Experiment No. 3.

7.3.1 The importance of continuity in a line stimulus was the next topic to be studied. Experiment No. 2 had indicated an interesting variation of detection threshold with line length. These lines were unbroken stimuli, and it was not known how the introduction of a gap in a line would affect the threshold.

In this experiment the straight line stimulus of Experiments 1 and 2 was again employed as the basic unit. Now, however, a section could be removed from the centre of the line. The distance, L, between the furthest extremities of the line was kept constant, so that the insertion of the gap, of size G, reduced the total length of line to L - G. Three angular lengths of unbroken line were employed, 3.5 degrees, 1.6 degrees and 0.9 degrees, and three different gap sizes could be introduced in each line. Two examples are shown in Figures 7.7(a) and (b). The detection threshold for the entire broken line was found, with reference to the "parent" unbroken line, by the same method employed in Experiments No. 1 and 2. Four observers were used in each part of the experiment, selected from E.M., K.P., H.R., A.W., and R.W.,

In Figure 7.8(a) the average variation of threshold with line length for an unbroken thin line is reproduced. On this graph are superimposed the average threshold curves of the broken lines, each line being treated as having a <u>continuous</u> length L - G. A logarithmic length scale is used.

The introduction of a gap into a straight line divides the line into two physically distinct parts. The interesting question is whether the line is also divided into perceptually distinct parts. To test how this division occurs a further curve has been drawn in Figure 7.8(b). This is the expected variation of threshold with line length for a line whose perceived length is only half its actual length. (This curve in fact describes the threshold behaviour when a broken line of length L - G has a perceived length $\frac{L - G}{2}$. It is obtained by allocating the threshold for a line of length $\frac{L - G}{2}$ to the length L - G. On the logarithmic

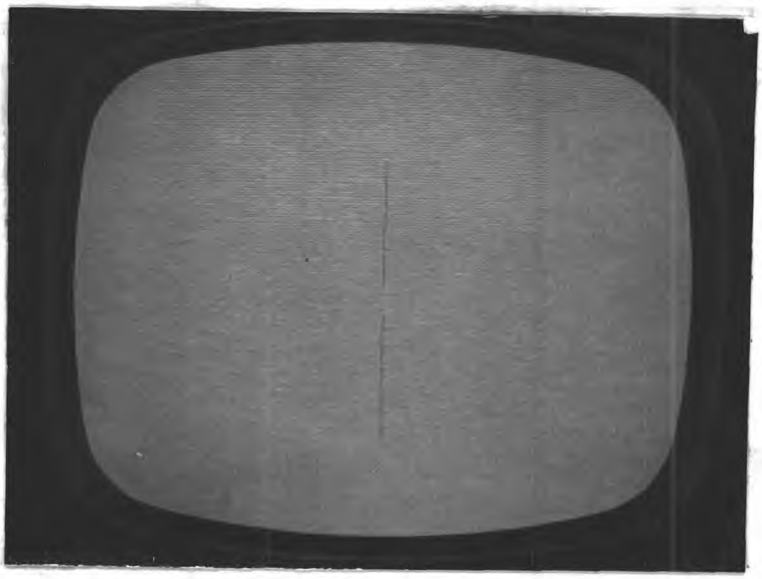


Fig. 7.7(a).

3.5° line : Broken.

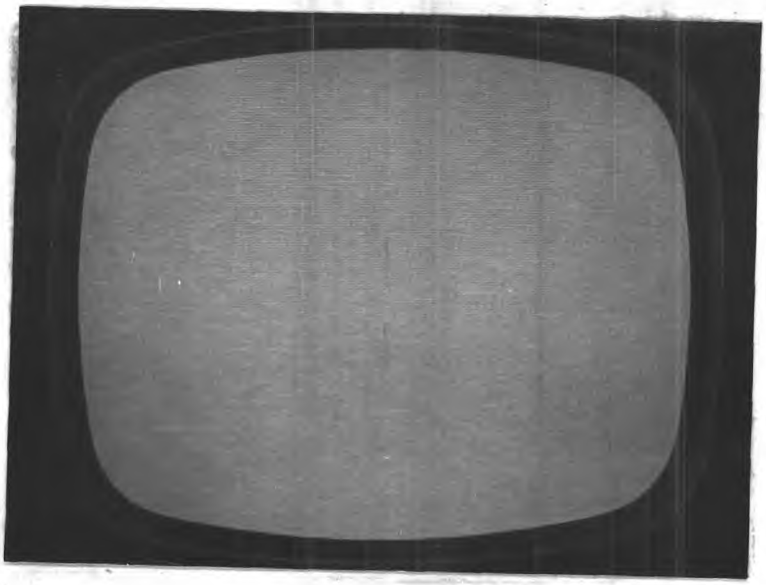


Fig. 7.7(b).

1.6° line : Broken.

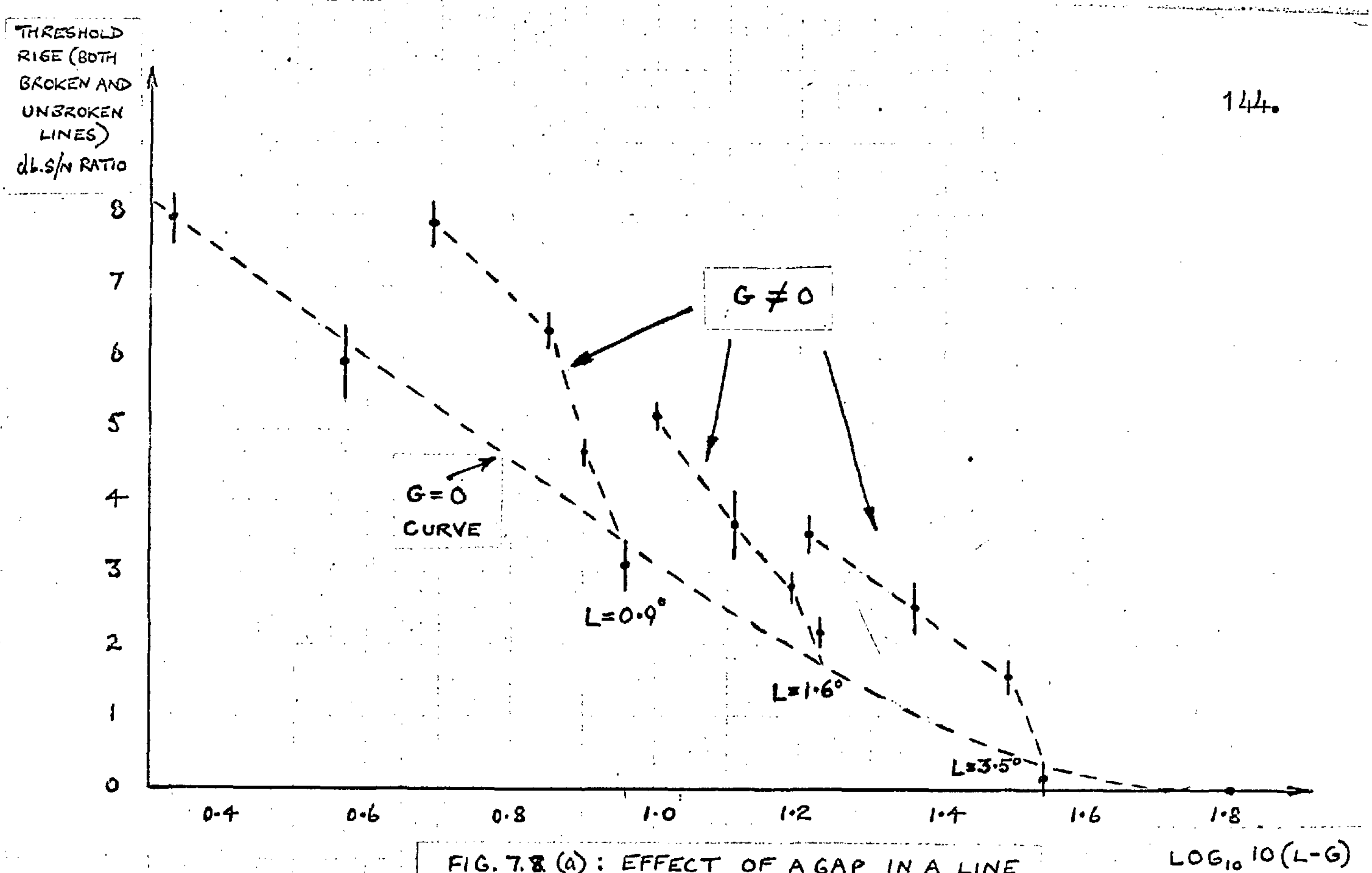


FIG. 7.8 (a): EFFECT OF A GAP IN A LINE. (THREE CASES: L= 0·9°, 1·6°, 3·5°)

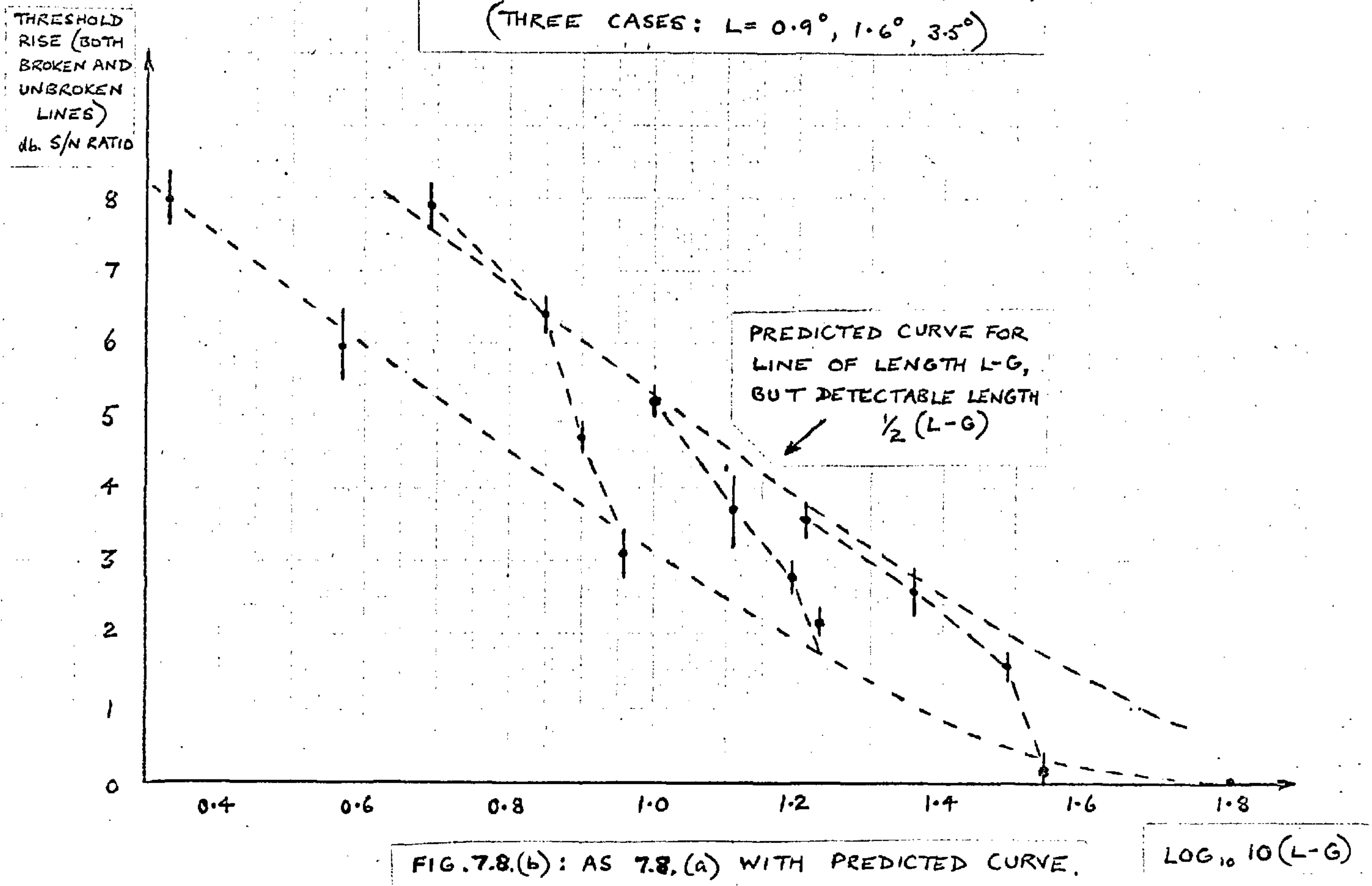


FIG. 7.8.(b): AS 7.8.(a) WITH PREDICTED CURVE.

Length of Unbroken line.	G - Length of Central Gap.		
3.50°	0.43°	1.20°	1.90°
Threshold rise when broken (db).	1.23	2.17	3.20
s/√n	0.20	0.13	0.18
Sig. of Threshold rise (t-test).	> 0.99	> 0.99	> 0.99
1.60°	0.17°	0.43°	0.72°
Threshold rise when broken (db).	1.08	2.02	3.50
s/√n	0.10	0.53	0.20
Sig. of Threshold rise (t-test).	> 0.99	> 0.96	> 0.99
0.90°	0.17°	0.22°	0.43°
Threshold rise when broken (db).	1.30	3.03	4.53
s/√n	0.18	0.27	0.32
Sig. of Threshold rise (t-test).	> 0.99	> 0.99	> 0.99

Table 7.4

length axes employed, this simply means moving the original curve to the right by 0.301.) From Figure 7.8(b) it appears that such a deterioration in detectability occurs when between one third and one half of the original line has been removed. The broken line is then no more detectable than either of its segments above.

