HUMAN VISUAL EVOKED POTENTIALS: A COMPUTER AIDED INVESTIGATION INTO THEIR ORIGIN AND VARIABILITY

by

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Thesis submitted for the Degree of Doctor of Philosophy

– 1974 –

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ABSTRACT

This thesis is concerned with the measurement of human visual Averaged Evoked Potentials (AEPs) to tachistoscopically presented pattern stimuli, i.e. the sudden appearance and disappearance of patterns into an otherwise continuously illuminated diffuse field, such that the overall change in luminance is zero or very small.

Previous work reviewed includes that on the response of single cells in the cat and monkey visual cortices to contoured stimuli, and also that on the measurement of human visual AEPs to patterned stimuli. The work of D.A. Jeffreys, indicating that AEP scalp distribution measurements showed promise for identifying source locations of the first two (temporally separate) pattern AEP components, is considered in detail.

The experimental apparatus and computing system are described, together with a detailed discussion of experimental errors.

The computing system was designed to be on-line and interactive, and a general discussion is included on the man-computer interface.

Four chapters report and discuss the experimental findings.

The first describes the adaptation effect of one stimulus on the AEP to another which follows it after a short time interval. The adaptation is plotted as a function of relative timings and pattern types. Monocular stimulation showed that the effect must be partially central in origin.

The second reports on variability of the AEP. The AEP standard deviation is plotted as a function of electrode position, and was found to be almost independent of the stimulus. A 'Running Average' technique is described for measuring longer term AEP variations.

The third describes a computerised AEP component separation method, which was developed and used to provide further confirmation that the two AEP components first identified by Jeffreys give scalp distributions compatible with dipole sources in the striate and extrastriate cortices. Four subjects were tested in detail, and the results compared with a simple dipole model.

The fourth describes the development and initial trials of an on-line Evoked Potential Stochastic Search Technique.

The results are discussed, and some confirmatory and extension experiments suggested.

DECLARATION

This thesis is my own account of the research reported. Apart from the experiments described in chapter 9, all the research work and analysis thereof is my own.

The experiments described and reported in chapter 9 were done in conjunction with Dr. D.A. Jeffreys. These experiments were based very much on earlier work by Dr. Jeffreys, and he suggested the stimulus conditions and prepared the stimulus patterns (which were also used in the earlier work). The experiments were conducted with his assistance. The computer programs and analyses are all my own. The dipole model is my own and differs slightly from that of Dr. Jeffreys, although it leads to the same conclusions.

Dr. Jeffreys built the two tachistoscopes described in Figure 4.2.

CONTENTS

ACKNOWLEDGEMENTS

"No man is an iland, intire of it selfe...."

(John Donne, 1624)

This thesis covers some five years of, at times, intensive work and it is with pleasure that I take this opportunity to thank all those who have helped in so many ways during that time.

In the first place I must thank the management of IBM (UK) Laboratories Ltd. for permission to undertake this research, and for support in the form of an IBM Advanced Education Award. I am also grateful to them for making available library facilities and for their help in the typing and preparation of the thesis. I am particularly indebted to Mr. L. Godson for his personal help, and to Mr. P.D. Atkinson for much encouragement.

My thanks are due to the experimental subjects who offered their services; and especially to Dr. D.A. Jeffreys for the many long hours he spent in the experimental chamber, under the control of what must have seemed a very demanding and untiring computer!

However my thanks to Dr. Jeffreys are chiefly for his help and direction in much of my work; and as a working partner in many experiments. I also acknowledge the value of many discussions with other members of the Department of Communication, and the technical assistance of Mr. P.W. Lynch.

I am much indebted to my supervisor, Professor D.M. MacKay for his guidance and encouragement; and also for extending my understanding of the research field through the many stimulating discussions I had with him.

Finally I must thank my wife for her patience over the long months during which this thesis was being written; and for the very necessary assistance in the correction and improvement of my use of the English Language. Any errors that remain are entirely mine.

SECTION A

INTRODUCTION, LITERATURE REVIEW, AND SCOPE OF THE RESEARCH PROGRAMME

CHAPTER 1: GENERAL INTRODUCTION

The existence of varying potentials on the surface of the scalp (electro-encephalographic, or EEG potentials) caused by activity in the underlying brain has been known for a long time. Incoming sensory signals cause changes in the measured EEG voltages, and when such a change can be correlated with a specific external stimulus it is usually called an *'Evoked Potential'* (EP). Evoked potentials offer to the physiological experimenter a useful tool with which to investigate the internal sensory information processes in the brain.

The measurement of evoked potentials to a restricted class of stimuli is the subject of this thesis. EPs have a number of advantages and also some disadvantages when compared with other methods of investigating sensory information processes, and in order to put EPs into their correct perspective, we shall first review briefly the alternative methods of study.

1.1 Alternative Methods of Study

These fall into four broad categories:

1. Psychophysics
2. Ablational methods
3. Cytoarchitectonic and degeneration methods
4. Electrophysiology.

1. *Psychophysics* is the measurement of a subject's perceptual response to an applied stimulus. Psychophysical experimentation has proved to be of great value in providing information about sensory mechanisms. It does, however, have two significant disadvantages. Firstly, the chain of processing between stimulus and response is very complicated, involving as it does, not only the sensory mechanisms, but also various effector mechanisms, such as motor or speech processes. All these processes are little understood and care must be taken to ensure that they do not affect the validity of the results obtained on the sensory mechanism being studied.

   Secondly, most psychophysical experiments are restricted to humans, owing to the

need for adequate communication between subject and experimenter. Experiments with animals are possible, however, but these usually require extensive training to overcome the communication barrier.

2. *Ablational methods* involve the study of behavioural or perceptual changes resulting from lesions or damage to the brain. In animals such lesions can be selective (within humane limits). On the other hand in man such studies are limited because one only has available lesions caused by accident or disease. Owing to the vast interconnectivity of the pathways of the nervous system, the results are, in many cases, open to more than one interpretation. It is, of course, an irreversible method.
3. *Cytoarchitectonic and degeneration studies* utilise suitable selective staining techniques to determine the positions of cells and their processes. The paths of degenerating axons caused by small selective lesions can be traced in this way, and this provides an ideal method for mapping nerve fibre connections. To obtain much more highly magnified detail of all structures and particularly the synaptic connections electronic microscopy can be used.
4. *Electrophysiology* is the direct measurement of the electrical activity generated by nervous tissue. Evoked potentials come under this heading. The recording of electrical activity in or near actual nerve cells or nerve fibres using microelectrodes (single unit recording) has developed very rapidly indeed over the last decade. These measurements fall roughly into two classes:
   a. Spike activity – observation of nerve cell discharges
   b. 'Slow wave' activity – measurement of the more slowly varying electrical voltages in the tissue surrounding the nerve cells.

   Single unit recording has, however, two disadvantages. In the first place, it is not normally possible for human subjects, except when clinical needs allow it, such as during a brain operation, and when the brain is anyway not in its normal healthy state.

   Secondly, in the case of animals the side effects of surgery are likely to put the animal into a condition not truly representative of its normal waking state. This is especially true if an anaesthetic is used, most of which are known to have some effect on neural

activity. Also the animal may be paralysed, a condition which may have further effects on neural activity. A number of approaches have been tried to circumvent the anaesthetic problem. One method is to use an animal with an isolated forebrain (cerveau isolé) (see [19], [35]). This allows that part of the brain to be investigated without an anaesthetic, but contingent effects of the actual surgical section are still possible. Another approach which has been tried [174] is to record from implanted microelectrodes in the awake animal, after taking suitable precautions to avoid pain, etc. In general, however, experiments with awake subjects (human and animal) present special problems because of the difficulties of controlling all the experimental conditions, and such studies must be considered as complementing those on relatively stable anaesthetised preparations.

Measurement of human EEG is possible, however, for normal healthy awake subjects. Thus EPs represent what is usually the only direct physical method for studying sensory mechanisms in the human brain.

1.2 Drawbacks of Evoked Potentials

That the EEG is *caused* by neural activity in the underlying brain is generally accepted, but the precise mechanisms for its generation are little understood. Also the electrical transmission characteristics of the layers of tissue and bone between the EEG generators and surface recording electrodes lead to severe attenuation and distortion of voltages measured by the latter. Both these factors make interpretation of evoked potentials rather difficult. This will be discussed in more detail later.

Furthermore, EPs are usually rather small in magnitude (0–10 μV), when compared with other apparently uncorrelated EEG voltages (30–50 μV). In order to extract the EP from the on-going random activity or 'noise', it is normally necessary to use special analysis techniques. These do not, however, completely remove the effects of the unwanted noise, and one of the purposes of this thesis is to discuss to what extent the residual effects of noise must be considered when interpreting the results of evoked potential experiments.

CHAPTER 2: REVIEW OF VISUAL EVOKED POTENTIALS

2.1 Important Parameters of Visual Input

The visual scene with which the human organism is confronted consists predominantly of a contoured or structured matrix to which is added such other details as colour, movement, brightness, depth, etc. Common sense tells us that it is the contours or boundaries within our visual scene which provide us with most of our useful visual information, and thus we should expect that when we investigate the appropriate visual information processing mechanisms in the brain we should find that this aspect of the visual scene receives particular attention. There is much experimental evidence in animals to support this conjecture. This evidence will be reviewed in the next section. It is also found that the brain has specific mechanisms for reducing the influence of 'uninteresting' variables. One such mechanism is the pupillary reflex of the eye, which reduces the effect of changing overall brightness. In man such physiological evidence as exists (see below) lends support to the view that what is known from animal experiments can be extrapolated to humans. Psychophysical experiments have also amply demonstrated that the human visual system contains mechanisms for the extraction of certain structural features of the visual field, such as orientation, spatial frequency, etc. Recently evoked potential work has also provided confirmation of some of these psychophysical results [105], [23], [101], [103].

In general, however, psychophysics can only provide evidence that a particular processing mechanism exists, rather than providing a detailed explanation of how it works and which particular neural networks are involved.

2.2 Functional Organisation of the Visual Cortex

Visual input from the retinae of most higher animals is conveyed first via the optic tract to certain mid-brain centres, which include the lateral geniculate nuclei (LGN). These nuclei then project to the occipital cortex, which assumes a major role in the processing of visual information.

In the following sections we review in some detail what is known about how this part of

the cortex is organised.

2.2.1 Evidence from Animal Experiments

Very extensive work has been performed on the cat's visual cortex and, more recently, much of this work has been followed up on monkeys. We shall first review the work on cats and then that on monkeys, paying particular attention to the latter as this is closest to the human case. The results from the two animals show no very striking differences, but there are gradational changes which one might expect phylogenetically.

It appears that the visual cortex of both these animals is retinotopically organised, with several distinct mappings, probably representing successive stages of complexity in visual information processing. This can be inferred from the types of stimuli to which cells in each particular area respond.

2.2.2 Results from Cats

Studies of the cell types and configurations in various regions of the visual cortex have led to the definition of three distinct areas, 17, 18, and 19. These were first defined for the cat by Otsuka and Hassler [115]. Area 17 is also called the striate area, because of its characteristic layered appearance.

Talbot and Marshall [150] and Talbot [149] recorded evoked potentials from the surface of the cortex, and found two areas over which the visual field was mapped in an orderly fashion. These areas they termed Visual I and Visual II. More recently Hubel and Wiesel [75] have identified areas 17 and 18 with visual areas I and II respectively, and have also found a third orderly mapping, which they term Visual III, identified with the anatomically defined area 19. There is also evidence for a fourth visual projection in the lateral bank of the supra-sylvian gyrus [75], [49], [172] and this has also been shown to be retinotopically mapped [77].

The retinal mappings on the cortical visual areas I, II and III are quite straightforward and are illustrated in Fig. 2.1 (which shows the monkey arrangement, but the cat is similar). The mapping is centrally inverted, bottom right to top left, etc. The area to area mapping is not linear, much more cortical surface being devoted to the central (area centralis) part of

the field than to the periphery. The projections within each visual area form mirror images across the boundaries, as shown in Fig. 2.1.

A number of degeneration studies have been undertaken to discover how the various areas are interconnected. It has been shown that the lateral geniculate bodies project to ipsilateral areas 17, 18, and 19 [60], [167] and that area 17 in turn projects to areas 18 and 19, and also to the suprasylvian gyrus in both hemispheres [75]. There seems to be some divergence of opinion and conflicting evidence as to whether the two area 17s in opposite hemispheres are interconnected [75], [123]. Hubel and Wiesel [75] find little evidence for such connections and are of the opinion that they do not exist as it is difficult to see a use for them.

Studies on the types of stimuli to which cells in these various cortical areas respond link in well with the pattern of connections found by degeneration studies. Hubel and Wiesel [74], [75] have identified several distinct types of cell, classified according to the type of stimuli evoking the greatest response. All these cells respond to contours of more or less complexity.

a. *Simple Cells:* These respond to a simple edge, bar or slit at a particular orientation, fairly critically located in the centre of an elongated receptive field. The receptive fields of these cells can be mapped out using small spots of light, and the pattern of excitation thus measured is consistent with the more complicated stimulus which gives the greatest response.

b. *Complex Cells:* These also respond best to an edge, bar or slit, appropriately oriented, but in this case the precise position in the receptive field is not critical. Diffuse light or small spots do not excite these cells. The length of the edge, bar or slit is critical only in that the maximum response is obtained when the bar is extended to the limits of the receptive field. If extended outside the receptive field, there is no change in the response. As Hubel and Wiesel have shown, the behaviour of a complex cell can be explained if it is assumed that each such cell receives afferents from a number of appropriate simple cells,

and they suggest that the two types of cell represent successive stages in the analysis of a complicated visual scene.

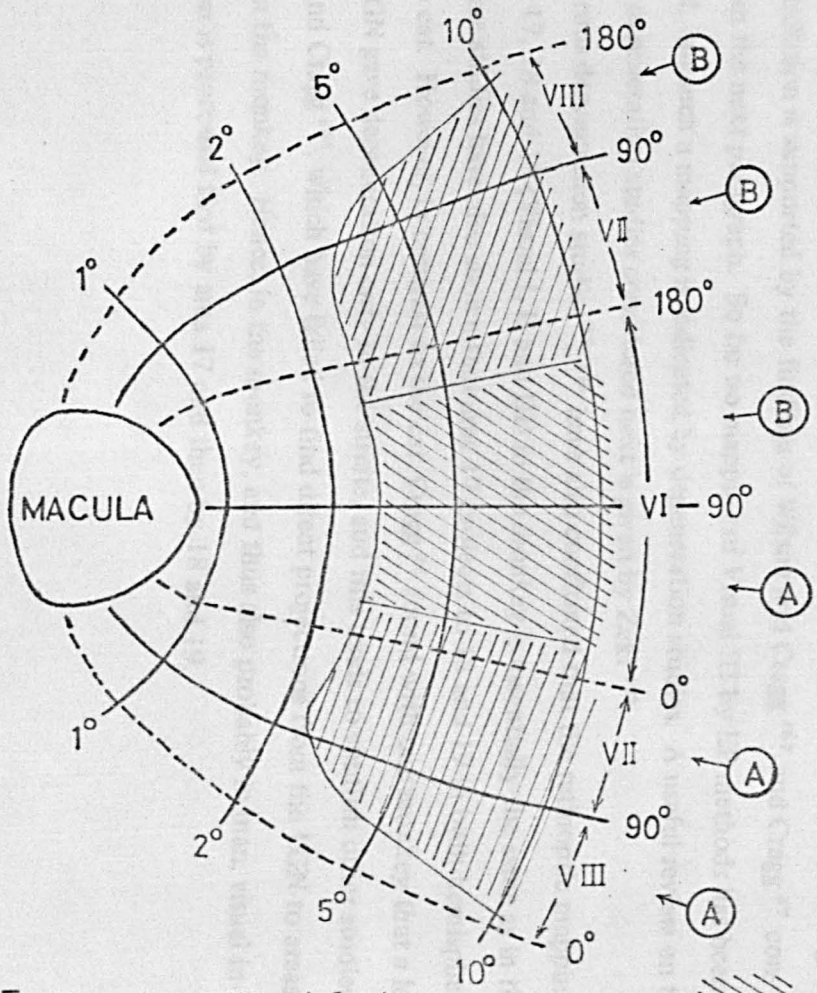
c. *Hypercomplex Cells (lower order):* These are again stimulated by edges of a particular orientation, as with complex cells, but there are now restrictions on the length of the edge. These cells apparently have a receptive field consisting of two parts – one 'activating' region and the other 'antagonistic'. To produce a response one has to have an edge at the correct orientation in the activating region, but *not* in the antagonistic region. Thus, the most effective stimulus is a 'stopped' edge. Other such cells have been found which have two antagonistic regions – requiring an edge 'stopped' at both ends for stimulation. Other cells respond similarly to slits or bars. It is also noted by Hubel and Wiesel that the properties displayed by this sort of cell can be explained as a combination of the features of two complex cells.

d. *Hypercomplex Cells (higher order):* The principal feature of cells of this type is that they respond to the presence of two edges 90° apart (or corners), and their behaviour seems to be explicable in terms of the combination of the selective properties of two lower order hypercomplex cells with orientations 90° apart.

Simple cells occur only in Visual I. However, the other types of cell occur in all three visual areas, but as we go from I to II to III, so the proportion of hypercomplex cells increases. Thus most cells in Visual II appear to be complex, while in Visual III hypercomplex cells predominate.

For all these cells movement of the line or bar perpendicular to its long edge was usually necessary to elicit a response, but not always. Often movement in one direction only was effective. Some workers have used exclusively moving stimuli to elicit the responses [19, 20].

Most of the cells in all three visual areas are binocularly driven and it appears that a major function of this part of the cortex is the analysis of retinal image disparity, presumably as part of the animal's depth perception. This has been studied by a

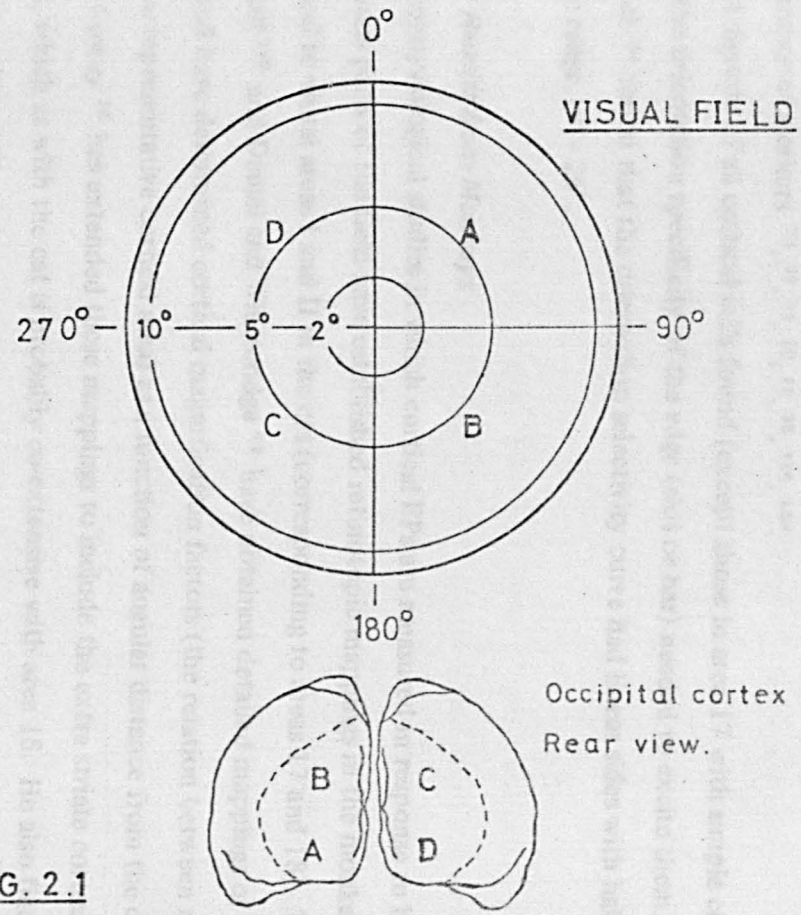


Flattened out Visual Cortex
LEFT Hemisphere representing
RIGHT half of visual field.

FIG. 2.1

in calcarine fissure

approximate areas on mesial surfaces



Occipital cortex
Rear view.

MONKEY CORTICAL REPRESENTATION

from Cowey (35)
Cragg (37)
Daniel and Whitteridge (42)

number of workers [75], [74], [11], [10], [19], [38], [114], [120].

A feature of all cortical cells found (except those in area 17 with simple circular fields) is the orientation specificity of the edge (slot or bar) needed to excite them. Campbell *et al.* [20] found that the orientation selectivity curve had linear sides with half width in the range 14°–26°.

2.2.3 Results from Monkeys

Electrophysiological studies in which cortical EPs are measured in response to light flashes in various parts of the field have established retinotopic mappings in the monkey almost identical to visual areas I and II in the cat (corresponding to areas 17 and 18). Talbot and Marshall [150] and Daniel and Whitteridge [42] have obtained detailed mappings of the striate area, and have determined cortical magnification factors (the relation between retinal area and the representative cortical area) as a function of angular distance from the centre of the field. Cowey [35] has extended these mappings to include the extra striate cortex, or Visual area II, which as with the cat is probably co-extensive with area 18. He also finds that if the striate area is removed responses from the extra striate cortex disappear. This seems to indicate that the striate 'drives' the extra striate, and they are sequential analysis stages. This conclusion is supported by the findings of Wilson and Cragg [167] and Cragg [37] considered in the next paragraph. So far no mapping of Visual III by EP methods has been reported, but such a mapping is indicated by degeneration studies. A useful review on this and the degeneration studies considered next is given by Zeki [178].

Numerous degeneration studies [37], [179] have also confirmed that the retinoptic mapping on to areas 17, 18 and 19 (Visual I, II and III) in the monkey is essentially the same as in the cat. These studies have also shown that area 17 projects to 18 and 19 in both hemispheres as in the cat. However, in contrast to the cat, Cragg [37] found with one monkey that a lesion in the LGN gave degeneration *only* in the striate, and this tends to confirm other studies, Wilson and Cragg [167], which have failed to find direct projections from the LGN to areas 18 and 19 in the monkey. Hence, in the monkey, and thus also probably in man, visual information is processed first by area 17 and then by 18 and 19.

Hubel and Wiesel [76], [78] have measured the responses of cells in the monkey areas 17 and 18 and found a very similar organisation to that of the cat. Simple, complex and low order hypercomplex cells were found in area 17, and complex and hypercomplex (high and low order) in area 18. In the following respects, however, the results were different from those of the cat:

1. In area 17, complex cells predominated, much more so than in the cat.
2. In area 17 most simple cells were driven by one eye only, and there is some evidence that in the monkey, binocular depth analysis is performed in area 18 [78].
3. Receptive fields are smaller than those in the cat by a factor of about 3 or 4.
4. Only a few (about 10%) of the cells showed any colour preference. This is surprising since the monkey has well-developed colour vision, similar to man; and also since the majority of cells in the monkey lateral geniculate nucleus are colour coded [165].
5. No results have so far been reported on the stimulation characteristics of cell types in area 19 of the monkey.

One of the criticisms referred to above concerning electrophysiological experiments on animals was the effects on the functioning of the nervous system of the anaesthetic, paralysing agent, and surgery. To overcome these disadvantages Wurtz [174] has devised a method of measuring receptive fields in the striate cortex of *awake* monkeys. This is done by training the monkeys to fixate. Eye movements are not otherwise restricted. Unfortunately his recordings were mostly limited to units in or near layer IV of the striate cortex and thus it is difficult to make a fair comparison with the distribution of unit types found by Hubel and Wiesel [76]. However, some cells corresponding to the simple and complex cells of Hubel and Wiesel were found. The most significant difference was, however, the discovery of a large number of cells which gave good non-adapting responses to stationary stimuli. Many such units responded with bursts of spike discharges, and it is tempting to link these to eye movements, but Wurtz failed to find any connection between these bursts and the measured EOG (electro-oculogram). In contrast to these non-adapting units, however, others were found which responded only to moving stimuli, but adapted rapidly. This sort of behaviour has not been found in paralysed, anaesthetised animals, and suggests that

in the awake animal there may be habituating mechanisms (possibly central) at work, which are not present under anaesthetic.

Further evidence found by Wurtz [173], [175], [176] in monkeys has shown that some units in the cortex are inhibited by sudden displacements of patterned retinal images, both saccadic or externally induced, providing further support for the influence of eye movements.

It is relevant at this point to make a few remarks about changes in evoked potentials as a result of eye movements (or absence of them). The evidence is somewhat conflicting. Riggs and Whittle [132] found that the EPs to both flashed patterns and displaced patterns were unaffected by stabilising the retinal image. This would indicate that the EP generating mechanism comes before that which causes perceptual suppression. Keesey [89] has recently found that the EP to flickering light was reduced by stabilisation, but only at low flicker frequencies and high modulation depth. Other workers [61], [50] have found, however, that during a saccadic eye movement EPs are often highly attenuated. Thus it seems that eye movements are necessary for perception and not for an evoked potential, but eye movements themselves do influence the EP.

These considerations are discussed at some length here since most EP experiments on humans (including those reported in this thesis) have been done with eye movements restricted in no way except that of voluntary fixation.

The role of eye movement effects in the functioning of the visual centres is thus probably very important. The normal 'awake' eye is in continuous 'saccadic' motion, and that these eye movements are necessary for sustained visual perception is apparent from the well known fading phenomenon of a stabilised retinal image. However, in most of the single unit work referred to above (except Wurtz) paralysed preparations were used, and thus we should expect the picture they give of visual processes to be necessarily an incomplete one.

2.2.4 Evidence from Human Experiments

Since it is not normally possible to do similar histological or electrophysiological experiments on humans, other, less direct methods have to be resorted to, mainly in clinical cases.

A number of workers have measured EPs on the human cortical surface [71], [117] but they have usually used flash stimuli. Perez-Borja *et al.* [117] did, however, measure λ-wave responses to patterned stimuli.

The only single unit work in the human visual cortex so far reported has been that of Marg *et al.* [106], [107], who recorded from a few units with chronically implanted electrodes in awake patients. It was found that the most effective stimuli were moving bars or discs, but detailed comparison with the results from animals is virtually impossible.

Extensive studies on lesions owing to accidents [72], [154] have enabled a crude retinotopic mapping to be made on the human striate cortex. Brindley and Lewin [16] were able to stimulate directly the striate cortex of a blind patient, and by observing the position of the subjectively reported light flashes, they were able to provide direct evidence for retinal mapping in the striate area.

These experiments provide crude confirmation that the visual cortex in man is organised similarly to that of the monkey. There are differences, however. Man's striate cortex is confined much more to the internal surfaces of the calcarine fissure and the medial surfaces [124], in contrast to that of the monkey, which has more striate cortex on the outer cortical surface. Man's cortex is also more folded than that of the monkey.

2.2.5 Summary

The above review does not claim to be complete but was designed to show that the occipital cortex visual centres in man are probably arranged in several spatially separate, retinotopically mapped regions containing cells which respond to contoured stimuli of different complexities, and which probably represent sequentially excited stages in the analysis of visual information. This part of the cortex seems to be very predominantly concerned with contour and depth information, while colour and luminance specificity are conspicuous by their relative absence. The role of eye movement is difficult to assess, because of the paralysed state of many of the animals used.

2.3 Origin of Scalp Evoked Potentials

Electrodes attached to the surface of the scalp can pick up potentials generated by a number of sources (muscles, eyes, etc.,) but we shall consider only those potentials derived from neural activity in the underlying brain. The electrode on the surface is separated from the brain by the scalp (about 0.7 cm thick), which has a fairly low resistivity, and the skull bone (about 0.5 cm thick), which probably has a somewhat higher resistivity. It is fairly well established that the scalp EEG is an attenuated and spatially averaged form of the potentials existing on the surface of the cortex itself [44], [32], [69], [160], [34]. The origin of the EEG measured on the surface of the cortex is, however, less certain. One possibility is that the EEG is the result of summated neuron action potentials. Fox and O'Brien [56] measured firing time histograms, and found that in a large number of examples these were a good approximation to the EP. However, this does not demonstrate a cause and effect relationship. On the other hand, Amassian *et al.* [1] consider it unlikely that neuron action potentials summate to produce the surface potential, and suggest that the most likely causes are the post synaptic potentials, or other slow cortical potentials. This is supported by other work [40], [59], and Creutzfeldt *et al.* [39], [41] have proposed a detailed mechanism to explain the generation of a cortical surface evoked potential resulting from the arrival of an afferent volley of discharges from a receptor. With this mechanism cortical activity leads to the generation of a potential difference *across* the cortex, and thus lends support to any model of EEG or EP generation which assumes that the cortex acts like a dipole, or dipole sheet, with axes perpendicular to the cortical surface. A number of theoretical models have been proposed relating the surface voltages with the position and orientation of dipoles within the brain [159], [143], [55], [161], [139], [90], [80]. The most significant result of these calculations is the severe attenuation which can exist between the cortical generators and the EEG electrodes. This can qualitatively be seen to be the result of the shunting effect of the comparatively low resistance scalp overlaying the high resistance skull. A further effect is that the 'spread' of potential on the scalp surface is much greater than that on the cortex. Thus widespread EP distributions measured on the surface may be much more localised in the cortex.

In summary we may say about EP origins:

1. The EP is a very much attenuated and diffused form of the underlying cortical surface activity.
2. A large EP is symptomatic of widespread, coherent, cortical activity.
3. Absence of EP does not mean absence of cortical activity related to the stimulus, since the spatial average may be zero. Thus the magnitude of the EP is not necessarily a measure of the number of neurons involved.
4. Real sources may be equivalent to dipoles perpendicular to the cortical surface.

2.4 Evoked Potentials and Noise

Mention has already been made of the high level of uncorrelated noise which accompanies the scalp recorded EP. Normally the "EP" as such cannot be distinguished by inspection of the "raw" EEG trace. To extract the EP from the noise, it is necessary to present multiple stimuli (not necessarily regularly spaced in time) and then use a cross correlation technique. The method usually employed is 'time locked averaging' which is simply described as follows:

In each stimulus period, suppose the stimulus is presented at t = o, on a time scale redefined for each period. t is called the 'latency'.

Suppose N stimuli are presented, and that the EEG voltage measured during the ith stimulus period is Vi(t), then the 'average evoked potential' $V_A(t)$ (or AEP) is defined as:

$$V_A(t) = \frac{1}{N} \sum_{i=1}^{N} V_i(t)$$

$V_A(t)$ will be a measure of the correlated response, after the uncorrelated noise has been (approximately) averaged out. Practical limitations restrict the value of N, and as a result $V_A(t)$ will always be subject to the residual effects of the noise. For this reason every AEP measurement or comparison should include some estimate of the significance of the result being quoted. Too often in the literature this is neglected, although some authors have computed variability estimates. Donchin [46] gives a useful review of the extent to which such statistical methods have been used in AEP research.

2.5 Results from Human Visual Average Evoked Potentials

2.5.1 Averaged Evoked Potentials to Flash Stimuli

Much early work on visual AEPs was done using simple light flashes as stimuli, principally because such stimuli are simple and easy to generate. The AEP to flashes is, however, in general very complex [27, 94], and is often followed by a decaying oscillation at a frequency approximately equal to the α-rhythm [53, 163, 116]. It is also found that most components of AEPs to flashes have a very wide distribution over the head. The most extensive studies on the topographical distributions of flash responses have been reported by Rémond [130]. In general he and other workers find that early components of the flash AEP show greater variation over the scalp than the later components. He also points out ([101], p. 240) that simultaneous recording at multiple sites on the scalp is necessary to obtain maximum information on temporal relations between sites. It seems that instrumental limitations often prohibit multi-channel recording for many workers, but as will be seen below for pattern responses, measurement of topographical AEP distributions is essential if the AEP is to be related to its underlying sources. In general, flash AEPs are complex, widespread, long-lasting and difficult to relate to underlying brain mechanisms. A useful review on the results and significance of AEPs to flash stimuli is given by MacKay and Jeffreys [103].

2.5.2 AEPs to Pattern Stimuli

Since it became evident that the human visual system (and particularly the occipital cortex) was more concerned with the analysis of spatially structured fields, some AEP workers turned their attention to patterned stimuli. Initially 'flashed' patterns were used [144, 131, 67, 66, 33, 29, 68, 65] and it was found that the presence of a pattern had a marked effect on the form of the response, but that the responses were still rather complex. If, however, the response to an unpatterned light flash (of the same luminance change) is subtracted from the 'flashed' pattern response [131, 164] a much simpler response is produced. Jeffreys [81] has further shown that this 'subtracted' response is very similar to that produced by a tachistoscopically presented pattern, where the pattern appears on a uniformly illuminated field, such that the overall luminance change is zero. Jeffreys has also shown [101] that the distributions over the head of the 'flash' response and the tachistoscopically presented

pattern response are different. This is strong evidence to suggest that these two types of response have different origins. This has also been suggested by Spekreijse [145] and Regan and Heron [128], based on results using alternating checkerboard stimuli. Coupled with what is known from single unit work in animals (section 2.2) concerning the predominance of contour analysing units in the visual cortex, it is tempting to suppose that these 'pattern' AEPs (i.e. without change of luminance) arise in the visual cortex. This has been proposed by Jeffreys [101, 84, 82, 83, 85] and by Halliday and Michael [63].

Thus it would seem that the most promising stimuli for investigating the processes in the visual cortex will be those which involve a change in spatial structure, but with little or no accompanying change in overall luminance. We now review the AEP work which has used this form of stimulus.

This stimulus type can be categorised in two ways:

A Nature of Pattern Change

1. Transition from a 'blank' field to a 'patterned' one, or vice versa. These are termed 'pattern appearance', or 'pattern disappearance' respectively.
2. Transition from one pattern to another, which is usually the inverse of the first (pattern reversal).

B Time Course of Change

1. Sinusoidally modulated patterns as used by Spekreijse [145], Campbell and Maffei [23], Halliday and Michael [63] and Regan [128]. A narrow band analysis technique is used here.
2. Step changes, as used by Jeffreys [84]. A wide band, transient analysis technique is used here.

Narrow band analysis has the advantage that the resulting reponse is relatively free of noise, but a good deal of information is lost, when compared with the transient analysis method. The analogy here between the two common methods of analysing electrical networks is obvious.

2.5.3 AEPs to Alternating Patterns

The stimuli used by most workers have either been alternating checker boards [145], [63], [30], [128], [129] or alternating stripes [23], [4], [5], [30], [105], [108], [109] and the variables which have been investigated include modulation depth, spatial frequency of pattern, rate of alternation, direction of stripes, etc. The principal results may be summarised as follows:

1. The check size or stripe width which gives the maximum response lies between 10′ – 20′ arc subtended at the eye [145], [5], [108], [129].
2. The responses are derived almost entirely from the central 3–4° of the visual field [145].
3. Campbell and Maffei [23] have shown that in the human visual processing mechanisms there are channels highly selective to orientation and spatial frequency of the alternating stripes. They have also shown that horizontal and vertical bars give a greater response than diagonal bars [105].
4. The response decreases markedly with loss of accommodation [145].

Most workers have not investigated the effect of change of retinal locus or the distribution of the responses over the scalp. Halliday and Michael have, however, investigated both these variables, and since [63] this is particularly relevant to this thesis, their results will be described in more detail. They measured the longitudinal and transverse distributions of the AEP using an array of electrodes over the occiput. They stimulated with 45° sectors of alternating checkerboards, in each of the 8 octants of the visual field. The field-size was large (16° diam.) and so was the square-size (50′), which must be compared with the optimum value of 10′ – 20′ quoted above. In addition the transition time between the patterns was about 8 ms.

They measured the amplitude of a prominent transition at 100 ms latency, (i.e. peak to peak amplitude) and their results for this transition may be summarised as follows:

1. The response is in general positive (5–7 μV) for the upper half field and negative (7–10 μV) for the lower.
2. Contralateral responses were larger than ipsilateral ones.
3. Octants near the vertical meridian gave larger responses than those near the horizontal.
4. Longitudinally the maximum response occurs between 5 and 7.5 cm above the inion,

for all octants.

They concluded that the responses are unlikely to originate from the striate area, since the amplitudes were not compatible with the known projection of the visual field in this area. This would predict that the horizontal octants should give the greatest responses, whereas the vertical octants were in fact the largest. In addition the maximum responses came from a region well anterior to the striate area, making the striate origin less likely.

However, the inversion of polarity between upper and lower half fields and the greater contralateral responses are in broad agreement with cortical mapping. An alternative explanation is that the responses arise in the extrastriate areas on the upper and lower surfaces of the occipital lobe. The similar amplitudes of the upper and lower half field responses make this explanation less likely, but it is also supported by Jeffrey's results [84] considered below, although with a different form of stimulus.

It should be pointed out that if the cortical sources behave like dipoles, the measured surface potentials will depend on the orientation, as well as position, of the dipoles, and thus the maximum response need not occur at the nearest point on the surface. With dipoles the position of the reference electrode is also important. This consideration was taken up in a second paper by Michael and Halliday [111], in which they provide further evidence that their responses come from the extra striate.

The transition times used in these pattern reversal stimuli are worthy of comment. If the reversal is brought about by mechanical means, the transition times cannot be less than several milliseconds. Cobb *et al.* [30] quote 3 ms and Halliday and Michael considered above quote 8 ms. These times are quite significant physiologically and a more correct definition of the stimulus would be the sequence 'pattern – fast moving blur – pattern'. If the pattern reversal is electronically switched, this complication does not arise as transitions can be made very fast.

2.5.4 Transient AEPs to Pattern Appearance

Relatively few workers have used this form of stimulus, which is surprising since it represents one which is closely related to normal visual experience. Work is reported by Jeffreys [101, 84]

and Van der Tweel *et al.* [158].

Van der Tweel *et al.* use equal 'pattern' and 'blank' durations, at a stimulus frequency of 2.1 Hz and a modulation depth of 15%. The response shows clearly separated 'on' and 'off' responses, of opposite polarity. Increasing the transition time has relatively little effect – lengthening the 'on' response and reducing the 'off' response. They did not vary retinal locus or measure scalp distributions.

Jeffreys (private commun.) has also measured 'on' and 'off' responses to pattern over a range of pattern durations and stimulus rates (both periodic and aperiodic). He finds that for stimulus durations greater than about 50 ms separate 'on' and 'off' components can be distinguished in the response. For durations less than 50 ms two separate components cannot be distinguished. The response is also affected by the frequency of the stimulus, and on the pattern/blank duration ratio. These effects seem to be explicable in terms of the influence of one response on the next, the 'pre-exposure' effect, and more work on this particular effect is reported in this thesis.

Jeffreys [84] has also been able to show that, by studying in detail the distributions of this type of AEP over the scalp for stimulation in different retinal areas, some correlation between the AEP and the known retinal mapping on the cortex can be found.

In ref. [84] he reports on the distribution along the midline of pattern appearance AEPs. He used a 6° diameter field, and a pattern consisting of hollow checker-board squares of side 14'. The stimulus duration was 25 ms. His results are summarised as follows:

1. The pattern appearance response consists of three principal peaks at approximate latencies 80, 110, and 180 ms after the onset of the stimulus.
2. For stimulation in the lower half field these peaks were +ve, –ve, +ve respectively. These polarities are reversed for the upper half field.
3. If the responses to the upper and lower half fields (presented separately) are added algebraically, the result is very good approximation to that obtained to full field stimulation.
4. The longitudinal distributions of the second peak (latency 110 ms) are consistent with the hypothesis that this particular peak originates in extrastriate cortex above and

below the occipital pole for the lower and upper half fields respectively. He relates this to a model which assumes that the cortex behaves as a surface negative dipole sheet.

Jeffreys also suggests that the inversion of polarity of the first (80 ms) peak is the result of dipole surface generators lying on the opposing surfaces of the striate cortex within the calcarine fissure.

The additive property of the upper and lower half field responses, and the fact that they have different longitudinal distributions strongly support the hypothesis that they originate in different, spatially separate locations.

Jeffreys concludes this paper by stressing the need for simultaneous multi-channel recording of AEP distributions to stimulation of discrete areas within the upper and lower visual fields. It is this work that the techniques and results reported in this thesis were designed to extend.

2.6 Summary

1. Animal experiments have shown that the visual cortex is primarily concerned with processing the contour or pattern information in the visual input.
2. AEP responses to luminance changes and to pattern changes have different scalp distributions and seem to have independent origins.
3. Pattern appearance AEPs have been found to show some correlation with underlying cortical organisation.
4. Very little reported work on pattern AEPs has included error estimates.
5. Further extension of the work on relating the AEP to its cortical sources requires simultaneous, multi-channel recording of AEPs to a wide range of stimuli at different retinal locations.

CHAPTER 3: SCOPE OF THE PRESENT RESEARCH PROGRAMME

3.1 Practical Considerations of AEP Measurement

With the desire to answer more advanced questions concerning the origin and significance of pattern AEPs comes the need for greater refinement in experimental techniques. This need manifests itself in several conflicting respects. We shall state briefly the factors involved, showing how they interact and then establish the approaches to be taken to overcome the problems.

1. Simultaneous multi-channel recording is required to measure AEP scalp distributions.
2. Stimuli covering smaller retinal areas give smaller signals and thus, since the noise is unchanged, a poorer signal to noise ratio results.
3. If possible a single experimental session should include all the stimulus conditions which are to be compared. This is to ensure that the effects of unwanted experimental variables are minimised. This raises the problem of subject endurance, and generally an experimental session should be less than 4 hours.
4. The signal/noise ratio can be improved by increasing N, the number of presentations per run. This however takes more time and conflicts with (3). In addition the signal/noise ratio only improves as $1/\sqrt{N}$
5. A way of increasing N, without sacrificing time, is to decrease the interstimulus period, Tp. This was the approach used by Campbell and Maffei [23]. However, it brings with it the disadvantage that successive responses interact (the pre-exposure effect), and since the purpose of the experiments is to measure certain components of the AEP which are suppressed by the pre-exposure effect, reduction of the interstimulus period below about 500 ms should be avoided. This aspect is considered more fully in chapter 7.

It was decided that the best compromise to meet the above practical difficulties was to use values of N and Tp which gave a run time of about 1 minute or less (well within the subject's range of maintained attention), but at the same time to make routine estimates of the variance (or std. dev.) of the average, and thus enable proper assessments of significance to be made. Thus typically N = 100 and Tp = 600 ms, although, as will be seen in the results sections,

these values were often adjusted to suit particular experiments.

It may be, however, that such an approach does not result in sufficient precision to answer certain questions, or is too time consuming, thus calling for a different approach from the normal averaging run. In this work one alternative technique was tried and is reported in chapter 10. It was an attempt to introduce automatic search methods into EP work.

A possible experimental technique, which overcomes the problem of substained subject attention, but does not save overall time, is to do the averaging run in stages, allowing the subject to rest between stages. The duration of each stage is best controlled by the subject himself. In the experiments reported here, the subject was provided with a 'hold' micro-switch, which could be pressed to stop the averaging process (without stopping the stimulus presentation). In practice few subjects used this facility during runs of less than about 3 mins. A similar feature was used by May *et al.* [108].

3.2 Other Factors which may influence the AEP

There are a number of variables, other than those of the stimulus being tested, which may influence the AEP measured and which must as far as possible be controlled. We shall consider such variables under three headings.

3.2.1 Psychological Variables

Here we must be careful to distinguish between our use of terms which relate to subjective attributes, as described by a subject, and those which relate to objective measurements. There has been a good deal of work reported on the influence of 'psychological variables' on evoked potentials. Much of it is inconsistent because of vague or ambiguous definitions of these psychological variables. Useful reviews are given by Sutton [148] and Regan [127].

It is reasonable to conjecture that the AEP may be correlated with some 'psychological variable' such as 'attention'. The trouble begins when it is required to 'measure' this variable, because to do so one must resort to a physical measurement, and then the investigation is reduced to looking for correlations between the AEP and this physical

measurement. In fact it is questionable why it was necessary to introduce the intermediate term called a psychological variable in the first place. Donchin and Cohen [47] illustrate this point when they show how different workers have used a variety of definitions of the variable 'attention' and suggest that this is the reason why results differ.

The main question however, which concerns us here is how to control adequately these psychological variables so that they do not affect the result of an experiment designed to investigate only the sensory processing mechanisms. The only practical approach here is to conduct the experiments in such as way that these variables are as far as possible always constant. Confidence that one has achieved this can be gained if it is observed that on different occasions responses to identical stimuli agree within the expected error limits.

3.2.2 Receptor Variables (of the receptor being investigated)

In the case of vision, variations in the characteristics of the eye will almost certainly affect the AEP measured on the scalp. Such factors include accommodation, convergence, eye movements, pupil diameter, and blinking. It is well known that accommodation has a marked effect on pattern AEPs (Harter and White [67]) and this is perhaps the most important factor. It will inevitably vary during a run, but its effects can be minimised by using fairly short runs, or by giving the subject rests within runs. The effects of eye movements on AEPs have been briefly considered in section 2.2.3. With stimuli of unchanging overall luminance, pupil diameter should be constant. Eye blinks, and the muscle potentials associated with them, will cause contamination of the AEP, but their effects will be averaged out provided the subject is instructed not to blink synchronously with the stimulus.

Donchin and Cohen [47] suggest that the changes observed in the AEP as a result of varying a so-called psychological variable may in fact be the result of the indirect effect on a receptor variable (a peripheral gating mechanism). For example, a reduced AEP as a result of decreased attention may really be because of impaired accommodation. If this is so then it is more important to control accommodation directly than attempt to control psychological state.

3.2.3 Other Experimental Variables

The effects of numerous other experimental conditions on the AEP cannot be ruled out. Such factors include auditory stimuli, temperature, pressure, humidity, subject position, etc. These should be kept as constant as possible, and care should be taken to ensure that there are no auditory stimuli occurring synchronously with the stimulus.

3.2.4 Extra-cerebral Sources of Noise

There are a number of physiological generators lying outside the brain which can give rise to potentials across regions of the scalp, and thus would constitute extra noise on the EEG. Such sources include muscle potentials, including the heart, electroretinogram and electro-oculogram potentials. The averaging process will reduce the effects of these sources, and std. dev. measurements will enable their effects to be assessed quantitatively. However, as with auditory stimuli care should be taken to eliminate any activity synchronous with the stimulus.

3.3 Aims of the Research Programme

In chapter 2 we reviewed the previous work on pattern appearance AEPs. We have shown that, in contrast to flash AEPs, measurement of pattern AEP scalp distributions promises to be a fruitful method with which to identify the cortical origins of these AEPs. Previous results also suggest that temporally separate components may have different, and identifiable, cortical origins. In addition we have drawn attention to the lack of any consistent study of pattern AEP variability.

The principal aim of the research programme was to extend this work on pattern AEP origins and variability.

A subsidiary aim was to develop and study new experimental techniques deemed necessary to achieve this principal aim. At the outset it was assumed that this would involve the use of a general purpose digital computer, and so several of the later chapters discuss ways of using such a machine as an on-line experimental tool.

The first part of this chapter has briefly reviewed the problems of experimental technique,

and has high-lighted the following needs:–

1. The need for simultaneous multichannel recording of AEPs. Only in this way can scalp distributions be satisfactorily measured.
2. The need to devise efficient experimental methods to overcome time limits on experimental sessions.
3. The need for efficient separation of AEP components at different latencies.
4. The need to investigate critically the variability and criteria of significance of AEP measurements.

This led to the planning of a research programme to answer the following questions:

1. To what extent is it possible to use a general purpose digital computer to meet the needs listed above?
2. How does the variability of the pattern appearance AEPs depend on time, stimulus, and position on the scalp?
3. Can the scalp distributions of the various components of the pattern appearance AEPs give a positive indication of the cortical origin of these responses?
4. Is it possible, in the high noise EP situation, to perform a stochastic search operation?

3.4 Brief Summary of the Following Chapters

In chapters 4,5, and 6 we describe the experimental computing system developed, and consider what factors must be taken into account when using it interactively on-line.

Chapters 7, 8, and 9 report on the use of the system to answer questions about the properties and origin of pattern appearance AEPs.

In chapter 10 we report on attempts to make the machine perform a stochastic search operation.

SECTION B

EXPERIMENTAL AND PROGRAMMING METHODS

SECTION B

EXPERIMENTAL AND PROGRAMMING METHODS

This section will be divided into three chapters. In the first (chapter 4) we shall consider the experimental apparatus used to present the stimuli and record responses. In chapter 5 we shall describe the techniques used in the computer programs. This chapter also includes a discussion on the accuracy of the analysis methods used. Finally, in chapter 6, the special considerations appertaining to the use of a computer as an on-line interactive experimental aid will be discussed.

The system as a whole was designed to be very versatile, allowing the user to conduct a wide variety of experiments. The information given in this section is that common to all experiments. Details relevant to particular experiments will be given when these are described.

CHAPTER 4: EXPERIMENTAL APPARATUS

A diagram of the overall experimental configuration is shown in Figure 4.1. Individual parts of it will be described in the following sections.

4.1 Stimulus Presentation

For early experiments (chapter 7) a 4-field tachistoscope of the form shown in Figure 4.2(a) was employed. This has been described by Jeffreys [180]. For this the stimulus field was circular, subtending an angle of 6° at the eye, with a viewing distance of 98 cm.

For later experiments (chapter 8, 9, and 10) a simpler 2-field tachistoscope was used, with a larger stimulus area (12° diameter), and a shorter viewing distance (50 cm). This is shown in Figure 4.2(b). Illumination was provided by sets of fluorescent glow tubes which back illuminated opal glass screens. Patterns, either on photographic film or drawn with black ink on tracing paper were placed in front of these screens. The colour of the light was white with a slightly bluish tinge.

Photomultiplier measurements showed that the on and off transition times of the light outputs were about 300μs. Compared with physiological processing times this can be considered as effectively instantaneous. When one field was coming on at the same time as another was going off, the maximum overlap or deadspace periods were about 100μs.

Potentiometer controls were available to adjust, independently, the luminance of each field. These were adjusted, with the fields switching and with no patterns in position, so that the fields all had the same subjective brightness. A series of control experiments was done to determine the effect on the pattern appearance EPs of small differences in the luminances of the tachistoscope fields. It was found that a difference of ± 150cd./m^2 could be tolerated before any significant change in the pattern AEP was observed. This was much larger than the precision with which the luminances could be subjectively set as equal. The actual value of the mean luminance does not affect the pattern responses very much, and for all experiments a value of about 400 cd./m^2 was used. (But see discussion in Section 9.5.2.)

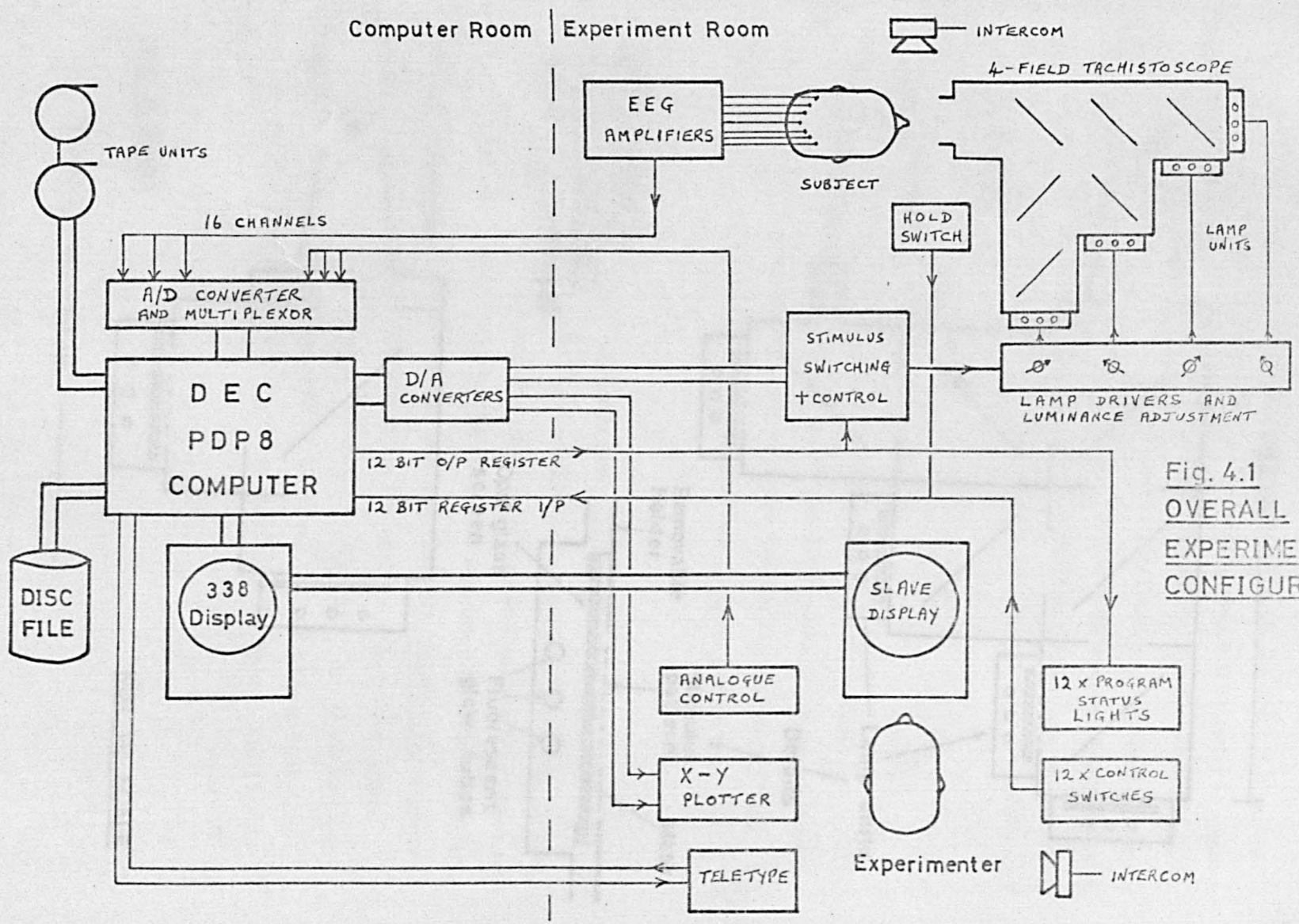


Fig. 4.1
OVERALL
EXPERIMENTAL
CONFIGURATION

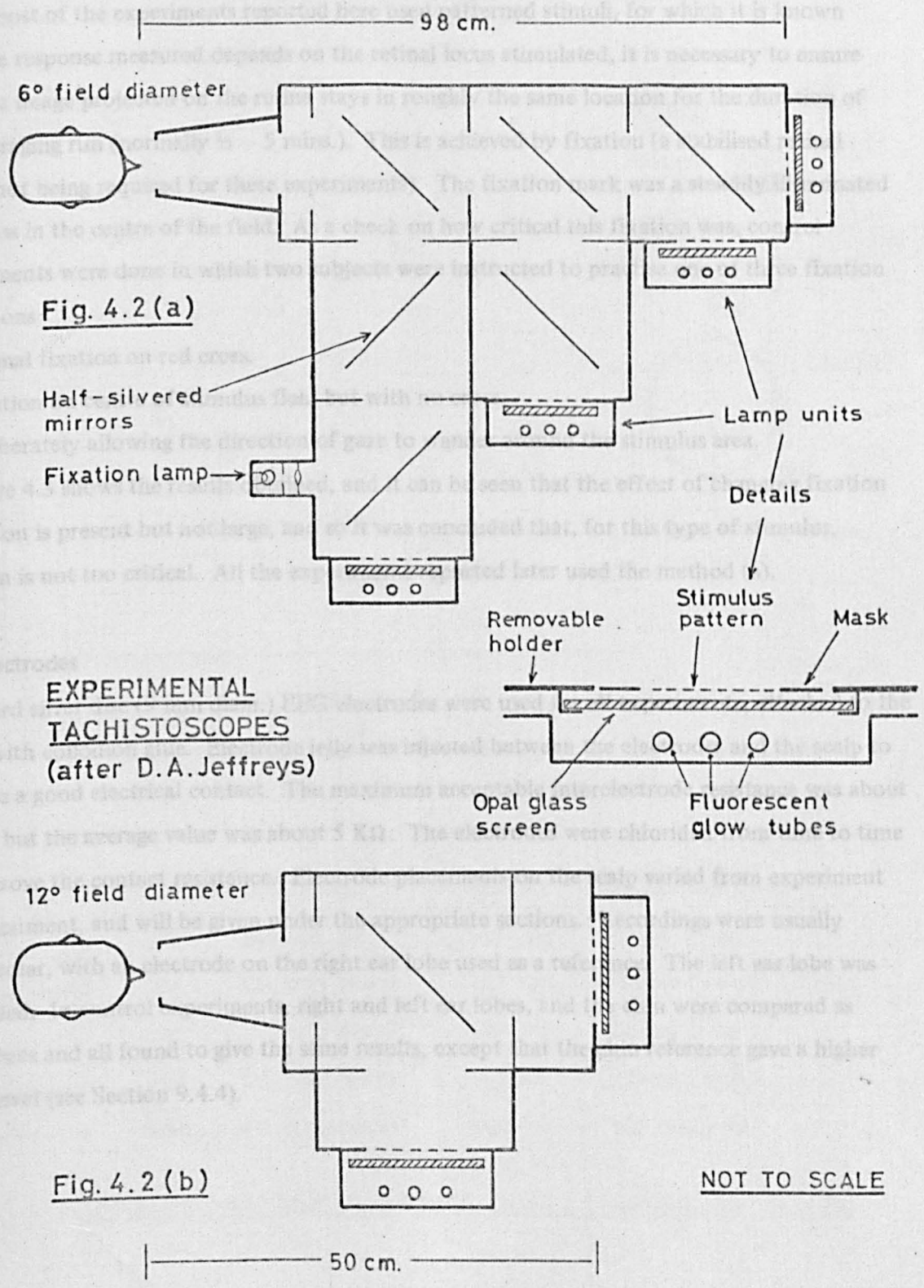


Fig. 4.2 (a)

EXPERIMENTAL TACHISTOSCOPES (after D.A. Jeffreys)

Fig. 4.2 (b)

NOT TO SCALE

4.1.1 Fixation

Since most of the experiments reported here used patterned stimuli, for which it is known that the response measured depends on the retinal locus stimulated, it is necessary to ensure that the image projected on the retina stays in roughly the same location for the duration of the averaging run (normally ½ – 5 mins.). This is achieved by fixation (a stabilised retinal image not being required for these experiments). The fixation mark was a steadily illuminated red cross in the centre of the field. As a check on how critical this fixation was, control experiments were done in which two subjects were instructed to practise one of three fixation conditions:

a. Normal fixation on red cross.

