SOME SPATIAL AND TEMPORAL FACTORS IN TACTILE DISCRIMINATIONS.

by

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ABSTRACT

A computer-controlled system was set up for the presentation of tactile patterns to subjects and the performing of psychophysical experiments. The display device was an array of 35 solenoid-operated pins, covering an area of about 1 sq. cm.

A number of experiments were conducted to investigate the effects of several parameters upon the discrimination of tactile patterns presented to the fingerpad.

Measures obtained with the system of some basic properties of the human tactual sense, the limen for duration, the limen for localisation, and the two-point threshold, were in agreement with those obtained by others with different techniques.

The new experiments have included a detailed study of the discrimination of short durations, the detection of simultaneity, the detection of increments of spatial extent and of gaps, a study of the interactions of stimulus points, and the effect of duration upon ability to localise.

From the results, some conclusions have been drawn concerning the operation of the tactile sense. In particular, it appears that the mechanical properties of the skin are very important; vibrations may be set up which affect the psychophysical results, and spatial interactions of stimuli can occur.

An appraisal of the experimental technique is made and the relevance of the results to the construction of communication

devices and aids to the blind, and a possible encoding scheme are discussed.

Suggestions are also made for future experiments.

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CHAPTER 1

INTRODUCTION

1:1 Formulation

The sense of Touch, although included among the Five Cardinal Senses, has only within the last twenty years been the subject of research as well coordinated as that upon the sense of Sight or Hearing.

As a sensory system, it possesses the disadvantage of requiring to be in direct physical contact with the object of scrutiny. It is perhaps for this reason that the tactual system has been considered to be of secondary importance only and that research has to some extent been concentrated upon the problems of using it as a secondary channel of communication with the blind or deaf.

The sense of Touch is, however, of primary importance. It is probably the oldest sense, from which Sight and Hearing have developed as specialisations and its innervation is somewhat simpler and more directly accessible. Geldard (53) has noted that the spatial and temporal properties of the tactual system are intermediate between those of eye and ear. For these reasons, investigations of the tactual system may well contribute to our understanding of the visual and auditory systems.

The research described here was orientated towards the production of an aid for the blind, being concerned with the determination of the 'language' in which to address the skin.

The experiments have been performed to discover the effects and interactions involved in the perception and discrimination of fine-scale patterns presented to the fingerpad. The apparatus used to display the tactile patterns was an array of thirty-five solenoid-operated pins, each capable of being raised independently. The experimental technique was, in essence, to present two patterns in succession to the subject and to require him to discriminate between them. The rate of error for this task is a measure of the apparent similarity of the two patterns.

By comparing a pattern with a slightly distorted version of itself, it is possible to determine the importance of a particular feature of a tactile pattern to the tactual system. The psychophysical experiments performed have investigated a variety of spatial, temporal and spatio-temporal factors in tactile discriminations. They have been directed upon a broad front, with a large number of types of experiment and a small number of subjects. All types of experiment have been performed upon the author, enabling comparisons to be made among them.

Because of the spatio-temporal interactions found in the sense of Touch, the patterns employed have been structured in time as well as space, necessitating the control of a large amount of information. A small digital computer has therefore been used and some time has been spent in developing a suitable program to control the display of patterns and to run the experiments.

1:2 The Thesis

Chapter two of the thesis is an outline of the structure and organisation of the human tactual system, followed by a review of its known processing properties.

Chapter three elaborates the methods of investigation, with details of the apparatus, the program and the techniques of experimentation and analysis of the results.

Chapter four describes the evolution of the computer program and the present structure and operation of the pattern-displaying and experiment-running routines.

Chapter five presents the details of the experiments performed, the results obtained, and the conclusions reached for each of a number of classes of pattern.

The effects of onset and finish of a pattern, the discrimination of durations, the effects of spatial extent, of duration of exposure and the discrimination of simultaneity have been studied.

Chapter six attempts a general assessment of the results in relation to the experimental technique, the human tactual system, and comminucation devises.

Chapter seven contains some suggestions for future lines of research.

There is also an appendix, in which signal detection theory is applied to the technique of presentation to derive a measure of pattern dissimilarity based upon error scores.

CHAPTER 2

THE TACTUAL SYSTEM

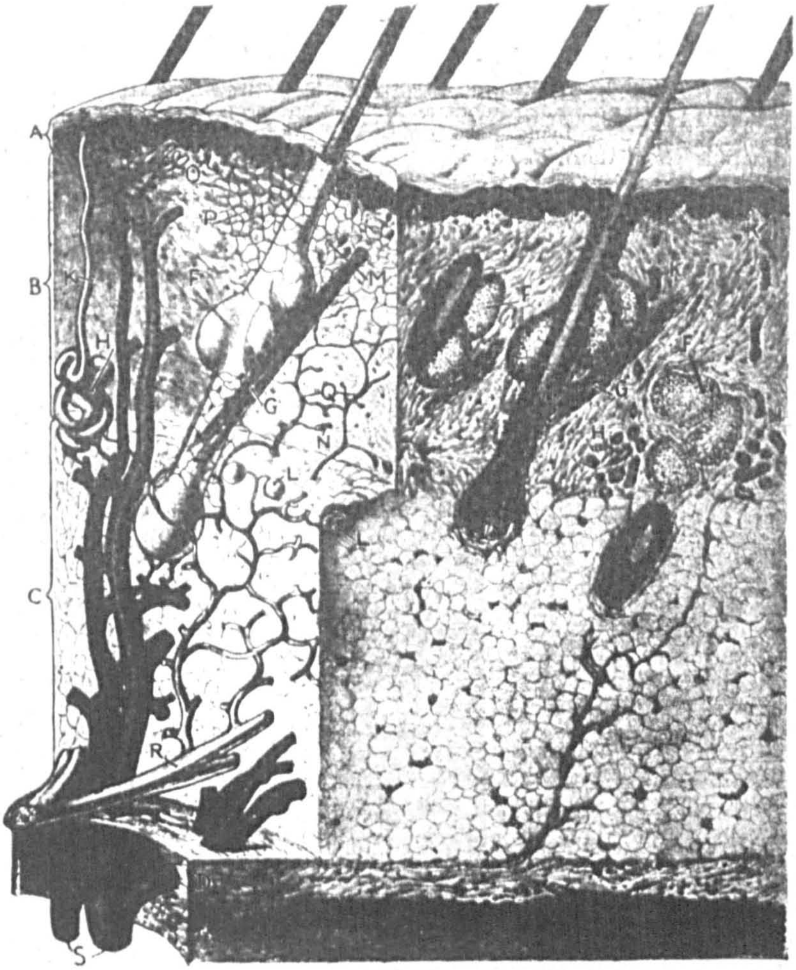
2:1 The Structure of Skin

The skin is a general purpose covering which has many functions. Not only does it protect the deeper tissues from mechanical shocks, it provides thermal regulation and also contains an elaborate sensory system.

Its structure is layered into well-defined regions; the stratum corneum, the epidermis, the dermis and the sub-cutaneous fat which overlies the deep fascia (Fig 1.). The epidermis is a layer of actively dividing cells which varies in thickness and texture over the body (98). The remains of the epidermal cells form an outer horny layer of keratinous material which is particularly tough and resilient. The dermis, thicker than the epidermis and composed mainly of collagen fibres and elastic fibres, is divided from the upper layers by an undulating boundary, the ridges of which are known as the sub-dermal papillae (67,98). The dermis contains the hair follicles and sweat glands as well as many of the skin receptor organs.

The deepest layer, the sub-cutaneous fatty tissue, provides both thermal insulation and cushioning against mechanical shocks.

The nails of the hands and feet are specialised structures, developed from the dermis (67). They provide support for the digital pads and as such probably deserve



A. Epidermis. B. Dermis. C. Subcutaneous fat. D. Deep fascia. E. Muscle. F. Sebaceous glands in association with a hair follicle. G. Arrector pili muscle. H. Sweat gland. K. Duct of sweat gland. L. Bulbous corpuscle. M. Lamellated end bulb. N. Pressure corpuscle. O. Tactile corpuscle in a papilla. P. Superficial nerve plexus. Q. Deep nerve plexus. R. Cutaneous nerve. S. Cutaneous vessels.

Fig. 1/ A scheme showing the structure of the skin. Magnified. Diagrammatic.

(Reproduced from 33rd. edn. of Gray's Anatomy, 1964.)

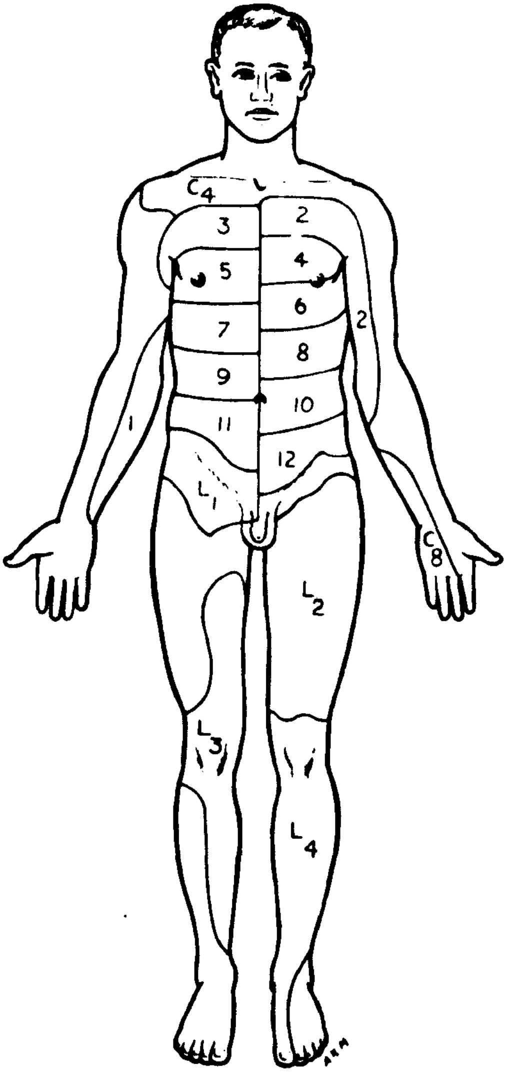
some consideration when mechanical stimulation of the finger-pads is occurring, as they can modify the mechanical properties of the neighbouring tissues.

In addition to its function as a buffer between the organism and its environment, the skin is an important channel of communication with the external world; the entire body surface is subserved by an extensive system of receptors sensitive to mechanical and thermal stimuli.

2:2 The Innervation of the Skin

The innervation of the skin is performed by pseudo-unipolar neurons of the dorsal root ganglia (or the Gasserian ganglion in the case of the face) whose axons extend into the spinal cord and centrifugally in fibre bundles to specific regions of skin (44,122). The region innervated by cells of a particular ganglion is known as the dermatome of that ganglion. The entire body surface is covered by the set of dermatomes, which overlap each other (Fig 2) (96,97). The fibres branch as they reach more peripheral regions, dividing and subdividing many times.

Beneath the epidermis, in the subpapillary dermis, the axons form a network of fibres and branches, the subpapillary plexus, which almost completely underlies the human integument (87). From the plexus the axons branch further toward the



Note.—By comparing both sides the degree of overlapping and the area of exclusive supply of any individual nerve may be estimated. See text for the T. 1 area on the trunk.

Fig 2/ The cutaneous areas supplied by the ventral rami of the thoracic and upper four lumbar nerves. (After Foerster).

(Reproduced from 33rd. edn.. of Gray's Anatomy, 1964.)

surface, terminating in various types of 'end-organ' in the vicinity of the interface of the epidermis and the dermis (Fig 3.) (87).

The density of end-organs is high, of the order of 100 per sq. mm. (115), and their morphology depends partly upon the type of skin in which they are found, i.e. whether in hairy, glabrous (fingerpads, palms, lips and soles of feet) or mucous skin. Several forms of end-organ are observed, authors vary in their classifications and many transitional forms are described (115). Winkelmann (120) points out the underlying similarities and expresses the opinion that detailed categorisation is unjustifiable.

Three broad categories are, however, represented in each type of skin;-

i/ Free endings; these are myelinated and unmyelinated fine arborisations found in the epidermis, dermal papillae and subpapillary dermis of all skin and in the deep fibrous structure beneath. The cornea of the eye is entirely innervated by free endings, which can produce sensations of warmth, cold, touch and pain (114).

ii/ Expanded tips; these usually occur in groups of ten to forty at highly branched endings. They are further classified as Merkel discs or Ruffini endings according to shape, the latter being found deeper, even in the deep fibrous

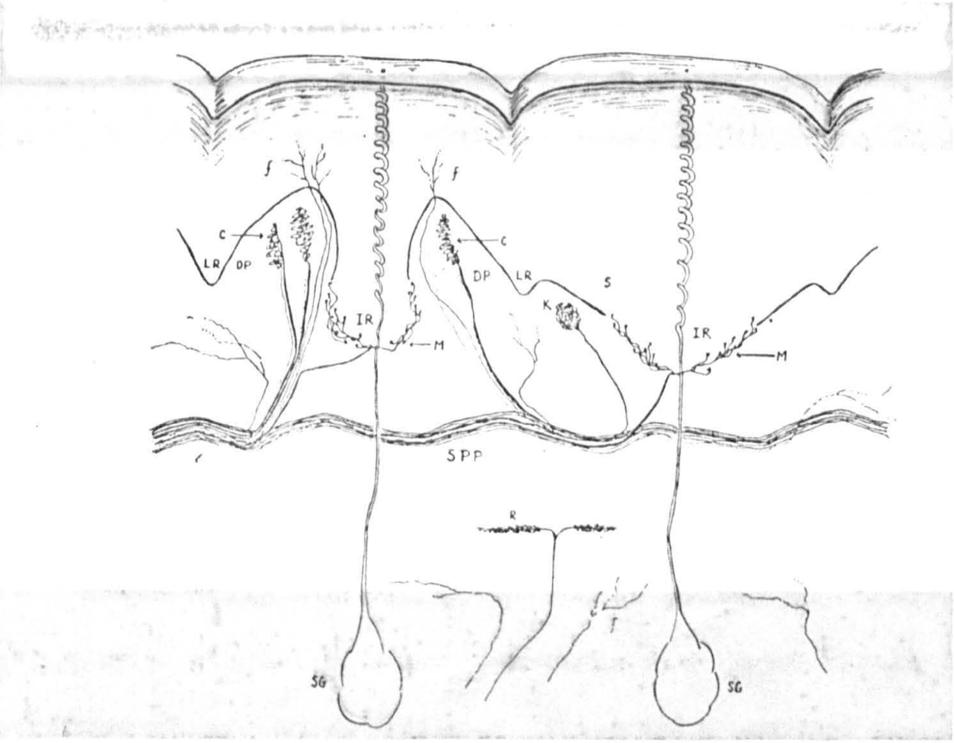


Fig. 3/

A diagrammatic vertical section of the epidermis and underlying dermis and the associated nerve endings in the human fingertip. Two papillary ridges are shown. Two sweat glands (*SG*) are shown in the dermis. Their ducts proceed toward the skin surface and enter the base of the intermediate epidermal ridge (*IR*). The coiled sweat-gland duct progresses upward through the epidermal strata and opens in the central portion of the papillary ridge. The epidermis extends most deeply into the dermis in the region of the intermediate ridge (*IR*). At the lateral edge of the papillary ridge is another epidermal ridge projecting into the dermis, the limiting (*LR*) or anchoring ridge. The upward dermal projections between the intermediate and lateral ridges form the dermal papillae (*DP*). A dermal papilla is seen on each side of the intermediate ridge of the left papillary ridge. Dividing the papillary dermis transversely are septa (*S*) connecting the intermediate and limiting ridges. Partitions may further subdivide the papillae.

Ruffini endings (*R*) are found in the dermis. Free nerve endings (*f*) are encountered in the dermis, the dermal papillae and the epidermis. Krause end-bulbs (*K*) are usually located just under the epidermis. Meissner's corpuscles (*C*) occur in the dermal papillae. Merkel's discs (*M*) are closely associated with the lowermost layer of cells of the epidermis in the region of the intermediate ridge (*IR*) and the septa (*S*). *SPP* is the subpapillary plexus.

(Reproduced from Miller, Ralston and Kasahara (87).)

structure (87).

iii/ Encapsulated endings; usually occurring in a connective tissue sheath. They are often classified as Krause end bulbs, Meissner corpuscles, Pacinian corpuscles and Golgi-Mazzoni endings. The first three are found in hairy and glabrous skin. Pacinian corpuscles, which may have up to forty layers of membrane, are found in the deeper tissues, the subpapillary dermis and the deep fibrous structure (87).

Loewenstein and Skalak (81) have peeled successive layers from a single Pacinian corpuscle and found little change in performance of the receptor. Since such endings are less common in children under ten years and increase in number with age (115), it remains uncertain whether the encapsulation serves any very useful purpose, or whether it is the result of continual decay and regrowth.

In addition to these endings, hairy skin possesses its own characteristic sense organs associated with hair roots. Each root is surrounded by a basket of endings, which may be of expanded form (Fig 4.). There are two systems, the circular fibres which encircle the root and orthogonal to these, the pallisade fibres which extend along it (87,96,44,115,121). It is assumed that hair root fibres are mainly concerned with movements of the hair, which acts as a lever, increasing effective sensitivity.

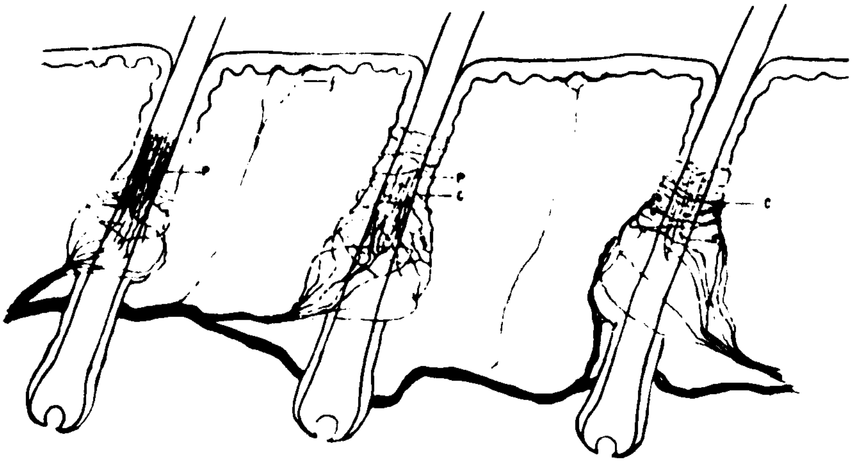


Fig. 4/

A diagrammatic vertical section of the hairy skin of the human extremities showing the relation of the nerve endings to the epidermis and hair follicles. Free nerve endings (*f*) are seen terminating in the shallow dermal papillae or between the epidermal cells. The hair follicle is innervated by both the freely terminating tips of the branches of the circular (*C*) fibers and the expanded tips of the palisade (*P*) fibers. The hair follicle on the right shows some expanded tips associated with the circular fibers, an uncommon occurrence.

(Reproduced from Miller, Ralston and Kasahara (87).)

The receptive properties of the endings and the question of their specificity have been disputed for decades without resolving the issue.(78). Some degree of specificity has been claimed for classification according to fibre size and type (26).

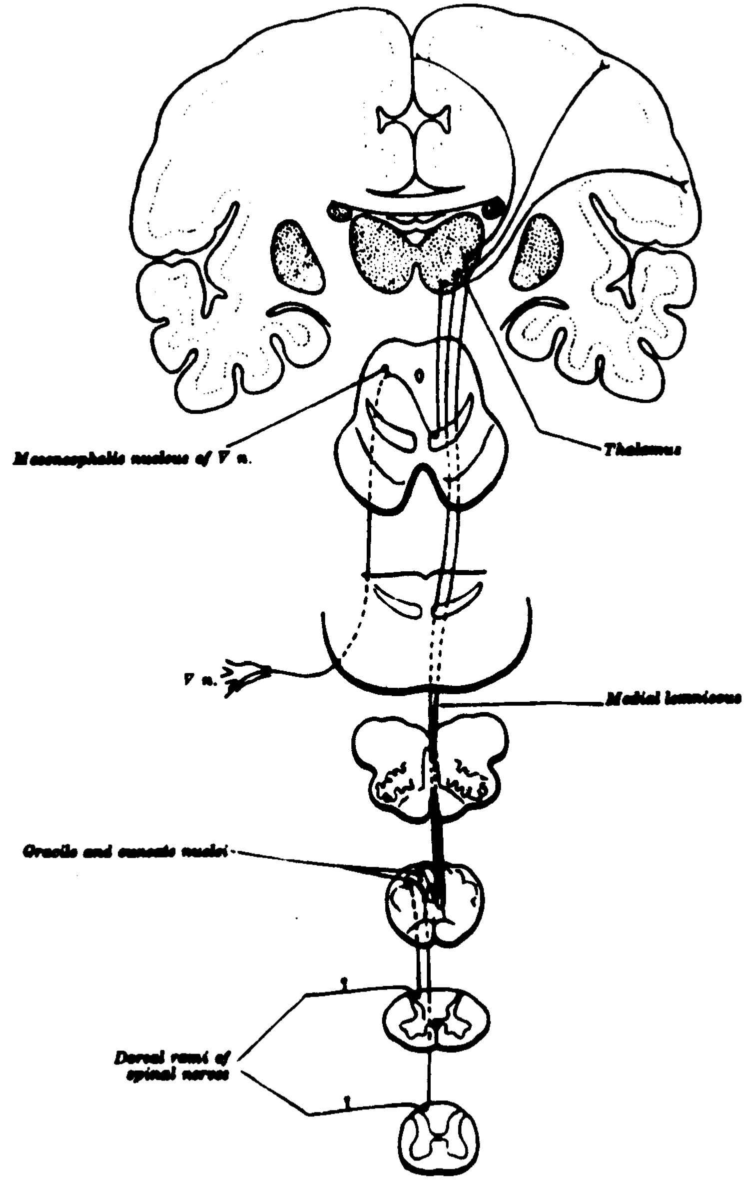
There is no doubt that information is conveyed in a spatio-temporal pattern of impulses from the receptors, but the relative importance of spatial (equivalent to receptor specificity) and temporal factors remains undecided. Melzack and Wall (85) have reviewed the controversy and have postulated a compromise. They claim that a single fibre could encode different qualities (touch, warmth etc.) into different temporal patterns of impulses which can be decoded and classified by higher order cells.

Each axon which transmits information to the central nervous system branches many times in the plexiform layer and at the end-organs. In the case of the rabbit, each axon branches to about twenty hairs, while each hair is innervated by two to thirty axons (115). Maruhashi, Mizuguchi and Tasaki (83) have found receptive fields up to nine by five centimetres in the cat for peripheral axons of the limb. Armett, Gray et al (5) conclude the number of fibres innervating a pad to be about fifty.

There is thus considerable overlap of the receptive fields, and probably similar overlap in Man. Bishop (22-24) claims to have plotted receptive fields for fibres of the human forearm, and these do overlap. Localisation is possibly performed by identifying the intersection of receptive fields of axons stimulated. Such a system has the fail-safe property that failure of one receptor does not result in ignorance of the existence of the stimulus, as would occur in the disjoint field case, only in decreased accuracy of localisation.

On entering the spinal cord, all fibres divide into ascending and descending branches, both of which distribute collaterals to cells in the dorsal grey column. The ascending branches travel rostrally up the dorsal columns to the gracile and cuneate nuclei of the medulla, where they are relayed. From these nuclei, fibres travel to the ventrobasal nuclear complex of the thalamus via the medial lemnisci where they are once more relayed before reaching the S1 area of the cortex. Some of the dorsal column fibres terminate below the medulla and are relayed. This pathway is sometimes referred to as the 'Dorsal Column Pathway'. (Fig. 5) (43,44,115,122).

Many of the second order cells of the spinal cord cross over to the opposite ventral spinothalamic tract (44,115), up which they travel, through the medial lemnisci, to the ventrobasal nuclei of the thalamus (27,44,115,122). This pathway will be referred to as the 'Lateral Column Pathway' (Fig. 6).



The proprioceptive pathway for the trigeminal nerve is still uncertain.

Fig. 5/ The Dorsal Column Pathway.

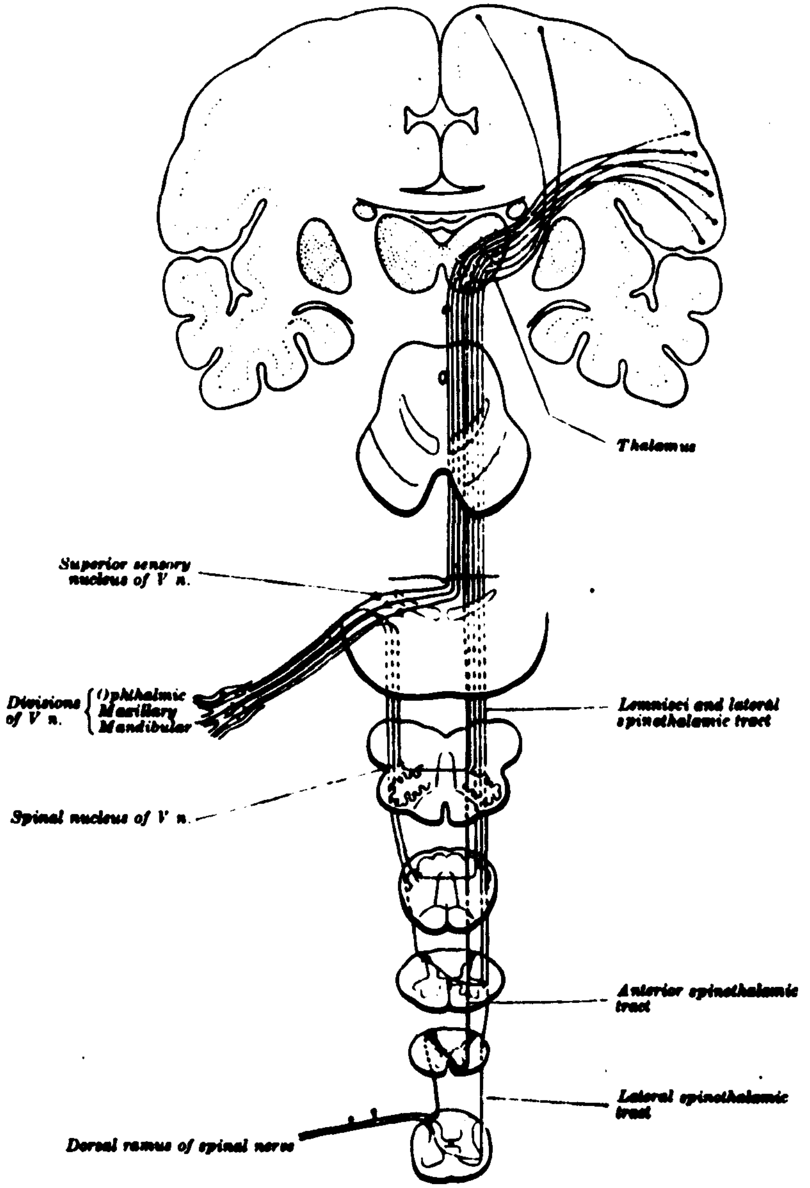
(Reproduced from 33rd. edn. of Gray's Anatomy, 1964.)

Wall has pointed out the differences between the two pathways, fibres of the dorsal column are highly specific, while those of the dorsal horn cells are subject to wide convergence in both modality and spatial field. He suggests that the lateral column pathway, which is phylogenetically older, conveys the afferent information necessary for action, while the dorsal column path is for higher order control purposes, or deciding which action is to be brought about.

Throughout the route from receptor to cortex via the dorsal columns, a one to one mapping is maintained (94), though there is evidence of some lateral inhibition. In a study of cortical responses to vibratory stimulation of the skin, Dewson (39) has shown that the area of cortex excited by two simultaneous point stimuli on the lip of cat is the intersection of the areas which respond to the two stimuli separately. The one to one mapping thus breaks down for multiple point stimuli.

Eccles (43) has shown that in the cuneate nucleus both pre- and post-synaptic inhibition exist, mediated by inter-neurones, the former being dominant. There may also be descending inhibition from the cortex. At the thalamus the inhibition is predominantly post-synaptic.

The dorsal horn cells do not map so neatly. The convergence upon them is very great. Armett, Gray et al (5) suggest there is mutual lateral excitation; Eccles (43)



The course of the fibres from the anterior spinothalamic tract in the brain stem is uncertain. The tactile fibres travelling in the posterior funiculus are shown in fig. 808.

Fig. 6/ The Lateral Column Pathway.

(Reproduced from 33rd.edn. of Gray's Anatomy, 1964).

reports that even afferents from muscle (Ib, II and III) give rise to presynaptic inhibition through interneuron𝑠s in the spinal cord. Wall also claims there is evidence that these interneurons are subject to central control (private discussion).

Adkins, Morse and Towe (1) have shown that stimulation of the pyramidal tract in cat causes changes in the receptive fields of dorsal horn cells, usually increasing but also occasionally decreasing the area. This, they claim, is clear evidence of central control over second order cells. Armett, Gray et al (5) in experiments concerning the input/output function of first and second order neurons have shown that for low stimulation rates the second order cells behave very erratically, but for rates above 10 per sec. they become stable in their response. This is also taken as an indication that central control is occurring.

From these observations, it is clear that much processing of the stimulus information is occurring, even at the first relay. The interconnections are complex and so far it has not been possible to decide what form the processing takes.

2:3 The Effects of Stimulation

The anatomical structure of the tactual system does indicate possible processes which may alter the pattern of impulses entering the central nervous system.

Firstly, the properties of tissue in which receptors are embedded are of importance. The site of the receptor may well determine the types of disturbance which reach it, so that different events would be signalled by similar end-organs in different locations. The mechanical properties of tissue preclude any trulynpunctate stimulation; mechanical and electrical stimuli diffuse over a finite area. Whether it is possible to excite axons individually is uncertain, but in view of the ramifications and entanglement of the branches and the high density of the end-organs it would appear unlikely.

Tissue does not behave either as an elastic solid nor as a container of fluid, but as something between the two. When pressure is applied there is an initial deformation, followed by a flow lasting some seconds. Nafe and Wagoner (91) measured the movements of tissue and found that sensation only occurred during the motion. When the tissue became static the sensation had disappeared, indicating that the receptors may respond most readily to rates of change. It is well-known that a steady stimulus on the skin seems to die away within a few seconds, In general, the receptors of the tactual system adapt with time courses which may be from a fraction of a second to many seconds for a steady mechanical pressure. Loewenstein and Skalak (81) in their investigation of the Pacinian corpuscle, found a large transient response which decayed to a much smaller steady-state response in a few milliseconds. A transient response also appeared when pressure was released. They state that the adaptation is entirely explicable by mechanical adaptation of the encapsulation.

Werner and Mountcastle (116) have determined the function relating total number of impulses constituting the response to the indentation of the skin. They found that response is approximately proportional to the square root of indentation.

Under mechanical stimulation, travelling waves are produced on the surface of the skin (12). These may be several wavelengths long, encircling the forearm, possibly stimulating a large area of skin, but are well-damped on the fingerpad.

Fuller amd Gray (49) have compared experimental and theoretical responses of axons for punctate mechanical stimuli. The theoretical results assume the presence of such travelling waves and amplitude thresholds for the receptors; they predict qualitatively and approximately quantitatively the spatio-temporal pattern of impulses excited by a brief stimulus.

The effect of travelling waves is to increase the spatial area of stimulation, thus firing more receptors and possibly providing more information to the central nervous system. Electrical stimuli do not set up mechanical waves but the spreading of current as it passes through the outer resistive layers to the inner, more conductive layers occurs and is another possible source of multi-axonal excitation. It is not known whether the waves assist localisation or whether they produce masking.

During the encoding at the receptors, temporal structuring of the pulses may occur. For a single receptor, the refractory period limits the temporal resolution that is possible and the rate of transmission of information.(42,106). Uttal (107,108) has found from electrophysiological recordings from the peripheral fibres that the response to the second pulse of a pair of electrical stimuli decreases as the time interval is reduced below a few milliseconds, indicating refractory states for increasing numbers of the afferent axons.

The relative refractory period also gives rise to the phenomenon of phase-locking. Mountcastle et al (89), recording single unit responses of receptors to mechanical vibration has observed phase-locking of the impulses to the stimulus when the frequency of vibration is comparable with the rate of firing of the cell.

Since each axon terminates in several receptors, there may be constructive or destructive interactions - in the forms of generator potential facilitation and refractory period inhibition, respectively. Further, interactions may exist between adjacent fibres, axons in the plexus or in nerve bundles, causing facilitation or synchronisation of impulses (85).

There is no synaptic interaction involved until the spinal cord is reached, where reflex arcs may occur, together with central control of the sensory afferents and synaptic processing of the information before it reaches the higher centres.

Behavioural Experiments

In any consideration of the tactual system it is difficult to draw dividing lines between aspects of its function. In particular, spatial and temporal factors cannot easily be separated, for they interact extensively.

2:4 Temporal Factors

The innate properties of neural fibres limit the maximum rate at which information can be transmitted to the higher centres. Uttal (107,108), using electrical pulse stimulation and recording from the ulnar nerve the mass action potential has observed that if the interval between two successive pulses is reduced to the order of a few milliseconds then both the amplitude of the neural response to the second pulse and the intensity of the sensation are reduced together. Uttal puts forward the theory that the total number of fibres firing is what determines the magnitude of sensation.

Rosner (95) has reviewed the evidence for a similar phenomenon with a much longer time course. The presence of a stimulus at one locus raises the threshold for detection of a second stimulus at another locus. The elevated threshold persists for about 40 milliseconds after the masking stimulus.

The question of what constitutes the threshold for sensation has been considered by Bourassa and Swett (33). Cats were conditioned to respond to direct electrical stimulation of a peripheral nerve and hence the threshold intensity of the stimulus for behavioural response could be determined. It was found that the threshold was approximately the same as that for eliciting a neural response. Measurements with cortical surface electrodes indicated that the threshold for measurable cortical response was about the same intensity. The conclusion drawn by Bourassa and Swett is that threshold for conscious sensation is approximately the same as that for exciting a single axon.

For electrical pulses up to about 10 milliseconds long, it is known that there is a trading relation between duration and threshold amplitude (70,6062,63,34). Barrow (10) has suggested that this is largely a property of the tissue, which acts as a charge integrator.

It appears that integration also occurs for mechanical stimuli, but with a much longer time course, of the order of 200mS. Zwislocki (123) has put forward a theory of temporal auditory summation involving a time constant of about 200mS. Verillo (112) has found that the theory is applicable to the tactual system for vibratory stimulation with contactors of more than $3cm^2$. For small contactors, less than $0.01cm^2$, no summation occurs.

More evidence for temporal summation comes from Berglund et al (20) who have used subjective magnitude estimation to determine the dependence of sensation intensity upon duration of a vibratory stimulus. They find that sensation increases up to about 200-1200mS and then remains constant.

A well-known phenomenon is the adaptation of the tactual system; some seconds after steady stimulation has commenced, sensation is greatly diminished and may even disappear (59). This can largely be explained by the adaptation of the receptors. Because they respond mainly to changes, the rate of onset of the stimulus is of importance. Von Frey (32) found that the pressure threshold varied inversely as the rate of application.

Long-term adaptation can also occur; Hahn (72) has plotted its time course over a period of 36 minutes. It appears to proceed rapidly for the first two minutes or so and thereafter to continue more slowly, but with no sign of ceasing.

The temporal resolution of the tactual system has been determined by Gescheider (57,58), using two successive 'clicks'. He finds the skin to be an order of magnitude worse than the ear at such tasks, requiring about 10mS delay to resolve two clicks of equal intensity, 35dB above threshold. Decreasing the intensity of both clicks from 35dB to 10dB impairs resolution from 10mS to 50mS. Decreasing the intensity of either click relative to the other is also found to impair resolution, 30mS delay being necessary when one click is reduced by 15dB from 35dB above threshold. Gescheider found little difference in performance of a single finger tip, two ipsilateral finger tips or two contralateral fingertips.

The threshold for vibration as a function of frequency has been determined by many investigators. It is usually described as a U-shaped curve with a minimum at about 250Hz (111). Sherrick has found that this frequency coincides approximately with that for maximum mechanical impedance of the tissue, possibly indicating a mechanical explanation for the threshold function (71).

Geldard disputes the traditional result (51). He obtains different curves for sensitive and insensitive spots on the wrist, using point contact stimuli.

Mountcastle et al (89), comparing single unit recordings from monkey and psychophysical threshold data in Man, deduce that the threshold function below 300Hz has two regions, due to the existence of two sets of receptors. Frequency sensitivity in the range 50-300Hz is possibly due to Pacinian corpuscles, while the dermal ridge innervation may be responsible for the low frequency region.

Von Bekesy (14,16) has suggested that receptors may fire in volleys synchronised to the rate of vibration; Mountcastle et al (89) have observed the phase-locking of the response of a single receptor to the stimulus.

Complicated temporal patterns have not been studied in much detail.

Uttal and Krissof (110) have found that for the detection of a gap in electrical pulse train, a gap of about 25mS longer than the interpulse interval is necessary. This time is independent of intensity and largely so of number of pulses and position in the train.

Some attempts have been made to present speech to the tactual system, either electrically (4) or mechanically (2) but these have met with little success. The tactual system does not appear to be capable of dealing adequately with a speech waveform directly.

Very long term phenomena have been described by Melzack and Eisenburg (84). An after-sensation, to which they refer as an 'afterglow', persists after momentary stimulation, fluctuating in intensity and lasting perhaps 20 minutes. This is unlikely to be a phenomenon of the peripheral innervation and is probably central in origin.

2:5 Spatial Factors

The more elementary spatial properties of the skin have been determined repeatedly by many investigators; the early experiments are linked with the development of adequate psychophysical methods, and are commonly recounted in psychology text-books (32,121). They are generally easier to perform than those upon temporal properties.

When point stimuli are used, the sensitivity of the skin is found to be variable over a small region, with sensitive and insensitive spots, the scale depending upon the density of innervation of the region (32,121). Each modality, touch, heat, cold and pain, appears to have its own distribution. Von Frey in 1895 proposed that with each type of spot was associated a particular end-organ. Further, he claimed that a vibrating bristle or a constant voltage applied to a sensitive spot elicited the sensation to which the spot was specific. Intensive investigations have been made repeatedly in an effort to locate the end-organs under sensitive spots (78,85). No correlation has been found.

Geldard (51) has made a long-term study of the stability of the sensitive spots. He found that after a year the distribution had changed; new spots had appeared and old ones had disappeared.

The punctiform nature of Touch is not in doubt, but its cause is.

The ability to localise a stimulus has been well studied (32). Howell (76) and Geldard (52-54) consider bodily locus to be a good parameter to incorporate in a tactile code. They propose a small number of vibrators to be affixed to the body, spread over a large area. Determination of the site of stimulation is relatively easy for the subject.

An often-used measure of the ~~sensitivity~~ acuity of a body region is the two-point threshold; the subject must determine whether he is being stimulated by a single point or by two separated by a small distance. The minimum separation he can detect is known as the two-point threshold (32). Gomulicki and Zangwill (65) have produced an homunculus based on extensive two-point threshold measurements over the entire body surface.

It ~~agrees quite well with~~ is similarly proportioned to that produced by Penfield based upon the areas of cortex to which unit areas of skin map.

The error of localisation is slightly greater than the two-point threshold.(32).

Such investigations have shown that not only does the sensitivity or acuity vary over the body (the extremities are the more sensitive regions, while the chest and the back are the least), but the sensitivity at a point may be anisotropic. In particular, the ~~resolution~~ two-point threshold across the fingerpad is about 1.2 times ~~better~~ smaller than that along it (65). Neurophysiological evidence (66) supports this by showing that individual receptive fields of fibres are elongated along the digit.

If we now consider stimuli which have a finite area, we find evidence of spatial interactions. Verillo (111) has studied the effect of contactor area upon threshold for vibration. He finds that sensitivity is proportional to area at a given frequency, rising by 3dB on doubling the area. There also appears to be a minimum sensitivity, which Verillo takes to imply the existence of two populations of receptors, in agreement with Mountcastle et al (89) to some extent.

Further evidence for spatial summation comes from Foley and Dewis (45) who have found that for vernier acuity, accuracy depends upon the diameter of the rods, improving as the diameter increases. They have not investigated the effect of rod length.

Franzen (48) has investigated summation for electrical stimulation of the fingers. He has made recordings of the whole nerve response to stimulation of several fingers and finds a linear law; the area under the curve recorded for simultaneous stimulation of two digits is the sum of the areas under the curves for stimulation of the digits singly.

He also finds that a power law relates the intensity of the stimulus to the sensation magnitude, as has been found by others for other forms of stimulation. However, Franzen reports that sensation magnitudes obey a vectorial summation law; i.e. If stimulating two digits singly gives rise to sensation magnitudes s_1 and s_2, then the resulting sensation magnitude, S, from stimulation of both digits simultaneously is given by:-

$$S^2 = s_1^2 + s_2^2$$

Inhibition as well as summation phenomena are also observed. Von Bekesy (13,17,19) records that when sensation is observed for static two point stimuli, it is found to be markedly reduced when separation is just resolvable. He attributes this to mutual inhibition of the responses to the stimuli, indicative of a lateral inhibition process similar to that described by Hartline and Ratliff (74,93) in the eye of

Limulus. The existence of such a process in the tactual system is supported by Eccles (43) and Dewson (39). Theoretical considerations of lateral inhibition lead to the prediction of Mach bands and their analogues in other modalities (31,21) such as the enhancement of contours and suppression of signals from homogeneous regions.

Inhibition has widespread effects; the presence of a stimulus on one part of the body can affect greatly the perception of a second stimulus at another, quite different part. This effect is probably central in origin.

Several experimenters have been concerned with the design of coding systems based upon several electrodes or vibrators distributed over the body (3,35,36,56). The universal conclusion is that the more stimuli that are applied simultaneously, the greater the response errors that may occur. The distinguishability of two patterns depends upon the number of sites stimulated and the number of sites the patterns have in common (56).

Uttal (109) has found, using the fingers as sites of stimulation, that the further apart the loci, the less the 'masking' interaction.of the stimuli.

Sherrick (101) has studied the time course of the masking. He finds it to be greatest when the stimuli are simultaneous, falling off with delay until about 20-40mS.

2:6 Spatio-Temporal Factors

Spatio-temporal interactions have already been mentioned in the descriptions of studies of purely spatial and purely temporal phenomena. However, some investigations have been made of situations in which space and time are intimately concerned.

Von Bekesy, in a series of experiments investigating the similarities between the skin and the cochlea (12-18), has found that brief mechanical stimuli of broad area elicit the sensation of a much smaller stimulus, while for longer durations the sensation increases in area.

Czermak (32) in 1855 noted that two-point thresholds for successive stimuli were smaller than those for simultaneous stimuli. This has been studied further by Wieland (118). Measuring the time interval required for discrimination of two successive electrical pulses at different sites from a single pulse, she finds the interval dependent upon spatial separation with a law of the form:-

$$\log T = a - b.D$$

Where T is the temporal separation required for discrimination,

D is the spatial separation of the two loci, a and b are constants.

The tactual ø-effect, in which successive brief stimuli at two locations produces the illusion of a moving single stimulus, has been known for many years. Burtt (32) confirmed Korte's laws and Whitchurch (117) has determined optimal durations and intervals. More recently, Sumby (103) and Gibson (61,64) have also investigated tactual ø-effect for vibratory and electrical stimuli respectively. Sumby substantiates the older results, while Gibson finds that for intervals between onsets of 20mS to 150mS the effectiveness of perceived movement is independent of interval (contrary to Korte's laws). Possibly this is evidence of the importance of travelling waves on the skin.

2:7 Pattern Recognition and Discrimination

Several attempts have been made to devise coding schemes for the transmission of information through the skin, and have met with varying degrees of success. Geldard (52-54) proposed a code based upon five locations, three intensities and three durations of a vibratory stimulus for the letters of the alphabet. He achieved a transmission rate of 38 words per minute. Bliss (28,29) has produced a tactile-kinaesthetic code which causes the fingers to move in the directions they would in normal typing. This has acheived a transmission rate of only 15 w.p.m. Bliss and Crane (30) have used an array of 12x8 airjets to present embossed versions of normal printed capitals, with a transmission rate of 30 w.p.m.

These figures do not compare very favourably with Braille (60 w.p.m.), auditory Morse code (75 w.p.m.) and certainly not with spoken reading of visual text (250 w.p.m.) nor sight reading (up to 500 w.p.m.) (69).

Various attempts have also been made to determine the 'channel capacity' of the tactual system, in the sense of Garner and Hake (50,6,90). Miller (86) has presented the general theory that each dimension of a stimulus can only convey 2 or 3 bits of information. This has been found to be substantially true for several parameters in different modalities. Using an array of six poke probes, Lynch (82) has endeavoured to determine transmission rates in bits per second as a function of the number of patterns in the set. He finds transmission rate increases with the number of patterns in the set, but not linearly.

It is generally found that as the number of dimensions (parameters of stimulus) is increased, the transmission rate also increases but less rapidly (41); the dimensions do not appear to be truly orthogonal as far as the tactual system is concerned. Foulke, Coates and Alluisi (46) have studied various parameters and their usefulness as parameters of a coding scheme, including locus, intensity and duration. They found highest information transmission rate for a code based upon four loci and two intensities.

Foulke and Warm (47) have investigated static dot array patterns, finding that accuracy falls with increasing complexity (array size), while the use of redundant metric (histogram-like) figures does not improve accuracy.

In addition to the question of the passive performance of the tactual system, it appears that perception may be markedly affected by action. J.J. Gibson (59) has shown that recognition of objects by touch is improved if the subjects are allowed to make voluntary movements. From 29% accuracy, the score can be improved to 95%. Karp (77) has taken these investigations further. He has compared placing of the stimulus on the skin, movement by the experimenter of the stimulus and movement of the stimulus by the subject. He obtains 63%, 54% and 32% ~~accuracy~~ errors respectively for the three conditions. Bauer (11) has performed similar experiments with a variety of surface textures as stimuli and reached similar conclusiions. There is little doubt that active exploration of the environment by the subject yields much more information to him than passive observing. Any blind aid should necessarily allow the user to explore under voluntary control.

2:8 Summary

The neurophysiological picture is one of overlapping receptive fields of peripheral and central cells, a many-many mapping of points on the skin to points on the cortex. There is also a possibility that two systems of innervation exist, conveying different forms of information. There is interaction, particularly inhibition, at all levels of the nervous system as well as control of afferent information by the higher regions.

The behavioural experiments described in this chapter map out some of the general processes performed by the tactual system. There is evidence for adaptation, spatial and temporal summation and lateral inhibition. Space and Time are found to interact on the skin to a great extent and in many circumstances cannot be considered separately.

CHAPTER 3

BACKGROUND TO THE EXPERIMENTS

3:1 Introduction

The field of investigation described in this thesis was delimited by the underlying intended application of the results to a tactile communication system. In particular, the main long-term aim was the construction of a mobility aid for the blind. To use such a device most effectively, the subject must be able to actively explore the environment.

A natural region of the body to which information can be presented is the fingerpad. The fingers are innately used in tactual exploration; they are extremely mobile and possess high density innervation for fine detail discrimination. The fingers are well practised in such tasks and are capable of a high standard of performance, e.g. in reading Braille print. It is therefore from a study of the fingerpad that most benefit would be derived. There is also the important factor that it is a region easily accessible to the experimenter, requiring no special preparation.

The immediate aim of the research was to determine some of the factors used by the observer when he makes discriminations with his sense of Touch, and to try to discover some of the mechanisms by which such discriminations are performed. It was therefore necessary to present patterned stimuli to the subject and it was decided to use an array of stimulators to do this.

Various investigators have used multiple stimulator arrays. Brown et al (34-36) have employed arrays of electrodes on the abdomen. Geldard and Sherrick (56) have used ten vibrators distributed over the entire body. Starkiewicz and Kuliszewski (102) have applied an array of eighty electrodes to the forehead, but with little success. Experiments most closely related to the present study have been performed by Bliss et al (30,80) with a 12x8 array of airjets or piezo-electric transducers.