7.3.2 This experiment provided insufficient data for the exact estimation of the shape of the curves relating gap size and threshold rise. It did show, however, that the introduction of a gap always raised the detection threshold, and indicated that the size of the rise depended on the relative magnitudes of the gap and the original line, rather than on the absolute size of the break.

In all, this result poses an intriguing problem. The findings of Hubel and Wiesel, at present, do not indicate that a broken line falling within a single receptive field would necessarily cause less neural activity in the appropriate cortical cell than a complete line of the same total length. The difficulty is to explain why the segments produce less excitation than they would if combined into a continuous line. This fact suggests that the two segments may be falling on retinal areas whose outputs are inadequately or antagonistically combined. However, the writer decided that at this stage of the investigation, the search for an explanation should remain subordinate to the main aim of the series of experiments, which was to test whether the discoveries of Hubel and Wiesel are relevant to human vision. The results of Experiment No. 3 do not explicitly deny this possibility, but certainly suggest that if the hypothesis is true the mechanisms involved are very complex. The important questions raised by this experiment will, therefore, not be discussed further here, but will be considered again in Section 8.4.3 with suggestions for further research.

7.4 Experiment No. 4.

7.4.1 Experiment No. 3 indicated that the human visual system is unable to make full use of a line stimulus for detection purposes if its components are spatially separated. An alternative to breaking a line is to display two similar elements side by side. Experiment No. 4 was therefore designed to test the detectability of parallel straight lines.

The basic stimulus was, once more, a narrow vertical straight line such as that shown in Figure 7.1(a). Now, however, a second identical parallel line could be added to the display, a fixed distance from the first, and with a range of spacings of up to 6 minutes of arc. The experiment was performed twice, once for each of two different line lengths, one subtending an angle of 3.5 degrees and the other an angle of 0.35 degrees at the observer's eye, as shown in Figure 7.9(a) and (b). In any one test, the length of the single line, and of each member of the line pair, was constant.

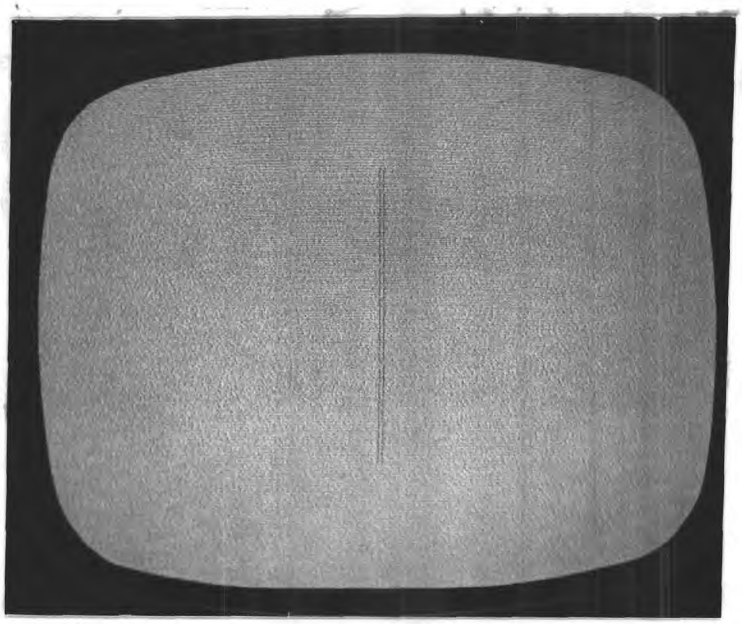


Fig. 7.9(a).

Parallel lines : length 3.5°.

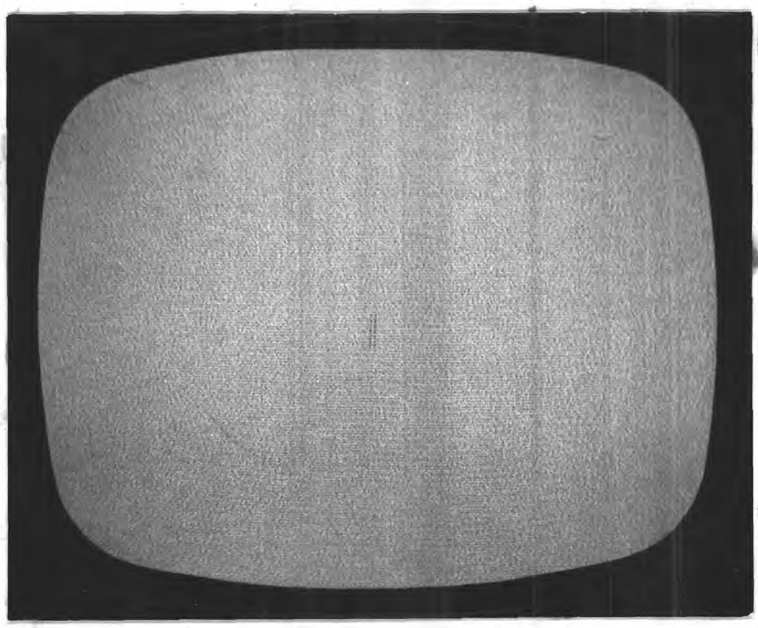


Fig. 7.9(b).

Parallel lines : length 0.35°.

The detection task given to the observers was intended to investigate how the human visual system can make use of extra information. The observers (H.R., A.W., and R.W.) were instructed to seek one line only in the display. Even when they knew two lines were being presented, if they were certain of seeing either one the signal "Yes" was to be given. The experiment was also modified at one stage to test the importance to the observer of prior knowledge of the exact nature of the stimulus. The observer was introduced only to the single line stimulus and was not told that on some occasions two lines would be shown together. (The sequential presentation technique made this variation possible since the displays were concentrated in the threshold region and no "easy" tasks were ever given. The success of this approach was confirmed when no observer reported seeing more than one line in these particular tests.) Each threshold difference measurement was repeated on four different occasions, in order to provide sufficient data for detailed analysis.

7.4.2 A multiple factor analysis of these results was made using the computer at Hatfield College. The factors investigated were (i) separation of the parallel lines (three levels - the three smallest separations), (ii) length of line (two levels), (iii) prior knowledge of the experimental conditions (two levels), and (iv) observers (three levels). The results are shown in Tables 7.5(a) and 7.5(b).

Factor(or Interaction)	Sum of Squares.	Degree of Freedom.	Mean Square.
Separation,S.	2,558,082	2	1,279,041
Length,L.	6,267	1	6,267
SxL.	22,040	2	11,020
Knowledge,K.	50,625	1	50,625
SxK.	58,620	2	29,310
LxK.	851	1	851
SxLxK.	33,446	2	16,723
Observers,O.	338,030	2	169,015
SxO.	98,090	4	24,522
LxO.	16,832	2	8,416
SxLxO.	64,236	4	16,059
KxO.	78,620	2	39,310
SxKxO.	81,970	4	20,495
LxKxO.	81,102	2	40,551
SxLxKxO.	48,194	4	12,049
Replication,R.	608,125	108	5,631

Table 7.5(a). Factorial Analysis of Expt. No. 4.

9

Factor (Or Interaction)	Num. (M.S.)	Denom. (M.S.)	Degrees of Freedom	F	Significance.
Separation,S.	S.	SxO.	2,4	52	> 0.99
Length,L.	L.	LxO.	1,2	1	Not Sig.
SxL.	SxL.	SxLxO.	2,4	1	Not Sig.
Knowledge,K.	K.	KxO.	1,2	1.29	Not Sig.
SxK.	SxK.	SxKxO.	2,4	1.43	Not Sig.
LxK.	LxK.	LxKxO.	1,2	1	Not.Sig.
SxLxK.	SxLxK.	SxLxKxO.	2,4	1.39	Not Sig.
Observers,O.	O.	R.	2,108	30	> 0.99
SxO.	SxO.	R.	4,108	4.35	> 0.99
LxO.	LxO.	R.	2,108	1.39	Not Sig.
SxLxO.	SxLxO.	R.	4,108	2.85	> 0.95
KxO.	KxO.	R.	2,108	7	> 0.99
SxKxO.	SxKxO.	R.	4,108	3.65	> 0.90
LxKxO.	LxKxO.	R.	2,108	7.21	> 0.99
SxLxKxO.	SxLxKxO.	R.	4,108	2.14	Not Sig.

Table 7.5(b): Tests of Significance.

It was found that the threshold difference between displays with a single line and with two lines depended significantly on the spatial separation of the pair of lines, for all three observers. Neither the length of the lines involved nor prior knowledge of the presence of two lines, made any significant difference to the average result at each separation. However, when individual observers were considered, several small differences and factor interactions were revealed. The results of the observers were significantly different from each other, and varied slightly both with line separation and with prior knowledge. The factors of line separation and prior knowledge also interacted in their effect on the individual estimates. In general, these effects were small compared to the average threshold differences at each separation, and showed no systematic direction. For example, while prior knowledge produced a slight improvement in the detection performance of R.W. with double lines under certain circumstances, a deterioration occurred in the case of A.W. The conclusion can again be drawn, (as in Experiment No. 1), that while individual observers do give significantly different results, the variations are of degree only and not of fundamental behaviour. It is therefore again sensible to use an average estimate to predict the characteristics of the population as a whole. The chief drawback here, as in all the experiments, remains the relatively small sample from which the inference is made.

The results, averaged over the three observers, are shown in Table 7.5(c), and in Figures 7.10(a) and (b), and 7.11. In Figures 7.10(a) and (b), the average effects, at each separation, of prior knowledge and length, respectively, are illustrated.

7.4.3 The average results of Experiment No. 4 can be summarised by stating that for line centre separations of more than about 5 minutes of arc, the detection threshold of the pair of lines was much the same as for a single line. For smaller spacings, the detection threshold became lower until the theoretical minimum was reached, (with the two lines superimposed). In short, the experiment indicated that, under the stated conditions, those elements of the visual system concerned with line detection are unable to make use of parallel information presented with a spatial separation of more than 5 minutes of arc.

This experiment emphasises the difference between the way the human visual system makes use of lines presented in different spatial arrangements. In the language of Gestalt theory, a broken line has "good continuation" until the gap becomes comparable with the lengths of the segments. The two parallel lines, however, although "similar", do not reinforce each other until they are very close indeed.

It is again possible to explain all the features of this experiment on a straightforward receptive field model.

Line Separation(').	Threshold rise (db).	s/√n	Significance of rise.
2.4	3.97	0.22	> 0.99
3.7	2.55	0.27	> 0.99
4.8	0.80	0.28	> 0.90
6.0	0.16	0.18	Not Sig.

Table 7.5(c): Averaged results at each separation.

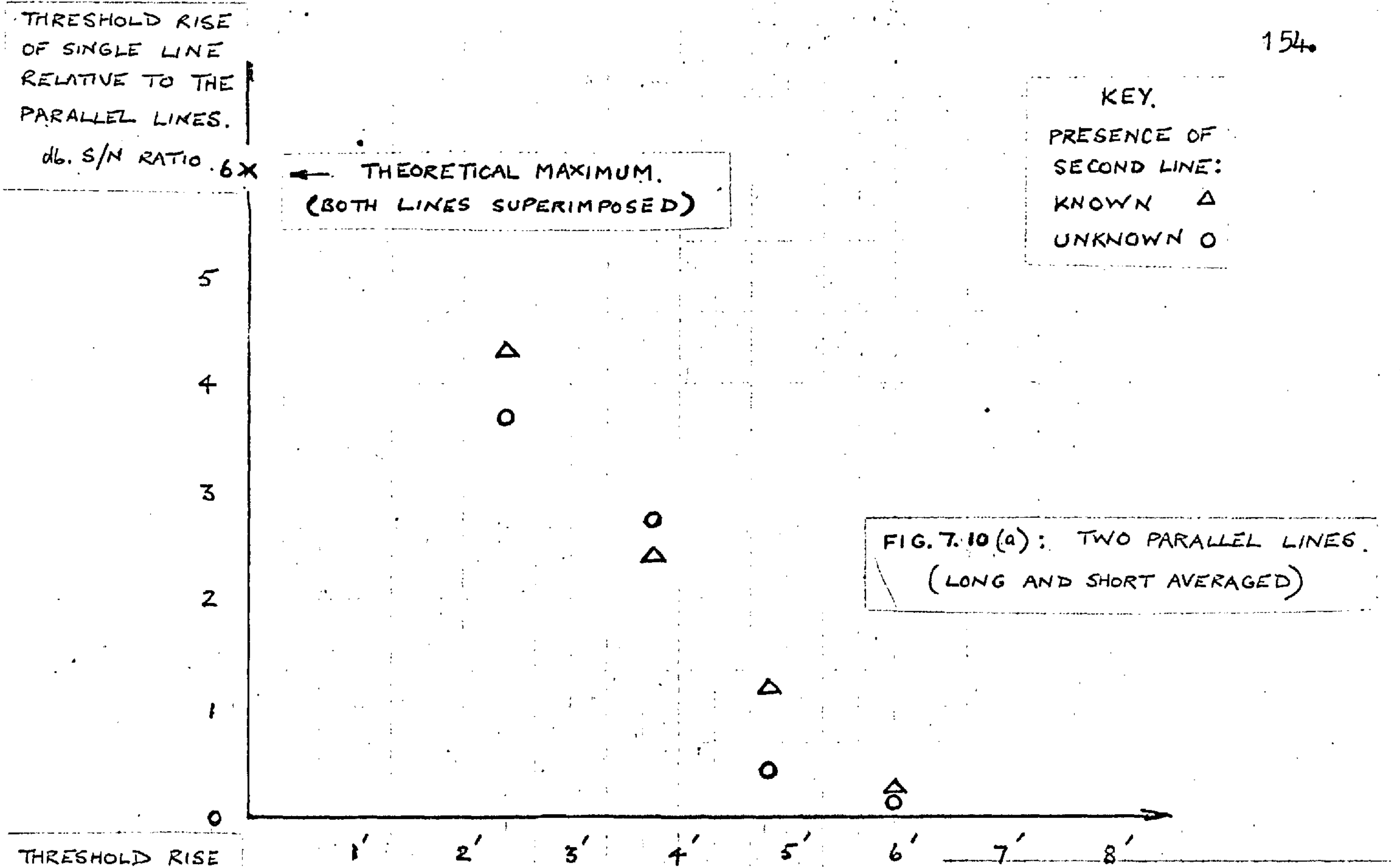


FIG. 7.10 (a): TWO PARALLEL LINES. (LONG AND SHORT AVERAGED)