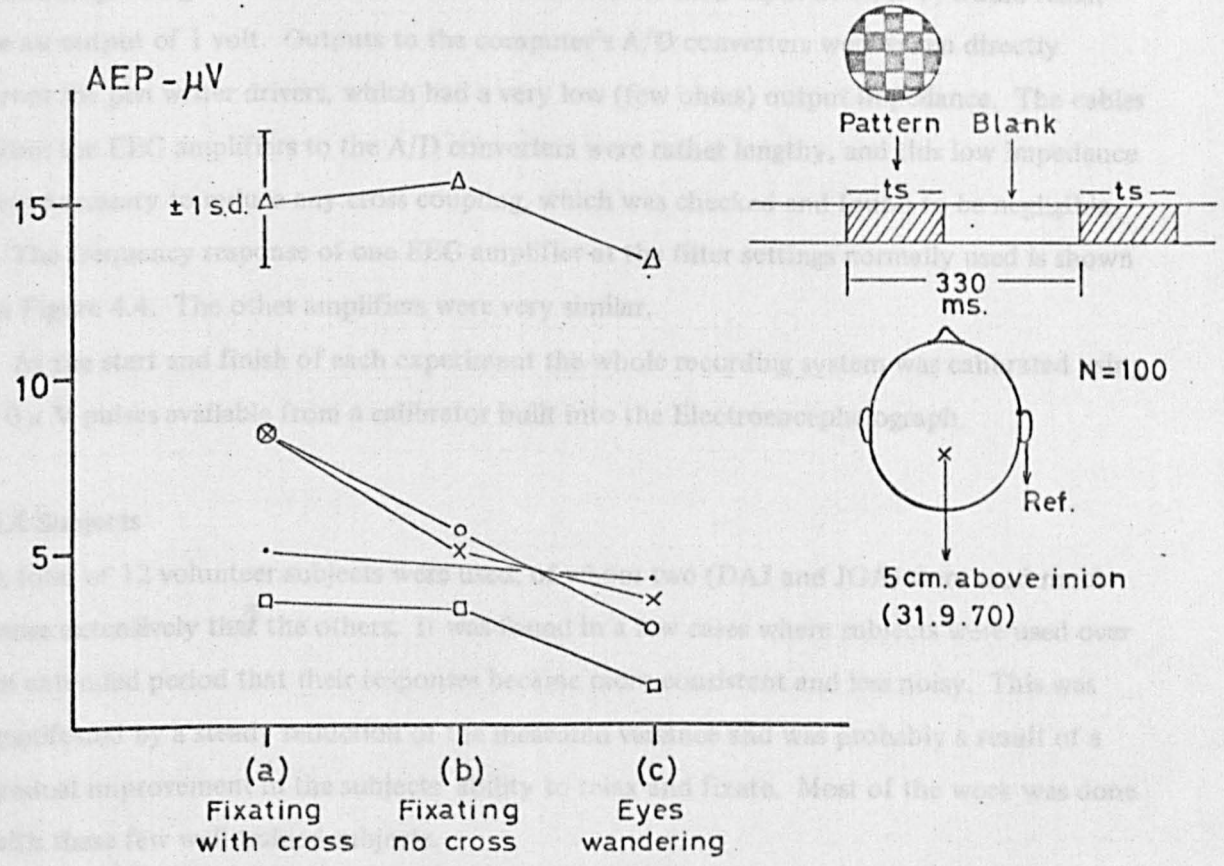
b. Fixation on centre of stimulus field but with no cross.

c. Deliberately allowing the direction of gaze to wander around the stimulus area.

Figure 4.3 shows the results obtained, and it can be seen that the effect of changing fixation condition is present but not large, and so it was concluded that, for this type of stimulus, fixation is not too critical. All the experiments reported later used the method (a).

4.2 Electrodes

Standard silver disc (9 mm diam.) EEG electrodes were used for all experiments, attached to the scalp with collodion glue. Electrode jelly was injected between the electrodes and the scalp to provide a good electrical contact. The maximum acceptable interelectrode resistance was about 8 KΩ, but the average value was about 5 KΩ. The electrodes were chlorided from time to time to improve the contact resistance. Electrode placements on the scalp varied from experiment to experiment, and will be given under the appropriate sections. Recordings were usually monopolar, with an electrode on the right ear lobe used as a reference. The left ear lobe was grounded. In control experiments, right and left ear lobes, and the chin were compared as references and all found to give the same results, except that the chin reference gave a higher noise level (see Section 9.4.4).



	Subj.	Stimulus	ts ms.	Response peak
□——□	JM	Alt. ch. bd.	167 ms.	80 ms (-ve)
×——×	JM	Ch. bd./ blank	167 ms.	110 ms.(+ve)
·——·	JM	Ch. bd./ blank	15 ms.	80 ms (-ve)
○——○	MM	Ch. bd./ blank	167 ms.	90 ms.(-ve)
△——△	MM	Ch. bd./ blank	167 ms.	160 ms.(+ve)

Fig. 4.3 Variation of AEP Amplitude with Fixation Condition

4.3 EEG Amplifiers

A 16-channel Beckman TC Electroencephalograph was used for all experiments. The mid-band amplifier gain was about 5×10^4 which, with an EEG input of 20 μ V, would result in an output of 1 volt. Outputs to the computer's A/D converters were taken directly from the pen writer drivers, which had a very low (few ohms) output impedance. The cables from the EEG amplifiers to the A/D converters were rather lengthy, and this low impedance was necessary to reduce any cross coupling, which was checked and found to be negligible.

The frequency response of one EEG amplifier at the filter settings normally used is shown in Figure 4.4. The other amplifiers were very similar.

At the start and finish of each experiment the whole recording system was calibrated using 10 μ V pulses available from a calibrator built into the Electroencephalograph.

4.4 Subjects

A total of 12 volunteer subjects were used, of whom two (DAJ and JGA) were used much more extensively than the others. It was found in a few cases where subjects were used over an extended period that their responses became more consistent and less noisy. This was manifested by a steady reduction of the measured variance and was probably a result of a gradual improvement in the subjects' ability to relax and fixate. Most of the work was done with these few well-trained subjects.

The subject was seated comfortably in a sound-proof room and could be instructed over an 'intercom'. At the start of a 'run'. he would be given a warning 'buzz', which alerted him to fixate. He then replied 'ready!', and the computer operator would start the appropriate analysis section of the program. Apart from the instruction to fixate on the central cross, the subject was normally given no other task. At the end of a run the computer automatically stopped the stimulus switching, and this was a signal to the subject to relax. 2 – 3 minutes rest were usually allowed between runs.

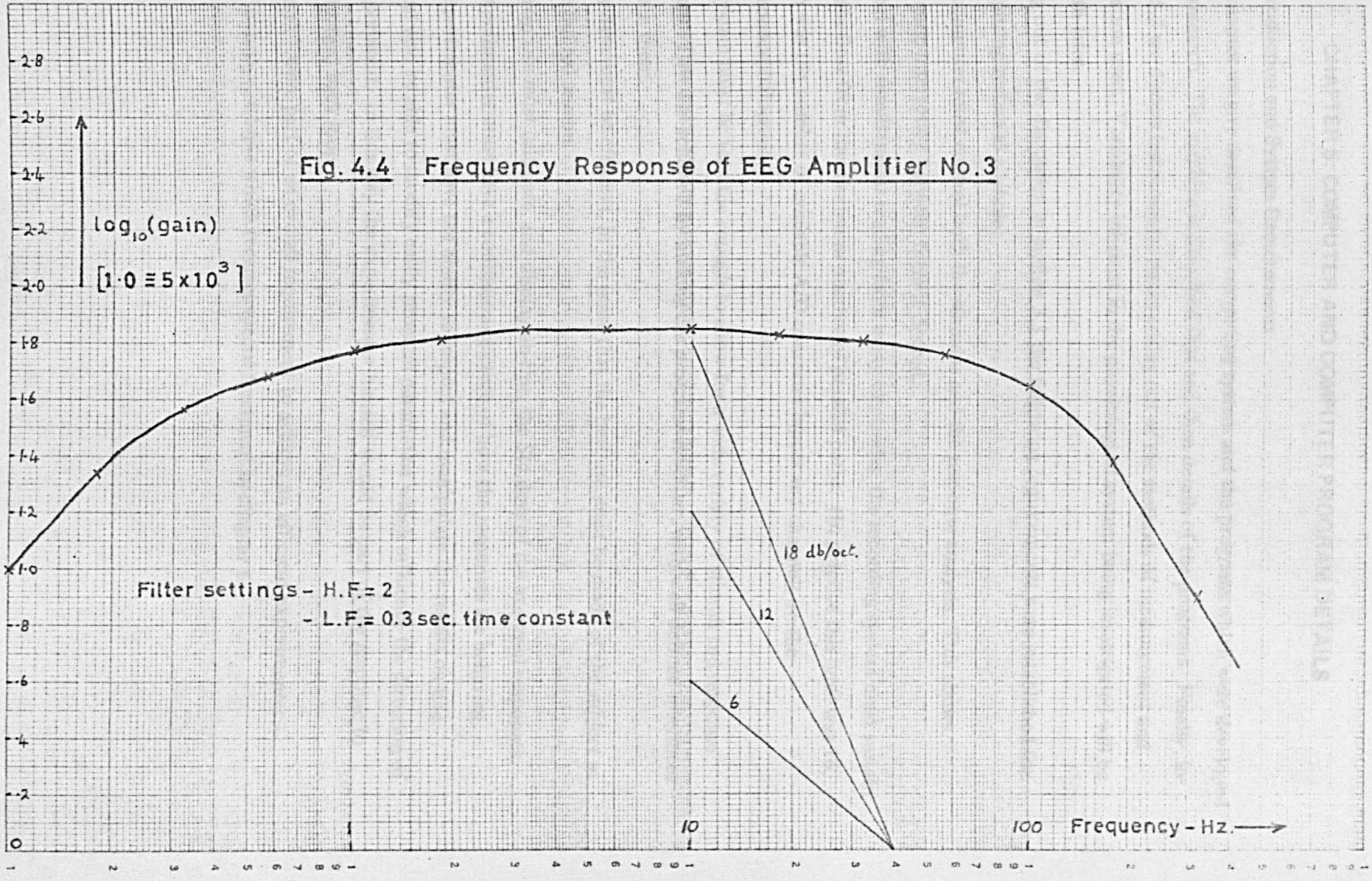


Fig. 4.4 Frequency Response of EEG Amplifier No.3

CHAPTER 5: COMPUTER AND COMPUTER PROGRAM DETAILS

5.0 Introduction and System Requirements

In this chapter we give details of the computing system and the programs which were developed for the research. The machine is described first and then details of the programs. Finally, in section 5.3 we discuss instrumental errors arising out of the methods of measurement and computation used. Variability inherent in the physiological system being investigated will be dealt with later.

Arising out of the discussion in section 3.3 the following requirements were established for the computing system as a whole:

1. The computer must control both the stimulus and the response analysis. This allows automatic interaction between them if desired.
2. To deal with simultaneous reading from many electrodes, the recording system must sustain the data flow from the maximum number of parallel paths. (In practice this limit was 16, which was the number of available A/D converter inputs and channels on the Electroencephalograph.)
3. The system must be versatile enough to allow for a wide variety of stimuli and response analyses. This was achieved by making the programs modular, with well defined interfaces between them.
4. The system must be efficient, in the sense that the best use must be made of the subject in a time limited session.
5. The programs must calculate, and display on-line, the Std.devs of the averaged responses.
6. The experimenter must have a continuous picture of how the responses are behaving.
7. The experimenter must have the ability to inspect and manipulate the results on-line. He must also be able to modify easily program parameters which influence the direction of the experiment. In this way the experimenter himself would be part of the response to stimulus feed back loop.

Item 6 and 7 were part of an overall requirement to achieve an efficient experimenter – computer interface, a topic which receives special treatment in chapter 6.

5.1 Machine Description

The computer used was a Digital Equipment Corporation PDP8. The machine was equipped with a number of peripherals making it very suitable for on-line work. The basic word length was 12 bits and the size of the main store 8192 words. The machine was equipped with an 'extended arithmetic element', which allowed such operations as 'multiply' and 'divide' to be initiated directly from the standard instruction set.

Peripheral storage consisted of two fixed head disc files giving a total of 64K words storage at an average access time per word of 20 ms. Also available were two magnetic tape drives (Type TU55), each capable of holding one tape with a capacity of 184K words. Tape access time was, of course, very slow and normally the magnetic tapes were only used during an experiment to record data for future analysis, using sequential loading, so that the time taken was quite acceptable.

Other peripherals and facilities are briefly described in the following sections. Refer to Fig. 4.1 for their arrangement in the total configuration.

5.1.1 Type 338 Programmed CRT Display Unit

This unit provides a 10" x 10" display area which is divided up into 1024 x 1024 matrix of points, each of which can be separately illuminated. Although it has its own instruction set, the display shares the computer's main store and can be initiated, modified, or stopped directly by main computer instructions.

A slave display in the experimental room was attached to the main display. A light pen attachment was also available for the master display, but this could not be used with the slave. The light pen was used with certain off-line analysis programs.

5.1.2 Teletype

The standard teletype input/output device was available to the experimenter.

5.1.3 Analogue to Digital Converters

A Type AF01A Multiplexed A/D Converter system was attached to the machine. The multiplexor has a total of 16 channels which could be scanned under program control. A

switch allowed selection of conversion word length. The maximum available accuracy was 12 bits, but for all the work recorded here a 9-bit conversion was used. The reason for this is explained in the section on instrumental errors. Since the machine time for conversion depended on the word length, the latter was made no longer than necessary. The dynamic range of the converter was −5V to +5V.

5.1.4 Digital to Analogue Converters

Four of these were available, each converting a 10-bit binary number into a voltage in the range −5V to +5V. These were used for a variety of purposes, which included driving X-Y plotters or chart recorders, and for controlling the stimulus in the hill climbing experiments (chapter 10).

5.1.5 Output Register

The state of a 12-bit register located within the computer and loadable under program control could be sensed externally. This was used for controlling the switching times of the tachistoscope fields, and for driving a set of indicator lamps.

5.1.6 Switch Register Input

Under program control the state of a 12-bit external switch register could be read into the accumulator. Hence program branching and general control could be accomplished through this, and it was used by the experimenter as his main on-line control. Run, start, stop, interrupt, data store, etc. were all controlled in this way.

5.1.7 Analogue Potentiometers

For certain applications analogue control of variables in the machine was desirable. To this end a number of simple potentiometers were available, connected into some of the A/D converter channels. Examples of their use will be given in chapter 6.

5.1.8 Real Time Clock

The computer had a real time clock facility which operated as follows. A crystal oscillator produced a series of pulses with a nominal cycle of 7.8 μs. The pulses incremented a 6-bit clock

register, which would thus eventually overflow, causing a program interrupt. The register could initially be loaded with an arbitrary number. Hence it was possible to perform timing operations quantised in units of 7.8 μs. Normally, however, the register was loaded with zero, and this gave a basic clock timing interval of about 500 μs.

In practice, however, the effective clock interval was a little longer than 500 μs. This was because of the time taken for the machine to do a few 'housekeeping' instructions connected with the program interrupt. Thus it was necessary to calibrate the internal timing against an external time standard. For this a Wavetek oscillator Type 112 was used.

As a result of this calibration a correction factor of 1.08 had to be applied to all nominal timings. This factor was checked from time to time during the research. All timing information given in this thesis is corrected.

5.2 Programming Details

Although certain software packages for on-line experimentation were available for use with PDP8, these were neither fast enough nor versatile enough to meet the demands of the present system. In many ways it was necessary to use the speed and throughput capabilities of the machine at their limits. Thus all programs (except for a standard floating point arithmetic package) were written from scratch in the machine assembly language (PAL).

The programs were incorporated into a 'disc operating system' written specially for the purpose. This and other programs will be described in the following sections.

5.2.1 Disc Operating System

The philosophy used here was to store all available programs on the discs, and transfer them into or out of the CPU store by means of a directory specification, also stored on the disc. Initiation of transfers could either be by direct call from the program, or by the operator, via the teletype.

Each directory 'entry' contained the following information:

a. Size of program or data block to be transferred.

b. CPU storage location.

c. Disc storage location.

d. Address to which control jumps after transfer.

A program 'CALL' instruction would specify the number of the directory entry and the direction of transfer (into or out of the CPU store). Thus, by building up a suitable directory, any disc operation, from merely storing or fetching data, to calling and automatically executing programs, could be accomplished.

A number of utility programs were included in the operating system as follows:

1. *Loader* – for writing and initiating the whole system on the disc from a master tape.
2. *Data Transfer* – enables any tape-core-disc transfer to be accomplished as specified via the teletype.
3. *Error Routine* – arranges for type out of details when a program error occurs.
4. *Examine and Modify* – allows the operator to inspect the value of (and modify if necessary) any program parameter.

All programs, including those normally used only for off-line analysis, were stored on the disc during an experiment and could be called if desired. This immediate availability of programs was found to be a great asset during an experiment.

5.2.2 The On-Line Experimenter Program

This consisted basically of two parts:

a. The real time phase (RTP).

b. The analysis and control phase (ACP).

Simplified block diagrams of the operations performed by these two phases are shown in Figure 5.1. More detailed flow charts appear in Appendix A.

The Real Time Phase

As its name suggests this is concerned with operations to be controlled in the external environment which require precise timing. It uses the real time clock facility.

The RTP generates a series of time periods (called epochs) during which one stimulus would normally be presented and one response measured. It performs the following operations:

1. Generates the basic timing sequence (Figure 5.2).
2. Generates timing pulses to control stimulus presentation.
3. Reads the A/D converters and puts the data into a buffer.

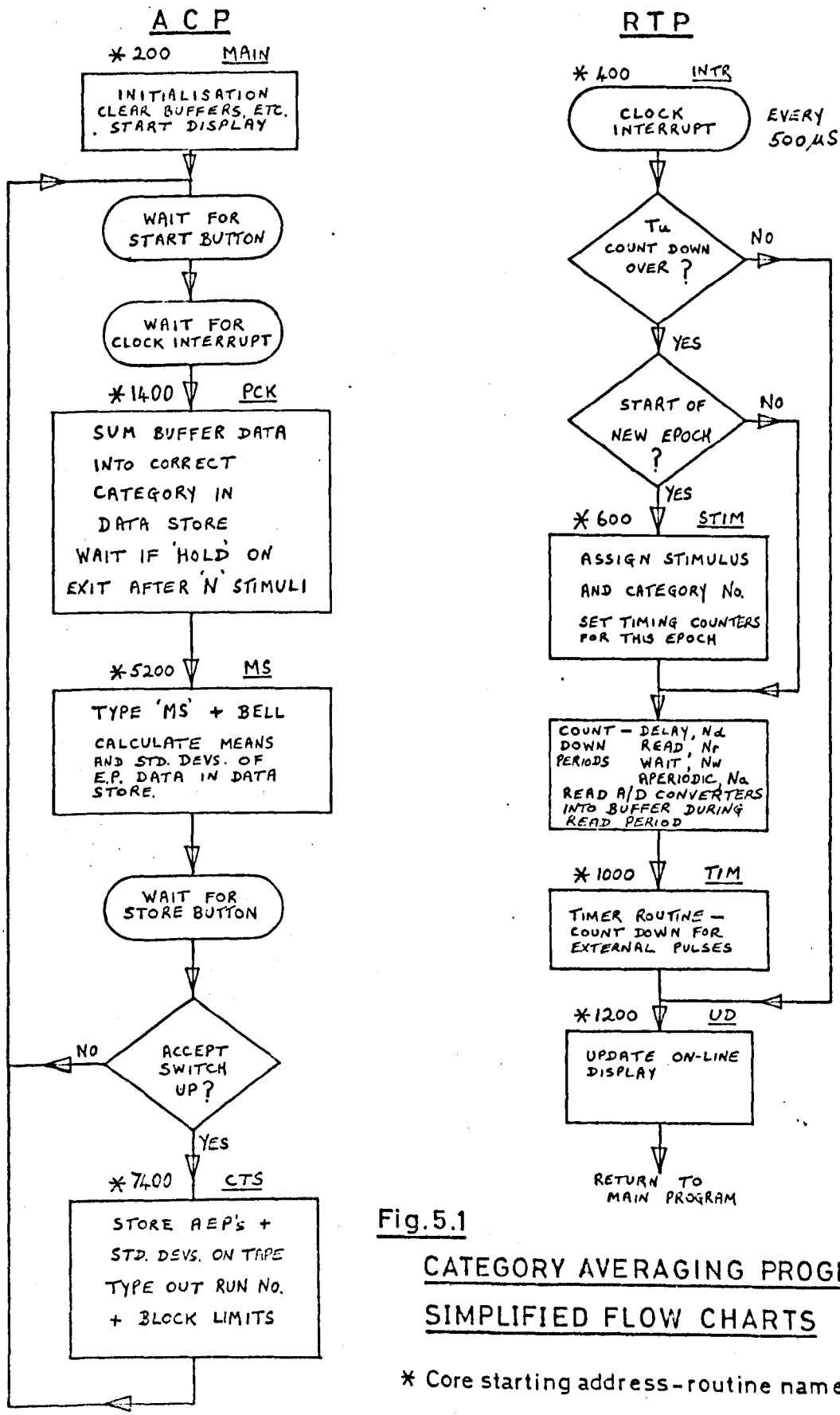


Fig.5.1

CATEGORY AVERAGING PROGRAM - SIMPLIFIED FLOW CHARTS

* Core starting address - routine name.

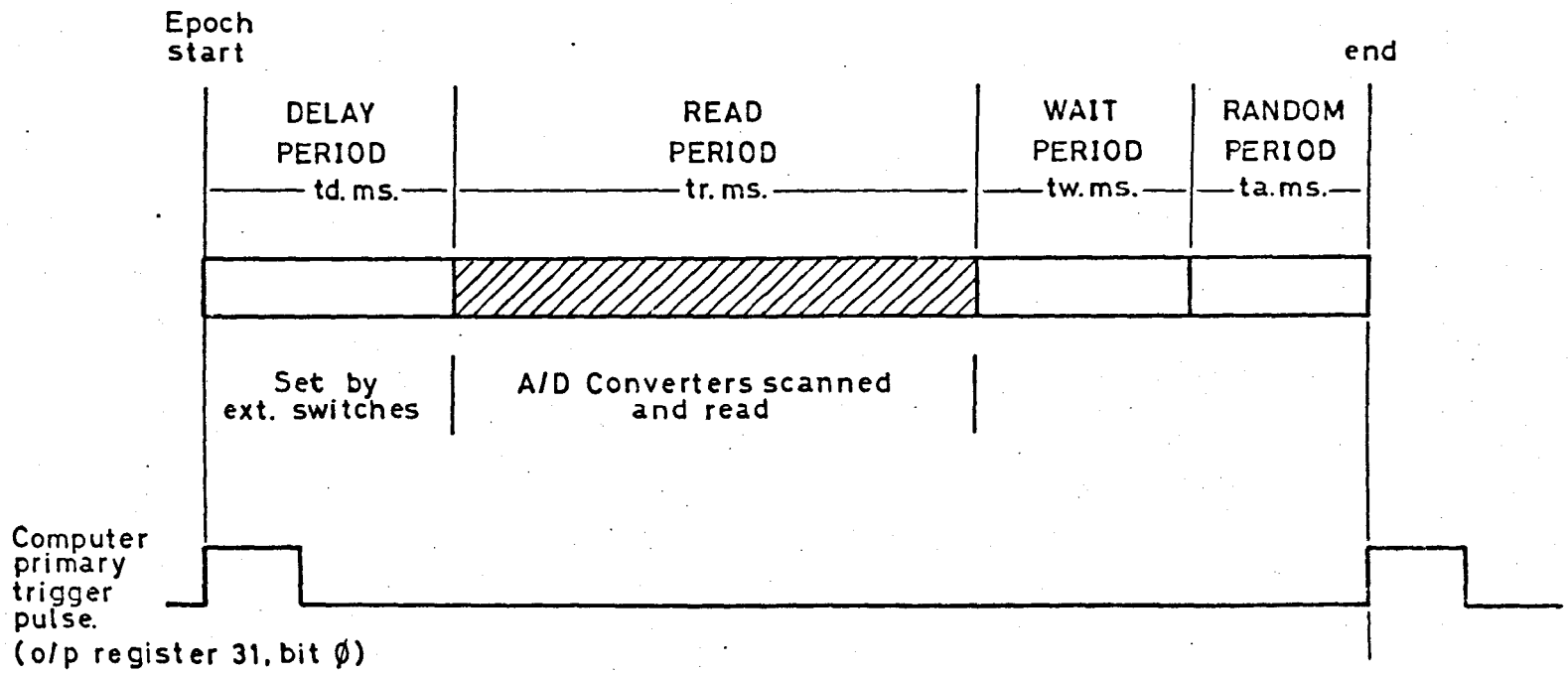


Fig.5.2 BASIC TIMING SEQUENCE

Fig. 5.3 Subject with Electrodes attached -looking into Tachistoscope

4. Senses external trigger pulses.
5. Updates the on-line display.

The following parameters govern the operation of the RTP:

Nr = No. of data points read per channel per epoch.

Nd = No. of units in delay period.

Nw = No. of units in wait period.

Tu = Time unit (usually 0.54 ms).

Tm = Time scale multiplier.

Nad = No. of multiplexor channels scanned.

$T_1 - T_9$ = Timing pulse specifications.

Int = 0 – external trigger of epoch start.

Int = 1 – internal trigger of epoch start.

The basic timing sequence is shown in Fig 5.2. It consists of four time periods defined as follows:

td = Nd Tm Tu

tr = Nr Tm Tu

tw = Nw Tm Tu

ta = Na Tm Tu

Nd can be set from the external switch register and enables the read period to be shifted in time in order to overlap with that part of the response which is to be measured.

Na is a random variable (constrained within defined limits) enabling the epoch duration to be variable, resulting in aperiodic stimulus presentation. For periodic presentation Na can be set to zero.

During the read period the Nad converter channels are scanned once every Tm x Tu milliseconds. Hence during one epoch a total of Nr x Nad data points are read in and stored in a temporary buffer, from which they will be collected and analysed by the ACP.

The Analysis and Control Phase

In this phase, which operates concurrently with the RTP, data collected by the latter is analysed and stored. Results of the analysis can be fed back to the RTP to modify the stimulus parameters of subsequent epochs.

A variety of analysis methods were used, according to the needs of the particular experiment being performed. During the research the following techniques were developed:

1. Normal averaging into a number of pre-defined categories.
2. Calculation of standard deviations of the averaged responses.
3. 'Running' average computation.
4. Calculation of AEP component amplitudes (SIR routine).
5. Stochastic search procedure ('Hill climber' program).

Note that more than one of these could be used in a single experiment on the same set of data. Each of them will be described in more detail in the results sections. However, the technique of averaging into categories (Item 1 above) will be considered more fully here, as this formed the basis of most of the other methods.

Category Averaging

Suppose the Nr data points read in during a particular epoch 'p' for channel 'i' are:

$$X_{ijp}(t)$$

where 'j' defines a particular 'category' to which this response belongs.

The program computes the averages:

$$A_{ij}(t) = \frac{1}{N_j} \sum_{p=1}^{N_j} X_{ijp}(t)$$

where N_j is the total number of epochs for category j.

This facility enables a number of different stimuli to be presented in a random order and their responses can then be sorted out by the machine, which assigns a category to each stimulus type.

Definition of category is, however, entirely arbitrary. It can be a function of stimulus or response, and can be assigned internally or externally.

Other Features of the On-Line Experimenter Program

a. *'HOLD' Facility:* Using this the subject could, by means of a microswitch, stop the computer's analysis activity. This facility has a variety of uses, such as giving the subject a

chance to rest or readjust his position. While the 'hold' was in operation, stimulus presentation still continued. The experimenter also had a similar overriding switch.

b. *Errors:* Throughout both phases various error checks were made. Whenever one of these came up an error routine was called from the disc and an error message was typed out on the teletype, identifying the error check. The computer then requested the operator if he wished to restart.

c. *Machine Speed:* Although the basic instruction cycle times of the machine were very much faster than the 'real time' scale of the experiment, it was still possible for the machine to be too slow for the input data flow, particularly when a large number of A/D converter channels were being used. If such a condition occurred one of the error checks would come up. The experimenter was then able to readjust appropriate program parameters on-line and proceed with the experiment.

d. *Data Storage:* At the end of each run the experimenter was asked to decide whether or not he wanted the responses for that run stored on magnetic tape. He could scan over the results on the display to enable him to decide this, and then press a switch to initiate the storage program. The results could subsequently be displayed again and plotted out if required by using the DMP program.

5.2.3 Data Manipulation Program (DMP)

This program was designed to allow the AEP responses to be displayed and operated upon in various ways, thus permitting the experimenter to try out various hypotheses on the data quickly and easily. A full description of it appears in section 6.4.5.

5.3 Instrumental Errors

When considering sources of uncertainty in our measurements we must distinguish between:

1. Inherent Variability – owing to the uncertain nature of the physiological system being investigated.

2. Instrumental Errors – owing to imperfections in the measuring instruments.

In this section we shall deal only with item 2. Item 1 will receive extensive consideration in Chapter 8.

The second important consideration is to define exactly the quantity or measurement we are supposing to be in error. For the purposes of this section we shall take this to be the amplitude of an averaged evoked potential waveform, reconstructed from a set of quantised values.

In the case of AEP measurement we can divide instrumental errors into two further categories:

1. Digital Computation errors (rounding off, etc.).
2. Quantisation errors (sampling at finite times and into discrete levels).

The logic of our approach to instrumental errors will be as follows. We shall first obtain a rough estimate of the expected inherent variability of the results. Then we shall design the instrumentation so that the instrumental errors represent only a small fraction of the total variability.

Most AEP amplitudes lie within the range 0 – 10 μV, whereas the raw EEG out of which the AEP is extracted has a mean amplitude of between 10 – 50 μV (depending upon subject and electrode position). Thus taking 10 μV as the best value of the standard deviation of the EP owing to the noise, and considering an averaging run of 50 presentations, we obtain a *best case* standard deviation of the AEP of:

$$\frac{10}{\sqrt{50}} = 1.4\,\mu V$$

which with an AEP of 10 μV represents a variability of about 14%. Normally the variability will be greater than this.

5.3.1 Digital Computation Errors

The basic computer word length is 12 bits. Higher precision can be obtained by using two, three, or even more 12-bit words to represent one number. Greater numerical range, but *not* precision, can be achieved by having an extra word to specify a multiplying factor, in

terms of a power of 2 exponent by which the number should be multiplied. This then gives a *floating point* representation. In general the more words used to represent a number, the greater is the precision but, as a penalty, the greater is the processing time and storage space taken up by the program.

In a digital calculation it frequently happens that the number of digits in the result exceeds the maximum value and 'rounding off' must be used. This leads to error in the result.

For the calculations involved in the present work, error considerations were effectively reduced to making a choice between single-precision (12 bits) or double-precision (24 bits) arithmetic. In appendix B1 it is shown that errors resulting from the use of double precision are likely to be negligible. A double-precision floating point program package was available for use on the PDP8 which was reasonably fast but occupied a fair amount of storage space. Since it would have to be in store even if it were to be used only once, it might just as well be used whenever there was no good reason for doing otherwise. Thus most computations were performed using double precision arithmetic.

However, there was one particular operation where speed requirements precluded the use of the double-precision arithmetic. This was the operation of summing the raw EEG data as part of the computation of the AEP, which had to be done rapidly to keep up with the rate at which the real time data was being read in. It is shown in appendix B2 that is single-precision fixed point arithmetic is used for this summing, an accuracy of approximately ±2% can be achieved, provided a rounding up and down procedure is adopted instead of the simple truncation normally used.

5.3.2 Sampling and Quantisation Errors

A further source of errors in the measurement of AEPs arises out of the digitising process itself. The EEG voltage entering the A/D converters is a continuous function which is measured only at discrete time points (this we shall call sampling) and the voltage measurements themselves are quantised into a finite number of levels. Both these operations introduce errors, simply because information is *lost*. As with the digital calculation errors, the acceptable intervals of sampling and quantisation depend on the results required from the data. For instance, if only statistical parameters are required, then quantisation requirements are far less stringent than if a reconstruction of the analogue data is required

(see Susskind [147]). We shall assume, however, that the object of the measurement is to reconstruct the analogue data.

Sampling and quantisation have been dealt with very thoroughly in the literature. Sources which have been used for the following arguments are Susskind [147] who gives a very good general theory, and Macy [104] who considers the particular problems relating to biological research.

The Sampling Process

A continuous waveform is to be sampled at certain times only. It is necessary to decide on the sampling interval (assumed constant) between successive samples. The choice will depend upon:

1. The frequency spectrum of the data to be sampled.
2. The desired spectrum of the reconstructed data.
3. The acceptable error in the reconstructed data.

A block diagram of the recording system is shown in Fig. 5.4. The filter characteristics selected will depend upon the required spectrum of the reconstructed data. The filter removes the unwanted information in the original data.

The choice of sampling interval is usually made on the basis of the rather generalised sampling theorem which says – 'A continuous function can only be exactly represented by equi-spaced samples if the sampling rate is at least twice the highest frequency present in the function'.

This is not quite good enough for our purposes, however, since we need some estimate of the actual error involved.

The reconstruction error will depend upon:

1. The spectrum of the raw EEG.
2. The filter characteristics.
3. The sampling interval.

Macy [104] gives curves for a simple high pass filter, showing the relationship between sampling ratio (Rs), the filter cut-off characteristics, and the reconstruction error. Sampling ratio is defined as:

$$Rs = \frac{1}{Ts.fc}$$

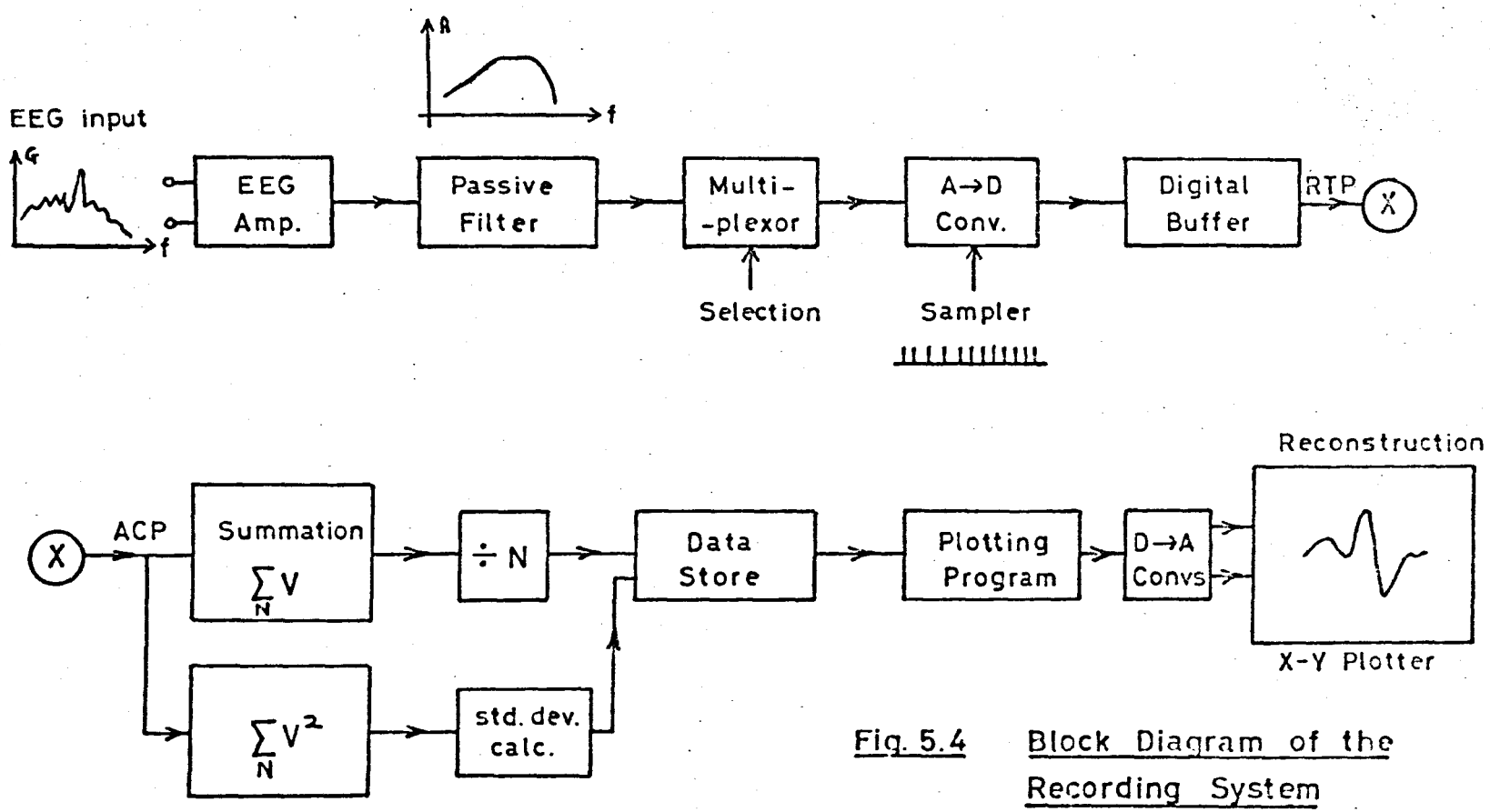


Fig. 5.4 Block Diagram of the Recording System

where Ts = sampling interval

fc = filter cut-off frequency.

Using these curves we shall calculate the approximate sampling interval required to give a reconstruction error of about 5%. The filter response of the EEG amplifiers used for this work is shown in Fig. 4.4. The roll off rate is about 12 dB/octave and the cut off frequency about 20 Hz. Using this data and referring to the curves in Macy, we find that a sampling interval of about 5 ms is required. This value can be considered as a guide only, and in practice a variety of sampling intervals were used, the most common being about 4.7 ms.

Fig. 5.5 shows a typical spectrum measured for a well trained subject during a run (A) and during a rest period (B).

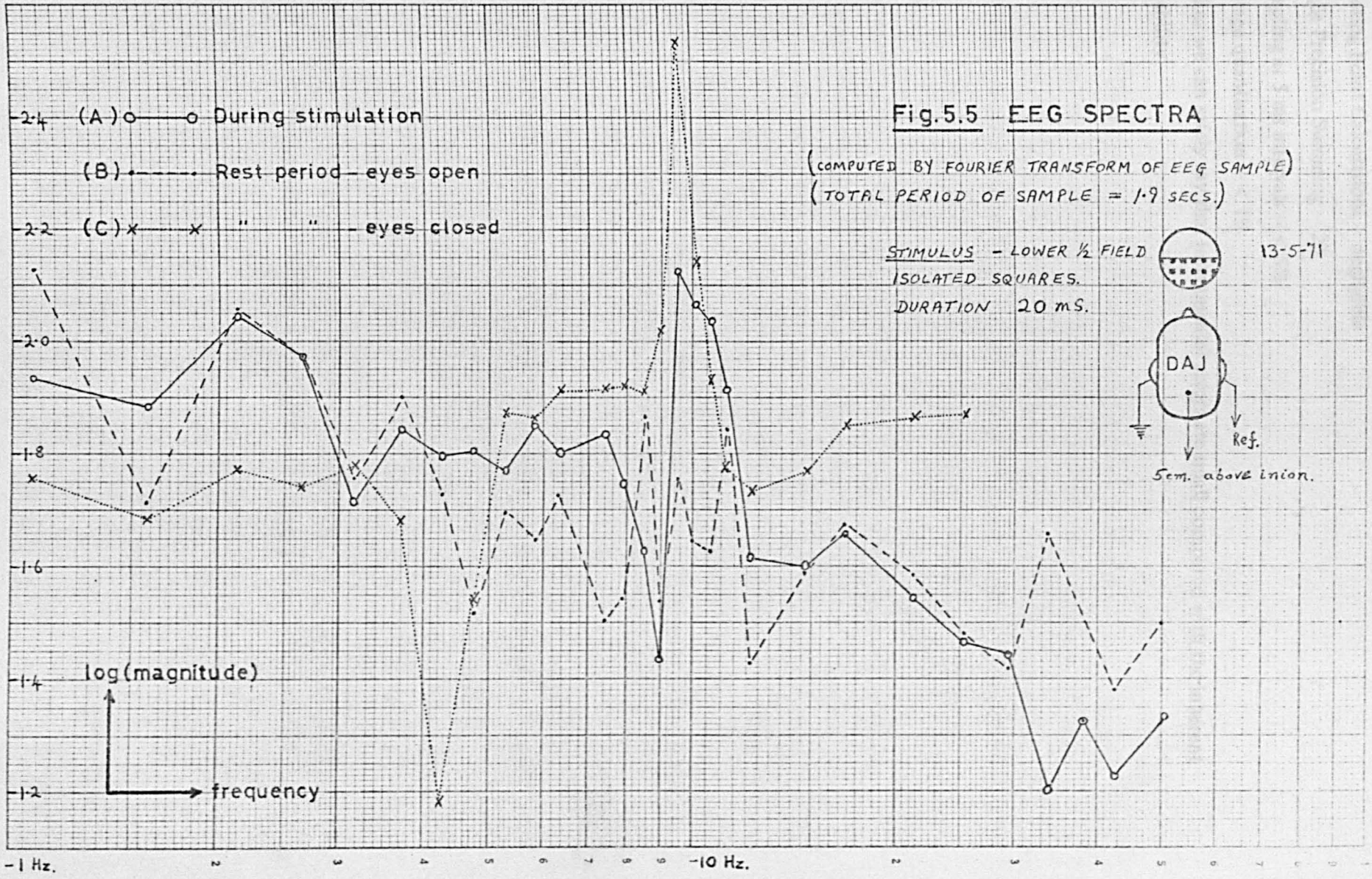
Since the spectrum is not flat to above the filter cut off, this means that the energy present in the higher frequencies will be less than the above calculation assumes, and the error value assumed above will be pessimistic.

Voltage Quantisation

It was shown in appendix B2 that 8 bits or 256 levels had to be used for voltage quantisation in the A/D converters. This was a result of the need to use single precision arithmetic for the summation process. In the case of quantisation the problem of how to calculate the error in reconstruction has not been solved explicitly, as was the case for sampling errors [147]). However, we can make the following judgements which show that the 8 bits used are quite adequate for our purpose. The full range of 256 levels would be taken up by an AEP of about 15 μV. If we assume that the average AEP is about ¼ of this value, then any direct measurement made on the reconstructed data would not be in error by more than $1/128$ of this, or about 1%. Alternatively ½ of the least significant bit corresponds to a voltage of about $15/512 \approx 1/30$ μV, which is too small to be of any significance.

5.3.3 Summary

We have considered the following sources of instrumental error and have evaluated approximate values for the errors resulting from them. Taking as a 'norm' an AEP of 4 μV:


(A) During stimulation
(B) Rest period – eyes open
(C) " " – eyes closed
2·4
2·2
2·0
1·8
1·6
1·4
1·2
log (magnitude)
frequency
1 Hz.
10 Hz.
Fig. 5.5 EEG SPECTRA
(COMPUTED BY FOURIER TRANSFORM OF EEG SAMPLE)
(TOTAL PERIOD OF SAMPLE = 1·9 SECS.)
STIMULUS – LOWER ½ FIELD
ISOLATED SQUARES.
DURATION 20 mS.
13-5-71
DAJ
Ref.
5cm. above inion.

Floating Point Calculations – negligible

Single Precision Summing – 2%

Sampling at 5 ms intervals – < 5%

Voltage quantisation – < 1%

Thus we can safely say that instrumental errors are small compared with the inherent variability.

CHAPTER 6: ON-LINE INTERACTION

6.0 The Man-Computer System

For an efficient overall system we must attempt to develop an interface between experimenter and computer which fully exploits the special but differing abilities of man and machine in a close-coupled interactive system. In this chapter we consider the *nature* and *efficiency* of this interaction. There has been much literature written on man/computer interaction and useful discussions are given by Licklider [97], Edwards [52], Shackel [141] and Taylor [153]. Most of these are, however, of a very general nature and do not consider in detail the mechanism of the *interface* between man and machine. MacKay and Fisher [102] and David [43] do, however, consider the interface requirements which lead to efficient interaction.

The interaction we are considering is between two basically very different mechanisms and we have to evaluate what leads to an efficient interface between them. To do this we must start by examining how each accepts and interprets information. For the machine this is relatively simple, but when we come to the man we find a complexity and variety which we can never hope to analyse completely. However, a considerable body of experimental data exists to help us understand at least approximately how the human brain receives and interprets sensory information. The next section will review this.

6.1 Perceptual Information Flow

As pointed out by Cherry (p. 290 of [26]), when examining human sensory processes we have to distinguish between two measures of input information flow:

1. Capacity of the sense organs (receptors) – millions of bits/sec.
2. Perceptual information rate, or the rate at which discriminating actions can be performed – tens of bits/sec.

The reasons for this redundancy is partly to provide a safety factor, but it is also useful for allowing efficient transformation from one coding scheme to another.

When considering man–computer interfaces it is the perceptual rate which is important and the most significant feature is that this rate is quite low. As Kidd [92] has pointed out 'One can go far in task and system design on the basis of the simple principle that perceptual capacity has a distinct and stable upper bound'.

We thus consider in more detail the human perceptual information rate. How do we evaluate a particular method of putting information into the brain? There have been three main ways:

1. Verbal information rate (reading speed).
2. Classification tasks.
3. Reaction time measurements.

For normal reading, Pierce and Karlin [121] estimate a rate of 30–40 bits/sec, and Cherry ([26], p. 290) 50 bits/sec, using the value of 1.5 bits per letter given by Shannon [142].

Miller *et al.* [113] measured information rates for briefly presented letter sequences and found that for a 500-ms duration of presentation, subjects were able to take in about 20 bits per presentation. Although the extension of this to a time average may be questionable, this does indicate an information rate of about 40 bits/sec.

By measuring the reaction time to make a correct response, Hick [70] has shown that the choice reaction time increases as log N, when N is the number of choices. This indicates a *constant rate* of information flow.

However, when we come to examine the situation in more detail, we find that this rate varies according to how the information is distributed among the senses, or *perceptual dimensions.*

A very considerable amount of work shows that the brain is extremely good at *discriminating* between two stimuli in the same perceptual dimension, if presented together or separated only by a short time interval.

On the other hand the brain is relatively poor at *identification* within a given dimension. Miller [112] in an interesting paper which compares results from a large number of perceptual dimensions has suggested as a rough rule that 7 ± 2 separate alternatives is the maximum that can be classified by the brain in one dimension.

These results suggest that the brain has extremely good 'comparators' for assessing separate items of information received in a short space of time, but is either reluctant or unable to set up long term scale standards.

Pollack and Ficks [122] have shown that the information flow into the brain can be increased by using more perceptual dimensions and, with a binary choice in each dimension, they found that the brain can sustain a much higher input rate than if all the information was restricted to one dimension.

Thus, as general rule, if we wish to maximise information rate into the brain via the normal senses, we should aim to use as many perceptual dimensions as possible. As an example, a display which added colour, motion and depth information to the usual two spatial dimensions would be perceptually more efficient in terms of information flow.

6.2 The Man-Computer Interface

Having discussed a few general findings about how the human brain can efficiently accept information, we now turn to see how this is relevant in the context of a man–computer interface. It is obvious when reviewing the literature on the subject that practical limitations hamper the optimising of a man–computer interface, on the lines of maximising information flow. For instance, it often happens that only limited means are available (e.g. a teletype machine) for the interface, which necessarily results in a very restricted communication link. In this case the rate of information flow may be limited by the hardware of the interface rather than the human user's limitations.

However, more advanced techniques, such as sophisticated visual displays, have been developed in recent years, and these make the optimisation of the interface with respect to the human user a much more realistic proposition.

MacKay and Fisher (p. 26 of [102]) discuss a number of features which a display should have if it is to make full use of the human perceptual characteristics. Briefly these are as follows:

1. The display should be organised (both spatially and temporally) so as the *minimise the decision time* required by the human operator.

2. *Trends* or *changes* rather than absolute values should be displayed. This can be seen to be desirable for a system which is very good at discrimination, and for which 'novel' stimuli produce large responses.

MacKay ([98], quoted in [102]) also makes the following, more psychological, points about the human in an interactive situation such as we are considering:

3. 'The human operator normally adjusts coefficients in a problem until he observes a result satisfying given conditions. . . The speed with which results can be obtained is therefore limited by the human rather than the instrumental element'.
4. 'It is felt that normal human reasoning is much more akin to a stochastic than a deterministic process, and that much of its essential character – ability to formulate hypotheses for example – may depend on this stochastic element'.

To these we shall add two further observations:

5. The human operator is *never static* and changes in two ways:
   a. He *tires* and becomes *less* efficient at a task if it has to be performed at a sustained stressful level, or if there is an unreasonable degree of interference or distraction (p. 163 of [92]).
   b. On the other hand he also *learns* and can become *more* efficient at a particular task as he performs it more often.
6. A human usually has an expectation, or 'cognitive set', in that he recognises more readily that which he *expects* to recognise. This can be taken a stage further to bring in deeper motives – he recognises not only what he expects, but also what he wants or needs to recognise. Thus display features which may run counter to observer expectation should receive greater emphasis or bias.

Item 1 above, the requirement to minimise decision time, is perhaps the primary criterion. However, very seldom do we find this principle stated concisely, although we may quote Chambers and Bartlett [25] who say 'Thus optimum relationships hold between man and machine when the probability is a maximum that, on the basis of the information input from the external environment, man will select the appropriate effector response within a minimum of time'.

Much of the literature on this subject is concerned with ideals or general principles, and very little real quantitative work has been done. Yntema *et al.* [177] have, however, measured user performance as a function of the response time of a computing system to an interrogation from the user. They were considering an on-line conversational mode time shared system, with a limited (teletype) interface.

6.3 Visual Displays Used in Electrophysiological Research

A number of workers have devised computer generated displays for showing EP and single unit data. Most of these can only operate off-line. Burns [17] and Harris *et al.* [64] describe interesting pseudo 3D off-line displays for EP data. The LINC system described by Clark and Molnar [28] has a number of display devices which can be used on-line.

6.4 Description of Display Systems Developed for this Work

Having discussed the criteria which determine how efficiently the human brain can accept and act upon presented information, we now describe the actual interactive techniques developed for this research.

For efficient interaction we must:

a. Minimise decision time.
b. Maximise perceptual dimensions.
c. Show trends or changes.
d. Whenever possible, use parallel operation of man and machine; and bear in mind the following more 'human' factors:
e. Human beings learn.
f. They tire under stressful conditions.
g. They have a cognitive set.

Point d. has not been specifically discussed, but is an obvious need in the interests of saving time.

It is obviously impossible to incorporate these principles fully in any practical design. They were thus treated as guidelines only, and it will be seen that the result is a practical

compromise. The limitations do in many cases lie in the actual hardware available.

The following devices were available for transfer of information from computer to experimenter:

1. Programmable display unit (see section 5.1.1)
2. Teletype
3. XY Plotter or Chart recorder
4. Loudspeaker driven by a variable frequency tone generator
5. A series of coloured lights.

Each of these is considered separately as follows.

6.4.1 Teletype

This prints at 10 characters per second, which is much slower than reading speed. Thus the teletype was only used when a permanent record was required, or when it was not necessary for the experimenter to make an immediate decision using the presented data.

6.4.2 XY Plotter and Chart Recorder

These devices are ideal for presentation of non-alphanumeric data at high speed. They also give a permanent record, and provide an easy means of comparing the 'present' value of a parameter with a 'past' value, thus giving differential or change information.

6.4.3 Audio Tone Generator

This extends the perceptual dimensions into the auditory domain. Sounds are good attention diverting stimuli if novel, and can be used as effective warning signals. Two variables are available, pitch and amplitude, but in the present work only pitch was varied.

6.4.4 Coloured Lights

These indicated the state of a 12-bit output register (see section 5.1.5) and, by writing into this register at appropriate points in the program some indication of internal machine states, could be directly observed by the experimenter. Such devices cannot transmit much

information but can be quickly interpreted by the user. Extra discriminating cues (above that of mere position) can be given by making the lamps of different colours.

6.4.5 Programmable Display

This constituted the major interactive device, and would command most of the experimenter's attention. The display actually observed during an experiment was that on a slave oscilloscope remote from the actual computer. Suitably programmed, anything from alphanumeric data to graphs could be shown. A feature also allowed particular parts of the display to flash on and off, and the brightness too was under program control. An especially significant advantage of this particular display unit was the fact that it did allow continuous presentation of the picture even when the main computer was performing its other operations. This feature was found particularly useful for meeting requirement d. above.

Thus it can be seen that a very versatile display medium was available, but it did suffer from a few disadvantages:

a. The plotting speed was about 15 μs/point. This precluded very complicated displays owing to the time taken to 'paint' the picture, which if too long (> 1 second) made it almost impossible to use.
b. The number of display instructions had to be limited owing to the small size of the main store.
c. Complicated displays take a long time to program.

The above disadvantages militate against complex displays. However, with the guideline of minimum decision time, simple displays are in fact the most effective. Thus it was found much better to have a large number of relatively simple displays (each one containing the 'bare bones' of the relevant information) rather than a few complicated displays. It may be argued that in some cases a complicated display is necessary, such as for instance, if one is interested in searching for a particular feature over a wide range of data. However, in this case it is often still better to stick to a simple display and incorporate the search dimension into some external control.

Since the display is 'redrawn' at approximately 20 ms. intervals (this is the limiting value even for simple displays), it is ideal for 'dynamic' data presentation. Changes in data or conditions within the machine can be immediately observed and, since the 'update' rate is so fast, impressions of actual movement can be obtained. The former makes use of the brain's efficiency at discrimination, while the latter adds another perceptual dimension.

Not all the display formats used will be described in detail. A few examples which serve to illustrate the use of the above principles will be described below. Later, displays appropriate to particular experiments will be mentioned briefly.

1. Data Buffer Display

The main AEP averaging program used a large data buffer in which were stored all the results for the current run. As the experiment proceeded the data in this buffer was continually updated. A display was necessary in order to give the experimenter a picture of the data stored in this buffer. The following requirements had to be met by this display:

a. It must be updated at least as fast as the data input to the main buffer.
b. Only subsets of the data need to be presented. The display would be too complex to use efficiently if all the data were present at once.
c. Quick selection of a particular data subset was necessary.
d. Data on the screen had to be easily identified.

A simple block diagram of how the buffer display worked is shown in Fig. 6.1. Requirement a. was easily met and, although the display was redrawn every 20 ms., in practice it was found quite adequate to update the display data every 64 ms.

The display system functions as follows. Every 64 ms. a subset of the data in the main buffer was transferred into the display buffer and displayed. The particular data subset transferred was determined by the setting on an analogue potentiometer controlled by the experimenter. Thus by turning this potentiometer he could scan a 'window' over the data assembled on an imaginary 'map' and, owing to the rapid update rate, this scanning would appear to him immediately responsive, and essentially continuous. A picture of what this display was like is shown in Fig. 6.2. This form of display proved to be very successful.