Such stimulator arrays possess the advantage of being capable of displaying a very large number of different types of pattern. They are therefore likely to be used in any general-purpose tactile communication system.

The technique employed in the experiments of this thesis was a method of comparisons. By asking a subject to discriminate between two patterns repeatedly and recording the number of mistakes he makes it is possible to arrive at a measure of the subjective similarity of the patterns. Having carried out a large number of such comparisons for a large set of patterns, it should be possible to discover which features of the patterns are important in such tasks. Patterns which are discriminable will indicate which parameters are being used in the discrimination, while patterns which are confused may indicate which features are ignored.

One possible approach to the problem is similar to that of Shepard (99,100). In this a very large number of patterns is chosen, preferably all possible patterns, and the measure of subjective similarity is determined for all possible pairs. Shepard's technique is then to attempt to position points representing the patterns in a multi-dimensional space so that the distance between a pair of points is proportional to the dissimilarity between the patterns corresponding to them. By an iterative process it is possible to obtain an estimate of the minimum number of dimensions the space must have, and also to determine what the dimensions may be, showing which features of the patterns are important for discriminations. The main advantages of such a technique are that nothing is assumed a priori about the methods of discrimination, they should become clear, a posteriori, in the analysis.

Necessarily in an investigation of pattern discrimination a great many patterns may be employed and an even greater number of comparisons may be made, indeed a practically infinite number. In order to progress at all, the set of patterns must be restricted; the experimenter is required to choose which comparisons are to be made and to exercise a large degree of judgement and control, based to some extent upon the results of earlier trials. A possible strategy is to endeavour to study one factor at a time. This is the strategy that was employed in most of the experiments of this thesis.

Despite such pruning of the possible combinations of patterns to be studied, there still remains a large number of experiments to be performed. All the experiments described in this thesis have been performed upon the author. Further trials have been made with a small number of other subjects where the results have been sufficiently unusual to warrant adequate confirmation. It has thus been possible to study a wide range of effects and the measurements made can be compared quantitatively with each other, free from possible differences due to different groups of subjects. In addition, qualitative observations have been made by the experimenter which assisted in tightening controls, forming hypotheses and setting the course of experimentation.

The stimulator used in most of the experiments was an array of 35 solenoid-operated pins in a 5x7 rectangular order. The spacing of the pins could be varied by changing the top guide plate, through which the pins passed. The solenoids were driven by 35 valve amplifiers and could be operated independently, enabling one of 2^{35} patterns to be presented at any given moment.

The electro-mechanical array was used for most of the experiments. However, for some purposes electrical stimuli were preferable. A controlled-current stimulator, described and constructed by Barrow (10) was also used to provide a single channel electrical stimulus when required.

There remained the problem of control of the stimulator. The primary requirement of the apparatus is that it should be capable of displaying spatio-temporal patterns of some complexity. This could be realised by a system of timers which could be preprogrammed, wired up in sequence to the appropriate channels of the tactile display. To set up a number of patterns would either require very many timers and programming boards, or some higher logic system which could store parameters of the patterns and feed these to timers in sequence.

The second necessity is that the equipment should be capable of choosing patterns to be presented in a pseudo-random manner so that the subject cannot learn the sequence, even over hundreds of experiments. The choosing device should be integrated into a system which will choose, present the patterns and then record the subject's response. Ideally, a protocol of presented patterns, subject's responses and possibly reaction times should be recorded so that analysis at a future stage can be performed in a different manner to that originally intended, should the need arise. Recording of the results would require extensive apparatus to eliminate human recording errors and to prevent the overall experimental time becoming excessively long. Automatic recording would enable the experimenter to be the principal subject and hence secure the services of an unpaid but highly practiced observer over a long period of time.

The PDP-8 computer in the Department was available with output peripherals which could easily be coupled to the display equipment and push buttons for recording the subject's responses. Being a digital computer, it contained a stored program and space for a great deal of data. It therefore seemed best to write a program to control the experiment and use the available hours of computing time to run the trials, rather than to spend considerable time at considerable expense in producing a special purpose piece of apparatus which would not be as flexible as the program, nor as simple and quick to use.

It was decided that a general-purpose program should be written for the Digital Equipment PDP-8 computer to run psychophysical experiments on-line. The experiments to be performed would be orientated towards a broad study of discriminations of spatio-temporal patterns presented to the fingerpad.

3:2 Description of Apparatus

The tactile display system was centred on an electro-mechanical stimulator array, adapted by Dr. J. P. Wilson. It had as its basis an I.C.T. printhead, intended for printing characters at the top of punched cards. Thirty-five solenoid-operated rods are arranged in a 5x7 rectangular array, normally about 3x5mm in the original form, but they can be spread out by replacing the top guide plate up to 12mm x 8mm quite readily. Energising the solenoids raises the rods by about 0.050". This can be reduced by raising the guide plate. The printhead has been modified by fitting a micfoscope focussing rack and pinion to the guide plate to enable simultaneous adjustment of amplitude to be made for all channelx. (Fig. 7)

A number of guide plates have been made with various spacings of holes for the rods; 2mm. and 1mm square arrays and anisotropic plates with 1mm. spacing in one direction and 2mm. in the other. In all the experiments to be described here the 2mm. x 2mm. spacing was used, with the pins rising by 0.010" (250 microns) above the guide plate. A single pin stimulus of this amplitude is invariably supra-threshold.

The solenoids require about 100mA to pull them on and 30mA thereafter to hold on. As they have a resistance of about 1000 ohms, this necessitates a supply voltage of at least 100V. The solenoids are powered by 35 valve amplifiers,

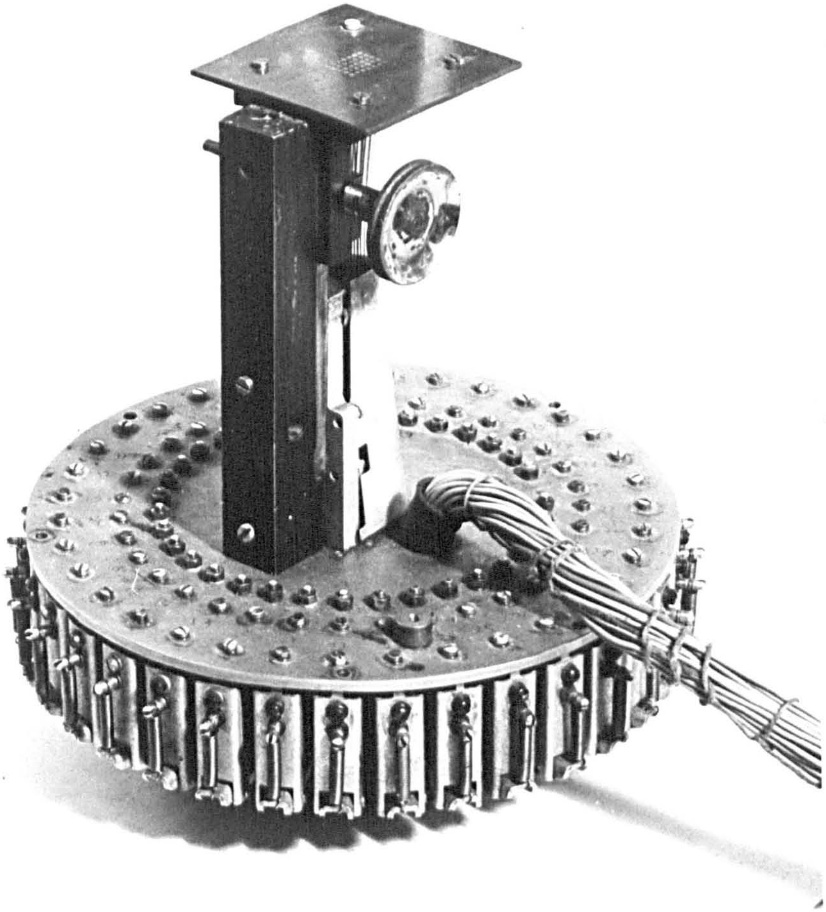


Fig. 7/ The electro-mechanical pin array. The operating solenoids are arranged in a ring at the bottom. The rods rise through the top guide plate, the height of which may be adjusted with the knob at the right.

(Fig. 8) consisting of a double-triode long-tailed pair with differential input, D.C. coupled to a pentode output stage. The circuit has been modified from its original form, which maintained holding currents of 100mA and consequently dissipations of about 10W in each solenoid, more than they can withstand for long periods. A resistor and condenser in parallel were inserted in series with each coil to provide the necessary transient 100mA, which then decays to 30mA, and a dissipation of only 1W. A speed-up capacitor was also connected across the inter-stage D.C. coupling to enhance transients, together with a neon to provide fast recovery.

Each channel has differential inputs which require about 24V swing to drive the output from cut-off to bottomed state. Normally, one set of grids is held at 5V positive to ensure that all channels are cut off. The other grids are driven positive by a 24V output from the computer to bottom the output stages and turn on the solenoids reliably.

For the purposes of specifying patterns and referring to single pins, the 35 rods have been assigned labels. Looking above the platform, with the array in the normal orientation, the columns are labelled from left to right A to E and the rows from top to bottom from 1 to 7. Thus any pin can be specified as A1, C5, D7 etc.

The electrical stimulator has been described elsewhere (10) and consists of a two-stage valve circuit with current

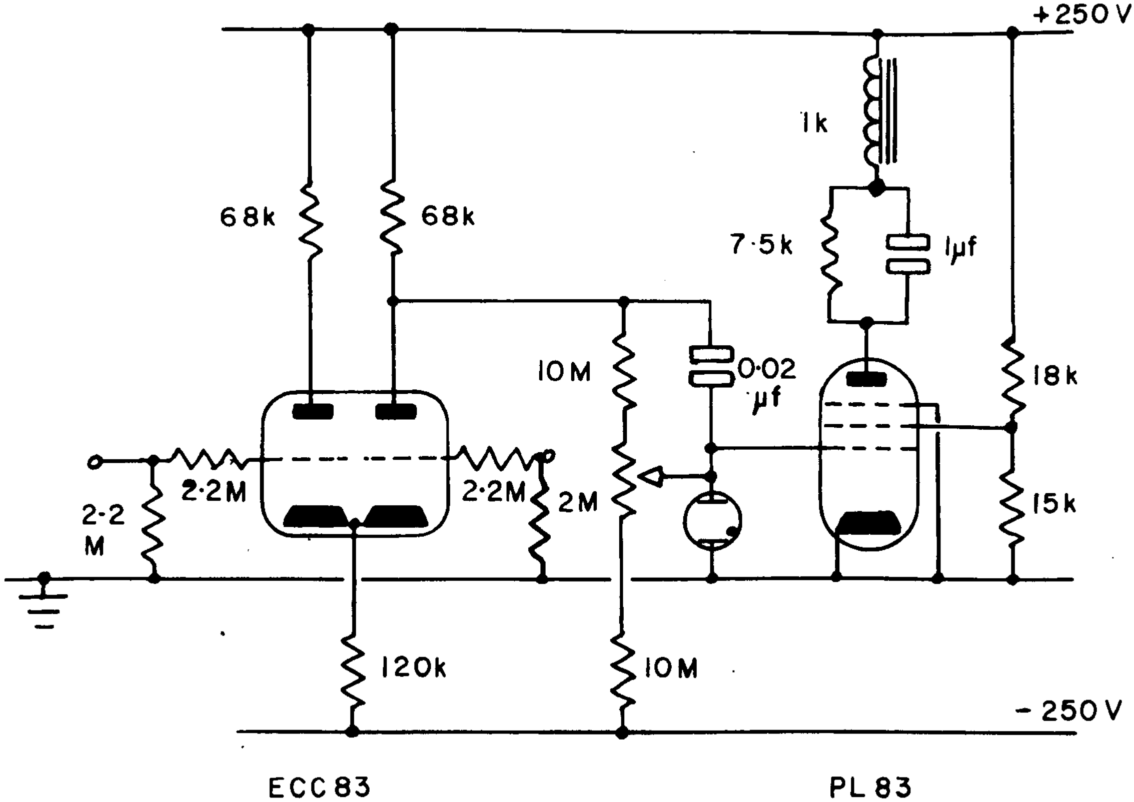


Fig. 8/ Circuit diagram of one of the driver amplifiers of the electro-mechanical stimulator.

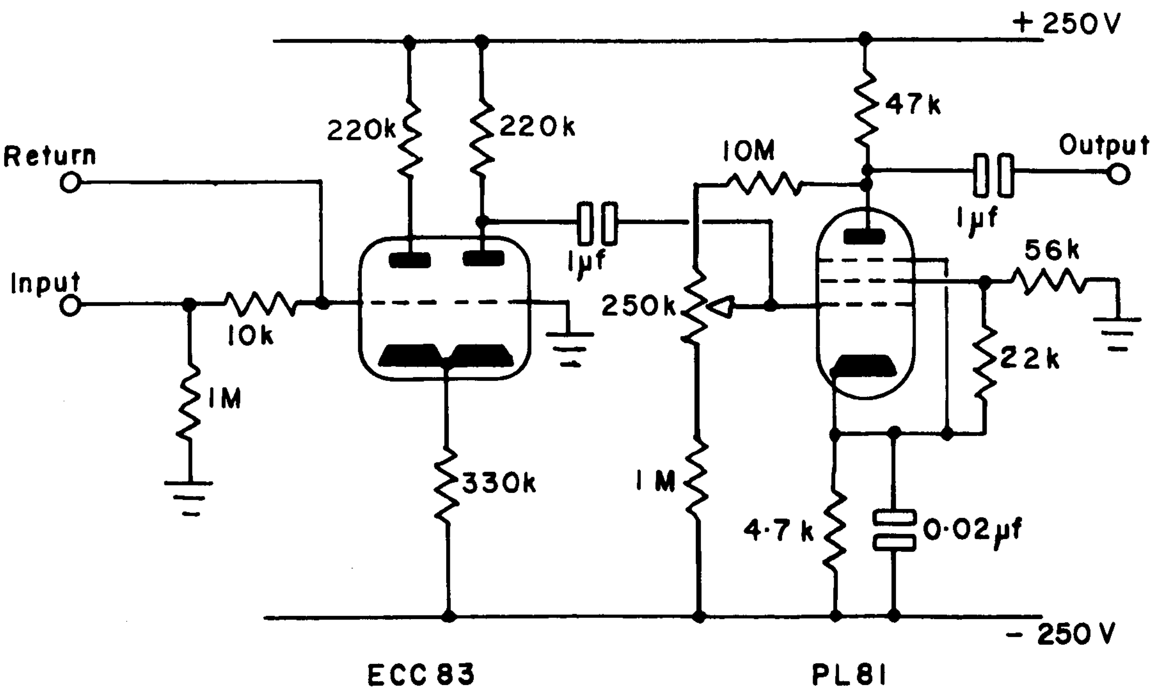


Fig. 9/ Circuit diagram of the controlled-current electrical stimulator.

feedback via the earth return (Fig. 9). It can deliver currents controlled by a voltage waveform of up to ± 5mA, with voltages up to ± 200V. The electrode used is concentric in form. A large ground plate forms the indifferent electrode The active electrode, 1mm dia. is in the centre of a hole 4mm dia. in the ground plate. The rest of the hole is filled with insulator, so that the surface of the device is flat.

The stimulators are connected to the PDP-8 computer through an output register and a multiplexer. The output register is simply a 12-bit register, loadable and clearable under program control, which can drive 12 digital lines. The multiplexer was designed to receive data from a high speed paper tape reader and thus accepts 5 bits of data from the register (plus a sixth bit, representing sprocket holes), ignoring the rest. Twelve successive 5-bit bytes are accepted from the register and are stored in a 60-bit core store in the multiplexer. On receipt of a thirteenth byte (all bits of this must be zero) the states of the 60 cores are simultaneously transferred to 60 avalanche transistors, which maintain their states while another set of data is read into the core stores. The action of the multiplexer is thus to read 12 successive 5-bit bytes and then to output the 60 individual bits simultaneously, on command.

Thirty-five of the outputs are connected to the tactile display. The minimum time in which loading can be accomplished is 2.6mS and this is the limiting rate at which patterns can be changed.

The output register has been modified to facilitate autonomic loading of the multiplexer. Two monostables and a bistable have been connected so that when the load instruction is executed, the I/O register is loaded, it waits 100 microseconds, clears itself, waits a further 100 microseconds and then switches the bistable to interrupt the computer. Another load is then loaded into the register. In this way, the thirteen bytes can be transferred in 2.6mS. All timings of the loading are thus performed automatically, enabling the central processor to perform more important functions.

Timings of the pattern display are performed by a real-time clock, which interrupts the central processor every 0.5mS. Timings are thus not dependent upon computation.

3:3 Tests of the Apparatus

The bias of the output pentode of each channel of the tactile display was adjusted with the potentiometer so that a step input would pull the solenoid on and hold it on until an off-going step. It was found that, if all the channels were turned on together, some failed to hold on, even after the adjustments had been made. This was cured by slightly reducing the bias voltage.

Tests were made of the delays involved in the operation of the solenoids. Each channel was tested individually by applying a 24V, 5mS pulse to the input. The response of the pin was monitored by placing a small metal plate on the platform of the stimulator, under pressure from a rubber band, connected in series with a battery and a large resistor earthed to the stimulator body. The voltage across the resistor was observed on an oscilloscope. When the pin rose and contacted the plate, the circuit was completed and a deflection observed. Similarly, when the pin fell, the loss of contact could be seen. Some bounce was detected on the leading edge and so the first contact was taken to be the mechanical onset. The onset delay was found to be very stable for an individual pin, and to range between 2 and 4 mS over the set of pins. The off-going delay was less reliable, but ranged between 0.5 and 3mS. There was little correlation between onset and offset delays. Durations were found to be between 2.5mS less and 0.4mS more than the applied pulse. In the succeeding experiments, where relative timings were important, the pins used were chosen to have similar onset delays and to decrease durations by less than 0.5mS.

The mechanical performance of a single pin (C3) was studied in detail. A pulse generator was used to drive the amplifier, either on from the off state, or vice versa, at about 50Hz with pulses of 2.5mS or 5.0mS duration. The prepulse from the generator was used to trigger a second pulse generator which, after a variable delay, produced a 200 micro-second pulse to fire a Strobosun strobe lamp. Thus, by setting the delay, the pin could be observed at any point in its motion, and its behaviour noted. The moment of operation of the strobe lamp was determined by observing the drive and strobe pulses on a Tektronix 525A oscilloscope, and using the delay potentiometer to determine the relative timing of the leading edge of the drive pulse and the middle of the strobe pulse. The height of the pin, expressed as a fraction of its maximum, was estimated by eye. Graphs of the pin position at various times were plotted for positive and negative pulses of 2.5mS and 5.0mS duration (Fig. 10).

It will be seen that there is a delay of commencement of motion, about 1.5mS for an on-going edge and about 2.0mS for an off-going edge, for the longer pulses. The motion lasts about 2mS when the pin is rising, and about 2.5mS when it is falling. For short pulses, the on and off edges are not independent; for the on-going pulse, full excursion is achieved but the response motion is of minimum possible duration; for the off-going pulse, the pin does not fall off fully before it is pulled on again. Thus an off-going pulse of 2.5mS duration results in a motion of only about 60% of full amplitude. Pulses

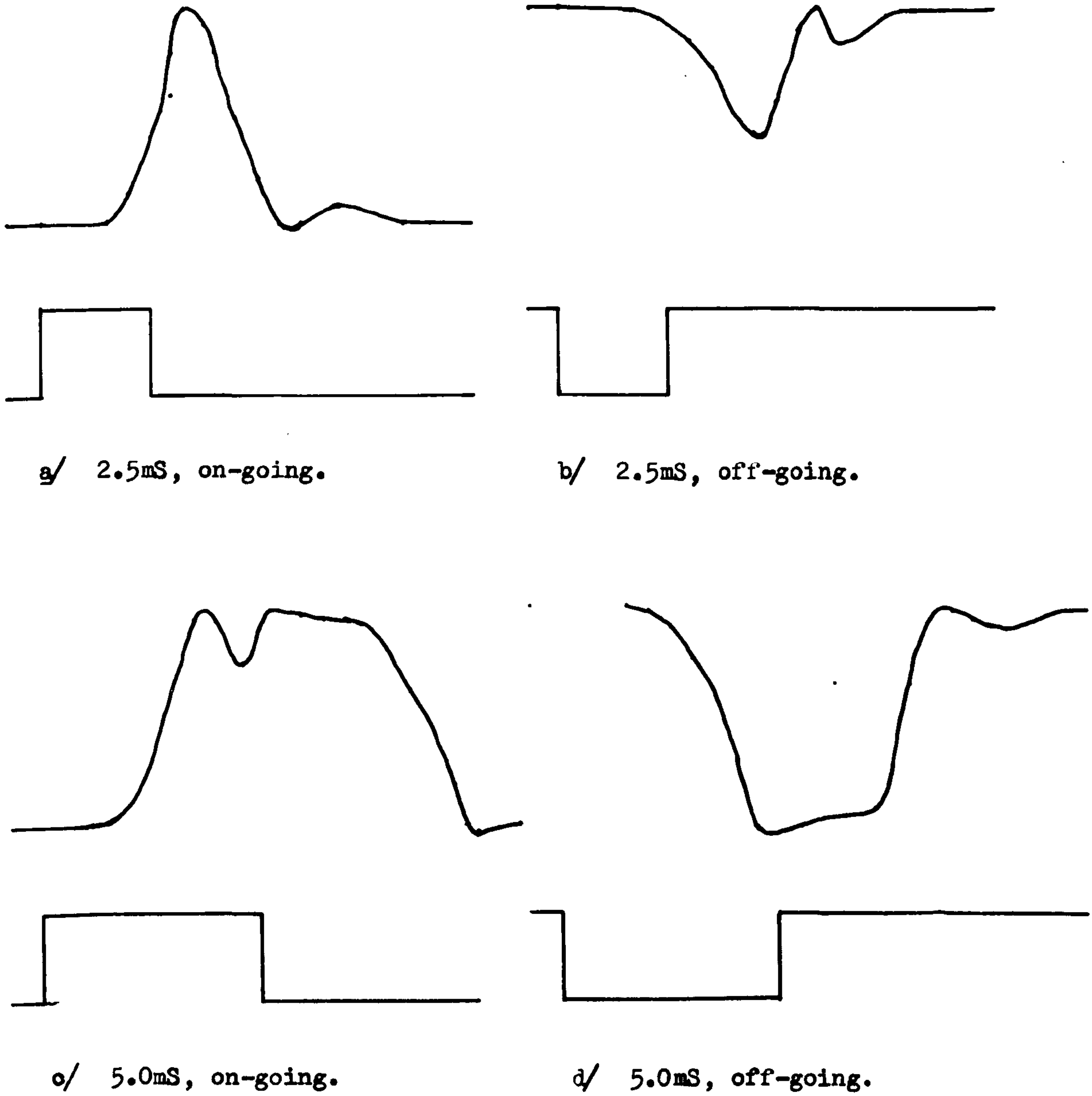


Fig. 10/ Mechanical action of pin C3 in response to an electrical pulse applied to the drive amplifier. Upper curve is the displacement of the pin, estimated by eye with stroboscopic illumination. Lower curve is the applied electrical pulse.

of 3mS or longer do reach full excursion. It is also to be noted that bouncing occurs, mainly after an on-going edge. The amplitude of bounce is about 25% of full excursion for an unloaded pin and duration is about 1.5mS. It appears to last only one cycle.

This study of the operation of a pin was taken further by applying double pulses of 2.5mS separated by 2.5mS, and 5.0mS pulses separated by 5.0mS, of both polarities. Pulses of 5.0mS duration, of both polarities are output adequately even when the pin is loaded by the application of a finger. Similarly for on-going pulse pairs of 2,5mS duration. However, when an off-going pair of 2.5mS pulses is applied, the first pulse only produces a pin excursion of about 60% while the second is of full amplitude. When the pin is loaded by a finger, the two pulses become almost a single, long pulse with a small deflection in the middle of about 30% full amplitude.

The main conclusion to be drawn from these observations is that pins cannot operate with pulses shorter than 2.5mS, and even this is cutting things rather finely. This is not a function of the electronics as it does not change when either the inter-stage coupling capacitors are removed, or the anode capacitor is changed. It is a fundamental limitation of the mechanical part of the equipment.

In order to test the timing of the real-time clock, a short program was written to compare its performance with the crystal-controlled computer clock by counting the number of computer operations which could be performed between the interrupts from the real-time clock. It was found that the clock was stable to better than 1% over long and short periods.

3:4 Description of the Program

Several investigators in the field of tactual pattern recognition have found it necessary to employ a digital computer to present patterns because of the high information transmission rate required to control a stimulator array with adequate temporal resolution. Bliss et al (30,80) have used an I.B.M. machine to present tactile patterns through a 12x8 array of airjets. Uttal (110) has also employed a computer to control a train of electrical pulses applied to the skin, and to record the subject's response. Peterson (92) has used a PDP-1 to control the display of Braille code to eight of the subject's fingers. The program that was developed for the present series of experiments, however, is capable of controlling the display of arbitrarily complex patterns and performing entire experiments unsupervised. It represents an advance in flexibility and scope.

The development of the program, given the code-name GENIE, has proceeded steadily during the course of research as experimental results demanded modifications to pursue lines of investigation arising from them.

The details of the evolution and operation of the program are described in a succeeding chapter, a brief outline only is therefore given here. A schematic diagram of the system is shown in Fig. 11.

The strategy of the research was to compare patterns in pairs and to measure confusion rates. Because a large number of patterns can be displayed, it is necessary to specify those to be used in an experiment, and even to specify which pairs are to be compared. The main function of the program is to store sequences for each individual pattern, a list of the pairs to be compared and the relative frequencies desired for those pairs.

When the experiment is in operation, the program chooses a pair of patterns, displays them to the subject in the specified presentation scheme. It then receives the subject's response, measuring his reaction time, records details of the trial on punched paper tape and proceeds to the next trial. On the tape are punched the patterns presented, the subject's reaction time and his response. At the end of a series of trials, a table of statistics is typed, if required, which shows the number of presentations and the number of errors made by the subject for each pair of patterns. The program

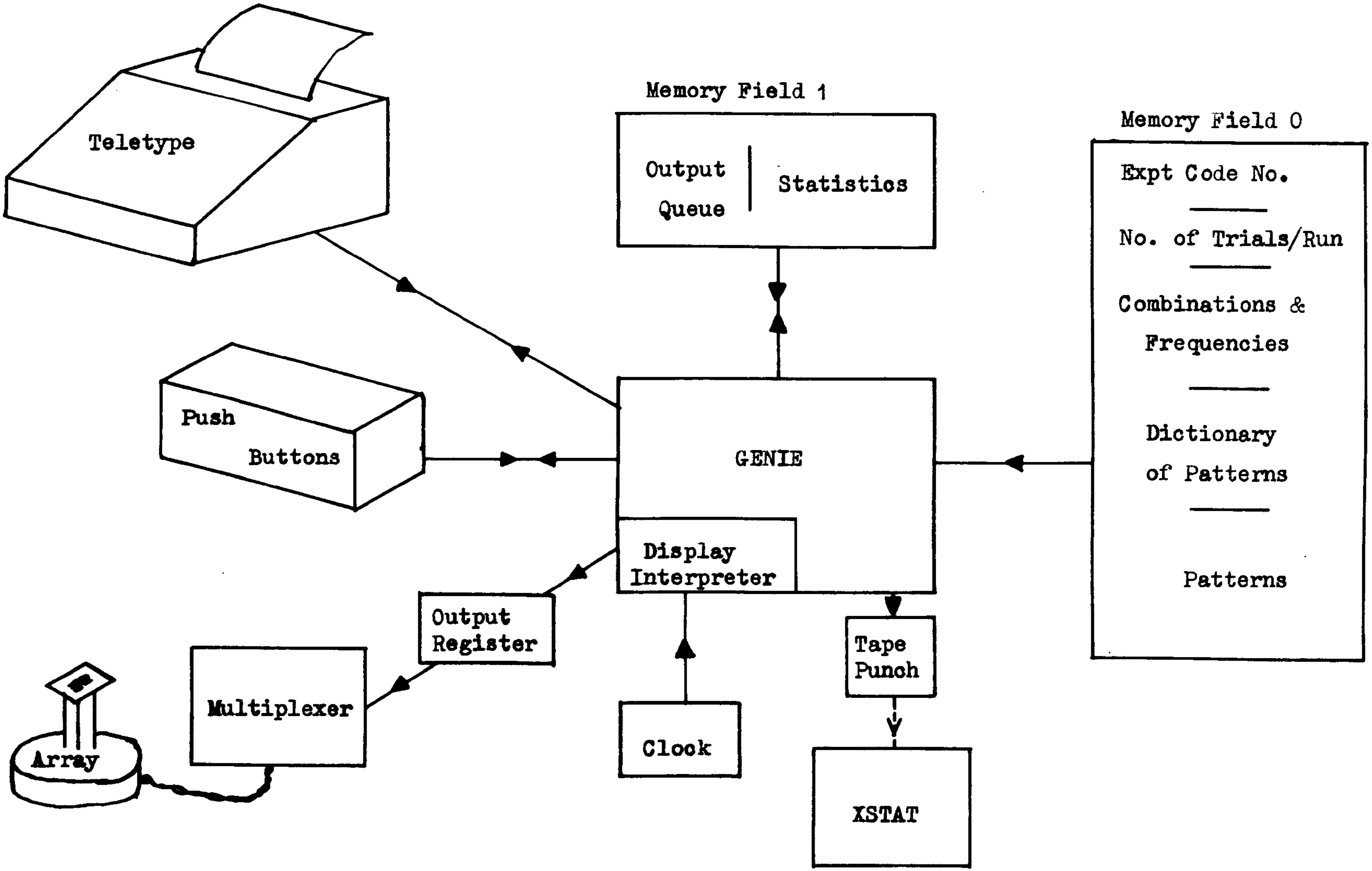


Fig. 11/ Schematic diagram of the experiment-performing system.

then prodeeds to the next sequence of trials.

A number of facilities are available, under control from the Teletype. Feedback may be provided to the subject so that he may know whether he has made an incorrect decision and which button he should have pressed. It is also possible to set the program into a teaching mode. In this case, the prescribed frequencies of occurrence of the pattern pairs are over-ridden and pairs which the subject is found to confuse are presented more often, with probabilities determined by his performance. This technique has two advantages. It enables the subject to learn to discriminate patterns in a minimum of time and also more results will be obtained for those discriminations which the subject finds difficult, economising upon experimental time.

The experiment can be run with trials presented at a fixed rate, or as fast as the subject can deal with them. The statistics printed between series may be full details of error rates for each combination of patterns, or simply total number of errors.

Two further modes of operation are usable. In the bit test mode, the pins are raised one by one in sequence to test operation of the apparatus. In the demonstration mode, the patterns may be presented singly to the subject to familiarise him with the set.

To use the program, it is called from a magnetic tape library system. A tape containing specifications of the experiment to be performed is read in. The program is then started and will proceed to perform as many trial sequences as desited.

The specification tape contains several sets of information. The code number of the experiment, the number of trials per sequence are required together with pattern data, a list of combinations of patterns to be presented and the relative number of occurrences of each combination.

The pattern data can be written in an intermediate language which permits such functions as display loops and subroutines to be executed. A tape of information written in this form is processed by an assembler program into a form which can be entered with the disphay program. Once this final data tape has been produced, it can be entered at any time and thus set up the experiment in a matter of seconds. The writing of the initial tape and the processing can be done within half an hour.

A second program, XSTAT, is used to process the record tape of an experiment. It reads the tape and will then type out for each combination of patterms the number of occurrences, the number of subject errors, the percentage error and a measure of the reliability, and the d' transformation of the error rate, the mean reaction time and the number of samples upon which it is based (very slow reactions and corrected responses are not included).

XSTAT also contains facilities for summing results over a number of tapes and over a number of pattern combinations, as well as the facility for analysing the results as a time series.

3:5 Experimental Technique

Some thought was given to the problem of presentation technique. As the computer was to be used, the presentation could be made as complicated as necessary with little added to the task of programming. The principle of the experiments was that two patterns should be presented to the subject and that he was to choose one of them on the basis of some criterion of discrimination. This end could be achieved by allowing a great deal of practice with each pair, so that the subject could recognise them and then to present them individually a number of times and require the subject to name them. This is susceptible to the effects of observer criterion, any shift of which would alter the error rates measured. There would be little stability of the results over long periods of time and comparisons of results would be difficult.

A better approach would be to present the two patterns in a random order and to require the subject to state which was which. This would avoid effects of criterion shift for the experiment is now a 2-alternative forced choice (2AFC) requiring the observer to decide only which pattern possessed 'more' of a particular property, not to assess how much of that property it contained. In such a situation the effects of learning are less marked.

However, the 2AFC presentation suffers from a major defect; the subject must be told the criteria upon which to base his judgement. The experimenter must know in advance the dimension of sensation involved and must endeavour to communicate this information to the subject. For very simple patterns such a problem should be surmountable, but for patterns of any complexity it could well prove insoluble. Varying the duration of a pulse changes the intensity of sensation as well as its duration. If a small change is made to a standard pattern of many points the changes of sensation may occur along several dimensions simultaneously.

One way of achieving the desired results would be to present the pairs of patterns many times, and to indicate the correct response each time. This would allow the subject to determine for himself the dimensions upon which to base his decisions. Once more, much training would be needed.

An improved method of experimentation which does not suffer from these disadvantages is a comparison technique, for example an ABX presentation scheme, in which two patterns, A and B, are shown as standards to define the pair under consideration. A third pattern, X, is then shown which is either A or B and the subject must decide which of the two patterns X was, or in other words, which of the patterns was shown twice. Training should now have a much smaller effect ~~in that~~ once the subject is familiar with the experimental situation and has learnt to remember A and B and to compare them with X. Only relative judgements need to be made in deciding which patterns are similar, and criterion should not enter into the situation. The alternatives bear no penalty or reward,, so they are symmetrical. The ABX presentation scheme has been employed by Bliss (30) to a limited extent.

An extra advantage of an ABX presentation scheme is that a number of different comparisons may be made during one series of trials. e.g. Patterns A and B may be compared , and so may C and D, with trials of each sort randomly mixed. The criterion for judgement is now similarity of the test pattern to the two reference patterns and not a particular property, like duration or width. Thus several measures of similarity may be compared, having been evaluated under closely similar experimental conditions. ~~E.g.~~ The effect of shift of a single point in a pattern can be determined for patterns of 1,2,3 and 4 points, or for different directions of shift in one trial series.

The ABX scheme may still involve time order errors; the presence of B between A and X may interfere with their comparison Slight improvement may be gained by presenting AXBX, with X occurring after A as well (suggested by Dr. M.M. Taylor of Defense Research Establishment, Toronto). As a final precaution, ensuring that X may be either A or B equally often and interchanging A and B as well should lead to virtual elimination of time-order errors.

i.e. In the AXBX presentation of two patterns, A and B, the four alternatives;

AA BA

AB BB

BA AA

BB AB

should be presented equally often, and the results summed over the four situations.

A simple way to treat the trial, from the subject's point of view, is to regard it as the presentation of two pairs of patterns and for him to decide which pair is more dissimilar (i.e. which pair contains the odd pattern out).

Another experimental approach is to present an ACBC scheme. C is not A or B and the subject is then required to state whether pattern C is more similar to A or to B. The facility for this technique exists, but it has not yet been employed.

It was felt that in the early stages of experimentation at least, the experimental variables would be limited to one factor as much as possible, and that the advantages of minimal training requirements meant that the AXBX scheme was to be preferred.

3:5:1 Trials of Presentation Schemes

In some of the initial experiments, other presentation schemes were tried. Some of the experiments comparing edges and pulses were performed with a 2AFC scheme; only two patterns were compared and the subject was required to identify one of them. It was found that this teqhnique was perfectly usable but suffered from the disadvantage that ~~comparing~~ measuring confusions among several patterns required a separate experiment for each pair. It was also possible for the subject to perform identifications based upon the wrong parameter of sensation, ignoring the rest. For this reason, it was decided to use an ABX or AXBX scheme.

Experiment 8, a simultaneity judgement, was performed with both ABX and AXBX schemes. No significant difference in error rates was obtained, but the subjective impression was that it was slightly easier to respond to the AXBX scheme.

On the basis of these observations, all succeeding experiments were presented with an AXBX scheme.

3:6 Analytical Technique

All the experiments described here yielded as their result the percentage of trials on which the subject made the wrong response. This error rate measure thus lies between 0% and 50%; perfect discrimination would yield no errors, hence 0%, while if the subject could detect no difference between the patterns, on the average he would score 50% errors. Should the subject score significantly above 50%, this would imply that he was capable of discriminating to some extent, but was responding incorrectly through misunderstanding, or cussedness.

As an index of performance, the error rate is monotonic and hence unambiguous, and independent of any theoretical model of the decision process, but does suffer from some disadvantages of convenience. The scale upon which error rate is measured is finite. Consequently, if error rate is plotted against some parameter of the patterns which can take a wide range of values, the region where an error rate is about 25% will have the steepest slope and probably the clearest performance. Far from this region, the curve will tend asymptotically to 0% or 50% and it will thus be unclear exactly what is occurring. What is required is an index of performance which is some transform of error rate with the following properties: It should be monotonic to avoid ambiguity and its range should not be limited, to avoid cramping at the ends.

It is possible to plot the error rates on probability paper to eliminate the problem of limited range. This method, however, tacitly assumes that error rates should follow a portion of a normal ogive. It is known that for threshold measurements of some types, the results do follow such a curve (121), but there is no sound basis for expecting it to be the case for this type of experiment also, particularly since the error rates only cover half the possible range of values. The use of such a transform would have to be made on an ad hoc basis.

Information rate, in the sense of Garner and Hake (50,6, 90), is a monotonic transform of error rate. For a given pair of patterns in an AXBX presentation, the pair which are different may be either first or second, implying an information content of 1 bit at the input. The subject has two possible responses with equal probability (ideally), hence an information content of 1 bit at the output. By comparing input and output, it is possible to determine how much of the input information is reaching the output; it will be between 0 and 1 bit. Thus, although this particular transform may in some experiments prove to be useful and informative, it still suffers from a finite range of values. It does not, therefore, comply with the second of our requirements for a suitable measure of performance.

One measure which does fulfil both requirements is the d' (D prime) measure of Tanner, Swets and Green (104,105,79) based upon signal detection theory. It assumes that the stimulus being observed is representable as a point in a space defining the state of the receiver, and that variation of some parameter of the signal causes the representative point to move along some dimension in reception space. Moreover, some noise is associated with the transmission and detection process so that a single value of the signal parameter gives rise to a probability distribution in reception space. Two values of the parameter will give rise to two overlapping probability distributions.

When two different stimuli are presented to the subject he observes two points in reception space, one from each distribution. He will then assume that the point further along the dimension in reception space came from the distribution whose mean is further along this dimension and will respond accordingly.

The probability of a correct decision can be calculated, as it is the probability that a single sample from the further distribution will be greater than one from the nearer distribution. The greater the separation between the means of the two distributions, the greater the probability that the subject will respond correctly. When the distributions are close together then the error rate will be high, rising to an average of 50% when the two distributions coincide. The d' measure is the separation of the means of the two distributions, in terms of their standard deviation. (A d' value of 3 implies that the means are 3 standard deviations apart.)

The value of d' so calculated may take any value from minus infinity to plus infinity, thus satisfying the second requirement, and varying monotonically with error rate, satisfying the first. Negative values of d' imply that the subject is able to discriminate, but is responding incorrectly.

It has been found that the d' measure obtained for a particular comparison is stable and largely independent of the experimental technique used (104). e.g. 'Yes-no' detection technique will yield the same value of d' as a 2AFC technique, although the error rates are not necessarily equal.
Such a technique-independent measure is valuable and of more general use than error rates.

The outline of the derivation of d' values given above applies to the 2AFC situation. To compute d' for an AXBX scheme is slightly more complicated as there are four samples and two response categories. No calculation for this case appears to have been made previously, details of the derivation are therefore given in the appendix, together with tables for the conversion of error rate to d'.

In performing the transformation from error rate to d' we have assumed a particular method by which the subject makes his discriminations. Were there no other grounds for employing this measure than those of changing the range of results it would be difficult to justify. However, there is ample evidence that d'is a good measure in a wide range of circumstances (79,104,105). In this particular ~~case~~ series of experiments, it was found that plotting d' values against parameter values yielded straight lines in many cases, while error rates did not, especially at extremes of the range.

Plotting d' against parameter on log-log paper has often been done as this tended to be the most informative approach in many cases.

In the course of the experiments, it has been found that transformation of error rate to d' value has simplified the appearance and interpretation of results, with no loss of information incurred. This has been taken as sufficient justification for employing it.

3:7 Reliability of Results

Having obtained a value for the error rate of the subject's decisions, some measure of the reliability of the estimate is required.

For a single comparison, it was assumed that the process behind the decisions was probabilistic. i.e. That the probability of an incorrect decision was the same for every trial and was equal to some constant, say p.

For n trials, the expected number of incorrect decisions is $n.p$, while the number of correct responses is $n(1-p) = n.q$, where $q=1-p$.

From the theory of the binomial distribution, the standard deviation of the number of errors is given by; $\sqrt{npq}$.

When p is unknown, as in this case, it should be estimated from the results;

$$p = \frac{\text{no. of errors}}{\text{total no. of trials}} \qquad \text{(The error rate.)}$$

This is the technique which has been adopted;- The value of p is estimated as above and the standard deviation is calculated from it, as in the above formula.

As a ~~rough~~ guide, for 100 trials, the expected standard deviations would be;

for 50 errors, standard deviation is 5

" 25 " " " " 4.33

To calculate the probable error in the estimate of p, the derived standard deviation should be divided by the number of trials. Thus; for 100 trials,

50 errors yield estimate of $p = 0.50 \pm 0.05$

25 " " " " $p = 0.25 \pm 0.043$

The limiting values of the probability may be transformed, exactly as the estimate itself, to give probable limits for the value of d'.

3:8 Summary

The method of experimentation was determined to be as follows;-

An on-line computer program was required to display patterns and perform experiments. A mechanical stimulator, of 35 solenoid-operated pins in a 5x7 array was to be used.

Patterns were to be compared in pairs, presented in an AXBX scheme, and the subject's error rate measured.

From the error rate, d' was to be calculated as a measure of the degree of confusion of the patterns. The reliability of the result was calculated from the theory of the binomial distribution.

CHAPTER 4

THE COMPUTER PROGRAM

4:1 Evolution of the Program

The program which runs the experiments and computes statistics has evolved steadily during the course of the research to meet the demands of experimental results.

The very first program written to try out computer control of experiments was correspondingly simple. It displayed a visual pattern in the row of 12 accumulator lights on the main panel of the PDP-8 for a fixed time, then a second pattern. The subject was required to depress one of two keys on the console, according to whether he thought the patterns were the same or different. The patterns were generated by a pseudo-random number generating subroutine.

It was soon evident that permitting random patterns to be displayed was not a good approach. The 5x7 tactile display is capable of over 10,000,000,000 different states, which can change after any time greater than 3mS any number of times. Even if static patterns only were to be considered, to assess confusion rates between all possible pairs would clearly be an impossible task. The patterns must be chosen from a well-defined subset, specified by the experimenter beforehand. The second version of the linear visual display incorporated this feature.

The interactions of space and time in tactual perceptions were of interest and so moving patterns were required to be displayed. This was achieved by storing the patterns as a sequence of numbers in the core store. The first number was the duration of the pattern in arbitrary units and the second represented the bit-state of the pattern, each bit of the word corresponding to a panel light which was to be lit if the bit were 1. The spatio-temporal pattern was therefore representable by a list of durations and shapes. The end of the list was denoted by setting the duration equal to zero. e.g.

duration
shape
duration
shape
duration
shape
0

The above would show a changing pattern of three 'frames'. The display is thus analogous to the presentation of 'moving' cinematographic films, which are in reality a series of still pictures in rapid succession. The display program has the advantage that the frames need not be shown for equal lengths of time, thereby economising on core store requirements.

A more elaborate version of the display subroutine was then written to display 35 bits instead of 12. This required three computer words for storage of the pattern shape instead of one, and the visual display was now a CRT controlled by the computer in X and Y coordinates and intensity. The program thus was now capable of displaying two dimensional moving patterns as a 5x7 array of points.

At this point, the scheme of presentation was changed from 'same/different' to an AXBX scheme. The method of choosing patterns was also modified. Instead of choosing twice from a list of individual patterns, the program now chose once from a list of pairs of patterns. Thus, instead of presenting all possible combinations of patterns in one experiment, only pairs which would yield information would occur.

At about this time, further equipment was added to the computer, the most important of which from the viewpoint of this program was a multiplexer output. This was built to drive a speech synthesiser by Dr. W. A. Ainsworth. It is supplied by the computer, through the output register, with a sequence of 12 5-bit words which are then stored in its small core store of 60 bits. On receipt of a 13th. synchronising word, the multiplexer transfers the 60 bits simultaneously to avalanche transistors which hold their state until the next synchronising word. Thirty-five of the outputs are used to drive the tactile display channels. Thus it is possible to output up to 60 bits simultaneously at variable intervals. The minimum interval is 2.6mS and is determined by the rate at which the multiplexer can accept data. There is virtually no maximum interval. The display routine was once more modified to use the multiplexer and tactile dispaly.

The program written to perform tactual experiments at this stage accepted durations stored in terms of quanta. The duration specified the number of quanta that the pattern was to last. Initially the quanta were 10mS but experiments revealed that this was too large for adequate study of temporal resolutions and the quantum was reduced to 2.5mS. The response of the subject was made by pressing a button on a box associated with the 338 visual display. The buttons could also be illuminated under computer control and were therefore used to indicate when a trial was in progress. A routine was written to record the subject's response time.

The pattern storage scheme was also modified. Instead of specifying the pair of patterns to be compared and allowing the program to decide which was to be A, B and X, the system was generalised. The three patterns had now to be specified exactly by the experimenter. This enabled comparison experiments to be performed, if desired. i.e. Three patterns A, B and C, are shown and the subject must indicate whether C is more like A or B. The disadvantage of having to specify X in AXBX experiments was outweighed by the facts that the four sequences, AABA, ABBB, BAAA and BBAB, could now be made to occur equally often and balance out time order errors more exactly. Previously, the number of occurrences of each were random.

At this point it is worthwhile to elaborate on the exact method by which patterns are chosen and displayed.

The specifications that are stored in the core store are threefold. First, the number of individual pattern combinations is specified, together with the number of individual patterns and the number of trials to be made in one series. Second, is a list of pattern triplets (ABX) together with the relative number of times that the triplet is to be chosen. Third, the patterns themselves are stored, as described above, together with a dictionary of their starting addresses, for internal use only.

The method of choosing is effectively an urn model without replacement; the hypothetical urn is filled with balls on each of which is written a pattern triplet, the number bearing a given triplet is the number specified above. Balls are chosen randomly, using the random number generator, As each is drawn, it is discarded, so that each triplet only occurs the specified number of times at each filling. When the urn is empty, if the run has not ended, it is refilled exactly as before and drawing recommences. This method ensures that each triplet can appear at any point in the series with constant a priori probability, but only occurs the specified number of times.

After a series of experiments had been run, it was found that temporal resolution should be made as fine as possible. Without too much trouble it was possible to reduce the quanta to 0.5mS, provided no frame duration was permitted to be less than 2.5mS.

At this stage, considerable improvements were made to the program, now called GENIE. The storage was increased to use the second field of the computer store for statistical results, keeping the program and patterns in field 0. A new technique was adopted for timing the patterns and the transfer of data.

The output register was modified to facilitate the loading of the multiplexer. Previously, to drive the device, the I/O register had to be loaded for 100µS then cleared for 100µS under program control. The timing of this was achieved by the central processor counting up to some number, then proceeding to the next step. This has the disadvantage that the processor is unable to perform any other task while it is timing. The fetching of the next pattern must be done when this is over and can lead to trouble if the patterns are of short duration. The register was therefore modified to time itself. On giving the load command, the register now waits the requisite 100µS, clears itself and waits a further 100µS before raising an interrupting flag to signify that it is now ready for more data. The central processor can now operate in the interrupt mode, fetching and processing data ready for transmission while the multiplexer is being loaded.