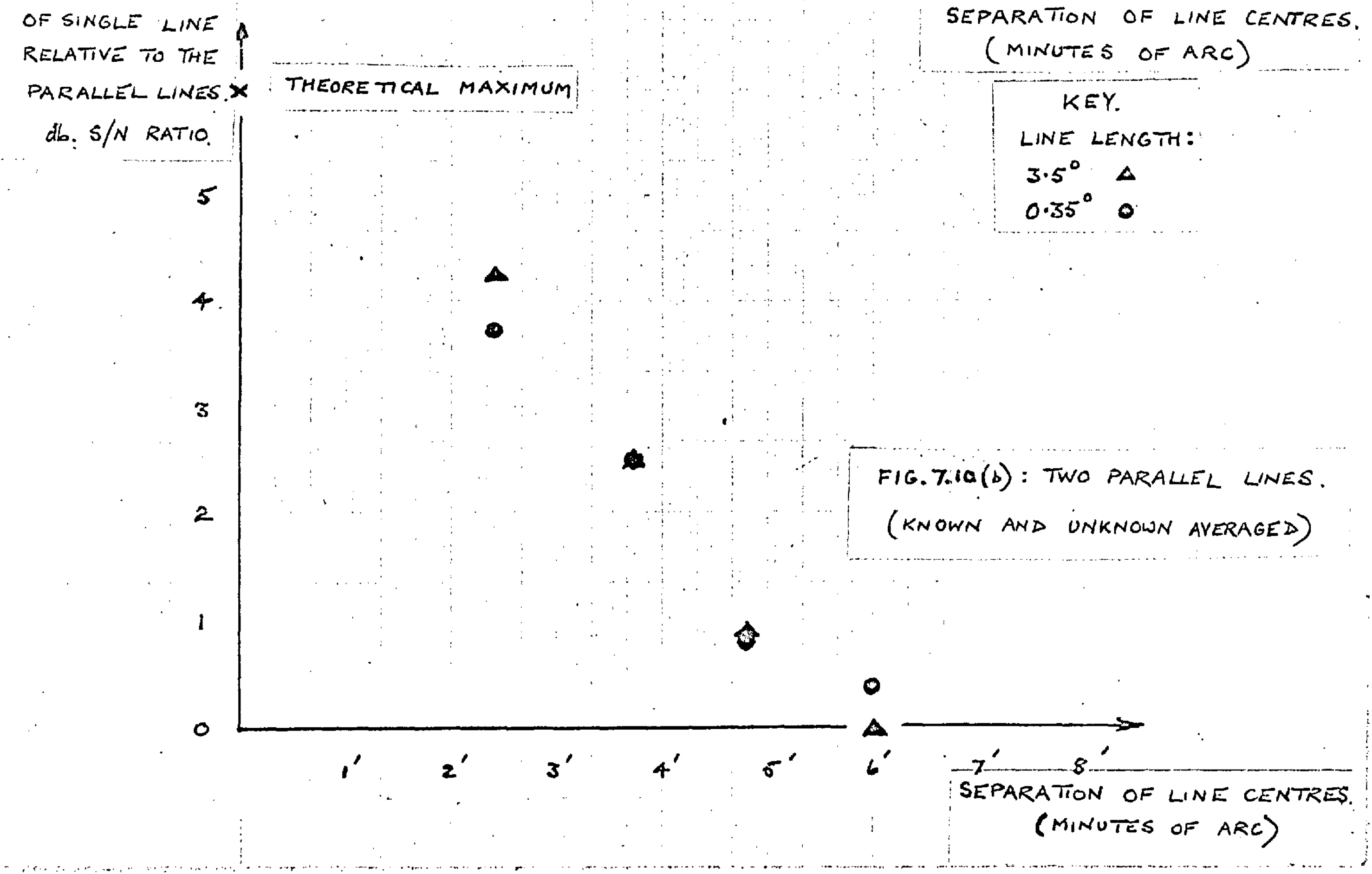


FIG. 7.10 (b): TWO PARALLEL LINES. (KNOWN AND UNKNOWN AVERAGED)

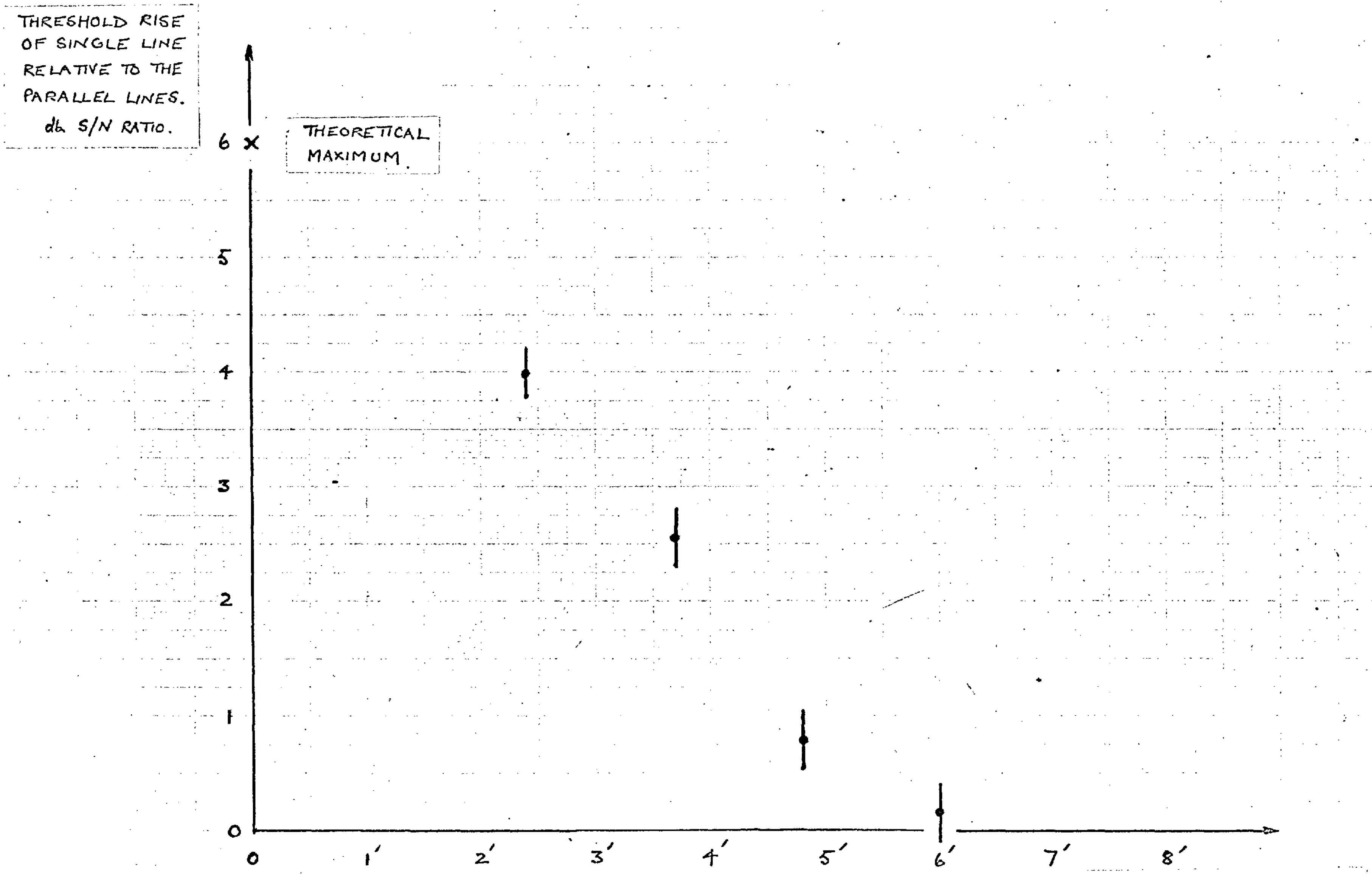


FIG. 7.11 TWO PARALLEL LINES.
(ALL FACTORS AVERAGED, EXCEPT SEPARATION)

It would be relatively easy to account for the stimulus reinforcement at close proximity on the grounds of optical blurring of the retinal image alone. Westheimer (1963) shows an optical line-spread function for the human eye with a width of about 5 minutes of arc. The superimposition on the retina of two blurred line images would thus cease when the sources were more than 5 minutes apart.

The reinforcement might also be attributed entirely to neural interaction, (Fry, 1957, 1965), or, more probably, to a combination of both neural and optical effects. The neural interconnections would necessarily be on a small scale, which suggests that their location might be in the retina or in the geniculate bodies. If this is the case, the two stimuli would be affecting the narrow central region of the receptive field of a simple cortical cell. The critical separation found is a little small compared with the figure of 10 minutes quoted by Hubel and Wiesel as the optimum width for a broad <u>continuous</u> stimulus, but is nevertheless of the right order of magnitude. The element contribution function derived by Kristofferson also indicates a useful contribution radius of between 2 and 5 minutes of arc for human subjects. While his figures were obtained using predominantly circular shapes, the discrepancies that he encountered with line stimuli indicate that his assumption of radial symmetry may be at fault. His width estimate could well be associated with the dimensions of a line receptive field. If this is so, it is interesting to note that at a background luminance of 10 ft. Lamberts the function was more narrow than at zero background luminance. The variations noted above might therefore be attributable to the differing light adaptation levels prevailing in the various experiments.

If this analysis of the detection process is valid, the most remarkable feature is again the inability of the system to make use of similar stimuli which stimulate different simple cortical cells. This is all the more surprising since Hubel and Wiesel report that many such cells apparently jointly drive a single complex cell. Any model based on this kind of neural analysis must seek to explain this phenomenon, (Section 8.5.4).

7.5 Experiment No. 5.

7.5.1 Since Hubel and Wiesel found that stimulus orientation is important if certain cortical cells are to be efficiently stimulated, the effect of angular variation in line stimuli was next investigated. The basic stimulus used was yet again the straight line of Figure 7.1(a). The line could now, however, be bent at its centre (but not broken) to form a symmetrical "arrowhead", as in Figures 7.12(a) and (b). The detection threshold of the whole bent line was then compared with that of either of its two components alone. Each test was divided into two sections. In the first either the upper

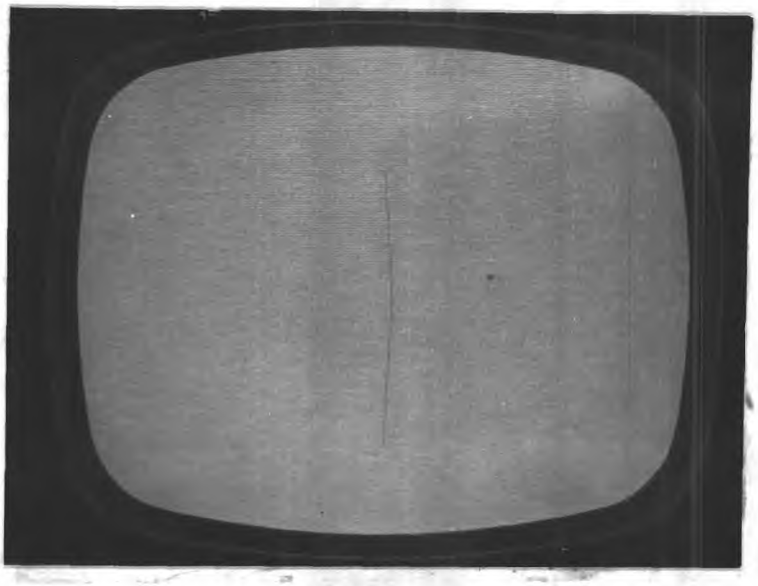


Fig. 7.12(a).

Complete bent line.

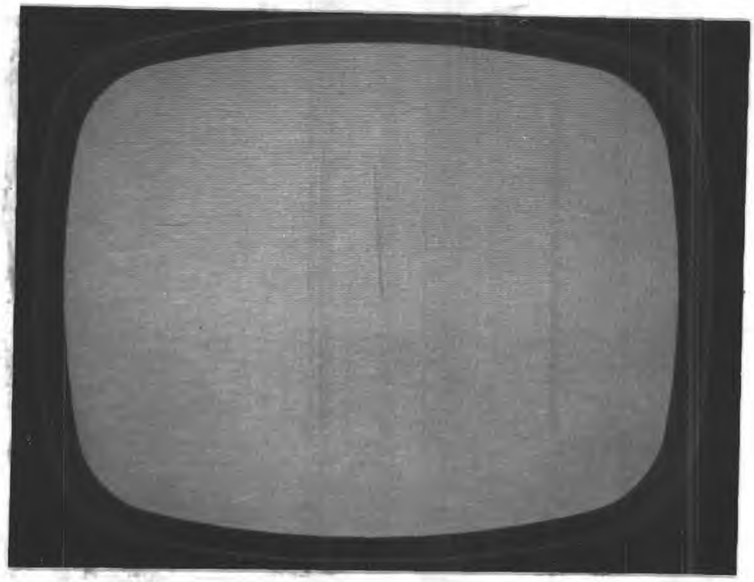


Fig. 7.12(b).