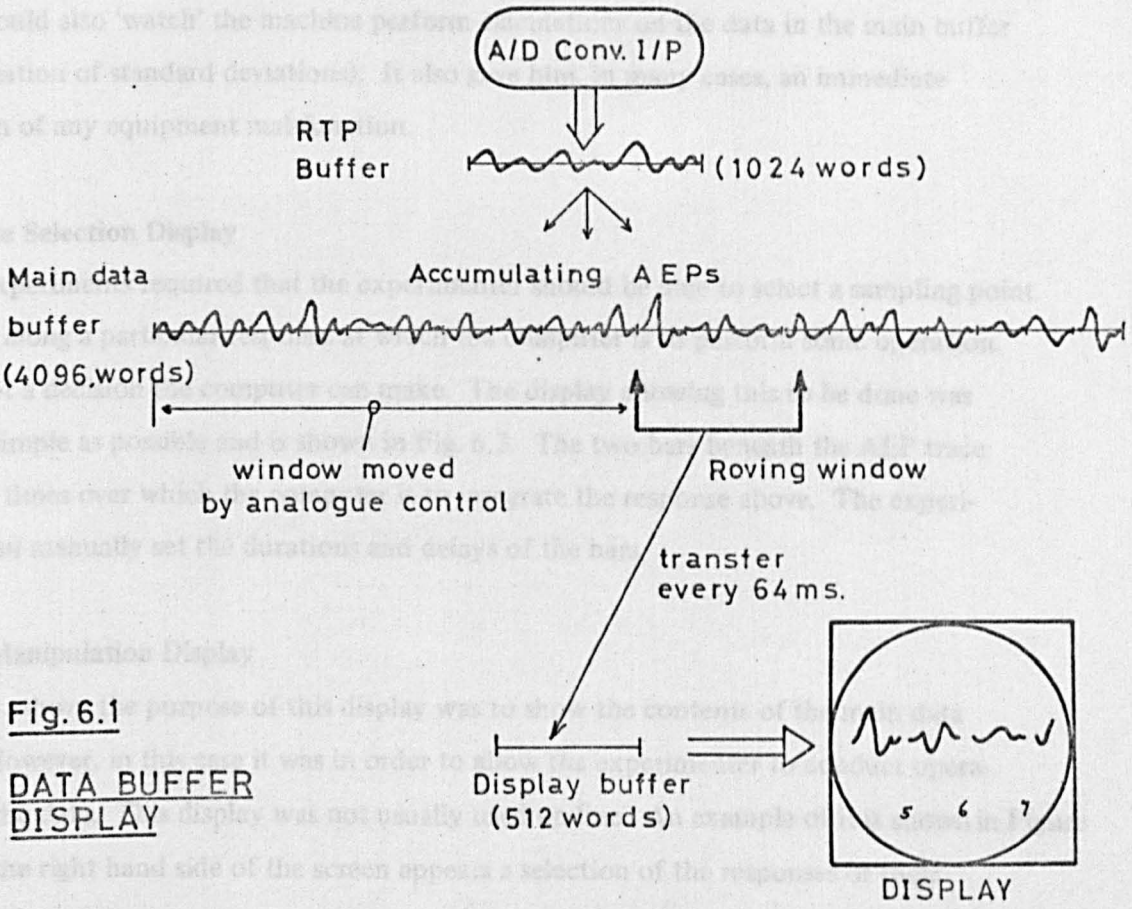
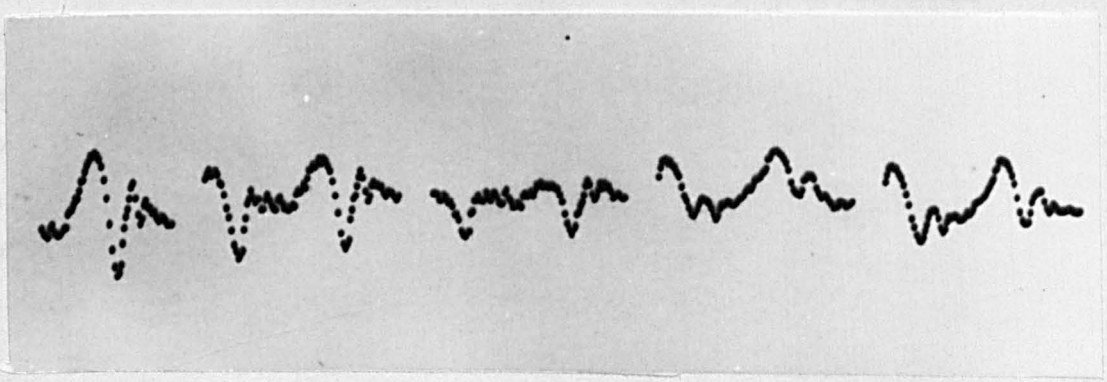


Fig. 6.1

DATA BUFFER DISPLAY

Fig. 6.2



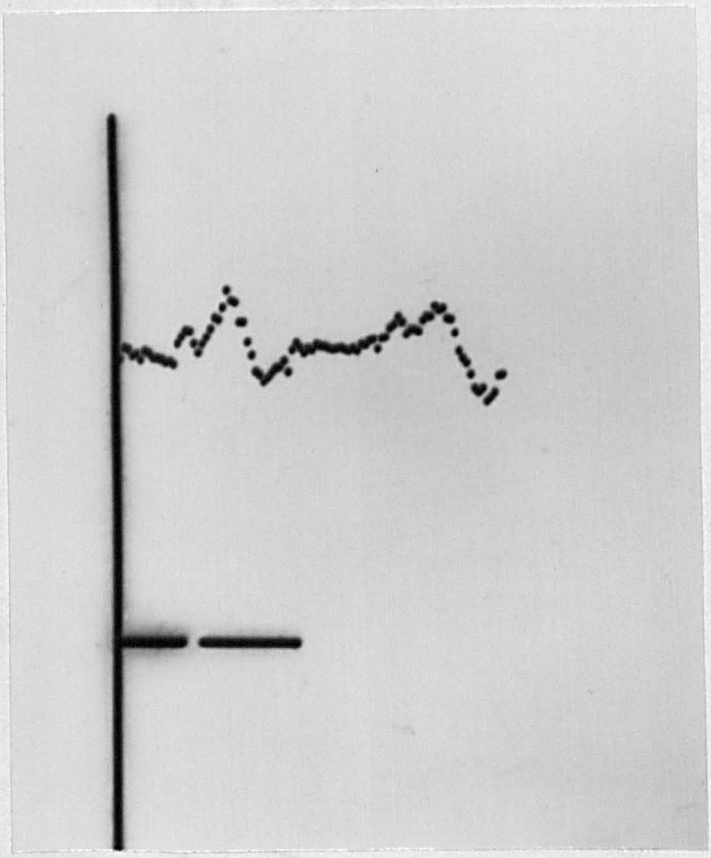
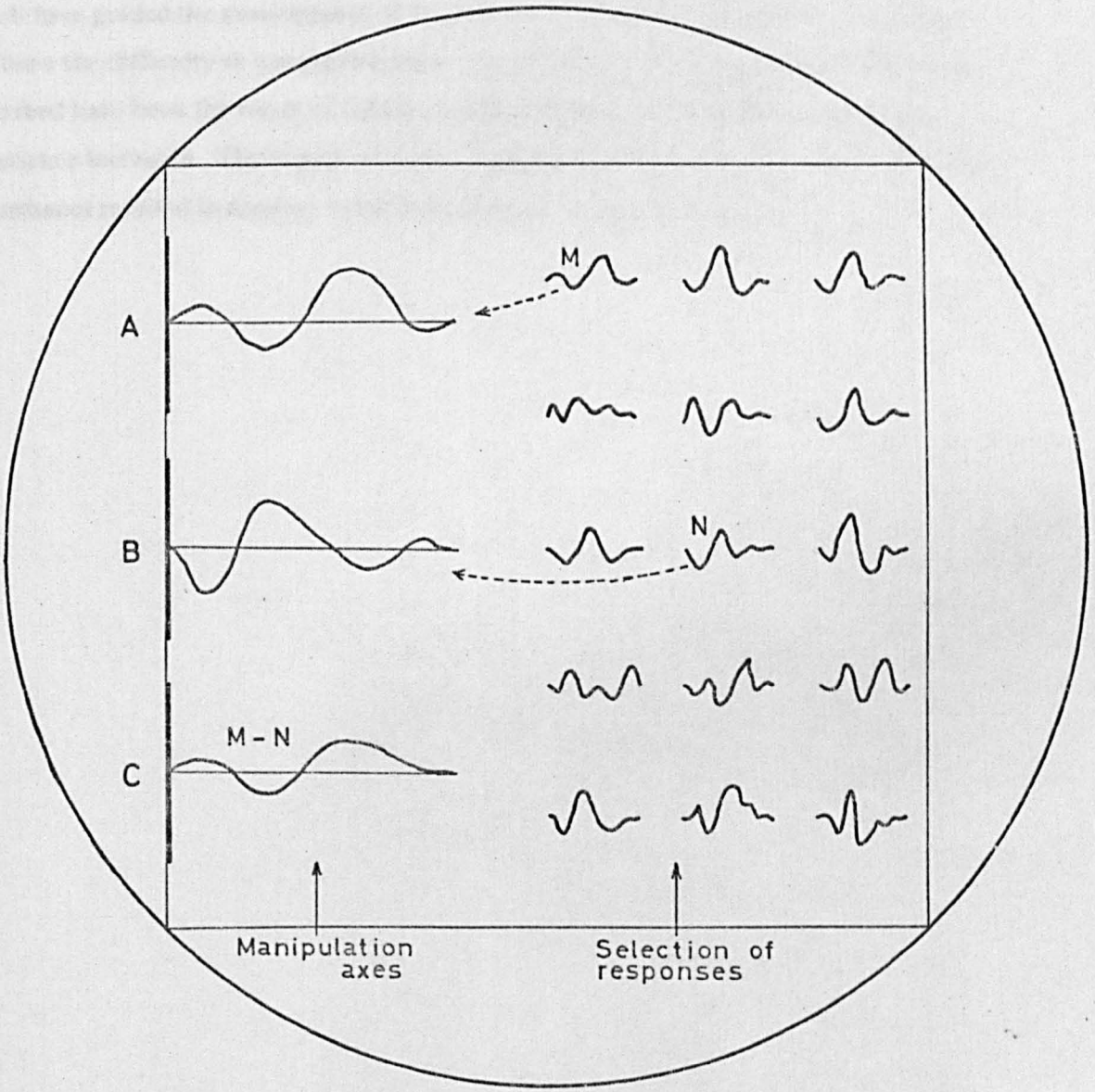


Fig. 6.3 Sample Selection Display

Fig. 6.4 DATA MANIPULATION DISPLAY



the response N into axis B. Pressing the appropriate switch would form (A – B) and display the result in C, which can then be plotted out.

6.5 Conclusions and Observations on Man-Computer Interaction

The above has been a rather brief survey of the man–machine interface considerations, which have guided the development of the research techniques. The principal drawback has been the difficulty in quantifying these considerations. The displays and techniques described have been the result of continuous development, improving the displays as experience increased. The impact of human learning was very noticeable, and in a number of instances resulted in displays being made *simpler* to improve efficiency.

SECTION C

EXPERIMENTAL RESULTS

CHAPTER 7: PATTERN PRE-EXPOSURE EXPERIMENTS

7.1 Introduction

As has been stated in section 3.1 it is necessary when measuring EPs to present multiple stimuli and, to achieve reasonably short experimental durations, the interstimulus period (ISP) should not be too long. However, decreasing the ISP has the unwelcome side effect of accentuating any interaction between successive responses.

The response obtained to stimuli well separated in time approximates to the transient response of the visual system and a study of its waveshape may be expected to give information concerning successive stages of neural processing. Owing to the non-linearity of the system much of this information is lost if one measures only the steady state response of the system, by stimulating at a single high frequency and measuring the frequency components of the response. Such methods have been used by Regan [125,126], Spekreijse [145], Campbell and Maffei [23], and others, in studies where the interaction between responses is tolerated.

Most previous work on the interaction between successive VEPs has been done using flash stimuli [7,27,48,54,140]. These workers have all used paired flashes as stimuli and have studied changes in the responses as a function of the time interval between the flashes. The responses were very complex, but it was found that interaction occurred at least up to inter-flash intervals of about 300 ms.

The only work so far reported on the interaction between pattern VEPs has been that of Campbell and Maffei [23], using alternating grating patterns. They found that the steady state EP to such a pattern was severely attenuated if the orientation of an adapting pattern was within about 15° of the test pattern.

The series of experiments reported in this chapter were designed to investigate the effect of one stimulus on the response to a succeeding one, when the stimuli are tachistoscopically presented patterns replacing a normally 'blank' field. The second (test) stimulus can either be identical to or different from the first (pre-exposure) stimulus. Both these cases were investigated.

7.2 Methods

Stimulus

Using the tachistoscope of Figure 4.2(a), three of the four fields were arranged to display three

patterns P_1, P_2, P_3. (For some later experiments P_3 was omitted.) The fourth field contained a 'blank' field, which was always, and only,illuminated when all the patterns were off, (logical NAND).

The stimulus sequence used is illustrated in Figure 7.1. It consisted of four time intervals $T_1 - T_4$,:

			Duration
T_1	– Pattern, P_1	– Pre-exposure (PE) stimulus	– Preset
T_2	– Blank	–	– Preset
T_3	– Pattern, P_1 or P_2 or P_3	– Randomly selected test stimulus	– Preset
T_4	– Blank	–	– Randomly variable

The variable T_4 resulted in an aperiodic presentation rate with a mean period of 910 ms, and a variation of ± 130ms. For large values of T_1, T_2 or T_3 the mean period was lengthened accordingly.

Subjects

A total of four subjects were used, of whom two (DAJ, JGA) were investigated in some detail. As far as results go for the other subjects they showed similar features.

Electrodes

Five midline electrodes were used, and six channels (5monopolar, 1 bipolar) were recorded, as shown in Figure 7.1. The right ear lobe was used for the monopolar reference electrode.

Response Analysis

The test stimuli (P_1, P_2, P_3,) were presented in random order, and the computer automatically sorted out the responses into the three stimulus conditions, i.e. P_1P_1, P_1P_2, P_1P_3. Fifty responses were averaged for each condition, and at least two runs were made for each timing condition. The mean of these two results was taken. Normally a range of values of T_3 was used for each pair of T_1, T_2, values, so that changes in EP thresholds could be observed.

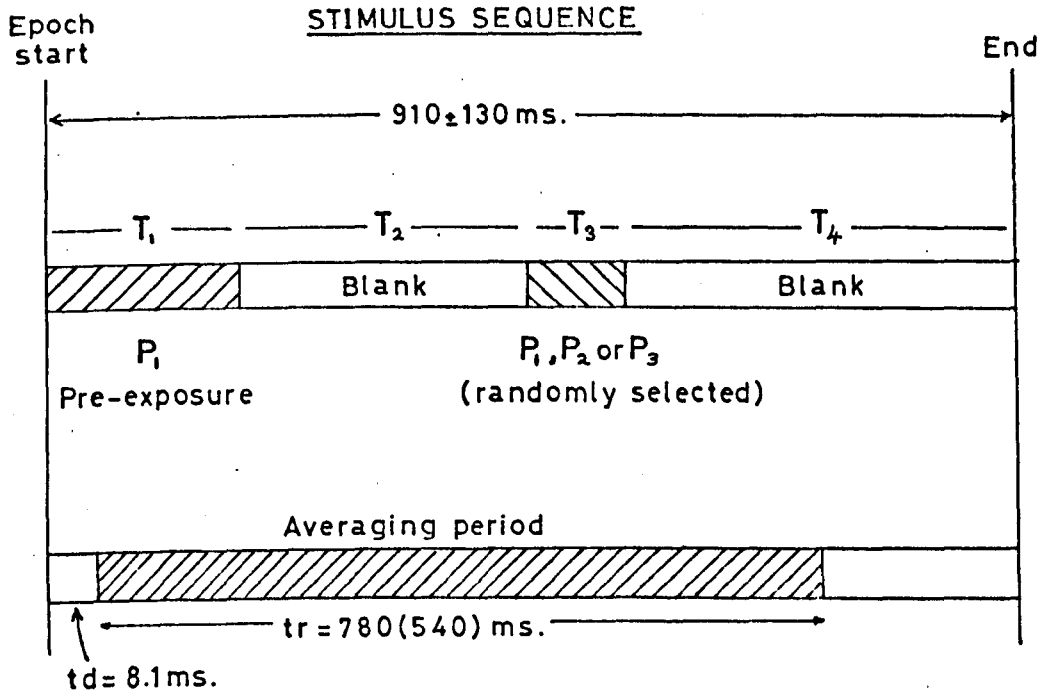
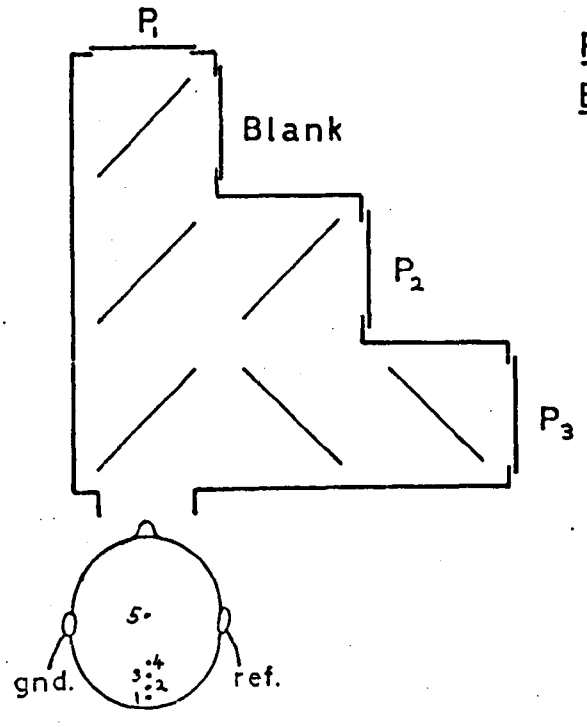


Fig. 7.1



1 on inion, 5 on vertex
separation 1-2-3-4 = 3 cm.

PRE-EXPOSURE EXPERIMENTS

4-field tachistoscope
Field diameter = 6°
Luminance = 37 cd/m²

Channel	Electrodes
1	1-ref.
2	2-ref.
3	3-ref.
4	4-ref.
5	5-ref.
6	4-2

The intermixing of the test patterns allowed differences in the responses to each of them to be measured under identical experimental conditions. It was found, particularly with monocular stimulation, that the responses were often rather small, and also variable from day to day. Thus it was important to do all the runs necessary for a given comparison during one experimental session.

The test patterns, although intermixed randomly within a particular run, were placed in different tachistoscope fields, and it is possible that this may have introduced response differences unrelated to the patterns themselves (even though the fields were subjectively matched for brightness). That such field differences were negligible was shown by a control experiment in which the patterns were changed around between the various tachistoscope fields and their responses compared.

The A/D converter sampling interval was 8.1 ms and 96 samples per response were measured. The resulting sampling period of 780 ms was long enough in most cases to encompass both the PE and test responses. For experiment 1 and a few results in experiment 2 a shorter averaging period of 520 ms was used.

When T_2 was fairly short ($\leq$ 200 ms), the pre-exposure response would overlap that of the test stimulus, thus creating problems of measurement of the latter. To overcome this a method employed by a number of other workers (Ciganek [27]; Schwartz and Shagass [140]) was used. This involved subtracting the pre-exposure only response from that for the double stimulus. Assignment of zero level, with respect to which the amplitude of a particular peak is to be measured, was always a source of inaccuracy however, and because of this, in one particular case considered later, the results must be considered with some caution.

Variance estimates computed on-line were used to calculate the ± 1 std. dev. limits shown on all the graphs. (These limits are omitted for some points, to avoid confusion, but are similar for the same electrode of the same subject.) The calculated limits take into account the variability of the zero level.

7.3 Experiment 1 – Comparison of Identical Versus Random Pattern Presentation

A preliminary experiment was conducted to determine if there was any difference between the response to a stimulus presented in a sequence of identical stimuli (condition 1) and the

response to the same stimulus presented within a random sequence of different stimuli (condition II). In this case $T_1 = 0$, i.e. no pre-exposure. Figure 7.2 shows the results for two subjects. Results for conditions I and II are given in the first two rows, and it can be seen that they are appreciably different. The third row shows results for condition III which was similar to condition I except that the interstimulus period was about three times its previous value. (In practice this was achieved by merely inhibiting the presentation of patterns P_2 and P_3). Again the responses are different, and it may be noted that certain components are larger in amplitude.

These results demonstrate that the shape of a response depends on:

a. the identity of the preceding pattern.

b. the relative timing of the stimuli.

7.4 Experiment 2 – Effect of Varying T_1, T_2 and T_3

For this experiment the following patterns were used:

P_1 – short vertical bars – lower half field

P_2 – short 45° bars – lower half field

P_3 – short horizontal bars– lower half field

Each bar subtended an angular area of 3.3′ x 20′ of arc at the eye. These particular patterns were chosen as it was desired to investigate the possible effects of different contour orientations on the responses. The lower half field was used because of its large responses.

A typical set of responses is shown in Figure 7.3 using the values $T_1 = 50$ ms, $T_2 = 300$ ms, $T_3 = 20$ ms. The separate responses to PE and test stimuli are easily seen. The response is greatest on the lower part of the occiput, with a maximum at electrode 2 (3 cm above the inion), and very little on electrodes 4 and 5. For this subject, electrode 2 was thus selected for measurement, and for all the results given in this section, the amplitude of the prominent negative peak at about 130 ms latency was measured. At the bottom of Figure 7.3 the electrode 2 responses for the PE only are given. These were used to assign the zero level when measuring the amplitude of the test response.

Each time interval T_1, T_2 and T_3 was varied independently, and Figures 7.4 – 7.8 show how the amplitude of the test response varied as a function of each of these. These results

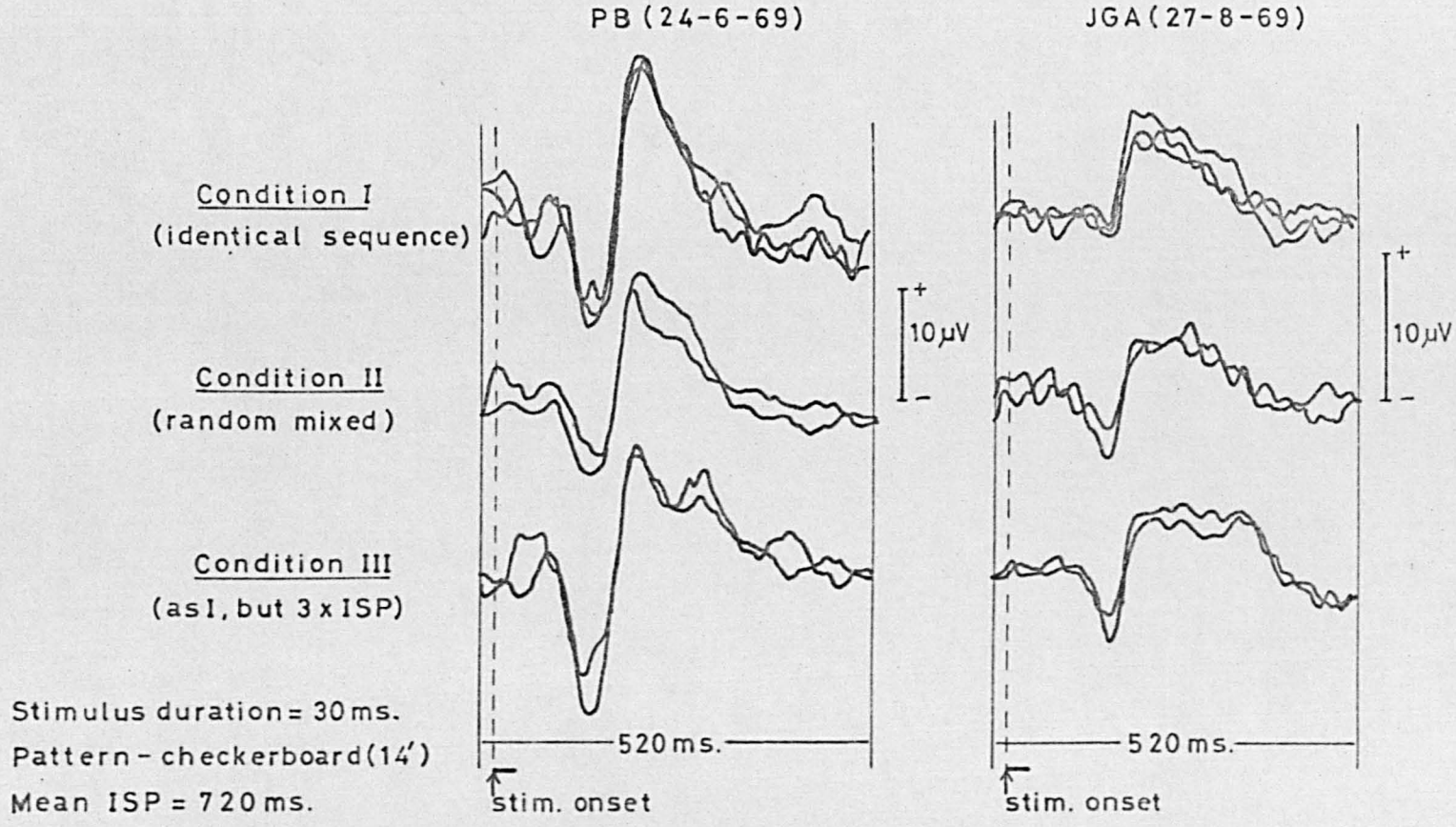


Fig. 7.2 IDENTICAL vs. RANDOM PATTERN PRESENTATION

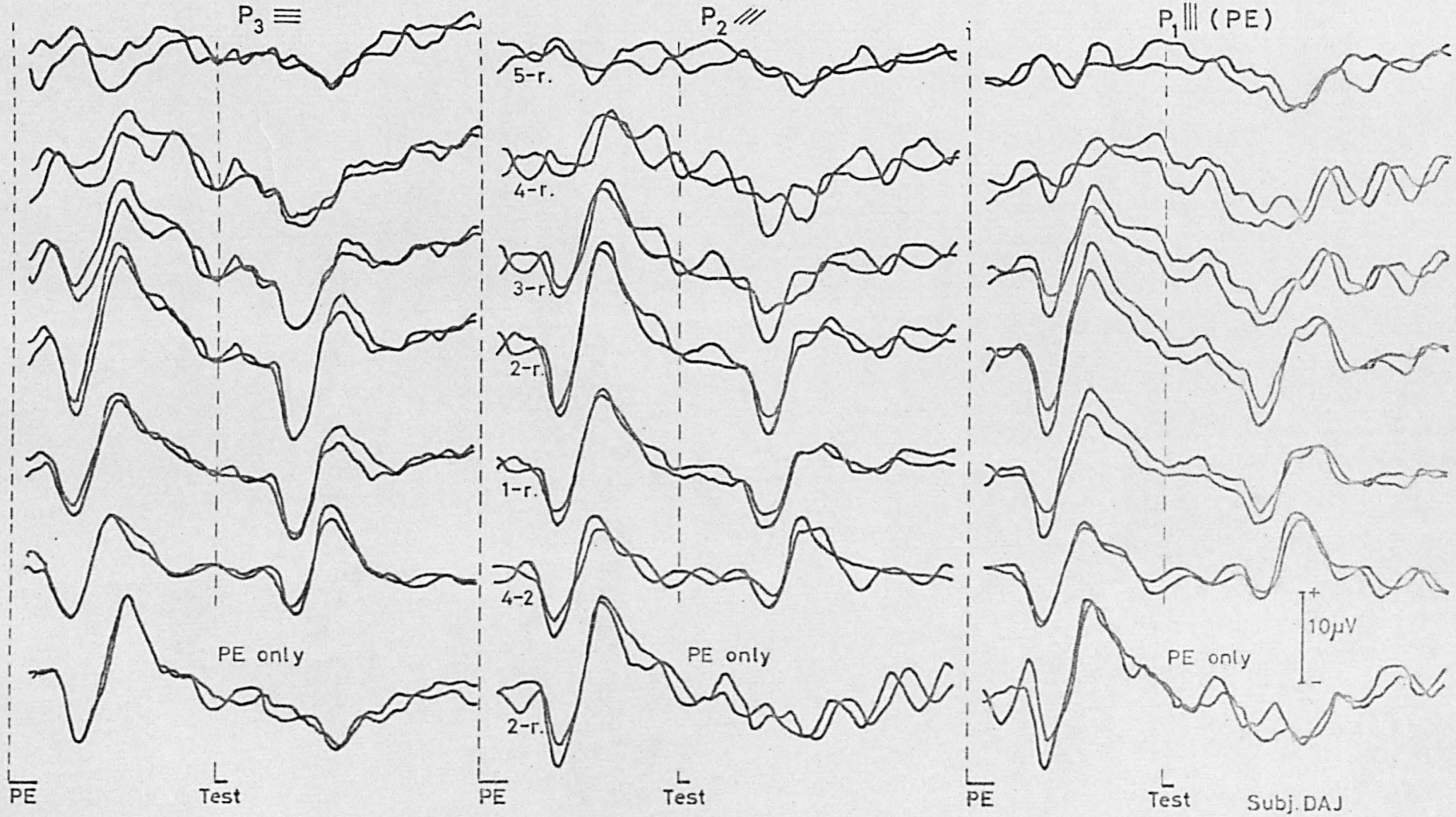


Fig. 7.3 AEP RESPONSES using $T_1 = 50$, $T_2 = 300$, $T_3 = 20$ ms.

were obtained in three experimental sessions. During each session the various timing conditions were selected in a random order.

7.4.1 Discussion of These Results

Figure 7.4 shows the effect of varying T_3 in the absence of PE ($T_1 = 0$). A typical saturation phenomenon is observed at about 25–30 ms. The three patterns gave essentially identical responses, and thus any subsequently observed differences between them must be due to the nature of the PE. These results provide no evidence for a smaller AEP to the 45° bars than to the vertical and horizontal bars. Maffei and Campbell [105] found such a difference using a grating pattern stimulus, but it is doubtful whether the present method was precise enough to show up such a small difference. Some psychophysical results [2, 22, 151] have also indicated that the human visual system is more sensitive to vertical and horizontal directions than to oblique orientations.

Figure 7.5 shows a similar plot of AEP amplitude versus T_3, this time with the PE at $T_1 = 50$ ms. The response to pattern P_3 is relatively little affected, while pattern P_1 (same as PE) is very substantially suppressed. The 45° bars (P_2) are slightly affected.

Figures 7.6 and 7.7 show the dependence on T_1. As before, it is found that pattern P_1 (identical with PE) is suppressed most, while P_3 is least affected and P_2 lies intermediate between the two. These also appears to be a critical value of T_1 above which the response falls off rapidly. For $T_3 = 15$ ms, this is about 30 ms (Figure 7.6) and for $T_3 = 20$ ms it is about 50 ms (Figure 7.7) and in general the longer T_3, the greater is the PE duration (T_1) needed for a significant effect.

The effect of varying T_2 is shown in Figure 7.8. Even at $T_2 = 500$ ms the PE is still quite effective for condition P_1P_1. The apparent increase in response for small values of T_2 (150 and 200 ms) seems to be due to enhancement of the test response by a late component of the PE response, an effect which makes the results at small values of T_2 rather difficult to interpret.

It is interesting to compare these findings with those of Campbell and Maffei [23] in a paper published after this work was done. They measured the steady state response to an alternating vertical grating after pre-exposure to a steady adapting grating at various other

Fig. 7.4 NO PRE-EXPOSURE, $T_1 = 0$

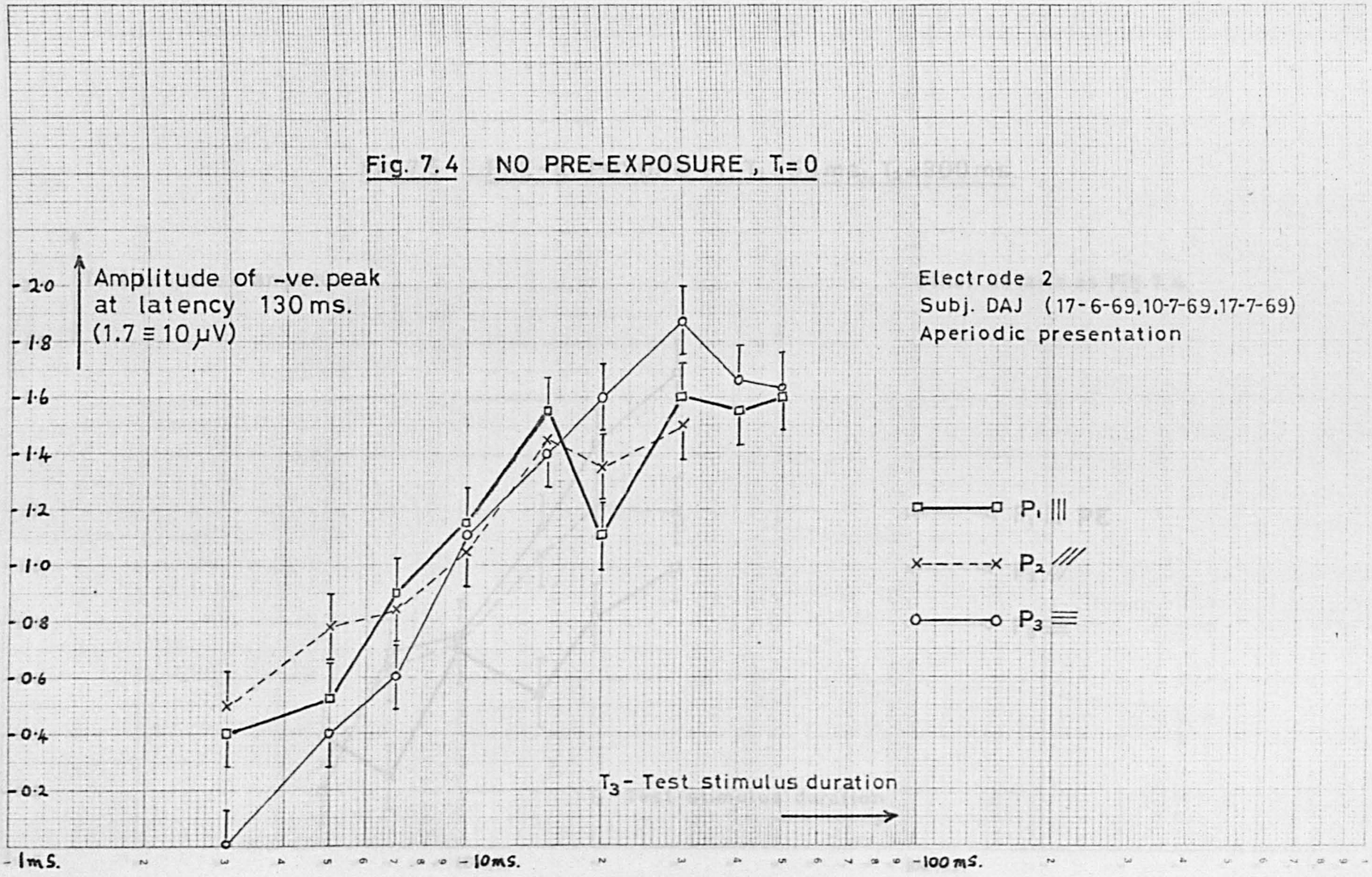
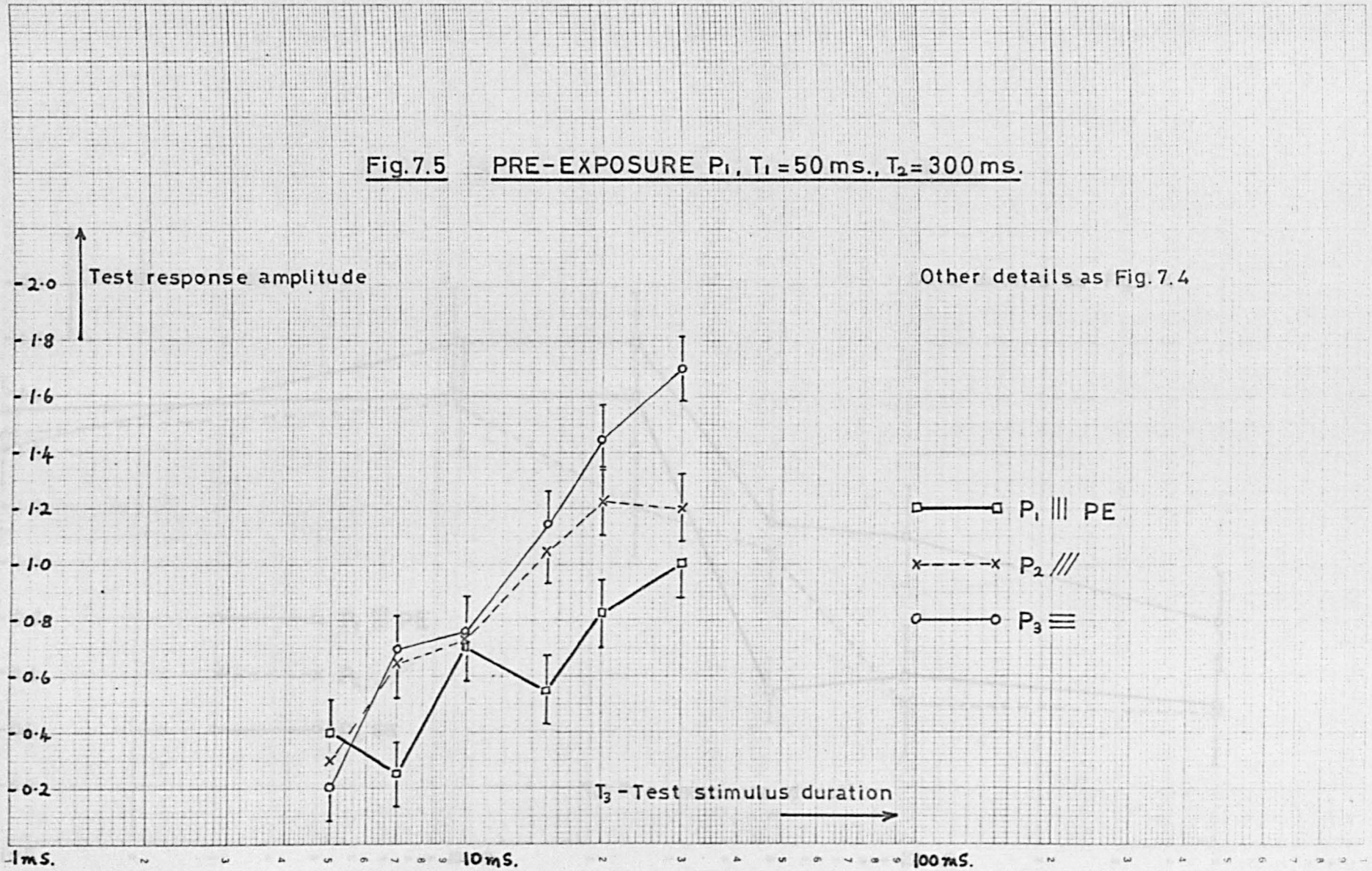


Fig. 7.5 PRE-EXPOSURE P_1, T_1 = 50 ms., T_2 = 300 ms.



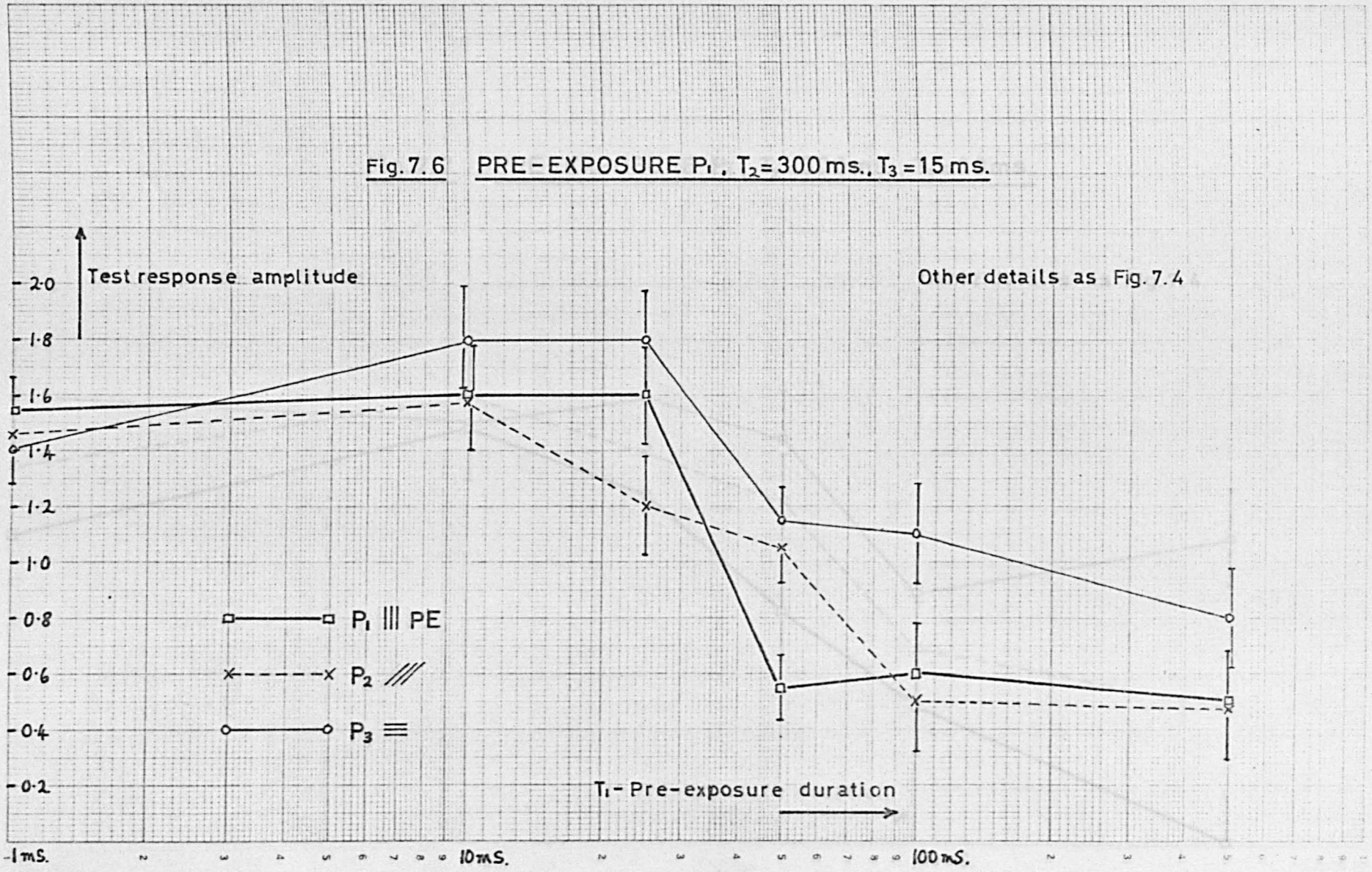


Fig. 7.6 PRE-EXPOSURE P1 , T2 = 300 ms., T3 = 15 ms.
Test response amplitude
Other details as Fig. 7.4
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
P1 ||| PE
P2 ///
P3 ≡
T1 - Pre-exposure duration
1 mS.
10 mS.
100 mS.

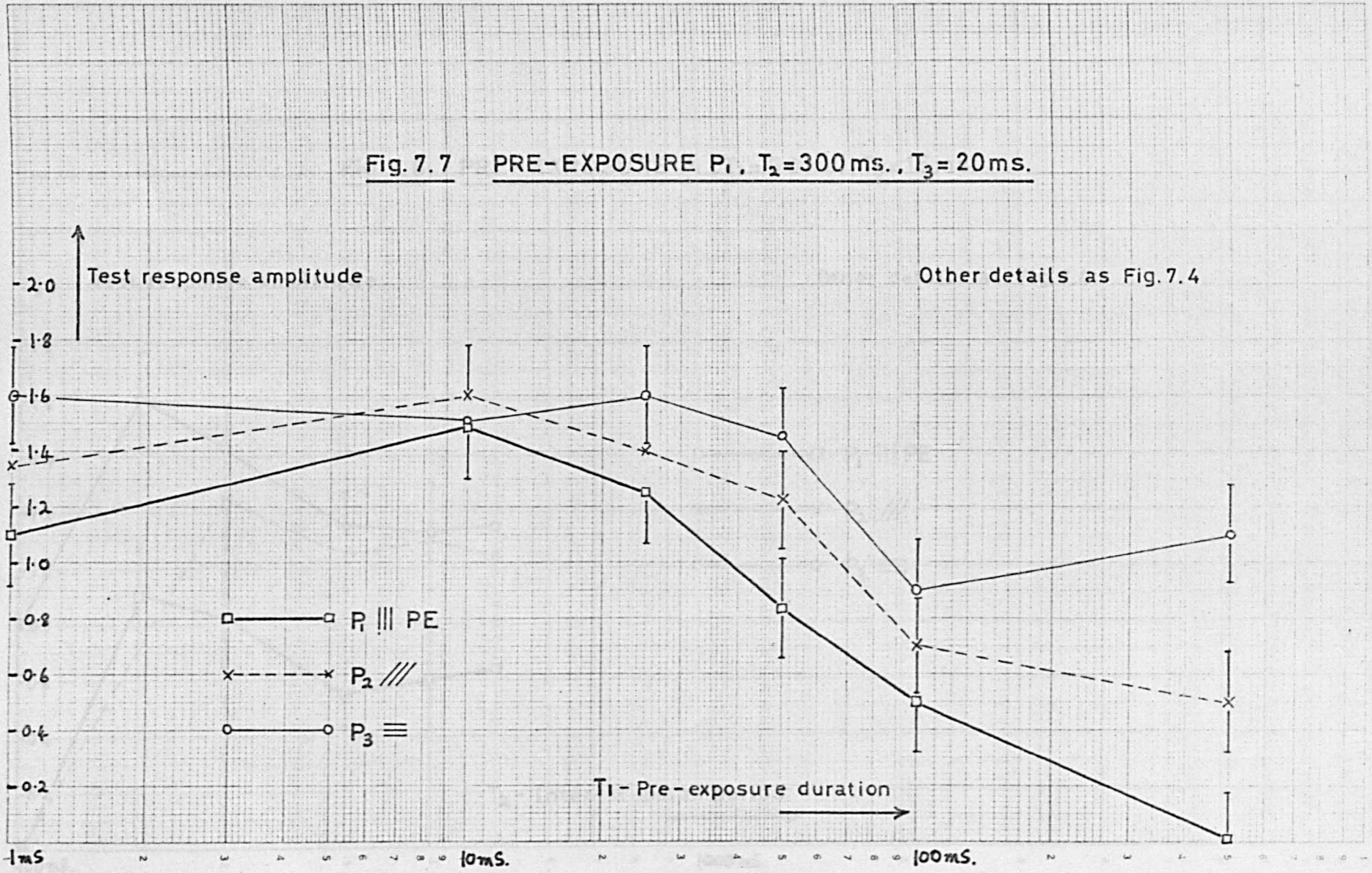
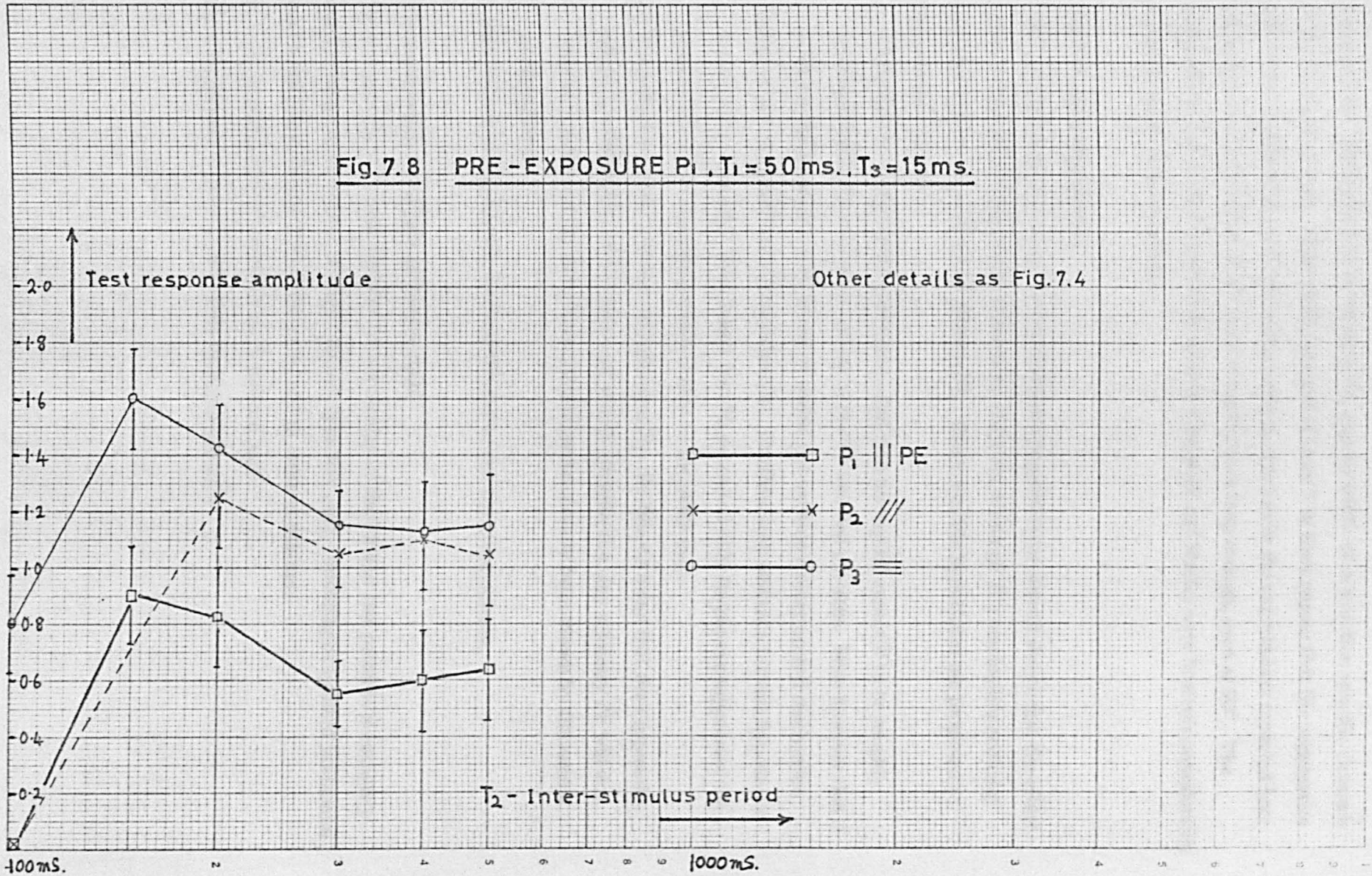


Fig. 7.7 PRE-EXPOSURE P1, T2=300ms., T3=20ms.
Test response amplitude
Other details as Fig. 7.4
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
P1 PE
P2
P3
T1 - Pre-exposure duration
1mS
10mS.
100mS.

Fig. 7.8 PRE-EXPOSURE P_1, T_1 = 50 ms., T_3 = 15 ms.



orientations. Their aim was to measure the angular width of orientation specific channels in the nervous system. Their results showed (Figure 9 in their paper) that the suppressive effect was confined to ± 15° about the vertical, whereas in the experiments reported here there was a definite effect at 45° and, if the PE were long enough, even at 90°. The stimulation and analysis conditions used by Campbell and Maffei were however considerably different from those used here.

7.4.2 Possible Mechanisms

The fact that suppression occurs even between perpendicular stimuli shows that the effect is more than just adaptation of orientation channels, although this mechanism probably operates in the case of identical pattern PE. Three possible hypotheses are proposed to explain these effects:

1. The effect is purely retinal adaptation, and thus we should expect it to be roughly proportional to the extent of overlap of the PE and test patterns. Note however that if such a proportionality were found, it would not exclude a more central mechanism.
2. The effect is central and stimulus-specific. Confirmatory evidence for this hypothesis would be provided if it were found that PE presented only to one eye suppressed the response to a test stimulus presented only to the other eye.
3. The effect is central and non stimulus-specific. By this we mean that the suppression effect is independent of the nature of the PE stimulus (i.e. any arbitrary PE will do). That this cannot be the complete explanation has already been shown by the results quoted above.

The following experiments were conducted to test these hypotheses.

7.5 Experiment 3 – Effect of Pattern Shift

In this experiment we ask whether or not overlap of the PE and test patterns is necessary for the suppression effect. A single pattern type was used, consisting of isolated horizontal bars as shown in Figure 7.9. Patterns P_2 and P_3 were as follows:

$P_2 - P_1$ pattern shifted vertically by ½ pattern unit

$P_3 - P_1$ pattern shifted horizontally by ½ pattern unit

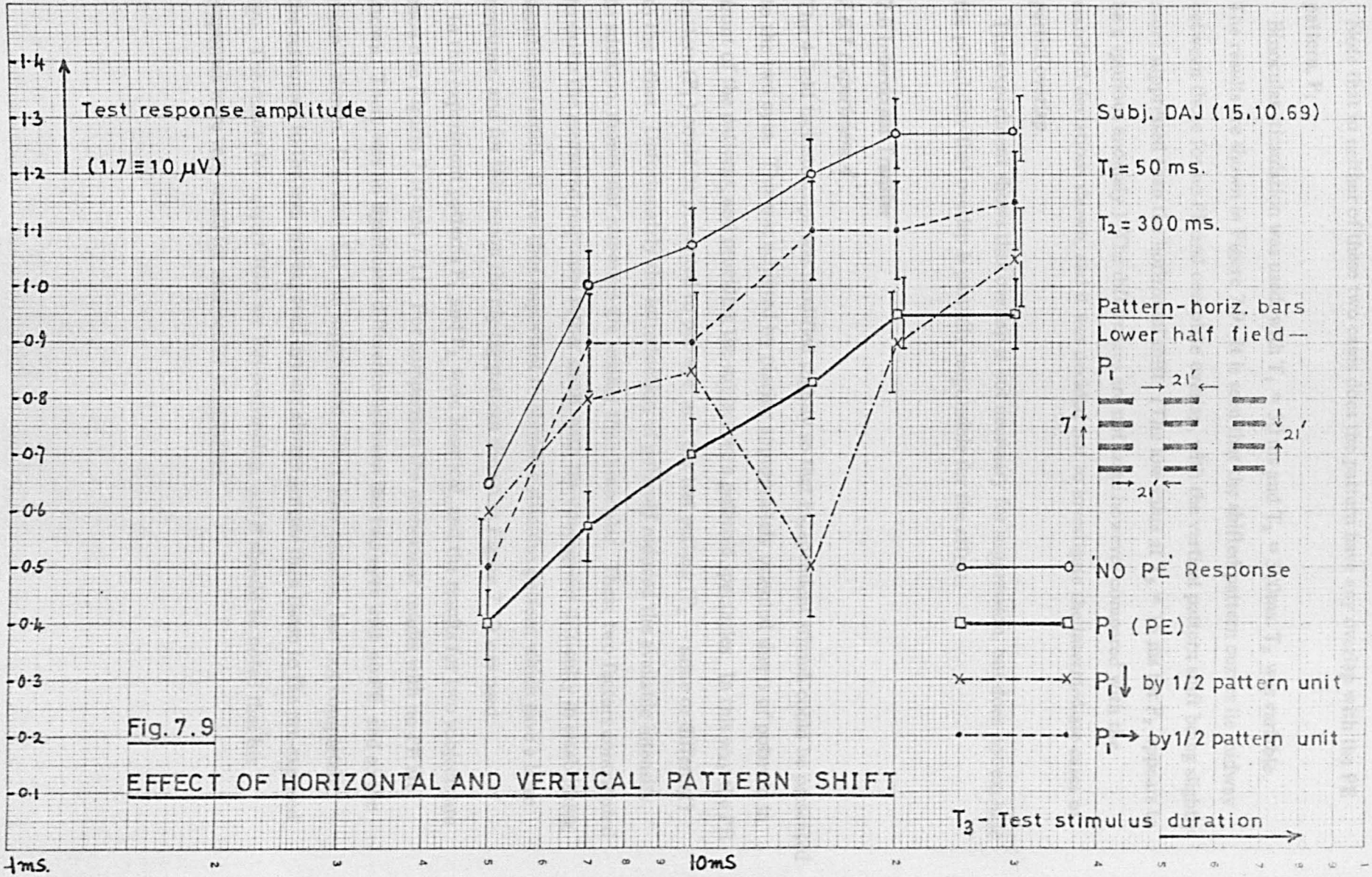


Fig. 7.9

EFFECT OF HORIZONTAL AND VERTICAL PATTERN SHIFT

Note that in neither of these two cases does the pattern have any overlap with the PE pattern, P_1.

Binocular stimulation was used, with T_1 = 50 ms and T_2 = 300ms. T_3 was variable. The results are shown in Figure 7.9. It is seen that the shifted pattern curves lie midway between those for no PE and complete overlap, with the vertical pattern shift being slightly more suppressed than the horizontal shift. (The low value at T_3 = 15 ms for P_2 appears to be a spurious anomaly.) The differences are not large however compared with the standard deviations shown, and it was decided not to investigate the intermediate cases of partial overlap.

This experiment shows that overlap is not necessary for suppression, but does not exclude the possibility that overlap is partially responsible for the effect.

7.6 Interocular Transfer

7.6.1 Experiment 4

The 4-field tachistoscope was modified slightly so that independent stimuli could be presented to the two eyes. This was achieved by placing appropriately oriented sheets of polaroid in front of the patterns, and providing the subject with polaroid spectacles. In this way the PE pattern (P_1) could be presented to one eye, and the test pattern (P_2 – same or different) to the other. Unfortunately the introduction of polaroid reduced the available intensity. In addition, monocular responses are smaller than binocular. These two factors contributed to make the measured responses rather small, with the consequent difficulty in establishing significant results. It was thus important to choose a stimulus pattern which gave a large response, and for this reason the zig-zag pattern shown in Figure 7.10 was used.

In this experiment patterns P_1 and P_2 were identical, and the results for two subjects are shown in Figures 7.10 and 7.11. For comparison the monocular results with no PE are shown. There was no significant difference between the two eyes with no PE, and so the mean is shown. It is seen that the suppression effect does transfer, but not completely; the responses to the non pre-exposed eye are always greater than those to the pre-exposed eye. The results for subject JGA are less convincing, and it should be noted that his responses were very small for monocular stimulation.

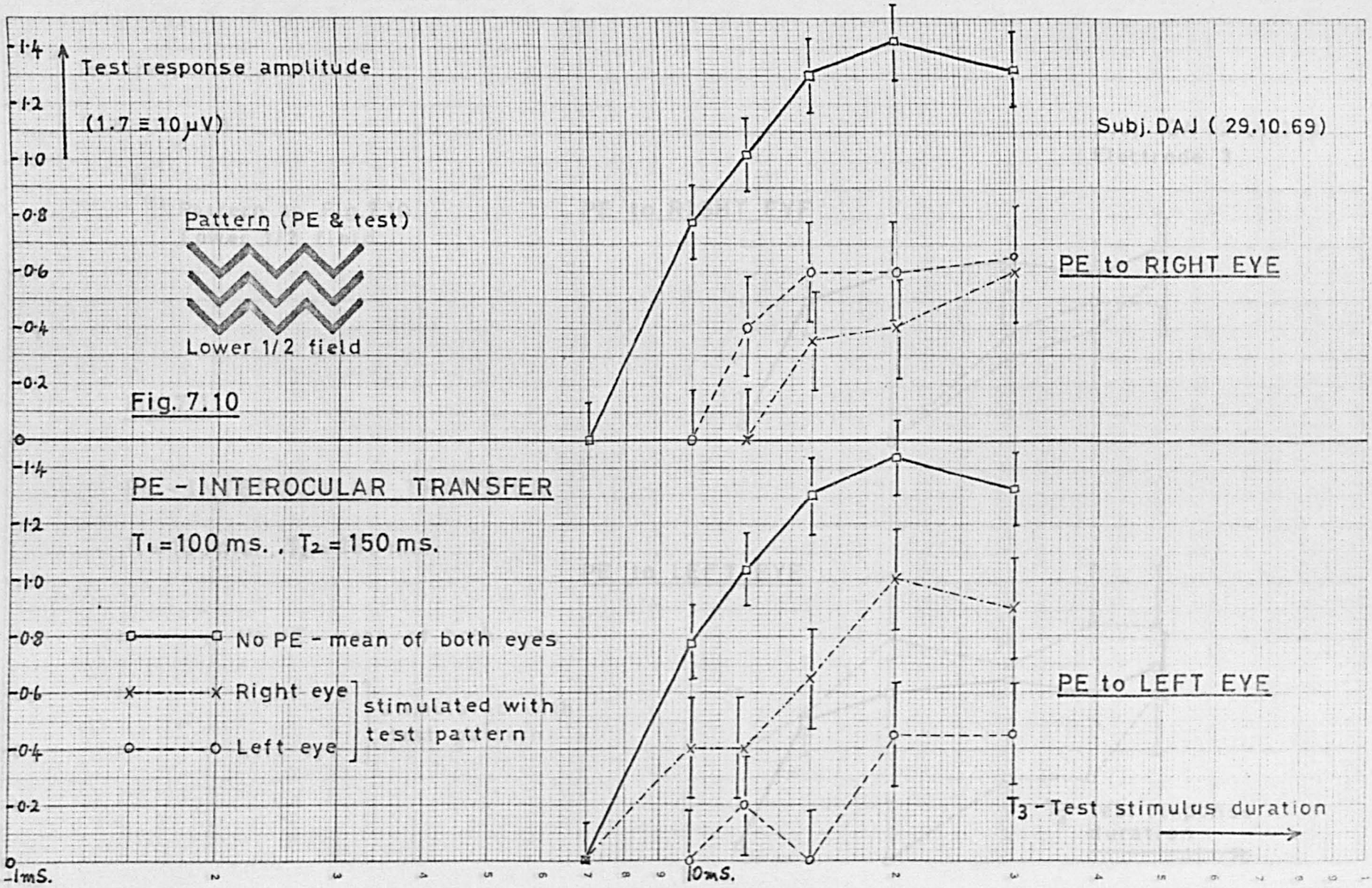

Test response amplitude
(1.7 ≡ 10 μV)
Pattern (PE & test)
Lower 1/2 field
Subj. DAJ (29.10.69)
PE to RIGHT EYE
PE - INTEROCULAR TRANSFER
T1 = 100 ms., T2 = 150 ms.
No PE - mean of both eyes
Right eye
Left eye
stimulated with test pattern
PE to LEFT EYE
T3 - Test stimulus duration
1mS.
10mS.