Even more efficient economies of time were made by the addition of an output queue. The background task of the program during display is to fetch the next frame and load it onto the queue, located in field 1. The I/O register interrupts this when ready for more data, whereupon the next byte is loaded and the succeeding one prepared. Data is output in 4-bit bytes, the first nine being genuine data and the next three dummy bytes, followed by the synchronising word.

While a frame is in progress, the timing is performed by the computer real-time clock, which interrupts every 0.5mS. When a clock interrupt occurs it is counted and when time has expired the next frame is output.

The storage of patterns was extended to enable commands to be inserted in the data sequence. Commands such as DO, which repeats a spatio-temporal sequence a specified number of times, PSHJMP, DJMP and POPJMP, which allow transfers of control, can be used and hence programming of loops and subroutines is possible. The queue-packing routine accepts these commands and constructs a linear queue of frames from which an unpacker can output in a straightforward manner. The interpreting routine performs its translations during odd snatches of available time, while the unpacker operates whenever it is called upon.

When the subject has responded, the program punches out a paper tape protocol, recording at each trial the three patterns displayed and which response is correct, together with the subject's response (one of six buttons) and his response time. A rubout character is punched between trials to delimit data.

At the end of the series of trials, statistics can be typed out if desired. GENIE can list the three patterns, the number of times they occurred and the number of errors made, as well as total trials and total errors. Error rates were chosen for typeout as it is easier to interpret the table when the error rate is low, dots being typed instead of zeroes to improve legibility.

4:2 Current Version of the Program

The heart of the current version of GENIE is the display routine. It consists of two parts, an output handling routine and an interpreting routine. The interpreter is an on-line assembler, in effect, for it reads the display file, obeying instructions in the file and extracting data and putting it on a linear queue in a simplified form. The output handling routine takes data from the queue and operates the display to provide the specified spatio-temporal patterns.

The form in which the data is stored in the queue is a list of pattern durations and shapes; one word denotes the duration of the frame in 0.5mS quanta, three successive words specify the state of the 35 pins of the array.

e.g.

Duration

State 1

State 2

State 3

Duration

State 1

.....

.....

State 3

0

Zero signifies the end of the queue and is the cue for exit from the display routine.

The file that is read by the interpreting routine is similar in form when a section of data is encountered. Zero in this case, however, does not mean a complete termination, but that succeeding words are to be taken as commands.

Commands that are currently in use are;-

INSTRN Enter control mode from data mode.

DATA	Enter data mode after this instruction. (Can be microprogrammed with other commands.)
DJMP	Jump to address contained in next word.
PSHJMP	Jump to address contained in next word and store current address on push-down stack for return from subroutine.
POPJMP	Return to top address on push-down stack and pop the stack.
POP	Pop the push-down stack. (To return through two levels of subroutining at next POPJMP.)
DO n	Do the following section n times.
END	End of section to be repeated.
FINISH	End of display sequence.

Other instructions are available for initialising the display file interpreter and for executing machine code under interpreter supervision.

The points of the array are given labels corresponding to their position. The columns are labelled A to E and the rows 1 to 7. Points are thus, A5, C7, E1 etc.

As an example of the method of use, a simple program is shown below. The sequence to be displayed is a pause for 1 second, presenting blank field to the fingerpad, then pin C4 is moved up and down seven times at 100 cycles per second.

The symbolic form of the display program is as follows;-

```
START,  INSTRN          /Instructions follow
        PSHJMP DATA     /Enter subroutine, change to data mode
        BLANK           /Name of subroutine
BUZZ,   DO 7 DATA       /Do the following 7 times, data mode
        10              /Duration 5mS
        0;C4;0          /Raise C4 only
        10              /Duration 5mS
        0;0;0           /Lower all pins
        INSTRN          /Instruction follows
        END; BUZZ       /End of DO loop
        FINISH          /End of display sequence
        .....
        .....
BLANK,  2000            /Subroutine: 1 second
        0;0;0           / of blank pattern
        INSTRN
        POPJMP          /Return from subroutine.
```

This alphanumeric form of the display program is punched onto paper tape, which is then processed by the MACRO-8 assembler into a binary code tape. The binary tape can then be read into the computer with the display operating program.

In the queued form, produced by the display interpreter, the sample program would be represented by;-

2000	(1 second of blank field.)
0;0;0	
10	
0;c4;0	(i.e. the code for pin C4)
10	
0;0;0	
10	
0;c4;0	
10	
0;0;0	
.....	(7 occurrences in all)
.....	
10	
0;0;0	
0	(End of sequence)

It will be noted that the use of an intermediate level language to program the tactile display reduces the amount of source program and eases the writing of experiment specifications.

In normal use, the main display file consists of a set of pushjumps to the subroutines for the patterns, A, B and X. The routine which chooses the patterns fills in the names in the

the main file and the patterns are written as subroutines.

4:3 Experiment Running Routines

Before an experiment is run a specification tape is read into core to provide the necessary data. This includes an identifying code number, which is punched on the protocol tape and on the record sheet on every series of trials, and the number of trials per series. The patterns must be provided in subroutine form, together with a dictionary of their starting addresses. The information required by the choosing routine consists of the number of pattern combinations, the combinations themselves (A, B and X) and the relative frequency of each combination.

On starting, or having just completed a series of trials, the program waits for information to be entered on the Teletype. For the purpose of typing headings and making notes, anything may be typed onto the record sheet and will be ignored by GENIE until the Alternate Mode key is struck. The program then types carriage return-line feed and a left square bracket and awaits an instruction.

Instructions are of two sorts; those which set up various facilities and those which initiate action. The former are used to turn on and off the facilities for feedback of performance to the subject, the facility for adaptive teaching of the pattern combinations. The printout can be set to a full form with details of performance with each pattern combination, or just total errors. The time between trials can be set to be constant, allowing about three seconds for the subject's response, or the next trial can be set to occur as soon as the subject has responded to the last one.

The second type of instruction sets the program ready to execute; the signal to begin is a space, after which a right square bracket and carriage return-line feed are typed by GENIE and the specified operation begins. There are four such commands; Start, Continue, Display and Bit test (given by typing the initial letter S, C, D or B).

When Start is given, the switch register is read by GENIE, the number to which it is set is taken to be the trial series at which it is desired to start. The program therefore simulates the choosing of patterns during all the previous series to initialise the random number generator. Thus the sequence of trials, choices and presentations for any given series, say the 12th., will be the same whether it is reached by working through the previous (11) series, of perhaps 100 trials each, or by the simulation method. Subjects can thus be asked to respond to identical trial series, if desired.

The Continue command is used between trial series to proceed to the next series, without reinitialisation.

Provided that D or B command has not been given since the last series ended, the C may be omitted and the next series begun by simply typing a space.

D is used to demonstrate individual patterns. The switch register is read and the pattern whose ~~entry~~ position in the pattern dictionary corresponds to that number is executed. Changing the number to which the register is set changes the pattern which is displayed. The most significant bit of the switch register is used to control the display. If it is down the register is read and the appropriate pattern is executed repetitively. If it is up, the program halts after displaying the pattern once. Pushing the Continue switch causes the pattern to be displayed once more.

Bit test command causes each pin of the display to be raised in turn for 200mS, as if scanning a raster, until the most significant bit of the switch register is raised, whereupon GENIE returns to the initial copying mode.

4:4 Operation During an Experiment

To perform an experiment, GENIE is loaded into core and the specification tape is read on top. The program is then started, a heading is typed if required, and the control mode is entered by typing Alternate Mode. The desired state setting commands are typed, followed by "S space" . Leader tape is then punched by the program and the experiment code number and run number.

The first pattern combination is chosen and the display file is set to execute the appropriate patterns. A row of lights on the push button box is illuminated to indicate a presentation in progress. The patterns are then displayed, usually in AXBX scheme, and the lights go off. The subject must then make his response, pressing one of two buttons according to his decision.

GENIE measures his reaction time and accepts his response The subject is at liberty to change his mind during a wait period of about 3 seconds, At the end of this period, the three patterns in the combination, his response and reaction time are punched onto the tape. Statistics of the trial are recorded, the number of occurrences of each combination and the number of errors made by the subject, The program then prodeeds to the next trial.

At the end of the specified number of trials, the statistics gathered are printed on the teletype. Each combination of patterns, the frequency of occurence and the number of erroneous responses are printed, together with total number of trials and total number of errors (Fig. 12). The program then waits in the copying mode.

At any stage during the series the subject may press a

8/3/68; #1
HGB; 1STBRH; 2X2MM; 0.5MS; AXBX; GENIE2; NOISE
2PT COMPARISON-VARN W EXPOSURE
2:46
[GUS]

EXPT CODE; 54
RUN NO. ; 24

STATISTICS:

PAT1	PAT2	PATX	FREQ	ERRS
1	2	1	10	.
2	1	1	10	.
1	2	2	10	.
2	1	2	10	1
3	4	3	10	.
4	3	3	10	.
3	4	4	10	2
4	3	4	10	.
5	6	5	10	.
6	5	5	10	.
5	6	6	10	1
6	5	6	10	.
TOTALS			120	4

3:08
[ ]

EXPT CODE; 54
RUN NO. ; 25

STATISTICS:

PAT1	PAT2	PATX	FREQ	ERRS
1	2	1	10	1
2	1	1	10	2
1	2	2	10	.
2	1	2	10	1
3	4	3	10	1
4	3	3	10	1
3	4	4	10	3
4	3	4	10	2
5	6	5	10	.
6	5	5	10	2
5	6	6	10	3
6	5	6	10	2
TOTALS			120	18

Fig. 12/ Example of intermediate results printed by GENIE.

button marked 'Interrupt' which will cause the program to pause after the current trial until the button is pressed once more.

If the most significant bit of the switch register is raised, the current series is terminated after the current trial. An experiment can thus be ended in the middle without loss of data.

The protocol tape produced during an experiment consists of several stretches of data separated by leader code between trial series. Each series is preceded by the experiment code number and the run number. It is terminated by a check sum as a precaution against errors in punching or reading. The trials are separated by a rubout character (all eight holes punched) and for each trial, the pattern numbers of A, B and X are recorded, followed by the subject's response time in 10mS units and his response. (Fig. 13).

A second program, XSTAT, is run off-line to process the information on the protocol tape. XSTAT reads any number of tapes and computes statistics based upon the total set of trials. It types out a table similar to that of GENIE, but containing more information. The table consists of the three patterns of the combination, number of presentations, number of incorrect responses, percentage of incorrect responses (error rate), the standard deviation of the number of errors, d'

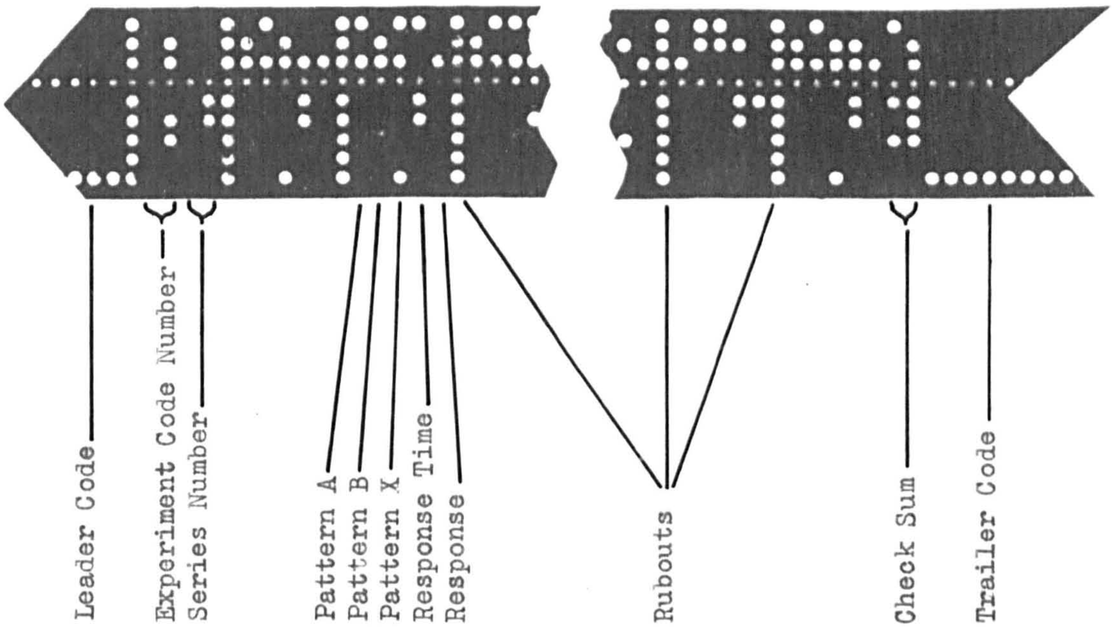


Fig. 13/ Example of protocol tape punched by GENIE.

XSTAT
RESULTS OF 8/3/68; #!
HGB; 1ST RH; 2X2MM; 0.5MS; AXBX; GENIE2; NOISE
EXPT 54; VARN OF 2PT THRESHOLD WITH EXPOSURE

PAT 1 FREQ	PAT 2 ERRORS	PAT X % ERRS	STD DEV	DPRIME	AV RT	NRT
+5	+6	+0				
+120	+15	+12	+4	+166	+50	+118
+3	+4	+0				
+120	+13	+11	+4	+174	+61	+119
+1	+2	+0				
+120	+8	+7	+3	+208	+70	+120
TOTALS						
+360	+36	+10	+6	+181	+60	+357

Fig. 14/ Example of analysis of results produced by XSTAT.

values corresponding to the error rate, average reaction time and the number of samples upon which the average is based (very long times and double responses are ignored). At the end of the table values of these statistics, computed over the entire set of data are typed. (Fig. 14).

Certain simplifications can be made to the full table, e.g statistics can be computed for pairs of patterns, A and B, independent of the actual order of presentation. It is also possible to analyse data in terms of time, giving statistics of the errors occurring in the first ten trials of the series, the second ten, and so on, averaged over all series.

4:5 Summary

The main program, GENIE, displays patterns and performs psychophysical experiments. It presents patterns to the subject and accepts his responses, punching out a paper tape of protocol. A second program is employed to make detailed analyses of the results.

CHAPTER 5

THE EXPERIMENTS

5:1:1 Experimental procedure

The subject was seated in a chair at the console of the PDP-8 computer with his elbows resting upon tall padded stools of suitable height (Fig. 15). His right index finger rested lightly upon the platform of the stimulator array, which was level with the console table. His left index finger rested between two buttons of the push-button box. The neon indicator array was hidden outside his field of view. To counter auditory cues that the subject might have gained from the solenoids, he wore a pair of Sharpe HA-10 earphones, which provide good sound isolation, and random noise was played through them at sufficient volume to mask the sound of pin motions. The continuous noise of the high speed punch also assisted in masking.

The subject, if new to the experimental situation, was informed briefly of the presentation scheme and was told to press a left-hand button if he felt the first pair of patterns to be the more dissimilar, or to press a right-hand button if he felt the second pair to be the more dissimilar. He was at liberty to change his mind, but subjects seldom did so.

The set of patterns was then demonstrated to him, each being presented several times. The subject was not instructed to attend to a particular aspect of the stimuli to perform discriminations, but was required to observe the difference for

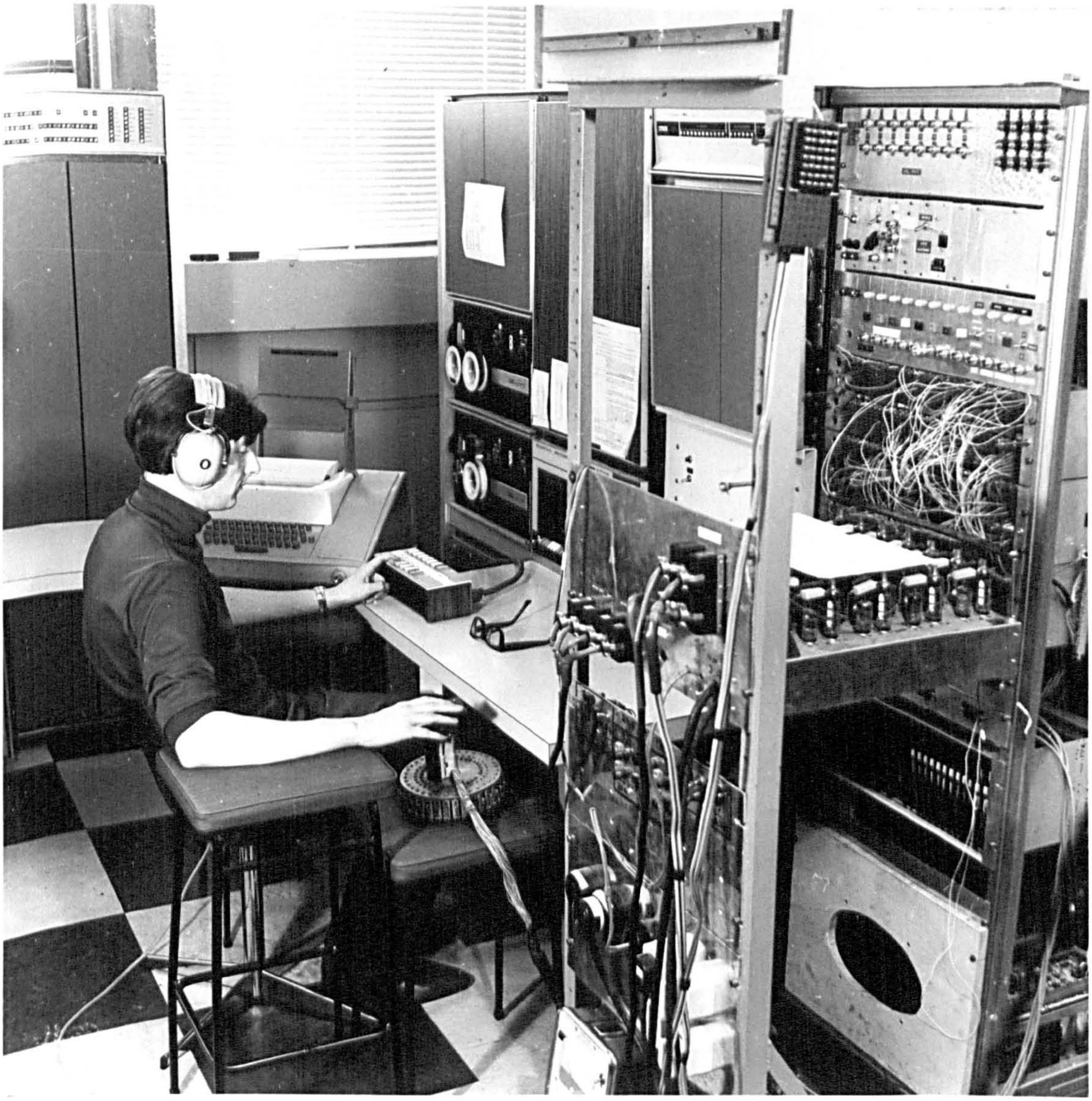


Fig. 15/ The apparatus and subject HGB during an experiment. The stimulator is under his right hand, the response buttons under his left. The rack in the foreground carries the drive amplifiers for the pin array. Hung from the top right hand corner is the neon indicator array. The rack at the extreme right carries the clock, the input/output register and the multiplexer.

himself. When the experimenter was also the subject he endeavoured to adhere to this principle. e.g. When discriminating durations the sensation differences are largely of intensity; judgements were therefore based largely upon apparent intensity and not apparent duration. The subject was also instructed not to be too concerned about difficult discriminations, but to make a good guess in order to encourage a relaxed judgement.

Finger position was not strictly contpolled; a small wall was constructed of plasticene around the array to constrain the finger, but slight changes of position were permitted. No control of finger pressure was made, other than instructing the subject to maintain a light pressure and to avoid undue force.

A series of trials was then presented to the subject, using feedback of errors to familiarise him with the experimental situation and the pattern combinations.

When a trial is about to commence, the subject is warned by a row of lights on the button box being illuminated. One second later the first pattern, A, is shown, then there is a gap of 0.5 seconds of blank field before X, a pause of 1 second, then B, another pause of 0.5 seconds and finally the second presentation of X. The lights go off and timing of the subject's response begins. The wait of 1 second before the patterns begin prepares the subject. The interval between the pairs is slightly longer than that between patterns of a pair to split the sequence into two sections. These times were found to be a reasonable compromise between speed and interaction of the patterns.

About thirty to fifty trials were presented and then the demonstration series was terminated. The results were shown to the subject but were not included in the analysis.

The feedback was then turned off and the system was set ready for a trial series. The subject pressed the space bar on the teletype to commence when he wished. In experiments when the experimenter was not also the subject, he left the room when the run was in progress, but observed through a window in the door in order not to perturb the subject by his presence. At the end of the series he reentered the room to check on performance and to instruct the subject to press Alternate Mode and the space bar to continue with the next series.

After the second series, the subject was allowed to continue with succeeding series by himself, but was observed from time to time through the window. He could read his error scores as they were typed out and this assisted in maintaining motivation. The experimenter entered between series occasionally to check that the experiment was proceeding smoothly.

After the second trial, subjects were often content to perform for about an hour at one session. The series were set in length to occupy about ten minutes. This appeared to be optimal for obtaining results without fatigue. One row of lights on the computer was set to display the number of trials left in the present series. This served to allay boredom, particularly towards the end of a series. However, most of the subjects said that they had enjoyed participating.

5:1:2 Subjective Observations

After some practice at the discrimination task, responding to the stimuli became automatic to such an extent that the subject would perform subconsciously. No change in error rates was observed when this occurred. On the other hand, overt efforts to concentrate upon the stimuli and to be certain about correct discriminations did not improve performance. It was thought, therefore, that automatic responding was not to be discouraged, as it might produce results less affected by extraneous events.

One fact that soon became apparent is that the subject's opinion of his performance does not predict his error rate. On many occasions when he thought that he had performed badly, the error rate was not significantly different from that for an average run of trials. Such independence of the observer's state of mind is a desired feature for the experimental results and is good vindication of the technique used.

The sensation elicited by a particular pattern was found to be maximal for light pressure. Sufficient pressure was required to ensure complete contact with the top plate of the stimulator array, but any increase caused a reduction in sensation. This observation does not agree entirely with Verillo's findings (111) that threshold falls steadily for increasing pressure.

In general, series were limited to about ten minutes duration. It was found that if they were extended beyond about fifteen minutes the fingerpad could become numbed. Ten minutes, which represents about a hundred trials, was also a convenient duration to avoid severe boredom.

Some evidence of a successive adaptation effect was observed during the course of a trial. The first stimulus almost invariably seemed to be the strongest, and the last the weakest. In order of subjective intensity the patterns would be rated A, B, X1, X2. It appears that sensation of the second pattern of a pair is inhibited by the first pattern 0.5 seconds before it, while the gap of 1 second between the pairs allows some recovery. The time constant involved must therefore be of the order of 0.5 second.

This successive interaction of sensations was not excessively great, but when making judgements based largely upon intensity it had to be taken into account by the subject.

The sensation elicited by a long pulse also seemed to adapt with a time constant of about 0.5 seconds. The leading edge of the pulse evoked a sensation which increased sharply and then decayed to almost nothing in the space of one second. The trailing edge then evoked a similar sensation, but of lower ~~ampli~~ intensity and slower onset.

For short durations, the intensity of sensation appeared to increase with duration. It also appeared to increase with spatial extent of the pattern. There thus seems to be some support for Uttal's hypothesis that sensation intensity is a function of the total number of neural impulses evoked by a stimulus (108).

5:1:3 General Quantitative Observations

As a check upon the techniques used and the performance of the subject, some of the experimental results were analysed in several ways.

Experiment 27 was chosen for the analysis because this experiment consisted of 50 series of 110 trials each, spread over a period of five days, and was thus the most extensive experiment carried out with a single set of patterns.

Experiment 27 involved comparison of durations; one pin, C3, was raised by a single pulse of variable duration. A duration of 15mS was used as a standard and was compared with each of 55 other durations, from 2.5mS to 30mS. In a single series of trials, each comparison was made twice, and over the whole experiment, the nth trial of a series should have been each comparison slightly less than once, on the average.

The results were initially analysed in terms of the presentation and the subject's response, summing over all the comparisons. The details of this analysis are recorded in Table I below.

Table I

Pattern X =	Correct Response	Errors	Correct	Left	Right	Total
A	Left	814	1936	1936	814	2750
B	Right	979	1771	979	1771	2750
Totals		1793	3707	2915	2585	5500
% of Grand Total		33%	67%	53%	47%	

It will first be noted that 67% of responses were correct and 33% were in error. If the subject had ignored the stimuli, these figures would each have been 50%(± 0.7%)

Of the total number of responses, 53% were pressing the left-hand button, and 47% the right-hand button. Had the subject either responded randomly, or had responded correctly every time, these figures would also have been 50% (± 0.7%). The fact that they differ significantly from this value demonstrates an inherent bias; the subject prefers to press the left button with his left hand.

A short experiment was performed to try and determine the innate preference of the subject. Under the conditions of the experiments, the subject was required to press left and right buttons as randomly as possible. No tactile stimuli were presented. Of 2000 pressings, several per second, 49% were left and 51% right. This difference is not statistically significantly different from the chance level of 50%. It would thus appear that the bias may be due to the presentation.

Whether the bias is simply innate in the mechanical activity, or whether it is caused by the subjective sensation produced by the AXBX presentation is uncertain, but it is not sufficiently great to present a problem. The randomisation of presentations should almost eliminate any effect upon the error rates.

An analysis of the results of experiment 27 was also made in terms of the time sequence. Two forms of analysis are possible; summing over the series to determine the variation of performance during a series of trials, or summing over trials for each series to determine the variation over a long time.

The variation through the series was measured by grouping the results in 11 blocks of 10 trials, then summing over the 50 series to obtain average scores for each block. Thus the number of trials upon which the scores are based is 500.

This average through the run represents performance over a period of about 11 minutes. From the graph (Fig. 16) it will be seen that there is no trend, showing no overall learning or fatigue during a run. The graph possesses fluctuations with a period of about 5 minutes. However, the maximum deviation of a point from the mean is approximately 3 standard deviations, and so the fluctuations may be only statistical. Reaction time shows little variation, apart from a slight rise over the first minute and some small fluctuations towards the end of the run.

The net conclusion is that during a run, performance remains reasonably stable, and error rate is constant within the limits of experimental error.

Analysis over the series does not indicate much from the plot of results series by series (Fig. 17); the points all lie within ±3 standard deviations of the grand mean. If the runs are treated as a continuous sequence (which they are not quite) and they are grouped in sets of five, the situation becomes slightly clearer. The curve shows no steady trend,

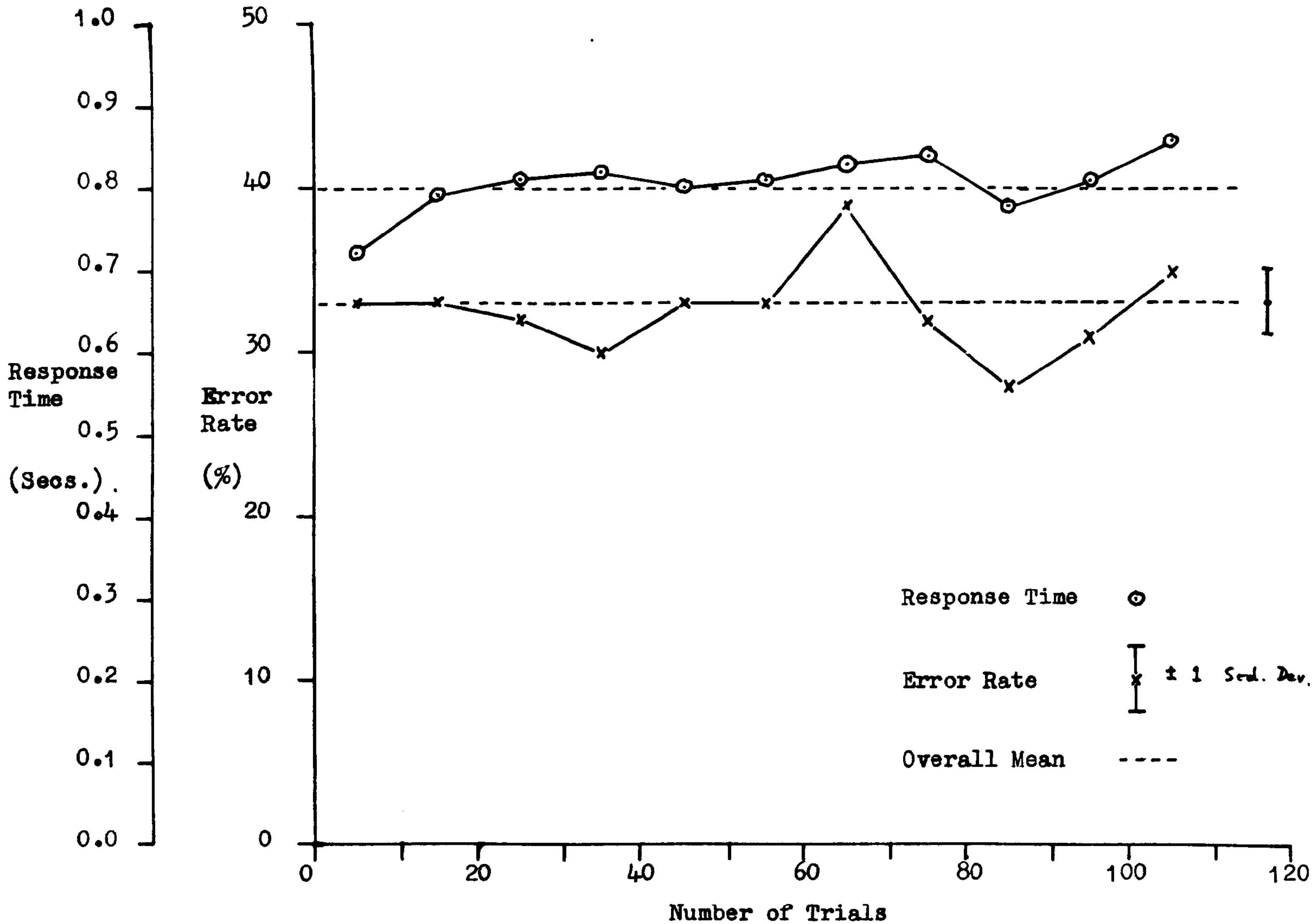


Fig. 16/ Expt. 27: Variation of average error rate and average response time during a run of 110 trials.

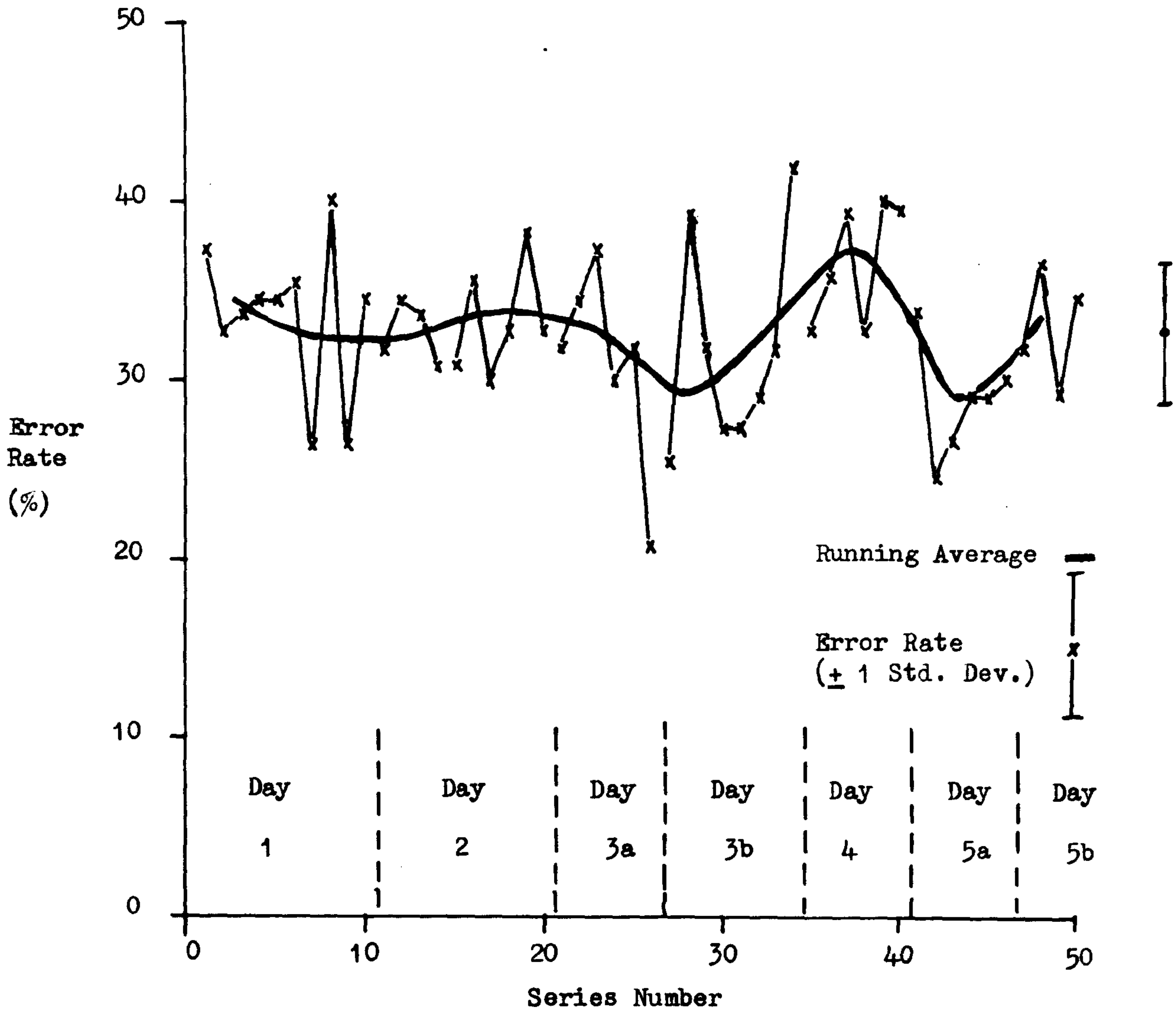


Fig. 17/ Expt. 27: Variation of average error rate over a period of several days.

but does possess fluctuations which may be increasing in amplitude with time. As each grouped point is based on 500 trials, the fluctuations are probably not statistical.

It is therefore to be concluded that over a long period of time (5 days) there is no steady change in performance, It is possible that there may be fluctuations which are less than the expected experimental error for an average over 100 trials.

It was concluded from these analyses that the conditions of experimentation were satisfactory, and that the technique of presentation and analysis yielded sufficiently stable measures of performance.

5:2 The Effect of Transients

5:2:1 Introduction

It is well-known that sensations upon the skin adapt out, particularly if the stimulus is static. One is usually unaware of the presence of one's wrist-watch and often can only be sure that it has been left off by looking at the wrist. As described in Chapter 2, there occurs mechanical adaptation of the tissue and adaptation of the receptors with various time courses.

Von Frey (32) reported that pulling a bristle glued to the skin produced sensations similar to those of pressing it.

In view of these facts, three hypotheses seemed likely;-

a/ Adaptation might be so great that after a pattern had been applied to the skin and had remained static for about half a second it would effectively 'disappear' in a manner similar to that of stabilised retinal images.

b/ Transients might feel similar, independent of direction of motion of the skin surface (pressure or release); on and off edges might feel qualitatively similar, if quantitatively different.

c/ Transients might feel similar to brief pulses; a brief pulse and an edge may be difficult to distinguish.

If any or all of these hypotheses were found to be valid, the study of pattern recognition would be simplified to some extent. In particular, b/ would imply that patterns and their inverses (up and down states reversed) would produce similar results, while c/ would imply that only changes of pin position would be important. Thus it might be possible to simplify the set of patterns to be investigated.

5:2:2 Initial Experiment

The first experiment, number 12, endeavoured to test the three hypotheses simultaneously. It was a direct comparison of a long pulse of 1 second duration with a pair of brief pulses, of 2.5, 7.5, 25 or 75mS duration, the leading edges of which were 1 second apart. The temporal patterns were applied to a single pin, C3, and an AXBX technique was used. The results are recorded below in Table II.

Table II

Pulse Duration	No. of Trials	No. of Errors	Value of d'	d' at ±1 S.D.
2.5 mS	40	3	3.4	2.9-4.4
7.5 mS	40	4	3.1	4.0-2.5
25.0 mS	40	0	>4.8	
75.0 mS	40	0	>4.8	

No errors occurred for the two longer durations; the four edges of the double pulses were obvious to the subject. Discrimination was only slightly worse for the two shorter durations.

Amplitude of sensation also seemed to provide information. Sensation for the brief pulses appeared less than that for the edges. The two edges of the long pulse aroused similar sensations which seemed to differ only in amplitude.

This preliminary experiment indicated that further study should be made of the components of the pulse; i.e. to compare on and off states, on-going and off-going edges and to compare a pulse with a single edge. Some idea of the relative amounts of information in steady and transient states would thus be obtained.

5:2:3 Further Experiments

The patterns presented in the following experiments were intended to be a single steady state or a single edge. It was necessary to eliminate all other information in the form of transients or the second edge. This was achieved by vibrating the test pin through 9½ or 10 cycles of operation at 100Hz, at the beginning and end of the pattern. The subject would thus be aware of the buzzing sensation but would not know whether there had been a net change of state.

The technique employed in this set of experiments was not the AXBX presentation, later used in all succeeding experiments. It was thought that the subject would already know what on and off states felt like and only two patterns were to be compared. A single pattern only was therefore presented and the subject was required to identify it. This would speed the course of the experiments. From the hit and false alarm rates, the value of d' was computed in the standard manner.

The ability of the subject to distinguish steady states was determined in experiment 15. The patterns consisted of the masking buzz, then 0.8 seconds of steady up or down state and finally a second buzz. The subject was required to respond 'up' or 'down'. Of 200 trials, 37 errors occurred; 84 of 100 presentations were correctly identified, 21 presentations of 'down' state were incorrectly identified. Applying standard signal detection theory, this corresponds to a value of d' of 1.8 as a measure of the discriminability of the steady states.

It is to be noted that had the subject been permitted to move his finger, very few errors would have occurred. As it is, slight tremor and pulsation may have assisted the discrimination.

The distinguishability of transients was studied in a similar manner (experiment 13). The patterns this time consisted of a masking buzz, then 0.4 seconds of one state, the on- or off-edge, a further 0.4 seconds of the other state and finally the second buzz. The subject this time endeavoured to determine whether the transient was off-going or on-going.

Of 100 trials, only 3 errors occurred; 48 of 50 presentations of 'on-going' were correctly identified, 1 of 50 'off-going' was incorrectly identified. This corresponds to a d' value of 3.8 .

It appears that the subject can discriminate between directions of pin motion better than he can between pin states (up or down). This may be due to two factors. Firstly, the amplitude of sensation is greater for an on-going transient than for an off-going: Possibly, the slow recovery of the tissue produces less sensation than the rapid motion of the forced displacement. Secondly, the steady states are still in evidence and are still contributing to the discrimination; the transient adds further information.

To investigate further the hypothesis that an edge may feel like a pulse, four further experiments were conducted, comparing off-going and on-going edges with pulses.

Experiment 14 compared an on-going edge with an on-going pulse in a similar manner to the above; masking buzzes were presented before and after the 0.8 sec. interval containing the pattern. Three durations of pulse were used, 2.5, 7.5, and 25mS, and once more an identification technique was used.

Table III

Pulse Duration	Trials	Errors	d'	d' at ±1 S.D.
2.5mS	100	13	2.8	2.4-3.1
7.5mS	100	7	3.4	3.1-4.1
25.0mS	100	3	4.6	>4.0

It will be noted that the on-pulse is readily distinguished from the on-edge, but shorter pulses less so than longer ones.

In experiment 16, an off-edge was compared with a 2.5mS on-pulse. In 100 trials no errors occurred. It thus seems clear that confusion of these patterns is very low.

A further experiment, number 17, was conducted to compare off-going edges with off-going pulses of various durations.

Table IV

Pulse Duration	Trials	Errors	d'	d' at ±1 S.D.
2.5mS	200	118	-0.46	-0.25to-0.65
5.0mS	100	6	3.3	3.7-2.9
7.5mS	100	5	>3.6	

The remarkable result for the 2.5mS pulse needs further comment. The judgements had been based largely upon the intensity and sharpness of the sensation, the pulses feeling stronger and sharper. The investigation of the mechanical response of the pin array had shown that a brief off-pulse did not allow the pin to move its full excursion when the pulse was less than 3mS long. Consequently, the sensation induced by such a pulse would be much less than expected and the confusions found in this experiment could occur. Had this defect not existed, it seems likely that discriminatioh would have been very much easier.

To complete this series of experiments, on-going and off-going pulses were compared in experiment 18. The duration of the on-pulse was 2.5mS and that of the off-pulse was varied.

Table V

Pulse Duration	Trials	Errors	d'	d' at ±1 S.D.
2.5mS	100	0	-	
5.0mS	100	5	3.3	3.7-2.9
7.5mS	100	6	3.1	3.5-2.7
10.0mS	100	2	>4.1	

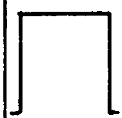
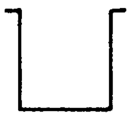
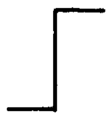
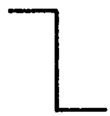
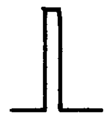
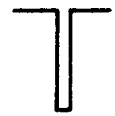
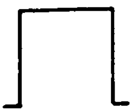
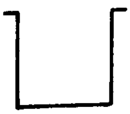
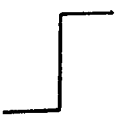
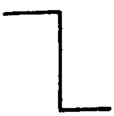
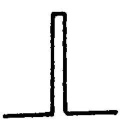
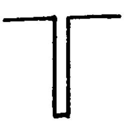
From these results it seems that on- and off-pulses are also readily discriminable. The result for 2.5mS off-pulse is probably affected by slightly diminished amplitude of response of the pin.

5:2:4 Summary and Conclusions

A table giving discriminabilities of edges, pulses and steady states is given below. Note that each entry is recorded twice, in positions symmetrical about the major diagonal.

Table VI

Values of d' for pairs of patterns. See previous tables for explanations of multiple entries.

						
	0	1.8	-	-	-	-
	1.8	0	-	-	-	-
	-	-	0	3.8	2.8 3.4 >3.9	-
	-	-	3.8	0	∞	-0.5 * 3.3 >3.6
	-	-	2.8 3.4 >3.9	∞	0	∞ * 3.3 3.1 >4.1
	-	-	-	-0.5 * 3.3 >3.6	∞ * 3.3 3.1 >4.1	0

- Denotes experiments not performed, but likely to yield high discriminability.

∞ No errors, therefore high discriminability.

* Denotes diminution in amplitude of pin motion.

It will be observed that the discriminability of any pair of this set of patterns is high, with d' better than 1.8 . The poorest results are those for a comparison of steady states. The comparison of edges and pulses is best described by saying that on- and off-edges and on- and off-pulses are all easily distinguished from each other.

It is thus to be concluded that it is not possible to treat transients and short pulses as similar. They possess features which enable them to be readily distinguished.

5:2:5 Discussion

It remains to be decided what comprises the 'features' by which the patterns can be identified.

Transients and pulses would possess one feature in common; they would both initiate a sudden burst of activity from a receptor, or group of receptors. This alone cannot be the means of discrimination.

An obvious difference between a pulse and an edge is that for the pulse the initial and final states are the same, whereas for the edge they are different. If this were the sole means of discrimination, however, we might expect performance to be inferior to that when steady states are compared, because the patterns differ for only half their duration. This is not so, hence the initial and final states must play only a minor role.

Transients will also produce tissue deformation which follows a different time course to that produced by a pulse. The edge consists of a single transient, whereas a narrow pulse consists of two such transients with a short delay between them.

Some receptors are capable of responding to on-going and off-going stimuli (81) so the output from these will depend upon the number of edges in the stimulus. Gray et al (,5,49) have postulated the existence of two populations of receptors sensitive to on- and off-transients respectively. This may be another contributing factor to the above results. Possibly the single edge excites only one population, but the pulse excites both.

5:3 Temporal Factors

5:3:1 Introduction

When experimentation was commenced, it was not intended to study the more simple judgements in any detail but merely to perform a brief experiment to verify results obtained by other workers and thus to increase confidence in the experimental system. The results obtained in succeeding experiments, however, demanded aa reappraisal and reexamination in more detail of even the most elementary judgements.

Hawkes and Warm (73) have measured the Weber fraction for duration of electrical stimulation over the range 0.5 to 1.5 secs. They have found that the Weber fraction decreases slightly with increasing duration and also with increasing intensity, being about 0.05 for a 1.0 sec duration at 2.0 times threshold current. They compare their results with those for mechanical vibratory stimuli obtained by Spector, who found that the fraction was approximately constant at 0.1 over the range 0.4 to 2.0 seconds, decreasing from 0.4 at 0.1 seconds with increasing duration. Both these results imply resolution of the order of 50mS for short pulses.

It was not intended to duplicate these experiments, but to perform a brief investigation of the order of magnitude of the limen of resolution over a somewhat extended range.

5:3:2 Preliminary Experiment

Five durations from 10mS to 1000mS were compared with each other in an AXBX scheme in experiment 4. A single pin, C3, raised for the appropriate time constituted each pattern. Two subjects were used; each comparison was made a total of 30 times. The results are plotted in graphical form in Fig. 18. Error rates have not been converted to d' measures in this case because many points represent no errors (infinite d').

The main feature shown by the graph is that a duration of 200mS seems to be critical in some respect. Durations less than 200mS are confusable with each other but not with durations greater than 200mS. In terms of the Weber fraction, for durations less than 200mS the fraction must have a large value, possibly as great as 3 or more, while for durations greater than 200mS the ~~fr~~ fraction will be much less than 3. Such an interpretation is not in disagreement with the results of Hawkes and Warm or those of Spector.

At this stage, it was decided not to pursue this line of investigation further, but to continue with a study of the temporal integration performed by the tactual system.