Upper segment.

or the lower component was compared with the complete stimulus, which was used as the reference. In the second, the process was repeated for the other component. The ordering of upper and lower component difference estimates was randomised between tests and observers.

A detailed study was made in the case of the line whose total length subtended an angle of 3.5 degrees at the observer's eye, with the angle between the segments ranging from 0 degrees to 30 degrees (Figure 7.13(a)). This was done using observers E.M., H.R., and A.W. Some extra measurements were also made for a line of length 1.6 degrees, with the angle between the lines at 5 degrees and 30 degrees, using observers E.B., E.M., H.R., and A.W.

No elaborate analysis of the data was made, and only the angle between the line segments was treated as an important factor. Each observer was regarded as a random sample from the general population. The average results are shown in Table 7.6 and Figure 7.13(b).

7.5.2 It is immediately noticeable that, for the 3.5 degrees line, once the angle between the two component lines exceeds about 10 degrees, the whole stimulus becomes no more detectable than either component alone. The use of either the upper or the lower component as the reference stimulus produced little significant difference in the average result. The two measurements on the 1.6 degrees line gave no indication of any great departure from this general behaviour.

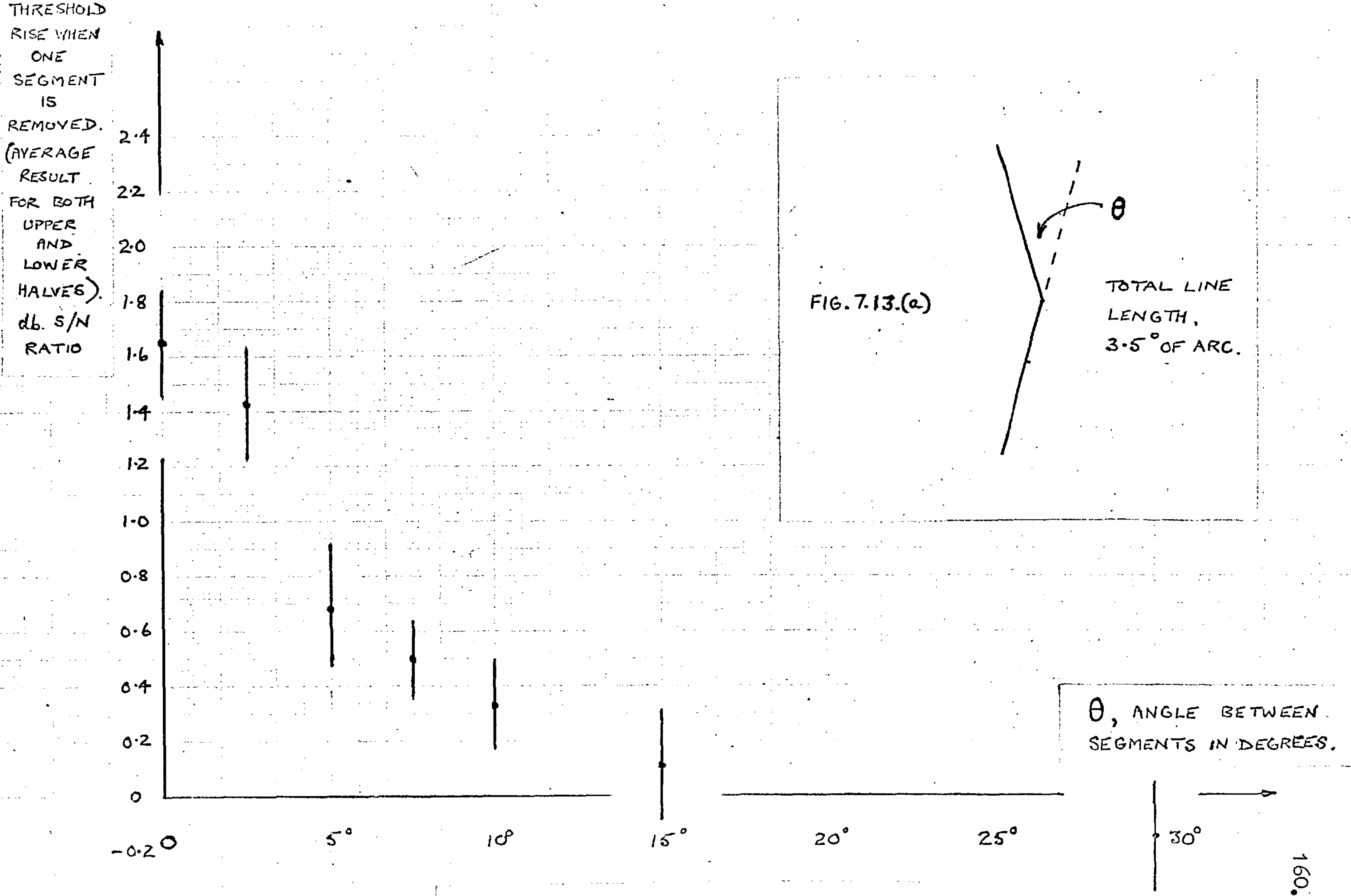


FIG. 7.13.(a)

FIG. 7.13(b). EFFECT OF BENDING LINE.

Angle between segments.	Threshold Diff. between segment and complete line(db) Upper.	Lower.	Average Threshold Difference(db).	s/√n	Significance of average difference. (t-test)	Significance of difference between segts. (t-test)
2.5°	1.52	1.34	1.43	0.22	> 0.99	Not Sig.
5°	0.30	1.06	0.68	0.25	> 0.95	Not Sig.
7.5°	0.48	0.52	0.50	0.12	> 0.98	Not Sig.
10°	0.30	0.35	0.33	0.16	> 0.90	Not Sig.
15°	0.29	-0.07	0.11	0.20	Not Sig.	Not Sig.
30°	0.08	-0.11	-0.15	0.20	Not Sig.	Not Sig.

Table 7.6

7.5.3 This experiment is most interesting in the light of its predecessors. Given the assumption that different simple cortical cells when stimulated cannot assist each other directly, or via some subsequent cell in the system, in making a detection decision, the behaviour is easily explained. In previous experiments, (Nos. 3 and 4), the stimuli components were spatially separated. In this case, the two are continuous but of different orientation. Thus while the angle between the two parts remains small, the majority of the stimulus can fall within one "straight" receptive field centre, and the ease of detection should be comparable with that for the equivalent straight line. Once the angle exceeds that which the field centre can accommodate, only one component of the stimulus can stimulate the cell. The shape then becomes two perceptually distinct halves and will be detected only as well as either single part.

Hubel and Wiesel record that the range of stimulus orientation tolerable, if the firing of a cell is to be maintained, is between 5 degrees and 10 degrees. The findings of Experiment No. 5 are thus in accordance with this result.

7.6 Experiment No. 6.

7.6.1 Hubel and Wiesel report that they found no evidence of a preferred stimulus orientation among the cortical cell receptive fields they investigated in the cat and monkey. If such is the case in the human visual system, then according to the simple detection model which has been suggested, there should be equal detection opportunity for lines of any orientation.

This hypothesis was tested for a line of angular length 3.5 degrees, by simply rotating the whole display monitor, using a specially designed cradle (Figure 7.14), to various fixed angles to the vertical (±30 degrees, ±60 degrees and 90 degrees). The detection threshold of each tilted line was compared with that of the same line in the upright position., for observers E.B., E.M., H.R., J.S., and A.W. At all times in this experiment the observer's head was clamped in an upright position, to eliminate angular movement. The same experimental technique as that used in all the previous experiments was employed.

The individual and average results are shown in Figures 7.15(a) and 7.15(b), and in Table 7.7.

7.6.2 In one way this was the least satisfactory of the experiments reported, although the results are nonetheless interesting. They cannot, however, be generalised for all observers with as much confidence as those in the preceding experiments. A wide divergence of threshold difference (relative to the vertical position) was found between observers at the various line orientations. The average difference between the vertical and horizontal thresholds is statistically insignificant. At the ±30 degrees and

Fig. 7.14.

Monitor Cradle.

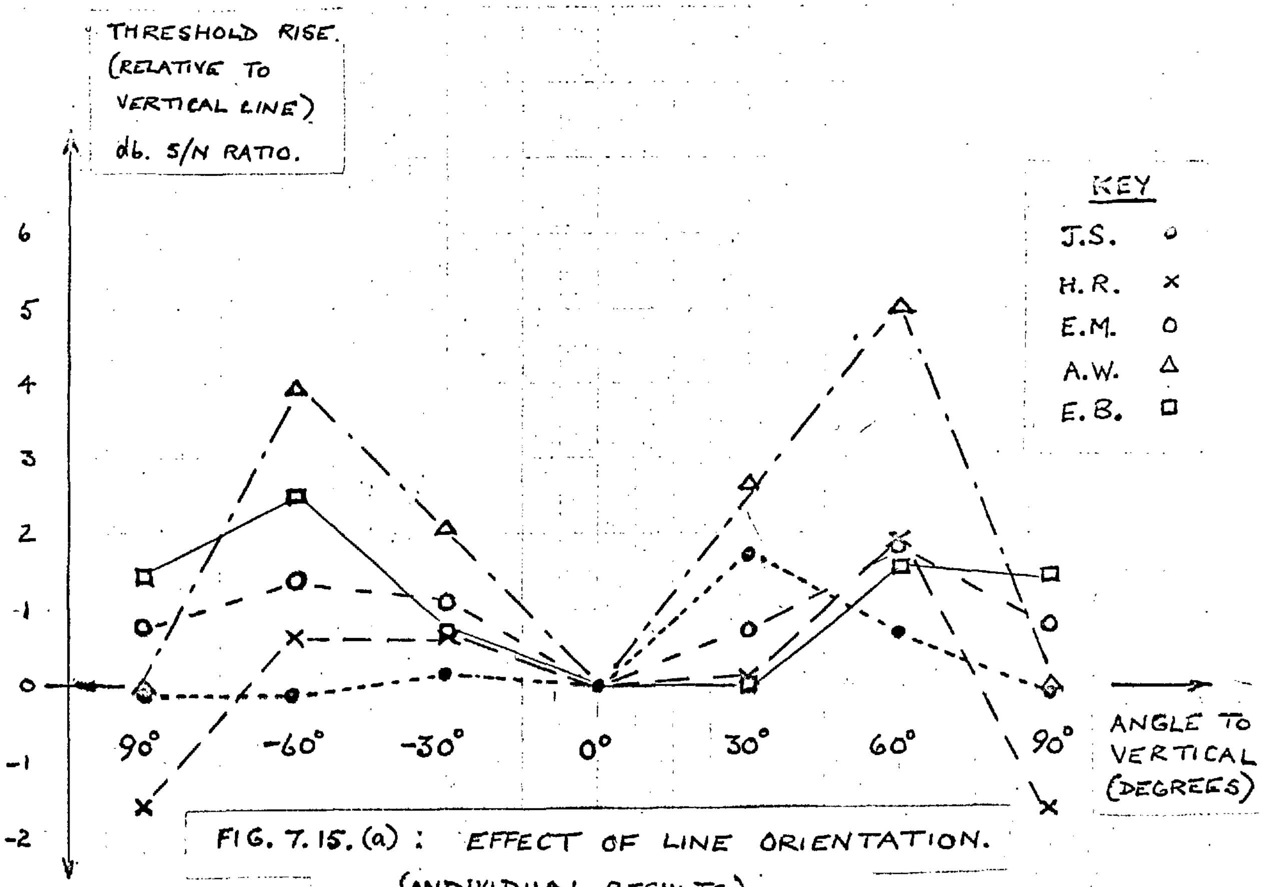


FIG. 7.15. (a) : EFFECT OF LINE ORIENTATION.
(INDIVIDUAL RESULTS)

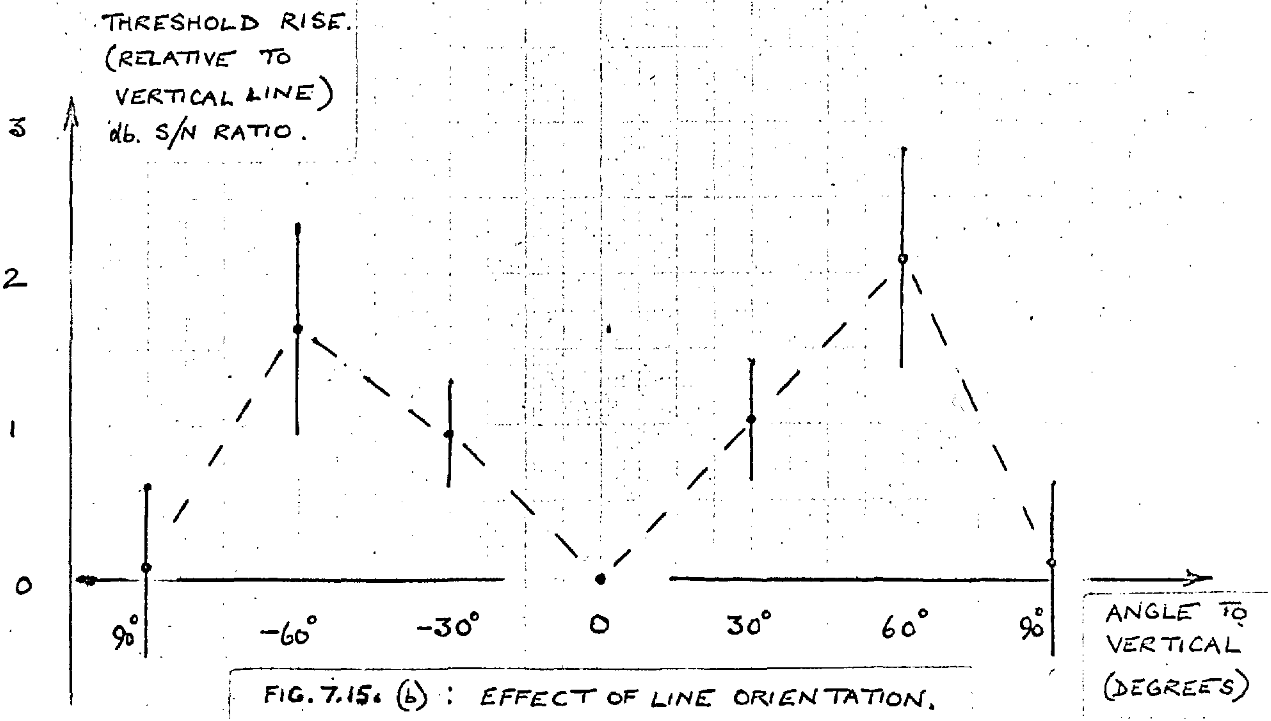


FIG. 7.15. (b) : EFFECT OF LINE ORIENTATION.
(AVERAGED RESULTS).