Fig. 7.10

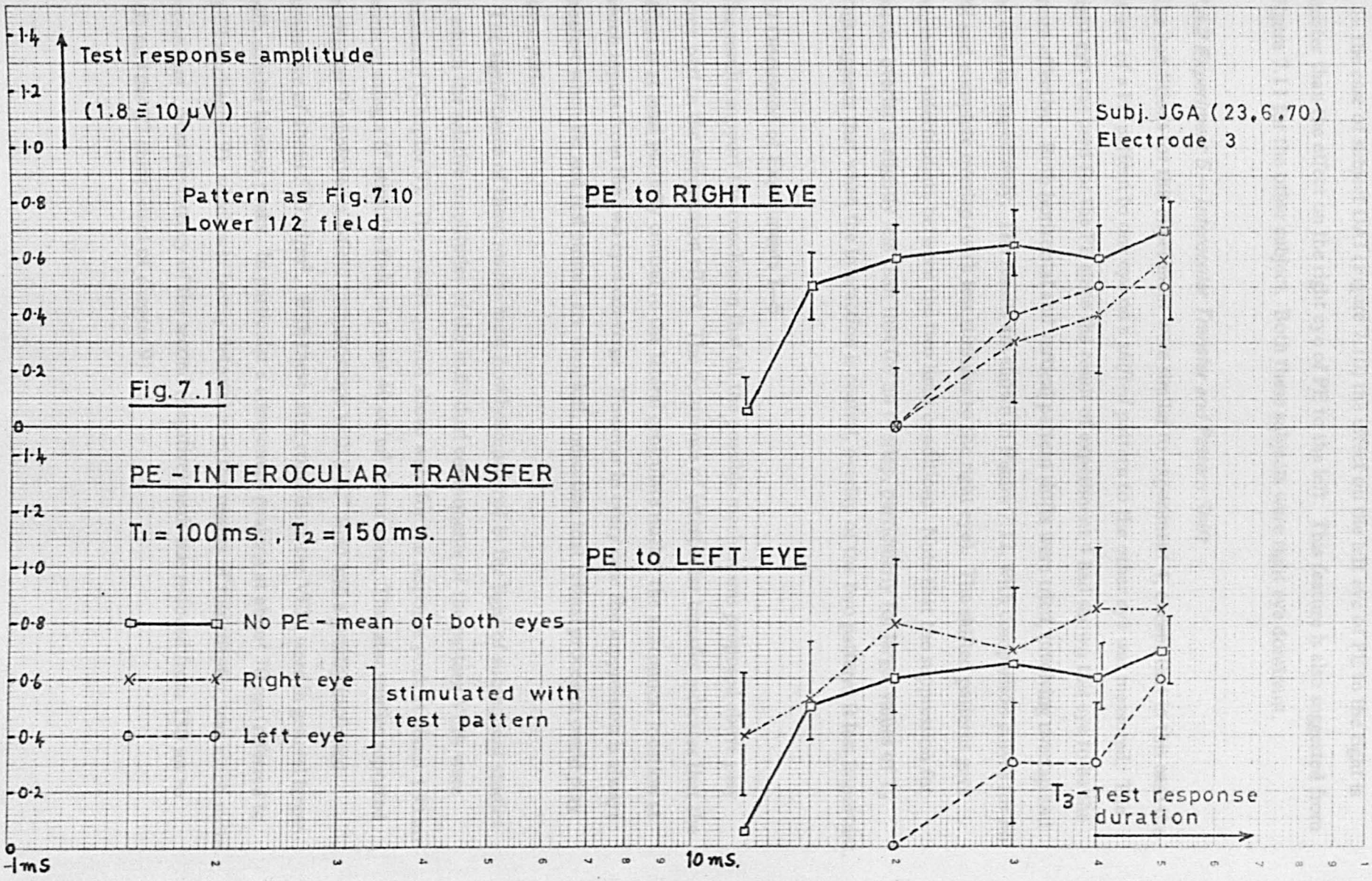

Test response amplitude
(1.8 ≡ 10 μV)
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
Pattern as Fig. 7.10
Lower 1/2 field
Subj. JGA (23.6.70)
Electrode 3
PE to RIGHT EYE
PE - INTEROCULAR TRANSFER
T1 = 100 ms. , T2 = 150 ms.
PE to LEFT EYE
No PE - mean of both eyes
Right eye
Left eye
stimulated with test pattern
T3 - Test response duration
1 ms
10 ms.

Fig. 7.11

7.18

In the case of subject DAJ (Figure 7.10) the effect on the left eye of PE to the right is greater than the effect on the right eye of PE to the left. This feature is also suggested from Figure 7.11 for the other subject. Both these subjects were right eye dominant.

7.6.2 Experiment 5 — Interocular Transfer and Pattern Shift

The conditions for this experiment were similar to experiment 4, except that in this case the effect of a PE pattern to one eye on a *shifted* pattern to the other eye was measured. The right eye was used for the PE since the result of experiment 4 had shown this eye to be the more effective. Both horizontal and vertical pattern shifts were tried, involving overlap and no overlap respectively. The results are shown in Figure 7.12, with comparison curves for no PE and complete overlap (with test stimulus to the right eye). The shifted patterns gave responses intermediate between the two limit conditions. Note that the suppression for partial overlap is slightly less than that for no overlap, particularly for larger values of T_3. This suggests that when the interaction is central, overlap of the two patterns is less important.

7.7 Discussion of Experiments 1–5

The results support the conclusion that all the possible mechanisms proposed above play some part in the suppression effect. The occurence of interocular transfer indicates that the effect is at least partially central to the lateral geniculate nuclei, the anatomical location at which inputs from the two eyes converge. However in every case the suppression is always greatest when PE and test stimuli are identical, indicating that retinal processes could play some part.

The significance of these results must now beconsidered in the light of subsequent studies in which the relative amplitudes of the individual components of the pattern VEPs were measured (Chapter 9). The results quoted above were for the response peak at about 130 ms latency, using a 6° stimulus field at about 40 cd/m^2 luminance. The later studies reported in chapter 9 employed a 2-field tachistoscope with a 12° field and a greatly increased luminance of about 500 cd/m^2. With these later conditions the VEPs were in general larger, with shorter latency peaks. In particular a component peaking at about 70 ms (referred to as CI in chapter 9), which was barely detectable in the results of this chapter, was much more prominent. Also the latency of the second (negative) peak was reduced from 130 ms to 100 ms (the C2 component of chapter 9).

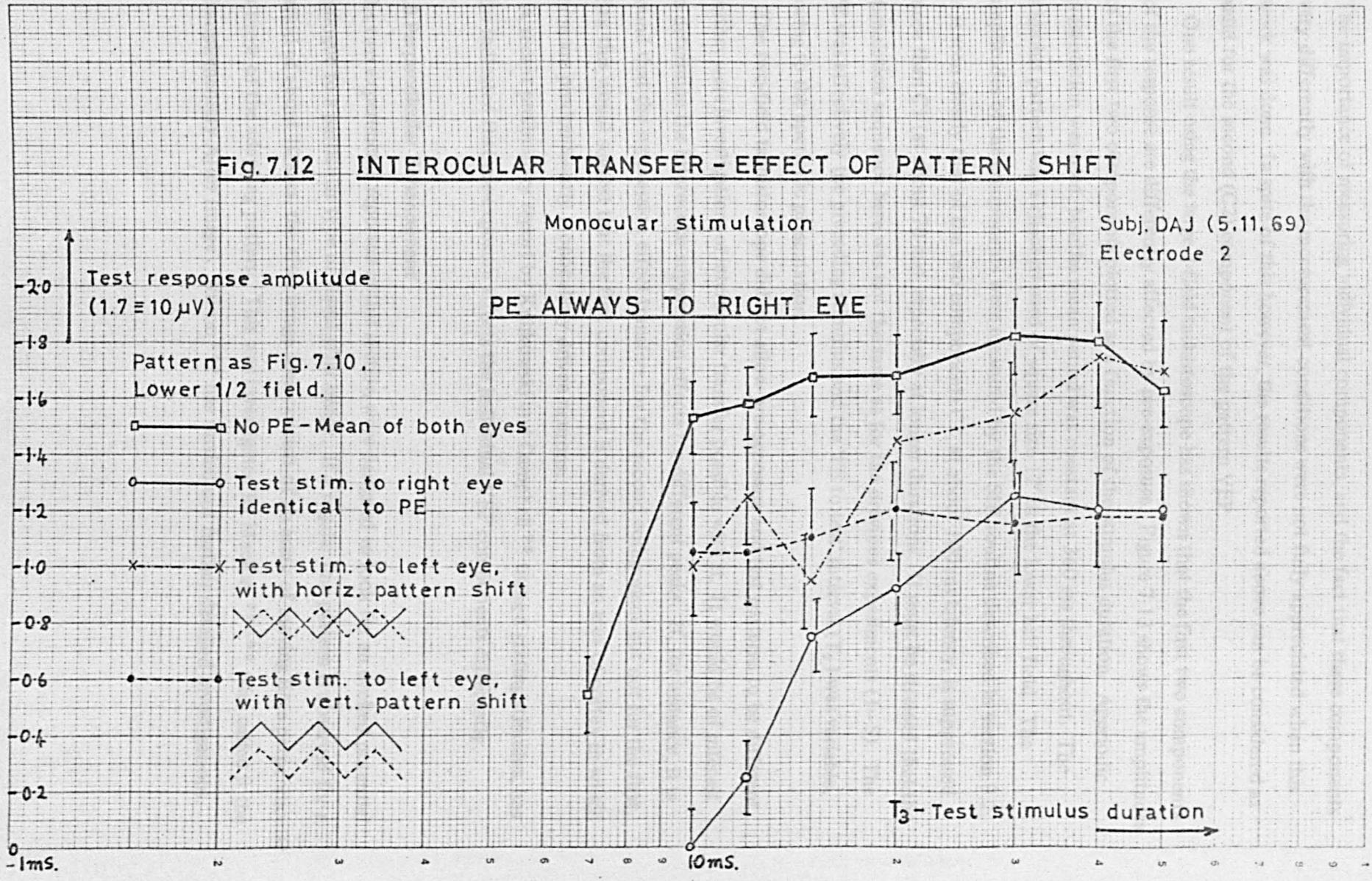


Fig. 7.12 INTEROCULAR TRANSFER - EFFECT OF PATTERN SHIFT
Monocular stimulation
Subj. DAJ (5.11.69)
Electrode 2
PE ALWAYS TO RIGHT EYE
Test response amplitude
(1.7 ≡ 10 μV)
Pattern as Fig. 7.10.
Lower 1/2 field.
No PE - Mean of both eyes
Test stim. to right eye
identical to PE
Test stim. to left eye,
with horiz. pattern shift
Test stim. to left eye,
with vert. pattern shift
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
1mS.
10mS.
T3 - Test stimulus duration
7-20

The importance of measuring individual components, and the fact that these components vary differently with the measurement conditions were not fully appreciated when this work was done. In spite of this however, the results reported above can be considered as valid for the second (C2) component of the pattern VEP.

One result using the large 2-field tachistoscope has shown that the first two components of the response are differently affected by pre-exposure. Figure 7.13 shows the amplitudes of the first two components plotted as a function of the stimulus duration. Aperiodic presentation was used, but the mean period was constant at 360 ms throughout. The stimulus pattern was a checkerboard of square size 12′ in the lower half field. The amplitudes of the components were measured by the SIR routine described in section 9.2. It is seen clearly that of the two components C2, at about 100 ms latency, is suppressed more than C1 (at about 70 ms), especially at longer durations. It must be stressed that the stimulation sequence here was not the same as for the previous experiments (1–5). The PE was effectively the preceding stimulus and the 'PE to test' interval (T_2) was variable, owing to the aperiodic presentation.

The two-field tachistoscope did not allow pre-exposure and test patterns to be different, neither were investigations of interocular transfer possible with it. It would be of interest to determine the interocular suppression effects for different peaks. If, for instance, it is found that the suppression effect transfers for the second component but not for the first, then this would suggest that the first component is derived from an area of cortex in which there are predominantly monocularly driven neurons.

A recent preliminary report by Kulikowski and Campbell [95] using a grating stimulus, has also indicated that pre-exposure affects the individual VEP components differently.

7.8 Perpendicular Enhancement

The two experiments reported in this section were designed to look for an evoked potential analogue to a particular type of visual after image. If a regular line pattern is observed for a period of about 10 secs, the after image seen consists of an array of moving lines perpendicular to those of the adapting pattern. This was investigated by MacKay [99,100] who called it the 'Complementary After Image'. Wilson [168] has carried out further detailed investigations.

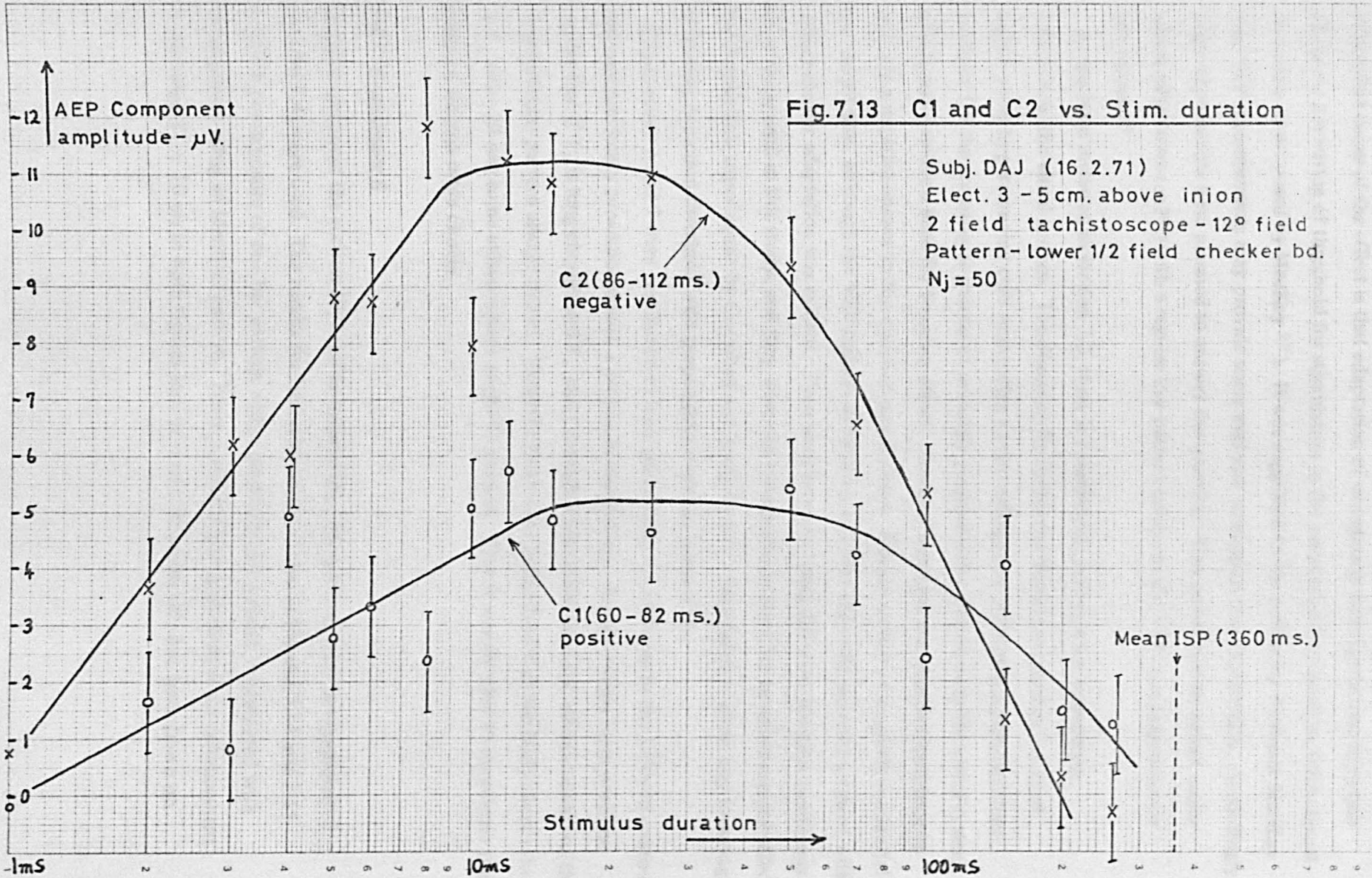


Fig. 7.13 C1 and C2 vs. Stim. duration

Subj. DAJ (16.2.71)
Elect. 3 - 5 cm. above inion
2 field tachistoscope - 12° field
Pattern - lower 1/2 field checker bd.
Nj = 50

7.22

A possible cause of the effect is that adaptation of orientation detectors in one direction produces a lowering of threshold for stimulation in the perpendicular direction, (Directional Satiation, as proposed by MacKay [99]). It was suggested to the author by Professor MacKay that VEP measurements may provide some evidence to support this explanation. Accordingly some experiments were planned to answer the question: 'Can conditions be found under which adaptation (or PE) with a regular line pattern enhances the VEP to a perpendicular line pattern?'

As has been reviewed in section 2.2, there is considerable evidence for orientation detectors in the visual system. The discovery by Hubel and Wiesel (see section 2.2.2) of higher order hypercomplex cells responding to two orthogonal orientations provides some evidence for the grouping or pairing of mutually perpendicular directions in the visual system, which may provide a basis for the after effect. However there are two results which tend to indicate a negative answer to the question posed above. Recent work by Campbell and Maffei [23] has shown that, although the VEP reflects orientation selective channels, no enhancement with perpendicular adaptation was evident. They were however using different stimulus conditions from those used in this study, and they were not specifically looking for an enhancement effect. Psychophysical experiments by Campbell and Kulikowski [25] have failed to show any lowering of grating detection threshold with perpendicular grating adaptation.

Experiments 6 and 7 were conducted to look specifically for increases in the VEPs to contoured patterns previously pre-exposed with a perpendicular pattern. It was evident from previous results that if T_1 is long enough and T_2 short enough suppression (and not enhancement) of the perpendicular pattern always occurs. However there were indications that for fairly short values of T_1 (20–30 ms) some enhancement might be present. Thus it was decided to investigate this range of timings more closely.

7.8.1 Experiment 6

In this experiment the vertical (P_1) and horizontal (P_2) bar patterns used in experiment 2 (section 7.4) were used. The results for two subjects are shown in Figures 7.14 and 7.15 in which pre-exposure of one bar pattern with a perpendicular pattern is compared with pre-exposure using an identical pattern. There is some slight suggestion of an enhancement in the range $T_1 \sim 10$ ms in both figures but, as is seen from the std. dev. bars drawn on

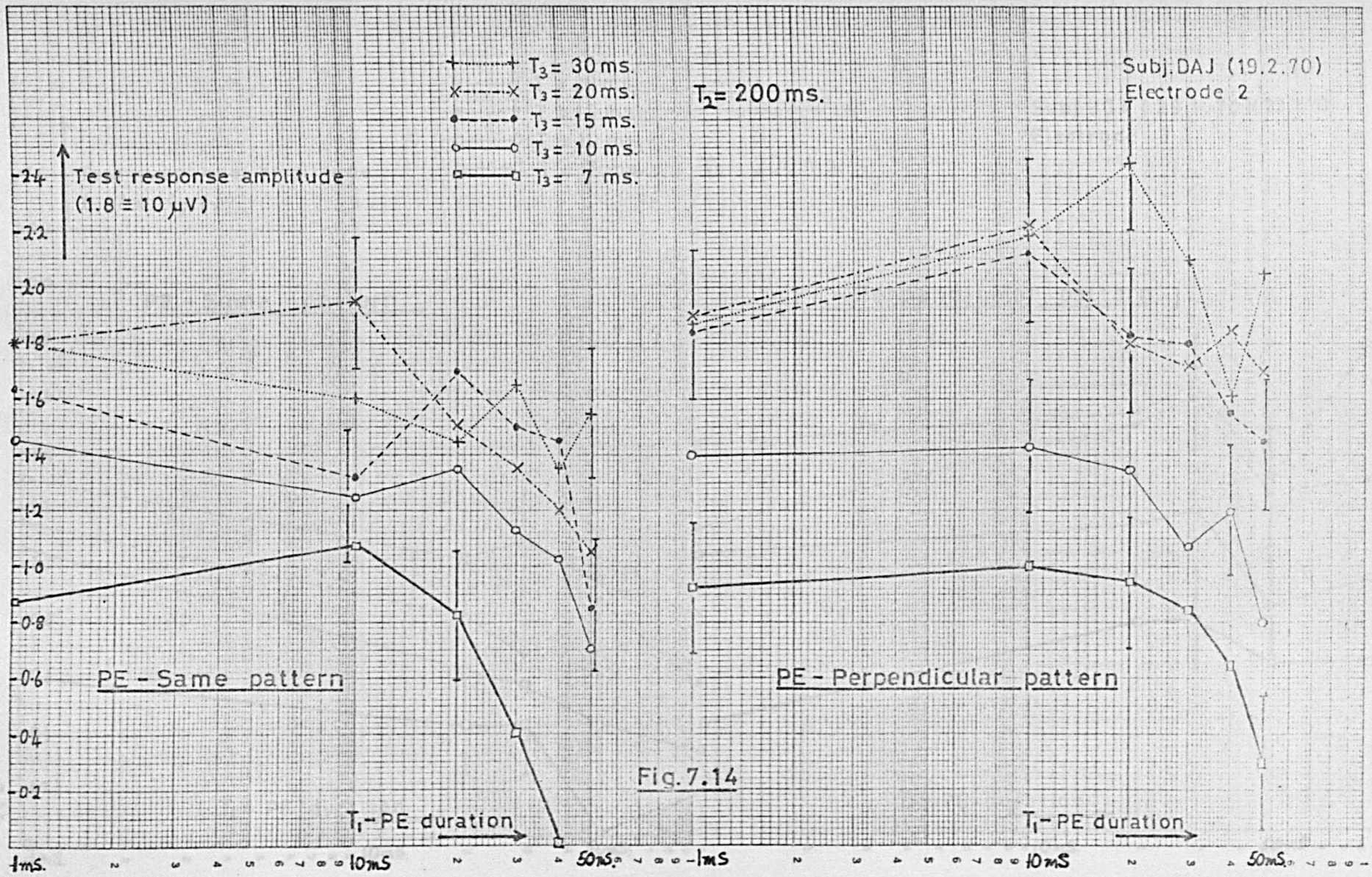

T3 = 30 ms.
T3 = 20 ms.
T3 = 15 ms.
T3 = 10 ms.
T3 = 7 ms.
T2 = 200 ms.
Subj. DAJ (19.2.70)
Electrode 2
Test response amplitude
(1.8 ≡ 10 μV)
2·4
2·2
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
PE - Same pattern
PE - Perpendicular pattern
T1 - PE duration
T1 - PE duration
1mS.
10mS
50mS.
1mS
10mS
50mS.

Fig. 7.14

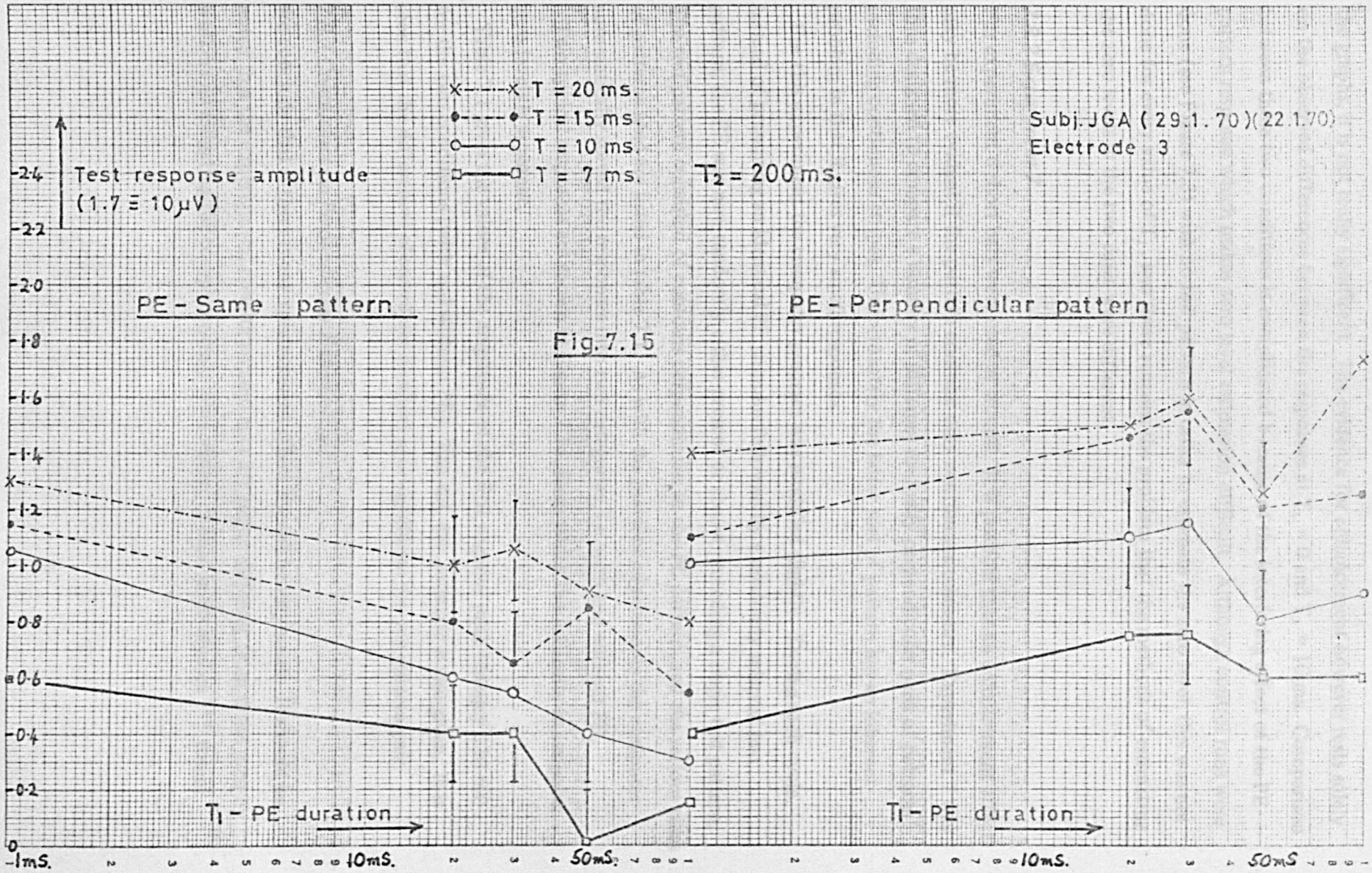


Fig. 7.15

7.25

the graphs, it is not really significant. The evidence for enhancement however rests solely on the observed differences between the responses at $T_1 = 0$ and $T_1 = 10$ ms. Comparison between these two conditions is complicated because of the interfering effect of the PE pattern response which makes zero level estimation difficult. Although control runs were done (see Figure 7.3) with no test pattern in order to estimate the zero level, this was not done for every value of T_1, and there remains the problem that the methods of estimating the zero levels in the two cases were different.

7.8.2 Experiment 7

For experiment 6 short bars were used as stimuli. It is possible that an enhancement effect may be more evident if the pattern contains only continuous contours. Experiment 7 was thus designed to compare a number of different mutually perpendicular pairs of patterns including continuous stripes. Unfortunately the latter sort of pattern has an inherent problem in that it gives very small responses.

For this experiment the computer program was modified slightly. During each cycle, instead of presenting an identical PE stimulus followed by a randomly selected test pattern, the PE was now randomly either present or absent preceding a single test pattern. The test pattern consisted of contours perpendicular to the PE pattern, and the various pairs of patterns used are listed in table 7.1. As with the previous experiments the computer automatically sorted the responses into two categories, i.e. with and without PE.

Two typical responses are shown in Figure 7.16, from which the difficulty in assigning zero levels is apparent.

Table 7.1 gives the values of the amplitude of the first negative peak (latency 130 ms) for the two conditions (with and without PE). The std. dev. estimate is also given. It is seen that the differences observed are nowhere near significant for any pattern pair.

7.8.3 Conclusions on Perpendicular Enhancement

We conclude that if there is any enhancement effect it must be very small. It should be noted that the experimental conditions used here are rather different from those used by workers investigating the complementary after image. Wilson in his studies [168] found

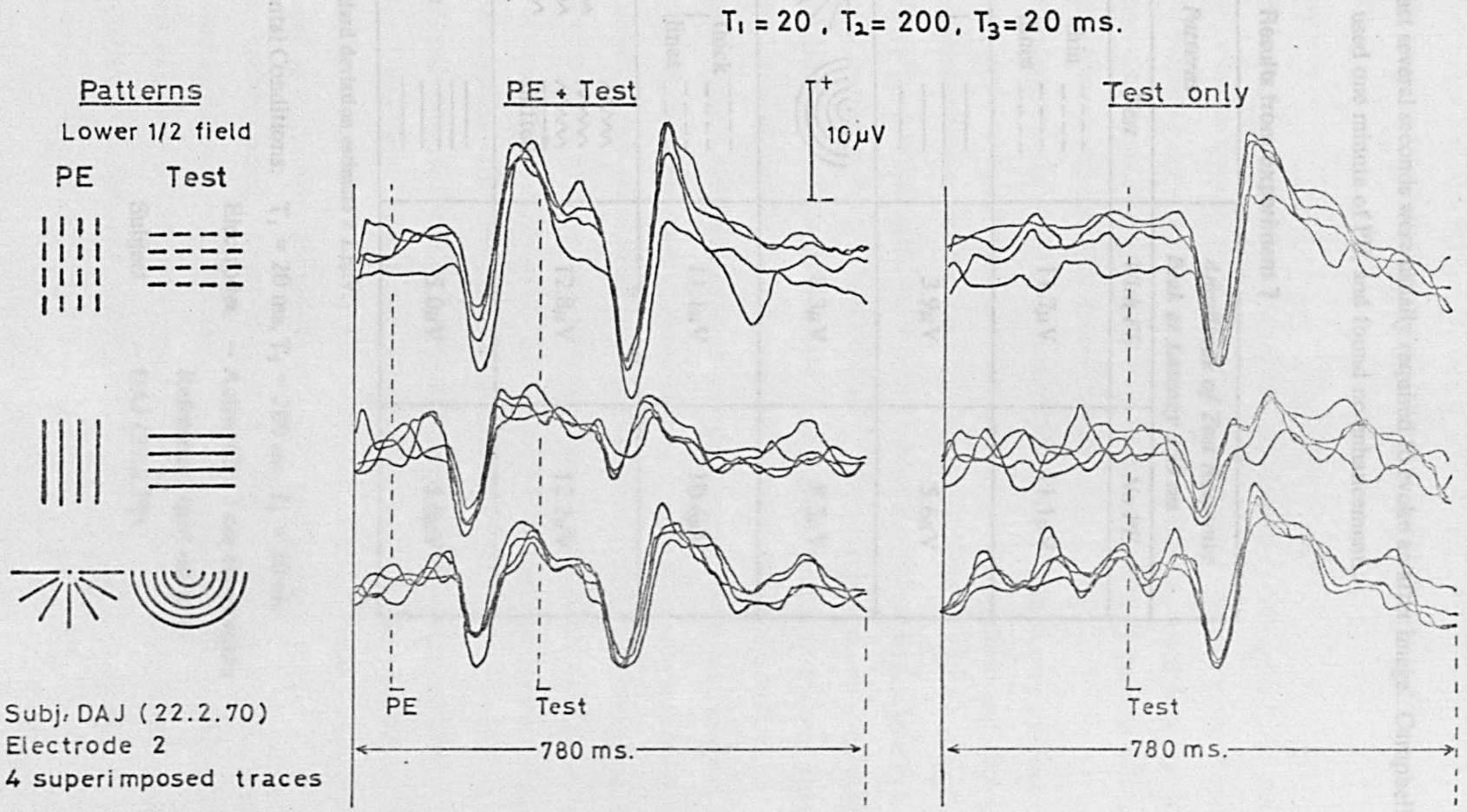


Fig. 7.16 TYPICAL RESPONSES - PERPENDICULAR ENHANCEMENT

that at least several seconds were usually required to evoke an after image. Campbell and Maffei [2 3] used one minute of PE, and found no enhancement.

Table 7.1 Results from Experiment 7

Patterns		*Amplitude of Test Response Peak at Latency 130 ms*	
PE	*Test*	*With PE*	*No PE*
thin lines	thin lines	11.7μV	11.1μV
		3.9μV	5.6μV
		8.3μV	8.3μV
thick lines	thick lines	11.1μV	10.6μV
	shifted	12.8μV	12.2μV
Noise		5.0μV	5.0μV

Note: Standard deviation estimate ± 1.6μV.

Experimental Conditions: T_1 = 20 ms, T_2 = 200 ms, T_3 = 20 ms

Electrodes – Active (2): 3 cm above inion

Reference: right ear lobe

Subject – DAJ (27.2.70).

CHAPTER 8: AVERAGED EVOKED POTENTIAL VARIABILITY STUDIES

8.1 Introduction

It was stated in section 3.1 that routine variance estimates would be made for all AEP measurements so that a proper assessment of their significance could be made. Thus AEP results presented elsewhere in this thesis are accompanied by such estimates. In this chapter we report on how such estimates were derived, and on experiments designed to investigate some properties of the variance itself.

In the literature, treatment of AEP variability has been very mixed, ranging from complete neglect to very extensive statistical analyses. However, numerous workers have drawn attention to the need for considering fluctuations in the individual responses which make up the AEP. In particular Brazier [14] notes that information is lost through the process of averaging. Perry [118] and Walter [163] also stress the need to study AEP variances. Although in 1959 Barlow [6] reported on a simple analogue computer which gave running values of the AEP and its standard deviation, instrumental difficulties have often prevented subsequent workers from calculating AEP standard deviations. Variability usually had to be more crudely estimated (e.g. by comparing two responses recorded under identical stimulus conditions). Even the CAT averager does not allow calculation of standard deviation; this normally requires a general purpose digital computer. Burns and Melzack [18] and Ruchkin [137] have employed ingenious cumulative summation methods for detecting variability, but they are not very precise.

Off-line digital computers were first used to calculate AEP standard deviations (e.g. Brazier [15] and Burns [17]), and more recently a computer has been used on-line by Horvath [73] who measured auditory AEP's in the cat cortex. Horvath's technique has been followed up in this work, for pattern appearance AEPs (section 8.5).

The above has been largely a review of *methods*, as there has been very little quantitative data published on AEP variances. No work has so far been reported for pattern AEPs.

This literature survey would not be complete without some reference to the various attempts to apply to EP data more sophisticated statistical techniques than normal averaging.

Among the most important we mention multivariate analysis, Donchin [45]; discriminant analysis, Walter [162]; principal component analysis, John *et al* [88]; adaptive filters, Freeman [58] and Woody [171]. The main aim of much of this work has been to reduce the dimensionality of EP data. Most results show that it is possible to reduce AEP data to 3–6 dimensions (parameters) but, although very sophisticated mathematically, it is difficult to relate these results to hypotheses about the underlying physiological mechanisms. A difference of emphasis is noted here. Most workers mentioned in this paragraph use simple stimuli (e.g. flashes) and very complex response analyses. This is to be compared with the work reported here, which uses more carefully constructed stimuli, but with a relatively straightforward response analysis. As a consequence their work is of little direct relevance here.

Rigorous analysis of the EEG signal is far from simple. The measured EEG voltage after a stimulus is usually assumed to be a mixture of stimulus evoked activity, 'the response', plus apparently random 'noise', The noise gives rise to short term high frequency fluctuations, owing to the low frequency cut off of the recording apparatus. The response itself can also vary in magnitude and shape, owing to habituation, etc., and this (in addition to the noise) contributes to the observed standard deviation of the averaged waveform. In contrast to the noise, response variations are likely to be longer term ones, lasting for many stimulus periods.

Further complications arise because responses from successive stimuli can interact with each other (see chapter 7) and with the noise. These interactions may confuse variance estimates, but on the other hand may help to uncover features about the underlying physiological processes. The second series of experiments reported in this chapter are attempts at investigating these interactions.

Plan of the Chapter

The initial experiments (section 8.3) investigate variability, in terms of the conventional standard deviation (s.d.) of the pattern appearance AEP, with respect to:-

1. Electrode position – section 8.3.1.
2. Stimulus or no stimulus – section 8.3.2.

3. Retinal area and position – section 8.3.3.
4. Latency – section 8.3.4.

Section 8.4 explores more carefully a latency effect observed during the initial experiments, and demonstrates a case of signal and noise interaction.

Section 8.5 (running average experiments) describes experiments to investigate long term changes (over minutes) of the pattern appearance AEP.

8.2 Computation Method

In terms of the notation given in chapter 5, the standard deviation for a particular response is given by:-

$$S_{ij}^2(t) = \frac{1}{N_j-1} \sum_{p=1}^{N_j} \left[X_{ijp}(t) - A_{ij}(t)\right]^2$$

Where $A_{ij}(t)$ is the AEP previously defined in section 5.2.2. This is simply shown to be equivalent to:-

$$S_{ij}^2(t) = \frac{1}{N_j-1} \sum_{p=1}^{N_j} X_{ijp}^2(t) - \frac{N_j}{N_j-1} A_{ij}^2(t)$$

In practice the sums –

$$\sum_{p} X_{ijp}(t) \quad \text{and} \quad \sum_{p} X_{ijp}^2(t)$$

were accumulated in the computer's data buffer during each averaging run, and then at the end of the run a routine (MS) was automatically entered which computed A_{ij} and S_{ij}. Thus for every single data point (latency t) of the AEP a corresponding value of S_{ij} was available.

Typical std. devs. (i.e. $S_{ij}(t)$) with their associated responses are shown in Figure 8.1 (a). The superposed traces are from two separate runs using identical stimuli. Note that $S_{ij}(t)$ is relatively independant of t for the examples given.

For most of the results given in chapter 9 the mean value of A_{ij} over brief sampling periods was calculated (by means of the SIR routine described later). In these cases the corresponding mean value of S_{ij} over the same or similar periods could also be computed. These are named S0, S1, S2 etc. in an analogous way to the corresponding C0, C1, C2, etc. components of chapter 9, (see Figure 9.1).

Thus we define,

$$S0 = \frac{1}{\Delta t_0} \int_0^{\Delta t_0} S_{ij}(t)\ dt$$

$$S1 = \frac{1}{\Delta t_1} \int_{t_1}^{t_1+\Delta t_1} S_{ij}(t)\ dt$$

and similarly for S2, S3 etc. (Note that there is no 'zero level' subtraction.)

Typical positions for these short duration sampling periods are shown by horizontal bars below the upper traces on Figure 8.1(a). In the following initial experiments the sampling period for S2 was t = 131–159mS, and the mean value of this component over several runs was calculated and plotted.

From the computed values of S0, S1, etc. we may also estimate the standard deviations of the corresponding C1, C2, etc.

To do this we have to make the not too unreasonable assumptions that the data points within one sample are fully correlated, although the samples themselves are drawn from independent distributions.

Thus Std. Dev of C1 = $\dfrac{(S1^2 + S0^2)^{1/2}}{\sqrt{N}}$ (similarly for C2 etc.)

N = total no. of presentations included in C1. However since in practice it was found that S0 ≈ S1 etc. this reduces to – Std. Dev. of C1, C2, C3 ≈ $S0\sqrt{\frac{2}{N}}$

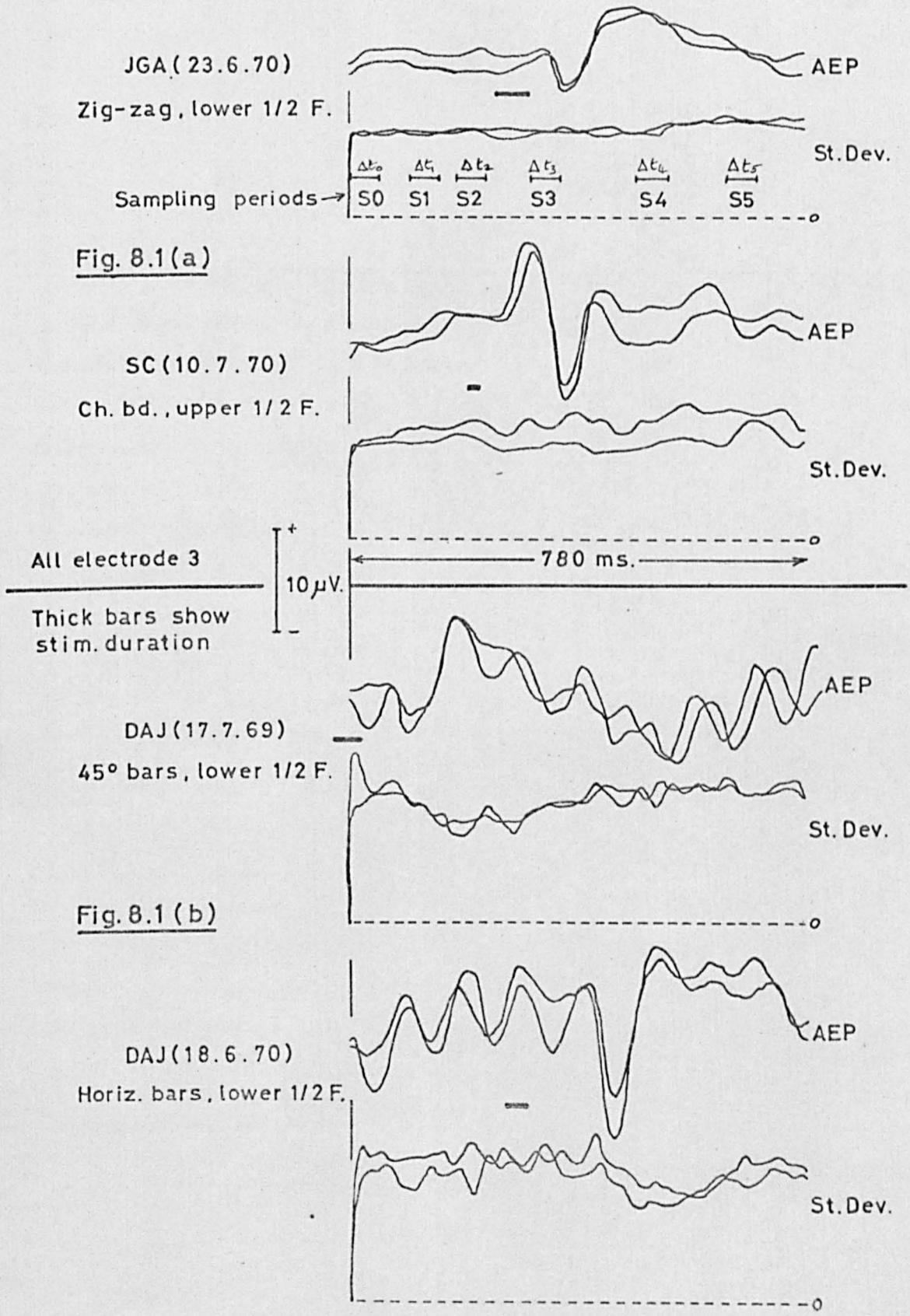


Fig. 8.1(a)

Fig. 8.1 (b)

8.3 Initial Experiments

The measurements reported in this section were obtained during the same experiments as those of chapters 7 and 9. Relevant experimental details are recorded on the accompanying graphs.

8.3.1 AEP Variances

Figures 8.2 – 8.5 show plots of variance distribution over the head for four subjects. Sample S2 (i.e. mean value of $S_{ij}(t)$ over t = 131 – 159 ms) is plotted versus electrode position. Besides being an average over time each point is also an average over several runs (usually 8), all with the same stimulus condition. (Note that the ± 1 std. dev. bars shown on each plot refer to the values of S2 themselves.) Electrode placings and stimulus pattern were the same as those described in chapter 9. Stimulus duration was 25 ms except for the lower part of Figure 8.4 where it was 400 ms.

For subject DAJ, this distribution was measured on several occasions, but was always substantially the same as Figure 8.3.

8.3.2 AEP Variance – With and Without Stimulus

The dashed curves on Figures 8.3 – 8.5 show the distribution of S2 with *no stimulus* under otherwise similar conditions to the solid curves. The no stimulus curves will simply give the RMS value of the raw EEG, since the average in this case is zero.

8.3.3 AEP Variance – Retinal Position and Area of Stimulus Pattern

The two solid plots on Figure 8.3 show distributions for left and right half field stimuli. It is seen that the difference between them is far from significant. A similar result was found for other comparisons using different retinal positions of the stimulus.

Figures 8.4 and 8.5 each show three plots (solid lines) giving distributions for stimuli occupying ½, ¼ and 1/8 of the stimulus field. The results show a small, but barely significant, increase with retinal area stimulated.

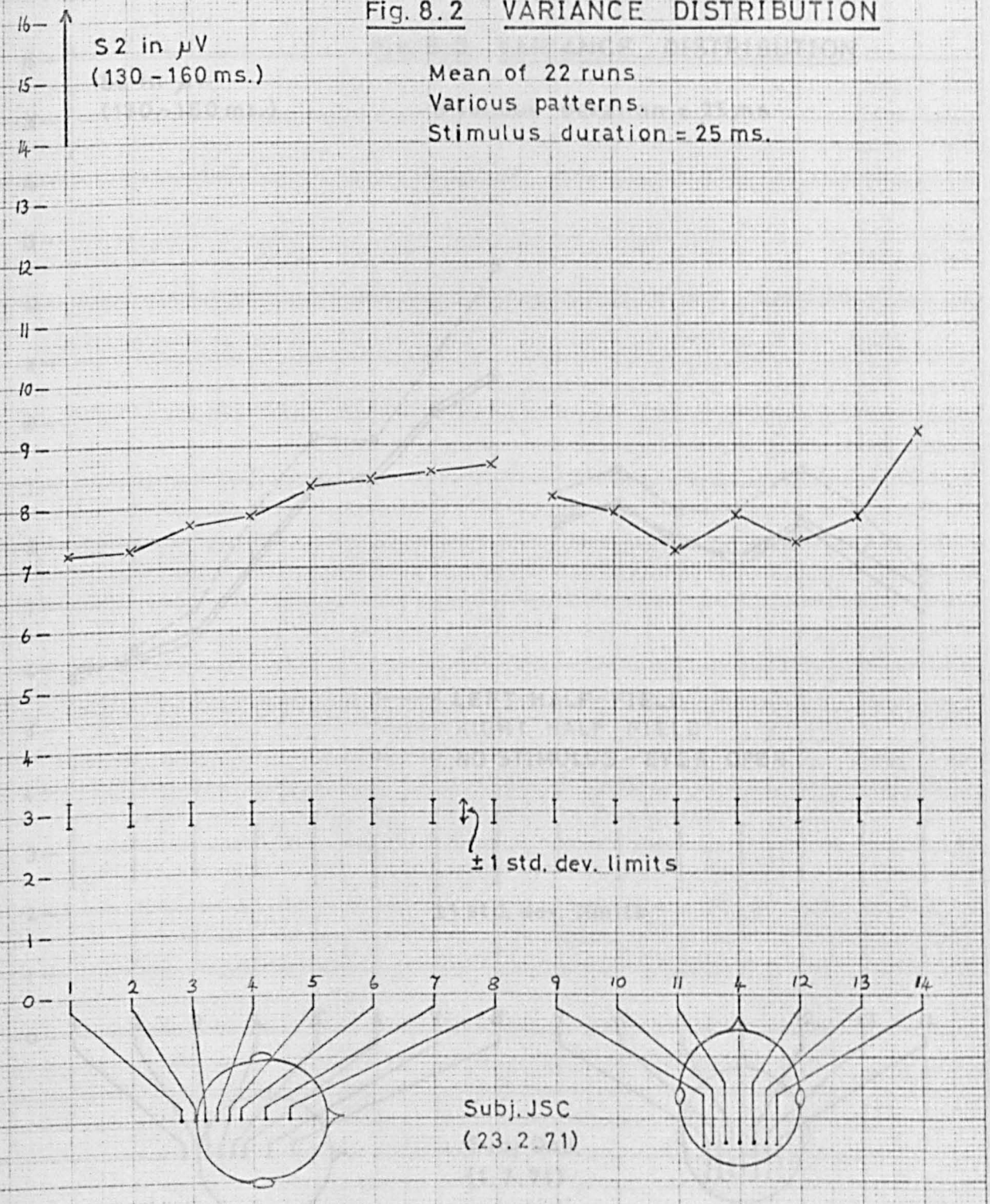
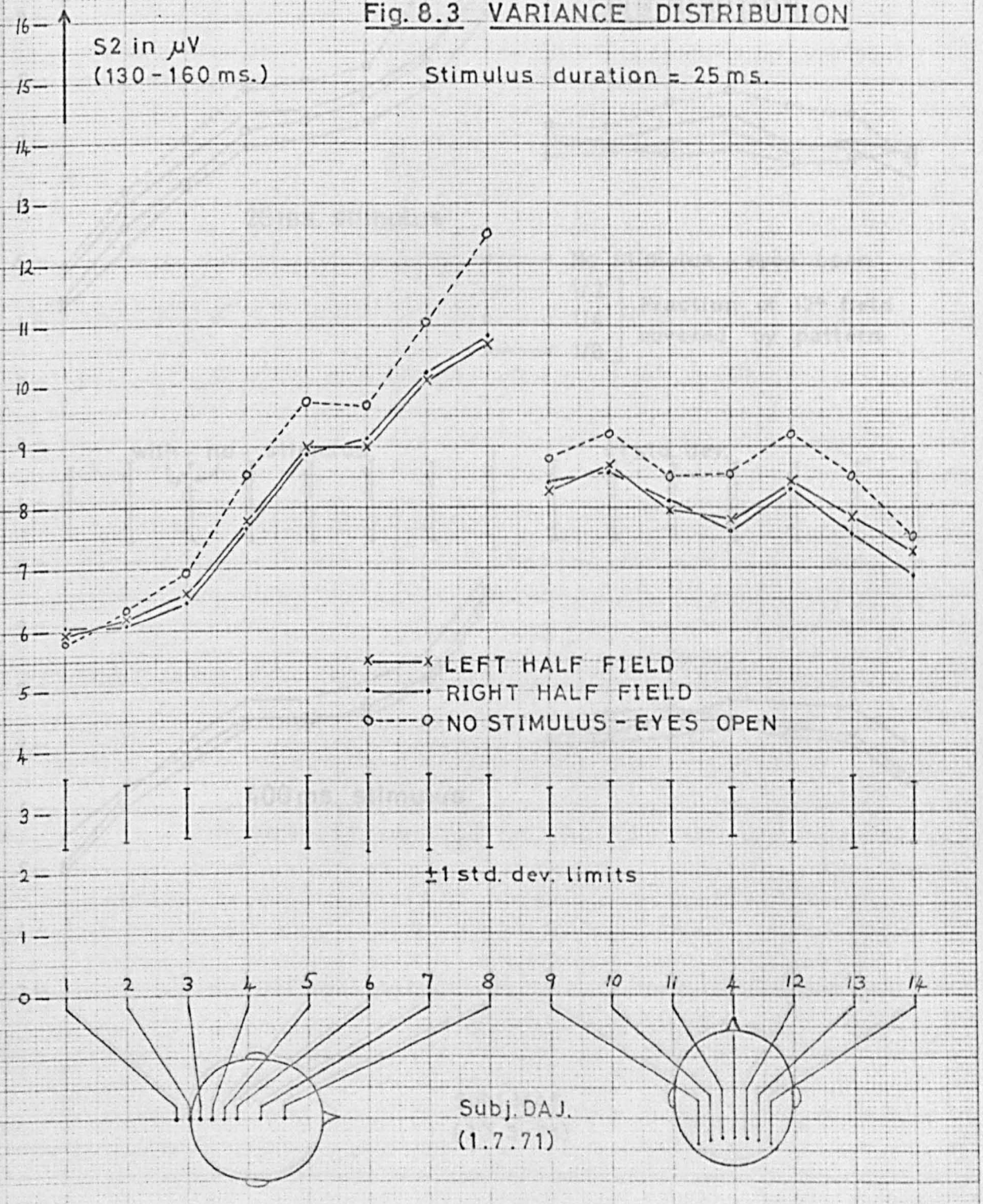


Fig. 8.2 VARIANCE DISTRIBUTION
S2 in μV
(130 - 160 ms.)
Mean of 22 runs.
Various patterns.
Stimulus duration = 25 ms.
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
± 1 std. dev. limits
1 2 3 4 5 6 7 8 9 10 11 4 12 13 14
Subj. JSC
(23.2.71)

Fig. 8.3 VARIANCE DISTRIBUTION



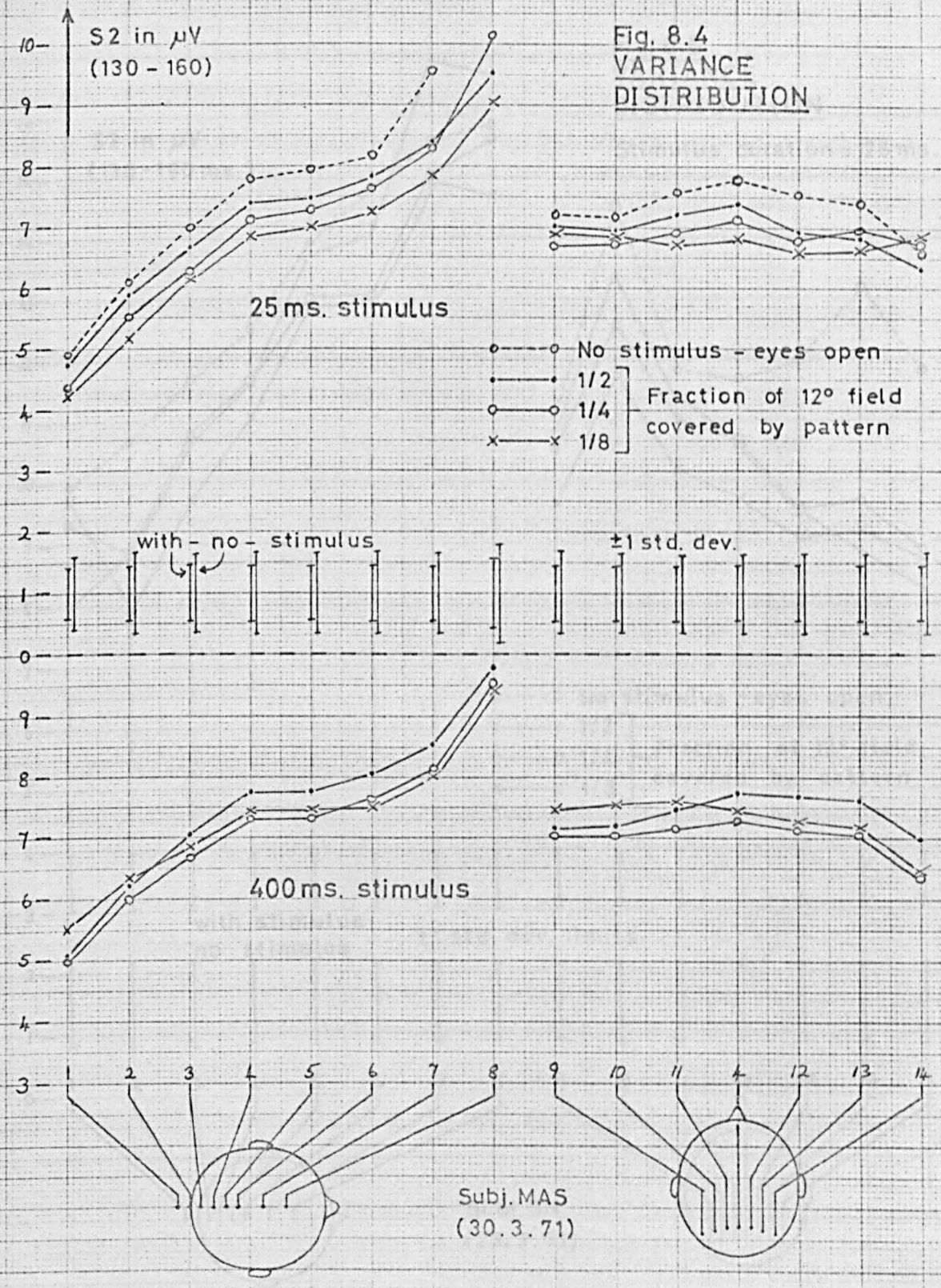


Fig. 8.4
VARIANCE
DISTRIBUTION

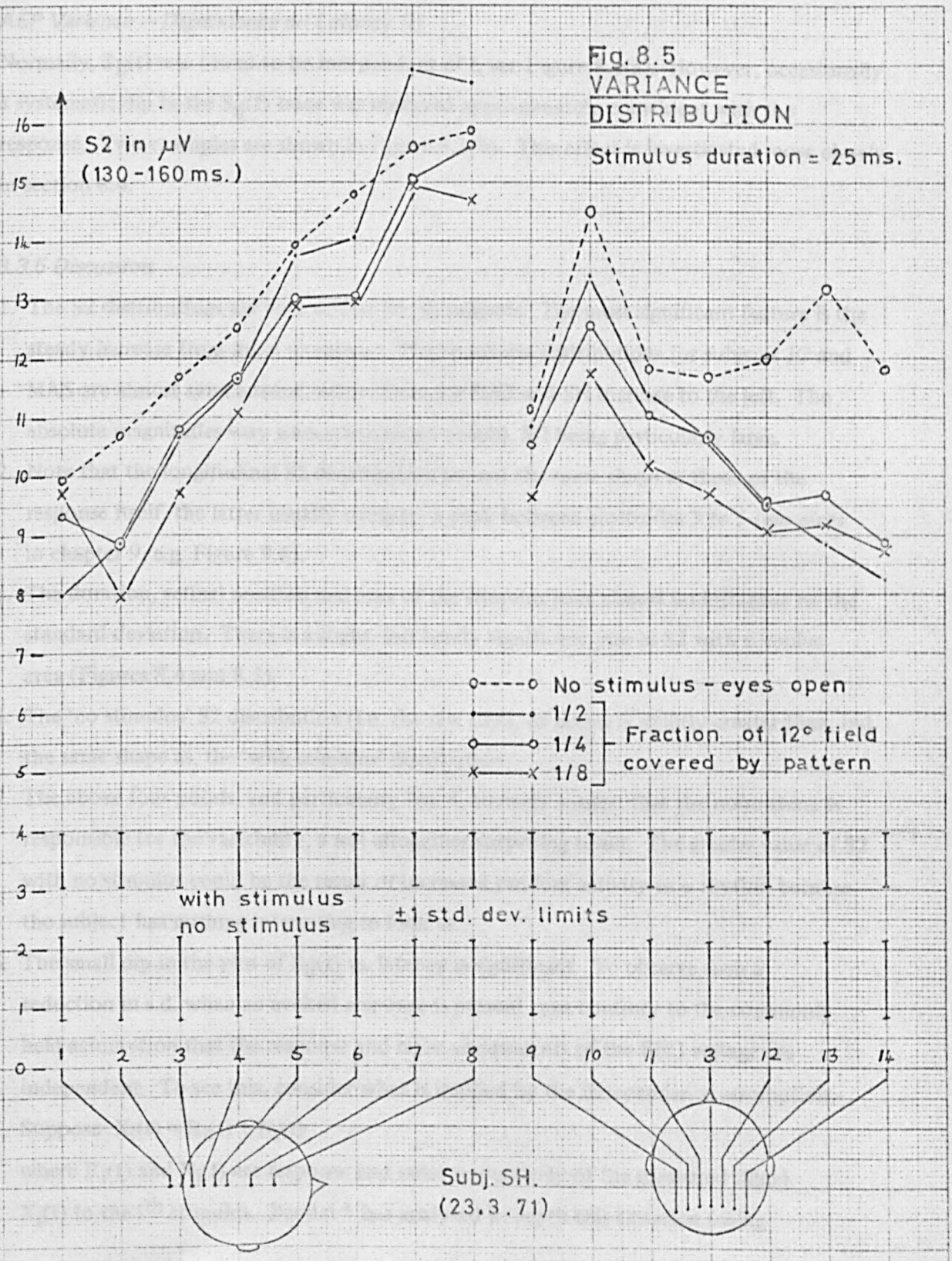


Fig. 8.5
VARIANCE
DISTRIBUTION
Stimulus duration = 25 ms.
S2 in μV
(130-160 ms.)
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
No stimulus - eyes open
1/2
1/4
1/8
Fraction of 12° field covered by pattern
with stimulus
no stimulus
±1 std. dev. limits
1 2 3 4 5 6 7 8 9 10 11 3 12 13 14
Subj. SH.
(23.3.71)

AEP Variance – Dependence on Latency (t)

Normally, $S_{ij}(t)$ was found to be independent of t, see Figure 8.1(a). However, occasionally a systematic dip in the $S_{ij}(t)$ trace was observed approximately coincident with the response. Two examples are shown in Figure 8.1(b). This effect is investigated more closely in section 8.4.