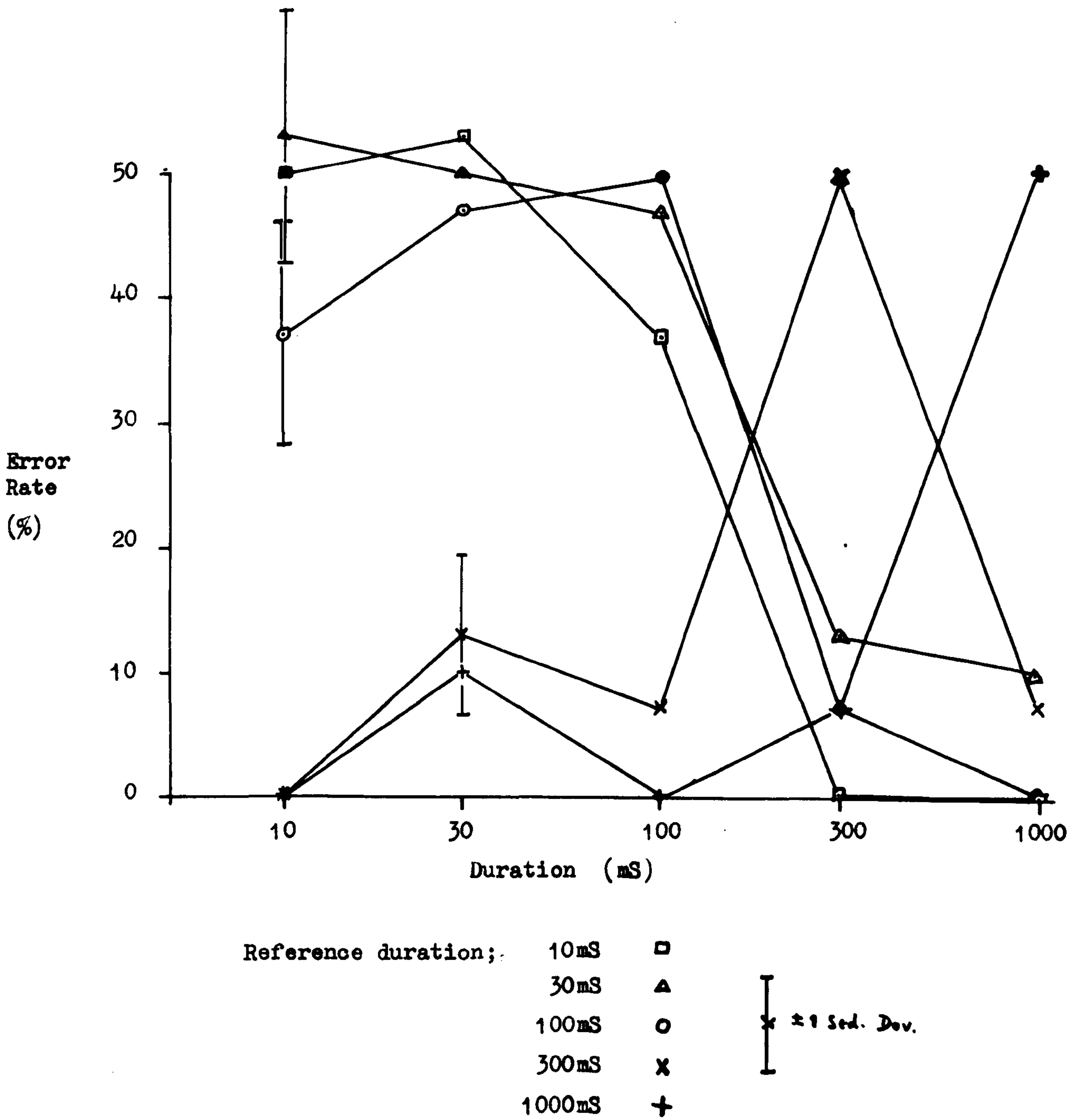


Fig. 18/ Expt. 4: Comparison of durations. Each curve is for a particular standard duration, which is compared with each of the other durations. The solid symbols represent the expected result of comparing a duration with itself (50% errors), not actually measured.

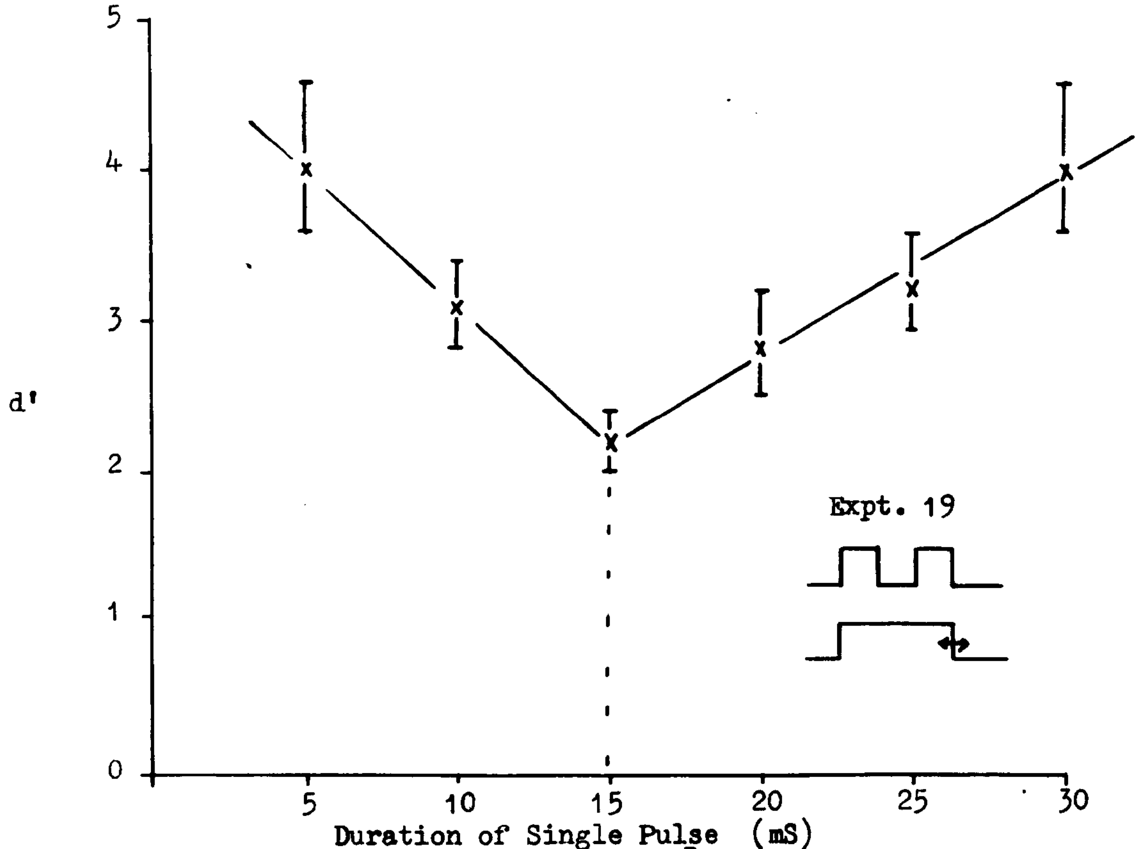
5:3:3 Single and Double Pulses

A series of experiments was begun to discover whether single and double mechanical pulses could be discriminated and how this is done.

The initial experiment, number 19, consisted of comparing single and double pulses of short duration, varying the duration of the single pulse and performing an AXBX experiment. The double pulse was 5mS on, 5mS off, then 5mS on again; the single pulse was of duration 5, 10, 15, 20, 25 or 30mS (specified by loading the number into the computer core store by hand). The single pin was C3 and one subject was used with 120 trials per duration.

Subjectively, the double pulse was usually felt as a double sensation and judgement was based upon this fact.

The results are reproduced in Fig. 19 (upper), from which it can be deduced that discrimination was not difficult. The most important feature of the graph appeared to be that confusion was maximal (d' minimal) when the overall duration of the double pulse and that of the single pulse were equal. Other results might have been expected; for example, possibly maximum confusion might have occurred when total 'on' times were equal, i.e. at 10mS. The actual results ~~indicate~~ suggest that the skin is probably not responding as rapidly as the pin, hence a more or less steady displacement might be occurring during the double pulse.



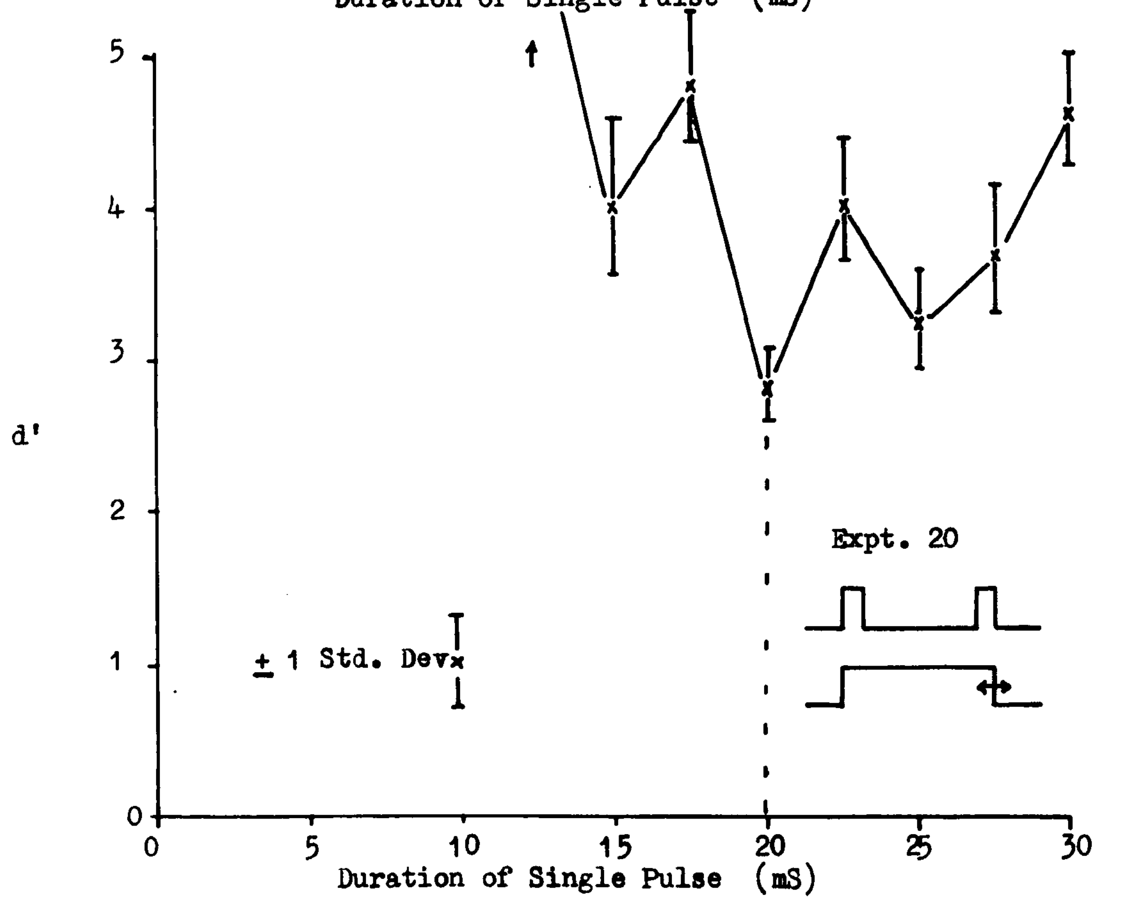


Fig. 19/ Comparison of double pulse with single pulse of variable duration.

To take this study further, another experiment was performed, number 20, once more comparing single and double pulses, but with a slightly different time course for the double pulse. At the suggestion of Dr. J.P. Wilson, the sequence was set to be 2.5mS on, 15mS off, then 2.5mS on once more. This was done in order to compare the results for the tactual system with those obtained by Dr. Wilson for the ear with a similar pulse sequence.

The conditions of the experiment were as previously; pin C3 was used with one subject. The double pulse was compared with various durations of the single pulse from 12.5mS to 30mS; the number of trials varied from 100 to 300 per point. The trials were made in blocks of 100 at a time, all the trials of one block being with one duration of the single pulse. The durations were chosen in a random order to minimise time-dependent effects.

The results are plotted in fig. 19 (lower). As can be seen, once more there is maximal confusion (minimum d') when the overall durations are the same (20mS), though at this point only 12% errors were observed. Overall performance implies that the discrimination is not difficult.

The next important observation is that there appear to be peaks of discriminability at 2.5mS on either side of the minimum. The reasons for the occurrence of the minor peaks was not obvious; they were possibly due to the particular time or frequency discriminating mechanisms associated with the skin, or to the particular waveform presented. It was therefore decided, before proceeding with a systematic variation of the parameters of the waveform, to check the results by comparing two single pulses, varying one in duration over the same range of time intervals as in the previous experiment. Absence of the peaks in the results of this experiment would indicate some sort of interaction of the time intervals involved in the double pulse, while presence might show apparatus faults, failings of the technique or a genuine dependence upon absolute or relative durations by the tactual system.

5:3:4 Discrimination of Duration

The next experiment (number 21) was similar in many respects to the previous two. One pulse was maintained constant in duration at 20mS, while the other was varied over the range 2.5mS to 45mS. Pin C3 was again used, an AXBX presentation scheme and one subject was employed. Once more blocks of trials, 50 in number this time, were performed at a fixed duration of the comparison pulse, and the duration was varied randomly from block to block. Most of the points of the graph represent 100 trials.

The graph (Fig. 20) shows that fluctuations of the error rate are apparent in this experiment also. There is a minimum value of d' (maximal confusion) once more when the pulses have equal durations; peaks and dips are apparent with periodicity of

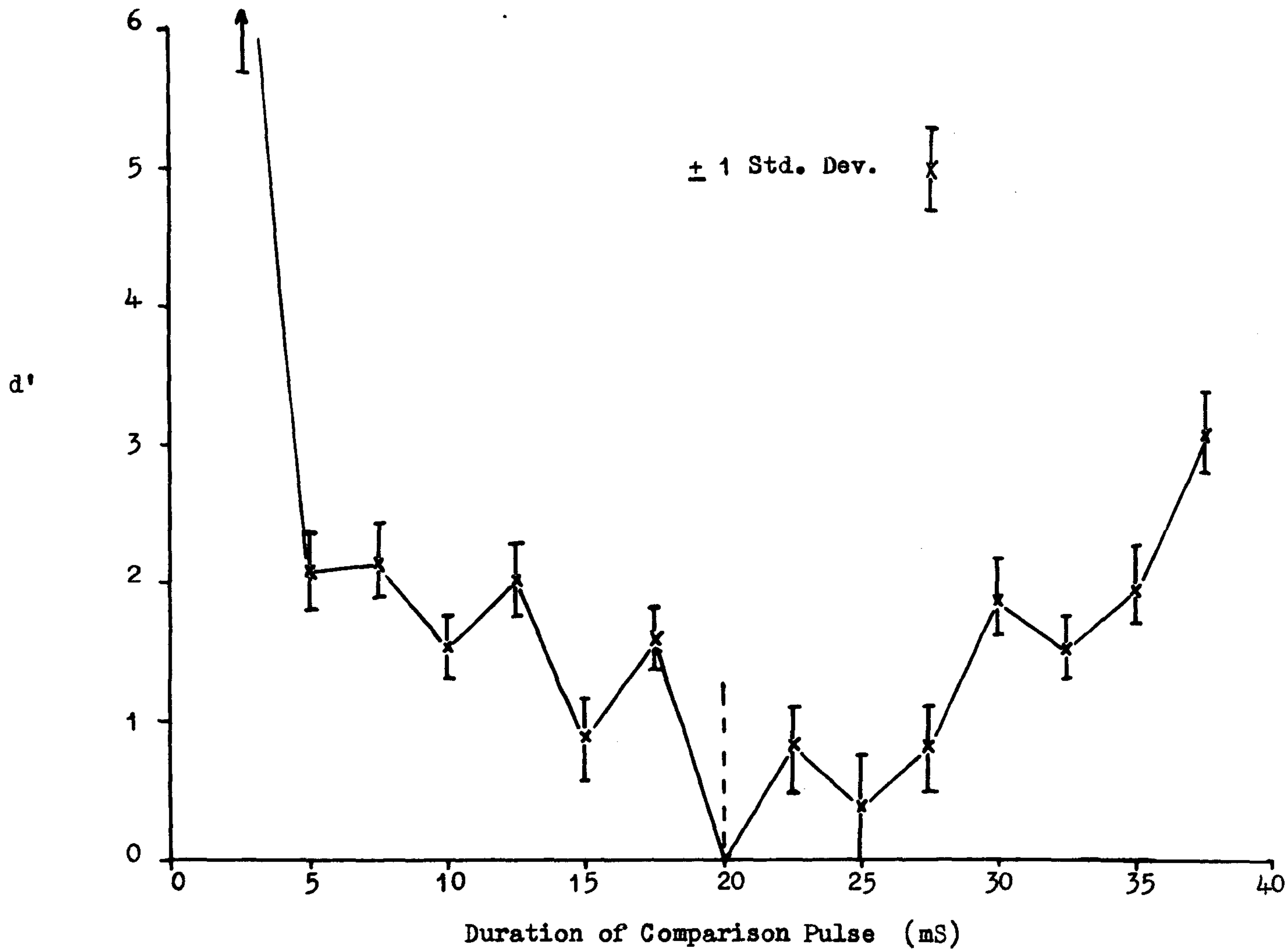


Fig. 20/ Expt. 21: Comparison of durations. Standard is 20mS.

about 5mS.

If the graphs of results of experiments 20 and 21 are compared, it will be seen that they correspond very closely. The main difference is simply a vertical shift. This was taken to imply two things. First, the fine detail of the curves is largely determined by the overall durations of the patterns involved. Second, the techniques of measurement and analysis are reliable; even with greatly differing degrees of difficulty, similar tasks produce similar curves.

At this point it was decided that further study of this phenomenon was necessary, In particular, graphs were required for similar experiments with different standard durations to discover whether the effect was one of relative or absolute durations.

A further experiment was conducted, similar to number 21, but with a standard duration of 12.5mS instead of 15mS. The first half of the data was collected in a manner similar to that of experiments 20 and 21, changing the duration by manually changing the contents of the computer core store and performing a whole block of trials with one duration. The experiment specification was reprogrammed to enable the computer to choose which durations to present on a trial-to-trial basis, instead of block-to-block. The second half of the data was collected using this revised system and was found not to differ significantly from the first half. Succeeding experiments of this type were performed with the computer choosing the patterns to be presented from a large set. This technique ensures that results obtained for systematic variation of a parameter are truly comparable; estimations of error rates for the various parameter values are effectively carried out simultaneously, rather than in some order which might allow time dependence to distort results differentially.

The results of this experiment revealed that peaks and dips were still occurring, but that the graph was not of quite the same form as the previous one. This indicated that the effects were dependent upon the absolute durations involved, not just differences in duration.

Three further experiments were carried out (23 to 25), each with a different duration for the standard, varying the comparison over a range of durations. Each comparison was made at least 100 times. A set of graphs depicting the results is given in fig. 21.

A somewhat more informative plot results if the curves are plotted not against absolute duration, but against difference in durations compared (Fig. 22). Such a plot reveals the presence of a local peak value of d' at 2.5mS on either side of the main minimum, followed by local minima at 5mS on either side of the main minimum. The shapes of the curves are not exactly similar, however. It appears there ~~are~~ may be two populations of curves;

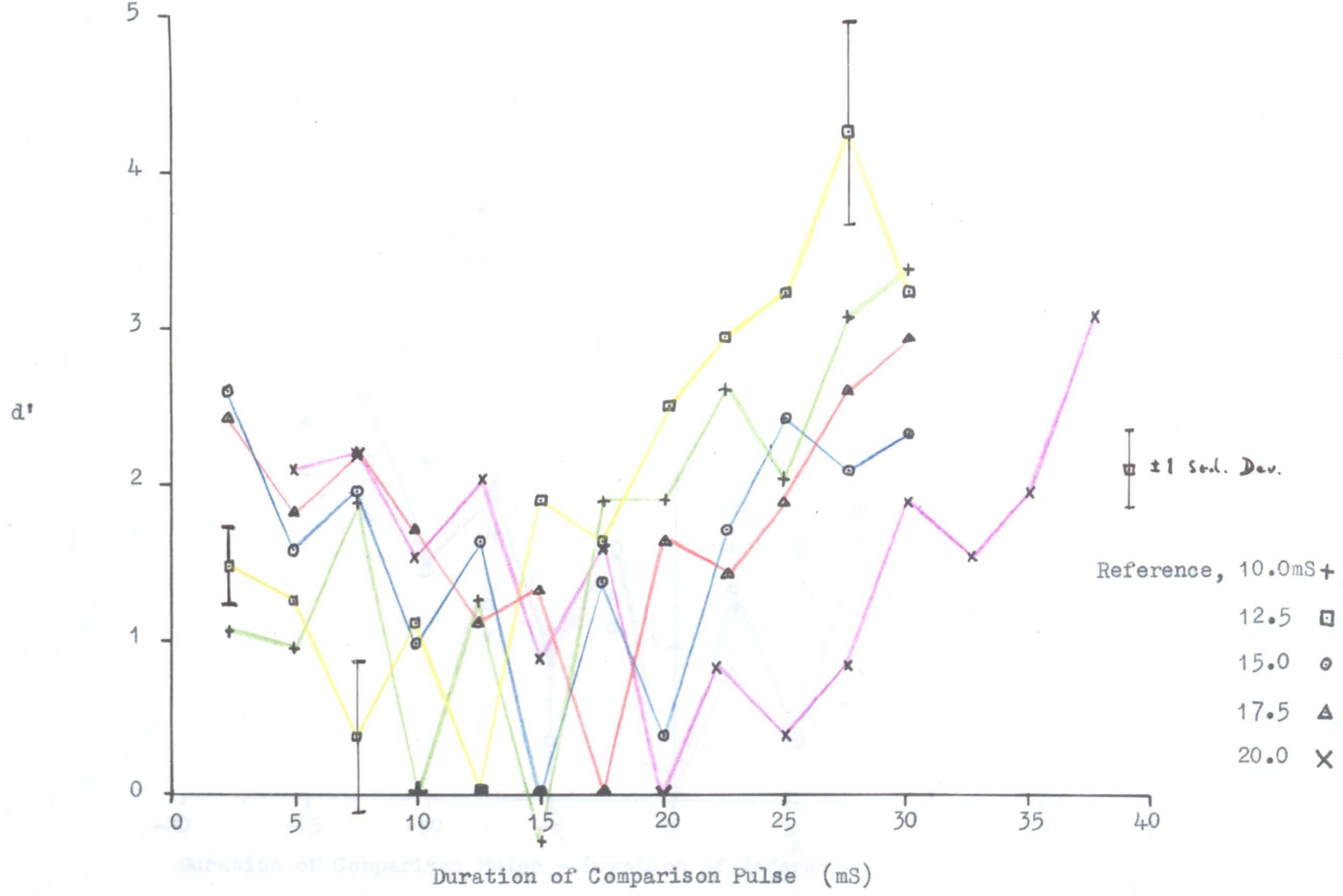


Fig. 21/ Expts. 21-25: Comparisons of durations with various values of standard duration.

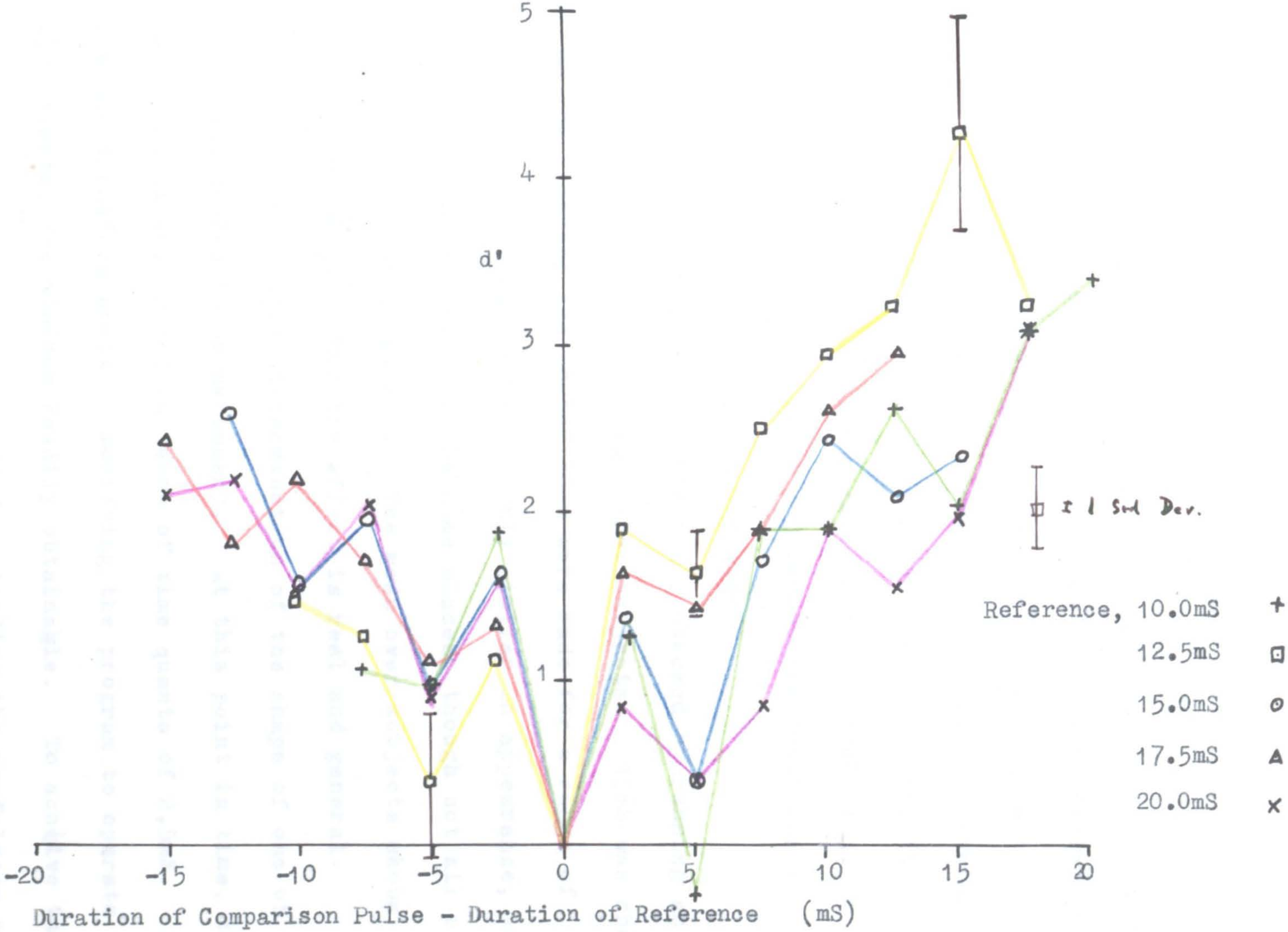


Fig. 22/ Expts. 21-25: Results plotted against difference in duration of comparison and standard.

one population consists of those curves whose standard is an even number of half periods (2,5mS) long, and the other population has a standard an odd number of half periods long. Collecting data for 'odd' and 'even' types of curve we can derive two average curves (Fig. 23). The two curves bear the similarity that on either side of the main minimum there occurs a local maximum, and the general shapes are similar. However, the 'odd' curve rises more steeply than the 'even' on one side.

The existence of the effect was checked by running an experiment (number 67) with two other subjects. 15mS was chosen to be the standard and comparisons were made for a range of durations. The results are roughly similar in appearance, with peaks and dips occurring in the same places, though not all of the same amplitude (Fig. 24). The mean over subjects shows the fluctuations well. Thus the effect is real and general.

A more detailed determination of the shape of one of the curves was deemed to be necessary. At this point in time, the display routine operated in terms of time quanta of 2,5mS. Some time was therefore spent in modifying the program to operate with 0.5mS quanta, the minimum readily obtainable. To achieve this, the display interpreter was added, extending the usefulness of the system by allowing a higher level of language to be used in the experiment specifications.

An initial attempt was made (experiment 26) to determine

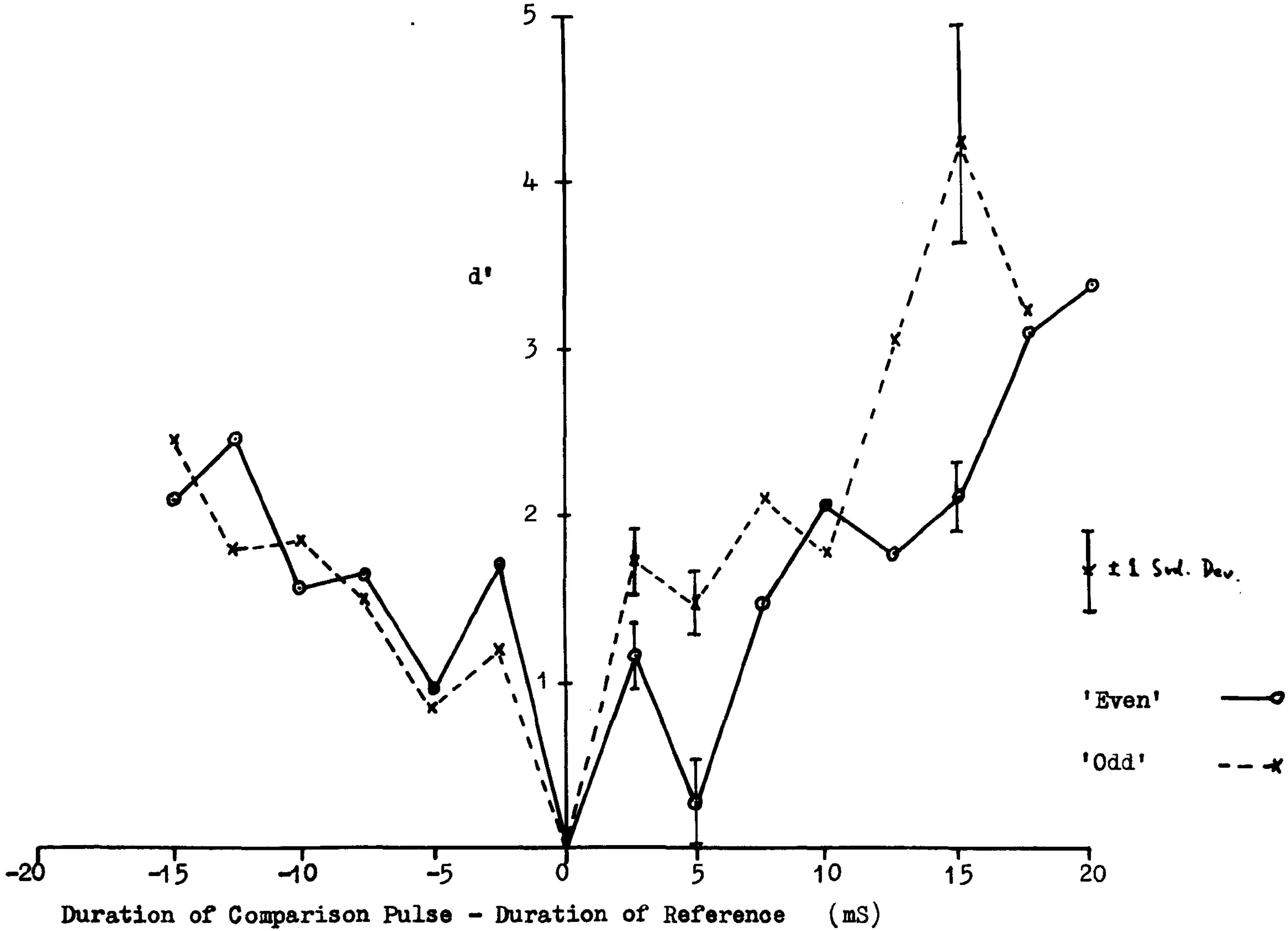


Fig. 23/ Expts. 21-25: Averages of 'Odd' and 'Even' curves.

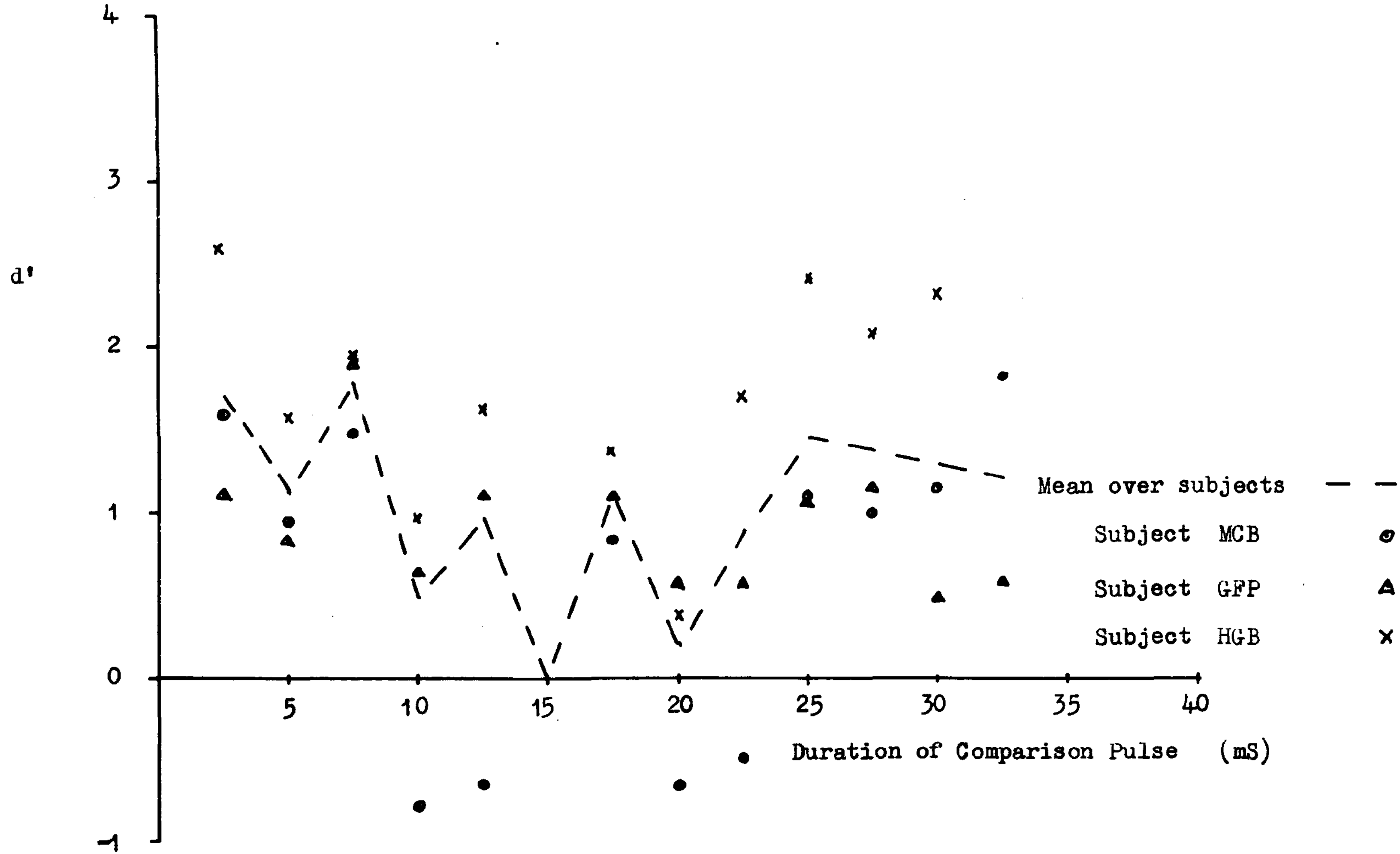


fig. 24/ Expt 67: Comparison of Durations. Standard is 15mS. Results for three subjects.

the shape of a portion of the curve, with a standard duration of 15mS and comparison which varied from 10mS to 14.5mS in 0.5MS steps. The results obtained did not agree with those of the more coarse experiment 23 (Fig. 25). It was thought that the reason for this non-agreement was that in the fine-scale study all the discriminations were difficult, with greater than 30% error rates. It seemed possible that such a task with high overall difficulty was not allowing the subject to be reinforced by obviously correct decisions and hence his choice of which dimension to base his judgements upon might be subject to variation. To present a wider range of stimuli, preferably the same range as that of the previous experiments might serve to stabilise performance by providing more information to the subject of the correctness of his decisions.

A more extensive experiment (number 27) was planned. It was intended to plot the whole of one curve in detail; the standard was chosen to be 15mS and the comparison duration was to range from 2.5mS to 30.0mS in 0.5mS steps. Each comparison was to be made 100 times, a total of 5500 trials in all. In terms of experimental time, this experiment occupied eleven hours, spread over five days. As the time scale of the proceedings was to be so long, it was necessary to spread the presentations of each combination of durations evenly throughout the series of trials. It was therefore written into the specification of the experiment that each series

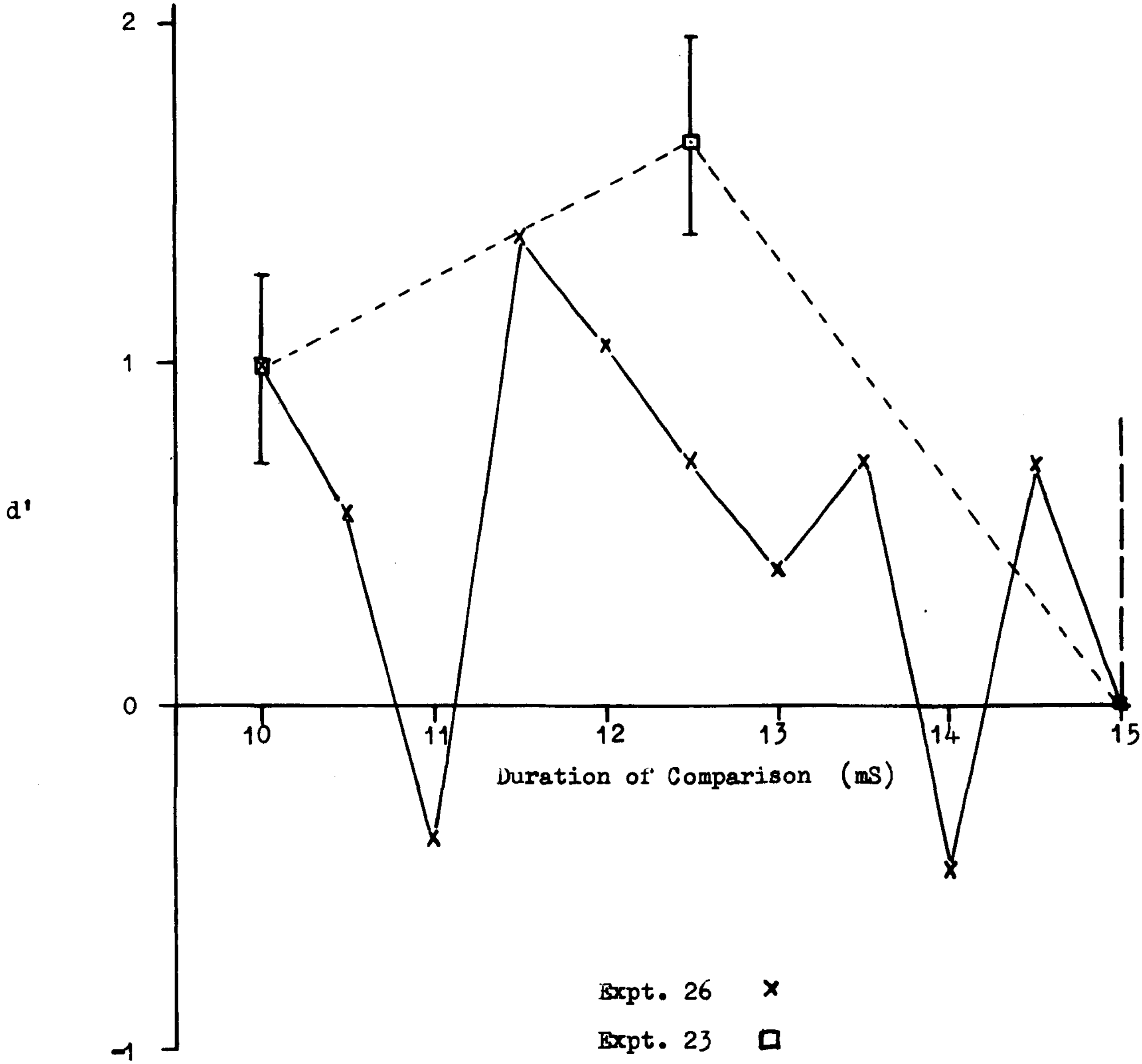


Fig. 25/ Expt. 26: Comparison of durations. Standard is 15mS.
Attempt to determine detailed variation of curve.

of trials was to be 110 trials in length, and in each series of trials each combination was to be presented twice. Thus any variation of performance with time would affect the data for each combination equally.

The results are plotted in fig. 26. It will be observed that the graph possesses fluctuations near its left hand side which are significantly greater than the possible error in measurement. These fluctuations have a periodicity of about 5mS. The results of this experiment are in quite reasonable agreement with those of experiment 23 obtained earlier and over a much shorter period. Only one point lies beyond two standard errors, that for 25mS, and it is not unlikely that a small change in the periodicity of one curve could give rise to the other.

A moving average over five points has been calculated to reduce the more rapid variations (Fig. 27). The resulting graph shows quite clearly that the fluctuations have a period of about 5mS and decrease in amplitude as the comparison duration is increased. Such a change could easily be the result of slight changes in the period of an otherwise regular event which gives rise to the fluctuations. The first few cycles will be fairly accurately superimposed, but later cycles will become progressively more out of step, averaging together to produce a smaller amplitude.

The mean response time of the subject to each pair of

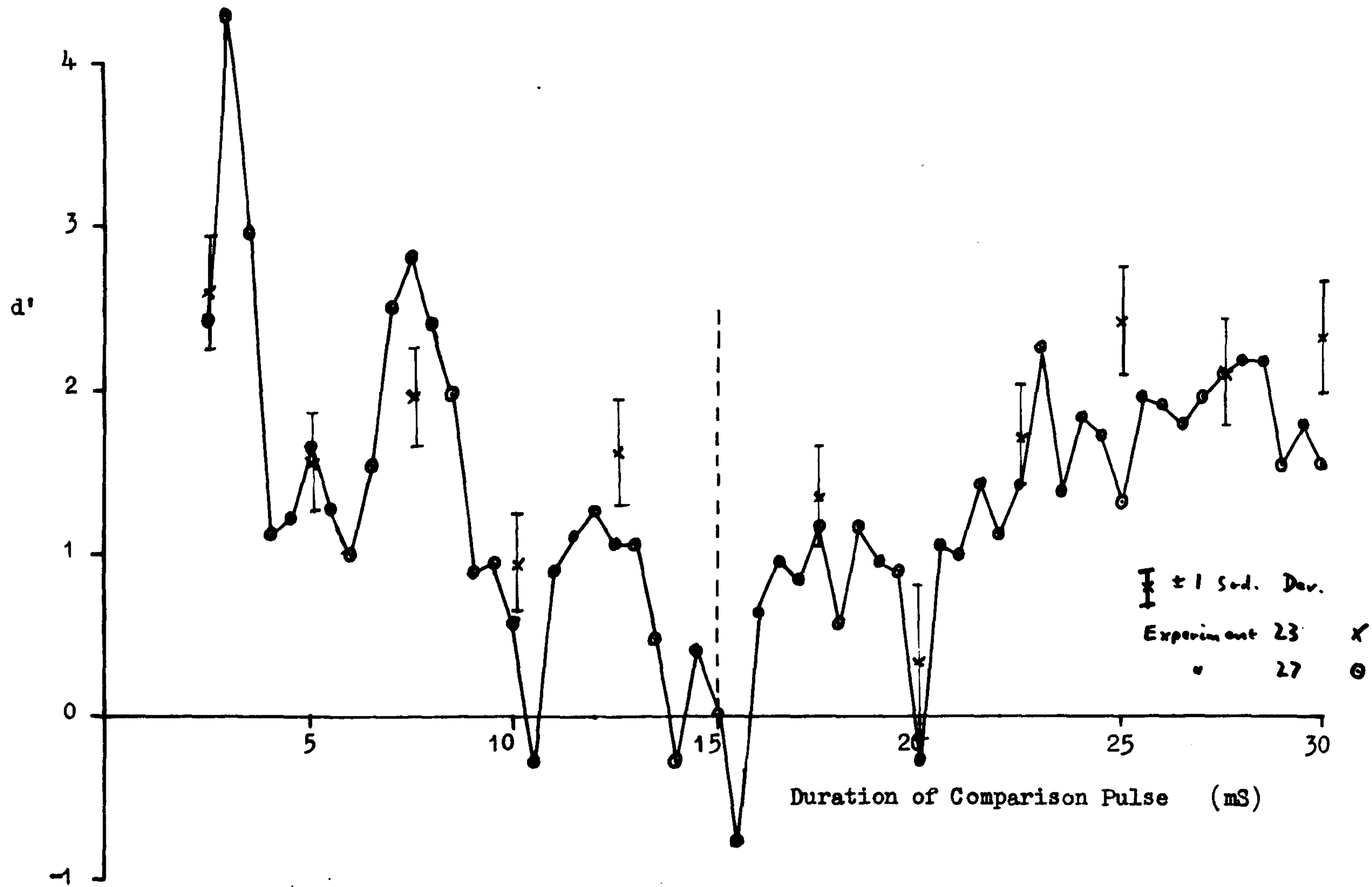


Fig. 26/ Expt.27: Comparison of durations. Standard is 15mS. Comparison pulse duration varied in steps of 0.5mS.

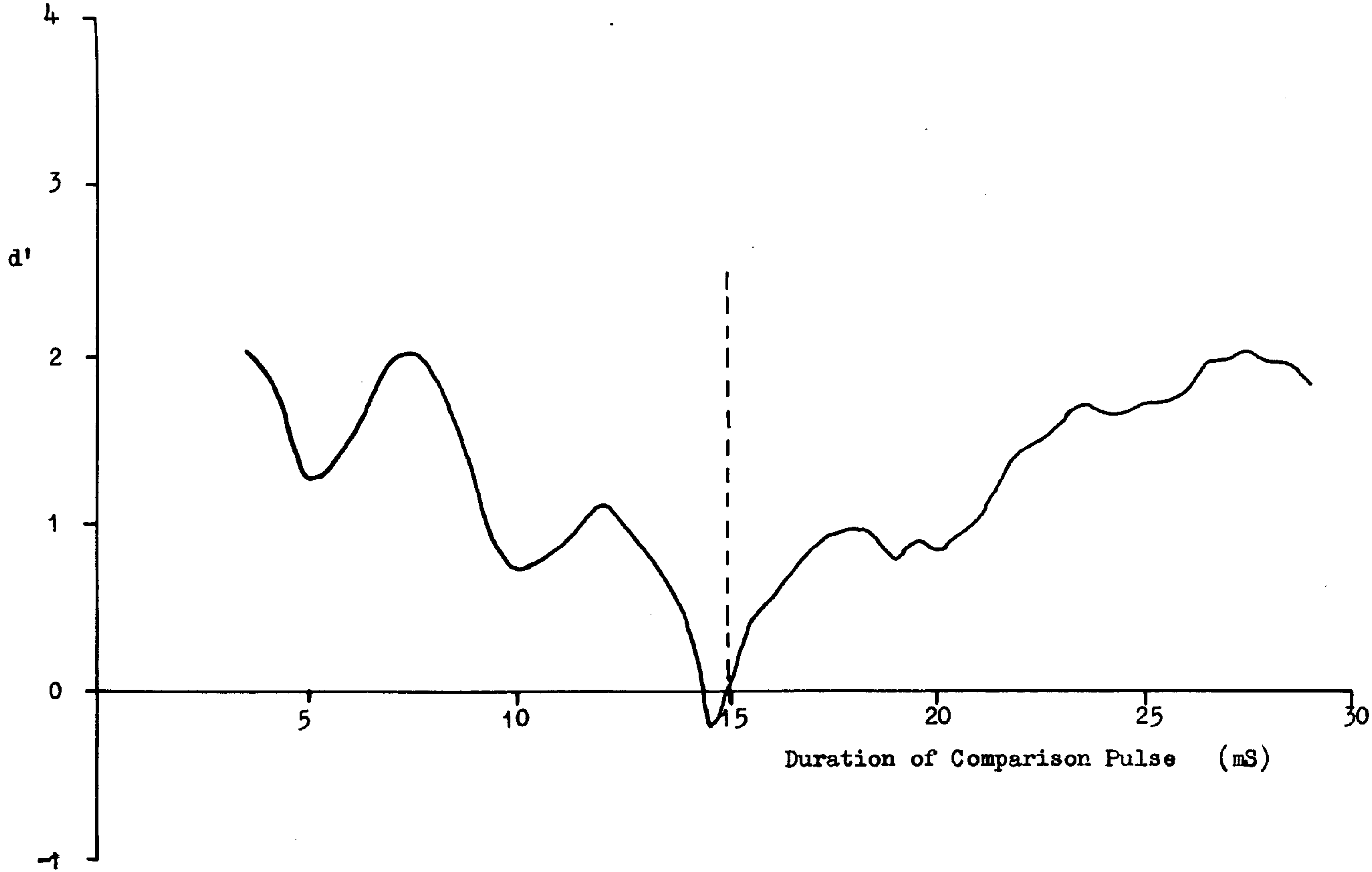


Fig. 27/ Expt 27: Moving average over five points of Fig. 26.

durations presented has been plotted in fig. 28. This graph also possesses peaks and dips with a period of 5mS, but they are not quite so clearly defined. Response time therefore appears to yield similar information to error rate concerning difficulty of discriminations, but perhaps not so reliably. Response time has not been employed extensively in the experiments of this thesis as a measure of performance, although it has been recorded for every trial.