Table 7.7

Orientation to Vertical. / Observer.	Threshold rise relative to Vertical line (0°).(db).				
	-30°	-60°	90°	60°	30°
E.B.	0.72	2.50	1.45	1.56	0.00
E.M.	0.16	0.14	0.80	1.85	0.75
H.R.	0.60	0.60	-1.60	1.90	0.06
J.S.	0.13	-0.14	-0.13	0.67	1.69
A.W.	2.06	3.90	-0.06	5.00	2.65
Average of Observers.	0.93	1.64	0.09	2.20	1.03
$s/\sqrt{n}$	0.33	0.71	0.50	0.73	0.38
t	2.88	2.31	0.18	2.86	2.70
Significance of rise.	> 0.95	> 0.92	Not Sig.	> 0.95	> 0.95

Average Threshold rise of all Observers:

At ± 30° : 0.98 + 0.37 db. (Sig. 0.95)

At ± 60° : 1.92 + 0.76 db. (Sig. 0.93)

No Sig. Diff. between ± orientations at either 30° or 60° (t-test 5% level).

±60 degrees orientations the average threshold differences relative to the vertical are only just of significance because of the considerable variation in observer performance.

Only tentative conclusions can therefore be drawn from these results. It appears that there may be slight preference for the horizontal and vertical orientations as regards the detection of a 3.5 degree straight line. Performance, on average, tends to deteriorate between these positions. This is in accordance with the results of much psychophysical research on topics such as orientation acuity, vernier acuity and grating acuity, although their relevance is arguable.

Kristofferson (1957) also tested the importance of orientation of a straight line on its detection threshold. The stimulus that he used was 1 minute by 64 minutes of arc in size. He found no significant variation in threshold at any angle. However, not only was the line length different from that used by the writer, but Kristofferson also employed the very short display time of 0.01 seconds. It is interesting to note here that Andrews (1965) in work on orientation acuity found that the ability of a subject to identify the orientation of a short line was at its best around the horizontal and vertical directions. Any bias in the mean judged orientation varied noticeably with display time. Andrews suggested a model involving an asymmetric distribution of orientation-sensitive "filter units" in the visual system, and a time-dependent inhibitory interaction between them. This tends to favour stimuli with orientations around the horizontal and vertical directions at exposure times exceeding 0.5 seconds. He went on to compare the behaviour of these "filter units" with that of the cortical cells found by Hubel and Wiesel, and to suggest a connection. If these cells not only influence the detection of line stimuli, but also affect orientation discrimination, a similar time-dependent process may be the cause of the discrepancy between the results of the writer and those of Kristofferson.

7.7 Summary.

7.7.1 Six main experiments have been described, investigating the relative detection thresholds of simple line stimuli. The results in many ways support the initial hypothsis (Section 7.1.1) that the early stages of neural analysis in human vision are similar to those found recently in the cat. Experiment Nos. 1, 2, 4 and 5 provide considerable evidence for this viewpoint. The results of Experiment Nos. 3 and 6, while not explicitly refuting the hypothesis, do indicate that the system is more complex than has so far been assumed. The implications of the experiments, and a simple model which explains the more straightforward results, will be discussed in the final chapter.

CHAPTER 8

Summary and Discussion of the Experimental Technique and Results

8.1 Introduction

8.1.1 The research described in this thesis has involved an investigation of the feasibility of using a "noisy" television image as a medium for studying visual perception. The particular subject considered was the relative ease of detection of simple line shapes under these conditions. The conclusions to be drawn from the experiments will be summarised and discussed in this final chapter. In addition, on the basis of these observations, a simple model to describe part of the visual system will be suggested, together with experiments to investigate its validity.

8.2 The Use of a Noisy Television Display

8.2.1 The technique of estimating detection thresholds for shapes shown in noisy television displays proved very successful. The practical arrangements and specification of the apparatus have been fully described in Chapter 5. The chief advantages and disadvantages of the method are discussed below.

8.2.2 In a television display a shape can be presented at such high contrast against a uniform background that it can always be detected by an observer. By the addition of background noise, the shape can then be obscured to make reliable detection impossible. The nature and magnitude of the noise is known and can be controlled as precisely as the generating equipment will allow. This is a slight advantage in comparison with simple contrast detection experiments, wherein uncertainty is caused, for example, by reducing the signal strength and/or display time, until "internal" noise in the visual system hides the shape. In such cases, the dominant noise sources are unknown (Blackwell, 1963) and cannot be easily controlled by the experimenter.

In theory, any type of noise can be added to a television display, but there are practical limitations. The bandwidth and therefore the "grain" of the noise can be controlled very simply by means of electric filters, but this only affects the horizontal structure of the display. When the noise "grain" is uniform in all directions, the background fluctuations are homogeneous, but if not, then the line structure of the display becomes noticeable. While such noise can certainly be used to obscure a display, the inherent asymmetry may give it unwanted perceptual properties. For example, perceptual interference with horizontal lines may be greater than with lines in other planes.

This interaction between noise "grain" and picture detail presents an intriguing problem. For example, in Experiment 2, during which a thick line (15 minutes viewing angle) was studied, the noise bandwidth was the usual 3 Mc/s. The S/N ratio was also specified as before. However, the definition employed (Section 5.4.2) takes no account of the thickness of the presented line. In fact, compared with the thin line (1.5 minutes viewing angle), ten times the signal energy was present in a thick line of the same length, at a particular

S/N ratio. This is equivalent to an effective increase of 20 db. in favour of the signal. Although no direct comparison was made of the respective detectabilities of the two lines, a difference of rather less than this figure was usually noticed. The improvement in detection threshold was generally between 10 and 15 db. While this fact is interesting from the viewpoint of efficient use of bandwidth in a television system, the perceptual question remains: if the thick line had been obscured by noise of comparable "grain", what would have been the effect on the threshold? In other words, how does the ability of the visual system to overcome the noise vary with size? Unfortunately, the simple apparatus used so far could not easily be modified to investigate this problem.

8.2.3 Another advantage of the television technique was, perhaps surprisingly, the simplicity of its operation. Once the necessary equipment had been constructed, the display shape could be changed and the S/N ratio altered just by turning a knob. The whole display sequence, once initiated, was automatic. This greatly improved the efficiency of the tests, since the interval between presentations was reduced almost to the absolute minimum. The only remaining improvement would have been to feed the experimental parameters and the observer's decisions directly on to punched tape for computer analysis, instead of recording them manually. This was not possible at the time of the experiments since no high speed tape punch was available.

All the control equipment necessary for the tests was accommodated in one 19 inch Post Office rack. More complex display shapes, although requiring the use of a camera or slide scanner, could be presented with little modification of the basic units. In fact, the writer's equipment has already been adapted to make this possible, (Powell, 1966). The rapid <u>changing</u> of the shape is more of a problem in these circumstances, but automatic slide-changing equipment (as used with modern projectors) may prove useful.

8.2.4 A feature of closed-circuit television systems is that the final video signal is usually sent to the display monitor via 75 ohm impedance coaxial cable. Within reasonable limits, the length of this cable is immaterial. Remote-control of an experiment is thus possible, if the circumstances require it. Yet another advantage of transmitting the picture and noise signals electrically is the possibility of diversification. Any number of display monitors can be driven with the same signal from one picture generator. With very little extra equipment, the picture and noise signals from one basic generating unit could be combined and controlled by different operators to make possible several simultaneous, yet independent, tests.

8.2.5 The chief disadvantage of using a noisy television display as a tool for psychophysical measurement is the structure of the display itself. This was described in some detail in Chapter 4. In consequence, for example, lines and edges in directions parallel or nearly parallel to the scanning lines are not usually faithfully reproduced. The display construction may also interfere with regular patterns in complex images to produce spurious effects, often referred to as "moiré" patterns.

Although these pitfalls were avoided, (or, at least, their effects minimised), in the experiments so far performed, the possibility cannot be ignored of interaction between the flickering, scanned, picture structure and the form factors found to be significant. However, with the assistance of Mr. T. Scott (of the Imperial College Visual Aids staff), a demonstration cine film has been made. This was produced by photographing different single frames of a noisy display and presenting a very large number of them in succession. This procedure effectively removes the sequentially scanned aspect of the display, although the line structure and flicker do remain. No quantitative tests have been made with the film, but the effects demonstrated, using long, short, parallel,curved and bent lines, have apparently survived the transition from one medium to another.

A feature in common to both ciné and television images is that the display field is very limited. The effect of the regular contours defining the screen is unknown. This is somewhat disturbing since observations have been documented concerning contour interaction and inhibition, (e.g. Craik and Zangwill, 1939). However, Powell (1966) has repeated the major part of Experiment No. 2, but with a circular mask obscuring the rectangular boundaries of the screen. His results do not differ noticeably from those given in Section 7.2.

The most obvious test of the generality of the method is to compare the results with those obtained by more orthodox means. Regrettably, it has proved difficult to discover experiments with which a direct comparison can justifiably be made. However, the findings of Kristofferson and his colleagues (1957) repay close examination. These, and other results thought to be relevant have already been considered in Chapter 7.

8.3 The Experimental Method and its Wider Use

8.3.1 The preceding section was concerned with the mode of stimulus presentation. The method of extracting the required information from the subjects is a most important feature in all psychophysical measurement. The development of the experimental technique was described in Chapter 6.

The final test procedure consisted of making a "running" comparison between a reference stimulus and another stimulus (or more) in each session. Each session was thus used to estimate a threshold difference rather than an absolute threshold level. A "pessimistic Yes-No" response indicator was employed, and the stimulus selection method was sequential rather than quasi-random. A 50% estimator (or "Up and Down" strategy) was generally used. With an experienced observer, each test session lasted about twenty minutes and seldom contained more than 120 individual presentations.

8.3.2 This technique proved very suitable for the purposes required by the writer, and most of its important features have already been discussed. One aspect of sequential testing should be considered further. This is the consequence of using on a human subject a testing method developed for investigating the properties of inanimate objects.

Care was always exercised to ensure that the observers did not consciously detect the ordering of the presentations. This was satisfactorily achieved by randomly interleaving "blank" presentations among the genuine ones, with a probability of about one in eight. These served both to break the ordered sequence and to check on the "false-alarm" detection rate. Since the pessimistic Yes-No response indicator was in use, the reply given after these displays was almost invariably "No". The writer was concerned to discover whether the response to the succeeding display was systematically influenced by the "blank". For example, while the stimulus might not normally be discernible in the second display, the difference between it and its predecessor might be sufficient to encourage the answer "Yes". Since the placing of the "blanks" was at random, on average, any bias of this kind would not affect the estimate of threshold difference between two stimuli. In the interests of a possible wider application of the technique, however, it is interesting to investigate the effect of these insertions. In both experiment No. 3 and No. 6, the relevant results were recorded, for E.B., E.M., K.P., H.R. and A.W. The data are shown in Table. 8.1.

On the assumption that no bias was caused by the blanks, an equal number of "Yes" and "No" responses would be expected. The results give no reason for rejecting this assumption.

Experiment No. 3.

Observer.	E.M.		K.P.		H.R.		A.W.	
Decision Sequence.	F_n	F_y	F_n	F_y	F_n	F_y	F_n	F_y
Totals.	21	20	35	31	21	18	27	26
Mean.	20.5		33		19.5		26.5	
Standard Deviation.	3.2		4.2		3.2		3.6	

Experiment No. 6.

Observer.	E.M.		E.B.		H.R.		A.W.	
Decision Sequence.	F_n	F_y	F_n	F_y	F_n	F_y	F_n	F_y
Totals.	32	37	28	21	23	19	24	29
Mean.	34.5		24.5		21		26.5	
Standard Deviation.	4.2		3.5		3.3		3.6	

F_n - Blank display followed by correct "No" response.