8.3.5 Discussion

1. The S2 distributions are very similar for all subjects. The most significant feature is the steady increase from inion to vertex. The transverse distributions for subjects JC and MAS are almost symmetrical, whilst those for DAJ and SH increase to the left. The absolute magnitudes vary somewhat, those of subj. SH being particularly large.
2. Note that the longitudinal S2 distributions are not the same shape as those of the response itself, the latter usually rising to a peak between electrodes 3 to 5 (see plots in chapter 9, e.g. Figure 9.6).
3. The duration, retinal position and area of the stimulus have almost no influence on the standard deviation. There is a slight, but barely significant, rise in S2 with stimulus area (Figures 8.4 and 8.5).
4. The 'no stimulus' S2 distribution (i.e. the raw EEG, or noise) is slightly greater than, but the same shape as, the 'with stimulus' distribution.
5. The above four points, and particularly No. 4, strongly suggest that the noise alone is responsible for the variability, a not altogether surprising result. The greater value of S2 with no stimulus could be the result of increased random activity or α rhythm because the subject has nothing interesting to look at.
6. The small dip in the plot of $S_{ij}(t)$ vs. latency is significant. To observe such a reduction in s.d. when an evoked response is present runs contrary to the commonly held assumption that the response and noise components of the EEG voltage are independent. To see this, consider what is implied by the independence assumption:-
   Suppose $X_i(t) = R_i(t) + N_i(t)$
   where $R_i(t)$ and $N_i(t)$ are response and noise respectively of the measured signal $X_i(t)$ to the i^{th} stimulus. Bendat [8] has analysed in depth this situation (using

standard statistical theory). He has calculated the expected s.d. of $X_i(t)$, assuming $R_i(t)$ and $N_i(t)$ to be *independent*. We quote his results for two cases.

a. If successive responses are independent, or non-correlated:-

$$S_A^2(t) = \frac{S_R^2(t) + S_N^2(t)}{n}$$

b. If successive responses are fully correlated (essentially this means a constant response to all stimuli):-

$$S_A^2(t) = S_R^2(t) + \frac{S_N^2(t)}{n}$$

Where – $S_A^2(t)$ = Variance $[X_i(t)]$ for n samples.

– $S_R(t)$ and $S_N(t)$ are similarly defined.

The true situation will be somewhere between these two cases, i.e. successive signals are partially correlated. However it is noted that since $S_N^2(t)$ is the same whether or not a response is present, the addition of a response can only *increase* $S_A^2(t)$. If a decrease is observed there must be interaction between response and noise, i.e. the independence assumption must be wrong. We can pursue this further and suggest the hypothesis that the so-called 'response' does not exist independent of the noise, and is in fact nothing more than a temporary correlation of the noise with the stimulus. In other words it could be that part of the noise periodically 'locks in' with the stimulus, and the result shows up as a non-zero average, which we call the response. If this were so we should expect the s.d. reduction to be observed more generally, and this possibility prompted the experiments of the next section.

8.4 Response – Noise Interaction

Following the observation reported in 8.3.4 that a plot of s.d. vs. latency at times showed a small but systematic reduction during, or a little after, the response, a special experiment (DAJ 13/3/71) was conducted to investigate this effect more closely. Subj. DAJ appeared to display the effect consistently; other subjects did not, but this could have been because

it was not obvious from the pen recorder plots, and so the following experiments used the more accurate sampling method.

In particular the question was asked whether the s.d. reduction was a general phenomenon to be observed for all AEP's of this type and , if not, what special conditions were necessary for its generation. If the former alternative were the case this would be evidence in support of the 'noise synchronisation' origin of EP's mentioned in 8.3.5 (6).

8.4.1 Method

The stimulus conditions were similar to the other experiments except that the mean inter-stimulus period (ISP) was made longer in order to observe more carefully the latency effects on the s.d. Five sampling periods S0 – S4 at times shown on Figure 8.6(c) were used. Three averaging conditions were employed:-

1. No stimulus
2. Stimulus with synchronised averaging
3. Stimulus with un-synchronised averaging

Condition (3) was achieved by recording the raw EEG on a tape recorder, and then replaying it later as input to the averaging program, but using a slightly increased repetition frequency for the latter. The aperiodic averaging periods rendered the chance of any spurious synchronisation negligible. For instrumental reasons it was not possible to record all electrodes under this condition.

Condition (3) was included to provide a reference s.d. derived from the same runs as condition (2). This was because it had already been shown that 'no stimulus' – condition (1) – runs tended to give larger s.d.s than the 'with stimulus' runs.

8.4.2 Results

The results are shown on Figures 8.6(a) and (b) for a stimulus duration of 20 ms, and 8.6(c) for 250 ms (two electrodes only shown). Plots are shown for each electrode (number encircled). Conditions (1) and (3) show a more or less constant s.d. with latency, as we should expect. Condition (2) however shows quite large variations, particularly for the midline electrodes 4, 5 and 6, and for the transverse electrodes. The

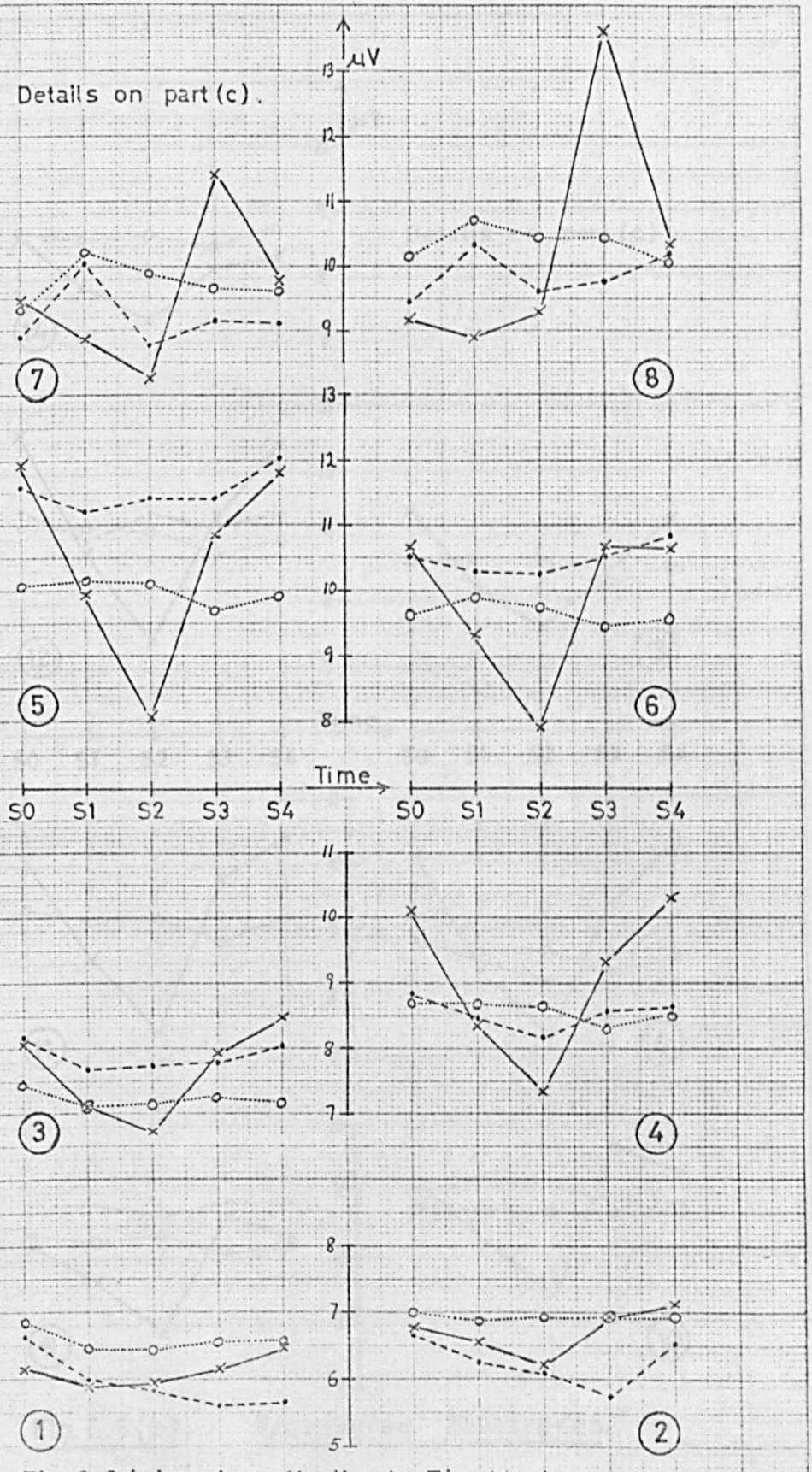


Fig. 8.6 (c) Longitudinal Electrodes

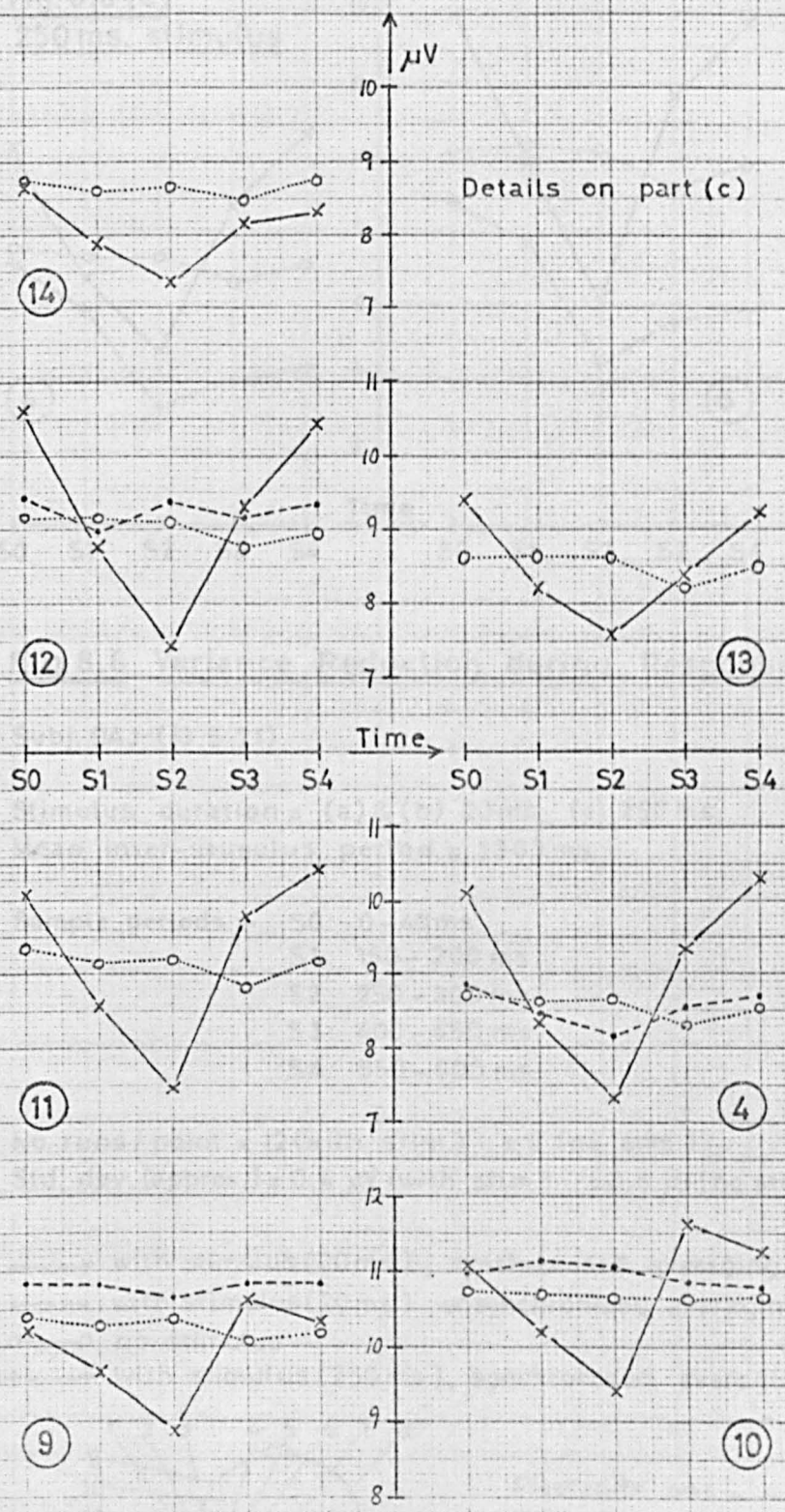


Fig. 8.6(b) Transverse Electrodes

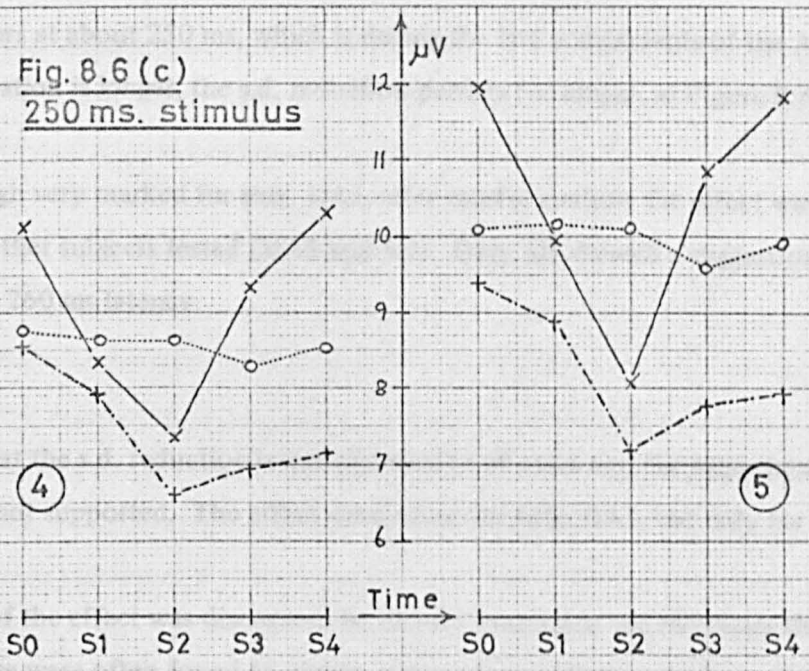


Fig. 8.6 Variance Reduction during Response

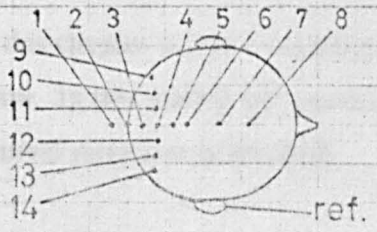
Subj. DAJ (13.5.71)

Stimulus duration = (a) & (b) 20 ms., (c) 250 ms.
Mean inter-stimulus period = 1300 ms.

Sample periods :- S0: 0 - 40 ms.
S1: 150 - 200 ms.
S2: 250 - 300 ms.
S3: 400 - 450 ms.
S4: 550 - 600 ms.

No. runs / point = 12 (with stim.), = 8 (no stim.)
Std. dev. (approx.) = 0.4 μV (with stim.), = 0.6 μV (no stim.)

(2) ×——× with stimulus (20 ms.), synchronised averaging.
(3) •-----• with stimulus (20 ms.), unsynchronised averaging
(1) o——o no stimulus
(2) +----+ with stimulus (250 ms.), synchronised averaging



Electrode nos. ringed on plots

minimum s.d. occurs at about 250 ms, which is during the late components of the AEP. If the stimulus duration is longer, the s.d. reduction persists for longer, as Figure 8.6(c) shows.

However, although very marked for subj. DAJ, after careful analysis the effect was *not* observed for two other subjects tested (MAS and SH). Only SH showed a suggestion of a reduction at about 260 ms latency.

8.4.3 Discussion

The net result is that the s.d. reduction is not observed in all cases and the hypothesis proposed above is not supported. The effect does occur for subj. DAJ, but only for some electrodes.

An explanation of the effect was discovered by closely examining the responses themselves. For subj. DAJ, these were often found to display a decaying oscillatory discharge following the response and approximately at the α frequency. It was in these cases that the s.d. was also usually found to show the reduction during the period of the discharge. This discharge phenomenon has attracted the attention of a number of workers, Walter [163], Cohn [31], Cazzullo [24]; and Peacock [116] has investigated it in some detail for flash stimuli. He concludes that the effect is basically a triggering of the α rhythm mechanism by the stimulus. The α rhythm continues but only the first few cycles are seen in the averaged response because of variability of the α frequency. This mechanism would explain exactly the observed reduction in s.d. The temporary synchronisation with the stimulus of part of the noise EEG (i.e. the α rhythm) results in a reduction of the s.d.

Previous workers have also observed that the after discharge only occurs in subjects showing well developed α activity. DAJ was such a subject, whereas the other subjects tested were not. In addition the electrodes displaying the greatest s.d. reductions were over those regions of the scalp where the α rhythm is highest.

8.5 Running Average Experiments

8.5.1 Introduction

In the previous sections of this chapter we have considerd short term variability, over the duration of one averaging run. In this section we report on some measurements concerned with longer term (over minutes) variations in the AEP.

It is well-known that many physiological responses tend to habituate, or decrease, if the stimulus is repeated for some time. Pattern AEPs may be no exception, but if a series of responses is averaged over a period of time all information about habituation would be lost.

An investigation into the long term variations of the AEP would thus reveal the presence of steady correlated changes in the response, in addition to the random noise fluctuations.

Brazier [14] and others have suggested that the VEP may display long term variations. Some have attempted to measure these, Barlow [6], Burns [18], Bogacz et al. [13] using flash stimuli, while others have tried to relate these variations to psychological variables, such as arousal, attention and vigilance (Isgur and Trehub [79], Haider et al. [62], Ritter and Vaughan [134]). No very consistent picture of longer term AEP variability can however be derived from these results. Armington [3] has observed short and long term variations in the VEP, and does report increased responses to the first few (5–6) stimuli at the start of a long sequence. None of the above workers has used patterned stimuli.

A variety of techniques have been used to assess the on-going variability of the AEP. The simple analogue computer of Barlow [6] and the cumulating sum method of Burns [18] have already been mentioned. The technique employed by Horvath [73] was adapted here, whereby the value of the AEP (at a particular latency), averaged over a prescribed number of responses preceding the current stimulus, was plotted on a chart recorder versus time, as explained in the next section.

8.5.2 Experimental Method

The full on-line capability of the experimenter program was used so that the 'running average' could be plotted out as the experiment proceeded. The overall experimental set-up is shown in Figure 8.7.

After each stimulus presentation a two-stage calculation was performed.

a. Computation of a weighted AEP to N previous stimuli. This was displayed on a CRT.
b. Computation of the mean ampitude of the above AEP during a specified brief sampling period. The result was plotted out versus time on an X–Y plotter.

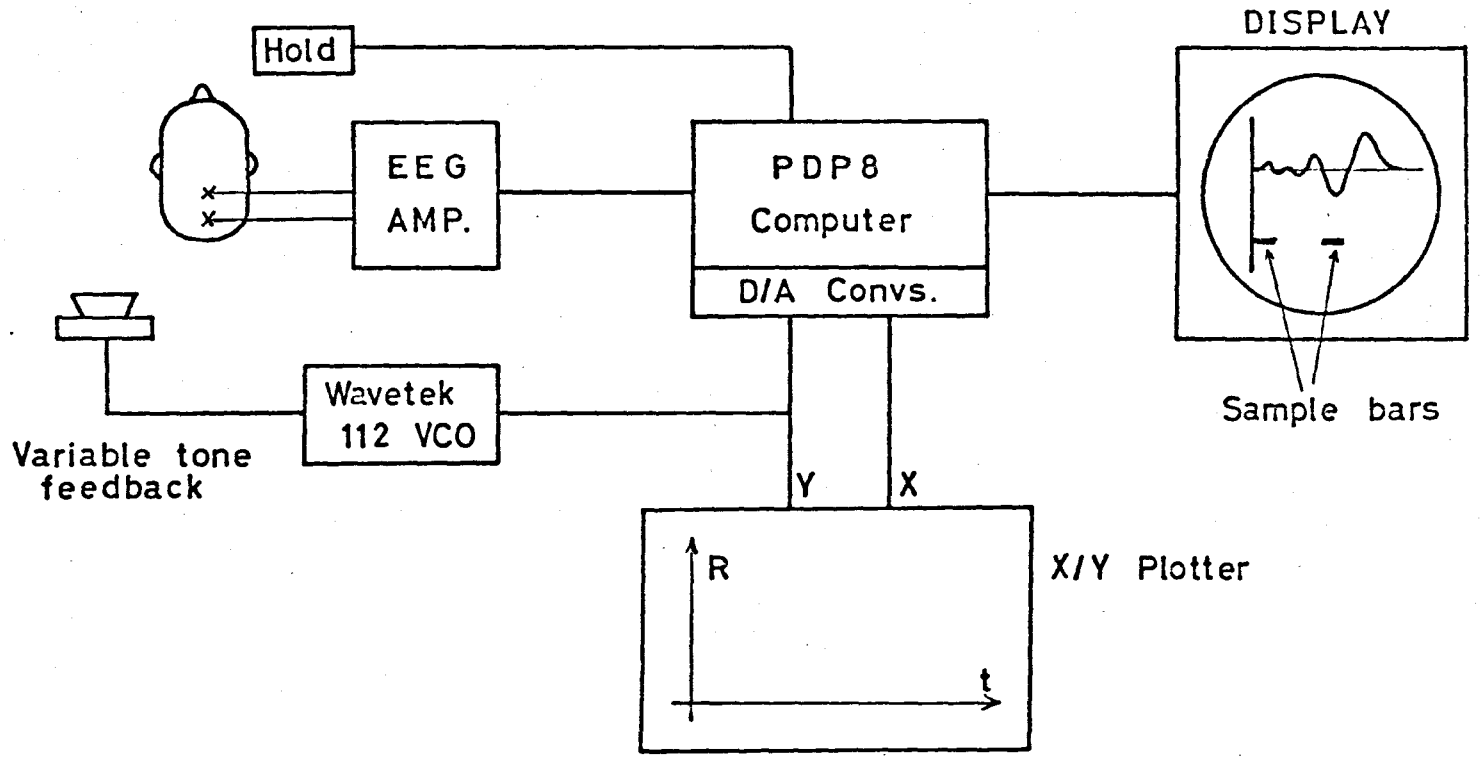


Fig. 8.7 RUNNING AVERAGE - EXPERIMENTAL CONFIGURATION

Suppose the current stimulus is the p^{th} and an individual response is $V_i(t)$, then stage (a) of the program computes.

$$V_a(t) = \sum_{i=1}^{p} f(p-i) . V_i(t)$$

Where f(p−i) is an arbitrary weighting (or decay) function which determines the contribution of any particular response to the overall average. f can be an exponential or linear decay function, but for all the results given in this section a rectangular function was used, specified by:-

$$f(n) = \frac{1}{N} \qquad \text{when} \quad n < N$$

$$f(n) = 0 \qquad \text{when} \quad n \geqslant N$$

Effectively this gives the normal AEP over the N stimuli preceding the current one. $V_a(t)$ was displayed on the CRT, and Figure 8.8(a) shows a typical display.

Stage (b) computes the mean ampitude of $V_a(t)$ over two short sampling periods Δt_0 and Δt_1, the difference between these is plotted out on the chart recorder as the 'running average' R, where:-

$$R = \frac{1}{\Delta t_1} \int_{t_1}^{t_1+\Delta t_1} V_a(t).dt \quad - \frac{1}{\Delta t_0} \int_{0}^{\Delta t_0} V_a(t).dt$$

This is illustrated in Figure 8.8(b). The Δt_0 sample sets a zero level and is measured at the start of the trace before the response itself arrives. Δt_0 was typically 20 ms. Δt_0 and Δt_1 can be set by the experimenter and in particular t_1 can be adjusted during the experiment by means of an analogue potentiometer. The sampling period (Δt_1) can thus be moved along the response such that is lies underneath a desired peak.

The trace on the XY plotter then gives the current value of the selected AEP peak

Procedure

Before each run 10μV pulses were used to calibrate the chart recorder. These are seen on some of the results.

The subject was given a stimulus condition and, by means of the HOLD facility, himself controlled the periods during which the running average was recorded, at times obeying instructions from the experimenter. Thus the subject could adjust himself comfortably before starting the run, and also terminate the recording if the strain proved too much. The recording periods were intentionally long.

For some experiments the subject was given an audible indication of the magnitude of the running average. This was a variable frequency tone generated simply by feeding the 'Y' plotter input also to a Wavetek voltage controlled oscillator (Type 112), see Figure 8.7.

Three subjects (DAJ, JGA, SH) were used in a total of 6 experiments. The normal AEP was also recorded in most cases, and measurements on this and its variance were cross-checked with the running average. Precise stimulus conditions are detailed in the results. In general they were chosen (from previous experiments) to give a large well-defined response. In all cases the stimulus sequence was blank – pattern – blank.

8.5.3 Experimental Results

Typical running average traces are shown in Figures 8.9 and 8.10. In all cases N = 16. The traces were very similar for all subjects tested, and for this reason only sections from two experiments are shown. The traces appear in short sections, with intervening returns to zero, during which the subject rested. t_1 values are given below each section, and it can be seen how t_1 influences the mean level of the trace. The horizontal time scale is given below each plot.

The following features were observed:-

1. The dashed line through each section marks the normally measured AEP at the appropriate t_1 value. The dash-dotted lines give the ± 1 s.d. limits, (adjusted for 16 samples). These should, on average, enclose about 66% of the trace. Agreement is good, as we should expect.

Fig. 8.8(a) Running Average - Typical Display

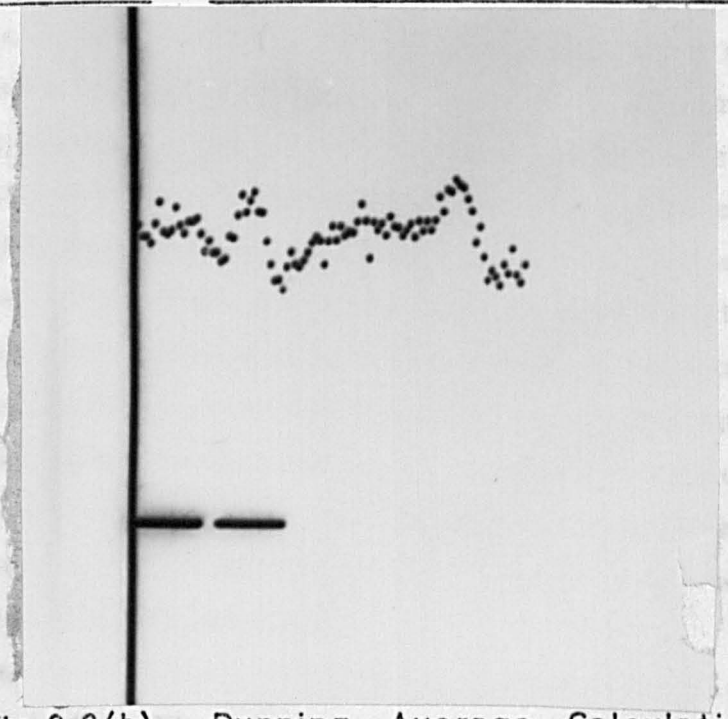
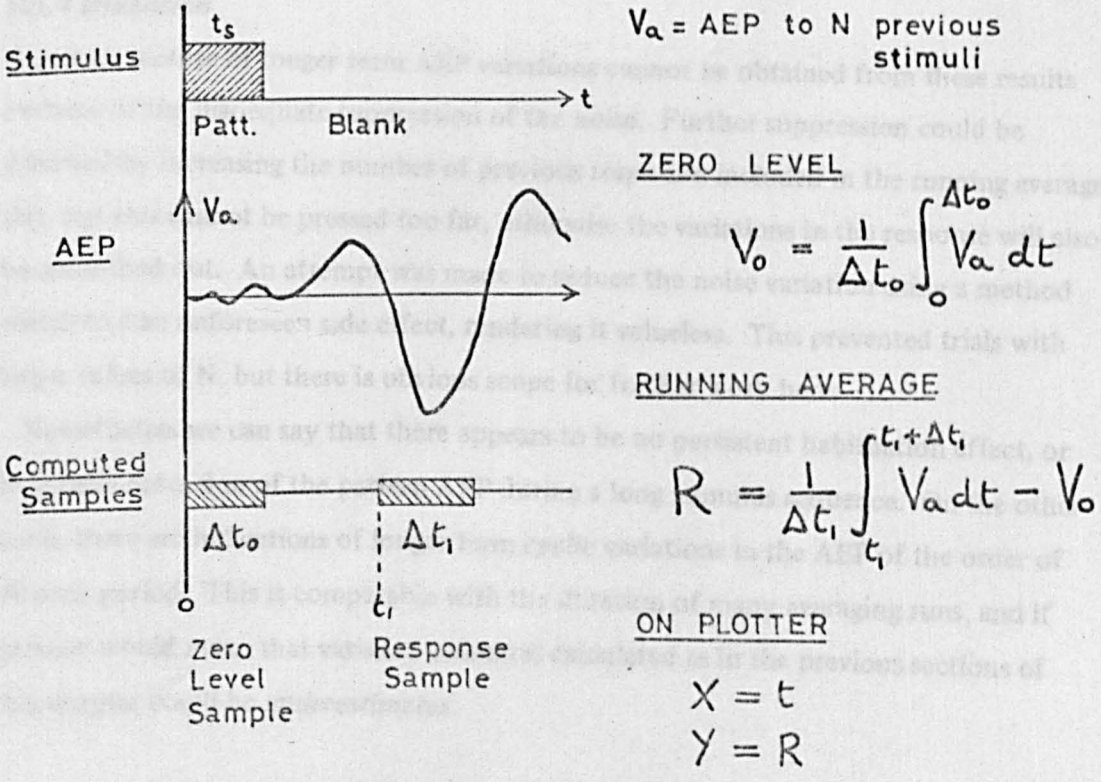


Fig. 8.8(b) Running Average Calculation



2. Several 'no-stimulus' sections are shown, and in most, but not all cases, these show increased short term fluctuations.
3. The general characteristic of all records is that of a relatively small H.F. variation superimposed on a larger, longer term, variation, the latter having a period of very approximately 30 secs. It is obvious that the random noise is far from completely smoothed out. The 'no stimulus' traces show this. The longer term variations are slightly more pronounced when the stimulus is present, indicating that these are genuine fluctuations in the response and are not due entirely to the noise.
4. Usually, but not always, in the first part of a section, just after a rest period, the running average is greater than the long term average. See Figure 8.9. This is in agreement with the above mentioned observation by Armington [3].
5. There is very little evidence of a steady decline in the response after the initial high peak, although one or two sections do show it. Low periods do occur but the response nearly always recovers at a later time.
6. There was no observable reduction in the variability when the subject was receiving audio feedback, Figures 8.10 parts (2) and (3).

8.5.4 Discussion

A precise picture of longer term AEP variations cannot be obtained from these results because of the inadequate suppression of the noise. Further suppression could be achieved by increasing the number of previous responses included in the running average (N), but this cannot be pressed too far, otherwise the variations in the response will also be smoothed out. An attempt was made to reduce the noise variation using a method which had an unforeseen side effect, rendering it valueless. This prevented trials with larger values of N, but there is obvious scope for further work here.

Nevertheless we can say that there appears to be no persistent habituation effect, or long term reduction of the pattern AEP during a long stimulus sequence. On the other hand, there are indications of longer term *cyclic* variations in the AEP of the order of 30 secs. period. This is comparable with the duration of many averaging runs, and if genuine would mean that variance estimates calculated as in the previous sections of this chapter could be *underestimates.*

This is easily seen to be the case by observing that the averaging period (if less than 30 secs.) could well be during a period of consistently high or consistently low AEP.

Some evidence of cyclic variations has also been reported by Bogacz et al. [13] using flash stimuli, but the period seemed somewhat longer, about 2 mins.

Audio feedback offers no help. This is probably because the fluctuations are due to factors beyond the subject's control. Some insight was obtained from subjective reports during a long run. The sustained fixation does, after a while, force a loss of accommodation and an increase in blink rate. The AEP falls, but accommodation is soon recovered and the response rises again. The feedback provided confirmation that periods of low-signal were in fact also those of fixation difficulty.

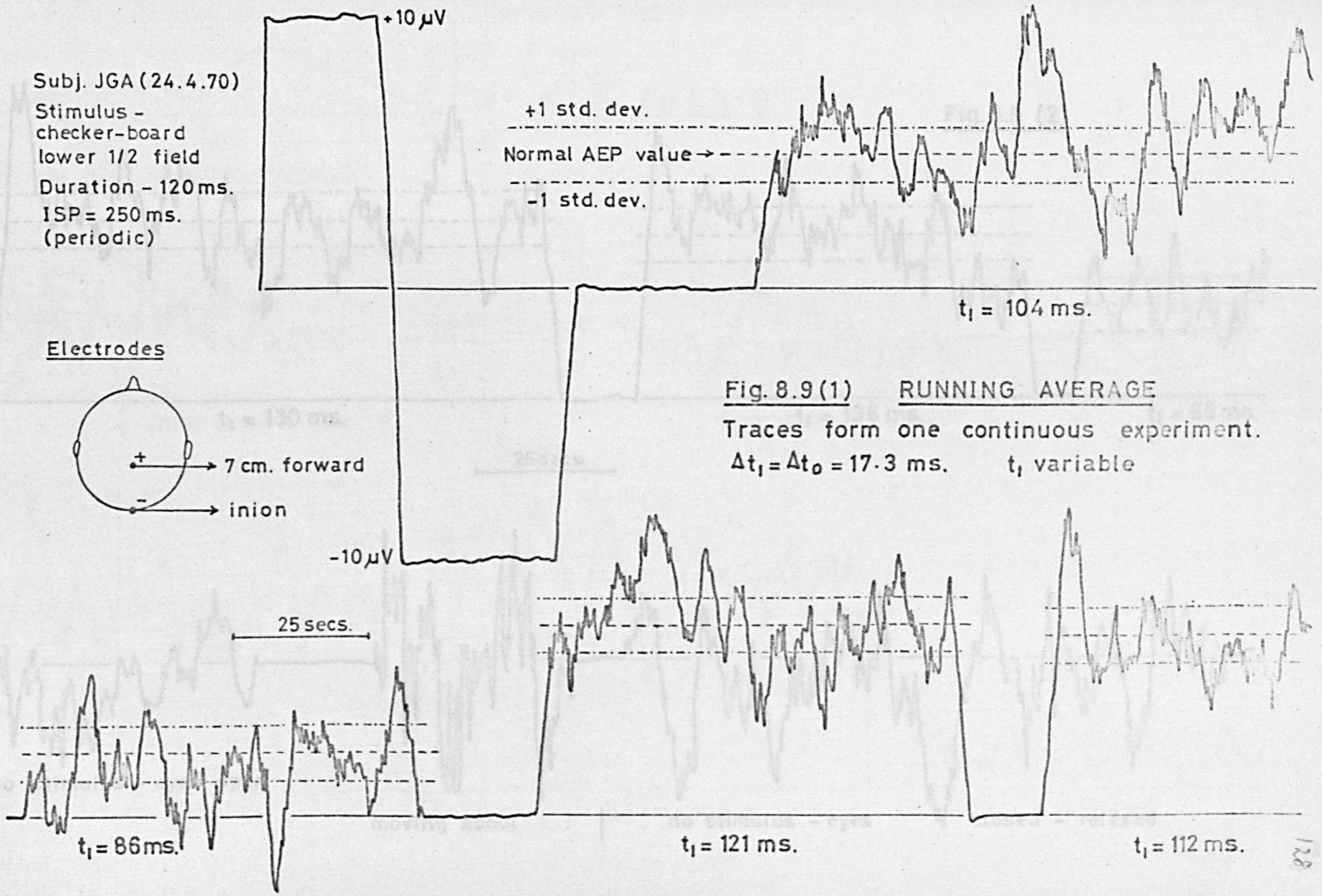
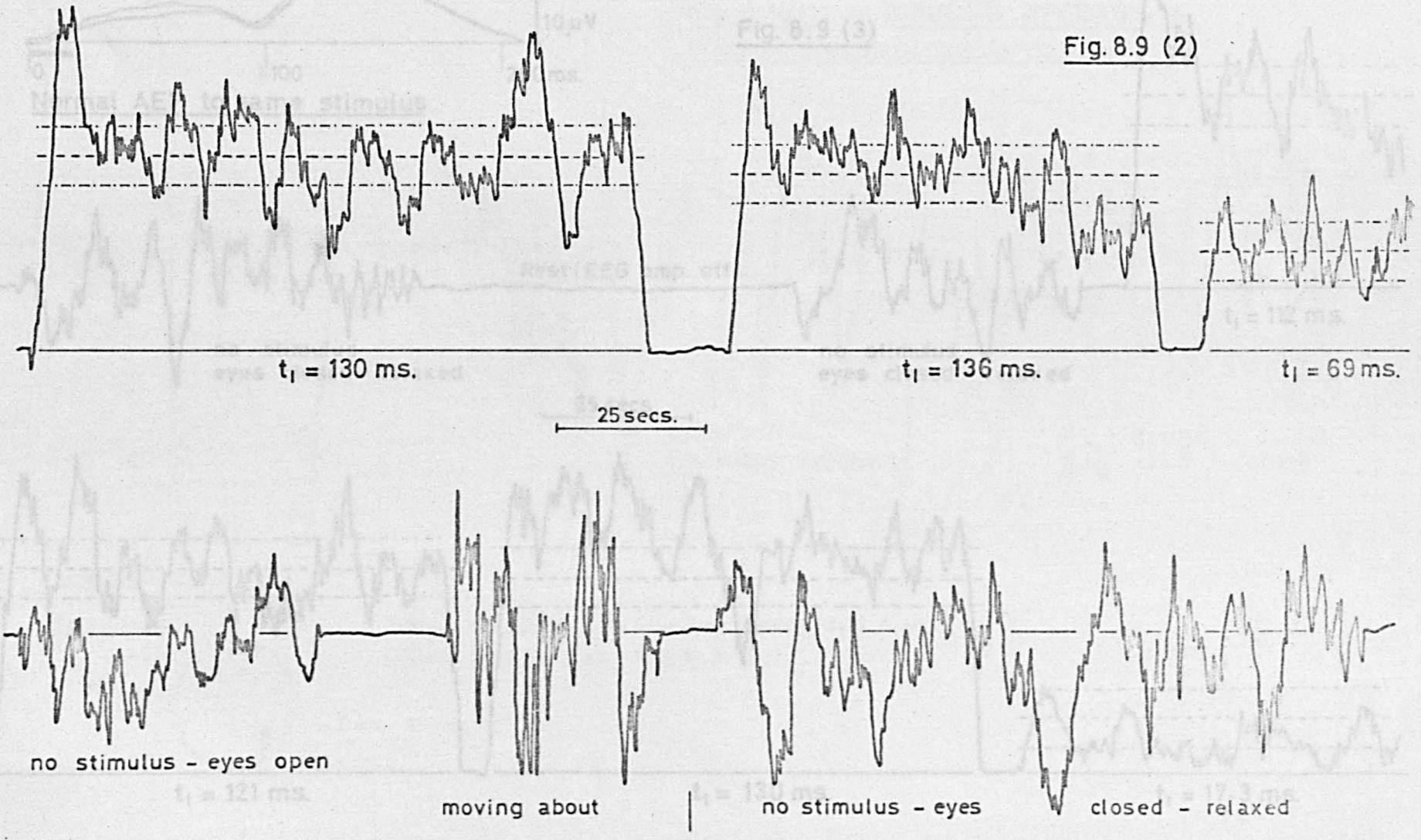


Fig. 8.9 (1) RUNNING AVERAGE

Traces form one continuous experiment.

$\Delta t_l = \Delta t_o = 17.3$ ms. t_l variable

Fig. 8.9 (2)


t_l = 130 ms.
t_l = 136 ms.
t_l = 69 ms.
25 secs.
no stimulus - eyes open
moving about
no stimulus - eyes closed - relaxed

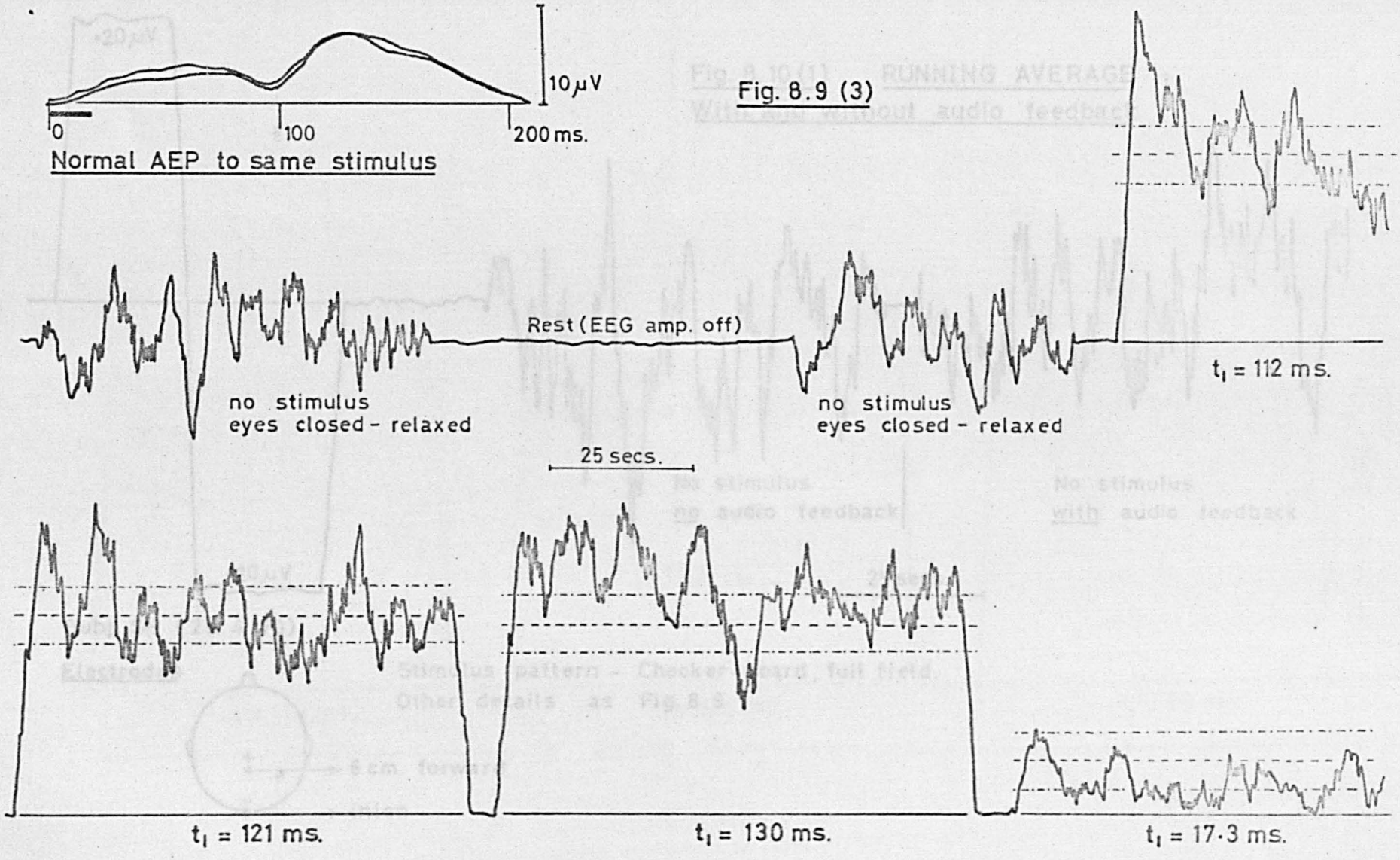
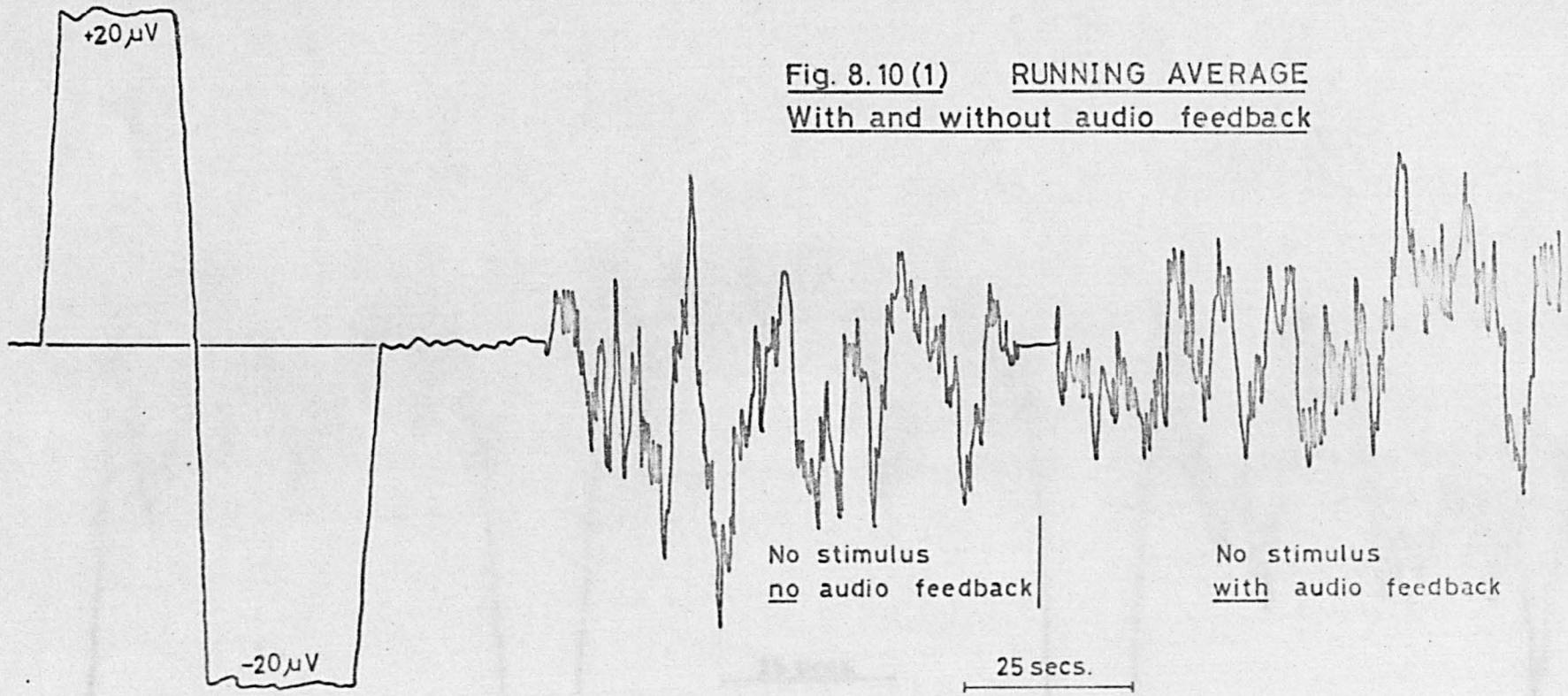
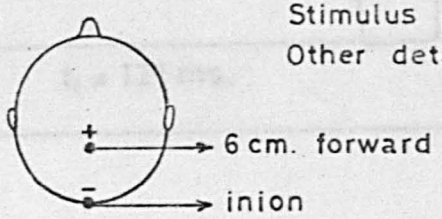

10μV
0
100
200 ms.
Normal AEP to same stimulus
Fig. 8.9 (3)
Rest (EEG amp. off)
no stimulus
eyes closed - relaxed
no stimulus
eyes closed - relaxed
t1 = 112 ms.
25 secs.
t1 = 121 ms.
t1 = 130 ms.
t1 = 17·3 ms.

Fig. 8.10 (1) RUNNING AVERAGE
With and without audio feedback



Subj. SH (28.4.70)

Electrodes



Stimulus pattern - Checker-board, full field.
Other details as Fig. 8.9

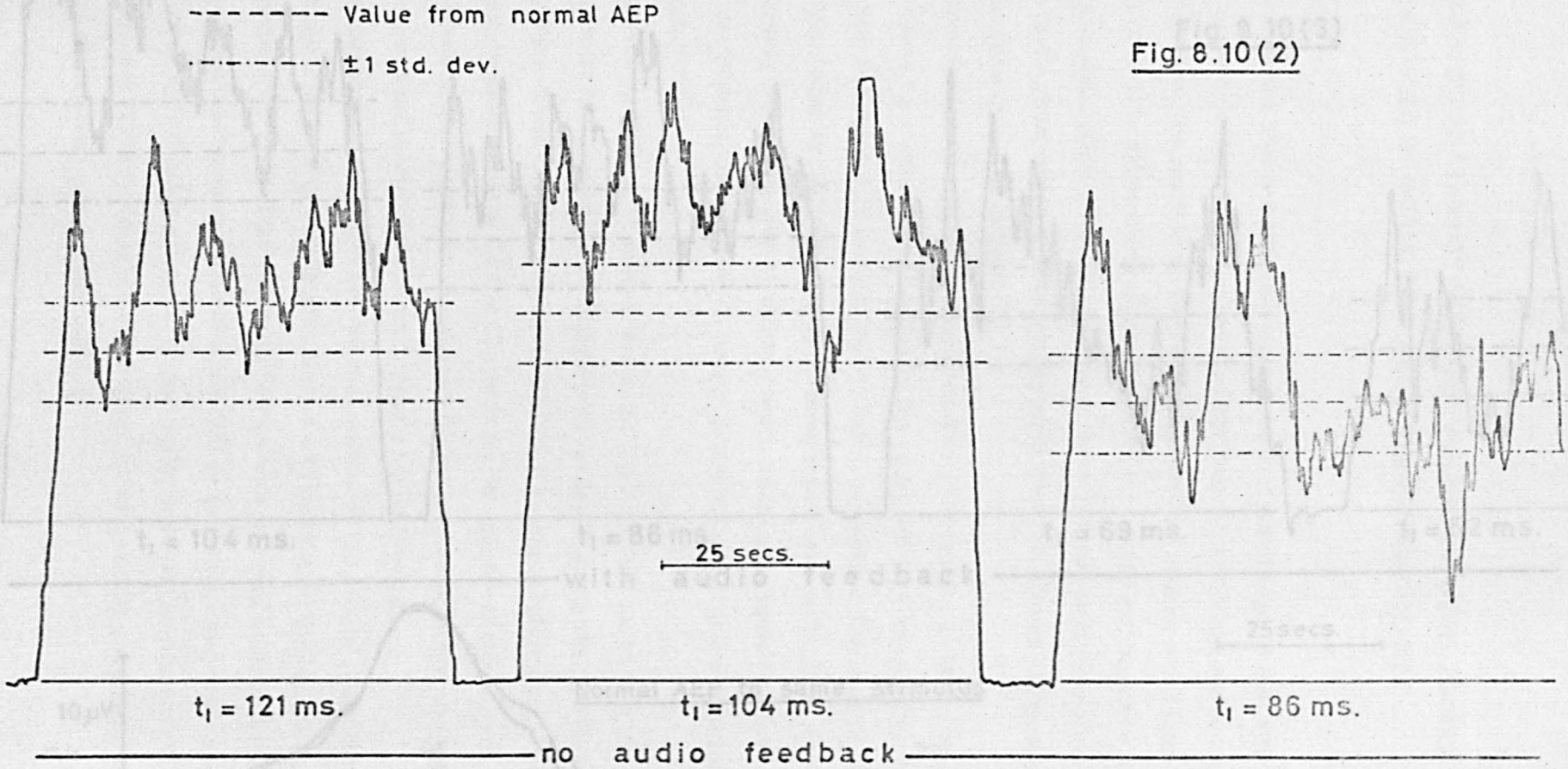

Value from normal AEP
±1 std. dev.
25 secs.
t_l = 121 ms.
t_l = 104 ms.
t_l = 86 ms.
no audio feedback

Fig. 8.10(2)

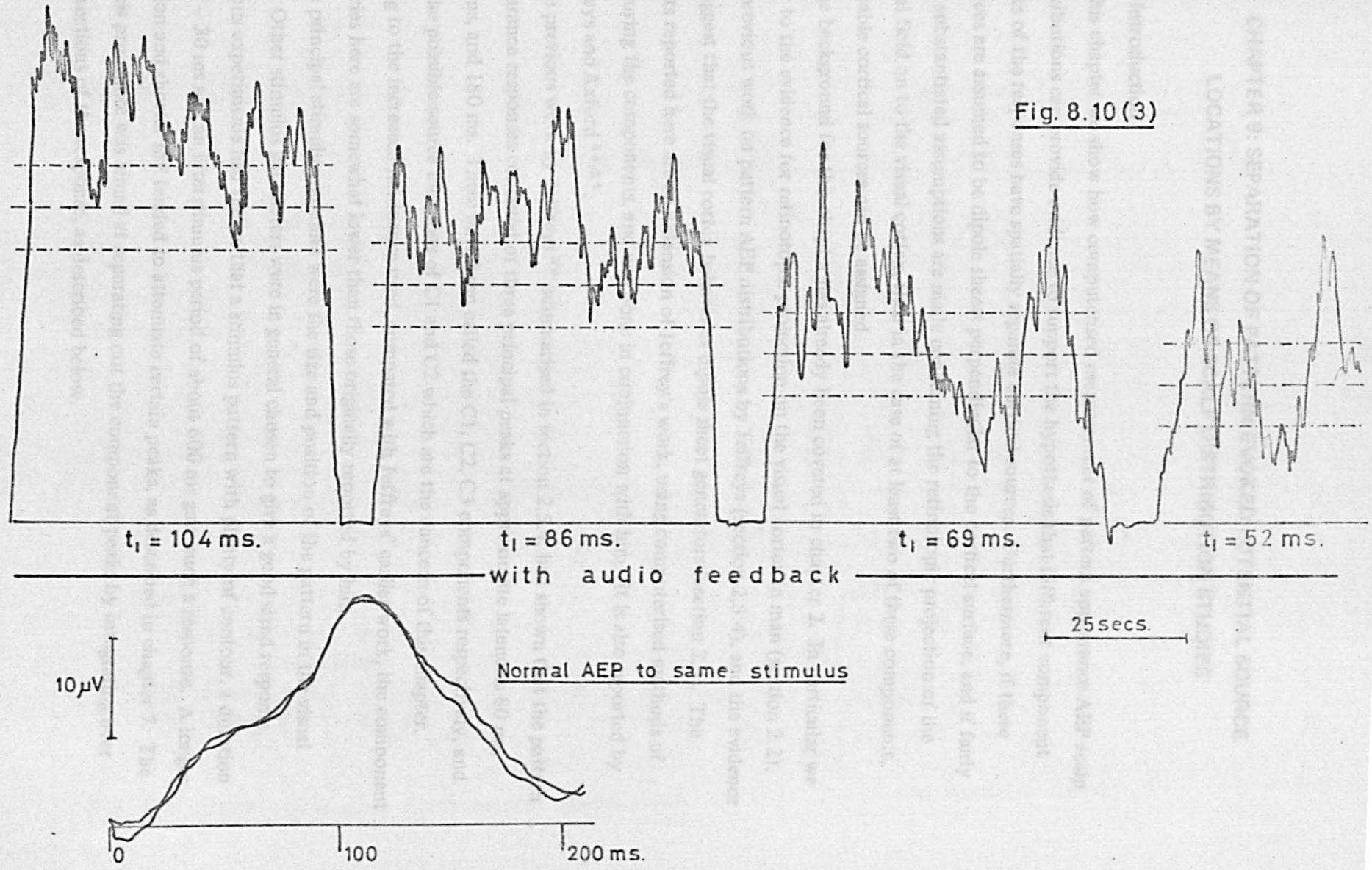


Fig. 8.10 (3)
t_1 = 104 ms.
t_1 = 86 ms.
t_1 = 69 ms.
t_1 = 52 ms.
with audio feedback
25 secs.
Normal AEP to same stimulus
10 μV
0
100
200 ms.