The error rate results have been subjected to an autocorrelation analysis to determine more accurately the period of the fluctuations. The autocorrelation function so obtained is reproduced in fig. 29. From this curve, it will be observed that there is a local maximum of correlation corresponding to a delay of 4.5mS, and susidiary maxima at 9.25mS and 14mS. It seems probable that the maxima all derive from a basic period of 4.6mS in the original graph. There is also evidence for a smaller set of maxima corresponding to delays of 8mS and 12mS. These could result from a secondary period of 4.0mS, the major peak at 4.5mS being in fact a compound of two peaks at 4.0 and 4.6mS.

There thus appear to be two factors at work in these experiments, one with a basic period of 4.6mS, and a second, lesser effect with a period of 4.0mS.

There are several possible explanations for the observed fluctuations. Almost certainly, at some point in the nervous

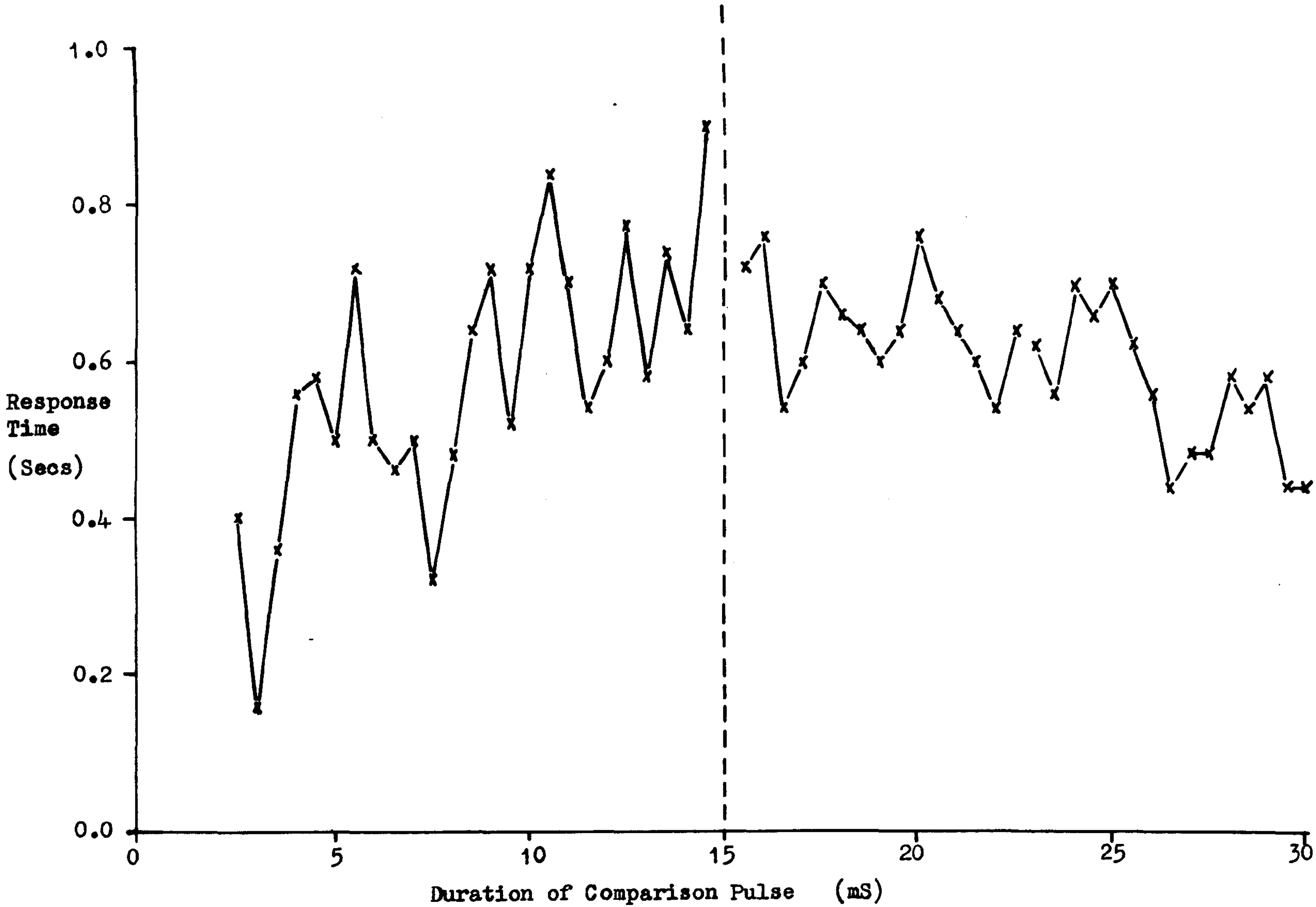


Fig. 28/ Expt. 27: Comparison of durations. Standard is 15mS. Response Times.

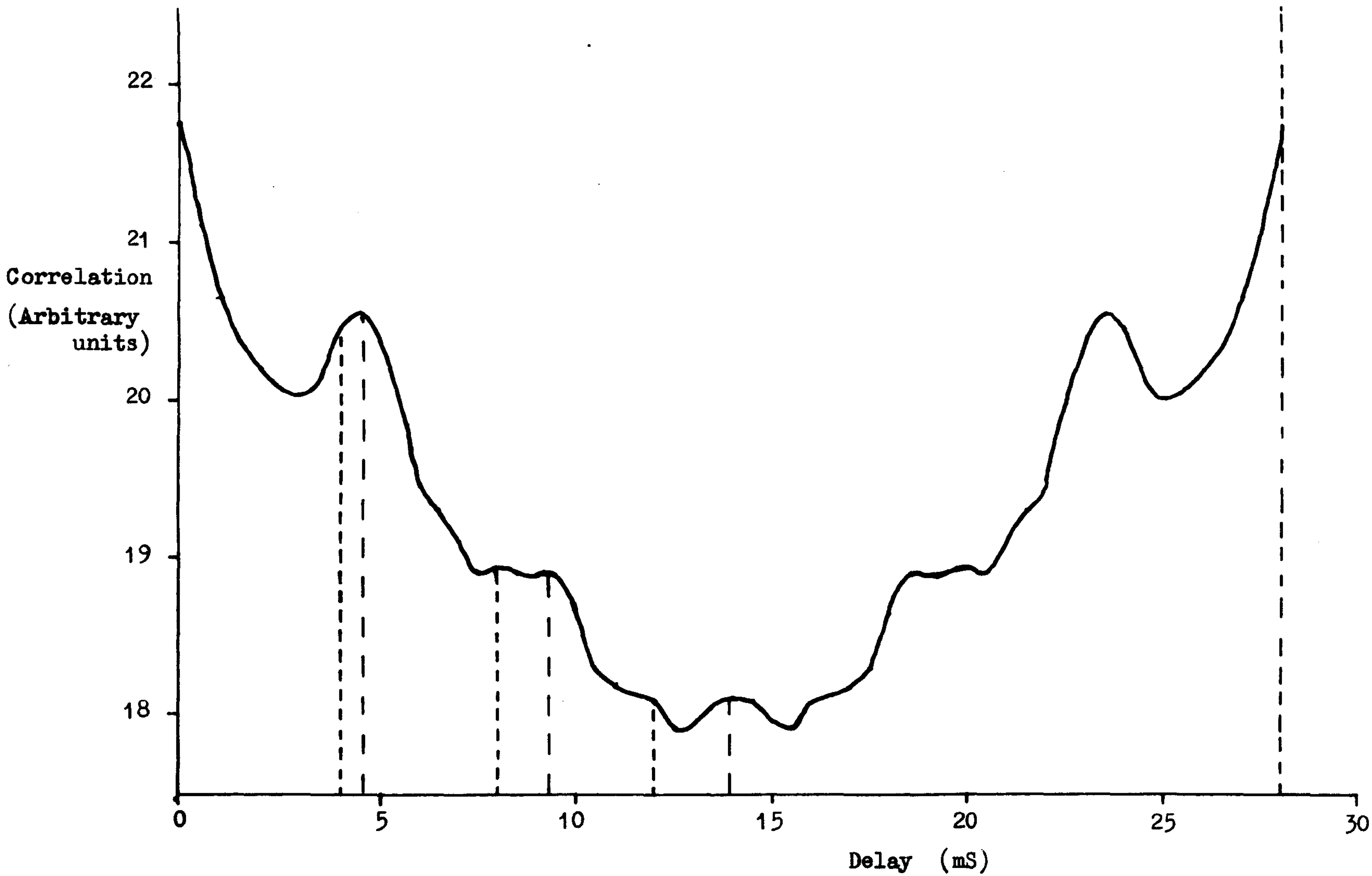


Fig. 29/ Expt. 27: Comparison of durations. Autocorrelation function calculated from Fig. 26.

system temporal fluctuations of activity are induced with the required period, but to decide at what point they are generated is difficult.

The apparatus may vibrate spontaneously at about 218Hz. If such vibrations are initiated by the onset of the pulse, their time course will be affected by the point in the cycle at which the pulse goes off. Thus the stimulus itself may change in a periodic manner with the duration of the applied pulse.

The tissue of the fingerpad may itself vibrate in a jelly-like manner. Travelling waves are well-known on the skin and it is possible that they are being set up in this case. As above, the point in the cycle at which the pulse is turned off will affect the motion of the tissue. Since the response of the receptors is dependent upon the tissue motion, information transmitted will vary in a periodic manner.

A third possibility is that the tissue deformation is not periodically time-dependent, but is constant throughout the pulse. In this case, the receptors would fire repetitively during the pulse, possible with a period of about 4 or 5 mS. The leading edge of the pulse would presumably initiate activity simultaneously in all receptors, their refractory periods would prohibit a second impulse from occurring within a few milliseconds. They would thus fire repetitively but with differing periods close to some minimum value. Initially, the impulses would be occurring in phase, but as time proceeded they would progressively become more out of step until finally their responses were ~~weefectvely~~ effectively independent. Thus the decreasing amplitude of fluctuations could occur. This hypothesis is perhaps not very likely as it imposes a condition of regularity of performance and distribution of the receptors which may not be met in practice.

A final possibility is that the fluctuations reflect a central periodicity, perhaps a central clock is set off by the start of a pulse and the clock tidks at 5mS intervals. The duration of the stimulus is timed by this universal clock to the nearest tick. Some mechanism of this sort would also give rise to the observed results.

The problem which remains is to decide which of these hypotheses, if any, are correct.

A direct attempt was made to observe the afferent impulses from the receptors. Dr. E. F. Evans endeavoured to record the response of the ulnar nerve at the elbow, following a technique described by Dawson and Scott (38). Recording electrodes were placed on the skin over the nerve about 2cm apart, just below the elbow. When electrical pulse stimuli were applied to the wrist whole nerve responses could be detected and averaged. However, when electrical pulses were applied to the fingerpad the response was much less. With mechanical stimulation by a single pin, no response could be seen. Even with 35 pins operated simultaneously and averaging over 500 stimuli, no significant response could be detected. Further attempts were therefore abandoned.

Resort was made once more to the psychophysical technique though this cannot by itself provide explanations of the operation of the tactual system.

The fourth hypothesis is the easiest to test. To avoid the complications of unwanted mechanical vibrations, however they might arise, electrical stimuli were used. Three experiments were performed.

The first experiment was designed to test whether the periodicity was central in origin, and was a modified version of experiment 25. ELGEN, a version of GENIE for use with an electrical stimulator, controlled the display of patterns. The experiment consisted of comparing durations once more, but the duration was not defined by the state of a pin or of a current. The interval was marked by a 0.5mS pulse at its onset and a similar pulse at its termination. To generate the pulses, the computer supplied triggering pulses through its output register to a pulse generator. The output of the generator was set to provide 0.5mS pulses at about 1.5 times threshold current intensity. These pulses were made to drive the constant current stimulator described earlier. The electrode was of concentric construction with a 1mm diameter central active electrode upon which the fingerpad was lightly rested.

The standard interval was 10mS and this was compared with durations from 2.5mS to 30mS in 2.5mS steps.

The subjective observations were that little variation in intensity could be detected as the inter-pulse interval varied. There also appeared to be some adaptation during a run.

The results are plotted in fig. 30 and are based upon 100 trials for each comparison. Minimum discriminability can be seen to occur when the standard and comparison durations are equal, but the rate of variation with duration is much less than that for the mechanical case. There is no conclusive evidence for significant fluctuations with a period of 5mS, certainly none in the region 0 to 15mS.

It thus appears that there is probably not a ~~specialised~~ general central mechanism for timing short intervals.

A similar experiment was conducted which was rather more directly related to the mechanical case. In this the duration was defined by a steady current maintained for the required time. Considerable difficulty was encountered because of the integrating properties of the tissue and tactual system. If the current amplitude was set at such a level that a 2.5mS interval was just above threshold, a 20mS pulse was painful. The range of comparison durations was therefore limited to 2.5 to 20mS, in 2.5mS steps. Judgements were performed upon the basis of intensity to a great extent.

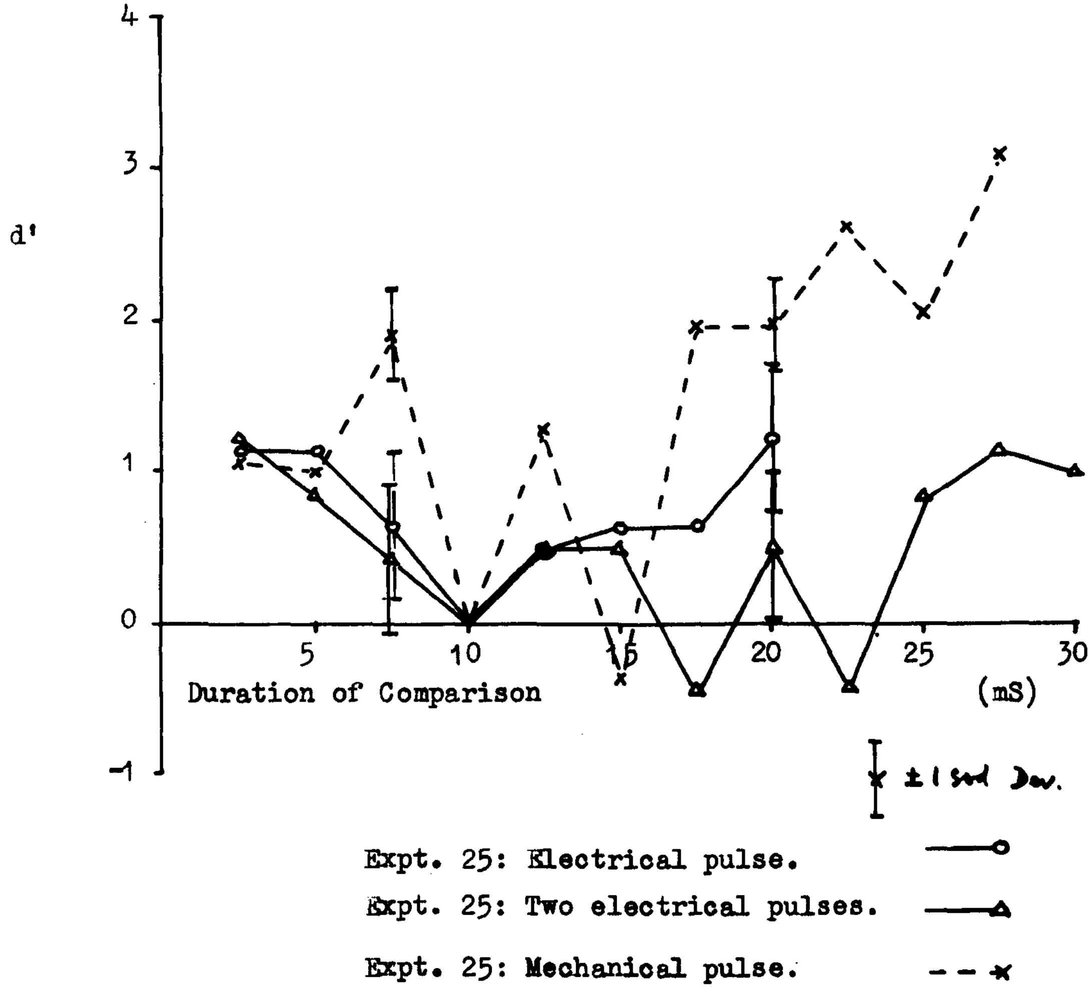


Fig. 30/ Comparison of durations with electrical stimuli.

The graph of results, Fig. 30, once more does not possess peaks and dips, nor perhaps, does it vary quite as rapidly as that for mechanical stimulation, although faster than that for the double electrical pulse stimulus.

This result indicates that the pattern of neural impulses occurring with such electrical stimulation is not similar to that for mechanical stimulation. It is expected that sustained current causes repetitive firing of the receptors but the periods probably vary widely,and do not remain constant for a single receptor. Probably also the electrical integrating property of the tissue causes staggered onset of firing to such an extent that no real correlation of the responses can be said to exist.

One further experiment was performed to verify that synchrony of firing of the receptors might be responsible for the general shape of the discrimination curve.

The stimuli to be used in this experiment (number 30) were trains of pulses 0.5mS in duration, spaced at 5mS intervals. The standard pattern was three pulses, which occupied a total time of 10mS, and this was compared with 1 to 9 pulses. The analogy with the mechanical case was that the onset of the duration initiated the first impulse and vibrations of some sort ensured that succeeding impulses were spaced at 5mS intervals. It was not possible to simulate responses to intervals not multiples of 5mS.

The results (Fig. 31) do not show particularly good

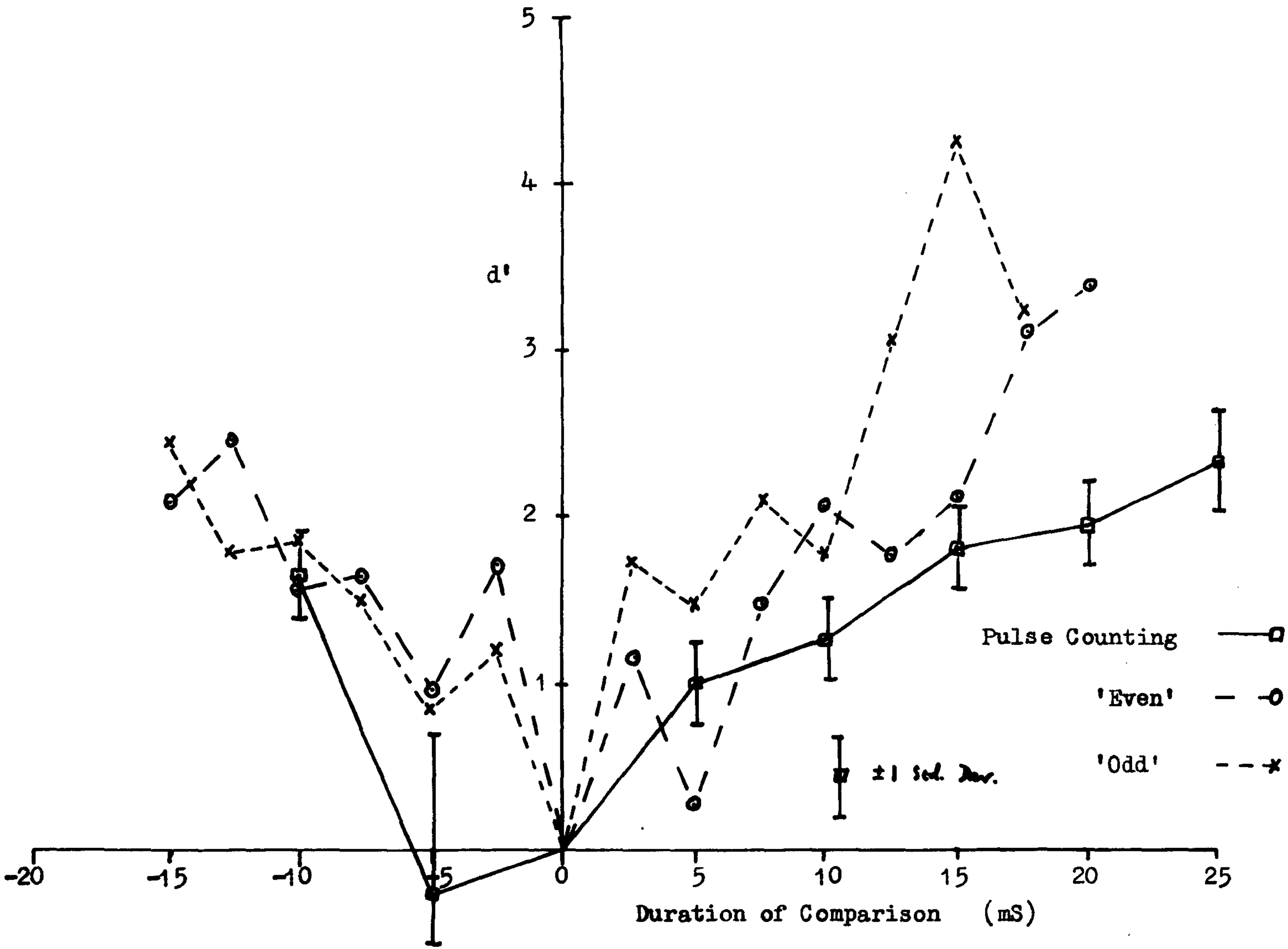


Fig. 31/ Expt. 30: Pulse counting. Pulses separated by 5mS. Standard is three pulses long. Results are plotted together with those of expts. 21-25, as in Fig. 23.

agreement with those for mechanical stimulation, but they are at least as good a fit as those of the other two electrical experiments particularly for the longer durations.

Perfect agreement was not expected. What these results do show is that the method by which durations are discriminated may be equivalent to counting neural volleys (or integrating them) in some way.

The conclusions to be drawn from these electrical experiments are firstly, that the periodicity observed in the discriminability curves for mechanical stimuli is probably not central in origin but arises at the receptors and secondly, that the discrimination of durations may be based upon the number of volleys occurring.

It would thus appear that mechanical vibrations are responsible. It remains to be determined whether they are artifacts of the apparatus or oscillations of the tissue.

The observations of the motion of the pin under stroboscopic illumination had revealed some inherent vibration and bouncing. However, the time between successive excursions was about 2mS and the vibrations appeared to decay rapidly.

To clarify the issue if possible, an attempt was made to record directly the vibrations of the skin under various conditions of stimulation. At Dr. Wilson's suggestion, an Acos GP.77 stereophonic gramophone pickup cartridge was used to detect the vibrations. It was taped to the finger with the stylus resting lightly upon the fingerpad. The output voltage was observed upon a Solartron CD 1400 oscilloscope.

Several forms of stimulation were tried; many transducers possessed resonances in the region 200-500Hz and were thus unsuitable for use. Eventually a dripping tap was employed to provide a repetitive impulse, the drop dispersing rapidly on contact with the skin. Observations were made with two subjects of the psychophysical experiments, HGB and GFP. It was found that oscillations lasting several cycles were induced in the unconstrained tissue.(Fig. 32) The period of successive cycles increased slightly with time, but the average period seemed to be about 2 to 3mS, not as long as 5mS.

It seemed possible that the pressure of the finger against the platform of the stimulator array might change the frequency of the oscillations somewhat. It was necessary to observe skin vibrations under the conditions of the experiments.

The pick-up cartridge was again employed. This time it was affixed to the platform. One of the stimulating pins was removed to one side and through the hole was inserted a short nylon bristle. One end was glued to the stylus of the pick-up and the other was cut to such a length that it protruded about 0.5mm through the hole. Thus when the subject placed his finger upon the array, it was ensured that vibrations of the skin could

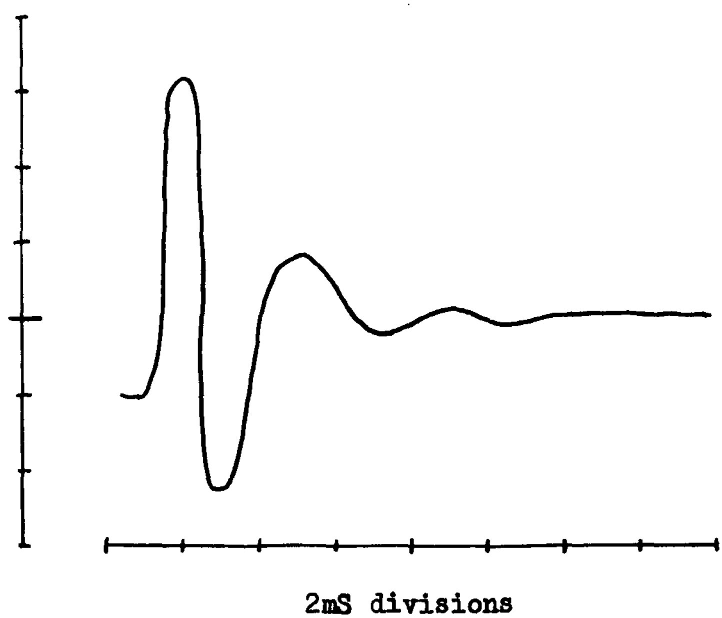
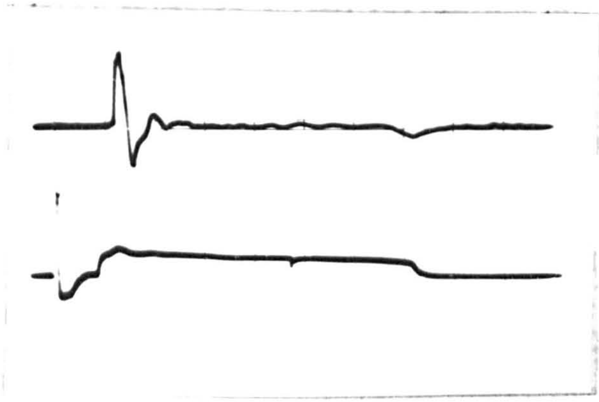


Fig. 32/ Mechanical vibrations of the fingerpad, induced by a drip of water.

be detected. Photographs of the observed waveforms were taken. Stimulation was achieved in the normal manner, pulses being provided by a pulse generator at a constant rate. The duration of physical contact was observed by connecting a battery and resistor in series between the subject and the pins. When contact was made a voltage was developed across the resistor and this was also observed on the oscilloscope.

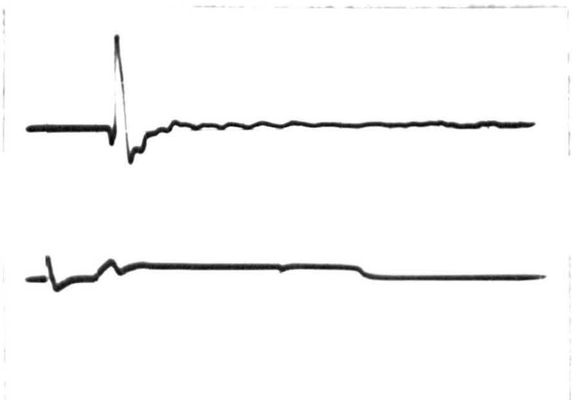
When a pin adjacent to the pick-up bristle was operated two cycles of oscillation with a period of about 1.8mS could be seen on the output waveform of the pick-up. The vibrations were excited by the onset of the pulse and decayed within a few cycles (Fig. 33a). Under some conditions, these oscillations could be almost eliminated; the exponential decay of the trace in fig. 33b is largely a result of the time constant of the pick-up, and not the skin. The amplitude of vibration was maximal with light pressure exerted. Increasing pressure decreased the amplitude, but very heavy pressure was required to suppress it completely. It is of interest to note that sensation was also maximal for light pressure.

Pins 2, 4 and 6mm from the pick-up were activated and it was found that vibrations were still detectable at the furthest distance. Pressure seemed to reduce the range, but even for heavy pressure oscillations were detectable at 4mm. The vibrations seem to travel over the top plate of the array like



a/ Pin 2mm from pick-up, moderate oscillation.

b/ Pin 2mm. from pick-up, small oscillation.



c/ Pin 4mm. from pick-up.

Fig. 33/ Recordings of motion of fingerpad. Upper trace is output from pick-up. Lower trace is record of contact between pin and skin. Time divisions 2mS.

waves along a rope laid upon the floor and shaken up and down. We cannot assume that such a plate will stop waves, as some authors claim, but only attenuate them.

Using two pins on either side of the pick-up, or the entire array, no qualitative change was observed in the vibrations. They were slightly bigger, and the initial double vibration may have persisted a further cycle or two, but the direct noise received by the pick-up was also increased.

The results of these observations indicate that tissue vibrations are occurring, largely excited or forced by the pin motion, but that they are of a higher frequency than the 218Hz implied by the psychophysical observations.

Support for these conclusions came later, in a psychophysical experiment designed to measure the subject's ability to determine simultaneity. In this experiment two pins were raised with a specified delay between them and the subject was required to distinguish between this pattern and that in which the pins rose simultaneously. Both the delay and the spatial separation of the two pins was varied.

The results (Fig. 34), when plotted against delay showed a periodic fluctuation with a period of about 2mS. Also, for the pin 4mm further removed from the first, the phase of the fluctuations was inverted. This was taken as evidence that travelling waves were being set up on the skin, with a period of of about 2mS and a wavelength of about 8mm.

5:3:5 Discussion

We can now draw a few conclusions concerning the discrimination of durations of mechanical pulses.

It seems that mechanical vibrations are occurring in the tissue, with a period of about 2mS. These may be natural vibrations of the tissue, as the experiments with the unconstrained finger would indicate, or they may be forced vibrations caused by the bouncing of the stimulating pin. In view of the fact that two components were found in the psychophysical fluctuations the truth is probably a compound of these possibilities. Coupled vibrations are probably occurring.

We now come to the problem of the neural coding of the durations. It does not seem probable that the 5mS periodic fluctuations are purely neural in origin. Even if we suppose the onset of the pulse to initiate synchronous firing in large numbers of receptors of widely differing characteristics, we should expect very little correlation after only a few milliseconds. It is more likely that the mechanical vibrations are responsible for the apparent synchrony more directly.

Let us assume that vibrations are occurring at about 435Hz. Few receptors would be able to respond at this repetition rate, but many would be capable of responding at half this rate. It is highly probably that many receptors will be phase-locked to the mechanical vibrations so that they respond repetitively at

4.6mS intervals, i.e. every other cycle. The initial transient would excite most of the receptors simultaneously so that they would all tend to be in phase with each other, not as two populations responding alternately at each cycle.

The vibrations are observed to decay within a few cycles, as do the fluctuations of the psychophysical curves. In view of the great sensitivity of some of the receptors, of the order of a few microns displacement (89), the effect of vibrations may persist after they have ceased to be visible but should nevertheless decay still.

The explanation of the observed fluctuations in discriminability with duration seems to be as follows.

The mechanical stimulator sets the tissue in motion at the onset of the pulse; most of the receptors are thus caused to fire. Oscillations ensue in the tissue at about 435Hz but as this rate is greater than that at which the receptors can respond, they fire together every alternate cycle, phase-locked to the vibrations.

When the off edge of the pulse arrives it may occur either when a volley of impulses is occurring or between two volleys. The impulse patterns set up by the two situations will be very different; discrimination between them will thus be comparitively easy. The existence of 'on'- and 'off'- sensitive receptors will enhance this effect. Discrimination between two durations which both end at the same point in the cycle, but in different cycles will not be as easy. In such cases, the difference between the two impulse patterns will lie solely in the number of volleys fired during the pulse.

It is worth noting that a difference between impulse patterns of only one volley (i.e. 5mS) is apparently detectable to some extent. A difference of two volleys, is fairly readily so. The difference limen for durations would thus appear to be of the order of 10mS for short pulses, after practice, a figure which corresponds with that of Gescheider (57,58).

The preliminary experiment suggests that a different mechanism is being employed in the discrimination of short durations from that for durations greater than about 200mS; the limen for long durations appears to obey Weber's law to some extent while that for short durations is approximately constant, as shown by figs. 21 and 22.

5:5 The Detection of Simultaneity

5:5:1 Introduction

The study of the ability of the tactual system to discern simultaneity is an important one. From the point of view of an investigator of pattern recognition, a knowledge of the limen for simultaneity would enable him to dedide better which classes of patterns to present. Those patterns which differ only by a relative timing within the limen could be classed together. In a more general sense, simultaneity is closely related to the perception of movement.

The effects of simultaneous, or near simultaneous, stimulation of the skin have been interpreted in two ways. Studies of the so-called 'masking effect' of several stimuli applied simultaneously at several loci have been made, and also of the resolution of two successive stimuli applied to one locus.

The former situation has usually been investigated by measuring the threshold intensity of a particular stimulus and determining how this threshold is influenced when one or more other loci are simultaneously stimulated. Uttal (109) has used electrical pulses applied to several fingers; he has found that 'masking' is more pronounced for fingers adjacent to the masked finger, although the degree of masking is considerable for all. Sherrick (101) has determined the time course of the masking by providing a delay between the two stimuli. He has found that masking is greatest when the stimuli are simultaneous, falling off with delay. When the masking stimulus precedes the test stimulus by 40mS or follows it by 20mS, the masking effect has declined to a constant value. Moreofer, such masking occurs for widely separated loci e.g. contralateral fingers, finger and lip. It would thus seem that the effect is central in origin.

The second way of interpreting the effects of simultaneous stimulation of the skin, the resolution of two successive stimuli, has usually been concerned with a single locus. Uttal (107) and Armett, Gray et al. (5) have employed the technique of applying a pulse, the 'conditioning' pulse, and then later a 'test' pulse at the same site, determining the threshold amplitude of the test pulse as a function of the inter-pulse delay.

Rosner (95) puts the threshold delay for temporal resolution at about 40mS. Gescheider (57,58), on the other hand, estimates it to be only 10mS under optimal conditions for mechanical 'clicks'. He has systematically varied the relative intensities of the two clicks and found that resolution is best when they are approximately equal in intensity, rising to 20 or 30mS for a difference of about 20dB. Gescheider has applied his stimuli to a single fingertip, ipsilateral fingertips and bilateral fingertips and found the performances under these three conditions to differ only slightly, a single finger giving the best results and bilateral fingers the worst.

Wieland (118), in an extension of two-point threshold experiments, has presented either a single electrical pulse or two pulses at different loci on the volar forearm, measuring the temporal delay between the two pulses required for discrimination from the single pulse. She claims that the logarithm of temporal delay is linearly related to the spatial separation;

$$\log T = a - b.D$$

Where D is spatial separation of the loci, T is temporal delay and a and b are constants.

The masking experiments, while examining dependence upon time course and spatial separations, do not explicitly yield estimates of the ability of the subject to detect simultaneity. The resolution experiments, while being more directly concerned with this ability, have not quite come close enough to what was desired for the furtherance of the present line of research; Gescheider has only considered a single locus or two widely spaced loci; Wieland has used electrical stimuli upon the forearm and her experiments have more bearing upon two-point thresholds than simultaneity detection. In both cases, threshold techniques have been employed; for supra-threshold stimuli, results might be different. The experiments performed by the author in this field have been a direct investigation of the ~~detectability of~~ ability of the subject to detect simultaneity and the manner in which this varies with delay and separation on the fingerpad.

5:4:2 Preliminary Experiment

A short experiment (number 31) was conducted to determine the order of magnitude of delays required for resolution on the fingerpad. If neural impulses travel at about 10M/Sec then the inherent time delay due to the increased path length of about 1cm for stimuli at the distal end of the fingerpad should be about 1mS, which is probably too small to be detected without extensive experiments.

The presentation scheme of the preliminary experiment was not AXBX, but a two-alternative forced choice. Two patterns were presented, each consisting of two point stimuli, 5mS in duration. In one pattern they were simultaneous, in the other there was a delay between them of 5, 10 or 20mS. The points were 8mm apart.

With 40 trials at each delay, there were only 11 errors, all occurring at 5mS delay. Thus the limen for resolution must be in the region 5-10mS, in agreement with Gescheider.

The next factor to be investigated was the orientation of the pair of loci stimulated. Experiment 33 was performed with an AXBX scheme and was intended to test discrimination of simultaneous stimuli and stimuli separated by 3mS (and 8mm spatially) in horizontal (lateral) and vertical (proximal-distal) orientations in the same trial series. Of 80 trials in each orientation, 45% errors occurred with vertical arrangement and only 16% with the horizontal arrangement. However, the changes in orientation during the series of trials were found to be very confusing, consequently further measurements were required.

In the same experiment, two-point comparisons were made in each orientation; two simultaneous stimuli separated by 8mm were compared with a single point in the middle. Only 5% errors were recorded in each case. Finally, a simultaneous vertical pair was compared with a simultaneous horizontal pair of points, also 8mm apart. The error rate in this case was 15%.

It was decided to check further the effect of orientation, but to compare only in one orientation in one series. In experiment 34 two pins 8mm apart in a proximal-distal direction were driven by 3mS pulses, either simultaneously or with 3mS delay between onsets. An AXBX experiment was run. Of 104 trials, 31% errors occurred, yielding a d' value of 1.4(±0.25).

The display was then rotated through 90 degrees in a clockwise direction, so that the pins used were oriented laterally, and the experiment was repeated. Of 104 trials, 36% were errors, yielding a d' value of 1.2(±0.25).

The experiment was reprogrammed so that the array could be used in its normal orientation, but two new pins were used, now oriented laterally to check that the subject was not disturbed by the rotated display. Of 104 trials, 34% were errors, yielding a d' value of 1.3(±0.25)

The average error rate in these experiments was 33%, implying a d' value of 1.3, and the two rates for the different orientations do not differ by a statistically significant amount. In view of the known anisotropy of receptive fields, performance may be expected to be slightly better for proximal-distal orientation by perhaps a factor of 1.2. The experimental results do not contradict this.

Before proceeding further with the fingerpad, a simple study was made of the detection of simultaneity by various parts of the body. The forearm was too insensitive for experimentation with the present system, but it was possible to study two adjacent fingers of the right hand, presenting one pin to each finger, the index fingers of both hands and the lower lip, though the latter was not an easy experiment for the subject and the results may not be reliable. Experiment 34 was used. When the index fingers of both hands were employed, the push buttons were operated by the feet. Under each condition, 104 trials were made.

Table VII

Sites of Stimulation	Error Rate	d' Value	d' at ±1 SD
Single forefinger	33%	1.3	1.56 - 1.04
Two fingers of R.H.	29%	1.5	1.76 - 1.25
Forefingers of both hands	23%	1.9	2.16 - 1.64
Lower lip	42%	0.83	1.13 - 0.53

It will be noted that the results do not differ greatly, at least as far as the fingers are concerned. However, it does seem that for the more widely separated loci d' is slightly greater. The lips show rather poorer performance, but this may be due to lack of practice and the difficulty of maintaining steady conditions, rather than any underlying fact concerning innervation.

The next stage in the experimentation was to make a series of measurements, varying both the spatial and temporal separation of the two point stimuli systematically. A number of experiments were thus run; in each, one of the parameters was held at a constant value and the other was varied over a set of values.

In this series of experiments, the effect of only one edge of the pulse was studied. The pulses were made long, about 100mS, to allow transient effects to die down. Their onsets were staggered, but they went off simultaneously. In each experiment, 96 trials were made under each condition.

Experiment 38 maintained the delay at 3mS and varied the separation between the points from 2mm to 8mm.

Experiment 39 was similar, but the delay was increased to 10mS.

In experiment 42, the delay was 5mS.

In experiment 40, the separation was maintained at 6mm and the delay was varied from 3mS to 10mS in 1mS steps.

Experiment 41 covered the same range of delays, but with a separation of 2mm.

The results have been tabulated for d' as functions of separation and delay (Table VIII), and have been recorded in graphical form in fig. 34.

One effect which will be noted is that the results, at first glance, appear to be fairly widely scattered, particularly those for delay. This is not solely due to statistical fluctuations, since many points are about one standard deviation from a smooth curve. If the curves for d' as a function of delay are examined, it will be observed that the fluctuations in the 2mm and 6mm curves mirror each other to a large extent. It thus seems likely that the fluctuations are real, not experimental artifacts. Further examination indicates that the fluctuations are approximately regularly periodic, with a period of about 2mS. This was taken as evidence that travelling waves are responsible, with a period of 2mS and a half wavelength of 4mm to explain the resulting curves. It appears to be some confirmation of the conclusions drawn from the experiments upon duration discrimination.

Let us now consider smooth curves to be drawn through the graphs of results. We observe that as delay is increased, discriminability increases also, more or less linearly. As separation is increased, however, ~~contrary to what might perhaps have been expected,~~ discriminability decreases. Temporal

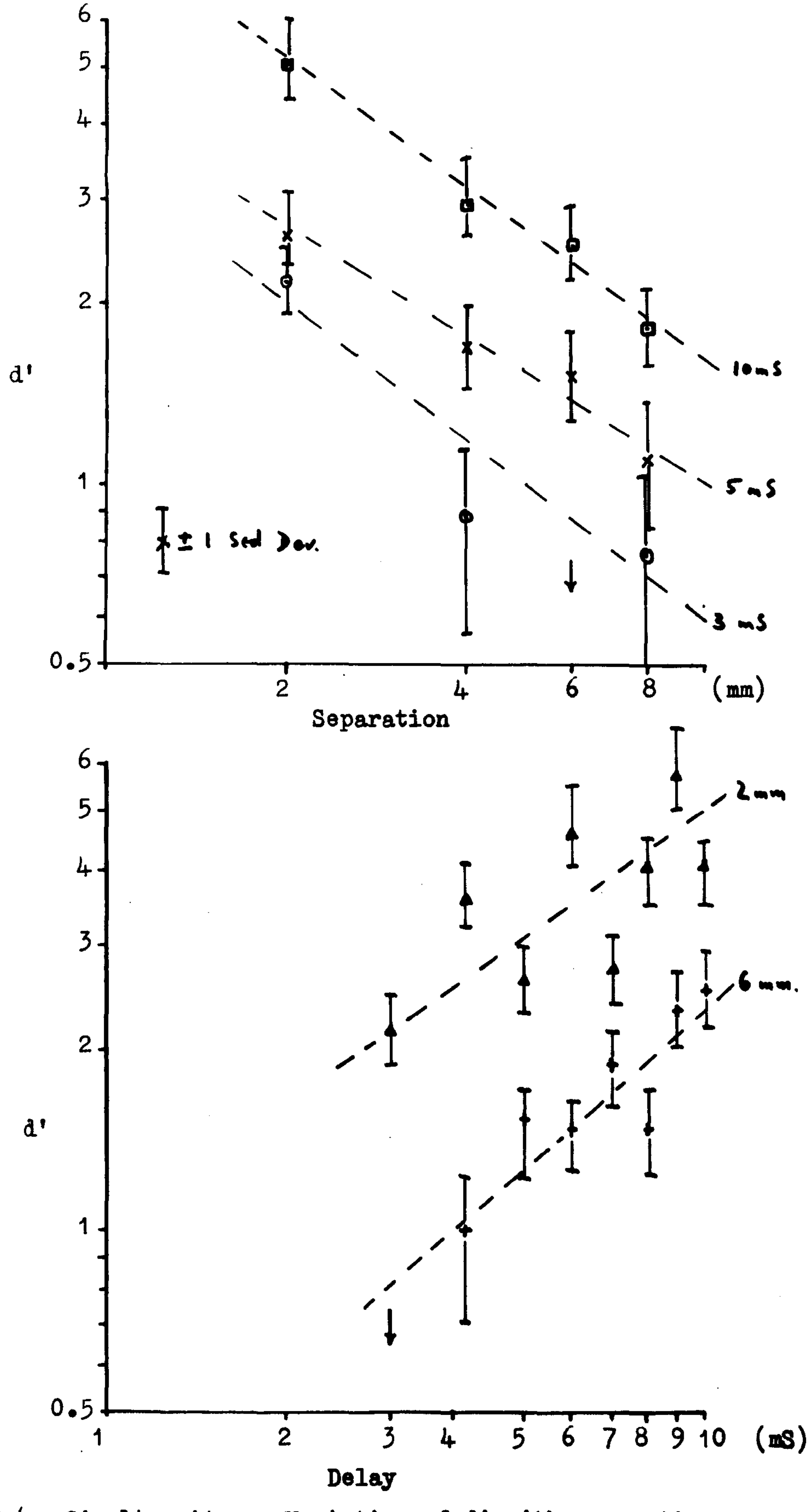


Fig. 34/ Simultaneity. Variation of d' with separation and delay.

judgements therefore appear to be easier when the stimuli are close together.

When the graphs were originally plotted in terms of d' it was noted that the variation of d' with separation appeared linear on a log-log plot. Thus for each of the curves, d' x separation was approximately constant. Moreover, the constants appeared to be proportional to the delay. Thus d' x separation/delay was also roughly constant over the entire range of variation of the parameters. This function was also computed for the full set of observations, and is tabulated below.

Table VIII   Values of d'

Delay:	3mS	4mS	5mS	6mS	7mS	8mS	9mS	10mS
Sepn:								
8mm	0.77	-	1.10	-	-	-	-	1.82
6mm	-0.28	1.00	1.53	1.48	1.89	1.53	2.33	2.50
4mm	0.88	-	1.70	-	-	-	-	2.94
2mm	2.17	3.56	2.60	4.60	2.71	4.00	5.70	5.03

Table IX   Values of d' x Sepn/Delay

Delay:	3mS	4mS	5mS	6mS	7mS	8mS	9mS	10mS	Mean
Sepn:									
8mm	2.05	-	1.76	-	-	-	-	1.46	1.76
6mm	-0.56	1.50	1.84	1.48	1.62	1.15	1.55	1.50	1.26
4mm	1.17	-	1.36	-	-	-	-	1.18	1.24
2mm	1.45	1.78	1.04	1.53	0.77	1.00	1.27	1.01	1.23
Mean	1.03	1.64	1.50	1.50	1.19	1.07	1.41	1.29	1.31

It will be noted that although the range of variation of the function is from -0.56 to 2.05, half of the values are between 1.15 and 1.55. Also, the marginal means show no steady trend of any magnitude. In short, the value of d' x Separation/Delay is approximately constant at 1.31 Metres/Sec.

The near constancy of this function and the fact that its dimension is that of a velocity, immediately leads one to consider whether it might be related to the phi-effect and the conditions for optimum sensation of apparent movement.*

*If two separate loci are stimulated in succession, the sensation elicited may, under some conditions, be that of a stimulus which moves steadily from one locus to the other. This phenomenon is known as the phi-effect.

The experiments of Gibson (64) and Sumby (103) concerning the phi-effect have not been performed upon the fingerpad and so it was deemed necessary to perform a simple experiment to determine the velocities involved. Two pins of the stimulator array were operated by pulses from pulse generators. The pulse durations were set to 100mS and the delay between their onsets was variable over the range 0-100mS. The separation between the pins used was either 2mm or 6mm. The subject was asked to place his finger on the array and to adjust the delay until he felt the best movement effect. This was done for the two separations.

Subject HGB had difficulty in sensing movement and was unable to decide upon a best value for the delay. JPW and GFP did not have good sensations of movement, but did succeed in finding optimal delays. The values the two subjects chose were very similar. At 2mm separation the best delay was about 25mS, yielding an apparent 'velocity' of 0.08M/Sec. At 6mm the best delay was about 45mS, yielding an apparent 'velocity' of 0.13M/Sec.

It was thus found that the 'velocity' for best sensation was an order of magnitude smaller than the constant derived from the simultaneity experiments and not particularly constant.

From the graphs of fig. 34, the wavelength and period of the travelling waves had been found to be 8mm and 2mS respectively. The product of these gives the velocity of the waves, 4M/Sec. This value is a factor of 3 bigger than the simultaneity constant, which is, however, within an order of magnitude.

It is not possible, on the basis of the above results, to relate conclusively the constancy of d' x Sepn/Delay in the simultaneity experiments to the travelling waves in the skin or to the phi-effect.

The results of the simultaneity experiments were also analysed for symmetry, over all separations and delays. Of the 1344 trials in which the left pin was raised before the right, 22.2% errors occurred; of the 1344 trials in which the right was raised before the left, 21.2% errors occurred. The difference is not statistically significant, and so there is no evidence of lateral asymmetry.