F_y - Blank display followed by correct "Yes" response.

The table shows the expected Means and Standard Deviations if F_n and F_y are equally probable. In no cases do the measured figures differ from those expected by more than one Standard Deviation.

Table 8.1

8.3.3 While it is reassuring that the insertion of the "blank" displays produced no great effect on a trained subject, the wider question of long-term response dependence remains. The sequential testing methods have been developed on the assumption that successive responses in a test are entirely independent, and it is unlikely that such a condition can be achieved completely in a psychophysical experiment. Although the correlation between successive decisions may be small, the same may not be true when a wider range of judgements is considered. Even if the subject is unaware of the method employed, he cannot be expected to forget the many previous decisions he may have made in a test session. This is not a problem peculiar to the sequential approach and it will occur even when the sequence is randomised. The difficulties occur in the analysis of the results of the sequential tests.

For the valid estimation of a 50% threshold, there is probably little to choose, in theory, between the use of randomised selection and the sequential "Up and Down" method. Both depend to a great extent on the accuracy with which the starting point is selected and on the parameter spacing. Provided the Routine 11 starting procedure is followed, the practical advantages of the "Up and Down" method are clear.

When an estimate of variance of the threshold is required from within an individual "Up and Down" sequential test, the analysis is not straightforward. Dixon and Mood (1948) and Wetherill (1963) have suggested similar methods whereby the variance may be obtained by considering the scatter of peaks and valleys of the runs. An estimate of this kind has been found by Wetherill to be very dependent on starting point errors, the size of the step spacing and the length of the test. When dealing with human subjects, the degree of correlation between succeeding runs becomes an additional hazard.

Wetherill and Chen (1965) have proposed a method for correcting the estimated value of variance by allowing for correlation between adjacent runs. They quote a value of 0.6 (obtained from empirical sampling trials on inanimate objects) as a reasonable value for the correlation between adjacent runs. All correlations extending beyond adjacent runs were assumed by them to be zero.

The validity of this assumption for psychometric tests was investigated by White (1967) in an experiment on auditory pitch discrimination. Identical measurements were made by both sequential and randomised presentation methods. The mean correlation coefficient relating the midpoints of a pair of adjacent runs (W_i and W_{i+1}) was found, and also those relating the midpoints of a run and its second and third successors (W_i and W_{i+2}, W_i and W_{i+3}, respectively). A significant positive correlation was found, of magnitude between 0.6 and 0.7, relating adjacent runs, and only slightly smaller figures for the more widely separated runs. The most important practical result of the experiment was that estimates of variance obtained by the randomised presentation method were up to twice as large as those given by the sequential tests.

It was noticed by the writer, on inspection of the extended tests performed in Experiment No. 1, that estimates of variance obtained from within test sessions were generally smaller than those obtained by replication. While the differences were not significant, the small size of the sample made the statistical test rather weak. Consequently, it was decided to analyse the data from these sessions, and also that from Experiments Nos. 2, 3, and 5. The correlation coefficients, r_1 and r_2, relating W_i and W_{i+1}, and W_i and W_{i+2}, respectively, were found. This was done for the three runs at the start of a test and again for the three concluding runs. The results are shown in Table 8.2.

These figures should be treated with caution, as the experiments were not designed to investigate inter-run correlation, and certain important assumptions were necessary in the evaluation of r_1 and r_2. Unfortunately, a worthwhile test of whether a correlation coefficient is significantly different from zero requires a large sample. (A coefficient of 0.5 is only significant at the 0.05 level with a sample of 16 or more). The runs from Experiment No. 1 were all obtained from tests involving one particular stimulus, since four replications of the test were made with each of the three observers. The correlation coefficients found here are thus the average figure for the observers in this specific test. In the other experiments, only one sample was available from each observer at each factor level. Therefore at each level the values of r were deduced using the

Experiment	No. of Samples. (n)	First 3 runs.				Final 3 runs.			
		r_1	Sig.	r_2	Sig.	r_1	Sig.	r_2	Sig.
No. 1.	12	0.46	Not Sig.	0.67	> 0.99	0.46	Not Sig.	0.35	Not Sig.
No. 2.	20	0.86	> 0.99	0.65	> 0.99	0.89	> 0.99	0.83	> 0.99
No. 3.	24	0.72	> 0.99	0.67	> 0.99	0.26	Not Sig.	0.32	Not Sig.
No. 5.	24	0.58	> 0.99	0.08	Not Sig.	0.49	> 0.95	0.52	> 0.99
Average (Weighted by n).		0.67		0.49		0.52		0.52	

See accompanying text for assumptions involved in tests of significance.

Table 8.2

runs of different observers as different samples. The correlation coefficients so obtained at each level were then averaged to give the quoted values for that experiment.

In these cases, it has thus been assumed in assessing the degree of freedom applicable in the significance tests, both that samples from the same observer on different occasions are independent, and that a sample from an observer at one level of a test is independent of a sample from the same observer at another level. This is admittedly unsatisfactory, since it is quite possible, for example, that some observers will always exhibit greater correlation than others. This would lead to bias in the average value of r, in comparison with an estimate obtained from truly independent samples.

With these considerable reservations in mind, there appears to be a consistent positive correlation between succeeding runs throughout a test. Moreover, the values of r are similar to those obtained by White. There is evidence, therefore, that the estimate of variance correction suggested by Wetherill and Chen is inadequate for psychophysical experiments, in so far as the assumption of zero correlation between non-adjacent runs is concerned. However, they report that this aspect of the sequential testing strategy is still under investigation. Until more is known about the magnitude and stability of inter-run correlation when human subjects are involved, it would seem unwise to estimate variance within tests directly from 50% threshold data.

For this reason, the writer did not rely on such methods in estimating the error to be associated with particular threshold measurements. In Experiments Nos. 1 and 4, where individual results were studied, the variance estimates used were obtained by replication of the appropriate tests. In the other cases, where only results averaged over all observers were considered, the variance estimate was calculated by regarding the threshold result for each observer as an independent sample of the whole population.

8.4 Summary and Discussion of Experimental Results

8.4.1 Because of the novel means by which the detection thresholds have been measured, any generalisation of the results is somewhat speculative.

The findings with regard to television communication, however, are straightforward. If visual information, involving narrow lines, is to be transmitted under low S/N ratio conditions, some of the principles for obtaining optimum detection are as follows. Wherever possible, the lines should be straight, not bent or curved, and also as long as is convenient (although increasing the length beyond 1 or 2 degrees of arc produces little extra advantage). No advantage is gained by placing two lines side by side if their spacing is greater than about 5 minutes of arc. Gaps in the lines should be avoided. Whether vertical and/or horizontal orientations should be favoured remains a matter for further experiment, possibly including the factor of display time.

While these rules are not especially profound, and apply to strictly limited circumstances, they do represent an initial step towards optimising the contents of a television display.

8.4.2 If the use of a television display is not a dominant factor in the results, then the rules can be extended to apply to vision under adverse circumstances. Perhaps the closest parallel to watching shapes in a noisy T.V. display is vision in conditions of fog or heavy snow. In road, rail, sea and air transport, the design of warning signs which can be detected at the earliest possible moment is vital. Here, the question of object size, for example, is directly linked to the minimum safe viewing distance.

The generalisation can probably be extended with safety to certain cases of shapes seen against confusing backgrounds, provided the background structure is of a random nature. This category would include objects or markings which must be detected against "natural" backgrounds, such as life-rafts in the sea or distress signals on land, (Section 1.5).

8.5 A simple model to describe visual detection.

8.5.1 The practical examples of the importance of visual form depend fundamentally on what happens to a signal within the visual system. Although no certain conclusions can be drawn from the experiments, there is strong circumstantial evidence that "simple" cortical cells, of the type found by Hubel and Wiesel in the cat and monkey, play a part in the initial signal processing.

These cells possess many appropriate properties. They are most efficiently stimulated by straight lines or edges at the correct orientation. The response of a particular cell drops rapidly when the orientation of the stimulus is changed by more than about 5 degrees, and the optimum width of a line stimulus is a few minutes of arc. The most common receptive field size is between 1 degree and 2 degrees of arc. All these features are consistent with the results of Experiment Nos. 1, 2, 4, and 5. It is possible, on the basis of this evidence, that in the human visual system these cells act independently as "line detecting units".

The two remaining experiments (Nos. 3 and 6) while not necessarily contradicting this supposition do not provide confirmatory evidence. Experiment No. 3 did not indicate the existence of a simple "summation of excitation" mechanism in a single receptive field. The lengths of the three lines used were chosen to be above, below and within the critical range found in Experiment No. 2. However, the change of threshold when the line was broken showed no marked variation in character among the different lengths. It was the relative sizes of the gap and the remaining segments which proved important. In terms of neural excitation, therefore, once the size of the gap becomes comparable with the size of each segment, then the neural activity leading to detection is equivalent only to that for one segment alone. It is intriguing that this should occur when the gap is in the centre, but not when it is "moved" to the end, leaving a shorter but unbroken line. If receptive fields are involved, such behaviour implies that the mechanism of neural summation within a single field may be very dependent on position. This is reasonable in view of the partial success obtained by Kristofferson with the element contribution theory. The non-linear contribution function which he derived had radial symmetry, which is consistent with the pattern of neural interaction existing prior to the cortex. The change in receptive field structure which occurs when the simple cortical cells are reached, may well require a modification of the dimensions of the contribution function, along the linear central region. What is not clear from Kristofferson's experiments is whether such functions are simply the aggregate of many like inputs whose influence depends on retinal position, or are the result of a very complex interaction of inhibitory and excitatory stimulation.

Since the writer's experiments indicate that the relative size of line segments and gap are important, this latter possibility cannot be ignored. Before any specific conclusions can be drawn, however, much more research is necessary, to investigate, in particular, a wider range of line lengths, the effect of varying the location of a gap within a line, and also of increasing the number of such gaps. Powell (1966) has begun an investigation of this kind.

Experiment No. 6 was less conclusive than its predecessors, insofar as general findings are concerned. On average, a slight improvement in detectability was exhibited for the horizontal and vertical lines compared with other orientations, although there was considerable variation among individuals. Hubel and Wiesel could find no dominant orientation among the receptive fields of simple cortical cells, albeit from a fairly small sample. In view of the findings of Andrews (1965), (Section 7.6.2) the writer regrets that the factor of display time was not given more attention, especially in this particular experiment.

Although the results of Experiments 3 and 6 do not correspond to any particular findings made by Hubel and Wiesel in the cat, they do not exclude the possibility of a similar neural network existing in the human system. They simply indicate that its details must be more complex than has so far been assumed, which is not a surprising conclusion. Thus, despite these difficulties, the idea of simple cortical cells acting as "line detecting units" remains tenable. In fact, the writer is not the first to suggest that such cells have an important role in human perception.

8.5.2 Andrews (1966) in a model presented to explain his observations on orientation acuity, postulated "filter units" in the visual system. He pointed out that these have properties consistent with those of cortical cells. However, a requirement of his theory is that, for displays of a reasonable duration (greater than about 0.5 seconds), the outputs of these units can be combined or integrated to establish the orientation of a stimulus. Although the writer's experiments suggest that there are "line detecting units" in the system, which also have properties akin to those of simple cortical cells, the outputs of these "line detection units" apparently are not always efficiently combined.

This apparent contradiction need not affect the validity of the comparison, if it is remembered that the perceptual levels of the two tasks are very different. In one, a stimulus attribute, namely orientation, is being judged, and the existence of the stimulus is certain; in the other, so little visual information about the stimulus is available that its actual presence is in doubt. An attempt to explain this difference in terms of neural processing is described below.

8.5.3 There is much physiological evidence to suggest that, in the early sections of the visual pathway, the processing of a visual signal takes place at discrete locations. Considerable neural convergence and reduction in the numbers of efferent neurons occurs at each retinal synapse, and convergence certainly occurs at the synapses in the geniculate body and the first layers of the cortex. At such junctions, where many inputs stimulate one neuron, a decision must be made as to whether the total incoming nervous activity constitutes a genuine signal, or is merely the combination of the noisy firing inherent in each afferent neuron. A simple means of guarding against frequent mistakes would be to set a threshold level, (perhaps controllable from elsewhere in the brain), by which the aggregate firing rate must change before the cell can respond.

The writer therefore suggests a model, which requires the following postulates. (Many of the details have been tacitly assumed in the foregoing experiments and discussion):

(i) That there exists in the human visual system a neurophysiological organisation very similar to that found by Hubel and Wiesel in the cat and spider monkey. This includes the appropriate interconnection of retinal receptors, bipolar cells, ganglion cells, simple and complex cortical cells, and, possibly, hypercomplex cells. The receptive field properties found for these neurons will also be assumed.

(ii) That the firing rate of such neurons is "noisy", i.e. subject to random changes in the absence of change of external stimulation.

(iii) That where many neurons stimulate one cell, that cell responds to the sum of the inputs (which may be excitatory or inhibitory or a mixture of both, depending on the types of synapse involved). In addition the strengths of the inputs may be weighted according to position in the receptive field, but this refinement will be disregarded at this stage).

(iv) That where many neurons stimulate one cell, the firing rate must change by a critical amount before the cell can respond. This precaution, as explained earlier in this section, ensures that the cell is not frequently "stimulated" by noise.

The evidence for postulate (i) has already been discussed in great detail. Postulates (ii), (iii) and (iv) are consistent with experimental evidence obtained from elsewhere in the nervous system, (e.g. Pringle, 1962; Rushton 1962).