CHAPTER 9: SEPARATION OF PATTERN EVOKED POTENTIAL SOURCE LOCATIONS BY MEANS OF SCALP DISTRIBUTION STUDIES

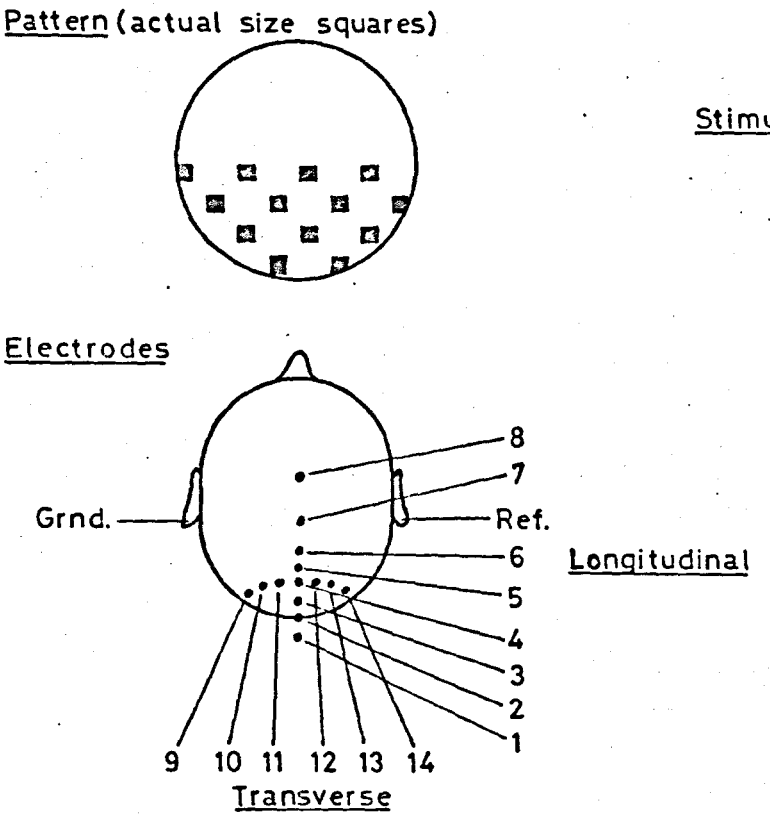
9.1 Introduction

In this chapter we show how computerised measurement of pattern appearance AEP scalp distributions can provide evidence to support the hypothesis that different component peaks of the responses have spatially separate cortical sources. Furthermore, if these sources are assumed to be dipole sheets perpendicular to the cortical surface, and if fairly well substantiated assumptions are made concerning the retinotopic projection of the visual field on to the visual cortex, then in the case of at least two of these components, probable cortical sources can be assigned.

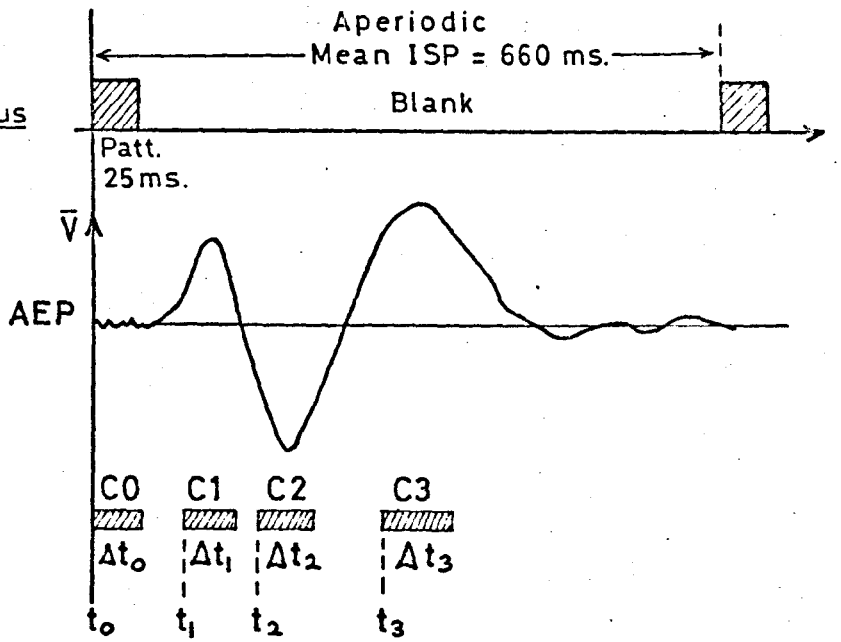
The background for this chapter has already been covered in chapter 2. In particular we refer to the evidence for retinotopic projection on the visual cortex in man (section 2.2), the previous work on pattern AEP distributions by Jeffreys (section 2.5.4), and the evidence to suggest that the visual cortex behaves as dipole sheet generators (section 2.3). The results reported here are an extension of Jeffrey's work, using computerised methods of measuring the components, and was done in conjunction with him. It is also reported by Jeffreys and Axford [86,87].

The previous work by Jeffreys [84] summarised in section 2.5.4, had shown that the pattern appearance responses consisted of three principal peaks at approximate latencies 80 ms, 110 ms, and 180 ms. These have been called the C1, C2, C3 components respectively, and it is the possible source locations of C1 and C2 which are the concern of this chapter. Owing to the increased luminance used, compared with Jeffreys' earlier work, the component latencies here are somewhat lower than those originally reported by him.

The principal stimulus variables were the size and position of the pattern in the visual field. Other stimulus parameters were in general chosen to give a good sized response. Previous experiments had shown that a stimulus pattern with plenty of contour, a duration of 20 – 30 ms and an interstimulus period of about 600 ms gave such a response. A longer duration and shorter ISP tended to attenuate certain peaks, as described in chapter 7. The analysis procedure was aimed at separating out the component peaks by integrating over short sections of the response, as described below.



No. 2 on inion.
All separations 2.5 cm.
except 6 - 7 - 8 which were 5cm.



$$C_0 = \frac{1}{\Delta t_0}\int_0^{\Delta t_0} V(t)\,.\,dt$$

$$C_1 = \frac{1}{\Delta t_1}\int_{t_1}^{t_1+\Delta t_1} V(t)\,.\,dt \;-\; C_0$$

and similarly for C_2, C_3.

Fig. 9.1 Electrodes and Component Definition

9.2 Methods

Stimulus Presentation

The two field tachistoscope shown in Figure 4.2(b), and described in section 4.1 was used. The diameter of the field was 12°.

The stimulus pattern was an array of black isolated squares, of side and separation 14′ of arc. Various sections of the pattern were made up to cover the desired fraction of the visual field. This is shown shaded on the plots. The square sides were always vertical and horizontal.

Stimulus duration = 25 ms

Stimulus luminance = 540 cd./m^2

Subjects

A total of four were used, with one (DAJ) tested more extensively.

Electrodes

Normally 8 longitudinal along the midline, and 7 transverse (sometimes 9) as shown in Figure 9.1. The level of the transverse row was chosen from pilot experiments to be roughly where the maximum response was in the longitudinal direction. The common electrode was 5 cm above the inion (no. 4) for subjects DAJ, JSC and MAS, but 2.5 cm for SH (no. 3). The right earlobe was used for reference and the left earlobe was grounded.

Program

The basic averaging program (section 5.2.2) was used, with an additional routine called SIR (Segment Integration Routine) which was entered after each averaging run. This computed the amplitudes of the various AEP components.

Other measurement parameters were:-

Interstimulus period – aperiodic 585 – 735 ms

Sampling interval – 4.7 ms

No. of samples per response – 64

Averaging duration – 300 ms

No. of presentations/run – 50

Run Time – 35 secs.

Normally two runs under identical conditions were recorded, and the plots superposed. For the component amplitudes the mean of the two runs was taken.

Response Analysis

The SIR routine operated as follows. A number of sampled periods, C0, C1, C2, C3, were assigned prior to the experiment, and the routine computed the mean value of the response during each period. The first sample (C0) always started at the beginning of the trace and provided a zero level, which was then subtracted from all the other values.

$$C1 = \frac{1}{\Delta t_1} \int_{t_1}^{t_1+\Delta t_1} \bar{V}(t) \, . \, dt \quad - \frac{1}{\Delta t_0} \int_{0}^{\Delta t_0} \bar{V}(t) \, . \, dt$$

and similarly for C2, C3.

$\bar{V}(t) = A_{ij}(t)$ is the AEP (see Figure 9.1).

The duration of the zero level sample (Δt_0) was usually 37 ms. Scaling was automatic, and scaling factors were set within the computer for each EEG channel by means of 10μV calibration pulses at the start of the experiment. A switch on the control panel could set the SIR routine into 'calibrate' mode. The calibration was checked at the end of the experiment.

Standard deviations were computed for the component values as described in section 8.2.2. These are shown only on Figure 9.2; but for a given subject and electrode may be taken as valid for Figures 9.3 to 9.11. They take into account the variability of the zero level sample.

The results of the next section are shown as plots of C1 etc. as a function of position on the scalp, i.e. spatial distributions.

The actual sampling periods used for the C1, C2, C3 components were selected by careful examination of previous recordings for the subject concerned. They were:-

C0 – 0–37 ms

C1 – 52–80 ms

C2 – 85–113 ms (DAJ, 94–122 ms)

C3 – 150–178 ms

9.3 Results

For each of the four subjects responses were measured for the four half field, the four quadrant field, and the eight octant field positions of the pattern. The results are plotted in Figures 9.2 – 9.8 grouped as follows:-

Component C1 – 4 subjects – ½ field distributions – Figure 9.2 a, b, c, d
¼ field distributions – Figure 9.3 a, b, c, d
1/8 field distributions (right) – Figure 9.4 a, b, c, d
1/8 field distributions (left) – Figure 9.5 a, b, c, d

Component C2 – 4 subjects – ½ field distributions – Figure 9.6 a, b, c, d
¼ field distributions – Figure 9.7 a, b, c, d

Component C3 – Subject MAS– ½ field distribution – Figure 9.10

The electrode numbers are shown below each plot.

Although distributions for all three components and four subjects were recorded, out of the large volume of data thus generated, only the above are presented here.

Also measured were the responses to ½ field annular regions of pattern, moving progressively further from the centre of the field. These results are shown in Figure 9.8 (C1) and Figure 9.9 (C2).

Figure 9.11 shows the result of a control experiment to determine the effect of moving the reference electrode. It will be discussed later.

The following observations are made on the above results, which will be discussed in more detail in section 9.4.

1. With some exceptions all subjects show roughly the same distribution for the same stimulus condition. In some cases we note that the *shape* of the distributions agree, but they differ in zero level. This was often traced back to a spurious shift in the zero level sample, which was common to all electrodes.
2. It is quite evident that stimulation of different areas of the visual field gives significantly different distributions. This holds for both C1 and C2, but is less true for C3.

3. It is also evident that C1 and C2 have different and apparently independent distributions. In general the transverse C1 distributions are bipolar, and the longitudinal ones mono-polar, whilst for C2 most distributions are mono-polar. A notable exception to this is the C2 upper field distribution for subject SH (see Figure 9.6d).
4. For the C1 transverse distributions, left hand field stimuli give distributions which are positive to the right, negative to the left, and vice versa for the right hand field stimuli. This is particularly evident for full ½ field stimulation, but much less so for octant field stimulation.
5. Dashed lines on the ½ and ¼ field plots show the sum of the distributions of the constituent ¼ and 1/8 field components respectively. In most cases agreement with the solid plot is remarkably good, for C1, C2 and C3. Sometimes the shapes agree well, but there is a zero shift, no doubt due to the effect mentioned under (1) above. This extends Jeffreys'[27] earlier finding that the two ½ field stimulation responses could be added to give a good approximation to the full field response. This summation property can sometimes lead to a cancelling effect whereby a larger stimulus area has a smaller and less well-defined distribution than its constituents. A good example of this is the left half field C2 distribution of subject MAS (Figure 9.6b) which is in fact composed of two much larger but opposing quadrant field responses (Figure 9.7b). In cases where one subject appears to be rather out of line with the others, the anomaly can often be traced back to a particular octant response. For instance, the vertical lower right octant for subject SH (Figure 9.4d) gives a C1 component which is negative on the left hand side of the head, compared with positive for the other subjects. This anomaly influences all the other responses involving that particular octant.
6. The C2 quadrant responses (Figure 9.7) show a very high degree of left–right similarity (i.e. corresponding left and right quadrants have very similar distributions), and in nearly every case upper field quadrants have monopolar positive distributions, while those of the lower half field have negative ones. (The upper half field for subj. SH is the only exception.) Note also that the maximum of the transverse distribution is nearly always on the contralateral side of the head.

Fig. 9.2 (a)

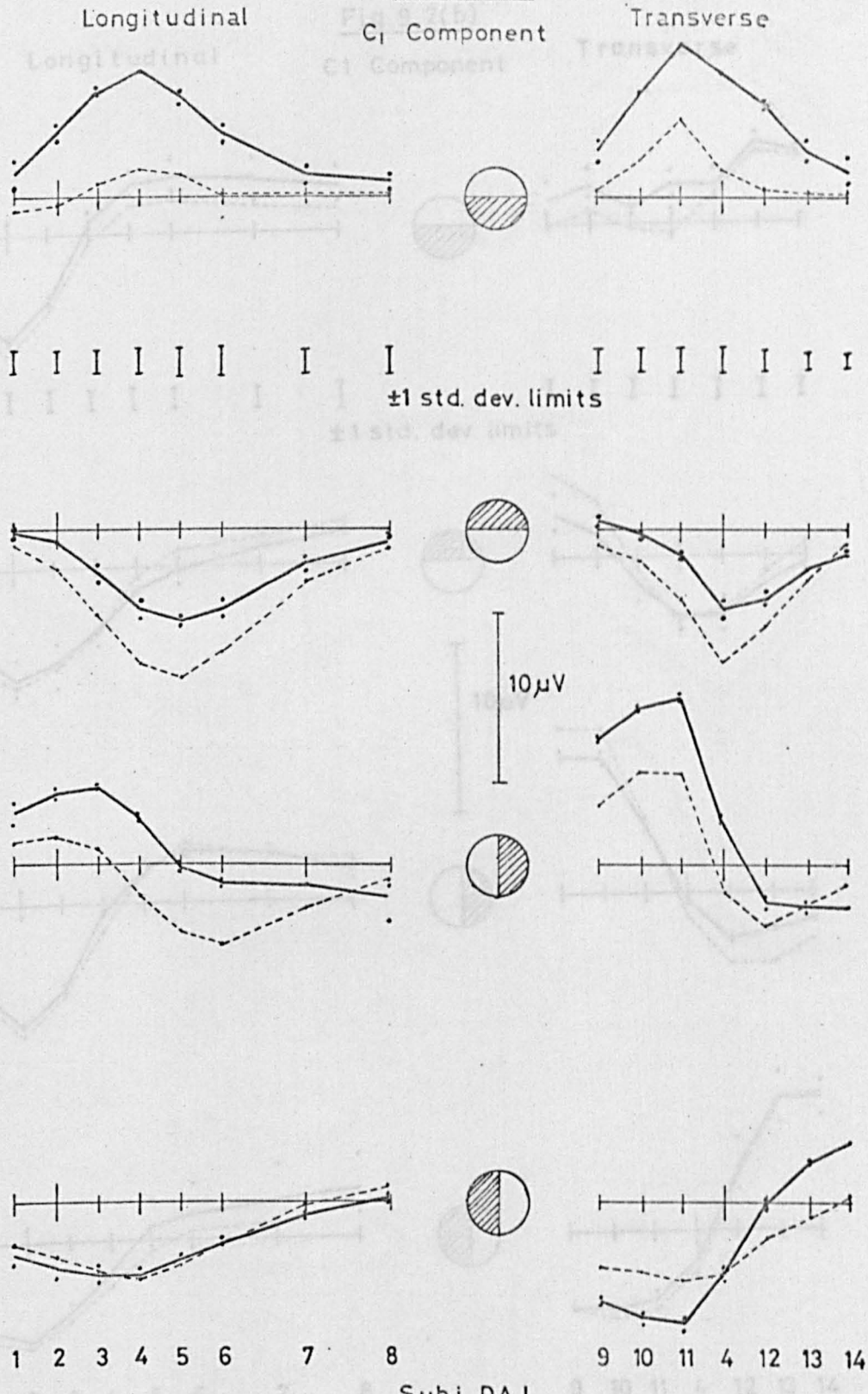
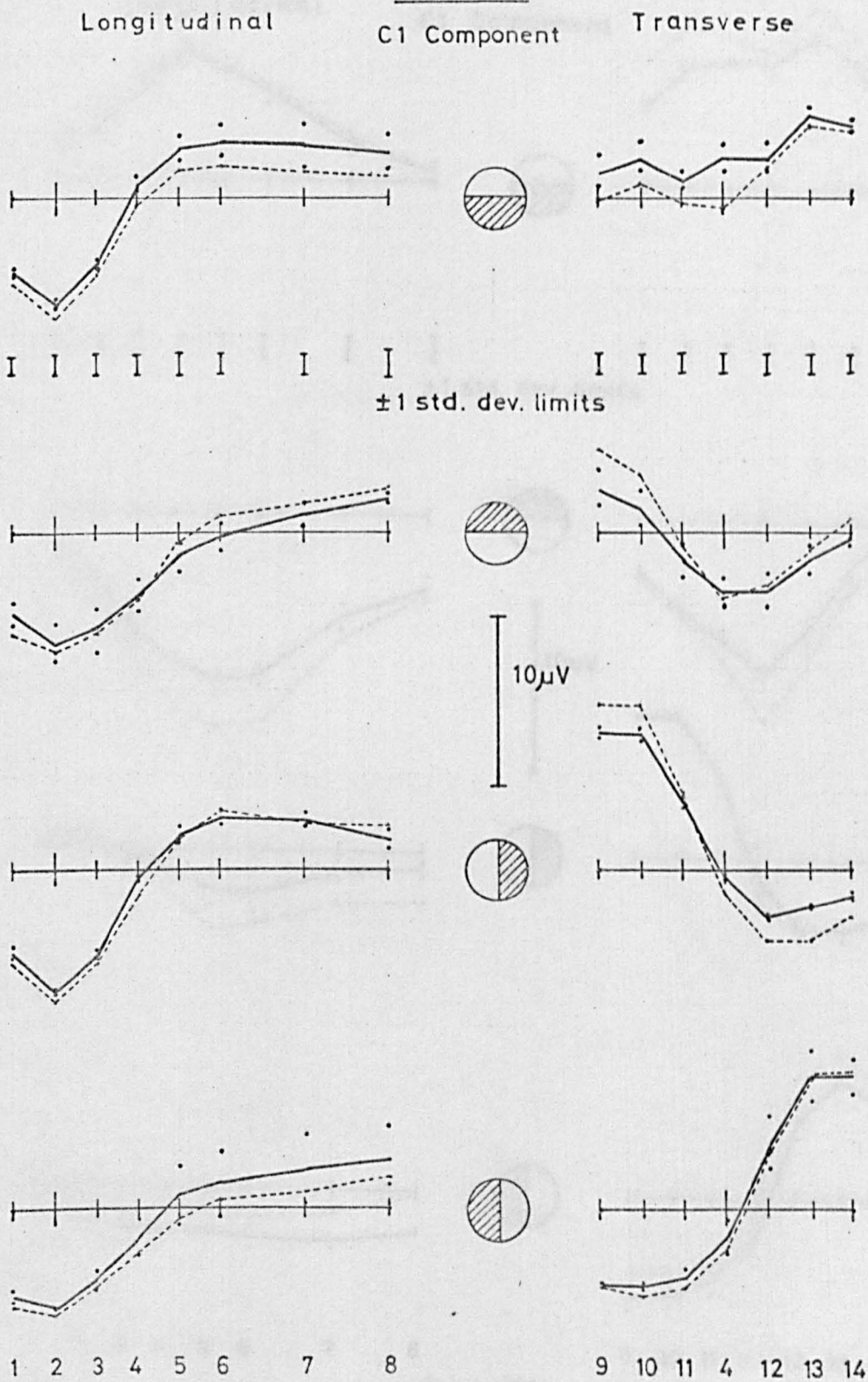

Longitudinal
C1 Component
Transverse
±1 std. dev. limits
10μV
1 2 3 4 5 6 7 8
9 10 11 4 12 13 14
Subj. DAJ
22.12.70

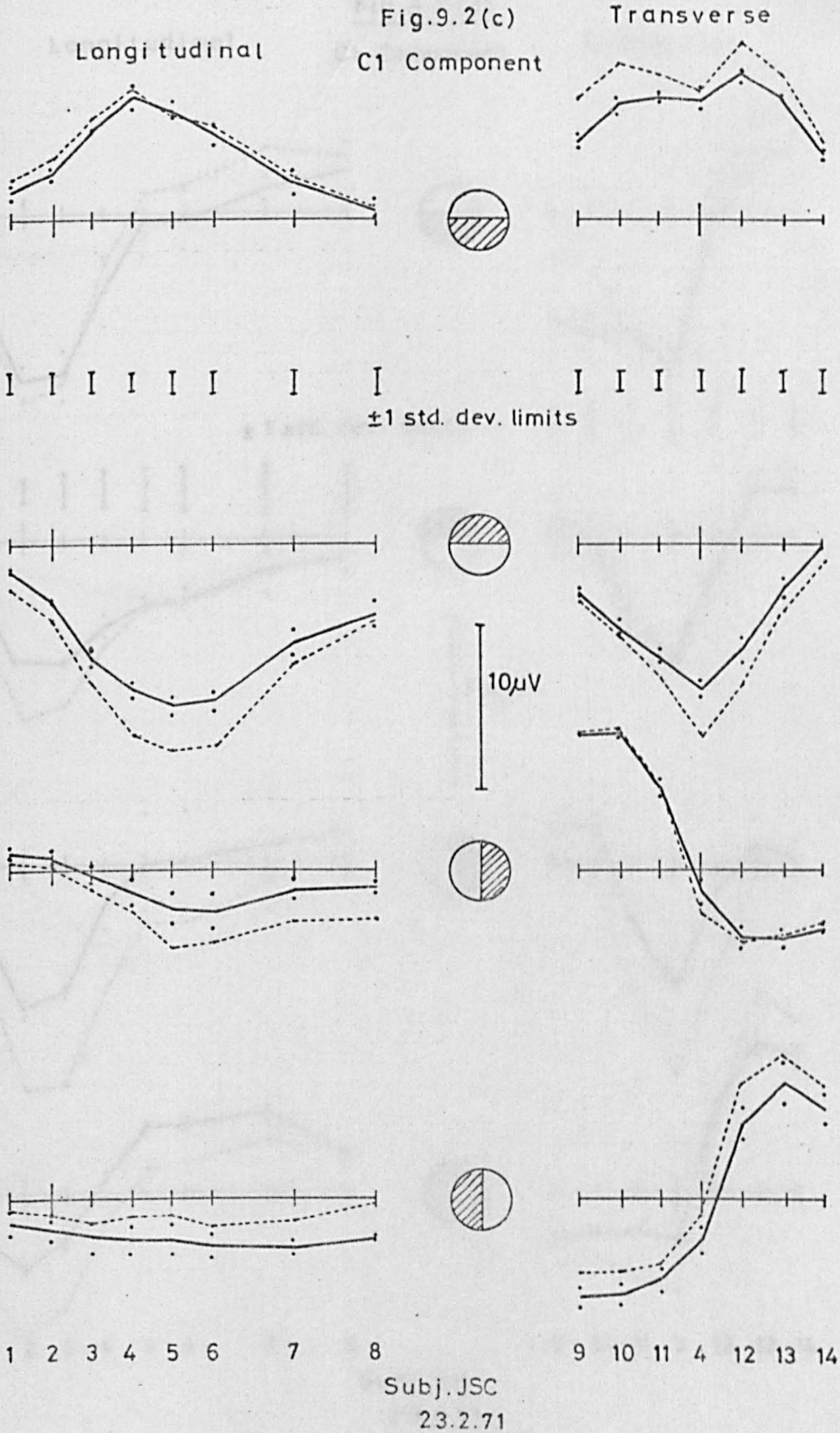
Fig. 9.2(b)



Subj. MAS
30.3.71

Fig.9.2(c)

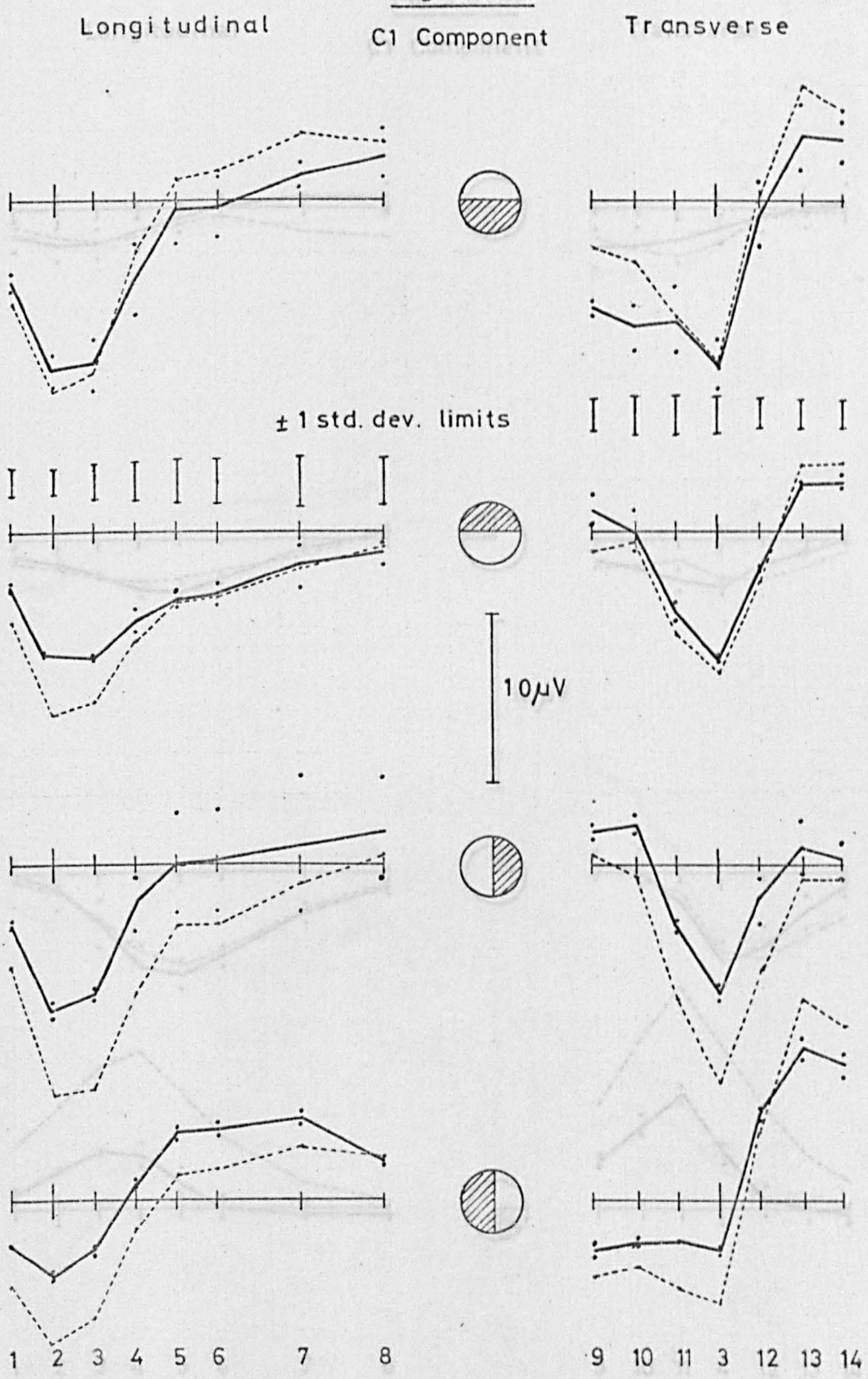
C1 Component



Subj. JSC

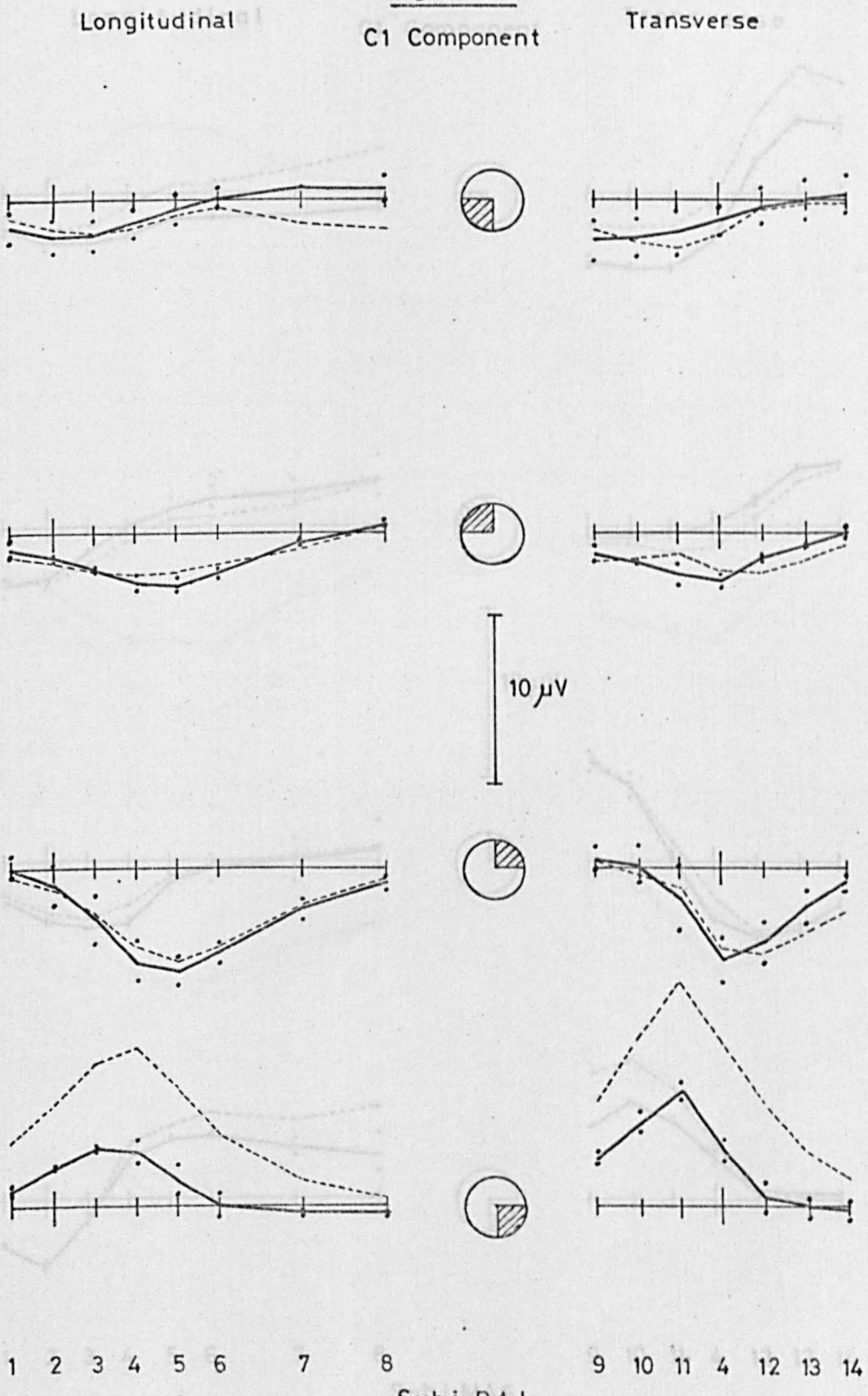
23.2.71

Fig. 9.2(d)



Subj. SH
23.3.71

Fig. 9.3 (a)



Subj. DAJ
22.12.70

Fig. 9.3(b)

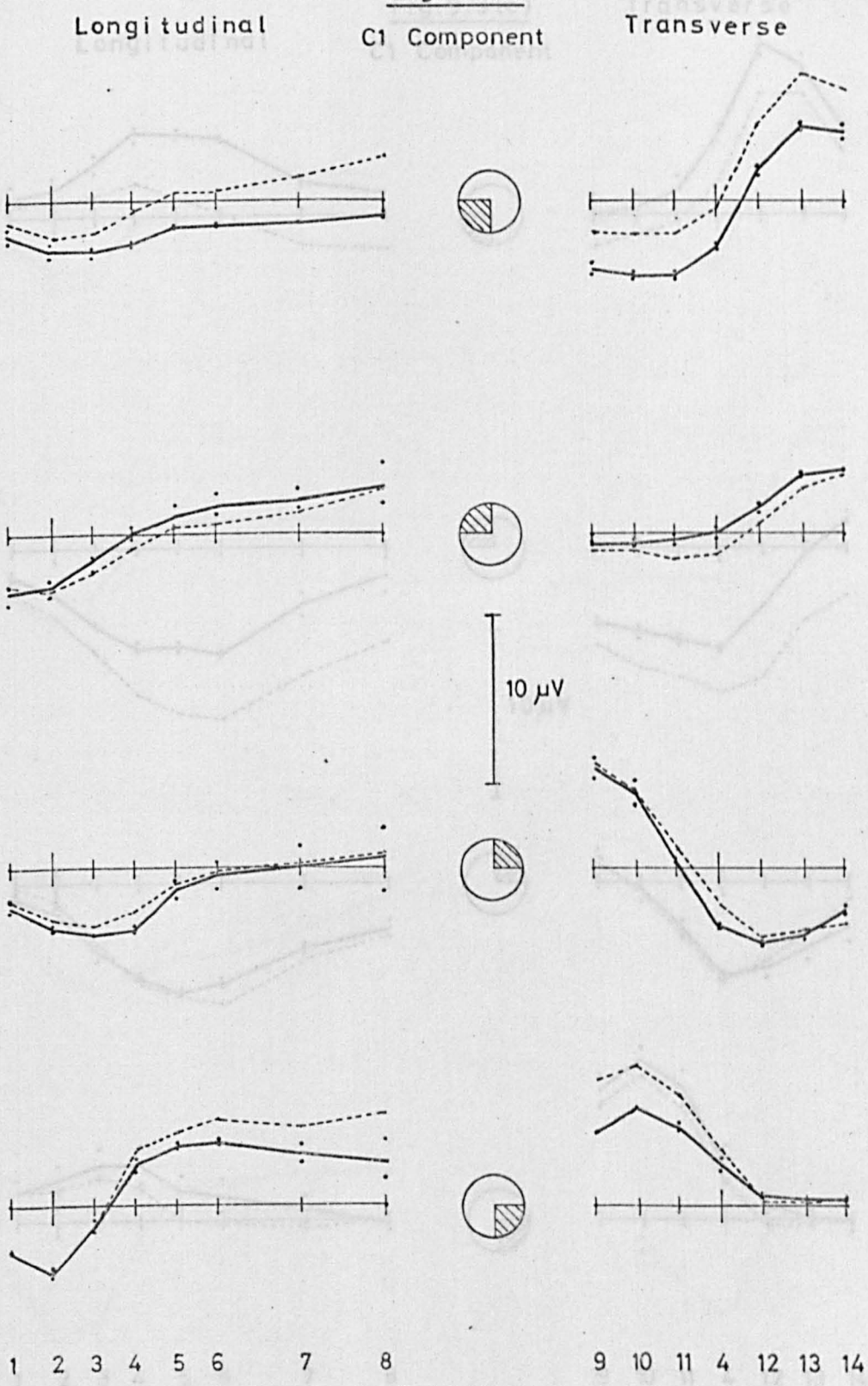
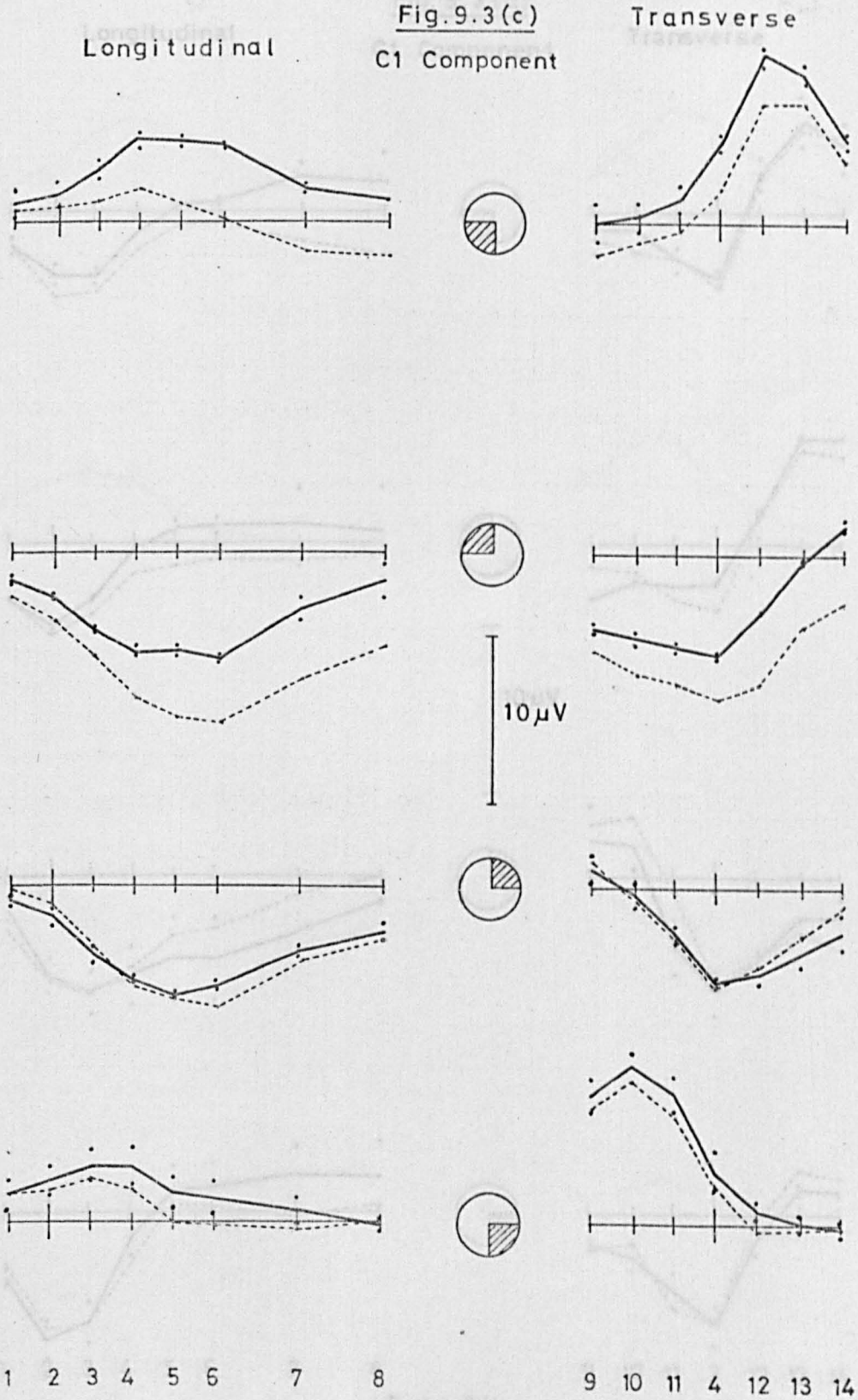

Longitudinal
C1 Component
Transverse
10 μV
1 2 3 4 5 6 7 8
9 10 11 4 12 13 14
Subj. MAS
30.3.71

Fig. 9.3(c)

C1 Component



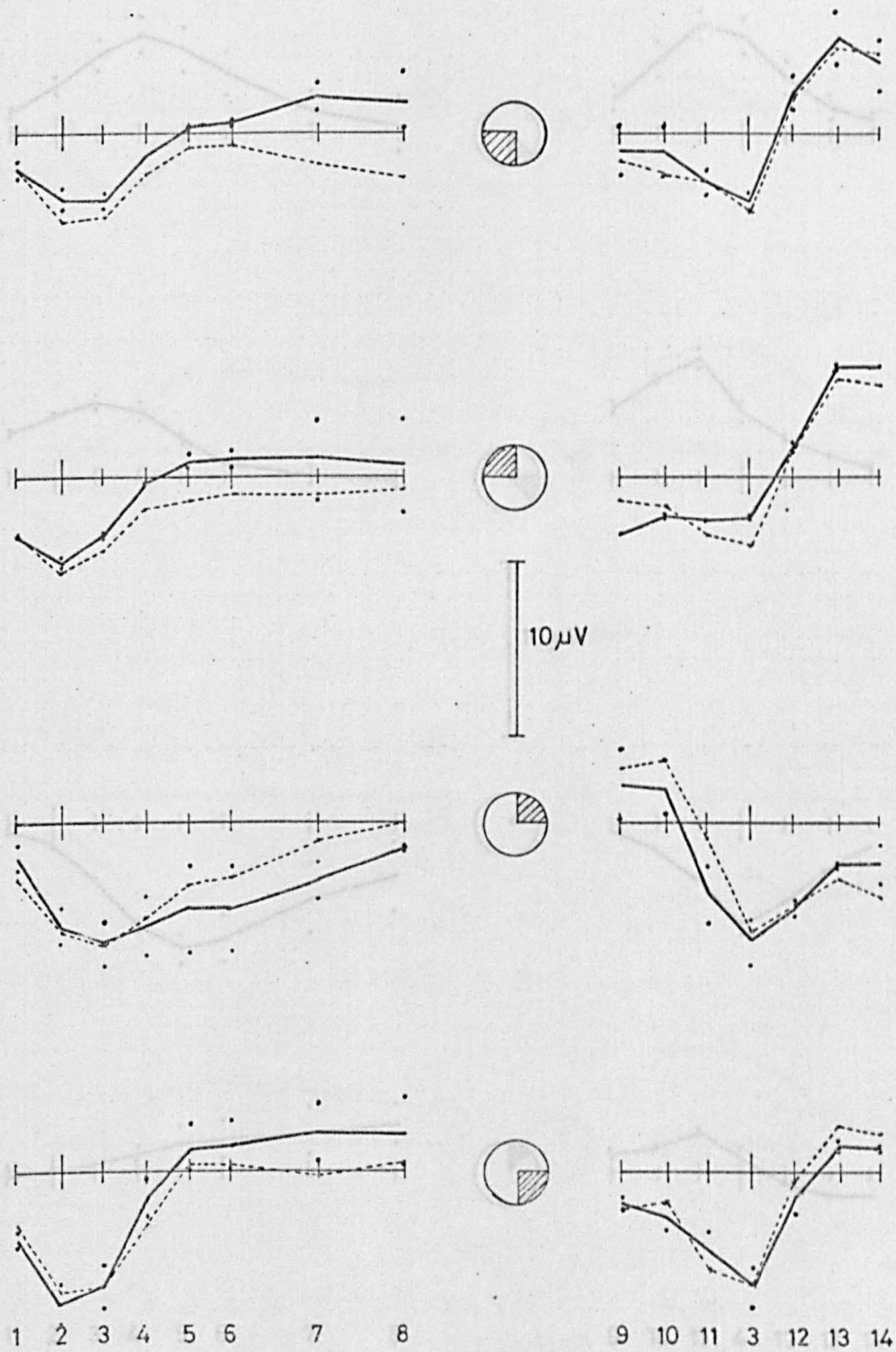
Subj. JSC
23.2.71

Fig. 9.3 (d)

Longitudinal

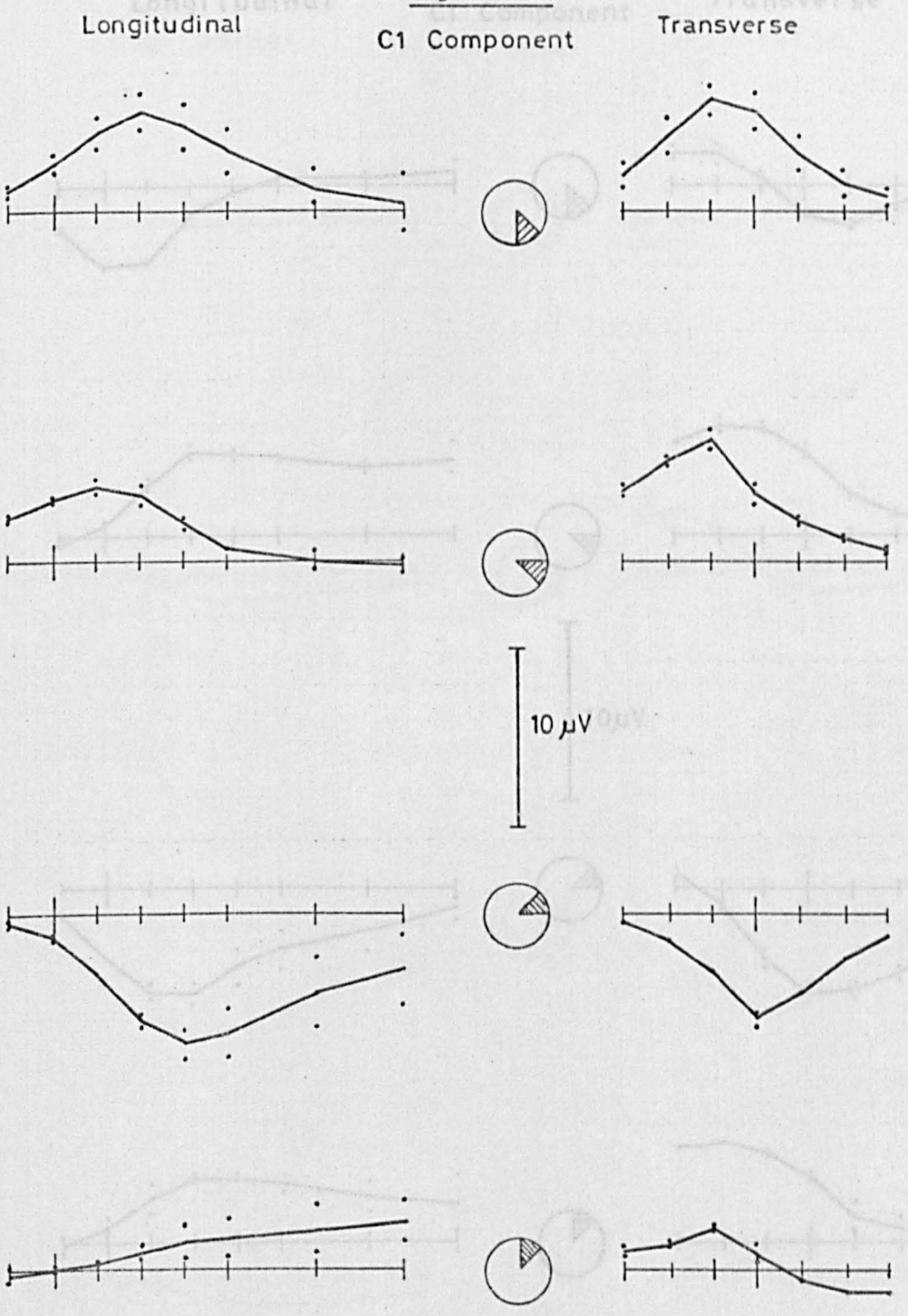
C1 Component

Transverse



Subj. SH.
23.3.71

Fig. 9.4(a)



Subj. DAJ
22.12.70

Fig. 9.4(b)

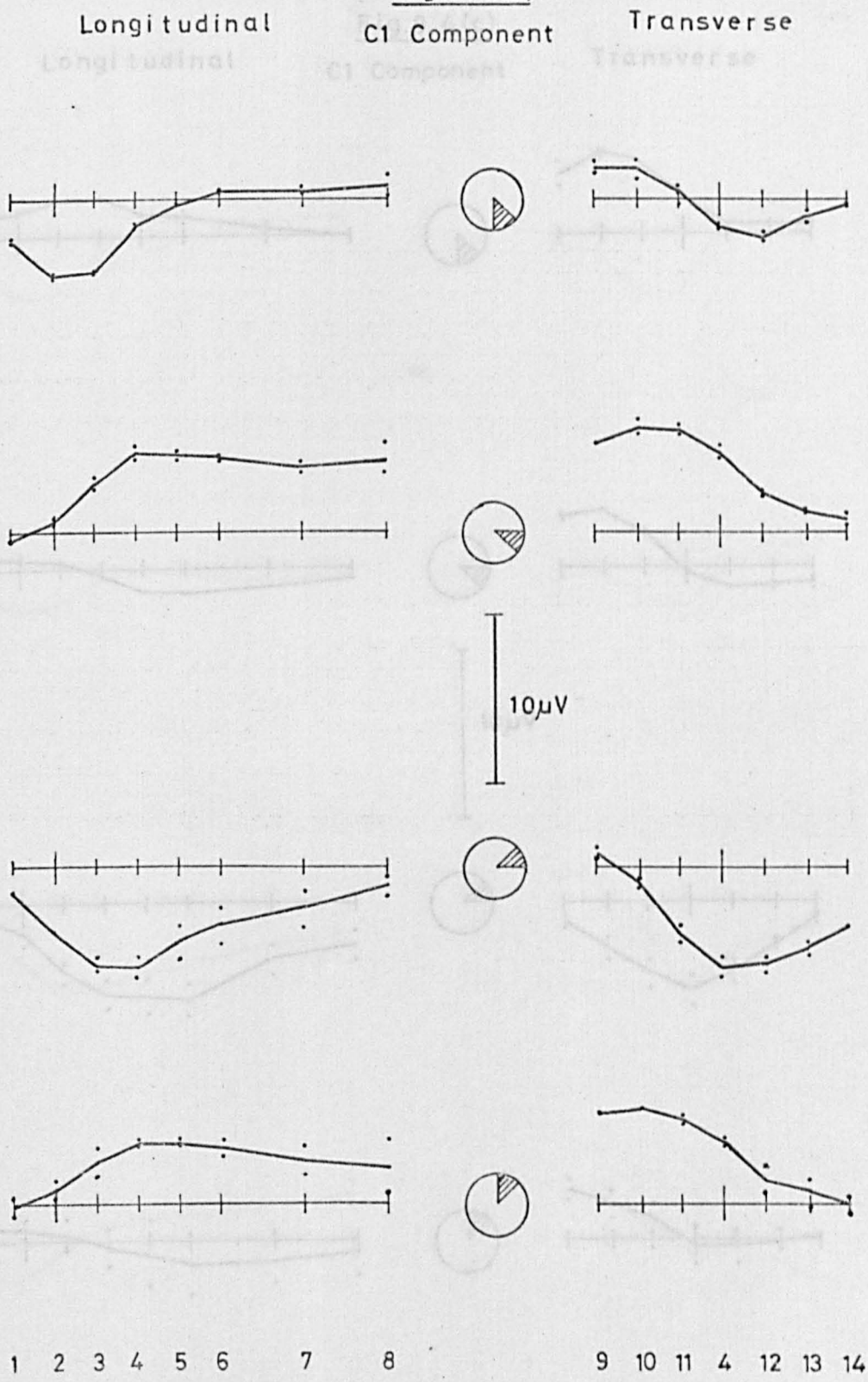
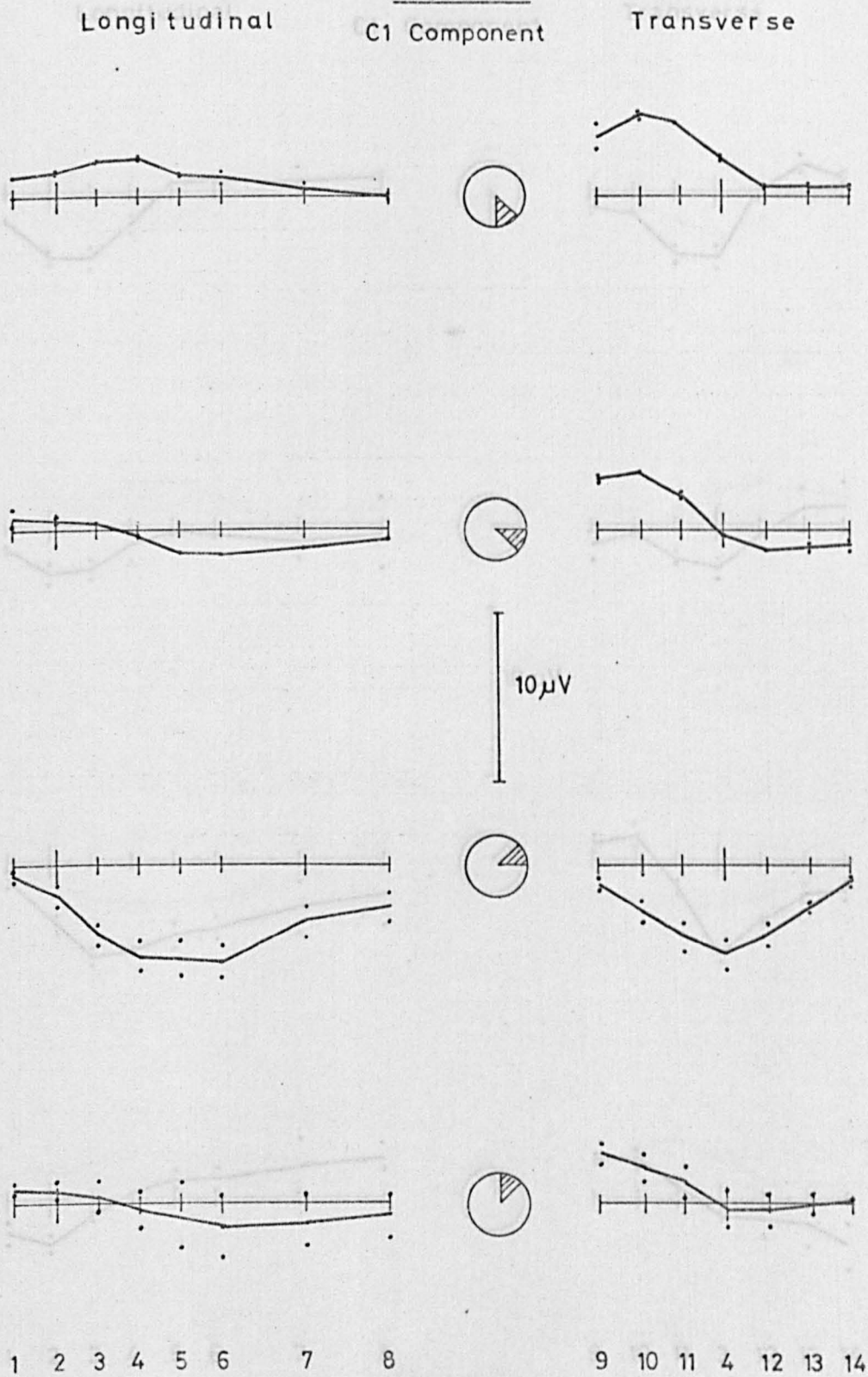

Longitudinal
C1 Component
Transverse
10μV
1 2 3 4 5 6 7 8 9 10 11 4 12 13 14
Subj. MAS
30.3.71