5:4:3 Comments

The effects of the double pulse stimulation in the simultaneity experiments deserves consideration. When the loci are widely separated, the receptors they stimulate are different. Thus, after a certain separation is reached, we might expect discriminability to be constant. As the stimuli are moved closer together the number of receptors whose receptive field encompasses both stimuli increases. When the stimuli are very close, they effectively excite the same receptors. From the results, it appears that the tactual system is better at resolving time delays when they are presented to a single set of receptors. It is easier to determine simultaneity of two pulses travelling down a closely related fibres than down those more distantly related. For sites very close together the task becomes that of determining whether one volley or two occurred. With very short delays as well, the refractory period of the receptors would cause the second volley to be inhibited, making discrimination difficult.

5:4:4 Summary

The discrimination of simultaneity has been investigated as a function of spatial separation and temporal delay of the two stimuli.

It was found that discriminability improves with increasing delay, but falls with increasing spatial separation on the fingerpad. These two effects are such that d' x Separation/Delay is approximately constant at 1.31M/Sec.

There is no evidence of asymmetry for such discriminations.

5:5 Spatial Factors

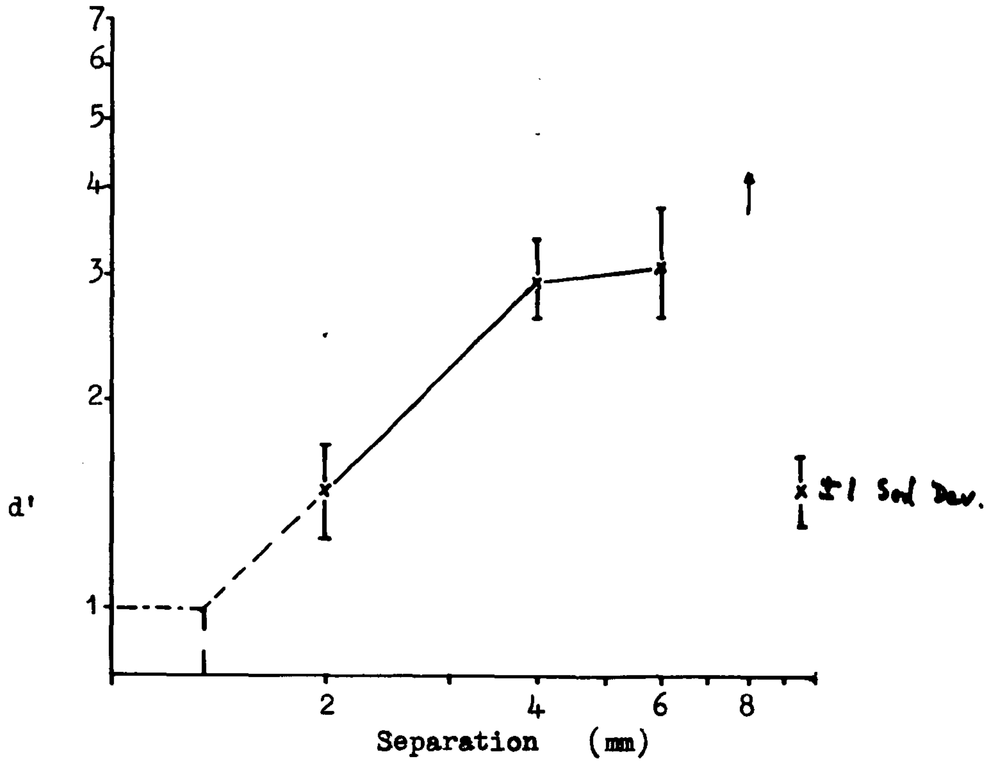
5:5:1 Introduction and Initial Experiments

Some of the simpler spatial effects were investigated. The very first experiments with the full experimental system were intended to perform two functions; to map out roughly the range of discrimination for various stimuli and to check the well known results as a test of the system.

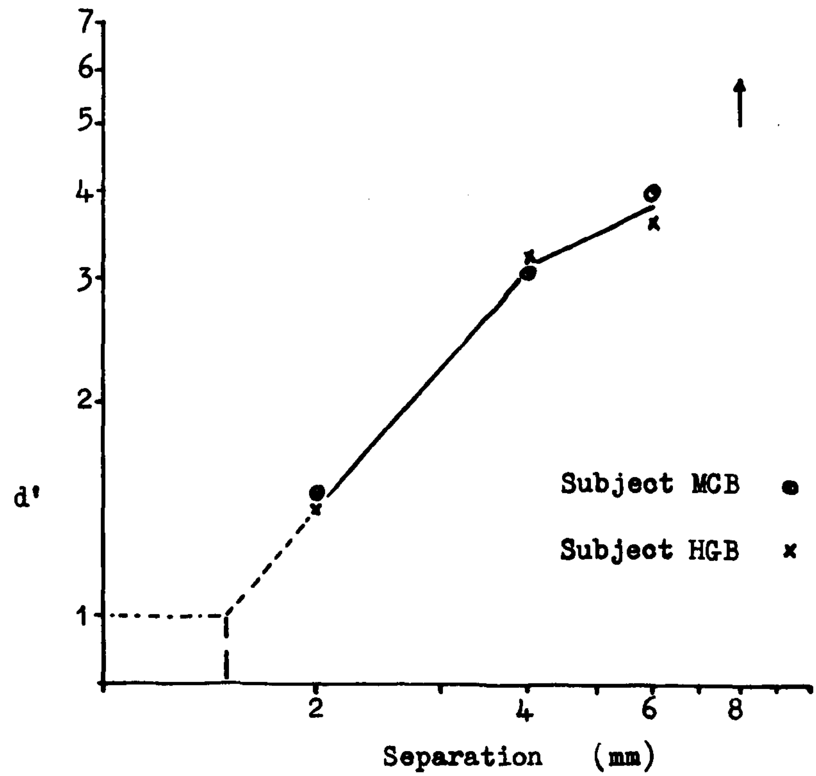
The first experiment run (number 1) was a determination of the ability to localise a single point and compared each point in a horizontal row of five, spaced 2mm apart, with every other. The duration of each pattern was 100mS and each combination was presented 40 times.

The graph of results (Fig. 35a) shows the value of d' to rise monotonically with separation, possibly slackening its rate of rise for separations greater than about 4mm. The separation for which d'=1 is very approximately 1.3mm. Bliss (30) has obtained similar results with an ABX experiment.

The next experiment (number 2) was performed with a vertical (proximal-distal) row of five points upon two subjects. The results (Fig. 35b) are similar in that they also show a monotonic rise of d' value with separation which lessens its rate of rise at about 4mm. The results for the two subjects agree very well. The separation for which d'=1 is very approximately 1.5mm.



a/ Expt 1: Lateral direction.



b/ Expt. 2: Proximal-distal direction.

Fig. 35/ Localisation of a single point.

It is well known that the two-point threshold is anisotropic (65,32) and that receptive fields are likewise. In the case of the fingerpad, the threshold in a proximal-distal direction is about 1.2 times greater than that in a lateral direction. The above values of d' are similarly related.

The spatial resolution was also measured in terms of the classical two-point threshold. In experiment 44, a single pin was compared with a pair of pins, oriented horizontally, spaced 2,4 or 6mm apart. Each pattern was presented for 50mS and 120 trials were made for each comparison in an AXBX scheme.

The results are plotted in fig. 36. They show that the two-point threshold under the conditions of the experiment must be very small, less than 2mm.

As a general introduction to spatial factors, an experiment (number 5) was performed to study the effects upon discriminability of various types of distortion of a simple pattern. A set of five points arranged in a quincunx was taken as the basic pattern, because it is made of several points and a number of simple distortions are possible. The basic pattern was compared with the results of applying various operations to it. The patterns were each shown for 100mS and each pair was presented 60 times in an AXBX scheme.

The results are shown in pictorial form in Table X.

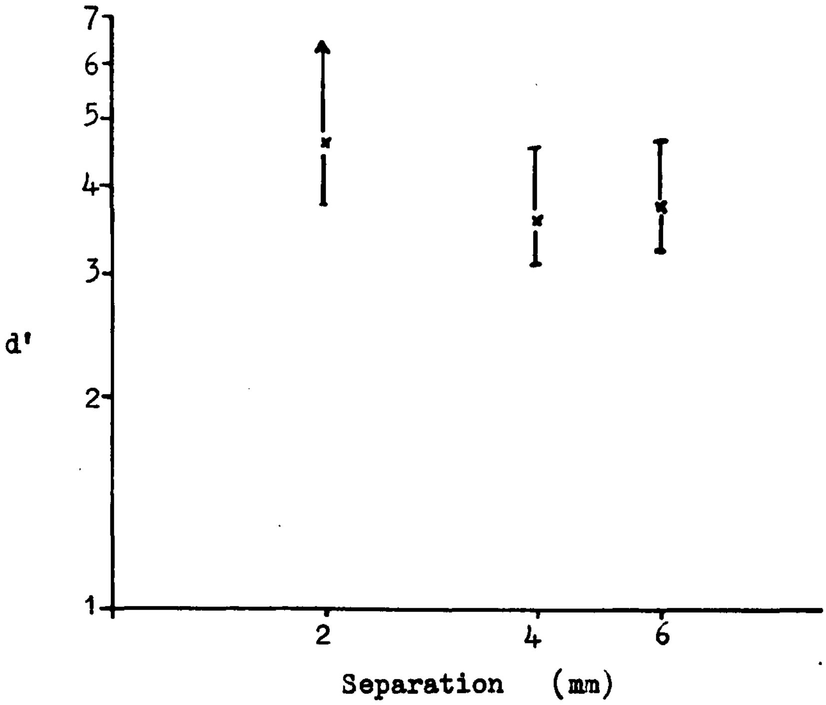


Fig. 36/ Expt. 44: Two-point threshold. Discriminability of single pin from a pair of pins as a function of separation of the pair.

Table X

Basic Pattern:

```
X . X
. X .
X . X
```

Where X denotes pin up,
. denotes pin down.

Distorted Pattern	Error Rate	d'	d' at ± 1 Std Dev.
X . X . . . X . X	48%	0.39	-0.6 to 0.85
X . X . X . X . .	45%	0.64	-0.3 to 1.0
X X . . X . X . X	40%	0.94	0.54 to 1.34
X . . X . X . X . X	17%	2.33	1.83 to 2.83
X . X . X . X X X	37%	1.10	0.70 to 1.50
X . X . X . X . X X	38%	1.05	0.65 to 1.45
X . X . X . X . X X	48%	0.39	-0.6 to 0.85

From the results it appears that, with one possible exception, the various distortions do not have significantly different effects upon discriminability.

The one deformation which gave substantially better discriminability was studied further in experiment 6. In this, several versions of the anomalous pattern were compared with the original. The effect of the central point was also determined. Each combination was again presented in AXBX scheme 60 times.

Table XI

Patterns:

```
 1        2        3          4          5          6

X . X    X . X    X . . X    X . . X    X . . X    X . X
. X .    . . .    . . .      . X .      . . .      . . .
X . X    X . X    X . X      X . X      X . X      . . X
                                                   X
```

Results:

Comparison	Error Rate	d'	d' at ± 1 Std Dev.
1 & 2	38%	1.05	0.7 to 1.4
1 & 4	22%	1.95	1.6 to 2.3
2 & 3	40%	0.94	0.57 to 1.31
2 & 5	37%	1.10	0.74 to 1.46
2 & 6	42%	0.83	0.41 to 1.25
3 & 4	48%	0.39	-0.6 to 0.8
3 & 6	30%	1.48	1.16 to 1.80

The results were further compounded together;

Centre v. No Centre	Of	120 trials,	43% errors.		d'=0.77±0.29
Basic v. Shifted	"	240 "	35%	"	d'=1.21±0.16

The results show that the special pattern resulting from shifting a corner point is not significantly more discriminable than those for other sorts of shift. The discriminabilities of variously distorted patterns were found to be not significantly different, on the basis of the above results.

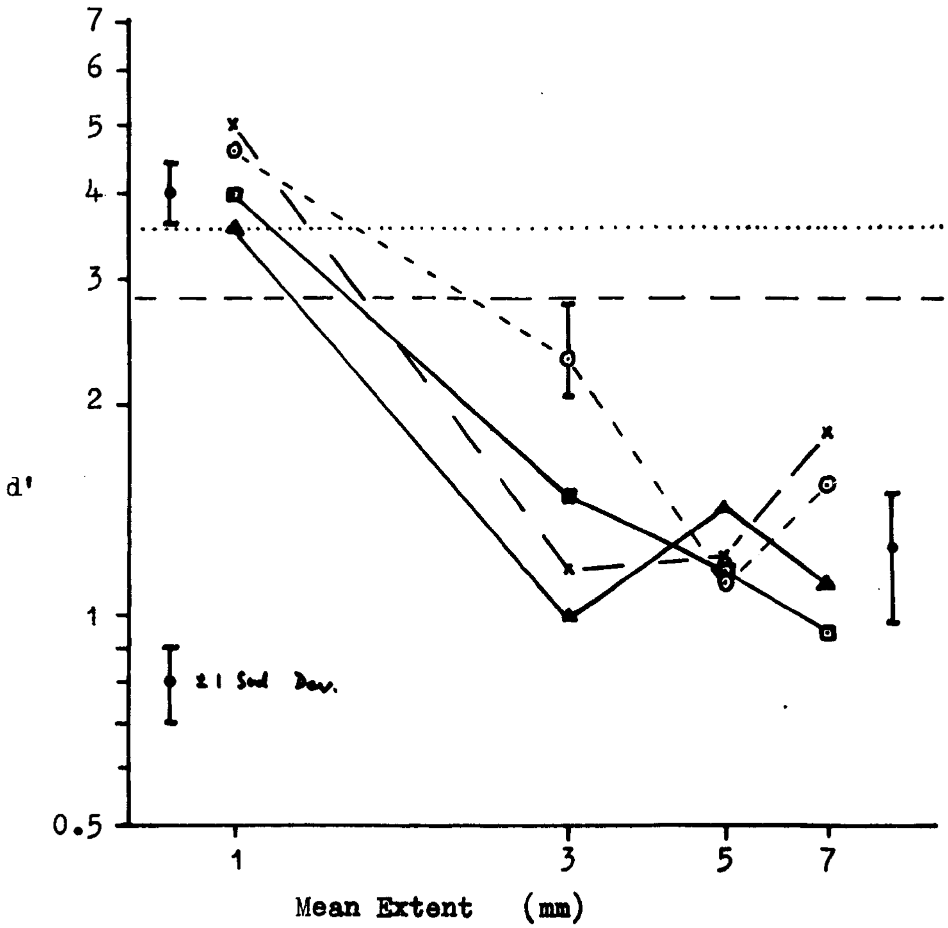
5:5:2 Spatial Extent

The next factor to be studied was the linear extent of a pattern and the ~~discrimin~~detectability of an increment,

In experiment 47, each pattern consisted of a pair of points in a horizontal row, presented for 50mS. Comparisons were made between pins N places apart and pins N+1 places apart. The results are shown in fig. 37. The d' measures, based upon 120 trials, are plotted against the mean separation of the pins for the two patterns. The point plotted for 1mm thus represents the result of comparing a single pin with two pins 2mm apart; the point at 3mm represents the comparison of two pins 2mm apart and two pins 4mm apart, etc.

Several other sorts of patterns were treated in a similar manner. Experiment 48 compared solid rows of N and N+1 pins, the results being plotted against the mean length of the row.

Experiment 49 compared patterns which consisted of parallel



ʘ- - - Expt. 47: Separation of two points. e.g. • • & • •

x— - Expt. 49: Separation of parallel lines.

▲——— Expt. 48: Length of a row.

⊡——— Expt. 52: Width of a block.

········ Expt. 56: Localisation of single point.

— — Expt. 57: Localisation of single line.

Fig. 37/ Spatial Factors: Detectability of an increment in spatial extent, as a function of mean extent.

vertical rows of five pins, separated by N and N+1 places, to determine whether there was any evidence of spatial summation and consequent improvement of performance by using parallel lines instead of points. Results are plotted against mean separation.

Experiment 52 compared solid blocks of pins, five pins vertically and N and N+1 pins wide. Results are plotted against mean width.

For comparison purposes, the value of d' found for localising a single point under the same conditions (experiment 56) is marked on the graph. The two patterns compared in this case were single points in one of two adjacent positions.

Comparing spacings between two points under the conditions of the experiment can be thought of as localising a single point while a second point is displayed in a constant position. Similarly for the parallel lines.

A further experiment was performed (number 57) in which the subject was asked to localise a single vertical line of five points, once more with 50mS duration and an AXBX scheme. The value of d' so obtained is also plotted in fig. 37 for comparison purposes.

The several curves obtained do not differ very greatly from one another. The left-hand point of all the curves is much higher than the rest; for the two point and solid row experiments this represents comparing a single point with two adjacent points, a classical two-point threshold test. For the parallel line and solid block experiments it represents comparing a single line of five points with a double line of five. The two patterns differ by a factor of two in the number of pins activated and spatial extent in each case, so this discrimination might be expected to be easier than the rest.

The remaining three points of each curve are rather more variable and it is difficult to make generalisations. Indeed, if we take the average of all four curves we find it to be fairly constant over the three right-hand points.

What deductions can be made? We might expect a law similar to that of Weber to apply; the detectability of the increment might fall linearly with increasing spatial extent. Such a possibility cannot be ruled out on the basis of these results, but it seems much more likely that the detectability may become constant for extent greater than 2mm. There may also be a difference in kind between the results for solid figures and those for the spaced dots or lines. The graph suggests that for parallel lines and points detectability may ultimately increase with increasing extent, while for solid figures it may ultimately decrease.

An alternative way of describing the performance of the subject to saying that he is estimating a length and discriminating on the basis of his estimates is to say that he is endeavouring to ignore the major part of the pattern and trying to base his judgement upon the position of a piece of it. The latter strategy would be expected to yield constant d' for large spatial extent.

It seems as though the presence of pins near to the pin upon whose position judgement is based can impair that judgement. For the solid figure, the effect will be constant and hence so will be d'. For the two lines or two dots, the further they are apart the less the effect may be, and hence the better the discriminability.

Adding together the results for the continuous figures, and those for the two-part figures we find overall error rates of 35% and 26% respectively. As these results are each based upon 720 trials, their standard errors are about 1.7% and thus their difference is significant. Performance is better for the two-part figures, supporting the interaction hypothesis.

Collecting the results together in a different manner, we can determine the effect of vertical extent. Adding those for the linear patterns (two points, solid row) we obtain an overall error rate of 32%. Adding the results for the figures with vertical extension, (the parallel lines and solid block) we obtain an error rate of 30%. Once more the standard errors are about 1.7% so the differences in this case are not significant.

Thus the vertical extent of the figures does not seem to assist or hinder the discrimination. Foley and Dewis (45), studying vernier acuity on the fingerpad, have found that increasing the width of the two lines assisted in producing more accurate judgements. Verillo (111) has found that threshold for vibration falls with increasing area of stimulation. Such a spatial summation effect does not seem to be at work here.

To provide more information on this subject, experiments were performed to determine the detectability and discriminability of gaps. Experiment 51 examined detectability; a row of five pins in a horizontal line was compared with a row with a gap of one, two or three pins, in an AXBX scheme. For each comparison, 120 trials were made, the duration of presentation again being 50mS. The results are shown in fig. 38, d' being plotted against mean gap size. It will be observed that the gap must be quite large, about 5mm, to be detected. Chan (37) has found a similar figure for the detection of gaps in rings, although in ~~this case~~ her experiments exposure time was not limited.

Experiment 50 was similar to those involving parallel lines etc. Gaps in a row of five pins were again used as patterns, and this time a gap of N pins was compared with one of N+1 pins. Again 120 trials were made for each comparison in an AXBX scheme and the patterns were shown for 50mS each. The results are shown in fig. 39.

In this case we see that the discriminability increases with increasing mean size of gap (roughly as the square root), in

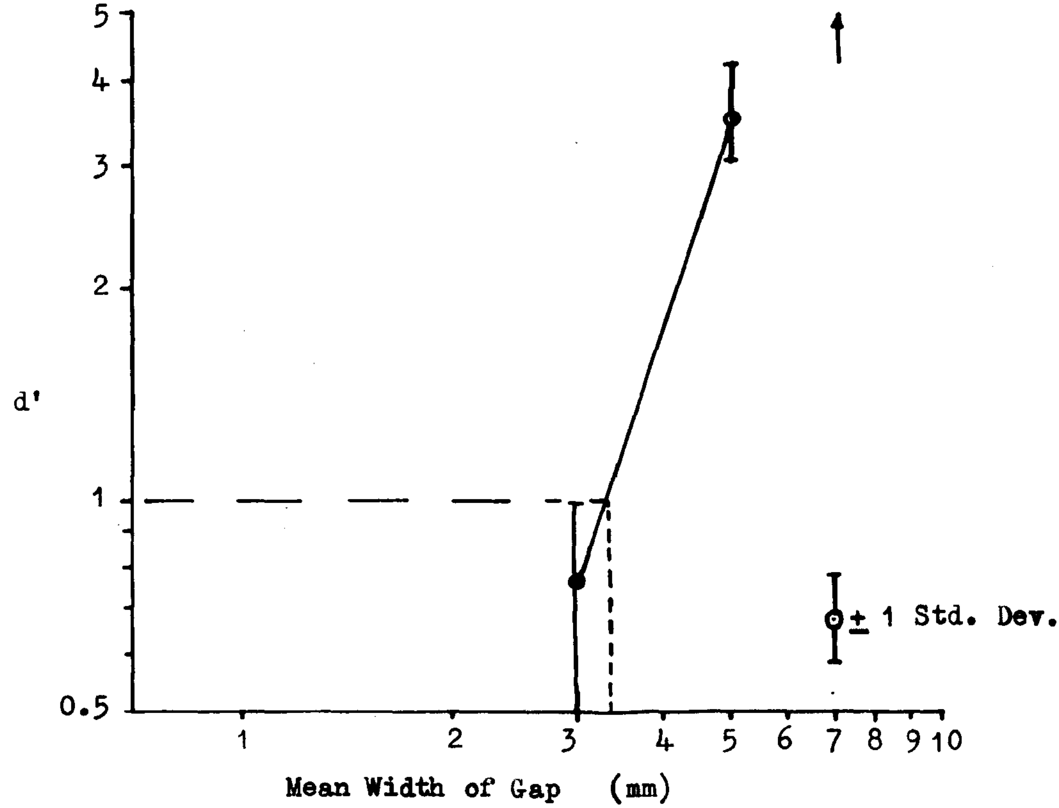


Fig. 38/ Expt. 51: Detection of a gap in a row of pins.

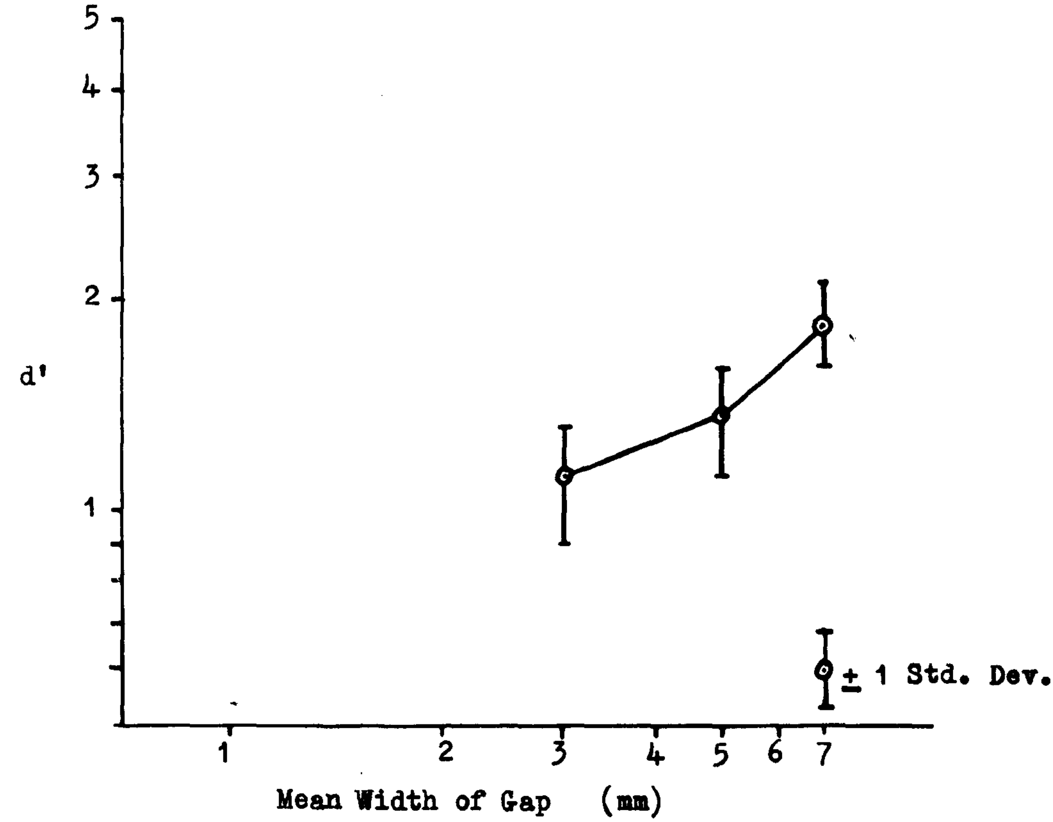


Fig. 39/ Expt. 50: Detection of an increment of a gap in a row of pins, plotted as function of mean gap width.

correspondence with the right-hand points of fig. 37. This provides further support for the hypothesis of interaction of adjacent stimuli.

The gap in a row of pins can also be considered to be equivalent to two separate rows of pins. As the gap increases, the mutual interaction of the two rows decreases. Also the remaining length of the original row decreases, so that the increment of the gap represents an increasing proportion of this remainder. From this also we should expect performance to improve as the gap is increased.

A Gestalt view can also be taken of the situation. Solid figures are obviously single entities, while figures with a gap in their middle can either be considered as a single whole or as two separate entities. Perhaps the increase in discriminability of such figures with the width of the gap reflects an increasing probability of interpreting them as two figures.

The interaction of points and the lack of spatial summation observed in the experimental results both require further investigation.

5:5:3 Summary

In a series of experiments, the effects of spatial extent upon the detectability of an increase in one dimension have been investigated.

The detectability of an increment in dimension is significantly greater when the dimension is represented by a gap, than when it is continuous.

There appears to be no improvement in performance obtainable by extending the figures in a perpendicular dimension.

5:6 Effects of Spatial Interactions

Having performed the series of experiments upon spatial extent, and having decided that there was evidence of interaction of stimuli on the fingerpad, it was deemed necessary to pursue a study of these interactions in more detail.

5:6:1 Introduction

The effects of stimulus interactions have been observed by several experimenters.

Geldard and Sherrick (56) employed 10 vibrators, distributed over the entire body. Each pattern consisted of stimulation at several sites simultaneously. Two patterns were presented in succession and the subject was required to state whether they were the same or different. It was found that error rates increased with the number of stimuli in the patterns and also with the number of loci the two patterns possessed in common.

Brown et al (36), in a similar experiment with electrical stimuli and 10 sites, also concluded that accuracy of recognition declined with increasing number of sites stimulated. Their experiments were performed with the electrodes distributed over the entire body and with them on the abdomen only. They concluded that accuracy was higher for the more widely dispersed case.

Hill and Bliss (125) used airjet stimulators, one applied to each of the 24 phalanges of the fingers of both hands. A single pattern was presented and the subject was required to list all the points stimulated. Analysis of the results showed that once more as the total number of stimulus points increases, the number of points perceived increases less rapidly, while the fraction of points correctly perceived actually decreases. The stimuli applied to the distal phalanges (the fingerpads) were more correctly reported than those applied to the other two phalanges.

The type of interaction which had been encountered in the experiments of the previous section were concerned with the accuracy of localisation. The investigations of other authors have been less specific, being concerned with the detection of the presence of stimuli as well as their location. Because of this more general approach, certain features of the interaction (e.g. how it varies with range) cannot be reliably assessed. A direct study of the effect of interaction upon accuracy of localisation of elements of a pattern was therefore made.

The task chosen was the discrimination of patterns whose only difference was in the location of a single pin, which could appear in one of two adjacent locations. In this case, the total peripheral neural activity should be reasonably constant and vary mainly in distribution. In the cases studied by other authors, the level of activity was allowed to vary widely also.

An alternative view of the experiments is that the subject was required to localise a pin while various distracting influences, identical in the two patterns being compared, were applied.

5:6:2 Variation across the Finger

The first experiment of this series (number 60) was designed to determine the variation in performance associated with position on the fingerpad. The patterns consisted of single pins, of a horizontal row of five, raised for 50mS. Each was compared with each of its neighbours 160 times in an AXBX presentation. Alternate trial series were made with the array rotated through 180 degrees to reduce the effects of idiosyncrasies of the individual pins.

Table XII

Pins Compared	Error Rate	d'	d' at ±1 Std Dev
1 & 2	9.5%	3.14	2.74 to 3.54
2 & 3	11%	2.94	2.64 to 3.24
3 & 4	17%	2.33	2.08 to 2.58
4 & 5	12%	2.82	2.52 to 3.12

From these results it was concluded that the deviation from uniformity was not statistically significant. It is possible that the task is slightly easier near the edge of the fingerpad, but this is not certain.

5:6:3 Interactions of Two Pins

The next stage in the investigation was to determine the extent of interactions between two pins as a function of their relative and absolute positions. The pin upon which discrimination was to be based could be raised in one of two adjacent locations. The second pin could occur in one of four positions, two in the same horizontal row, and two in the same vertical column. The second pin was raised and lowered simultaneously with the test pin and occurred in the same position in the two patterns compared. In the same experiment, trials were made without the second pin for comparison purposes.

To study orientation effects, four series of runs were made with the array rotated through 90 degrees between the series, but activating the same pins. As a further check, one of the four runs was reprogrammed so that the configuration of pins used was rotated while the array was kept in its normal orientation. Thus several combinations of events were represented. The two possible locations of the test pin could be oriented horizontally or vertically; the second pin could be either in line with these two locations or perpendicular to their line; it could also be at one of two distances from the test pin. The experimental results have been summed in various ways to show dependence upon each of these factors in turn.

Once more, the patterns were displayed for 50mS in an AXBX scheme.

The results are presented in graphical form in fig. 40. Graph a/ shows the results broken down fully according to whether the test pair of positions were oriented vertically or horizontally, and whether the second point was in line with or perpendicular to the line of the test points. The discriminability is plotted as a function of distance of the second point from the pair. Each point represents 240 trials.

Graph b/ shows the same results summed over orientation of the second point, also plotted as a function of distance of the second point from the first, Each point on this graph represents 480 trials. It will be observed that discriminability for horizontal orientation of the test pair is a factor of 1.2 times better than that for vertical orientation, both for a single point only and for the two point case. This is taken as further confirmation of the anisotropic sensitivity of the fingerpad. To achieve the same degree of discriminability, the positions compared in a vertical orientation must be 1.2 times further spaced than those oriented horizontally. This is in correspondence with the results of Gomulicki and Zangwill (65), who found that two-point thresholds bear a similar relationship on the fingerpad.

Graph c/ shows the results summed over the orientation of the test pair, so that the two cases considered are 'in-line' and 'perpendicular'. They are once more plotted against distance of the second point with 480 trials per graph point. It will be observed that for the larger separation, the two situations are

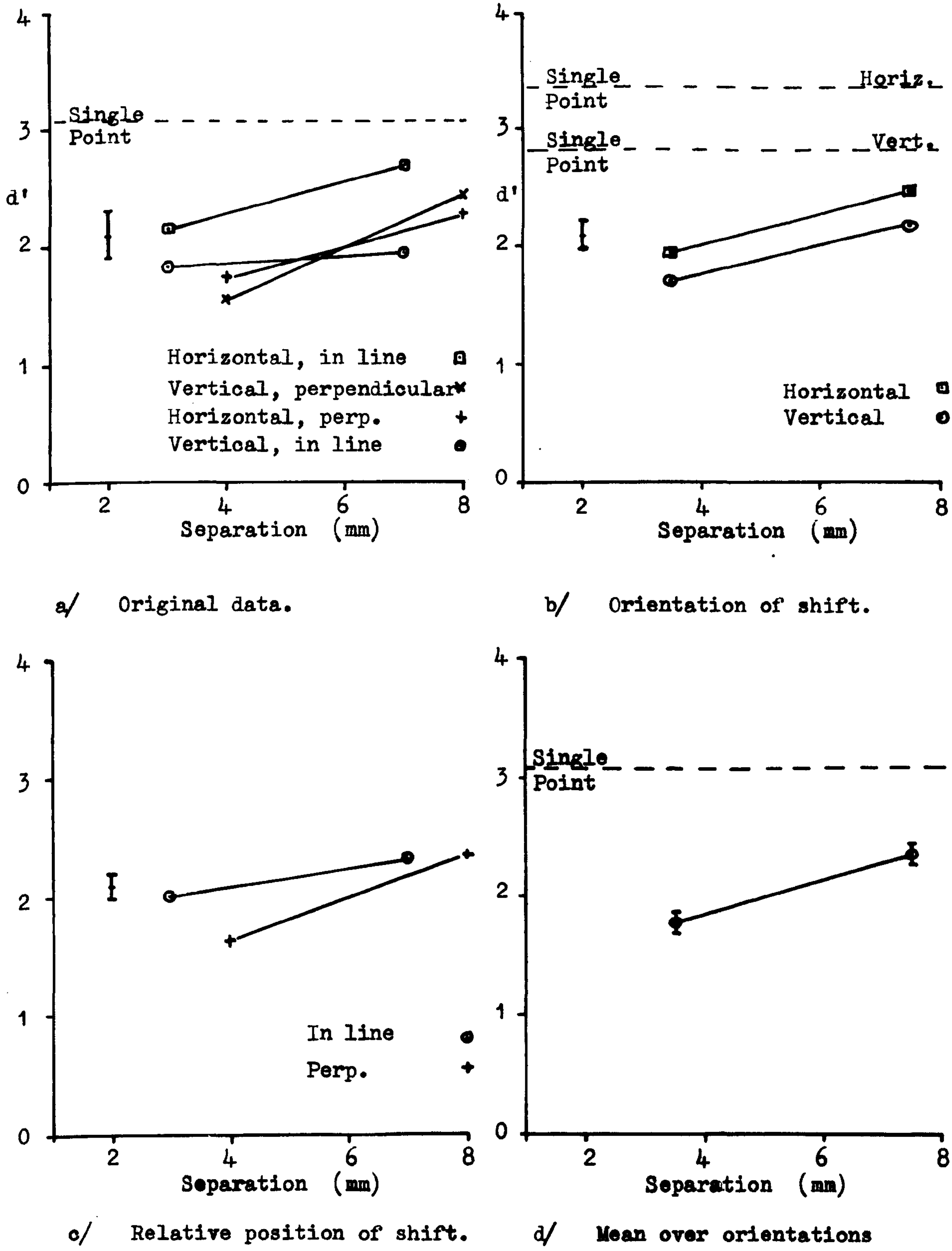


Fig. 40/ Interaction of two pins: Discriminability plotted against mean separation. (Note: The connecting lines have been drawn to assist the eye. They are not intended to imply linear functions).

equivalent, but for the smaller separation the interaction is greater for the perpendicular case. A possible explanation is that in the in-line case, the maximum separation of the two points is 4mm, while for the perpendicular case it is only 2.83mm (the minimum separation is, in each case, 2mm). Thus the former might produce a greater difference between the patterns of neural excitation than the latter.

Graph d/ shows an overall average, formed over all orientations. Each point is therefore based upon 960 trials. It will be observed that the interaction falls off with increasing separation, though it is still in existence at 7mm.

5:6:4 Variation of Interaction with Separation

The next step in the investigation of interaction was to perform experiments in which the separation of the interacting points was varied in small steps over a range of values. Because of the anisotropy of the fingerpad, the separation was varied in a proximal-distal direction, so that the effect of a 2mm step would be as small as possible, being made in the direction of least sensitivity.

Two experiments were performed. In the first (number 66) the pair of possible locations of the test pin were oriented vertically, the second pin being in one of five positions in line. In the second experiment (number 69) the test pair were horizontal and the second pin was in one of six positions in perpendicular orientation. In each case, trials were also made without the second pin. The duration of the patterns was again 50mS, and they were presented in an AXBX scheme, 120 trials per combination.

The results are shown in fig. 41. The value of d' is plotted against the average separation, i.e. the separation of the second pin from a point midway between the two test locations. From the graph, it can be seen that, for separations less than 4mm at least, the degree of interaction increases as separation decreases. For distances greater than 4mm interaction is approximately constant for the case of a vertical test pair, with the second pin in-line. The other case seems subject to large fluctuations, with a period of about 4mm. The reason for this is not clear. But for the point at 6mm, which is statistically significantly deviant, it would be possible to conclude that the two curves are similar. ~~It seems that~~ Possibly travelling waves may be responsible, the points of one curve possibly being associated with nodes, those of the other with antinodes.

It seems that even for large distances, interaction still exists. The two curves level out at values of d' below those obtained for single points, thus indicating that the interaction is widespread, covering an area at least the size of the fingerpad. It may also be comprised of two components, one with a range of about 5mm, which may be due to the deformation of the skin, and the

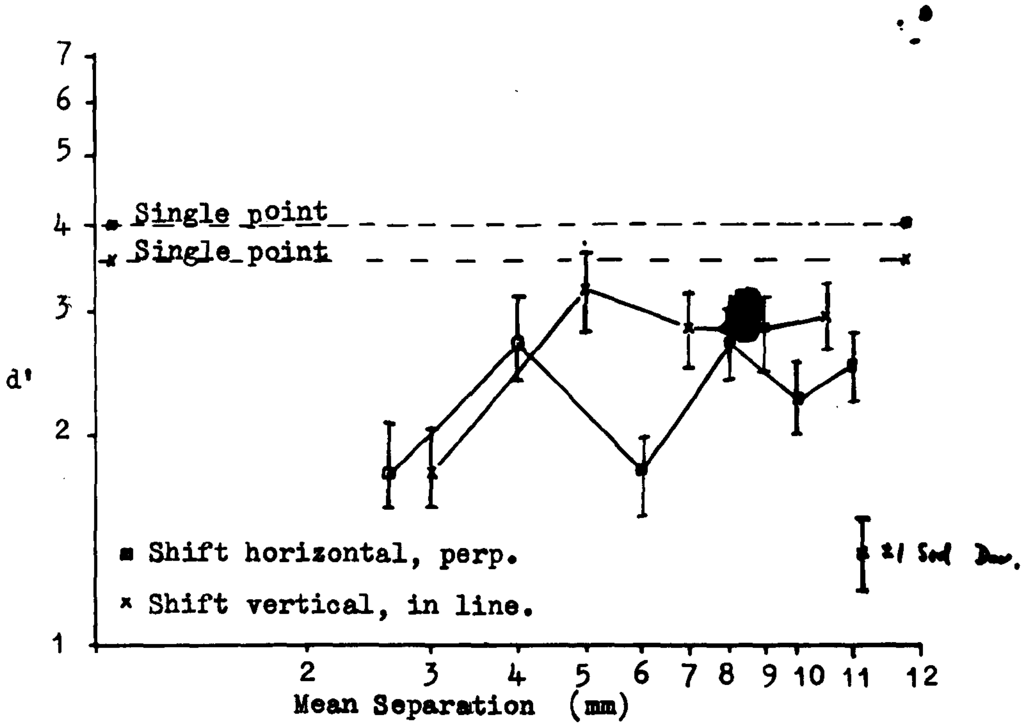


Fig. 41/ Expts. 66,69: Interaction of two pins. Discriminability plotted against mean separation.

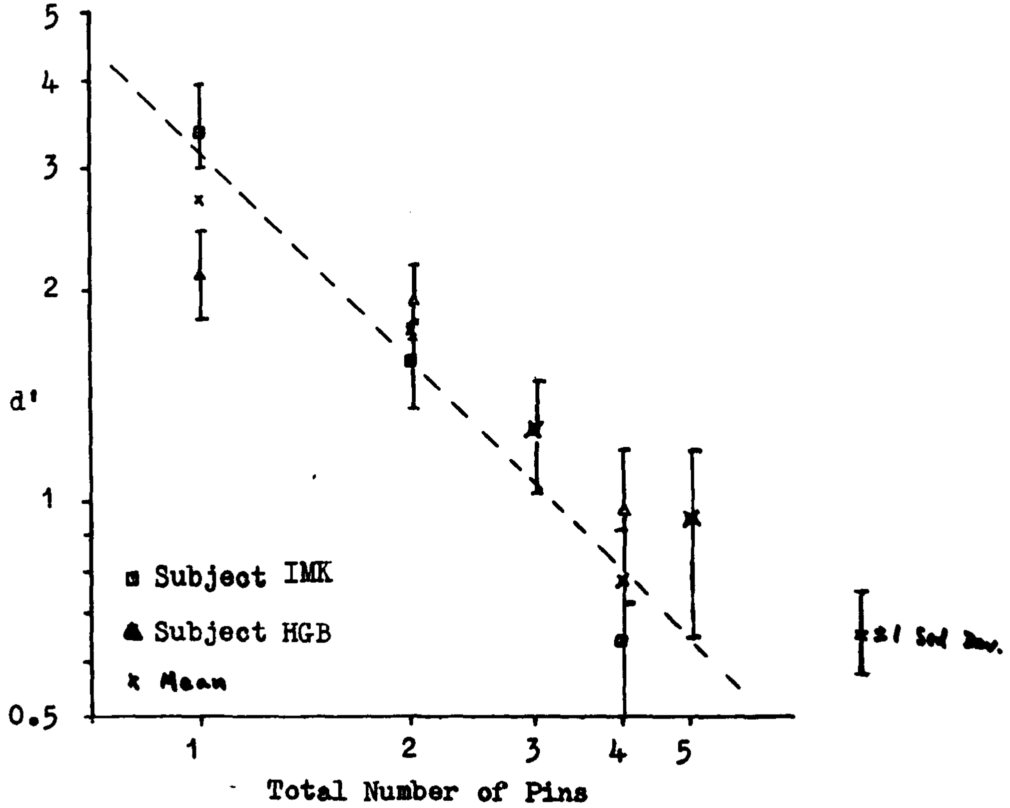


Fig. 42/ Expt. 70: Interaction of a number of pins. Detectability of a displacement of one pin as function of total number.

other with an indefinite range which is probably neural in origin.

5:6:5 Interaction of a Number of Points

Having determined the range and degree of interaction of two pins, the next stage was the investigation of the effects of a number of pins upon the same task.

Experiment 68 was designed to compare the interactions of up to three pins. The basic task was as before; one pin could be raised in one of two positions, C2 or C3, adjacent in a vertical direction. The extra points numbered one or two and were C1, C1 and C4, A3, or A3 and E3. Thus the effect of one or two points in line with or perpendicular to the test points could be studied. Once more, each pattern lasted 50mS and 120 trials were made with each combination in an AXBX scheme.

The results are given in the table below.

Table XIII

Extra Points	Error Rate	d'	d' at ±1 Std Dev.
None	12%	2.82	2.42 to 3.22
C1	20%	2.09	1.79 to 2.39
C1 & C4	40%	0.94	0.64 to 1.24
A3	25%	1.76	1.46 to 2.06
A3 & E3	31%	1.42	1.12 to 1.72

From the table, it can be seen that as the number of extra points is increased the value of d' decreases. However, for one extra point the interaction appears to be greater for the perpendicular case, while for two points it is greater for the in-line case.

The results have therefore been summed together and presented solely as a function of the number of pins.

Table XIV

Total Pins	Error Rate	d'	d' at ±1 S.D.
One	12%	2.82	2.42 to 3.22
Two	22.5%	1.92	1.72 to 2.12
Three	35.4%	1.19	0.99 to 1.39

It appears from these results that increasing the number of pins reduces d'.

A further experiment (number 70) was conducted upon two subjects to determine the effect of three and four extra pins as well. The details are as for the preceding experiment, and the results are presented in tabular and graphical form.

Table XV

Extra Points	Total no. of Pins	Subject HGB		Subject IMK	
		Error Rate	d'	Error Rate	d'
None	1	8%	3.38	20%	2.09
C1	2	28%	1.59	22%	1.95
C1 & C4	3	34%	1.26	33%	1.31
C1, C4 & A3	4	45%	0.64	39%	1.00
C1, C4, A3 & E3	5	40%	0.94	40%	0.94

From fig. 42 it will be observed that within the limits of error of the experiments, the discriminability of the patterns falls with increasing total number of pins. Moreover, on a log-log plot the results approximate to a straight line with slope approximately -1 (the dotted line) i.e. the value of d' is approximately inversely proportional to the number of pins in the pattern.

Hill and Bliss (124) concluded, from analysis of their experiment, that increasing the number of stimuli in the pattern decreases accuracy of localisation, though not as rapidly as in experiment 70 above. Their stimuli are, however, rather more widely dispersed than those of the experiments upon the fingerpad. In the latter case, there may be interaction of the deformations of the skin resulting from mechanical stimulation.

5:6:6 Comments

The results of this section may be indicative of an homeostatic system, which adjusts its gain to maintain a constant level of signal emerging from it. If such a mechanism exists in the tactual system, as more pins are raised to form more complex patterns and the receptor response is increased, ~~the gain~~ the gain would be reduced to maintain a constant level of activity at its output. Thus the difference between patterns of neural activity, resulting from the two positions of a single pin among many, would become ~~be~~ proportionately less as the total number of stimulus points increased. Hence, the discriminability would decrease.

The existence of much inhibition, even at the level of the spinal relay (43), lends weight to the possibility of such a mechanism.

An alternative view is ~~would be~~ that the tactual system might determine the position of the centre of gravity of the pattern, discrimination being based upon this average position. The more pins that are present in a pattern, the less effect the position of any one of them has on the centre of gravity, and hence the less the discriminability.

The manner in which the degree of interaction varies with range suggests that two mechanisms may be involved. For distances greater than about 4mm on the fingerpad, the interaction appears to be approximately constant. From the work of others, it also appears that interaction exists even when stimuli are applied to locations spread over the fingers (124) or the entire body (56). This component of the interaction must therefore reflect a general wide-reaching convergence of information in the somatosensory system, which is a property of the neural organisation.

For distances less than 4mm on the fingerpad, interaction increases as range is decreased. Since the range of deformation of the skin by a point stimulus is of the same order it seems likely that this component of interaction results from the physical properties of the skin and the stimulus.

5:6:7 Summary

It has been found that the presence of extra point stimuli impairs the ability to distinguish between two possible positions of a point.

The impairment decreases with increasing separation up to about 5mm, whereafter it may be approximately constant.

The impairment also increases with the number of extra points.

5:7 Pattern Duration

5:7:1 Introduction and Preliminary Experiments

In the previous series of experiments, the effects of some spatial properties of the patterns upon a spatial judgement had been investigated. In the succeeding experiments, the effects of a temporal property, namely duration, were also studied.

There is evidence of temporal summation in the tactual system. Verillo (112) has reported that for stimuli of several square millimetres in area applied to the fingerpad, temporal integration does occur. For stimuli of small area, however, he finds no such integration. Berglund et al (20) have found intensity of sensation to increase linearly with duration of presentation, up to about 200mS, whereafter it is constant.

It seems thus that there exists some form of temporal integration as far as thresholds and sensation magnitudes are concerned. It remains to be determined whether the same is true for discriminating features of patterns other than simple presence or absence of a point. Information concerning position might be accumulated by the tactual system over a period of time or might be present in even the most brief of supra-threshold patterns.

To resolve the question, a series of experiments was performed in which the subject was required to discriminate between patterns which differed spatially, while the duration of presentation was varied.

The first type of experiment to be employed in this way was a two-point threshold test (number 45). A single pin was compared with two adjacent pins, 2mm apart, and the duration of presentation was varied, the duration of all four patterns in the AXBX scheme being the same. With each duration, 120 trials were made. The results are tabulated below.

Table XVI

Duration	Error Rate	d'	d' at ± 1 S.D.
3mS	6%	3.77	3.27 to 4.27
10mS	7%	3.56	3.06 to 4.06
30mS	5%	4.00	3.50 to 4.50
50mS	3%	4.60	3.90 to 5.30 (expt 44)

The error rates were so low that they were liable to be affected strongly by a momentary lapse of concentration by the subject and are thus at almost the limit for usable results. A task which incurred much higher error rates would provide more reliable results as well as a greater range and improved resolution.