8.5.4 If the system operates on these lines, the neural analysis of an image of a noisy television display, falling on the foveal region, will take place as follows:

Individual retinal receptors are stimulated by the incident light and respond appropriately. The resulting activity is transmitted to the retinal bipolar cells, and thence to the ganglion cells. By this stage the information has been coded into repetitive impulses, and image processing has begun. If the eye is light-adapted, the effect of excitatory and inhibitory synapses is such that small, circular areas of high contrast provoke the most activity. This effect is even more marked after the synapse at the lateral geniculate body. Whether any temporal integration of the noise has occurred by this stage is uncertain, but there is evidence that it has not, (Lindsley, 1953). The geniculate neurons will thus be firing at a rate dependent on the instantaneous illumination of the relevant retinal area. If there is a signal buried in the noise, e.g. a straight line of length 1 degree of arc, the mean firing rate of the appropriate geniculate neurons will differ slightly from that of the remainder. Many of these neurons, as Hubel and Wiesel suggested, will synapse with a particular simple cortical cell. If the S/N Ratio is high, all the relevant geniculate cells will be consistently stimulating this cell. Under low S/N Ratio conditions, very few will provide stimulation at the same instant. The probability of the cell (the "line detection unit") being successfully activated is therefore greatly reduced. Detection of a stimulus at this stage, (i.e. response of the simple cell), will occur when the total input stimulation exceeds the critical amount. There will not be a clearly defined change from "no detection" to "detection" under these noisy conditions. Instead, as the S/N Ratio in the image is gradually increased, the stimulation of the cell will begin to differ, momentarily, from the "resting" level. Eventually, at a sufficiently high S/N Ratio, the change of stimulation will become virtually continuous, and the shape will produce a consistent effect on the cortical cell. In the intermediate stage, the stimulus will be detected only intermittently. If this is the sole indication of its presence in the observer's visual system, then the subjective "certainty" of detection will be low, and subject to random fluctuations.

Thus it is at this stage of the postulated system that a line stimulus of these dimensions can first produce a distinct effect. Suppose now that a second similar stimulus is now added to the display, either parallel to, or continuous with it to form a longer line. This extra line may excite another simple cortical cell. Once more, above the threshold S/N Ratio this cell will be significantly stimulated. Both simple cells will now probably be transmitting impulses to a single complex cell. However this cell has "noisy" inputs from several simple cells. If only two of them are firing regularly above or below their normal rate, this may be insufficient for consistent stimulation of the complex cell. Hence, although the stimulus energy may have been doubled, causing double the neural effect at different cells in the simple cortical level, no joint effect is produced.

This argument applies equally well to a stimulus consisting of lines at different orientations. Indeed, no interaction between lines of differing slope might be expected before the hypercomplex neurons are reached, according to the findings of Hubel and Wiesel. If the signals have to pass through extra junctions at which threshold processes operate, the S/N Ratio required before both stimulus elements can produce a joint effect may be even higher than for lines of similar inclination.

With such a model of the first stages of the visual system, the analysis which a signal undergoes is determined by how far it is able to penetrate into the network. At the retinal and geniculate body levels, the cells only respond efficiently to small symmetrical shapes and not to any other organised detail in the image. It is the simple cortical cells which undertake the first elementary form analysis, by responding to straight lines of suitable dimensions and orientations. If the S/N Ratio of an image is too low, then more complicated shapes may not be processed beyond this stage. In consequence, the detailed analysis of an image, involving, say, many line elements at different orientations, should require a high S/N Ratio. This conclusion provides several opportunities for exploring the usefulness of the model.

8.5.5 The writer holds no particular brief for the suggested model, other than that it apparently satisfies with simplicity many of the experimental observations, without contravening any established physiological facts. However, a model exists only to be modified and improved if it has elements of the truth, and discarded if not. There are several straightforward experiments which can be performed as a test of its validity. For example:

(i) Parallel Lines

It was found in Experiment No. 4 that two parallel lines with a separation exceeding about 5 minutes of arc were no more detectable than a single line. This result has been attributed to the lines exciting different simple cortical cells at this spacing. If this is so, then a similar effect should be observed with a misaligned broken line. Even when the total length is unaltered, so that half the line is merely displaced relative to the other, this theory predicts that a separation of 5 minutes of arc would reduce the detectability of the stimulus to that of one of its elements. In a preliminary experiment, Powell (1966) has obtained results that encourage this point of view.

An extremely interesting experiment on a similar basis would require the progressive addition of identical parallel lines, with separation greater than 5 minutes of arc, to a display. If each line excites a different simple cell, all of which in turn drive a single complex cell, this cell should eventually be successfully stimulated. Since this cell is more difficult to excite than those at lower levels, its successful excitation would be strong indication of genuine stimulation. This extra item of information available to the system might well result in a fall in detection threshold.

(ii) Moving lines.

The complex cortical cells found by Hubel and Wiesel are very suited for response to a moving line stimulus. Since they receive inputs from simple cells with adjacent receptive fields, they are subject to continuous stimulation if these cells are successively stimulated by a moving line.

It is sometimes asserted (e.g. Horn, 1962) that moving shapes are more easily seen than stationary objects under adverse conditions. This may often be true, but whether it is the case under the conditions of the experiments is debatable. At the threshold signal level for a stationary line, the appropriate complex cell will not be excited by a moving line, according to the model. If the system can respond efficiently to the successive stimulation of different simple cells, then no change in threshold should occur. If not, a threshold rise must take place. Any other result would be most difficult to explain without considerable modification of the model.

(iii) Additional lines at different orientations.

As was suggested in (i) the addition of extra lines to a display should eventually lower the threshold. If this occurs when all the lines are parallel, it would be informative to attempt to produce the same effect using non-parallel lines. Powell (1966) has recently investigated the relative detection thresholds of a square, right-angled cross, L-shape and single line, all formed from 1 degree line segments. The square was composed of four such elements, the cross and L-shape of two elements and the line of one. In each case the lines lay in either horizontal and vertical directions. He found no significant difference in threshold between any of the shapes. This is entirely consistent with the ideas suggested in the writer's model.

It would also be very informative to find the increase in signal strength required before the entire shapes could be recognised. (This would necessitate precautions to ensure that the observer did not merely detect a segment of the shape and infer the presence of the rest). Especially interesting would be the effect on the threshold S/N ratio of changing the angle between the segments of the shapes. Since Hubel and Wiesel have found interaction only between orthogonal stimuli at the level of the hypercomplex cells, varying the angle from 90 degrees might cause yet another rise in threshold.

An important problem arises when stimuli composed of more than one element are used. It has been assumed in the foregoing discussion that the detection of such stimuli is a process that occurs as a result of the joint effect produced by different cells. If this is not so, and the stimulus is detected in a piece-meal manner, element by element, then display time will play an important part in determining the threshold level. This question will be pursued in the following section.

8.5.6 The results of the experiments outlined above should at least indicate whether it is worth pursuing the ideas behind the model. Inevitably, many important factors have been omitted from its structure. For example, the question of how information about a weak stimulus reaches the higher levels of the brain has been avoided. Although a stimulus in the network of simple, complex and hypercomplex cells may produce no effect beyond a certain stage, this limited information must still be available to some other parts of the system, or no conscious decision about detection could be made. It may be necessary to postulate the existence of a neural channel linking each layer to higher levels of the brain. Presumably this would have limited capacity because of its inability to cope with the joint stimulation of more than one neuron, at least at the level of the simple cortical cells. The observations on stabilised retinal images (Section 3.2.1) which disappear and reappear, in whole and in part, could cast some light on the use of such a channel. The apparent random "sampling" of the stabilised image, in terms of particular segments of its construction, might be a means of making efficient use of a low capacity communication system somewhere in the network.

It must be emphasised that this "explanation" is no more than speculation. Indeed, at present it is difficult to conceive an experiment which would test this theory.

The model also ignores the influence of time in the detection process. There are two aspects to consider here. One is the question of short-term neural adaptation. Many of the workers whose research was referred to in Chapter 3 mention that a change in neural firing rate, induced by a fixed retinal image, usually decays within a few seconds. In other words, the system responds most markedly to changing rather than consistent stimulation. Such changes may in part be created by movement of the retinal image, as a result of the saccadic motion of the eyeball. However, with "noisy" television displays, shapes presented under threshold conditions are rarely seen continuously, so consistent stimulation is unlikedy to occur. Adaptation of this kind may not, therefore, play a significant part in the detection process.

There remains the problem of the time required for the system to assimilate visual information. The experimental results and the conclusions drawn thereon, apply strictly only to three second display times. An important feature of the model is that at a low S/N Ratio, a particular layer of the system cannot make simultaneous use of information arriving from different sources. Given sufficient time and the memory facilities which are available in the human brain, a complex shape could be recognised, with a particular "certainty" determined by the S/N Ratio, from the successive detection of its individual elements. The second preliminary experiment (Section 6.3) showed (although for a straight line only) that increasing the display time did not produce a proportionate decrease in threshold. The critical duration appeared to lie within the range 2 to 6 seconds. Increasing the time beyond this period gave little threshold improvement, and reducing it caused both a rise in threshold and a deterioration in the reliability of the judgements. If it is supposed arbitrarily that 3 seconds is the optimum time for the detection of a straight line stimulus, then if a shape contains two such elements (e.g. a cross), it might be necessary to double this display time before both can be found without change in noise level. Such a simple relation between threshold level, display time and number of stimulus elements, if observed for many varieties of compound shapes, would cast considerable light on the functioning of the visual system.

Perhaps the most obvious omission from the model, and from the reasoning and discussion preceding it, is the subject of control, (exerted either consciously or unconsciously) over the structure of the system and the threshold processes by the remainder of the brain. This approximation is necessitated by ignorance of any of the mechanisms which might be involved. Certainly, neurons carrying to the eyeball signals connected with its motor functions have been located among the optic nerve fibres, although they are relatively few in number. In addition, light adaptation effects on the neural processing have been observed at the retinal level, (Section 3.5.2). Whether this behaviour is influenced from elsewhere in the system, how great is the interconnection between the higher levels of the brain and its peripheral regions, and the extent of the control, are quite unknown. If the structure of the early stages of the visual system of a mature man is fixed, or subject only to gradual or slight change, then the model, and the approach that the writer has described, may have some chance of success. Only further experiment will show.

8.6 Summary.

8.6.1 This thesis has described the application of closed-circuit television to the study of human vision, and the development of a suitable experimental technique. The particular problem considered was the detection of line shapes, and the experiments, detailed in Chapter 7, while little more than preliminary in scope and complexity, have given encouraging results. The usefulness of the technique and the relevance of these studies to communication in general have been discussed, and a simple model to explain the detection process has been proposed. Several experiments to test the validity of the model are suggested.

Appendix 1

A.1 Video Signal Generator.

A.1.1 The picture signals used in the experiments were generated with simple switching circuits of the type illustrated in Figure A.1. (Mullard Reference Manual,1960).

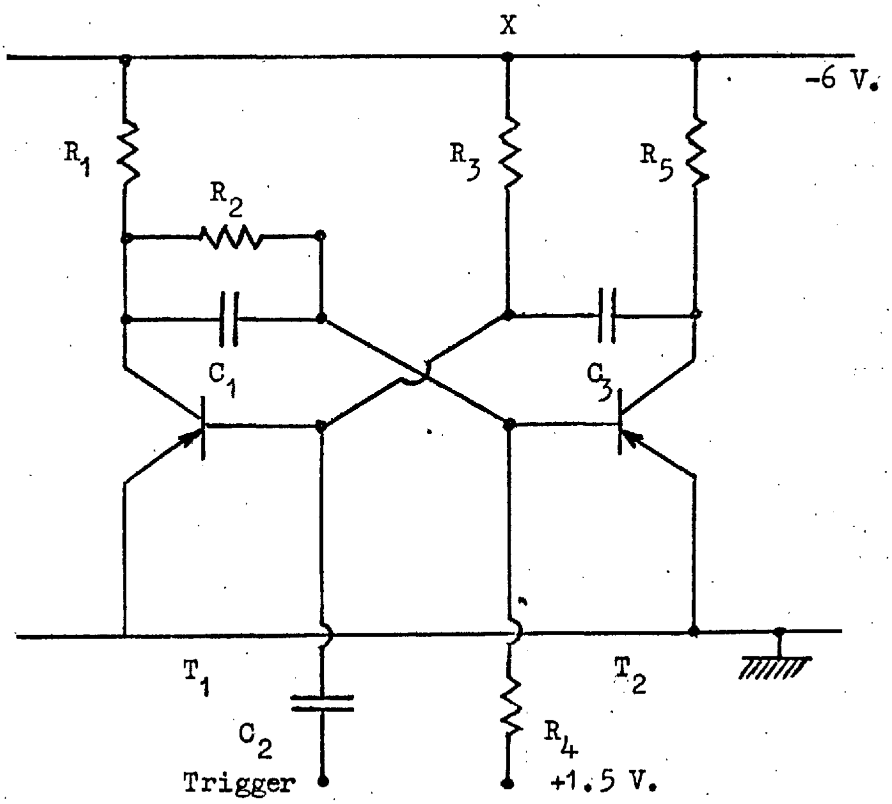


Fig. A.1.

Typical component values used were: $R_1 = R_5 = 1{,}200$ ohms, $R_4 = 10{,}000$ ohms, $C_1 = 500$ pf., $C_2 = 1{,}000$ pf. Transistors: $T_1 = T_2 =$ OC43. The duration of the output pulse is determined by the time-constant $t = 0.7\, C_3R_3$ seconds.