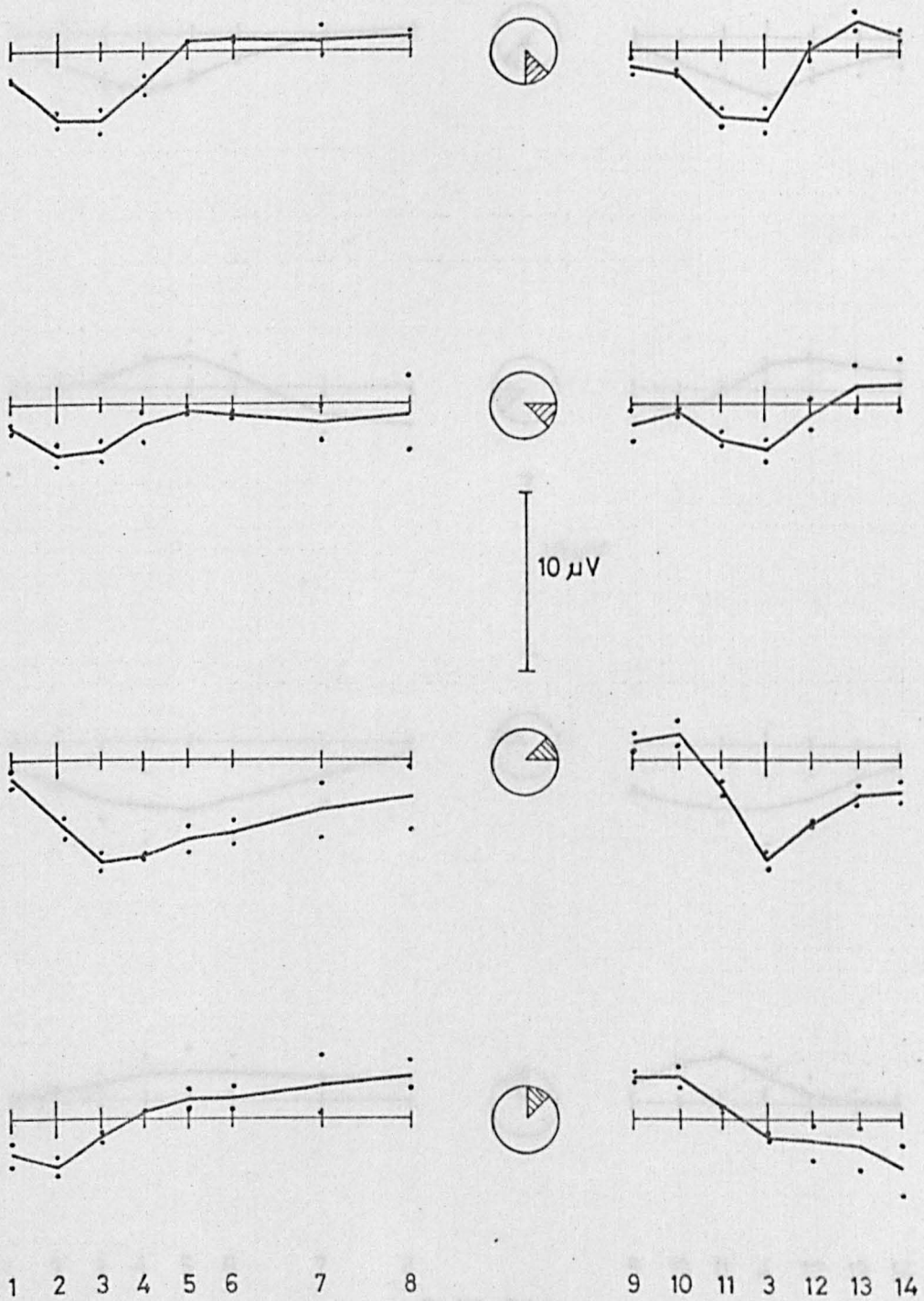
Fig. 9.4 (c)



Subj. JSC
23.2.71

Fig. 9.4 (d)

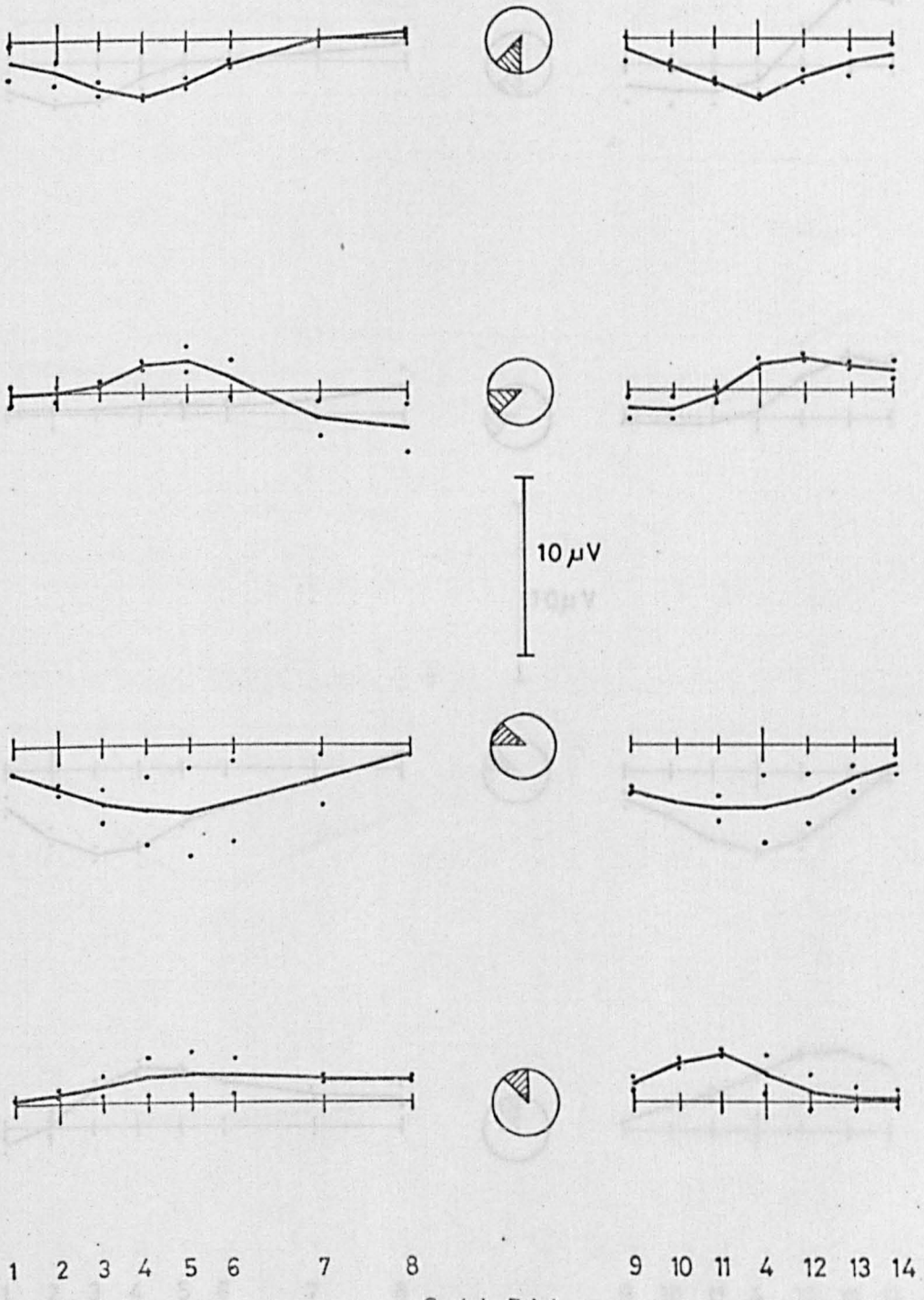
Longitudinal C1 Component Transverse



Subj. SH
23.3.71

Fig. 9.5(a)

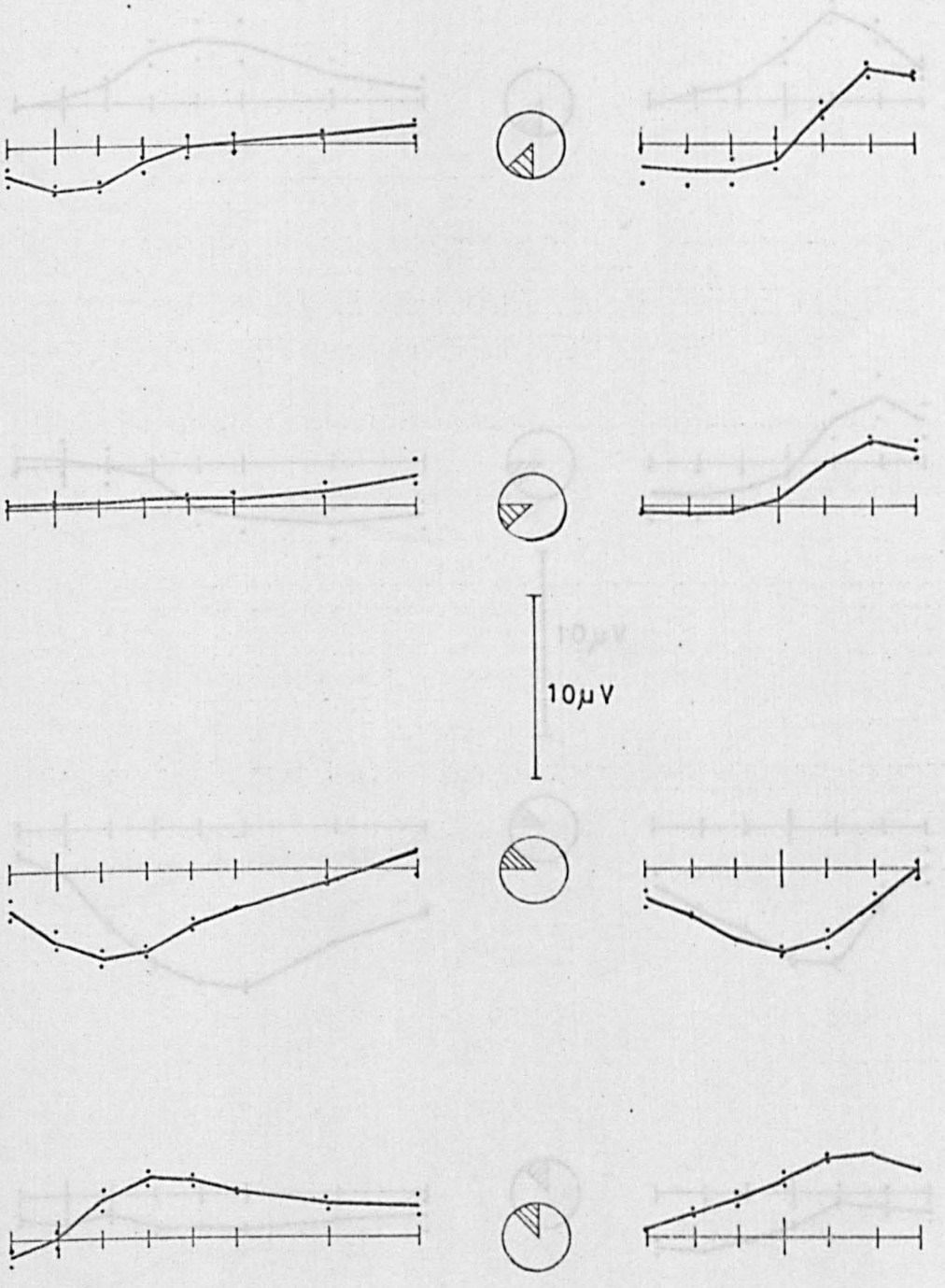
Longitudinal C1 Component Transverse



Subj. DAJ
22.12.70

Fig. 9.5 (b)

Longitudinal C1 Component Transverse



Subj. MAS
30.3.71

Fig.9.5(c)

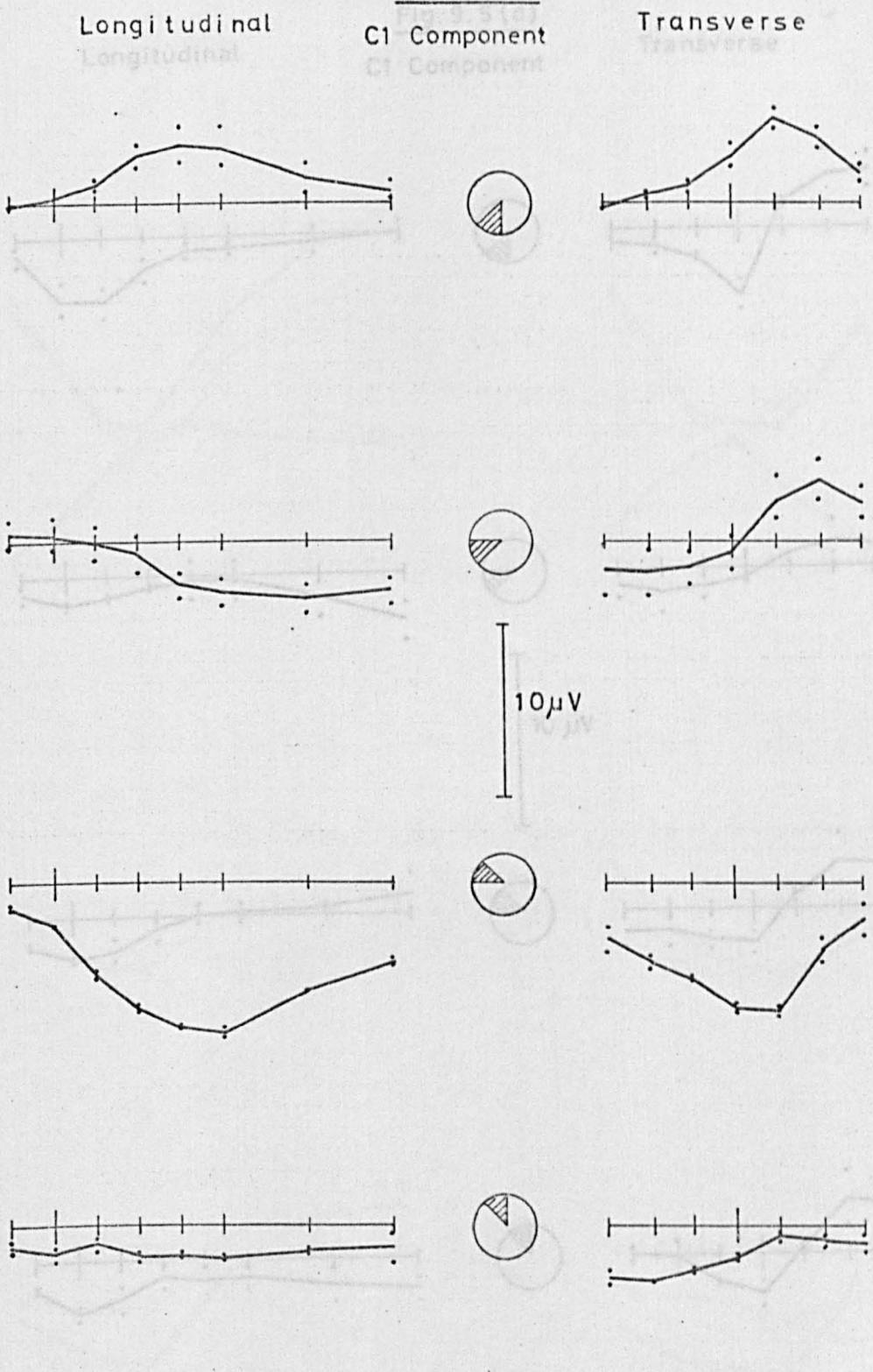
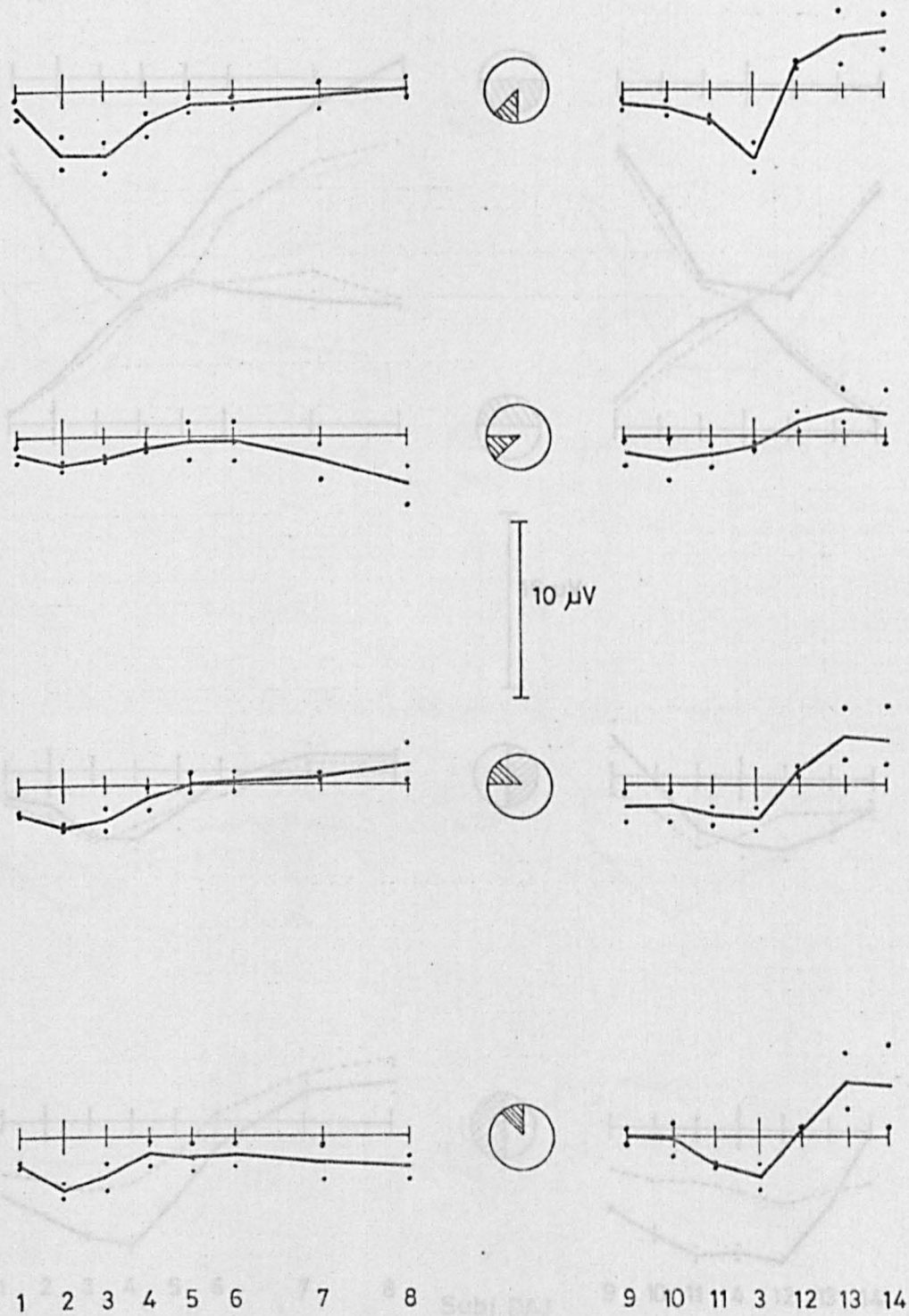

Longitudinal
C1 Component
Transverse
10μV
1 2 3 4 5 6 7 8
9 10 11 4 12 13 14
Subj.JSC
23.2.71

Fig. 9.5 (d)

Longitudinal

C1 Component

Transverse



Subj. SH

23.3.71

Fig. 9.6(a)

Longitudinal C2 Component Transverse

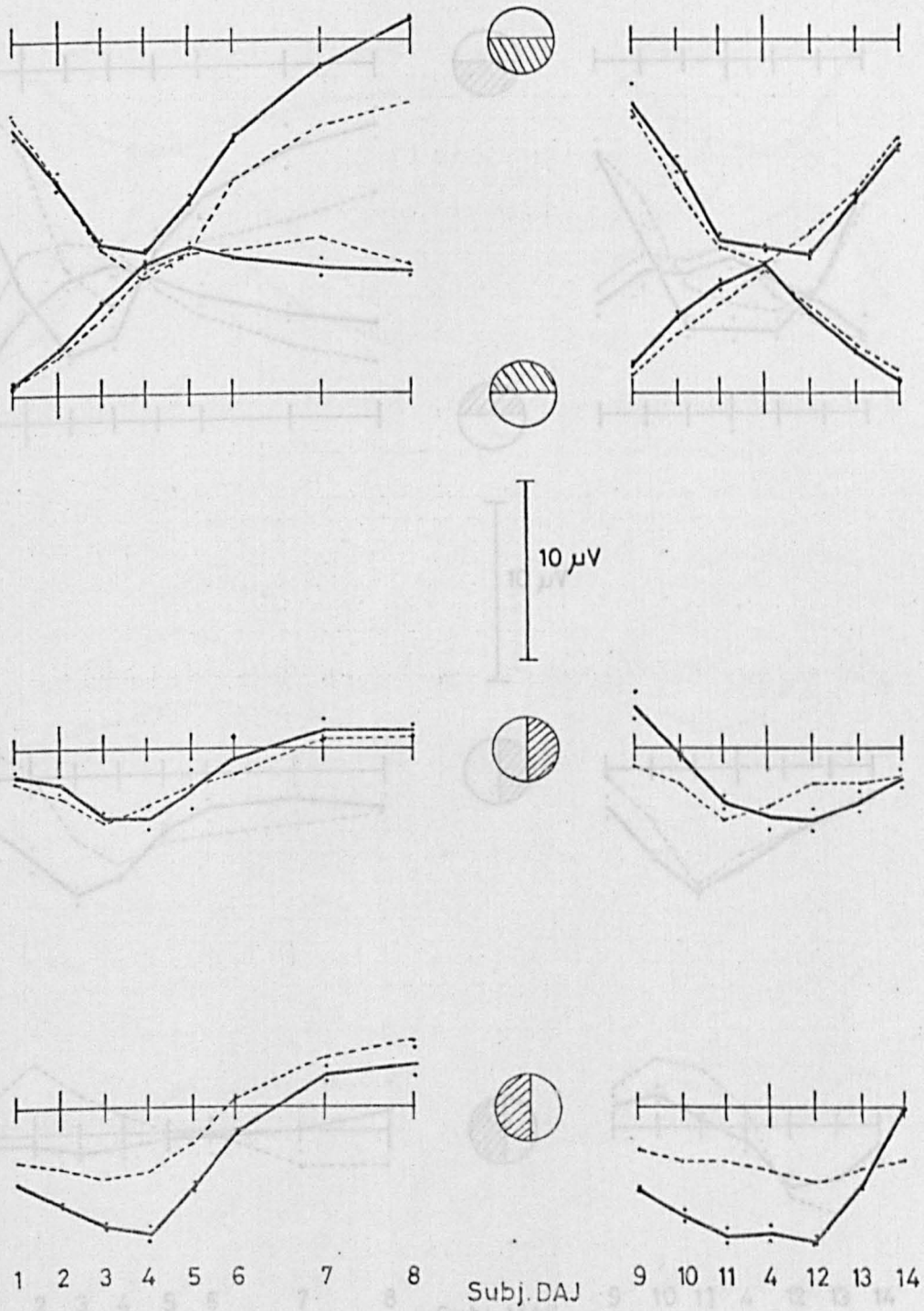


Fig. 9.6 (b)

Longitudinal

C2 Component

Transverse

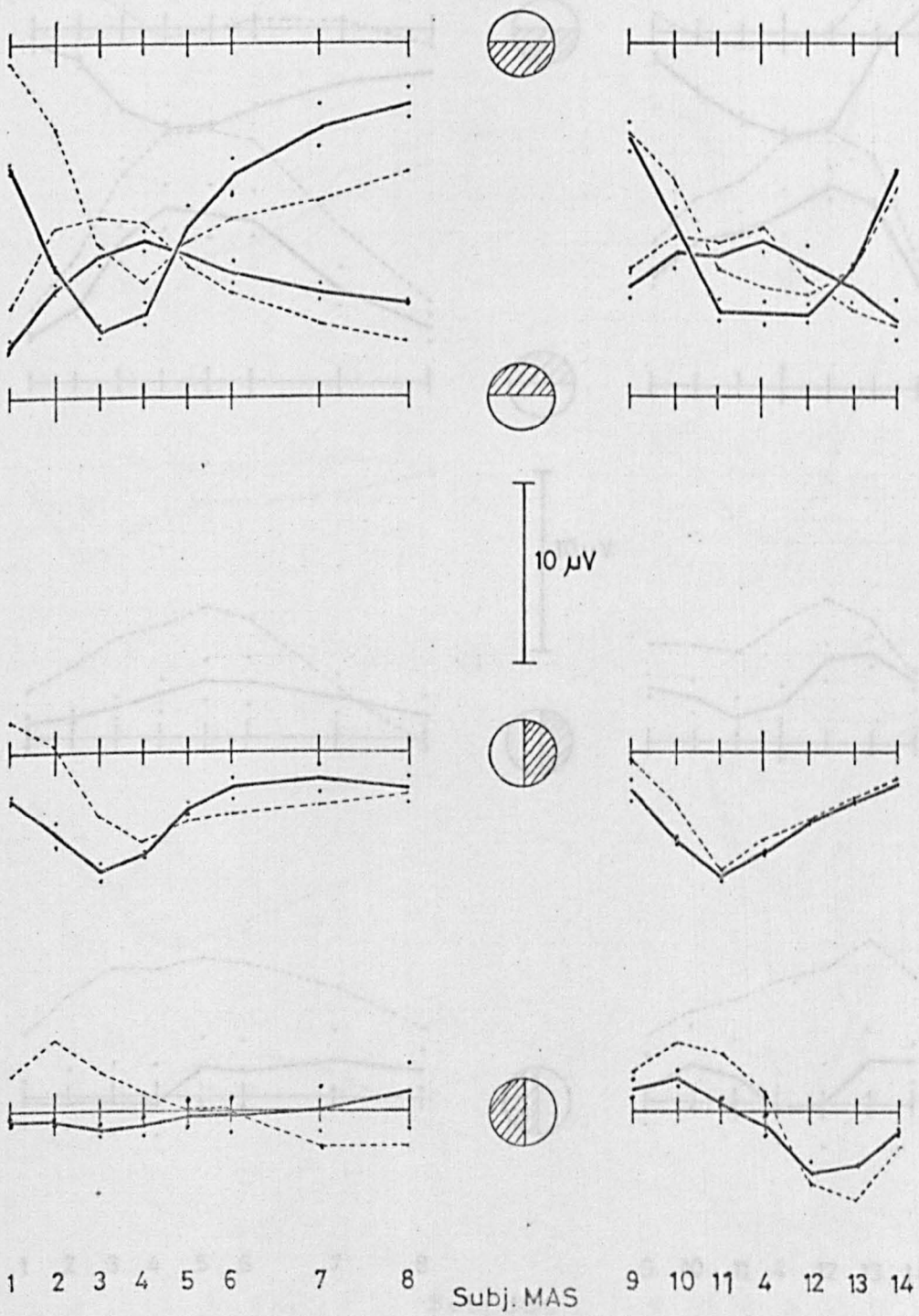


Fig. 9.6 (c)

Longitudinal C2 Component Transverse

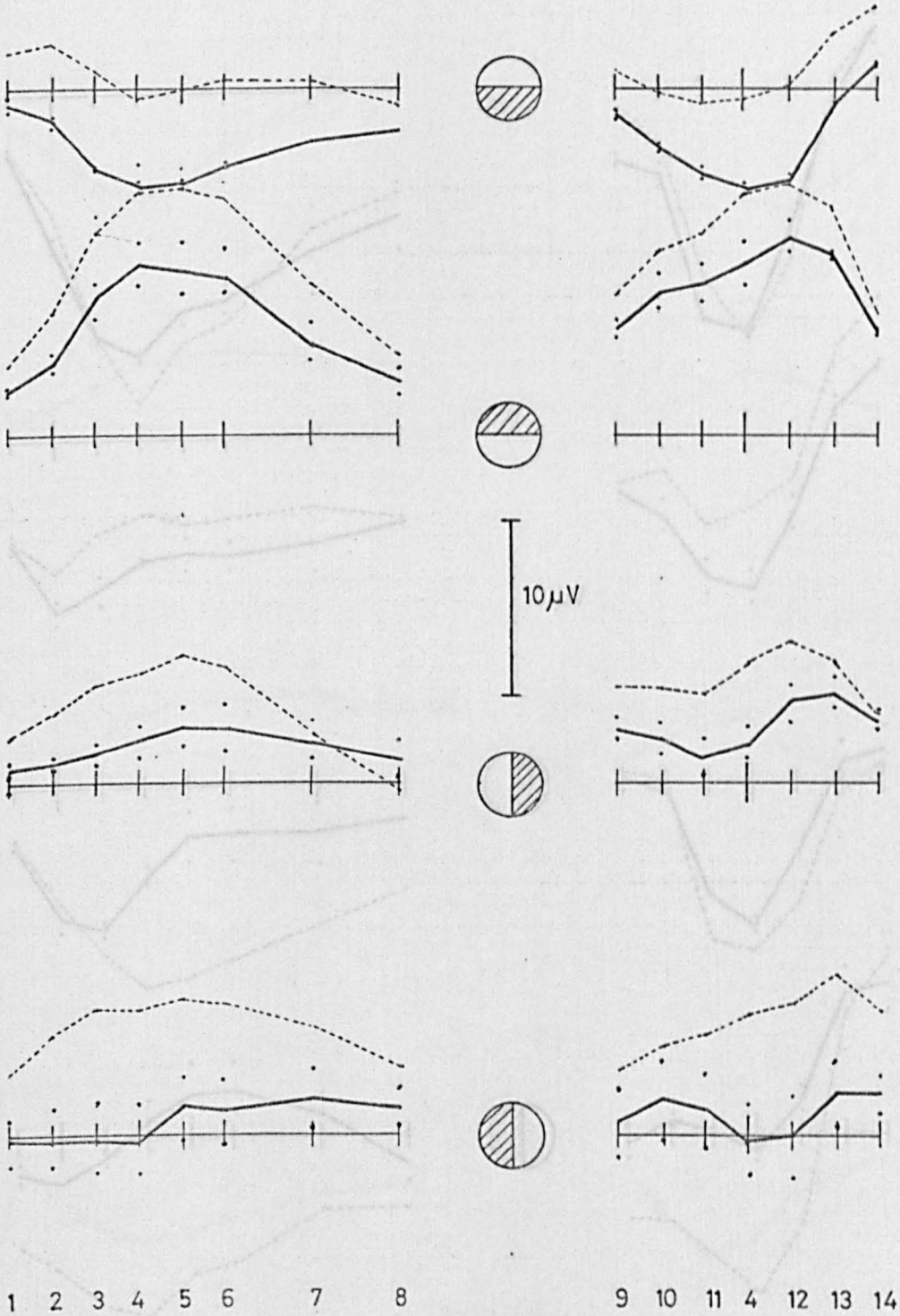


Fig. 9.6 (d)

Longitudinal

C2 Component

Transverse

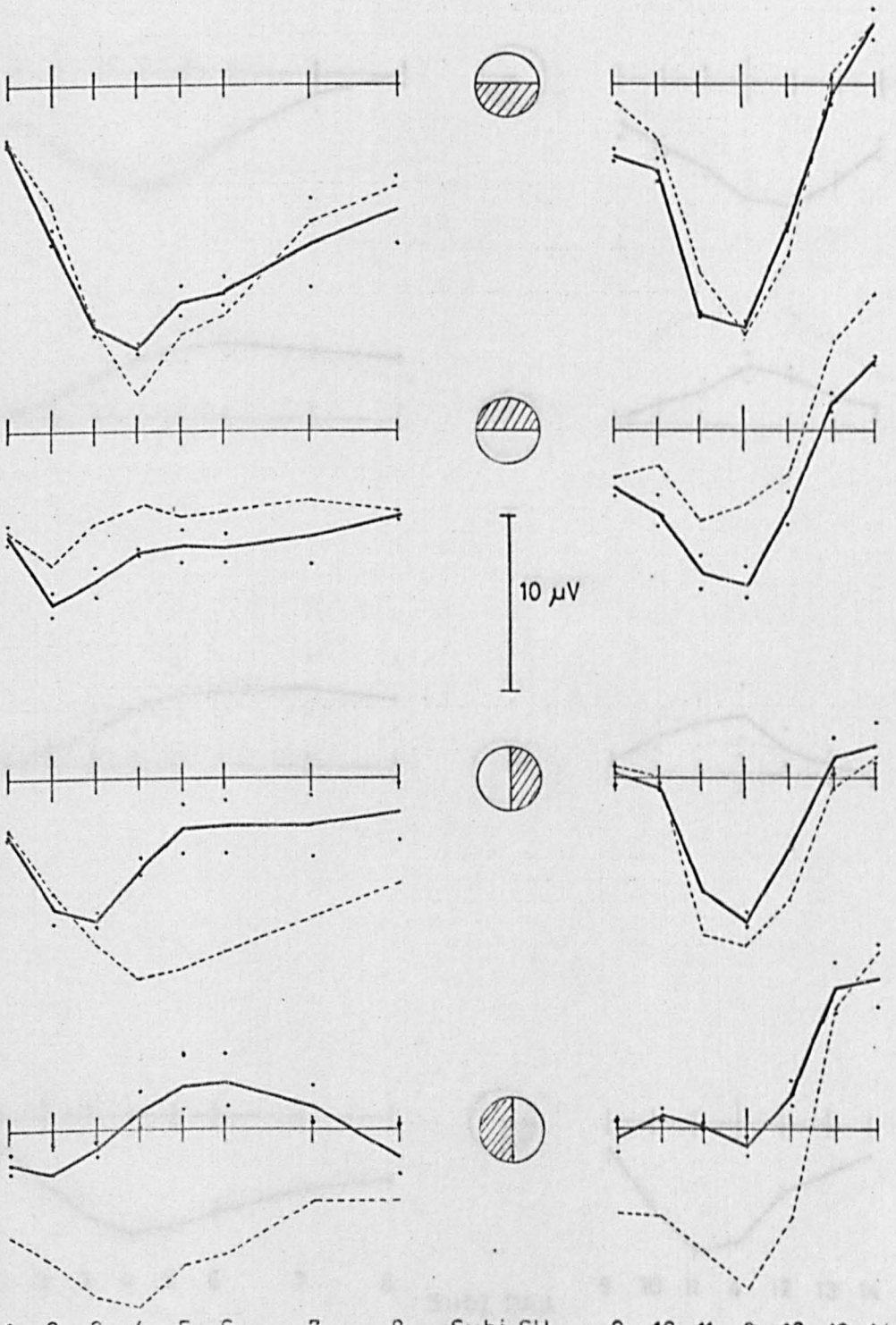
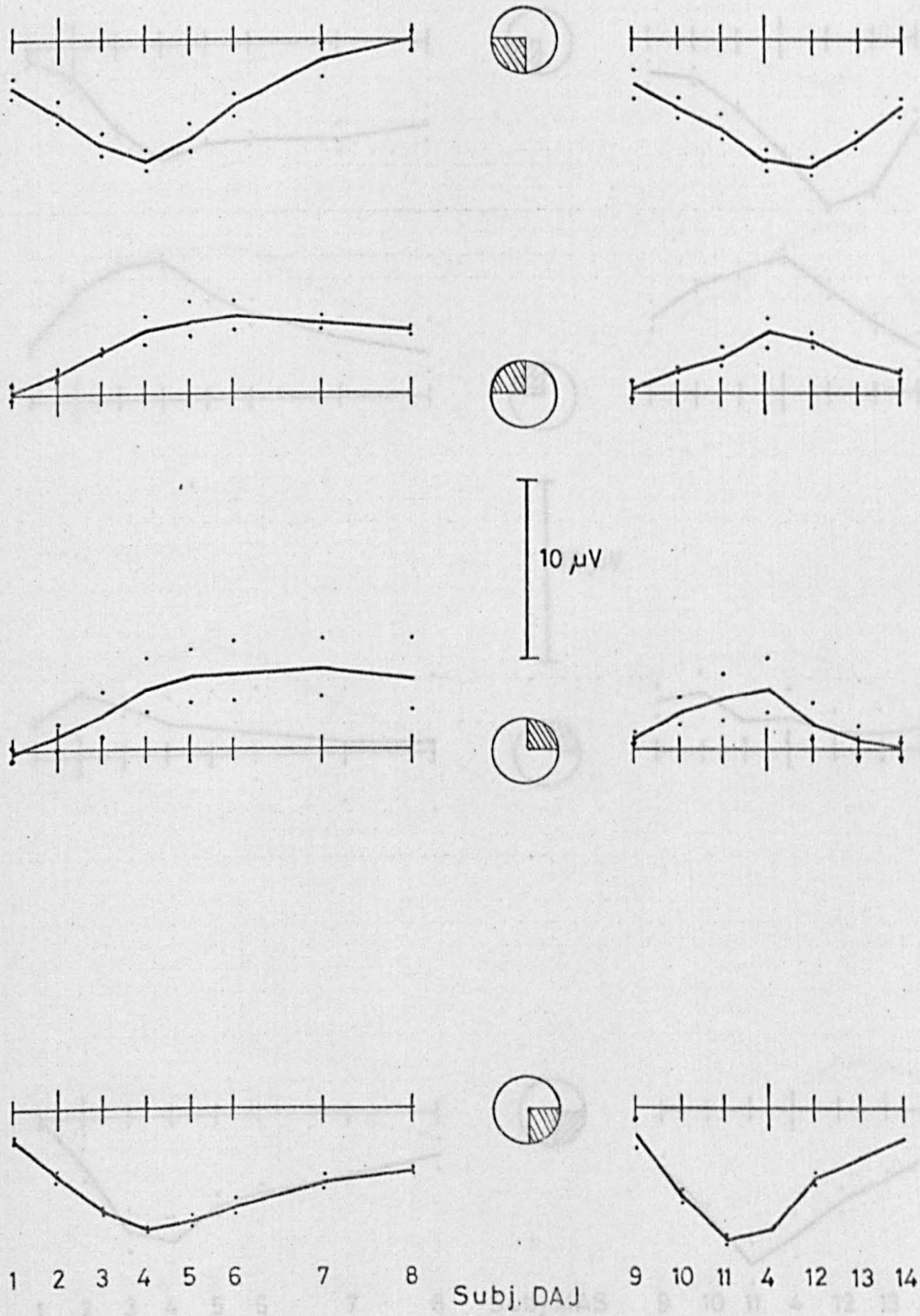


Fig. 9.7 (a)

Longitudinal

C2 Component

Transverse



Subj. DAJ
22.12.70

Fig. 9.7(b)

Longitudinal

C2 Component

Transverse

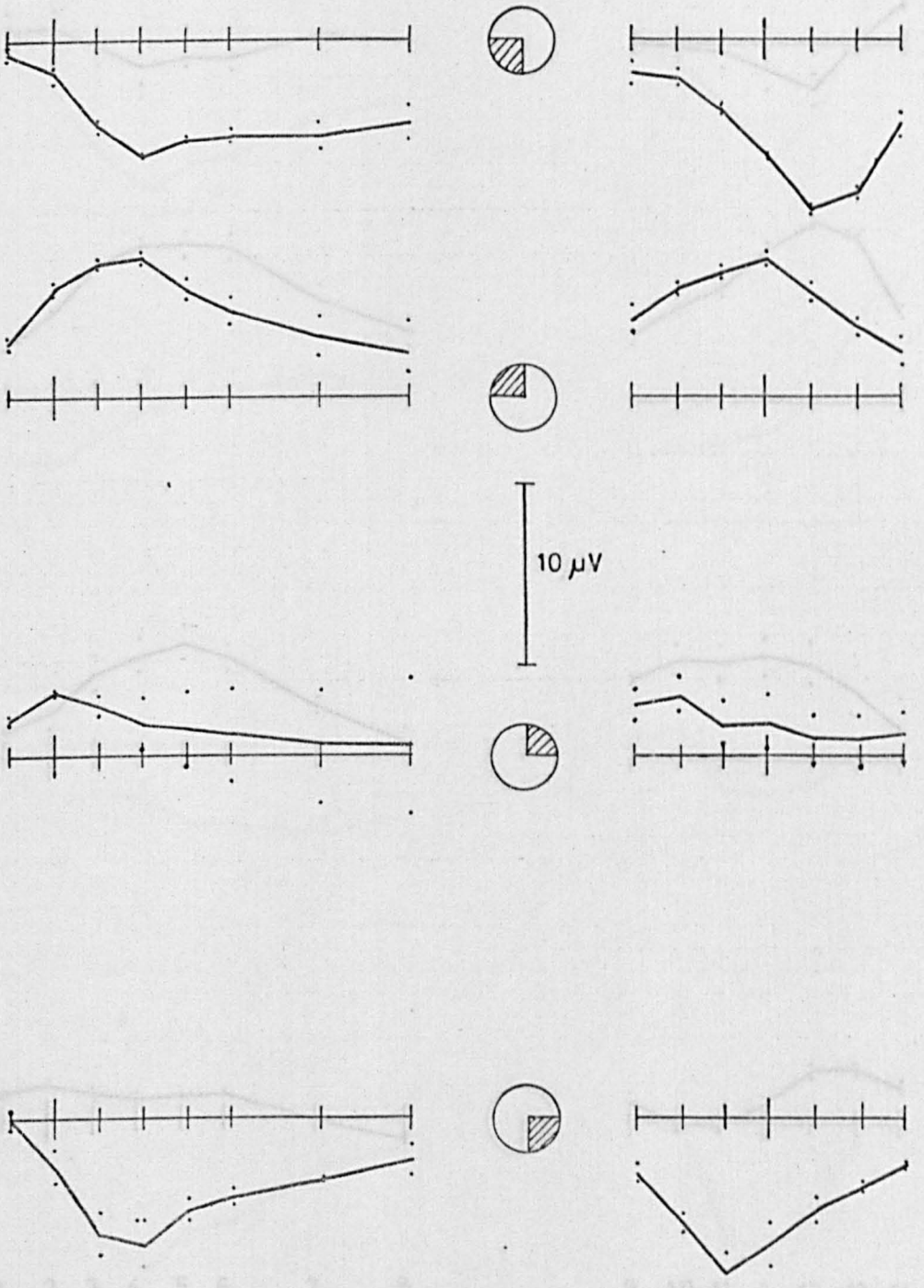
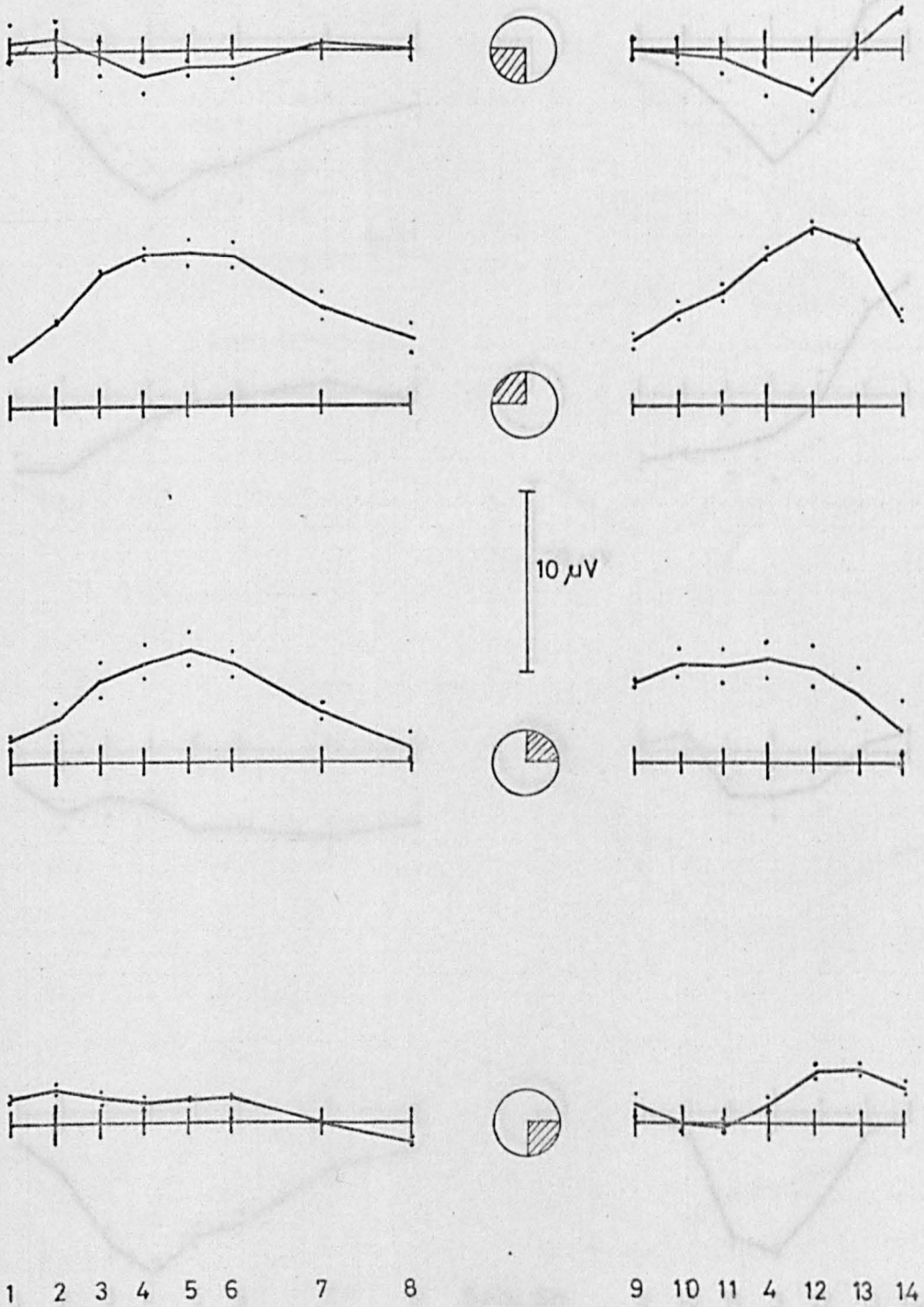


Fig. 9.7(c)

Longitudinal

C2 Component

Transverse



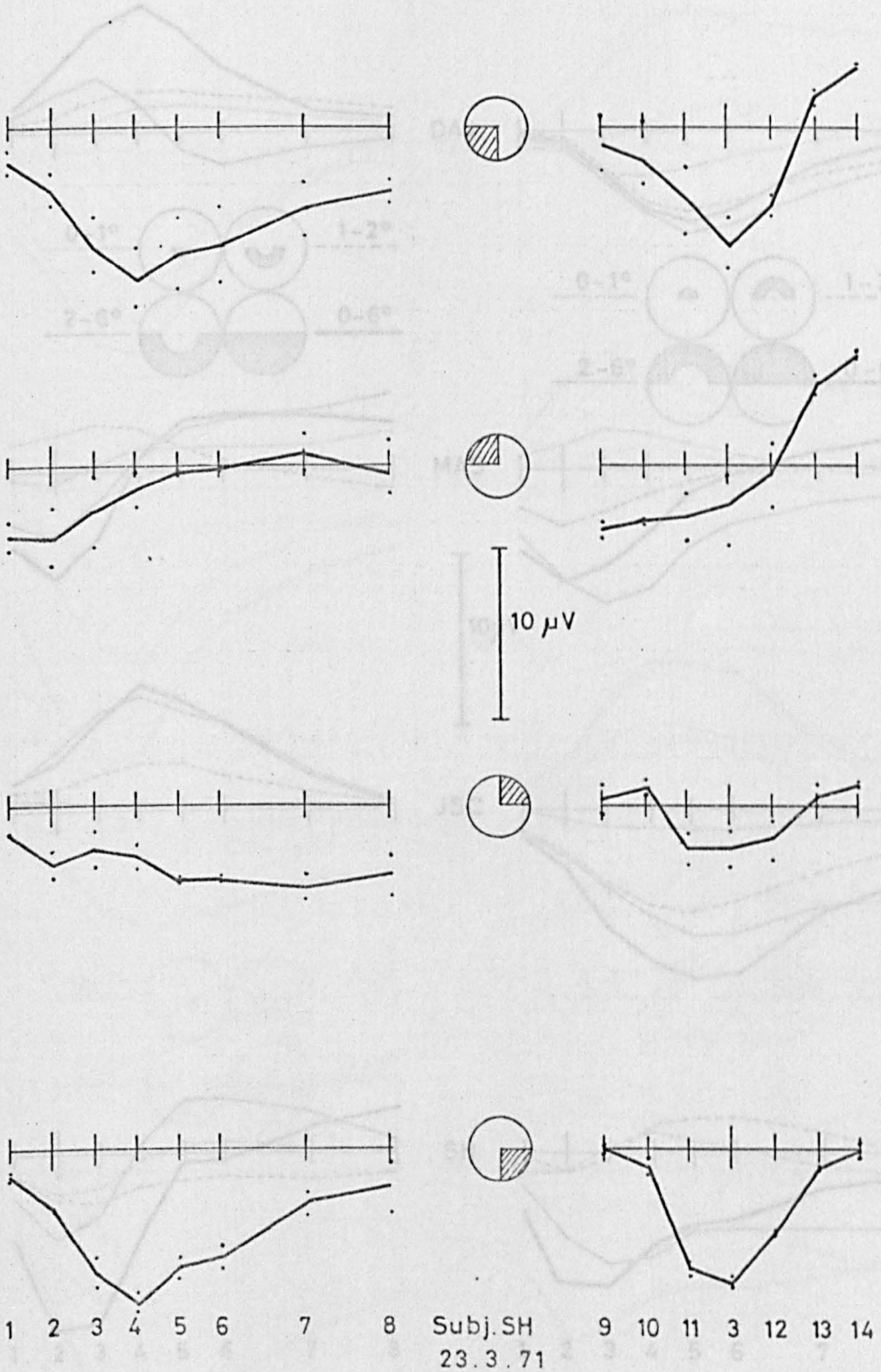
Subj. JSC
23.2.71

Fig. 9.7 (d)

Longitudinal

C2 Component

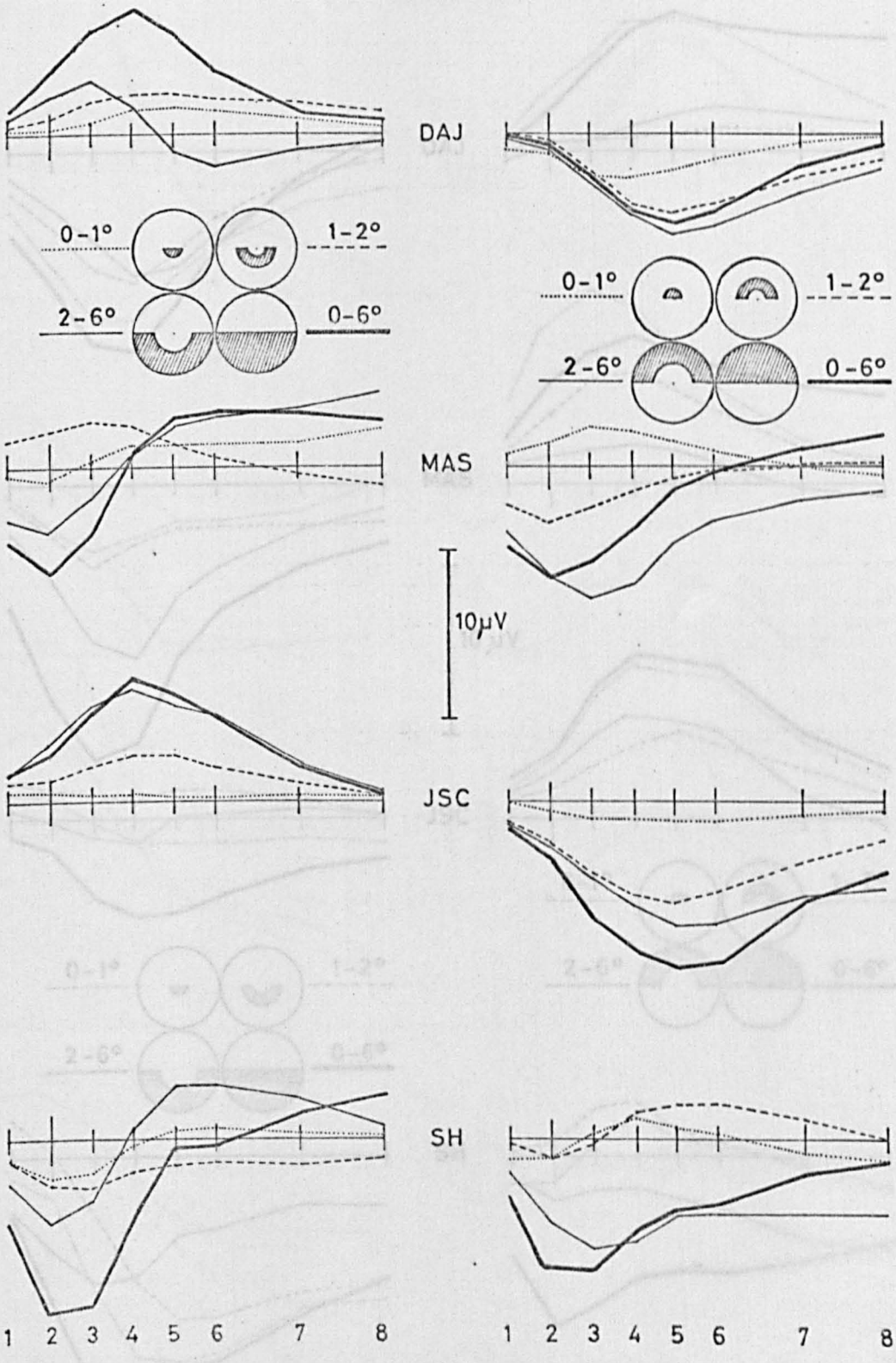
Transverse



Lower 1/2 Field
Longitudinal

Fig. 9.8
C1 Component

Upper 1/2 Field
Longitudinal



Lower 1/2 Field
Longitudinal

Fig. 9.9
C2 Component

Upper 1/2 Field
Longitudinal

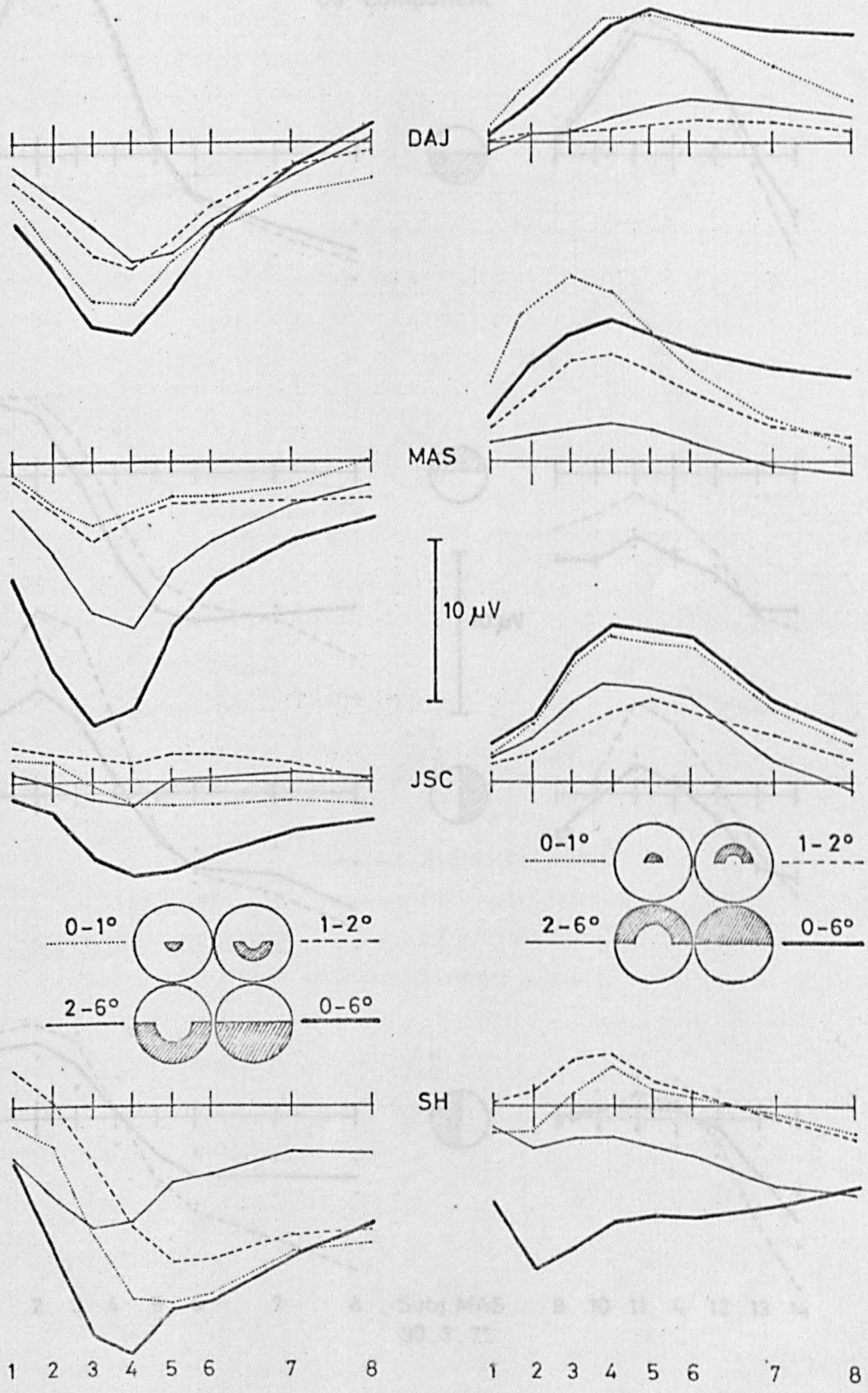


Fig. 9.10

C3 Component

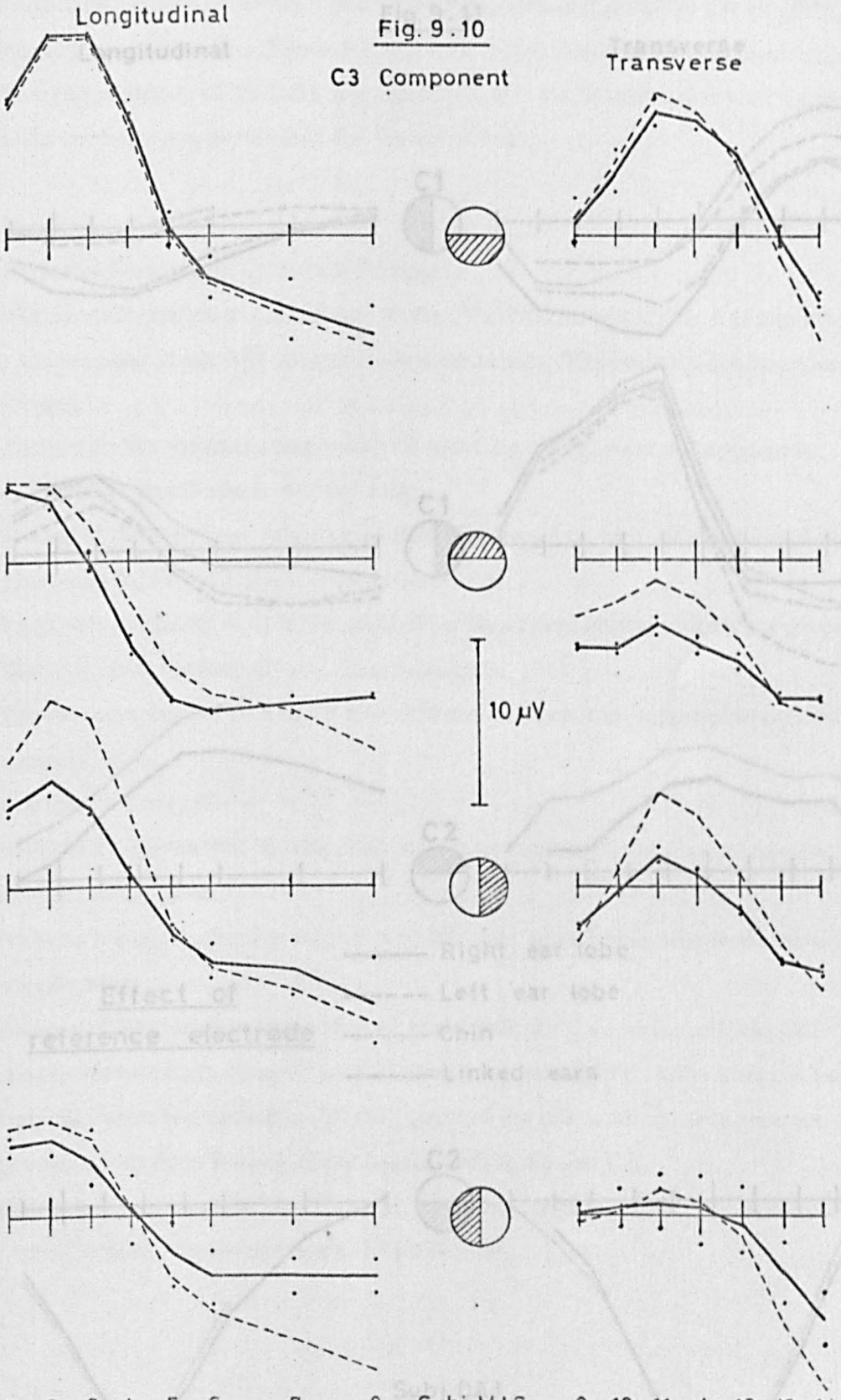
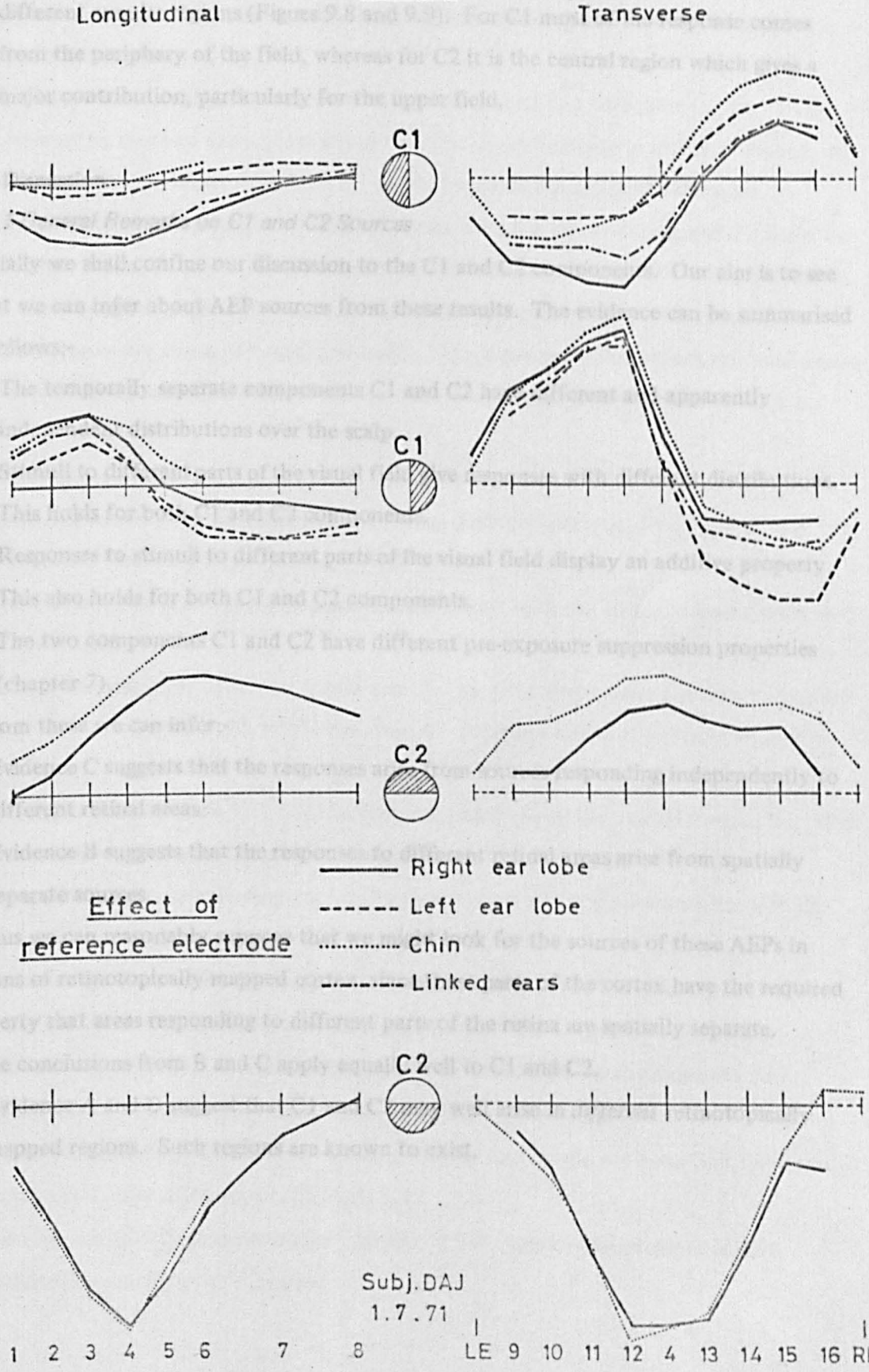


Fig. 9.11


Longitudinal
Transverse
C1
C1
C2
C2
Right ear lobe
Left ear lobe
Chin
Linked ears
Effect of
reference electrode
Subj. DAJ
1.7.71
1 2 3 4 5 6 7 8
LE 9 10 11 12 4 13 14 15 16 RE

7. Further differences between C1 and C2 become apparent from the distributions for different annular regions (Figues 9.8 and 9.9). For C1 most of the response comes from the periphery of the field, whereas for C2 it is the central region which gives a major contribution, particularly for the upper field.