As response in the previous experiment was based largely upon the intensity of sensation, it was felt that if the number of pins in the two patterns were equal the task would be made more difficult and would be one relating to spatial properties alone. The patterns were thus changed to a/ two pins separated by 2mm, and b/ two pins separated by 4mm, horizontally. The task can be thought of either as a judgement of the separation of the pins, or as a judgement of position of one pin in the presence of a second. The subject, however, was merely asked to discriminate to the best of his ability, in whatever way he felt best.

In this experiment (number 46) 120 trials were made with each duration, in an AXBX scheme.

Table XVII

Duration	Error Rate	d'	d' at ±1 S.D.
3mS	37%	1.10	0.85 to 1.35
10mS	32%	1.37	1.12 to 1.62
30mS	31%	1.42	1.17 to 1.67

These error rates were now suitable for analysis and further trials could be made with various other durations.

5:7:2 Main Experiments

A series of further experiments was performed. In each, three durations were involved, one of which had been presented in a previous experiment to enable consistency of results to be checked. In each experiment also, the three durations chosen were spread over the range 3mS to 1000mS in an endeavour to maintain stability of performance. The results are shown dotted in fig. 43.

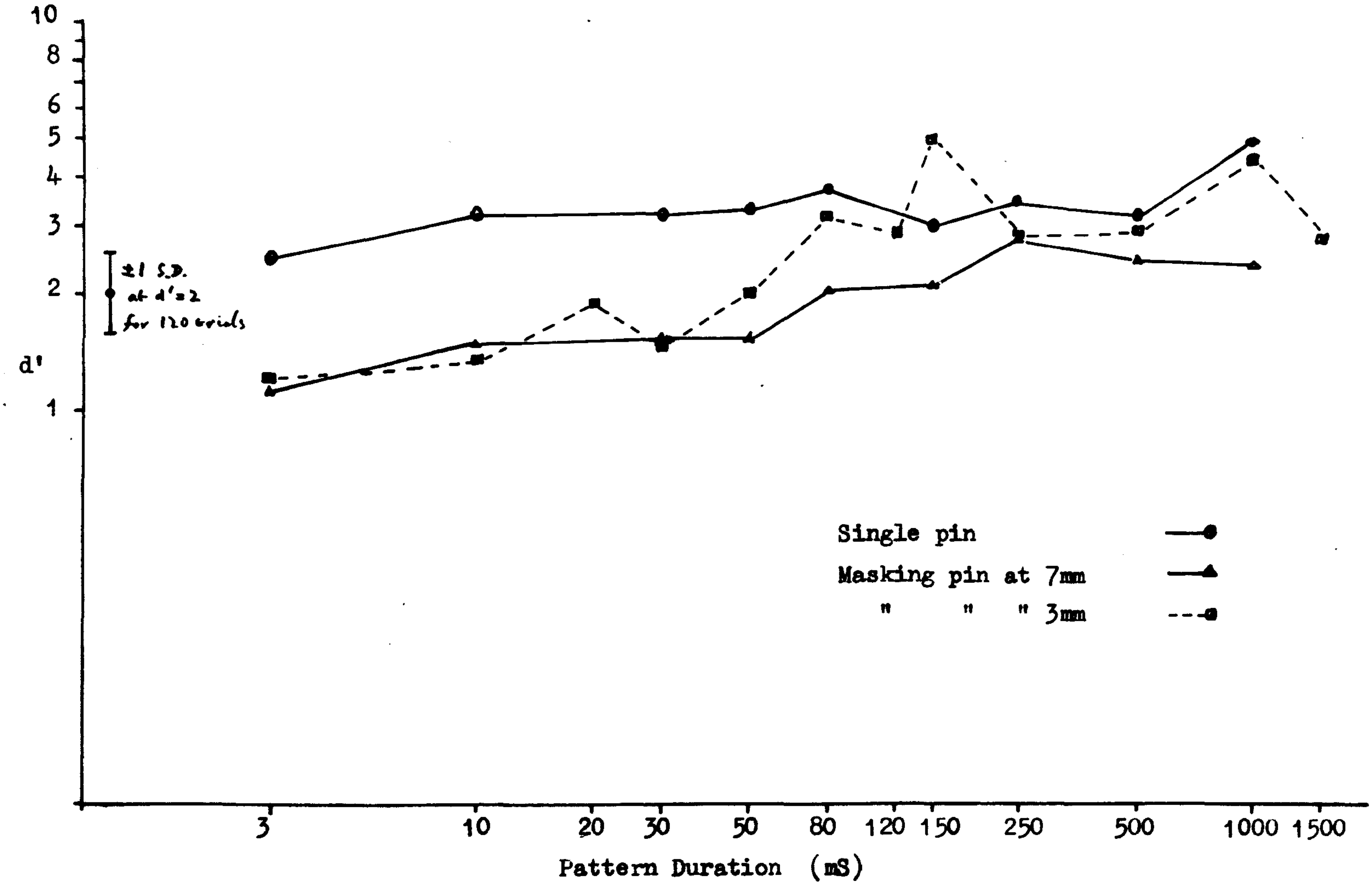


Fig. 43/ Pattern Duration: Discriminability plotted against pattern duration for one and two pin patterns.

The results indicate some ~~depence~~ dependance upon duration, particularly for durations less than 150mS. However, there being much variability between points on the graph, it was decided to perform another experiment in which data was gathered for all durations in the same series of trials, to minimise effects of variation of performance with time. Experiment 64 was therefore set up. In this, trials were made with durations chosen from the whole range 3mS to 1000mS and not just from three values. The patterns used in this experiment were slightly different from those of the previous experiment to gain information about the effect of pin separation. The two pins were separated by 6mm or 8mm. For each comparison 120 trials were made. The results are also plotted in fig. 43.

For comparison purposes, a similar experiment to number 64 was set up. In this (number 65) the two patterns were single pin patterns only, the pin being raised in one of two adjacent locations.

Fig. 43 shows the results of these experiments for one subject (HGB). Fig. 44 presents the results of experiments 64 and 65 for two subjects, the lines being drawn through the mean values of d'.

It will be noted that there is an improvement of performance with increased duration. The slope is, however, slight; it appears that d' varies approximately as the fourth to sixth root of duration.

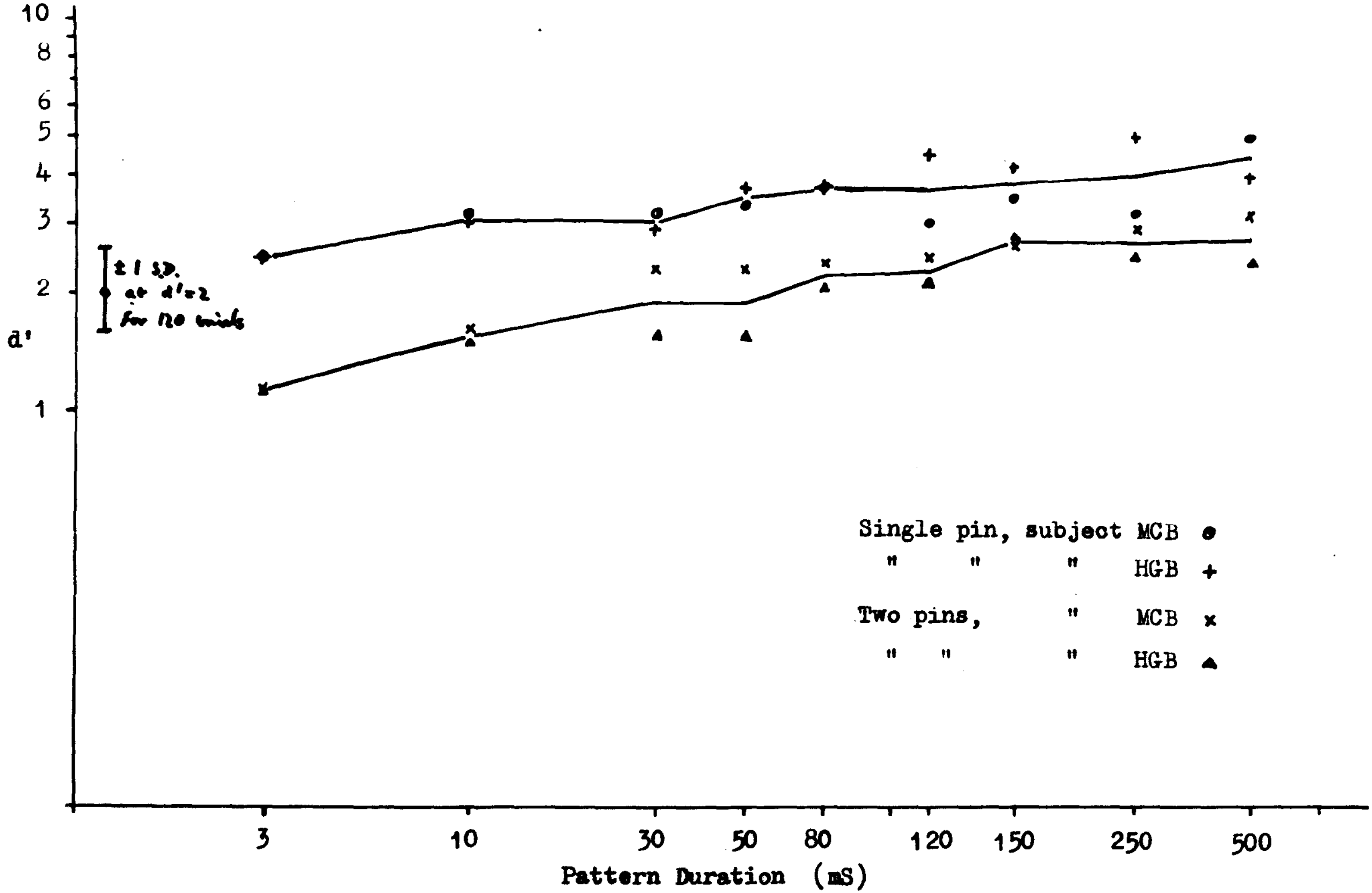


Fig. 45/ Pattern Duration: Discriminability plotted against duration for one and two pin patterns.

5:7:2 Discussion

A number of possible outcomes of these experiments might have been expected a priori.

Firstly, discriminability could have been expected to remain constant, independent of pattern duration. If positional information is conveyed by the distribution of activity in the peripheral fibres, then sufficient data for correct localisation may be transmitted by even very brief stimuli. Some slight improvement might result from averaging over longer durations to reduce statistical variation of the neural responses.

Secondly, if a simple integration mechanism exists, similar to that postulated by Zwislocki (123) in the auditory system to account for temporal integration, then the curves would be expected to rise linearly with increasing duration until a critical duration is reached, whereafter they would remain constant.

Thirdly, the results might indicate the presence of a channel of communication with limited capacity. In this case, information, in the mathematical sense, would be accumulated at a constant rate until all had been transmitted, whereafter no improvement of performance would result. Since the value of d' is approximately proportional to the square root of information content (See Appendix), d' would, in this case, increase with the square root of duration. The turnover points of the curves would probably occur at different durations, possibly at a critical value of d'.

Examination of the curves obtained from the experiments reveals that they rise slowly over most of the range of durations, certainly slower than the square root of duration. It is possible that they may become constant at about 150mS (a duration which corresponds approximately with the turnover points determined by Berglund et al. (20)) but in view of the variability of the points plotted this cannot be confirmed or denied. It is not even possible to say whether all the curves possess a turnover point, let alone whether such points are at one or several durations.

The one fact to emerge with certainty is that performance is better for the single pin experiments than for those of two pins.

The conclusions drawn tentatively from the results are that positional information can be conveyed within a short space of time and accuracy increases only very slowly with increasing duration. Possibly, therefore, the first hypothesis may lie closest to the truth.

5:7:5 Summary

It has been found that discriminability of patterns differing in the location of a single pin increases with duration of presentation. The rate of increase is slow; d' increases approximately as the fourth to sixth root of duration.

At all durations, performance is better for single pin patterns than for patterns of two pins.

5:8 Summary of Experimental Results

Transients: On-going and off-going edges of a pulse can be distinguished. They can also be distinguished from brief pulses of either polarity, though confusion increases as pulse duration decreases. Steady up or down states of the pin can also be distinguished.

Durations: The difference limen for duration of pulses is about 10mS. The discriminability of duration for two pulses fluctuates in a periodic manner as the difference in duration is increased, probably due to mechanical vibrations of the tissue.

Simultaneity: The distinguishability of simultaneity from delayed occurrence of two pulses increases as the delay is increased, and decreases as the spatial separation is increased.

Spatial Extent: The detectability of differences in spatial extent for several types of pattern decreases rapidly at first with increasing extent, then less rapidly. Lateral extension of patterns did not appear to improve discrimination. The detectability of an increase in a gap in a row of pins increases steadily with the size of the gap.

Spatial Interactions: It was found that the presence of ~~irrelevant~~ extra pins impairs the ability to distinguish between two possible locations of a single pin. The impairment decreases with separation up to about 5mm, whereafter it is approximately constant. The impairment increases with the total number of pins in the pattern.

<u>Duration:of Presentation</u>: It was found that discriminability of two patterns,differing only in the location of a single pin, increases with the duration of presentation of the patterns. The rate of increase, however, is low, varying perhaps as the fourth root of the duration.

CHAPTER 6

Discussion of the Experiments

6:1 Introduction

In the previous chapters, the work of building the experimental system and of performing the experiments was described. In this chapter, there follows a discussion of the conclusions reached. These fall into three categories, relating to the technique of experimentation, the human tactual system and the construction of aids for the blind.

6:2 Technique

A program has been written for the PDP-8 computer which can perform a variety of psychophysical experiments and produce a permanent record of every trial. In principle, it can be used to control the display of visual or auditory patterns (e.g. by operating a parametric talking apparatus) instead of tactile patterns. Features have been incorporated into the program as the need arose and the whole has been thoroughly field-tested. A program to analyse the records in detail has also been written. Both programs are now in a form suitable for general use.

The tactile display apparatus has been modified to make it suitable for use under computer control. Experience has shown that the electro-mechanical display can be usefully employed, though perhaps a piezo-electric display would respond better to transients and brief pulses.

The experiments have demonstrated that the AXBX presentation scheme possesses certain advantages. Because the decision criteria for similarity can be to a large extent independent of the type of discrimination, it is possible to mix the types presented in a series of trials, thus measuring two or more confusion rates effectively simultaneously. Comparisons can, therefore be made of the results for several different types of task with the knowledge that the experimental conditions and state of mind of the subject were similar for all.

It has been found, from experiment 26 (page 106), that it is advisable to intersperse easy and difficult tasks in order to stabilise the subject's performance. The AXBX presentation allows this to be done freely.

It was found that the duration of a series of trials should be less than fifteen minutes to avoid fatigue. Ten minutes is a convenient duration, representing about 100 trials, which allows the subject to maintain his interest. An interval of a minute or two between trial series also prevents the finger-pad becoming numbed by pressure against the stimulator.

The interval between patterns of a single trial should not be made too short. The interval of 0.5 sec, used in the experiments, between patterns of a pair, is perhaps the minimum for negligible interaction between the patterns; it takes this length of time for sensation to decay after stimulation. An interval of one or two seconds would probably ensure no unwanted interaction occurs.

Estimates have been made from the results of the experiments of the quanta of distance and time suitable for pattern presentation. The limen for localisation is about ~~4mm~~ 1.5mm for a single pin, that for duration discrimination is about 10mS. In the latter case, it must be noted that if the effects of travelling waves are to be investigated, then the quantum of time must be reduced to about 1mS. In the former case, as patterns become more complex, the limen for localisation of a single pin increases in size. The estimate of ~~1mm~~ 1.5mm. for the quantum is therefore a minimum value. The possibility has not been investigated, but should be recognised, that for complex spatio-temporal patterns, some limens for time may be increased. In view of the relationships between space and time (e.g. in the case of simultaneity judgements) the limens should not be regarded as constants; they merely express orders of magnitude.

The experimental results have also indicated the usefulness of the various measures of performance. Reaction times, while varying in a manner corresponding to that of error rates, do not vary over a comparable range and are seemingly more random in their variation. It is not so easy to fit theoretical explanations to response times as to error rates.

During the course of the experiments, the d' measure has proved to be both reasonably stable and informative as a measure of subject performance. The conversion of error rates to d' values has often resulted in an approximately linear function relating d' to parameters of the experimant (e.g. in the experiments upon simultaneity). In experiments 20 and 21 it has yielded curves which appear very similar in shape for similar tasks (more so than those of error rate), while representing very different absolute levels of discriminability. Such satisfactory outcomes indicate the suitability of d' as a measure of performance.

6:3 The Tactual System

6:3:1 Preliminary Comments

Before proceeding with a discussion of the experimental results in the context of the human tactual system, it is worthwhile to make some preliminary points.

In chapter two it was shown that the information encoded by the receptors is relayed several times before it reaches the cortex. At each synaptic level there is not simply a relaying of impulses from one neuron to another, there are a great many lateral exchanges as well. Many of these exchanges are mediated by interneurons and there is widespread convergence and divergence of fibres. A certain amount of processing is therefore being performed at each level.

If stimuli are observed to 'interact' in some way, not being simply independent, then they must lie within a 'stimulus catchment region' of the particular process involved. The catchment region may extend widely spatially. Stimuli widely separated over the body may mutually interact, as in the experiments of Geldard and Sherrick (56), indicating an extensive catchment region, and possibly interaction at a high level. Stimuli on the fingerpad have also been found to interact in positional judgements, implying a catchment area at least as large as the fingerpad.

Convergence is not limited to spatial factors. It is not possible to say that the nervous system treats space and time as separate dimensions, for space and time have been found to interact on the skin, as shown in the experiments upon simultaneity.

The picture is thus of a hierarchy of transformations of the original input, in both the spatial and temporal domains.

6:3:2 Mechanics of the Skin

If the forearm or thigh is tapped with the point of a pencil, waves will be seen to travel large distances. The tissue will appear to vibrate, as a jelly, and the vibrations will die away within a second or so. If the pencil is pressed steadily into the skin, when the vibrations have ceased it will be seen that there exists a region of indentation around the point, extending some distance, and the amount of indentation decreasing with distance. On the fingerpad the range of the indentation is one or two millimetres. The waves travel rather too fast to be observable with the naked eye.

A simple system which displays similar properties is a membrane subject to surface tension, a restoring force proportional to displacement and some form of damping. If an ideal membrane with surface tension only is deformed and then released, travelling waves will be observed which eventually reach all regions. If the membrane is subject to an additional restoring force the waves will be dispersive; different spatial and temporal components of frequency will travel with different velocities. The shape of the wave will therefore change with time and distance travelled. If there is in addition, a damping force, then the energy of the travelling waves will decrease with time.

Another interesting phenomenon can be observed, particularly well on the fingerpad, which is not predicted by the simple membrane model. If the pencil point is pressed into the fingerpad and then released, in addition to the initial rapid partial return, the tissue flows back slowly, perhaps taking several seconds. Sensation also persists during the motion. The ideal membrane model does not take account of the slow tissue motion, nor of lateral motion, but is a useful approximation.

To gain further insight into the mechanical properties of tissue, a computer program was written to display the behaviour of an ideal membrane in slow motion upon the 338 visual display. The parameters of membrane tension, restoring force and damping could be adjusted on-line by means of potentiometers connected to the analogue inputs of the analogue-to-digital converter of the PDP-8. The initial conditions of membrane position and velocity could be 'drawn' upon the screen with a 'light pen'. Constraints representing the stimulator platform and pins could also be drawn in. In addition, a graph could be displayed which depicted displacement of a chosen point plotted against time.

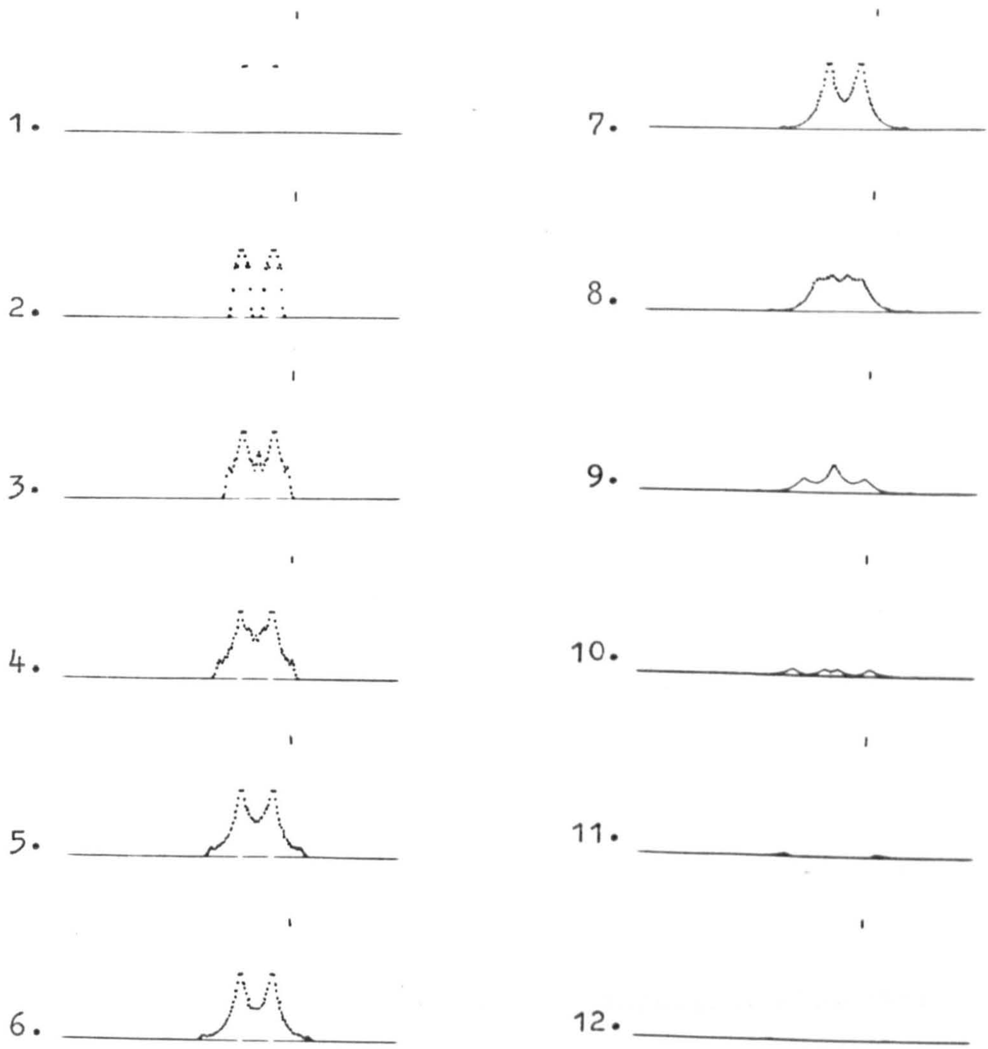
Thus the parameters could be adjusted until a suitable model for the fingerpad tissue was found. The effects of a number of different mechanical stimuli could be represented.

Fig. 45a shows the response of the model to a pair of pins which are suddenly raised, held steady for a time, and then lowered. In pictures 1 to 6 the 'shock-wave' can be seen spreading from the site of stimulation, and oscillations can be observed, particularly in the region between the pins.

In the steady state (picture 7) it can be seen that the membrane sags approximately exponentially on each side of the pair of pins. Between the pins, however, the displacement is greater than it would be for either of the pins alone. In this region, the deformations due to the pins individually can be said to interact.

On removal of the pins, the membrane collapses back to its rest state against the platform, the effects once more spreading at a finite rate.

Graph 45b shows the variation of the displacement of a point on the membrane with time. Oscillations are induced by the transient, and the point settles gradually to its steady state position. There are delays between pin motion and motion of the chosen membrane point.



a/ Successive displacements of an ideal membrane following application and withdrawal of two point stimuli.

b/ Time course of the displacement of one point of the membrane. (Indicated by the short vertical line in a/.)

Fig. 45/ Motion of an ideal membrane subject to constraint.

From the model and from observations of the skin, it will be realised that the application of an arrangement of raised pins to the skin will inevitably bring about several effects associated with the mechanical properties of skin. Firstly, from each pin will spread out a series of travelling waves. The behaviour of these will be influenced by the presence of other pins and also by the boundaries of the tissue. Oscillations of the tissue may be set up and these will die away. When a steady state is reached, the surface of the skin will be indented at the pins and also over a small range about each pin.

Thus, even before the pattern is encoded into neural impulses it has undergone a spatio-temporal transformation, and one which is too important to be ignored.

The results of the experiments upon durations show that the initial vibrations of the skin are detectable, small differences in duration causing periodic variation of d' discriminability. The effect of the vibrations seems to be much reduced by about 30mS after onset.

6:3:3 The Receptors

Let us now consider what is happening in the encoding process. Mountcastle (89,116) has found that a power law appears to be applicable; the firing rate of the receptor, a Pacinian corpuscle, varies roughly as the square root of the amplitude of indentation of the skin. With steady vibration he has found that the neural impulses are frequently phase-locked to the mechanical vibrations. It has been suggested in section 5:4:5 that the results obtained for duration comparison experiments can be explained in terms of such phase-locking of impulses at 4.6mS to mechanical vibrations at twice the frequency. Moreover, it woukd appear that differences in total number of volleys of only one or two can be detected, at least for very short durations. The phase of the skin vibration when the interval is terminated appears to be important. One can readily see that markedly different patterns of succeeding activity may be set up for pins withdrawn at different points in the cycle of vibration.

That on- and off-going edges can be distinguished has also been demonstrated. This may be due to the presence of specialised on- and off- sensitive receptors, as postulated by Gray et al. (5), or simply to the different time course of the deformation of the skin at the two edges. Pins rise rapidly, causing very rapid deformation of the tissue, and presumably vibrations. When the pin is retracted it may well fall before the skin, leaving a deformation which may take a comparàtively long time to recover. The off- edge will therefore feel much gentler and more diffuse, as has been observed.

The mechanical properties of the skin also give rise to spatial interactions. The receptive field of a fibre is determined in part by the spatial distribution of its endings, and in part by the properties of the skin above it. Even if the endings could be considered to be concentrated at a single point in the tissue, because of the range of the indentation produced by a pin, the pressure at a receptor will be changed by the application of a stimulus even several millimetres away. A pressure receptor at a point in the tissue would thus appear to have a receptive field of several millimetres diameter. The fact that receptive fields are known to overlap might merely reflect the fact that receptors are closer together than the range of indentation of the skin.

Receptive fields are, in general, anisotropic, and have been found to be so for the fingerpad in these experiments. If a point is pressed into the fingerpad, it will be observed that the depression produced is oval, with its long axis in a proximal-distal direction. This may be an explanation of the anisotropy observed in the experiments, or at least, a contributory factor. It is a further example of the degree to which the structure of the fingerpad can affect psychophysical and performance of the tactual system. In the experiments, the anisotropy seems to be representable by a scaling factor for dimensions in the proximal-distal direction of about 0.85.

For points close together, it will be realised that the indentations 'interact'. They do not do so linearly; two pins very close together produce almost the same pattern of indentation as a single pin. Thus, small changes in the position of one of the pins produce changes in the indentation pattern which are influenced by nearby pins. The neigbouring pin itself forms a barrier; the changes are confined to the near side. We can thus see how the mechanical properties of the tissue may cause apparent interactions among several pins.

To estimate the degree to which the interaction is mechanical a model was proposed. The model was simple and considered only a one-dimensional system. The steady state skin indentation was assumed to follow an exponential law on either side of a raised pin, an approximation to the observed facts. Between two pins the two exponentials were assumed to combine into a hyperbolic cosine curve (or cosh curve, which is the sum of two exponentials). A row of ten points was used and the space constant of the indentation was set to be one or two points. Some measure of similarity for the results of applying two pin-patterns had to be employed and the Euclidean distance measure was chosen as a reasonably simple and unbiased measure. i.e.

$$d^2 = (\underline{x} - \underline{y})^2$$

Where, d is the dissimilarity measure, $\underline{x}$ and $\underline{y}$ are vectors specifying the deformed states of the skin resulting from application of the two patterns. Each vector consists of the ten values of membrane displacement at the representative points. (N.B. It is not suggested that the Euclidean distance measure is computed by the human tactual system; it is merely a simple, useful measure for our analysis.)

The model thus gives a measure of the dissimilarity of the deformations resulting from the application of two pin patterns to a hypothetical membrane, or of the outputs of a set of linearly responding receptors. Many pairs of patterns were processed with this model and the results are presented in graphical form in figs. 46 to 50.

The effect of non-linearity of encoding at the receptors with output proportional to the square root of the indentation was also studied by computing the Euclidean distances for vectors representing the square roots of the deformations. Only slight changes of shape of the curves resulted from this modification; it was therefore pursued no further and the linear model was employed.

The results from this model agree to a limited extent with the experimental results.

It is found that for comparisons of patterns consisting of a single pin only, discriminability rises with increasing separation between the two positions (Fig. 46). As in the psychophysical experiments, (Fig. 35), the discriminability

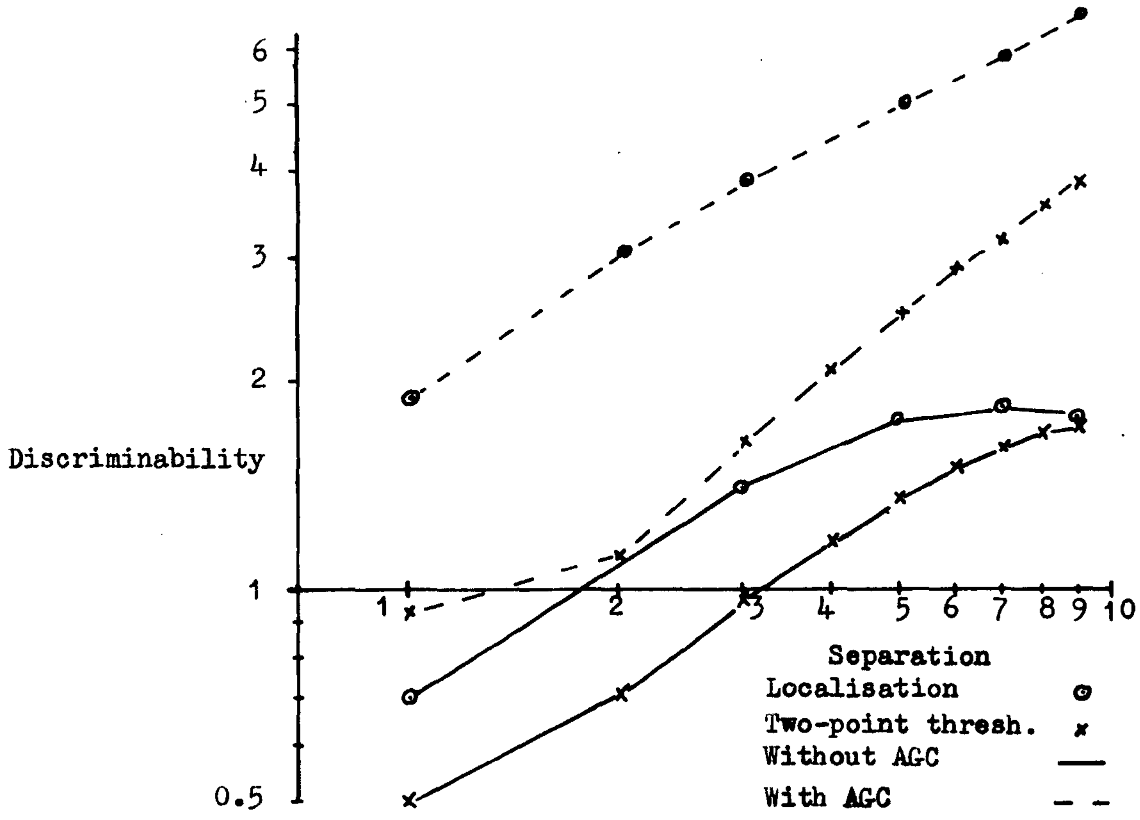


Fig. 46/ Theoretical performance of model for localisation and two-point threshold experiments.

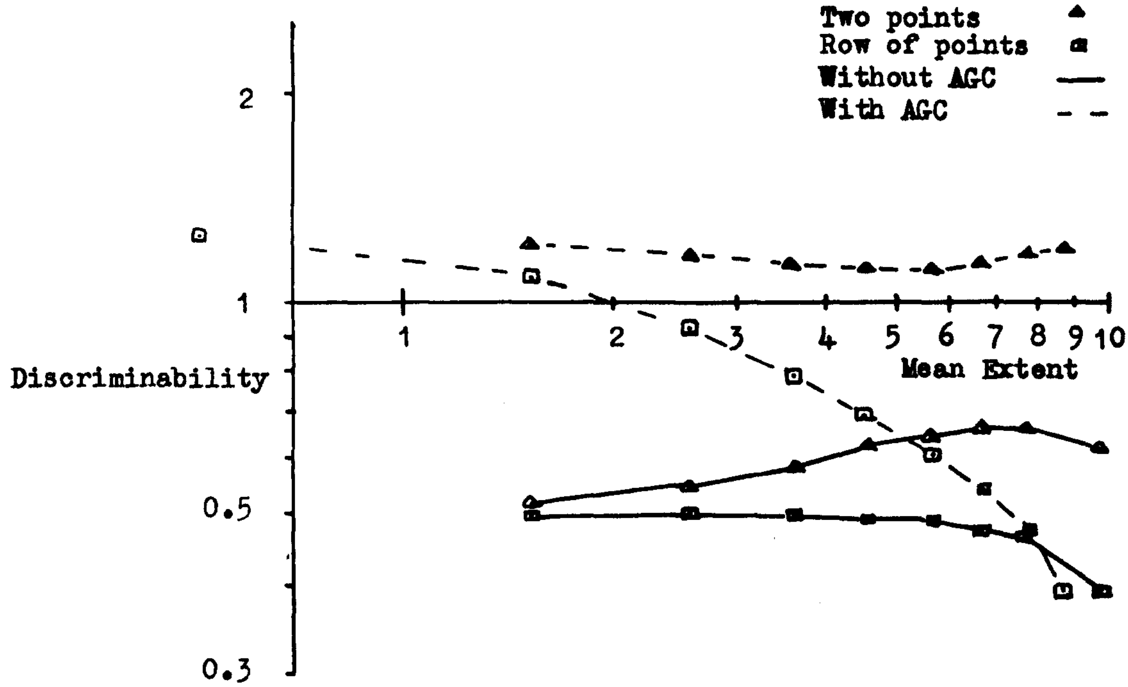


Fig. 47/ Theoretical performance of model for detection of an increment in spatial extent, as function of mean extent.

increases more or less linearly at first, then tends towards a constant value.

Comparing a single pin with a spaced pair, a classical two-point threshold experiment, yields a linear curve in the theoretical case (fig. 46). However, the psychophysical results (fig. 36) show an almost constantly high level of discriminability.

Two sets of measurements were made to parallel the experimental results concerning spatial extent. Pairs of points were compared, determining the detectability of a fixed increment in separation as a function of mean separation. Also, rows of points were compared to determine detectability of an increment in length. The theoretical results are plotted in fig. 47. For the solid row, discriminability is almost constant, perhaps falling off slightly for long rows, while for the pairs of pins, discriminability rises slightly as separation increases. The latter result indicates the variation of 'interaction' of the points. When they are close, the deformations interact more strongly, causing an impairment of discriminability.

These results should be compared with those of fig. 37. There is discrepancy for the minimal-extent case, in which one- and two-pin patterns are compared. For the more extensive patterns, however, there is correspondence. The curves for solid figures remain constant or fall slightly with increasing extent, while those for figures containing a gap appear to rise slightly.

The gap detection and discrimination experiments were also simulated with the model. Fig. 48 shows performance for detection and should be compared with fig. 38. Both figures show a rapid rise of discriminability with gap width, though it is extremely rapid for the experimental results. In both cases also, to achieve a given level of discriminability, the width of the gap must be at least twice the limen for localisation.

The theoretical results for detection of an increment in a gap are shown in fig. 49 and should be compared with those in fig. 39. The results of the model show an increase, initially, of discriminability with mean width of gap, tending towards a constant value for large gaps. The experimental results also show an increase, but as there are few points on the curve, it is not possible to say whether d' is constant for large gaps.

To parallel the interaction experiments (page 148 et seq.) the effects of the presence of a second and third pin upon the ability of the model to discriminate between two possible locations of the first pin were studied. It was found that as the extra pins were brought closer to the first, discriminability fell (fig. 50a), as in the psychophysical experiments (fig. 41). Though the curves of fig. 50a do not extend sufficiently far, it is to be expected that they would tend towards a constant value for very large separations, as domthe experimental results.

Replotting the theoretical results as functions of the

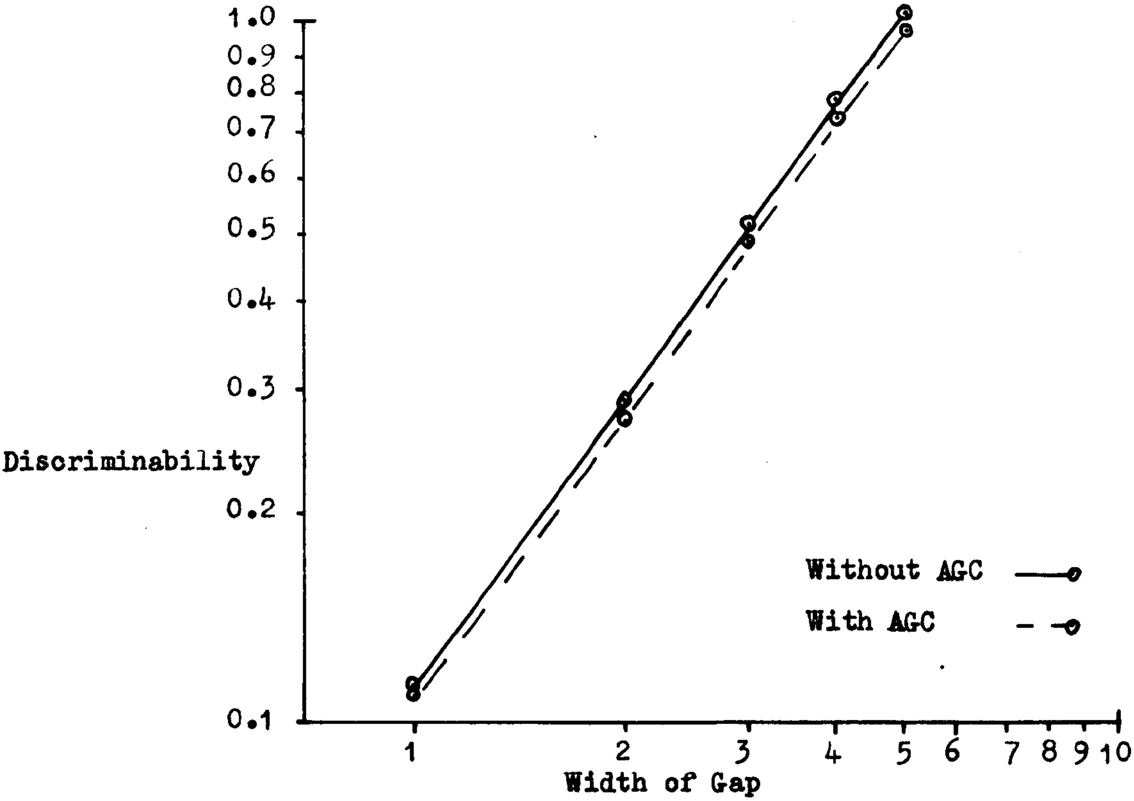


Fig. 48/ Theoretical performance of model for detection of a gap.

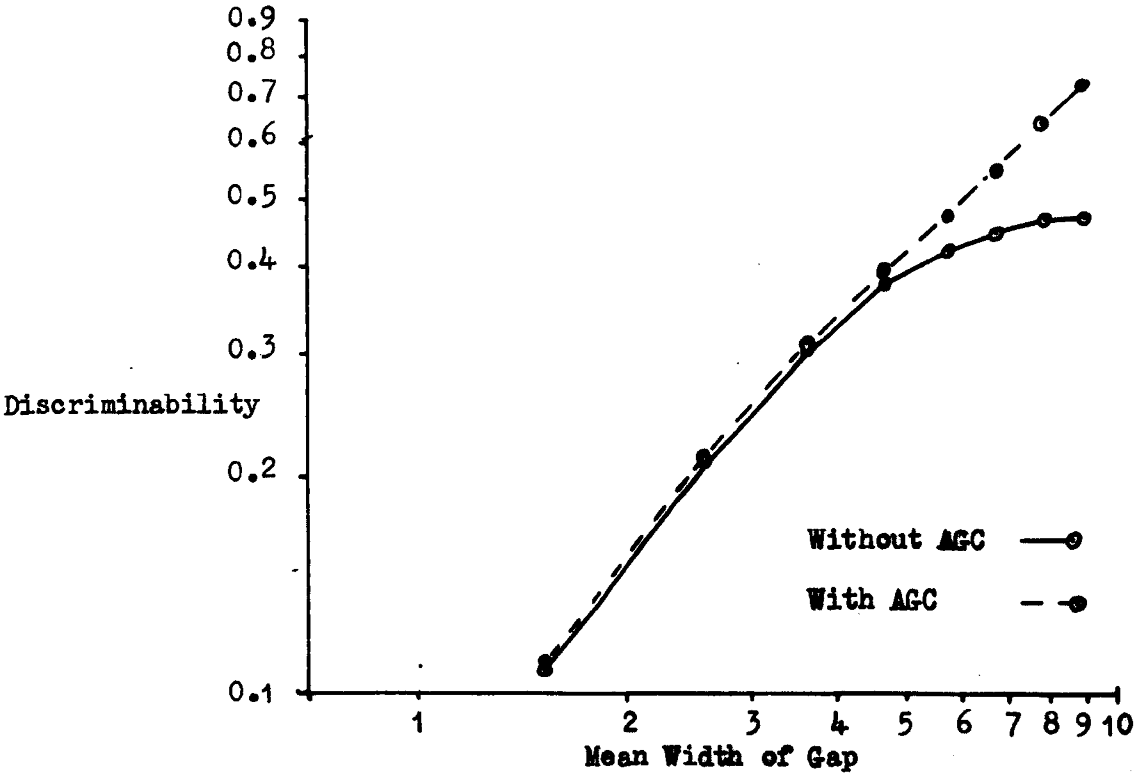
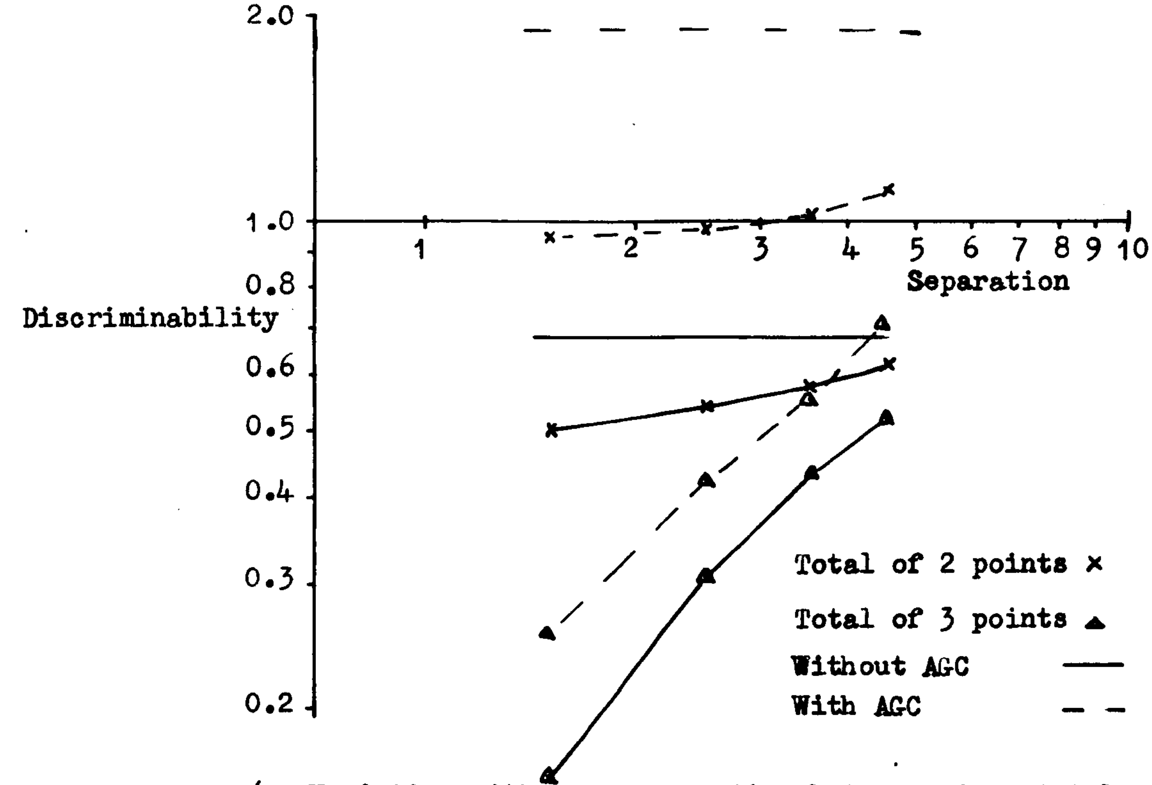


Fig. 49/ Theoretical performance of model for detection of an increment in gap width, as a function of mean gap width.

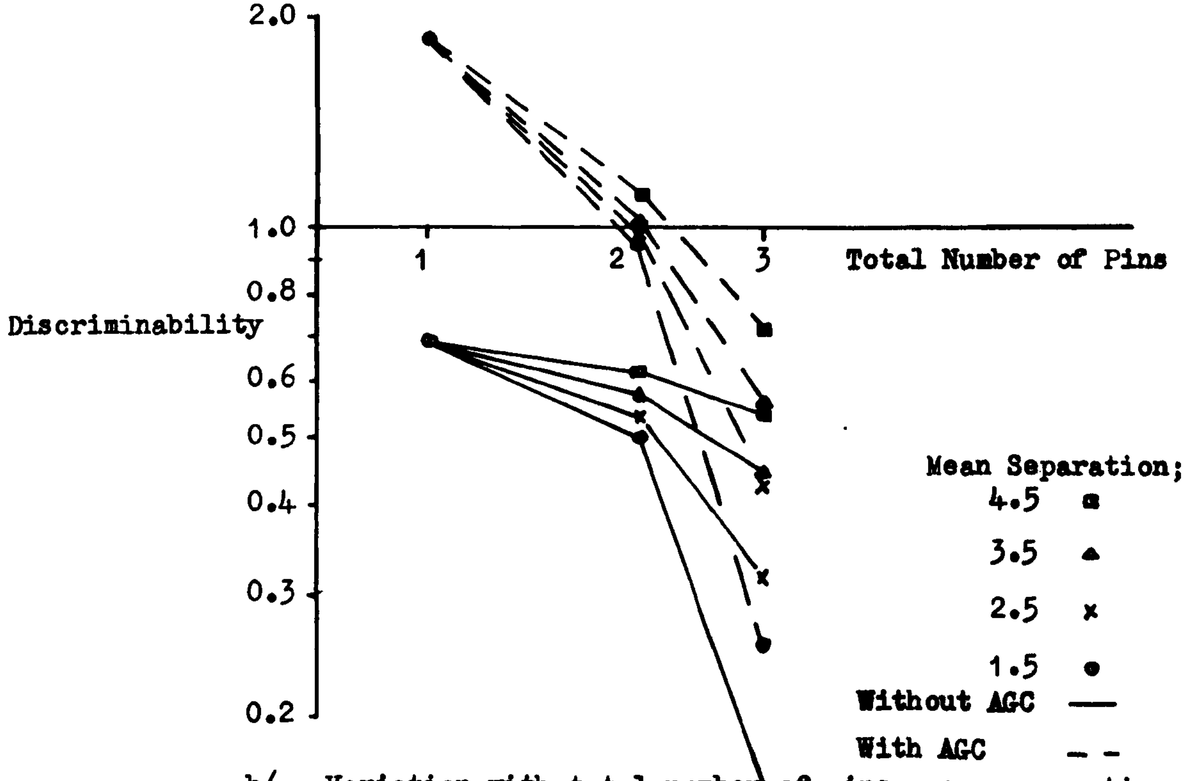
total number of pins in the pattern (fig. 50b) we find that as the number of pins increases, discriminability decreases, as does d' for the psychophysical experiments (fig. 42).