The circuit was variously used to generate short pulses to form the actual picture signal, and longer delay and gating pulses for operations on this signal. The trigger pulses were primarily obtained from a synchronising pulse generator, which supplied line, field and frame signals to British, 405-line television standards.

Consider, for example, the production of a line extending the full height of the display screen. The line synchronising pulses are first used to trigger a delay monostable circuit, which in turn drives the monostable circuit that provides the short picture pulse. This process occurs every time a line is scanned on the display monitor. Consequently, a series of short pulses can be presented in the same position on each line, giving the appearance of a vertical line. As an example, Figure A.2. shows part of one line of the picture pulse waveform used to produce the parallel lines of Experiment No. 4.

The position of the line may be varied at will, by altering the time-constant of the delay monostable circuit, and the width may be adjusted by altering the time-constant of the picture-pulse monostable circuit. If the length of the line is to be varied, the picture pulses may be passed through a gate circuit which removes the appropriate pulses from the output signal. This gate is controlled by pulses derived from the field synchronising pulses.

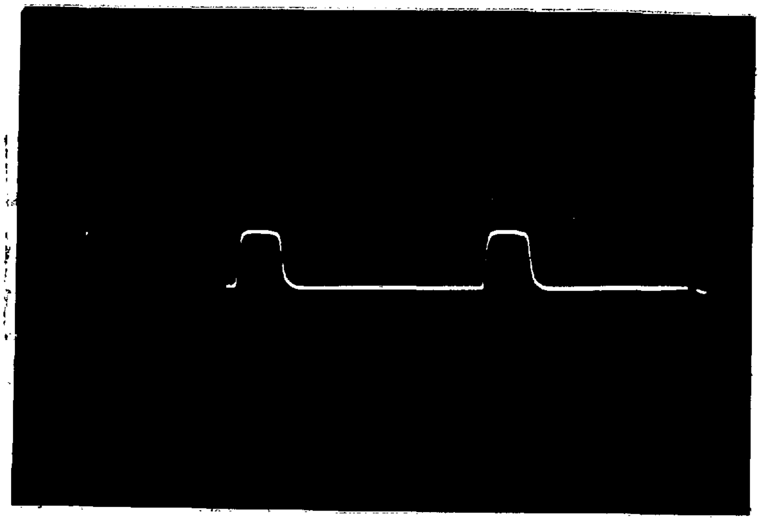


Fig. A.2.

Waveform for Double Line display.

(Horizontal Scale : 1 Division = 1.7 microseconds)

A.1.2 The production of a straight line of variable length is comparatively easy. If the required line is not straight, the problem becomes more difficult. However, simple shapes can be achieved with considerable success, if a voltage waveform, of the desired shape and synchronised to the field pulses, can be produced electrically.

To vary the time-constant of the line delay monostable, the timing resistance, R3 (Figure A.1) is disconnected from the -6 volts line at the point X, and connected instead to the "shape" signal. If the D.C. level of this signal is maintained at -6 volts, and provided its amplitude is low, (not greater than 1 volt), the duration of the delay pulse varies linearly with the signal shape. The position of the picture pulse in the eventual display is thus varied, giving a line of the same shape as the original signal. This technique can be used only for small variations, but the practical limitations of the experimental technique, (Section 8.2.5) made further refinement unnecessary for the writer's purposes.

An additional problem introduced when the shape of a line is altered is that of the duration of the picture pulse itself. When a line makes an oblique angle with the scanning lines in the display, the length of the necessary picture pulse must be considered. Provided the angle remains constant (e.g. the straight vertical line, on the bent line of Experiment No. 5), the pulse duration is also a constant, and no great practical difficulty exists. In Experiment No. 1, the curved line makes a different angle with the scanning lines at different points along its length. The requisite variation in pulse length can be achieved by modulating the timing of the picture pulse monostable circuit, using the same method employed for varying the pulse position.

To illustrate the process, the "worst case" example of the line in Figure 7.1(c) is considered:

The desired shape is a 74 degree arc of a circle, radius 5". In the experiment, one half-cycle of a cosine function was used to represent this figure.

The approximation can be analysed using Cartesian co-ordinates: (y and y' in inches).

Eqn. of circle: $y = \pm\sqrt{25 - x^2}$

Eqn. of sinusoid: $y' = \cos\frac{\pi x}{6} + 4.042$

(constants chosen to minimise error: $y - y'$).

The error $y - y'$ is plotted in Figure A.3. The maximum error is + 0.042 inches in a y range of 1 inch.

Because the curve is not perpendicular to the television scanning lines at all points, (only at the centre, in fact), it is also necessary to modulate the length of the pulses producing the figure.

FIG. A.3. CIRCLE – SINUSOID APPROXIMATION.

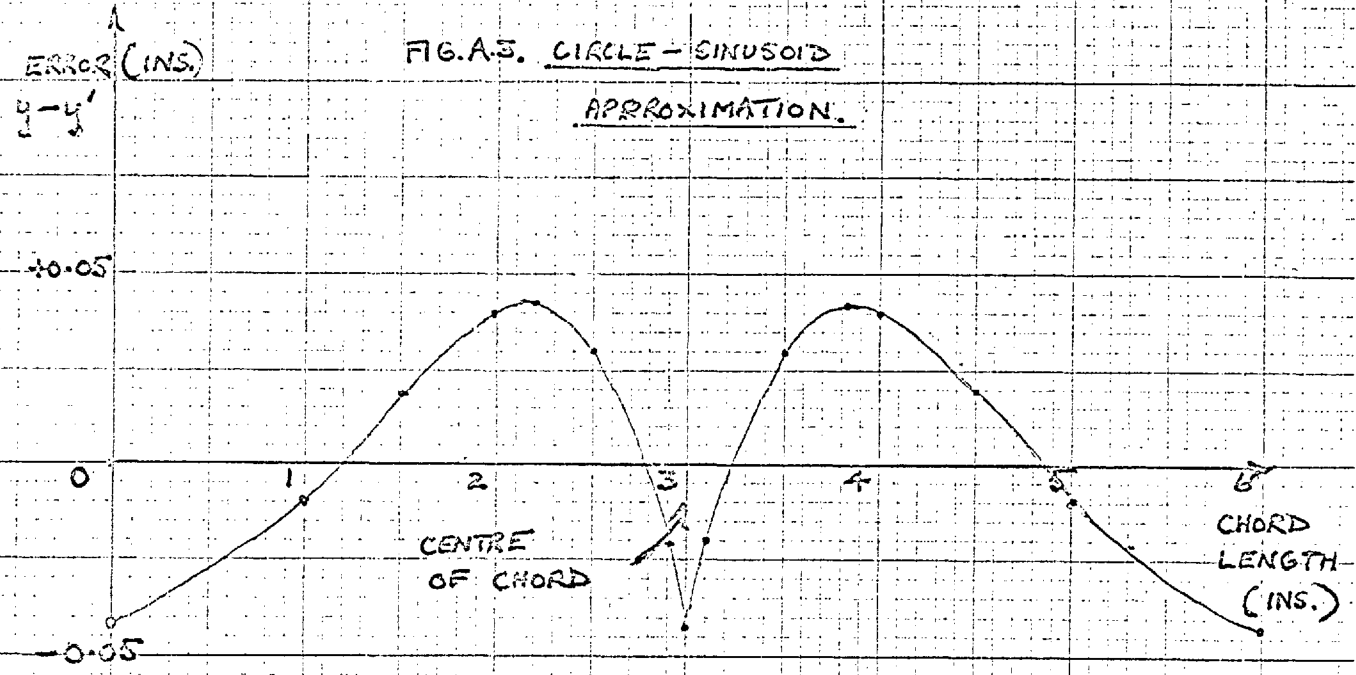
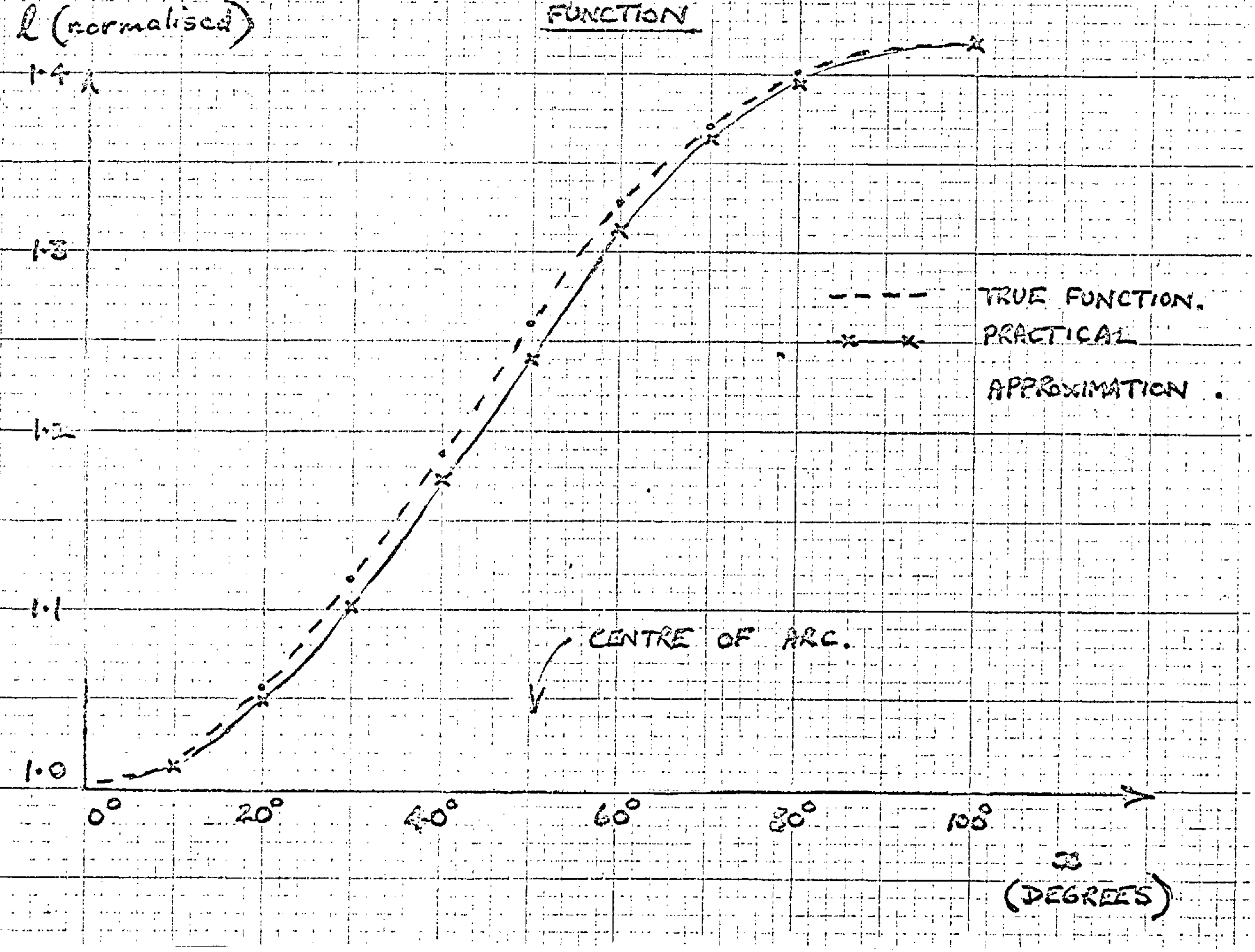


FIG. A.4. PULSE – LENGTH FUNCTION



For the sinusoid, $y = \cos x$, (ignoring constants), it is found that the desired pulse length, ℓ, is given by:

$$\ell \propto (1 + \sin^2 x)^{1/2}$$

In practice, ℓ was modulated so that:

$$\ell \propto \left(\frac{1 + \sqrt{2}}{2} - \frac{\sqrt{2} - 1}{2} \cos 2x \right) .$$

This function was very easy to generate, and by choosing the constants as above, a good approximation to the proper relation was obtained. The two functions are compared in Figure A.4.

Appendix 2

A.2 Random "Blank-display" switch

A.2.1 It became clear when the sequential experimental technique was adopted, that it would be necessary to provide "blank" (i.e. stimulus absent) presentations at random within each test. These displays served two purposes. They interrupted the ordered sequence of presentations necessitated by the method, and also enabled the experimenter to check the false-alarm rate of the observer.

The requirement was for a device which would remove the stimulus from an otherwise normal display, at random but with a fixed probability of occurrence.

A.2.2 The method adopted owes much to that described by Gregory and Devine,(1962). The device consists of a transistor operated astable switching circuit, driving a bistable circuit. While the astable and bistable circuits remain connected, the latter simply follows the former. When the link is broken, the bistable remains in the state immediately prior to the disconnection. The output from the bistable is used to control a relay which determines whether or not the picture pulse signal reaches the display monitor. If the connection is broken manually, using an ordinary switch, the probability of the signal being displayed will depend simply on the mark-space ratio of the astable waveform. For example, if the ratio is unity, there will be an equal probability of the bistable stopping in either state, and therefore a 50% probability of the resulting display being "blank".

The device was tested with two different ratios: 1 to 1 and 1 to 10. In the first case 98 "blanks" out of 200 presentations were obtained. In the second, 53 "blanks" out of 500 presentations occurred. These results were deemed satisfactory for the purpose envisaged. In practice, a "blank" probability of 12½% was normally used, and the switch was operated from the same mechanism which initiated the display sequence.

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