We find, therefore, that such a very simple model can predict qualitatively the occurrence of a number of observed phenomena. It is not proposed here that all the psychophysical results can be explained by reference to the mechanics of the skin. Indeed there are many that are not. The model does not predict wide range interactions, which have been found to exist; for the model, if pins are widely separated they interact little; the psychophysical results show interactions between pins widely distributed on the fingerpad. Also, the results of Geldard and Sherrick (56) demonstrate interactions for loci of stimulation on different parts of the body where there is little possibility of any mechanical interaction. Nor are the predictions of the model much more than qualitative. However, they do show that many of the short-range phenomena may be explicable,in part,in terms of the mechanics of the skin.

Obviously also, neural interactions play their part in sensory data transformations. In particular, the wider range effects imply some spatial convergence of information. It seems possible that, in the light of the inhibitory effect of widely separated stimuli, some form of mutual inhibition may be occurring, resulting in a process of automatic gain control (AGC). The



a/ Variation with mean separation between pins, total number of pins as parameter.



b/ Variation with total number of pins, mean separation as parameter.

Fig. 50/ Theoretical performance of model for detection of displacement of a single pin, for patterns of one, two and three pins.

neurophysiology of the tactual system has been shown in chapter two to be such that the necessary mutual inhibition does occur at many levels of processing.

The effect of a simple AGC system has been tried in the model; the deformation at each point was divided by the sum of the deformations, so that the new sum was always unity. Thus the total of the membrane displacements, or total 'neural response' was kept constant. The Euclidean distance calculations were made upon these modified quantities.

The effects of incorporating this AGC system are shown in figs. 46 to 50, the modified discriminability measures being plotted with dotted lines. From a qualitative point of view, many of the results are unchanged (e.g. fig. 48). The curves for localisation of a single point and two-point threshold (fig. 46) still rise steadily with separation; these for the gap detection and discrimination tasks (figs. 48 and 49) are hardly changed, even quantitatively. It is for the more complex tasks that effects are readily noticed. For the spatial extent discriminations, the two curves of fig. 47 still diverge with increasing extent, perhaps more rapidly so, but now it is the point pair which maintains constancy, while the solid row results fall. In this case, the fit of the curves to the experimental observations is slightly better without the AGC.

For the interaction study, however, the fit is improved as the curves are more nearly linear.

The conclusions to be drawn are, therefore, that the addition of an AGC system to the model causes only slight improvement in the agreement with the experimental results. This is not sufficient to prove or disprove the existence of such a system in the human tactual system. However, it does demonstrate that the effects of an AGC system are not as marked as might have been expected.

A full explanation of the tactile sense mechanisms may possibly include a hierarchy of feedback systems at many levels, so that inhibitory interactions occur between the most widely spaced stimuli. The control signals fed back might also yield information to the higher centres concerning the overall intensity of stimulation.

6:3:4 Some Temporal Factors

An important property of the tactual system is that, in common with other senses, steady states appear to be less important to it than changes. The receptors respond to changes in stimulation and this is an efficient way of encoding the information for transmission to higher centres. The experiments of section 5:2 have shown that it is more difficult to discriminate between steady states than between transients.

It appears that for some experiments 200mS is a critical duration. Berglund et al. (20) have found that intensity of sensation increases till about 200 to 1200mS,. whereafter it is constant. Hawkes and Warm (73) report that the Weber fraction for duration falls with increasing duration, but is approximately constant after about 400mS. The experiment of section 5:3:2 indicated a critical duration of about 200mS for duration discrimination.

Since the judgements of the latter experiment were made upon the intensity of the sensation, the above results appear to be linked. It seems that intensity of sensation integrates with a time constant of about 200 to 400mS, and this possibly reflects an adaptation, perhaps at the receptor level.

From the experiments of section 5:7, it appears that information concerning position is not integrated (or perhaps only to a limited extent); even for very brief pulses, localisation ability is not greatly impaired. This finding is important for the selection of communication codes, and may also prove to be important to the understanding of the operation of the tactual system.

The experiments with simultaneity have demonstrated that temporal judgements are performed better when the events concerned are spatially close. This is possibly a reflection of the fact that when the stimuli are almost at the same point, the same set of fibres will be excited by each. Simultaneous stimuli (of constant amplitude) will therefore produce a single volley in the fibres, delayed stimuli a double volley. It has been shown that the tactual system can distinguish between n and n+1 volleys for small n, the judgement of simultaneity would in this case be an extension of the duration discrimination experiments. Only for widely separated stimuli do we have true judgements of simultaneity. For intermediate separations, the situation is a mixture of the two extremes.

6:3:5 Conclusions

From the experiments of this thesis, and from those by others in neurophysiology and psychophysics, a number of conclusions have been drawn concerning the operation of the tactual system.

The mechanical properties of the tissue can result in spatial and temporal modification of the stimulus patterns. Travelling waves are set up, and possibly also natural vibrations of the tissue. These must be taken into account in a consideration of pattern recognition.

The neural coding of the mechanical pattern results in a series of impulses in the afferent fibres which may be phase-locked to vibrations. The minimal change in duration which can be detected by the subject depends upon the period and phase of the oscillations, but is typically about 5mS (for d'=1) for short durations.

The on- and off-edges of a stimulus pulse are readily distinguished and edges are distinguishable from brief pulses. Steady on- or off-states are, however, not so reliably discriminated.

The accuracy of localisation for a point stimulus on the fingerpad has been found to be about 1.5mm. Accuracy is also anisotropic, the error being a factor of 1.2 smaller in a lateral direction than in a proximal-distal direction.

The mechanical properties of the tissue and the receptive fields of fibres can also bring about apparent interactions of the components of a stimulus pattern over a short range. (There are also interactions between even the most remotely separated stimuli, which must be neural and probably central in origin.) These have been investigated. In general, for all ranges, it is found that the presence of other points of stimulation impairs the ability to make judgements about one point and the closer the extra points or the more there are of them, the greater the impairment. Such interactions are anisotropic.

In contrast, in the judgement of simultaneity of events at two points, discrimination becomes better as the time delay increases or the two points become closer together.

It also appears that intensity of sensation integrates with a time-constant of 200 to 400mS. Position information, however, appears to be conveyed by even very brief pulses and is integrated to a very limited extent.

6:4:1 Consequences for Communication Systems

The experiments of this thesis have been performed using a mechanical stimulator arrays, since such a device has already formed a basis for communications systems, and is likely to do so in the future. The present apparatus is not portable, as is desirable for a blind aid. This, however, is a technological problem which it is possible to overcome with present techniques of miniaturisation. The locus of stimulation, the fingerpad, was chosen with the fact in mind that it is also likely to be employed in using a communication system or blind aid. The results obtained should therefore prove of value in the design of such a system.

From the experiments upon localisation and upon duration discrimination, it appears that suitable magnitudes for the quanta of space and time in pattern presentation are about 1.5mm and 5mS (for d' values of 1 in discriminations). With such quanta the 'graininess' of the patterns would be just apparent.

Because of the adaptation of the tactile system, the patterns presented should not be staticly 'stabilised' upon the site of stimulation. Either the pattern should change at intervals less than about half a second, or the subject should be allowed to move relative to the stimulator. The latter case is to be preferred, since active movement seems to be more efficient than passive as far as information acquisition is concerned.

It has been found during the course of the experiments that intensity of sensation seems to be an important parameter as far as judgements are concerned. Intensity increases with duration and is thus useful in discriminating durations; it also increases with the area of stimulation as well as with amplitude of the mechanical stimulus. The dependence of intensity of sensation upon so many factors should be borne in mind when considering coding schemes.

The existence of travelling waves upon the fingerpad has been demonstrated, and also their effect upon discrimination of durations. Some discriminations are improved by their presence, some are impaired. It is therefore not possible to say without further experimentation and consideration of specific applications whether their existence should be encouraged or inhibited in a communication system. However, the results have shown that the human tactual system is capable of detecting very small changes in the duration of the stimulus because of phase-dependent effects and that waves could be employed in performing vernier temporal judgements. The use of electrical stimuli would circumvent the generation of waves and research should be carried out upon the recognition of fine-scale electrical patterns applied to the fingerpad.

The experiments upon spatial extent have produced a number of informative results. Firstly, each raised pin of the pattern impairs judgements concerning spatial details within a range of a few millimetres. This is a factor to be taken into account when specifying spacing between the stimulating pins.

The interaction is probably partly mechanical, dependent upon the properties of the skin, and partly neural, dependent upon receptive field sizes. On the fingerpad, the mechanical component may dominate, while in other body regions, the neural component may do so. Some work is required upon the relative advantages of the fingerpad and other regions as sites of stimulation. Further experimentation with electrical stimuli might assist in resolving the relative proportions of the mechanical and neural components, though care must be taken to limit the spread of current from the electrode.

Beyond the range of immediate interaction, there exists a more widespread effect; judgements of detail are impaired by pins remote from them. The greater the number of pins in the patterns, the more the details are obscured.

From one point of view, this spatial interaction is a disadvantage; it appears to place a limitation upon the amount of information that may be conveyed by a single pattern. From another point of view, however, it can be said that it is as if a built-in mechanism were adjusting the receiving system so that it is working to full capacity, under all conditions of stimulation. It is to be hoped that a future communications system might be able to make use of this innate property to perform useful processing of information, rather than treat it as simply an unwanted degradation of the stimulus.

Because of the spatial interaction, it would seem that temporal coding might provide better transmission rates. The experiments upon simultaneity detection have shown that performance is best for close proximity of the two stimuli; perhaps several temporally coded channels could be packed into a small area. However, a more extensive study to measure the impairment of judgements of temporal factors by interactions would have to be undertaken before any optimal coding method were designed.

One major fact to emerge from this work is that much more research is required before we can hope to construct an optimal communication device.

6:4:1 A Possible Coding Scheme

Taking the known facts together, certain deductions can be made and a suggestion put forward for a coding shheme which might achieve good transmission rates.

It has been noted above that intensity of sensation is dependent upon the duration and area of the stimulus, as well as its amplitude. In addition, it integrates slowly to its maximum value, with a time constant of the order of 0.5 to 1 second.

Because of its dependence upon so many factors, intensity of sensation is a basic and very useful parameter upon which to base discriminations. For the same reason, ambiguity could easily arise if amplitude, duration and area were used together as code parameters. Only one of these should be used for patterns of short duration. The use of stimuli of constant amplitude and/or duration would simplify matters considerably.

The adaptation of the tactual system means that stimuli which are 'stabilised' for longer than about half a second become insensible. Therefore, either the pattern or the subject must move periodically. The former case is probably better for three reasons; if the finger moves, it can move off the array and thereby lose information, if the device is portable it may be advisable to fasten it to the site of stimulation, and it may be faster to move the pattern rather than to allow the subject to move and wait for him to return. However, some degree of control of pattern position by the subject would be expected to improve speed and accuracy of recognition.

Location information appears to be transmitted rapidly and not to be integrated greatly over time; the results of experiments upon pattern duration (fig. 43) show an increase in d' for localisation of a single pin of only a factor of two for a variation in duration of 150:1. The shortest duration used is 3mS. Location appears to be a very promising parameter.

Accuracy of localisation does fall with increasing complexity; interactions take their toll as the number of pins is increased. More experiments upon the manner in which several pattern differences combine to aid discrimination are needed, but it seems that a good approach would be to keep the number of pins in a pattern low.

The experiments upon simultaneity have shown that discrimination is best, for a given temporal delay, when the two loci are close together. To take full advantage of the temporal discriminatory ability, the successive positions of a point should not be too widely separated. If points move far, it is likely also that the subject will become confused, being unable to relate successive patterns and requiring much longer durations of presentation of each.

In summary, a good coding scheme would consist of the following; a sequence of patterns should be presented in succession, each consisting of few points (preferably a constant number) which move only a short distance from pattern to pattern. (In a limiting case, we have only a single point in each pattern, which 'moves' around to 'draw' shapes.)

A coding scheme of this sort is fairly closely akin to the range of stimuli which are normally encountered by the sense of Touch.

A number of simple 'moving' patterns have been programmed for the tactile display, viz. a spirally moving point, lines moving horizontally an vertically and a rotating line. It has been found that many observwers are readily able to identify and describe them, though as yet, reliable experiments have not been performed with such stimuli.

A series of experiments with simple moving stimuli should yield much pertinent information for the design of communication systems and coding schemes. This is an obvious future line of research.

CHAPTER 7

Future Research

7:1 The Past and Present

The work described in this thesis has disclosed some new facts about the human tactual system, and thrown new light upon some previously known facts. It was intended at the outset of the course of experimentation to perform some of the more elementary experiments in limited depth only, before proceeding to a richer study of pattern recognition. It was found, however, that effects existed which demanded further investigation before the main theme could be continued. It is hoped that we are now a little further along the road to using the skin as an auxiliary channel of communication, and that we have a little more insight into the effects of stimulation of the skin and some of the more elementary processes involved in tactual discriminations.

7:2 The Future

In the limited time available, it has not been possible to study in depth every question that has arisen from the experiments. There are very many courses for future research which may prove fruitful.

As far as the apparatus is concerned, it might prove advantageous to develop other stimulator arrays. The present device possesses a natural resonance which is excited by transients, causing the stimulating pin to bounce. A piezo-electric transducer, it is hoped, would resonate at a sufficiently high frequency to be easily damped.

An array of electrical stimulators, capable of providing punctate stimulation of the fingerpad, without mechanical action, would prove most useful. Comparison of experiments with mechanical and electrical stimuli would be valuable in further studies of travelling waves and mechanical interactions.

There is a need too, for a series of experiments to determine the mechanical properties of the fingerpad in more detail. A more accurate model than that of the previous chapter would assist in the selection of stimuli and would define the boundary between mechanical and neural interactions rather better.

Discrimination of durations: The experiments have indicated possible methods by which the human tactual system may judge duration, but further work is required to decide between them. It would be informative to extend the pulse counting experiments by employing a wider range of pulse numbers and a range of pulse rates. Information concerning the operation of some of the integrative processes of the nervous system might thus be obtained.

The facts that intensity of sensation depends upon duration and spatial extent, and that it is also a basic parameter for discriminations imply that a trading relation might exist between duration and area of a pattern, at least over a small range of values. A check upon this possibility could be made fairly simply.

Simultaneity: A more general study could be initiated. The apparently constant 'velocity' for constant d' found in the experiments described earlier may or may not hold for a wider range of conditions.

So far, the standard pattern has been pulses simultaneously applied to two loci; non-simultaneous pulses could be used as standards instead, to measure difference limens instead of thresholds. In view of the known interaction of spatial and temporal factors, a series of many experiments to measure discriminability of a wider range of patterns would be valuable. Such a series would include two-point separation discriminations, and simultaneity discriminations as special cases, but would reveal the transition between the two, as well as providing further data concerning the Phi-effect. Previous studies of the Phi-effect have been concerned with measuring the 'goodness' of the apparent motion. Measurements of spatial and temporal limens for double pulses might throw light upon the phenomenon from a different angle.

Spatial Factors: The lack of conclusive evidence from the experiments for spatial summation in judgements of extent deserves further research, particularly in view of the fact that such summation has been reported for threshold of sensation. It is possible that there may be a trading relation between sensitivity and acuity for tactual discriminations, in which extent of the pattern influences the performance of the system. There is evidence in favour of this hypothesis in the results for the interaction of several pins.

Interactions: Several factors can be studied in more depth. The use of electrical stimuli might reveal to what extent the interactions are mechanical in origin. The effects of orientation, particularly whether there is a difference between the 'in-line' and 'perpendicular' cases, should be pursued. They may well help to determine whether special mechanisms for detecting collinearity exist in the tactual system.

The effects of neighbouring points upon other tasks than localisation, such as detecting presence or absence of a pin, or making judgements about temporal features, such as duration, should be investigated. The results will be of value in planning efficient codes for communication.

Duration of Pattern: An extended study of the variation of discriminability of two patterns with duration of presentation may prove extremely informative. If different modes of variation were found for different types of pattern distortion, then this might be taken as evidence for different neural mechanisms being employed, as well as indicating processes involved.

The apparent lack of summation of information over time for single pin localisation should be studied further, introducing more pins into the patterns. The integration of intensity of sensation is an established fact; how many tasks involve temporal integration and how many do not? Those which do employ it may show differing time courses, indicating simple integration with a fixed time constant, or channels of limited information capacity. The comparison of results obtained with very brief and very long durations for a variety of patterns may also assist in unravelling the operation of the tactual system.

The consideration of coding schemes in the previous chapter has shown that perhaps a whole class of patterns, namely 'line drawings' should be investigated. Initially, simple tasks would be set, judging velocities and distances and possibly directions of motion, Later, recognition of geometric shapes and letters would be studied to determine a suitable set of patterns for use in a communications device.

Ideally, the psychophysical work should proceed with many cross-references to neurophysiology, so that ultimately the many transformations the stimulus undergoes on its course through the nervous system may be understood. In this way it is hoped that the more basic functions of the tactual system may be determined and the long-term aim of this research, to use the skin efficiently as a medium of communication, may be achieved.

APPENDIX

Signal Detection Theory and AXBX Presentations

A:1 The Problem

For reasons outlined earlier, the AXBX presentation scheme was chosen for the experiments of thesis. It was also thought that an analysis of the results in terms of signal detection theory would be appropriate, but the necessary calculations could not be found in the literature. They are therefore presented here.

A:2 Signal Detection Theory

The application of signal detection theory to psychophysical experiments has been described adequately by Swets, Tanner and Birdsall (104) and by Licklider (79). An outline only is therefore given here.

It is assumed that the presentation of a stimulus to an observer sets a number of his internal state parameters to particular values. (What the parameters are remains unspecified. They might be the states of the receptors, or of the higher centres after much processing has been performed.) The set of parameter values can be represented as a single point in a multi-dimensional space. Different stimuli, therefore, are associated with different points, and the distance between two points is a measure of the subjective difference between the stimuli.

It is assumed also, that a certain amount of 'noise' is present in the system, so that successive presentations of the same stimulus do not necessarily give rise to the same point in 'observer-space'. We can say though, that there is a particular probability distribution for the position of the representative point of a given stimulus.

It will also be assumed that the observer classifies points in observer-space to maximise his pay-off. i.e. A single point could, in principle, result from the presence of any of a set of stimuli. However, given the point, the probabilities that it results from each stimulus can be calculated. The observer knows the relative values of rewards for correct decision and penalties for incorrect decision. He will set up decision criteria such that, in the long run, his expectation is maximised. e.g. Suppose there are two stimuli, A and B, The observer will set a boundary somewhere between the two distributions. Points on one side will be classified as type A, those on the other as type B. The position of the boundary is set by the observer to maximise his average pay-off. Experimental evidence,(104), supports this hypothesis.

Let us now consider a simple threshold experiment, in which the stimuli are: Signal and No-Signal. A single stimulus is presented and the observer must classify it.

There are two distributions in observer-space. For the purposes of calculation, we join the means of the distributions, label the line the z-axis, and project observer-space onto this line. We thus have two probability distributions on the z-axis which appear as in fig. 51. We now further assume that they are

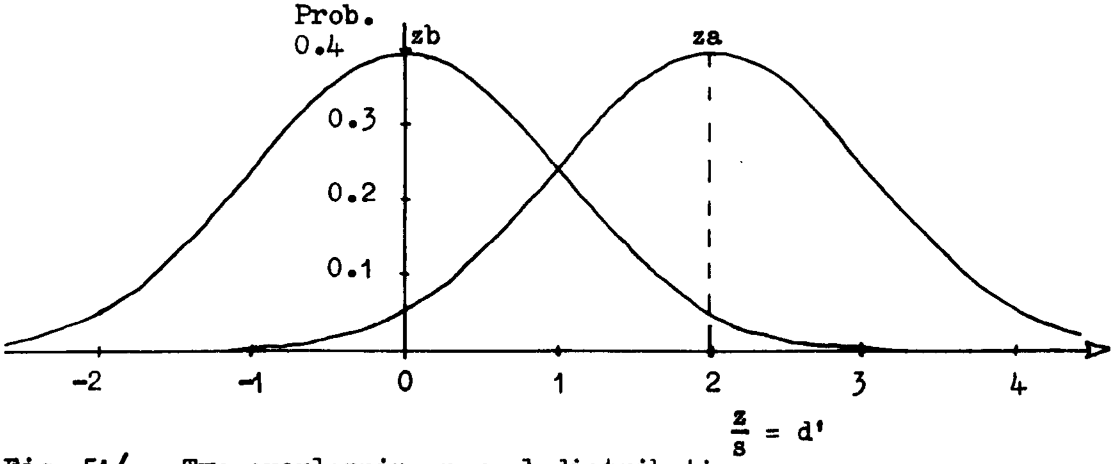


Fig. 51/ Two overlapping normal distributions.

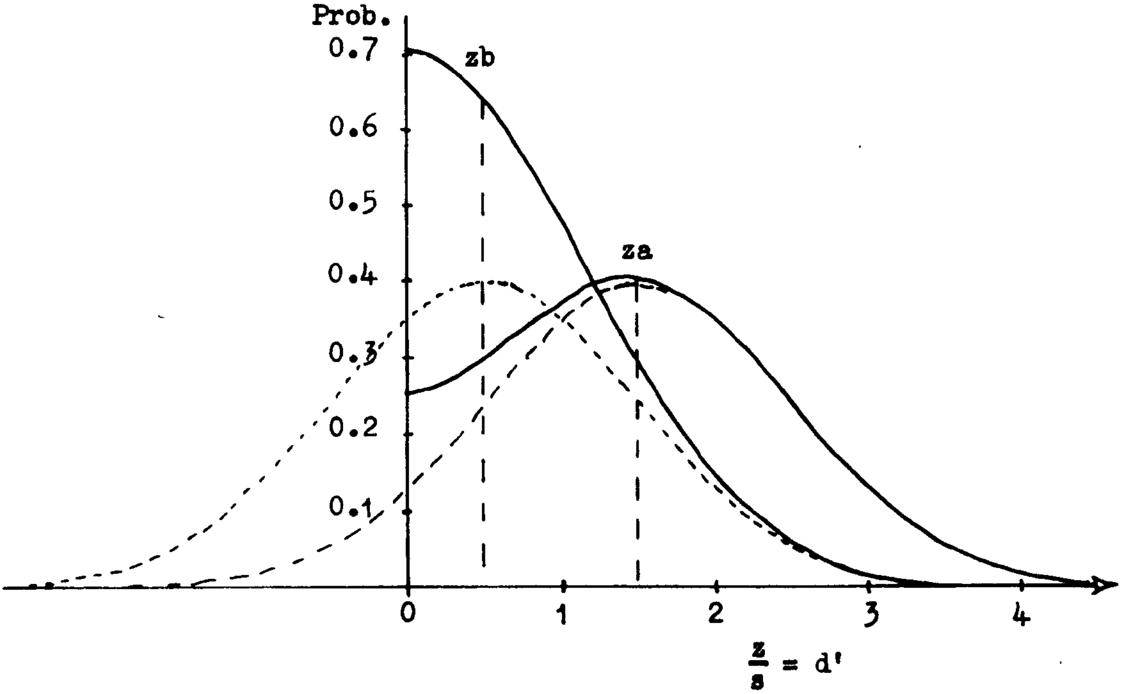


Fig. 52/ Probability distributions for values of the modulus of a variable, z, (solid curves). Distribution is obtained from normal curve (dotted) by 'folding' it at the origin.

i.e. $\text{Prob}(\ |z| = k\ ) = \text{Prob}(\ z = k\ ) + \text{Prob}(\ z = -k\ )$.

centred upon za and zb, that they are both Normal distributions and that they have the same standard deviation, s.

Rather than persist with the arbitrary z-units, we scale the figure by a factor of 1/s, and we shift the origin to zb. The distributions are now Unit-Normal (i.e. Standard deviation =1) and distances are measured in terms of numbers of standard deviations. The distance between the means, measured in standard deviations, we call d'.

An observer will have a criterion for his classification which will lie somewhere on the z-axis. If the representative point of a particular stimulus lies to the right of the criterion he will classify it as type A (Signal), if to the left, as type B (No-Signal). The position of the criterion will depend upon the pay-off values of the various outcomes; if the observer wishes to be sure of spotting every occurrence of the signal, his criterion will be to the left of centre, if he wishes to be very sure before he says 'Signal' that he is right, his criterion will be to the right.

For a given combination of d' and criterion, the probability of correct response can be calculated, and the probability of a false alarm. Conversely, if these two probabilities are measured in an experiment, by looking up a table, the values of d' and criterion can be determined.

If a Two-Alternative Forced-Choice (2AFC) technique is employed, the analysis is similar. In this presentation, two stimuli are presented, one being Signal, the other, No-Signal, and the observer must state which is which. There are, therefore, two points in observer-space.

In this case, it is assumed that pay-offs are symmetrical, so that the observer merely maximises his probability of being correct. This he does by assuming whichever stimulus produces the greater z-value is Signal, and responding accordingly.

The probability of a correct response can easily be calculated. It is the probability that a single drawing from the Signal distribution is greater than one from the No-Signal distribution, for a given value of d'. Once more, if this probability is found experimentally, the value of d' can be found from the calculated table.

There is an alternative way of treating this case, which will be used again later and is therefore given here.

The observer could equally well subtract the two values of z obtained from the two stimuli, and then choose according as the difference is positive or negative.

The difference distribution has mean (za-zb) and a variance which is the sum of the variances of the two stimulus distributions. Thus the standard deviation is $\sqrt{2}$ times larger than that of the stimulus distribution. It will be seen that the probability of a correct choice is thus the probability that a single drawing from a distribution with mean $\frac{d'}{\sqrt{2}}$ and standard deviation $\sqrt{2}$ is greater than zero.

The two methods of calculation are mathematically equivalent and yield the same numerical results.

A:3 The AXBX Presentation

In the AXBX scheme, the subject is presented with four patterns in sequence, which will here be called A, X1, B, X2. Patterns X1 and X2 are the same and are both either A or B. The subject is required to state whether the first pair (A and X1) are different, or whether the second pair are different (B and X2). Alternatively, the task can be considered to require the subject to state which pair contains the odd pattern out, since three patterns are the same.

Assumptions: It will be assumed that each stimulus pattern is associated with a Normal distribution in observer-space, and further, that the standard deviations of these distributions are all equal.

Notation: For the purpose of this analysis, it will be assumed that A is unique and hence X1 = X2 = B . It is required to determine the probability that the subject chooses the first pair, given a particular value of d'.

Let the distributions associated with A and B have mean z-values of za and zb respectively, and possess standard deviation s. Thus,

$$d' = \frac{za-zb}{s}$$

A number of possible strategies exist for the subject ~~situations can exist~~; these will be considered.in turn.

<u>2AFC of Pairs</u>: the subject treats each pair of patterns as a single entity which has a certain amount of a certain property called 'difference'. He chooses the pair with the greater amount of 'difference'.

From the probability of correct response found experimentally, a value of d' can be obtained by looking up published tables for 2AFC situations. However, the value obtained refers to pairs and not to individual patterns. i.e. We can only determine by how much the 'same' pair differs from the 'different' pair, not by how much the individual patterns differ.

Line 1 on fig. 53 represents d' for a simple 2AFC case. If the subject responds as in the above hypothesis, this curve gives d' measures of the difference between the two pairs.

In order to proceed from statements concerning the pairs to those concerning the individual patterns, assumptions must be made about the details of the subject's decisions. A number of these will therefore be discussed.

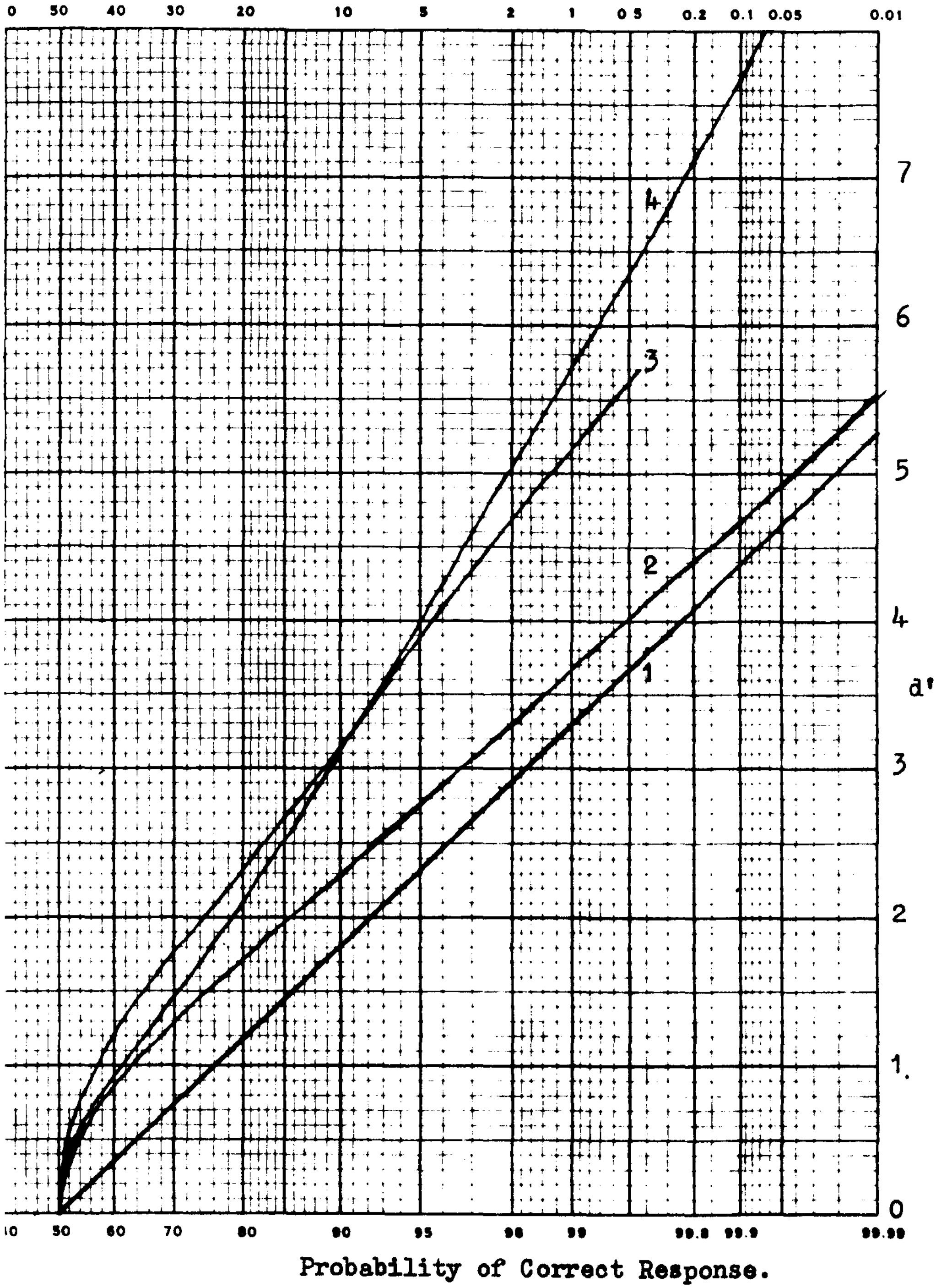


Fig. 53/ Relationship between the d' measure and probability of correct response for several experimental situations.

1/ 2-Alternative Forced Choice.

2/ AXBX, Signals Known Exactly.

3/ AXBX, Signals Unknown, Patterns Paired.

4/ AXBX, Signals Unknown, Overall Mean Estimated.

<u>Signals Known Exactly, X Known</u>: If the subject knows which patterns are being compared and also knows which of them is X, it only remains for him to decide which is A and which B. As the subject has only to determine the order of presentation, this situation reduces to a straightforward 2AFC task and the probability of correct response can be found from published tables.

<u>Signals Known Exactly, X Unknown</u>: If the subject knows the two patterns to be compared, but does not know which is X, his task is two-fold; he must decide which pattern is X and he must decide the order in which the two patterns are presented as A and B. Having done this his response is determined.

A statistically good strategy to adopt for the former task is to take the mean of X1 and X2 and to decide according as the mean is nearer to A or B in observer-space.

As we are assuming that X is B in the particular case under consideration, the mean of X1 and X2 will be represented by a distribution with mean zb and standard deviation $\frac{s}{\sqrt{2}}$. The probability of correct identification is the probability that the mean X will be less than $\frac{za+zb}{2}$. This is the same as the probability that a single sample from a unit normal distribution will be less than

$$\frac{za-zb}{2} \cdot \frac{\sqrt{2}}{s} = \frac{d'}{\sqrt{2}} .$$

This is exactly as for the 2AFC, leading to the same value of probability for a given d'.

Let us denote this probability by P_2.

For the second task, the subject has a simple 2AFC which will yield a probability of being correct of P_2 also.

Hence, the probability of correct outcome, P_c, is the probability of correct X identification and correct AB ordering plus the probability of incorrect identification and incorrect ordering;

$$P_c = P_2 . P_2 + (1-P_2).(1-P_2) .$$

Line 2 on fig. 53 represents this state of affairs.

It will be noted that because two independent decisions are involved, performance is poorer for a given pair of patterns than in 2AFC.

Signals Unknown: All the subject knows is that an AXBX scheme is being employed.

In this case, the subject has two alternative policies:

1/ To take the patterns in pairs, determining a measure of difference for A and X1, and for B and X2, and to choose the pair corresponding to the greater magnitude of difference.

2/ To estimate a mean pattern and to choose A or B, according to which deviates most from the mean.

If thresholds and conditions can be relied upon to remain constant throughout the presentation, then 2/ is probably better. If they vary, then perhaps 1/ is to be preferred, especially if a systematic variation exists. By splitting the AXBX scheme into two pairs, the second policy rejects the information that X1 and X2 are the same. It is to be expected therefore, that the second should yield inferior performance to the first.

<u>Patterns Paired</u>: the subject chooses the pair with the greater difference.

In order to analyse this case, we must assume a method by which the subject computes the difference measure. A number of alternatives are possible. One which does not lead to great difficulties of computation is the modulus of the difference of the positions in observer-space. i.e.

$$|A-X1| \quad \text{and} \quad |B-X2|$$

This has the desired properties of increasing with separation of the representative points and not complicating the probability calculations greatly.

Consider the two functions; (A-X1) and (B-X2) . These possess distributions whose means are at (za-zb) and O, respectively. Both distributions have standard deviation $\sqrt{2}.s$. To find the distributions of the moduli of these two functions we simply 'fold' the curves at the origin, as depicted in fig. 52. for distributions centred on z1 and z2.

It is now a relatively straightforward matter to compute the probability of correct response, which is the probability that a single sample from the first distribution is greater than a single sample from the second.

Curve 3 in fig. 53 depicts the results for this case.

It will be noted that, since less a priori knowledge is given to the observer, for a given pair of patterns (i.e. a given value of d') probability of correct response is always less than for the previous case.

Taking Mean: from an average of the four patterns, the subject estimates the differences of A and B from the mean, choosing accordingly.

The derivation of a mean can be made in two possible ways;

a/ From a sum over all four patterns. The subject simply chooses according to which of A and B differ most from the mean.

b/ From a sum over three patterns. The subject takes a mean over A, X1 and X2 and estimates by how much B differs from this. He also estimates by how much A differs from the mean of X1, B and X2, and he chooses according to which difference is greater.

a/ Mean over four patterns

The overall mean will be :

$$\frac{1}{4}\,(\,A+X1+B+X2\,)$$

This has a distribution over z which has a mean value:

$$\frac{za + 3.zb}{4}$$

and standard deviation, $\frac{s}{2}$.

Subtract the mean from A and B in turn, to yield

$$\frac{1}{4}\,(\,3.A - (\,X1+B+X2\,)\,) \qquad \text{and} \qquad \frac{1}{4}\,(\,3.B - (\,A+X1+X2\,)\,)$$

respectively. Corresponding to these weighted means we have two distributions over z which have means:

$$\frac{3}{4}\,(za-zb) \qquad \text{and} \qquad \frac{1}{4}\,(za-zb)\ ,\ \text{respectively}$$

and standard deviations both equal to $\frac{\sqrt{3}}{2}.s$.

Once more, samples from these two difference distributions can be positive or negative, so that in order to compare them, we must take the modulus of the difference as our measure of dissimilarity.

Fig. 52 also illustrates this case. If we consider two patterns which have a separation in observer-space such that d'=2, then the two dotted curves, with means at d'=0.5 and d'=1.5 , can be taken to represent the two difference distributions. The solid curves will therefore represent the distributions of the moduli of the differences.

The probability of a correct decision, in this case, is the probability that a single sample from the distribution of the first modulus, is greater than a single sample from the distribution of the second modulus.

b/ <u>Mean over three patterns</u>

The mean over X1, B and X2 will be:

$$\frac{1}{3}\ (\ X1+B+X2\ )$$

and subtracting this from A, we obtain:

$$\frac{1}{3}\ (\ 3.A - (\ X1+B+X2\ )\ ).$$

Similarly, if we take a mean over A, X1 and X2 and subtract it from B, we obtain:

$$\frac{1}{3}\ (\ 3.B - (\ A+X1+X2\ )\ ).$$

These weighted means have associated distributions over z which have means:

$$\frac{1}{3}\ (\ 3.za - 3.zb\ ) \quad \text{and} \quad \frac{1}{3}\ (\ za - zb\ )\ \text{, respectively}$$

and both possess the standard deviation, $\frac{2}{\sqrt{3}}.s$.

Comparison with the results of a/ will show that the two cases are in fact quite similar. The means of b/ are a factor of $\frac{4}{3}$ greater than those of a/ , and the standard deviations follow the same rule. There is simply an overall scaling factor relating the two cases, and consequently the calculations of probability will yield identical results.

Curve 4 of fig. 53 shows the results for these cases. It will be noted that for $d' < 3.3$, curve 4 is lower than curve 3, showing that the pairing of patterns dispenses with some of the information available to the subject.

A:4 Discussion

The problem remains that we have calculated several relationships between probability of correct response and d', and one of them must be chosen as appropriate to the experiments.

Let us re-examine the reasons behind the choice.

The experiments consist of comparisons of patterns, and their results of proportions, or probabilities. The measures of similarity of patterns, therefore, are numbers between 0 and 1. The disadvantage of such measures is that, while the experimental parameters can vary over an almost unlimited range, the results are confined to a very small range. Most plots of performance against parameter would therefore resemble a curve tending asymptotically from 0.5 to 1.

In an endeavour to show results in a more informative manner, a transformation of the performance measure from the range 0.5 to 1 to the range 0 to infinity would be very valuable. Very many such transformations exist, and one must be chosen which does not discard information and which, hopefully, reflects more accurately the internal processes of the subject.

The d' measure varies monotonically with probability of correct response and therefore satisfies the first criterion. It assumes a model for the decision process which, while not being provably correct, yields results demonstrably independent of technique of measurement and intuitively satisfying.

The transformations calculated in this appendix have taken the same model as their starting-point, together with a number of different possible strategies for the subject. They have all been found to be monotonic and to cover the desired range, and are, in consequence, all suitable candidates.

Of the four curves of fig. 53, the first two may be dismissed on the grounds of inapplicability to the present experiments. Curve 1 only expresses relationships between pairs of pairs of patterns, and curve 2 represents the situation when the subject knows the two patterns being compared well.

The choice is thus between transformations represented by curves 3 and 4. Over the range of differences within which most of the pattern pairs presented lie, curve 4 shows a more efficient use by the subject of the information available to him. In particular, it makes use of the fact that three of the patterns in the AXBX presentation are known to be the same.

Curve 4 was therefore chosen as representing best the strategy of an efficient observer.

Having decided upon the transformation to be used, a few points are worth making.

Firstly, it is dubious whether the results of any single experiment of this thesis could be shown to correspond better to any one of the curves of fig. 53, assuming some particular relation ship between parameter and d' values.

Secondly, a series of experiments could have been undertaken to have determined the transformation from probability to d' empirically, by making comparisons of AXBX and 2AFC presentations. However, in order to obtain a curve sufficiently accurately to be able to determine whether it were 3 or 4, for example, a very large number of experiments would have been necessary. Because the investigation undertaken was supposed to be a study of the tactual system and not of a particular technique of analysis, and because it would have been very time-consuming, the empirical approach was not embarked upon.

Thirdly, the particular choice of transformation is not of primary importance; most of the conclusions reached would have remained the same. The graphs plotted in the earlier chapters would look largely the same. The choice of transformation that has been made has yielded a number of roughly linear graphs, and thus appears to be substantially correct. It seems likely that if the choice is in error, application of a simple scaling factor would correct the results to within the limits of experimental error.

For purposes of comparison, in fig. 54 is plotted the amount of information transmitted to the subject in a single trial as a function of the probability of correct response. For tasks in which this probability is less than about 80%, it will be seen that information is approximately proportional to the square of d'.

Table A:I gives the calculated probabilities of correct responses for given values of d', as plotted on curve 4, fig. 53. Table A:II is the inverse of table A:I, giving values of d' for specified probabilities of correct response. It is this table that has been used to calculate d' values in this thesis.

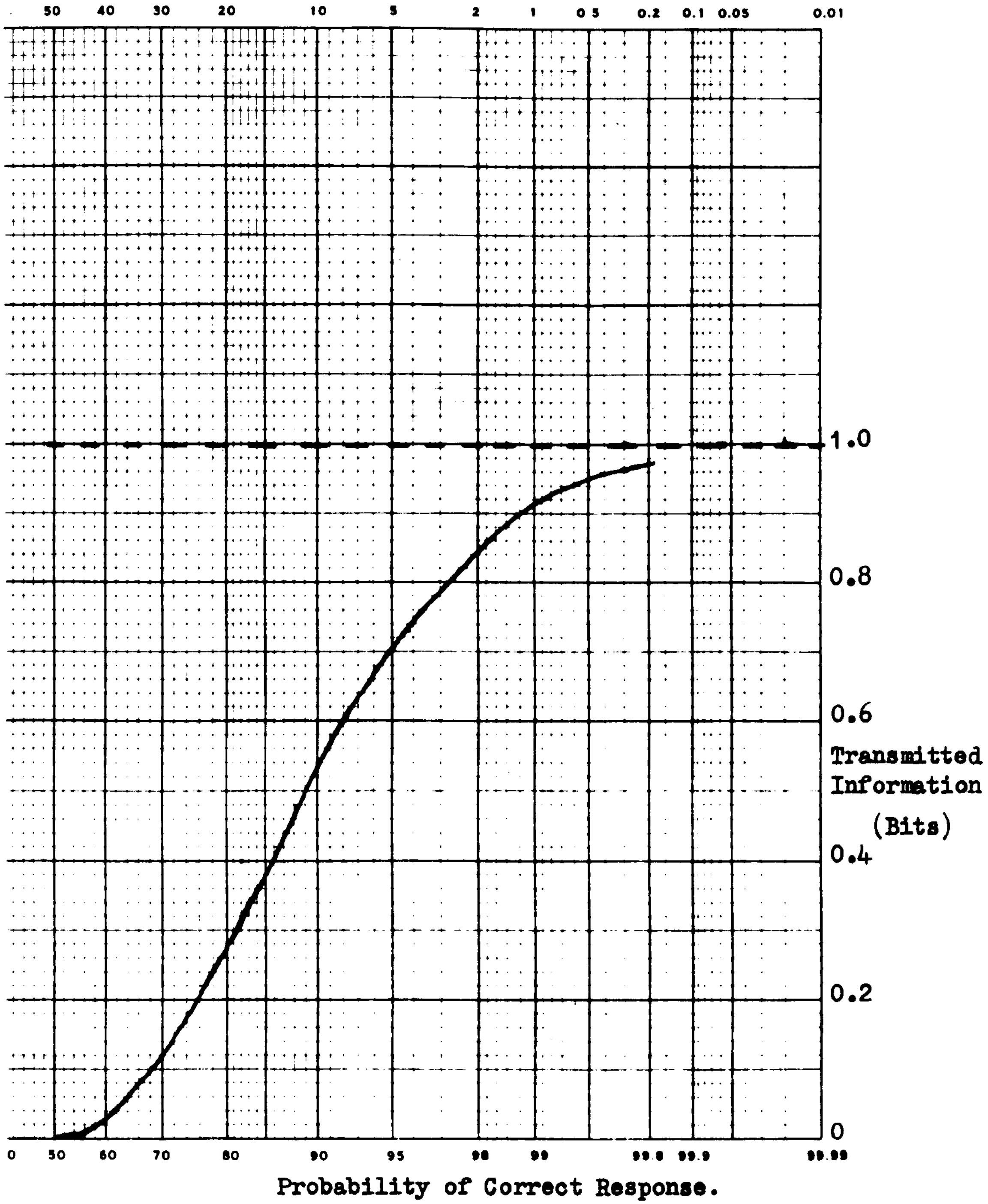


Fig. 54/ Relationship between transmitted information and probability of correct response for experiments involving two possible responses.

Table A:1

Probabilities of error and correct responses for given values of d'.

d'	% Correct	% Error	d'	% Correct	% Error
0.000	50.0	50.0	3.88	94.5	5.50
0.139	50.2	49.8	4.02	95.1	4.93
0.277	51.0	49.0	4.16	95.6	4.40
0.416	52.2	47.8	4.30	96.1	3.92
0.554	53.8	46.2	4.43	96.5	3.47
0.693	55.8	44.2	4.57	96.9	3.07
0.831	58.1	41.9	4.71	97.3	2.70
0.970	60.5	39.5	4.85	97.6	2.37
1.11	63.1	36.9	4.99	97.9	2.07
1.25	65.7	34.3	5.13	98.2	1.81
1.39	68.3	31.7	5.27	98.4	1.58
1.52	70.9	29.1	5.40	98.6	1.37
1.66	73.3	26.7	5.55	98.8	1.18
1.80	75.7	24.3	5.68	99.0	1.02
1.94	77.8	22.2	5.82	99.1	0.88
2.08	79.8	20.2	5.96	99.2	0.75
2.22	81.7	18.3	6.10	99.4	0.65
2.36	83.4	16.6	6.24	99.4	0.55
2.49	84.9	15.1	6.37	99.5	0.47
2.63	86.3	13.7	6.51	99.6	0.40
2.77	87.6	12.4	6.65	99.7	0.34
2.91	88.8	11.2	6.79	99.7	0.29
3.05	89.8	10.2	6.93	99.8	0.24
3.19	90.8	9.20	7.07	99.8	0.20
3.33	91.7	8.31	7.21	99.8	0.17
3.46	92.5	7.50	7.34	99.9	0.14
3.60	93.2	6.76	7.48	99.9	0.12
3.74	93.9	6.11	7.62	99.9	0.10

Table A:2

Values of d' for given probability of correct reponse, or error rate.

% Correct	% Error	d'	%Correct	% Error	d'
50	50	0.000	75	25	1.76
51	49	0.279	76	24	1.82
52	48	0.393	77	23	1.89
53	47	0.484	78	22	1.95
54	46	0.566	79	21	2.02
55	45	0.636	80	20	2.09
56	44	0.704	81	19	2.17
57	43	0.766	82	18	2.24
58	42	0.827	83	17	2.33
59	41	0.884	84	16	2.41
60	40	0.941	85	15	2.50
61	39	0.996	86	14	2.60
62	38	1.05	87	13	2.71
63	37	1.10	88	12	2.82
64	36	1.16	89	11	2.94
65	35	1.21	90	10	3.07
66	34	1.26	91	9	3.22
67	33	1.31	92	8	3.38
68	32	1.37	93	7	3.56
69	31	1.42	94	6	3.77
70	30	1.48	95	5	4.00
71	29	1.53	96	4	4.27
72	28	1.59	97	3	4.60
73	27	1.64	98	2	5.03
74	26	1.70	99	1	5.70

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