9.4 Discussion

9.4.1 General Remarks on C1 and C2 Sources

Initially we shall confine our discussion to the C1 and C2 components. Our aim is to see what we can infer about AEP sources from these results. The evidence can be summarised as follows:-

A. The temporally separate components C1 and C2 have different and apparently independent distributions over the scalp.

B. Stimuli to different parts of the visual field give responses with different distributions. This holds for both C1 and C2 components.

C. Responses to stimuli to different parts of the visual field display an additive property. This also holds for both C1 and C2 components.

D. The two components C1 and C2 have different pre-exposure suppression properties (chapter 7).

From these we can infer:-

1. Evidence C suggests that the responses arise from sources responding independently to different retinal areas.

2. Evidence B suggests that the responses to different retinal areas arise from spatially separate sources.

Thus we can reasonably suppose that we might look for the sources of these AEPs in regions of retinotopically mapped cortex, since these parts of the cortex have the required property that areas responding to different parts of the retina are spatially separate.

The conclusions from B and C apply equally well to C1 and C2.

3. Evidence A and D suggest that C1 and C2 may well arise in *different* retinotopically mapped regions. Such regions are known to exist.

These conjectures will be further strengthened if it can be shown that the observed distributions agree at least qualitatively with the known topography and retinotopic mappings of the visual cortex.

If this can be done then each component can be assigned to a particular source. To do this we have to make an assumption about the type of cortical source involved in generating the response. As explained in section 2.3 we shall assume the dipole sheet model.

Jeffreys [84] has already suggested that C1 comes from the striate cortex and C2 from the extrastriate (visual II) area. That C2 follows C1 in time further supports this argument, since we know from single unit work that the striate and extrastriate areas probably represent successive stages of neural processing. The measured distributions reported above provide strong supporting evidence for these source suggestions, as will be shown below.

9.4.2 Component C1

Suppose this comes from the striate cortex. What distributions would we expect? We shall make the following assumptions:-

1. The cortex behaves as a surface negative dipole sheet with the dipole axis perpendicular to the surface.
2. The interhemispheric or medial fissure and the calcarine fissure have the rather idealised form shown in Figure 9.12, where the areas A – H project to the visual field regions as shown.
3. The regions X on Figure 9.12 (on the occipital pole) will be the central foveal projection. This will be neglected in the present discussion but will be considered later.

Thus we have eight independent planar sheet generators which we shall assume give rise to the respective octant responses.

Theoretical predictions for the octant distributions using a simple dipole model are shown in table 9.3. The model is described as follows:-

1. For each octant region we assume that the dipole sheet behaves as a single dipole oriented perpendicular to a radius vector of a sphere (the scalp).
2. The surface potential distribution resulting from such a dipole has been computed and is shown as a family of curves in Appendix C1.
3. The response distribution predictions in table 9.3 are appropriate sections of this distribution assuming the following:-

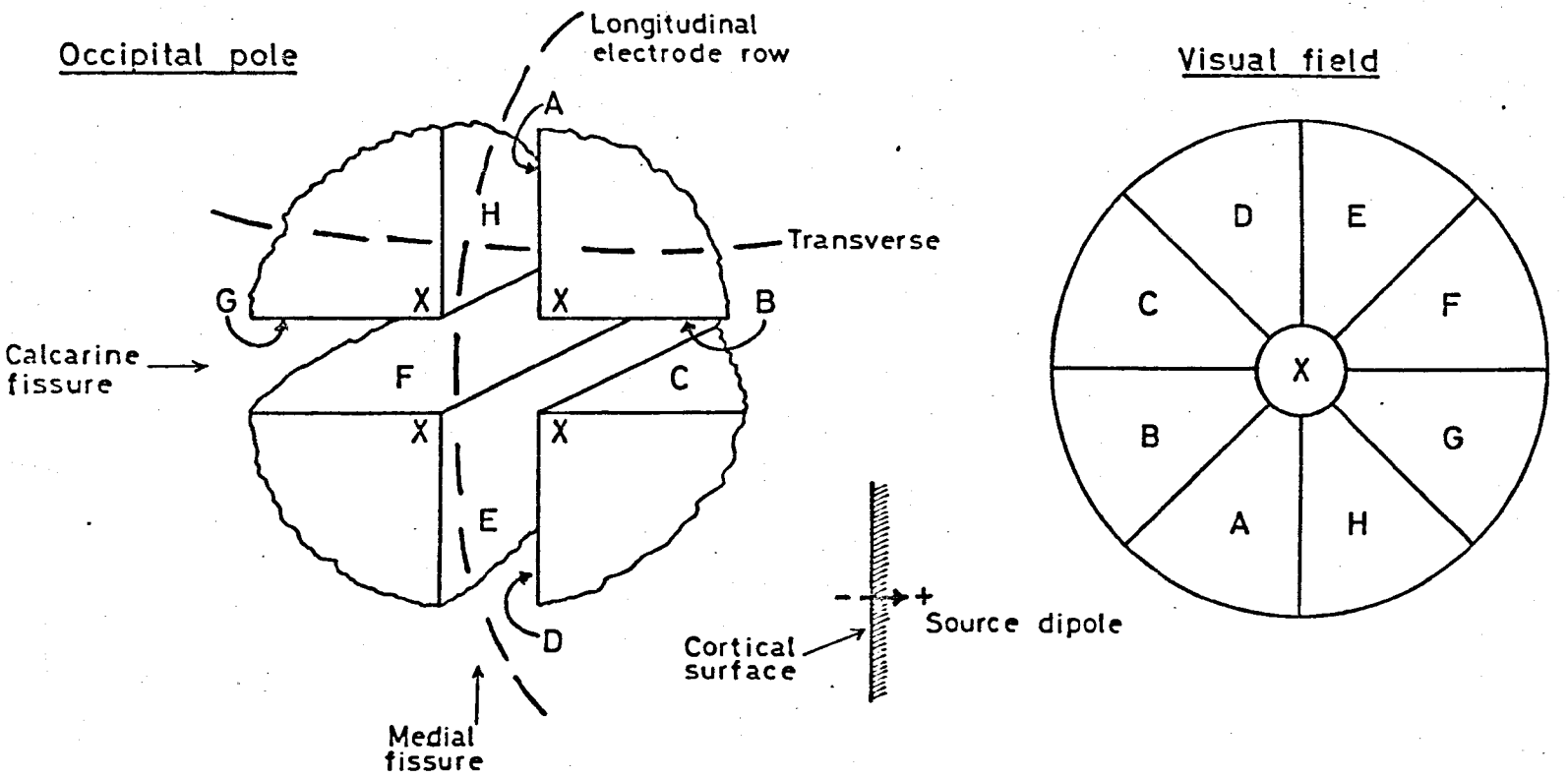


Fig. 9.12 Idealised Model of Striate Cortex

Table 9.1 Striate Half Field Responses

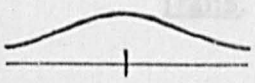
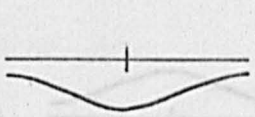
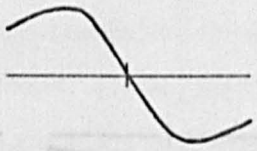
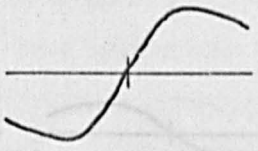
	Stimulated Areas	Effective Areas	Long.	Trans.
	G H A B	G B		
	C D E F	C F		
	E F G H	E H		
	A B C D	A D		

Table 9.2 Striate Quadrant Responses

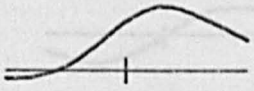
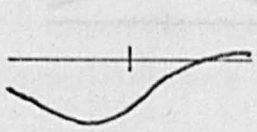
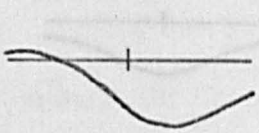
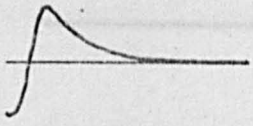
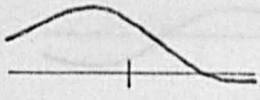
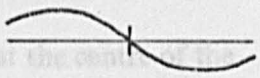
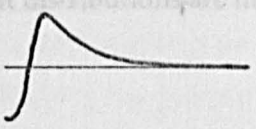
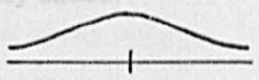
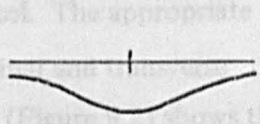
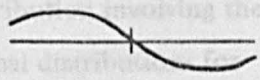
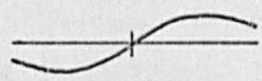
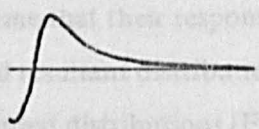
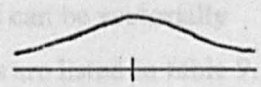
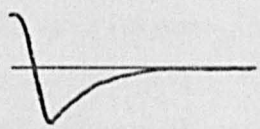
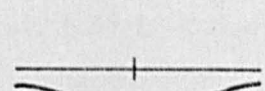
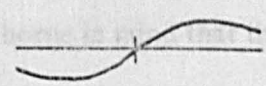
	Stimulated Areas	Effective Areas	Long.	Trans.
	A B	A B		
	C D	C D		
	E F	E F		
	G H	G H		

Table 9.3 Striate Octant Responses

Stimulated Area		Long.	Trans.
	H		
	G		
	F		
	E		
	A		
	B		
	C		
	D		

a. Scalp effective radius = 9 cm.
b. The striate cortex dipoles are all very close to the midline.
c. Depth of striate cortex dipoles = 2.5 cm.
d. The occipital pole is approximately under the inion.
e. Adjacent electrodes (at 2.5 cm separation) subtend about 16° at the centre of the sphere.

4. For the ½ and ¼ fields these primary octant distributions are merely added.

Half-field Responses

Each half field will excite four of the regions A–H. However, in each case the dipoles in two of these regions will be oppositely directed and thus will tend to cancel. The appropriate areas are listed in table 9.1, which also shows the calculated longitudinal and transverse distributions expected. Comparison with the measured distributions (Figure 9.2) shows the agreement to be quite good. Table 9.1 and the plots of Figure 9.2 have been laid out similarly to aid the comparison. Notable exceptions are any SH distribution involving the lower right hand quadrant, and the left and right half field longitudinal distributions for subjects SH and MAS. Theory predicts zero responses which are not observed in the latter cases.

Quadrant Field Responses

Again refer to Figure 9.12. Each quadrant excites two of the regions A–H. These will be perpendicular to each other and we shall assume that their responses can be vectorially added. The quadrant areas and the calculated resultant distributions are listed in table 9.2. These again compare very well with the measured distributions (Figure 9.3) although there are exceptions.

Octant Field Responses

Calculated distributions are listed in table 9.3 for the eight octant regions A–H. Comparison with the appropriate measured distributions for the four subjects shows a fair degree of agreement, although it is now less precise. When comparing it should be borne in mind that the

zero level could be shifted.

Perhaps the most obvious discrepancies are the longitudinal distributions for octants adjacent to the vertical meridian. Theory predicts zero response for these, but the measured responses are frequently as big as those for the horizontal octants.

Eccentricity of Stimulus Pattern

Refer to Figure 9.8. It is known from anatomical studies that the central foveal region projects to the exposed area of striate cortex at the occipital pole – or to the regions marked X on Figure 9.12. Moving into the periphery the projection gets progressively deeper into the interior medial and calcarine fissures.

Thus we should expect that those parts of the visual field giving C1 responses most in agreement with our model would be towards the periphery of the field. This is indeed the case as Figure 9.8 shows. The central 1° of the field appears to contribute very little to the C1 distribution, and most of the half field response comes from beyond 2° from the centre.

In addition it is observed that the central 1° and 2° distributions are much more interindividually variable for C1 than for C2 (see Figure 9.9). This could be the result of small, but topographically variable, fissures known to exist towards the posterior end of the calcarine fissure. Contributions from the exposed striate regions (X) could also be responsible for the vertical octant field discrepancies noted at the end of the previous section.

9.4.3 Component C2

Suppose this component comes from the extrastriate cortex on the upper and lower surfaces of the occipital lobe. In this case the topography of the cortex is less complicated. Most of the extrastriate mapping will be on the outer surfaces of the lobes, except perhaps some of the field near the vertical meridian, part of which may well be represented on the mesial surfaces of the two hemispheres. Whereas with the striate cortex we could reasonably assume upper/lower symmetry, this is certainly not the case for the extrastriate. The dipole sheets representing the upper and lower half fields will be roughly perpendicular, as was assumed both by Jeffreys [84] and Michael and Halliday [111].

The regions representing the visual field in the extrastriate are shown in Figure 9.13. The cortical surfaces are likely to be rather curved, and thus we may expect to have more difficulty in calculating the dipole fields for the smaller areas of stimulation. Hence we shall not attempt to predict individual octant responses from the model but restrict ourselves to the half and quadrant fields.

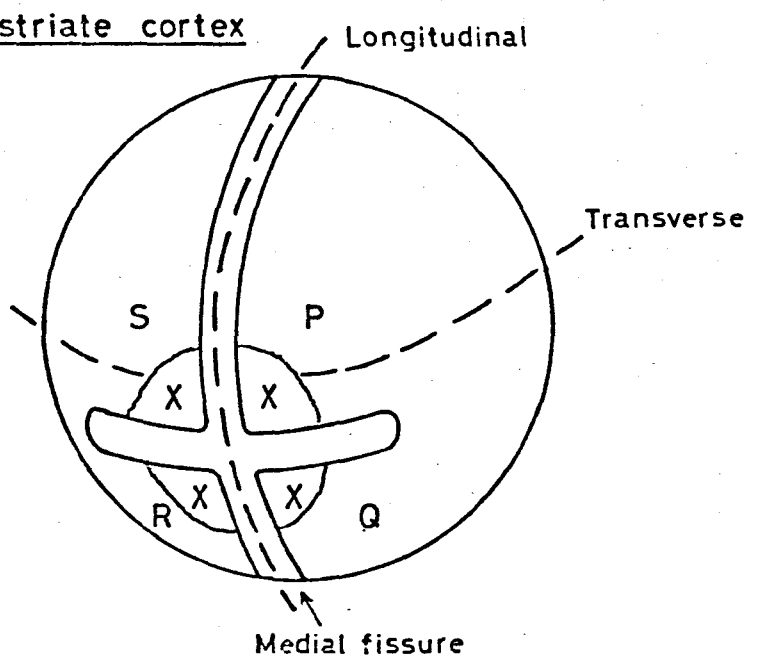
Suppose that the extrastriate cortex is laid out roughly as shown in Figure 9.13. The dipole sheets representing the lower half field regions P and S will have equivalent dipole directions perpendicular to the scalp surface and, for the two quadrants, angled slightly away from the midline. On the other hand, the dipole sheets representing the upper half field regions Q and R will give equivalent dipole directions approximately parallel to the scalp surface. These may also be angled away from the vertical medial plane, but less so than for the lower half field projection.

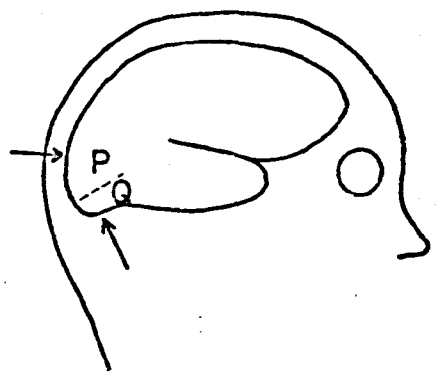
The dipole model described above was used to calculate the extrastriate quadrant distributions and these are shown in table 9.5. The assumptions were:-

a. The lower half field dipoles are directed 15° away from the midline and are at a depth of about 1.5 cm below the scalp surface. In this case the curves of Appendix C2 were used. These give the potential distribution for a dipole *parallel* to the radius vector.
b. The upper half field dipoles are directed 10° away from the midline and are at a depth of about 2.5 cm below the scalp surface. Appendix C1 curves were used.

C2 Quadrant Field Responses

The calculated distributions for the quadrant fields are shown in table 9.5. Each has a simple monopolar form, and it must be stressed that these are only very approximate, especially for the longitudinal distributions, where the only valid prediction we can make would be the polarity of the distribution. However, they are seen to agree well with those measured (Figure 9.7) although there are exceptions, notably that JSC shows very small responses to the lower half field quadrants (Figure 9.7c), and subj. SH (Figure 9.7d) shows predominantly negative upper field responses, whereas theory predicts positive ones.





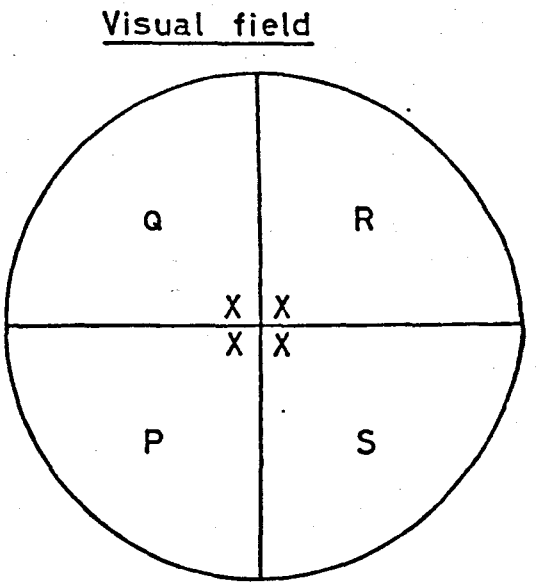


Fig. 9.13
Extrastriate Sources - Idealised Model

Table 9.4 Extrastriate Half Field Responses

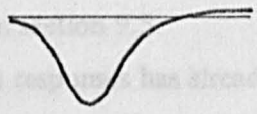
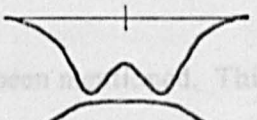
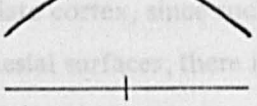
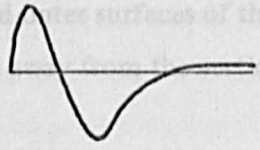
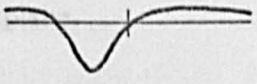
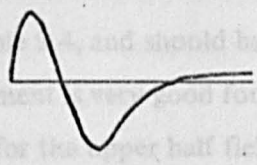
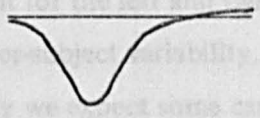
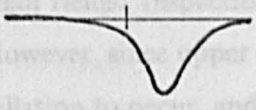
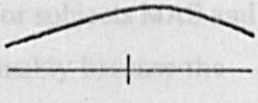
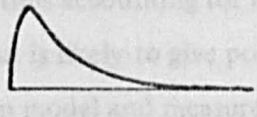
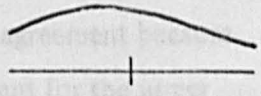
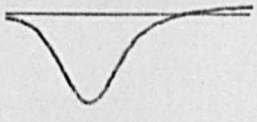
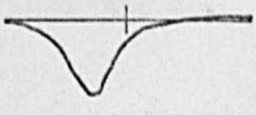
Stimulated Areas	Long.	Trans.
P S		
Q R		
R S		
P Q		

Table 9.5 Extrastriate Quadrant Responses

Stimulated Area	Long.	Trans.
P		
Q		
R		
S		

All subjects except SH show positive longitudinal distributions for the upper field quadrants, in agreement with the model. However it is obvious that the measured distribution is broader and has a maximum further forward than the dipole model predicts. Some possible explanations for this are suggested in section 9.5.

The left-right similarity of the C2 quadrant responses has already been mentioned. This is strong evidence *against* the hypothesis that C2 comes from the striate cortex, since such a source would involve oppositely directed dipoles on the internal mesial surfaces; there is no sign of this in the distributions.

Many of the transverse quadrant distributions show contralateral maxima. This is compatible with the model in that the curved outer surfaces of the extrastriate cortex would give equivalent dipoles angled slightly away from the vertical plane.

C2 Half Field Responses

Predictions from the model are shown in table 9.4, and should be compared with the observed distributions of Figure 9.6. Agreement is very good for the upper and lower half fields, which show large responses, positive for the upper half field, negative for the lower. This is because the constituent left and right quadrant fields have very similar distributions, and summate to give the bigger, basically monopolar, half field distributions. The only anomaly is the upper field distribution for SH which is negative.

By contrast good agreement is not apparent for the left and right half fields. Inspection of Figure 9.6 also shows a high degree of inter-subject variability. However, since upper and lower field quadrants are of opposite polarity we expect some cancellation to occur, and some of these distributions are quite small (e.g. left half half fields for subjects MAS and JSC). In most cases, however, the cancellation is incomplete, presumably because the dipoles representing the upper and lower fields are not parallel. In fact their relative orientation may be very subject dependent, thus accounting for the differences observed. The model predicts a bipolar distribution, but is likely to give poor agreement because of the above mentioned discrepancy between model and measurement for the upper field quadrants.

C2 Annular Regions

Refer to Figure 9.9. These results show clearly that for C2 (in contrast to C1) a much greater proportion of the response comes from the central part of the field, particularly for the upper half field. For subj. DAJ almost the entire upper field response comes from the central 1°. (Subj. SH again shows anomalous results).

These results indicate that if the extrastriate source location for C2 is correct, the cortex deep underneath the occipital lobe, corresponding to the very top of the visual field, contributes very little to the response.

This is not true for the lower half field, where both foveal and peripheral representation in the extrastriate cortex lie exposed on the top surface of the occipital lobe. The response distributions behave as we might expect from these considerations, adding extra evidence to support the hypothesis that the C2 component comes from the extrastriate cortex. The intersubject variability is less for these C2 annular regions than for C1, no doubt reflecting the relative flatness of the extrastriate, compared with the highly convoluted striate cortex.

9.4.4 Influence of Reference Electrode

Figure 9.11 shows that the right ear lobe location of the reference electrode used for all the previous results is not too critical. Changing the reference to either the chin or the left ear lobe does not substantially alter the distributions. The importance of reference electrode position should not be under-estimated however. (Michael and Halliday [111] have reported on a case where the choice of reference electrode position significantly affected the conclusions drawn from the results.) If our assumption of dipole-like sources is correct, every measurement we make is a potential difference between two points in the dipole field, and thus the position of both electrodes is important. No reference is truly 'indifferent', as some reported discussions on the subject assume. However, with multi-electrode recording it is much more convenient if a reference can be chosen which is in a region where the dipole field gradients of all sources being considered are small, so that the position of the reference is not critical. That the right ear lobe reference meets this condition is shown by the result of Figure 9.11. Note too from this figure that for left and right half field stimuli the small responses actually measured on the two ear lobes (with respect to the chin) are compatible with the dipole model proposed.

9.5 Further Discussion – Mainly on Limitations and Disagreements

9.5.1 Limitations of the Cortical Model

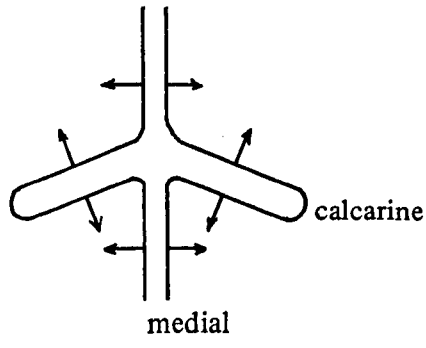
Many of the anomalous distributions observed can probably be explained by individual peculiarities in the cortex of the subject concerned, but this could not be checked. Perhaps the most severe unknowns are the orientations of some of the internal cortical surfaces with respect to the surface of the head. A good example is the plane of the calcarine fissure. The angle that this makes with the surface is probably variable with subject and so also would be the zero potential plane of any dipole source in the fissure. This may explain why some C1 longitudinal upper and lower half field distributions are bipolar for some subjects, and not for others.

The assumed 'square-cornered, smooth surfaced' model of the cortex is obviously only a very crude approximation. The real cortex is heavily convoluted, and particularly at the posterior end of the calcarine sulcus, has many small interindividually variable fissures. These small fissures would tend to make the response to smaller stimulus areas less predictable, and variable with subject – as was observed. On the other hand for large stimulus areas the perturbations caused by small fissures would tend to cancel, resulting in good agreement with theory for the half field responses.

It is sometimes observed that the two octant distributions for a given quadrant are more similar than the dipole model would predict. This suggests that there is some overlap or spill-over from one octant projection to its neighbour. Several possible reasons are advanced for this. It may be that the octant projection is not quite as we have supposed. The transition from vertical to horizontal cortex may not coincide exactly with the 45° directions in the visual field. The cortex has rounded corners, also tending to make octant responses similar. It is also possible that eye movements could be the cause of this overlap effect.

A further deviation could occur if the calcarine fissure was not horizontal (or perpendicular to the medial fissure). The effect here would be to make the two adjacent octant responses similar in one half field (upper or lower), but opposing in the other half field.

This is shown below, where we suppose the fissure to be angled downwards.



Some of the results for C1 actually show this effect (subjs. DAJ, MAS, and JSC in Figures 9.4 and 9.5).

The electrical characteristics assumed for the model are also grossly over-simplified. The sources are really dipole sheets, not isolated dipoles. We have also neglected the layers of skull and scalp which have differing conductivities. Both of these factors tend to make the distributions more diffuse and widespread – a feature which is in fact observed. The surface distributions are broader than seems justified from the cortical dimensions. As Vaughan [160] has pointed out, the signals from large dipole sheet generators are attenuated much less with increasing depth than single dipoles. This could explain why we get quite large responses from some peripheral field areas which we know project to regions quite deep in the cortex.

The additive property of the responses to different stimulus areas holds well for the half, quadrant and octant fields, but it is not so good for the annular regions. This can be seen by visual inspection of Figures 9.8 and 9.9, although the summated annular region distributions are not actually plotted. The additive property may break down in this case because dividing a pattern up into annular regions introduces relatively more extra 'edge' than radial division. The edge itself probably contributes something to the response.

9.5.2 Comments on the Analysis Method

It seems evident that the technique of isolating components and plotting them as spatial distributions has proved vastly superior for investigating underlying AEP mechanisms than mere inspection of the AEP traces.

The method does however rely on latency constancy of the components. Previous results by Jeffreys have shown that latency varies with over-all luminance, but seems independent of pattern size or location. For the current series of experiments luminance was held constant, and component latency variations were then much less than the durations of the sampling periods.

Although the latency of the various components is reasonably constant, the components do overlap somewhat. Thus, since the samples were of finite duration, there may be some contamination of one component with another. This however is only really serious when we have a very large component next to a very small one.

The 'baseline to peak' measure for each component seems amply justified in view of the apparent independence of successive components. A 'peak to peak' measure, involving two components, has been used by a number of workers (in particular Halliday and Michael[63,111] in source location studies) and in view of the results presented above the meaningfulness of this measure must be questioned. Nevertheless with a baseline to peak measure there is still the problem of choosing a suitable baseline or zero-level.

The 37 ms period immediately following the stimulus onset was used here. This comes before the first components of the response and proved to be adequate. Estimates of error in the components must (and did) include residual noise in the zero level sample.

Stray noise during the zero level sample is often common to all electrodes, causing a shift in the distribution, but maintaining its shape. This holds only if all electrodes are recorded simultaneously, and demonstrates once again the desirability of simultaneous recording at all electrode positions.

9.6 Conclusions

1. Measurement of pattern appearance AEP scalp distributions has shown that different components have spatially separate sources.
2. Responses to stimulation of different retinal areas can be linearly summated.
3. The longitudinal and transverse component distributions as a function of retinal area stimulated are consistent with the hypothesis that the C1 component (52–80 ms) comes from the striate cortex, and the C2 component (85–113 ms) from the extrastriate.

4. In spite of broad agreement between the measured distributions and those predicted some anomalies were observed, which could not be explained. Peculiarities in the cortical topography of the subject concerned may be the cause of these.

CHAPTER 10: EVOKED POTENTIAL STOCHASTIC SEARCH TECHNIQUES

10.1 Introduction

In this chapter we enquire whether it is feasible to make the computer conduct an automatic search operation which finds the stimulus conditions necessary to produce a desired EP response characteristic. The results presented are very preliminary. They represent feelers into the possibility of evoked potential automatic searches, and into the problems involved. Nevertheless, although practical reasons limited the experiments to searches in one dimension, the method was successful, and shows promise for further development.

We define the search procedure with reference to the diagram of Figure 10.1(a). The 'experimenter', man or machine, adjusts the 'm' dimensions of the stimulus to achieve maximum (or minimum) response, f. In general he is not interested in the path taken to reach the optimum, other than that it should be efficient.

To make such a search possible the dependence of the response on the stimulus should be continuous and well-behaved, a condition which we shall assume holds for the physiological system under investigation.

Automatic search methods fall into two classes, depending upon whether or not the response is affected by noise.

In the noise-free case a given stimulus value gives precisely the same response each time it is presented. In the noisy situation this is not so, and the measured responses are assumed to be randomly distributed about a mean value, which is defined as the 'true' value for that particular stimulus.

The noise-free and noisy situations in general demand different search techniques, and the latter only will be considered further. For a review of both methods see Wilde [166]. The 'noisy' search (or stochastic search) has been considered theoretically by a number of workers, who have established stringent conditions for convergence. This work will be briefly reviewed in the next section. The section following that will describe the method selected for the evoked potential search, and the final sections of this chapter will present some experimental results obtained.

Fig.10.1(a) SEARCH LOOP

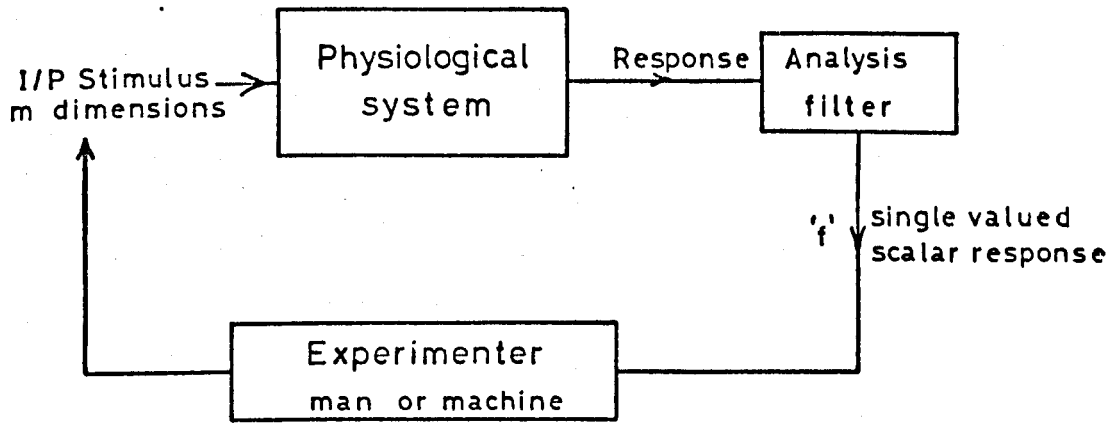
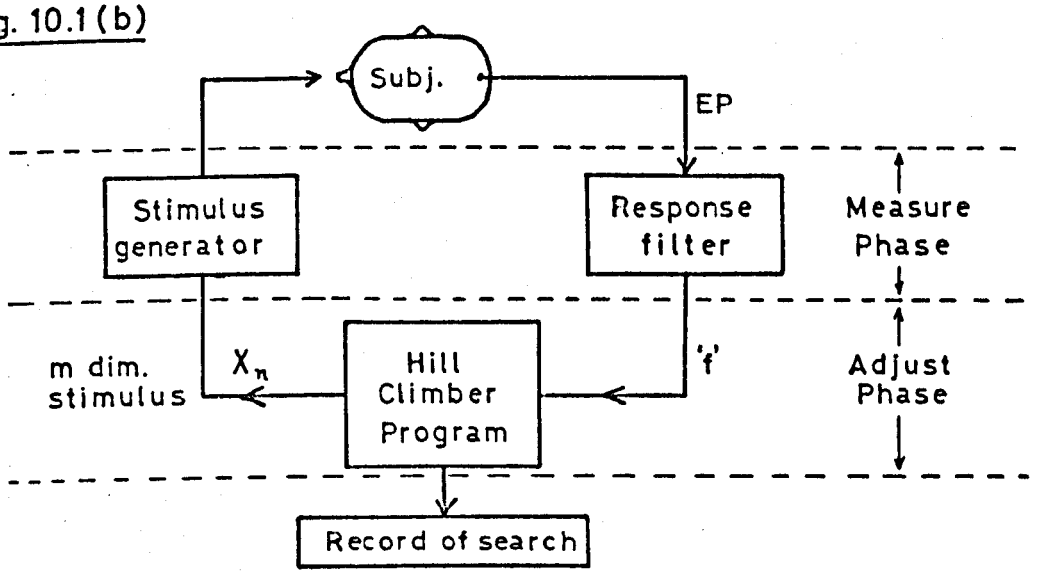
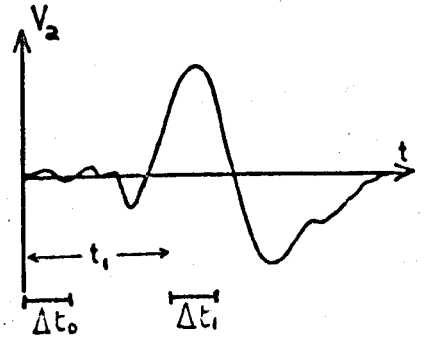


Fig. 10.1(b)





$$f = \frac{1}{\Delta t_1}\int_{t_1}^{t_1+\Delta t_1} V_a\,dt - \frac{1}{\Delta t_0}\int_{t_0}^{\Delta t_0} V_a\,dt$$

Fig.10.1(c) DEFINITION OF RESPONSE

10.2 Review of Stochastic Search Procedures

10.2.1 Theory

The various methods described in the literature are all basically similar and assume the separability of 'signal' and 'noise'. In simple terms all procedures involve measuring the response to a stimulus and then selecting the next stimulus on the assumption that the *measured response was the 'true' value and not affected by the noise.* On this basis, if the noise is random, its effects will average out as the search continues and the procedure will eventually converge on the desired optimum. The theoretical work reviewed is mainly concerned with defining the necessary conditions for convergence, which must be met by the stimulus-response function, the recursive relation, and the noise.

Robbins and Monro [177] proposed a search scheme to find a root of the equation:-

$$f(x) - K = 0$$

where f(x) is subject to noise. They discussed the conditions under which the scheme would converge.

Kiefer and Wolfowitz [93] adapted this procedure to find the maximum (or minimum) of the function f(x). Their recursive relation was:-

$$x_{n+1} = x_n \pm \frac{a_n}{2c_n}\left[f(x_n + c_n) - f(x_n - c_n)\right] \quad \text{.....10.1}$$

If the procedure is followed, then as $n \to \infty$, x_n will converge on a maximum or minimum of f(x).

'a_n' and 'c_n' are numbers which must obey certain rules if convergence is to be achieved. In general a_n and c_n will *decrease* with the iteration count n. c_n is seen to be a 'spread', or increment, parameter over which the gradient of the function is measured, whilst a_n is a 'weight' parameter governing how much value we assign to the newly measured gradient, and thus how much we shift the operating point. Note that two measurements of f are needed at each iteration.

The methods proposed by the above authors were extended into a general theory by Dvoretzky [51], who formulated a set of weak conditions for convergence, and showed that

some of the limits set by previous workers were in fact unnecessary. Dvoretzky isolates the noise component from the error-free deterministic search procedure (as embodied in the recursive relation) and places separate conditions on each. We shall not give his conditions in full as they are rather abstract formulations. Instead we shall give his restrictions on the noise, and sequences for a_n and c_n in eqn. 10.1 above, which satisfy his conditions. Thereby their meaning is more readily apparent.

Noise Conditions

If R_n = noise component of the response, and E[x] = mean of x

then $$E[R_n] = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots 10.2$$

$$\sum_{n=1}^{\infty} E[R_n^2] < \infty \quad \ldots\ldots\ldots 10.3$$

The first condition merely states that the noise must be unbiassed, otherwise the operation of the recursive relation will be distorted. The second condition states that the variance of the accumulated error due to the noise must be finite. Both these conditions are normally met by EEG 'white' noise. Note that there is no restriction on the stationarity of the noise, which is fortunate, as this does not always hold for EEG.

Other Conditions

$$\left.\begin{aligned} \lim_{n\to\infty} a_n &= 0 \\ \lim_{n\to\infty} c_n &= 0 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots 10.4$$

$$\sum_{n=1}^{\infty} a_n = \infty \quad \ldots\ldots 10.5 \qquad \sum_{n=1}^{\infty} \left[\frac{a_n}{c_n}\right]^2 < \infty \quad \ldots\ldots 10.6$$

These ensure that the search does converge (eqn. 10.4), but also that it does not happen too soon (eqn. 10.5). Eqn. 10.6 states that the spread parameter, c_n, must decrease faster than the weight parameter, a_n.

The sequences:- $a_n = \frac{1}{n}$, $c_n = \frac{1}{n^p}$ $(p > 1)$

satisfy the above conditions.

With p = 4, they were used by Wolfendale [169] in psychophysical experiments, and also in the work reported here.

The Kiefer–Wolfowitz method is for search in one dimension only. Blum [12] and Sacks [138] have extended it to 'm' dimensions, using slightly different recursive relations:-

Blum

$$X_{n+1} = X_n \pm \left(\frac{a_n}{c_n}\right)\left\{\left[f(X_n^1 + c_n) - f(X_n^1)\right], \ldots\ldots\ldots\ldots, \left[f(X_n^m + c_n) - f(X_n^m)\right]\right\}$$

Sacks

$$X_{n+1} = X_n \pm \left(\frac{a_n}{2c_n}\right)\left\{\left[f(X_n^1 + c_n) - f(X_n^1 - c_n)\right], \ldots\ldots\ldots\ldots, \left[f(X_n^m + c_n) - f(X_n^m - c_n)\right]\right\}$$

where $X_n = (x_n^1, x_n^2, x_n^3, \ldots\ldots\ldots\ldots, x_n^m)$
is now a vector representing the position in the search space at the n^{th} iteration,
and $(X_n^i \pm c_n) = (x_n^1, x_n^2, \ldots\ldots\ldots\ldots, x_n^i \pm c_n, \ldots\ldots\ldots\ldots, x_n^m)$
(Superscripts refer to dimension, subscripts to iteration.)
Thus at each stage the gradient is measured independently along each of the dimensions. This results in (m + 1) measurements per stage for the Blum method and 2m for the Sacks method. In spite of the greater number of measurements, the Sacks relation is claimed to be more efficient.

The above theorists have been concerned with proving that the search will converge. Others have proposed ways of improving the speed of convergence, but always within a system which complies with the Dvoretzky conditions. Among these Kersten [91] has suggested that the factors a_n and c_n should be decreased *only* when the gradient of the response changes sign. This keeps the search moving quickly in areas away from a peak. Kersten has also

suggested a speed-up feature called 'step-normalisation', whereby only the sign of the measured gradient is used, not its absolute value. This accelerates the search over flat regions.

10.2.2 Other Experimental Work

Computerised search methods have been used in psychophysical experiments by Taylor and Creelman [152], Uttal [157], and Wolfendale [169,170].

Wolfendale used basically the Sacks relation with the Kersten speed-up methods. His technique showed the greatest applicability in the EP field and was modified for the present work.

In the field of EPs, response–stimulus feedback (using a computer) has been tried in an operant conditioning situation by Fox and Rudell [157] for cats, and Rosenfield et al. [136] for humans. However, these are not strictly search procedures of the type considered in this chapter.

10.3 The Evoked Potential Search Method

10.3.1 General Remarks

In EP work a number of factors militate against fast efficient hill climbing:-

1. The noise is high and typically 4 – 5 times the signal.
2. The noise is not stationary and may not be independent of the stimulus.
3. The human nervous system is very labile, and the form of the physiological function being explored may change with the applied stimuli. (The phenomenon of the 'spongy hill'.)

A further practical consideration is that the search must be done on-line within a reasonable experimental time scale, and with a fairly small computer. This precludes the use of very complex mathematical operations. Of the difficulties mentioned, the high noise does not in principle prohibit convergence, it merely prolongs it. However the severity of the noise may well influence the search method chosen. The stationarity of the noise is not a necessary condition of Dvoretzky and will be ignored. The spongy hill phenomenon was actually observed and will be considered later.

It was decided to make the search multidimensional and to use the Kiefer–Wolfowitz relation with a simpler extension to m dimensions than either the Blum or Sacks methods—dispensing with the independent gradient measures along each dimension, which these methods use. Since the high noise means that most of the gradients measured will be wrong anyway, it was considered reasonable to make each successive measurement part of an advance along all dimensions. Thus the next stimulus point was chosen partly on the basis of the gradient measured from the previous two readings, and partly from a randomisation process. The result is a simple, quickly computed, recursive relation, as described below.

10.3.2 Recursive Relation and Explanation

Upper case variables refer to vectors of m dimensions. Lower case variables refer to scalars, and where appropriate the superscipt refers to the dimension.

Let $X_n = \left[x_n^1, x_n^2, x_n^3, \ldots\ldots\ldots\ldots, x_n^m \right]$ — actual stimulus vector.

$\bar{X}_n = \left[\bar{x}_n^1, \bar{x}_n^2, \bar{x}_n^3, \ldots\ldots\ldots\ldots, \bar{x}_n^m \right]$ — 'best-guess' value in stimulus space.

$n = 1, 2, 3, \ldots\ldots\ldots\ldots\ldots\ldots$ — iteration count.

f_n = measured response to stimulus Xn.

The recursive relation is:-

$$\bar{X}_{n+1} = \bar{X}_n \pm w_n . \Delta f_n . \Delta \tilde{X}_n \qquad \text{.....(10.7)}$$

with

$$X_{n+1} = \bar{X}_{n+1} + s_{n+1} E_{n+1} \qquad \text{.....(10.8)}$$

where $\Delta f_n = f_n - f_{n-1}$

and $\Delta \tilde{X}_n = \dfrac{X_n - X_{n-1}}{|X_n - X_{n-1}|}$ — unit vector along direction $Xn - X_{n-1}$

$$w_n = \frac{w_o}{n} \quad , \quad s_n = \frac{s_o}{n^4}$$

$$E_n = \left[\epsilon_n^1 , \epsilon_n^2 , \epsilon_n^3 , \ldots\ldots\ldots , \epsilon_n^m \right]$$

Notes

1. w_n and s_n correspond to the parameters a_n and c_n respectively in the Kiefer– Wolfowitz relation.
2. E_n is a vector of m independent gaussian random numbers each of mean zero and variance unity. This is the origin of the randomisation process.
3. The procedure is initiated as follows:-

$$f_o = 0 \quad , \quad X_o = \bar{X}_1 = X_s$$

$$X_s = \frac{P_{start} - P_{min}}{P_{max} - P_{min}}$$

$$P_{max} \geqslant P_{start} \geqslant P_{min}$$

P_{min} , P_{max} , P_{start} , w_o and s_o are input parameters.

Explanation

Eqn. 10.7 is the basic recursive relation (+ for a max. search, – for a min. search). $\bar{X}_n$ represents the 'best guess' of the position of the maximum or minimum at the start of the n^{th} stage. However the actual stimulus presented at stage n is not $\bar{X}_n$ but X_n, which differs from $\bar{X}_n$ by the randomisation factor $s_n E_n$ (eqn. 10.8). After the n^{th} stimulus has been presented and its response measured, $\bar{X}_n$ is modified according to eqn. 10.7.

The operation is best illustrated by means of the diagram in Figure 10.2, which shows a 2D search. $\bar{X}_n$ is at point A. The program calculates X_n in a random direction in the space around $\bar{X}_n$ (point P), and the stimulus is presented at P. As a result $\bar{X}_n$ is modified to $\bar{X}_{n+1}$ (point B), from which point another random direction is selected for the stimulus X_{n+1} (point Q), and the operation repeated. Note that the vector AB is parallel to ΔX_n = OP, and thus the shift in $\bar{X}_n$ always takes place along the direction of the difference between the two previous stimuli.

Since the spread parameter s_n decreases quite rapidly with n, the difference between $\bar{X}_n$ and X_n gets smaller as the search proceeds. Thus the search characteristically starts with a high random activity, with the stimulus position jumping about all over the place. Nevertheless, the accumulating results of each random excursion gradually polarise the

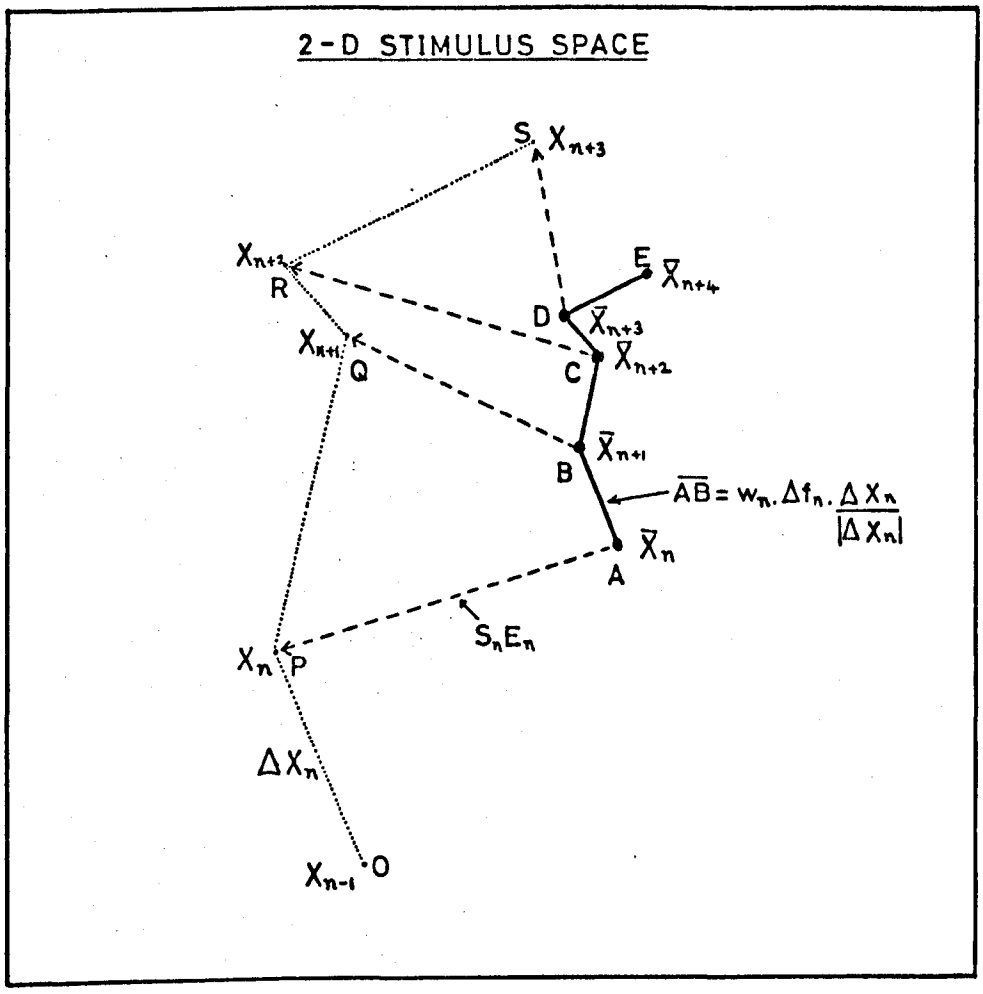


Fig. 10.2 2-DIMENSIONAL STOCHASTIC SEARCH

motion of $\bar{X}_n$, and after a while the process settles down and moves towards the desired optimum. In these later stages it is the w_n parameter which predominates. The randomisation technique proved to be an excellent method for getting the search moving out of any flat regions in the surface being explored.

The above recursive relation has not been shown to meet the Dvoretzky conditions. It is sufficiently close in structure to other relations, which do meet the conditions, to have confidence in it. Subsequent experiments showed that it does lead to convergence.

10.3.3 Action at Boundaries

It is necessary to assign limits to the m-dimensional space being searched. The modification rule when one of the values goes outside the limits can have a profound effect on the search. The rule chosen here was quite simple – values beyond a limit were set equal to the limit. This rule worked very well because the randomisation feature would bring the search away from the boundary if the optimum was within the limits. If the optimum was outside the limits, the stimulus point would remain close to the boundary.

10.3.4 Computer Program Details

The program was divided into two parts:

a. The 'Measure' phase

b. The 'Adjust' phase.

The measure phase was basically the experimenter program described in section 5.2.2, modified slightly to receive an 'm' dimensional stimulus specification from the adjust phase, and transmit back to the adjust phase the value of the response 'f'. (See Figure 10.1(b))

The adjust phase incorporated the hill climber program, which computed the recursive relations, etc. given above. It also kept a record of the progress of the search, and at the end of each run the values of n, $\bar{X}_n$ and f_n were stored on magnetic tape. It was from these run records that the time course plots shown in section 10.4 were made.

Within the adjust phase each component (x_n) of the stimulus vector had a value between 0 and 1, such that 0 corresponded to the external value Pmin., and 1 to the

external value Pmax. Hence if Px is a given external value then:-

$$x_n = \frac{P_x - P_{min}}{P_{max} - P_{min}}$$

The response 'f' was in all cases the difference between the mean amplitudes over two sampling periods, one of which was a zero level sample, as defined in Figure 10.1(c).

This is essentially the same measure as the C1, C2, etc. components of chapter 9 and the running average of section 8.5, except that only one response is included. The latency of the second sample could be adjusted by the experimenter to lie on a particular response peak, exactly as in the running average experiments.

10.3.5 Initialisation

At the start of each search the following information was requested from the experimenter –

m = No. of dimensions

w_o = starting value of w.

s_o = starting value of s.

and for each dimension – Pmin = min. value boundary

Pmax = max. value boundary

Pstart = starting value of this dimension

The initialisation then entered a routine to allow the operator to calibrate the external apparatus against the scales set in the machine. The output stimulus was first set at the Pmin. values for all dimensions, allowing the experimenter to set up the apparatus accordingly. After that Pmax. and Pstart followed similarly and then the program was ready to start the search.

10.3.6 On-line Displays

The on-line CRT display was that used for the running average experiments, see Figure 8.8(a). In addition, the time course of the stimulus parameter Xn (one dimension only) was recorded on an XY plotter. (For the rotating sector experiments the same plotter also controlled the stimulus.)

10.3.7 Initial Trials

Using a one-dimensional search the program was tried out on a simulated hill. This consisted of a partially differentiated pulse, the duration of which was the search parameter. Its amplitude was roughly that of a typical response. Tape recorded EEG was mixed in with this pulse as a source of noise. The program behaved as expected and this trial enabled rough estimates to be made of appropriate values for w_o and s_o.

10.4 Results

One dimensional searches were carried out using the following stimulus dimensions:-

(a) Stimulus duration

(b) Azimuth of a rotating sector pattern.

In other respects the stimuli were of the same type as used in the previous experiments (i.e. brief pattern appearance into an otherwise steadily illuminated blank field), so that the results could be correlated with already known response characteristics. Stimulus type (b) yielded the more important results and will be described first.

10.4.1 Rotating Sector Searches

Experiment 1 – Dependence on Search Parameters

The experimental arrangement is shown in Figure 10.3. The pattern was a 40° sector of 'visual noise', rotated about the centre of the visual field by means of an XY plotter servo. This rotating pattern was fixed into one field of the 2-field tachistoscope (Figure 4.2(b)) and illuminated for 25 ms each cycle. The electrode positions were as shown in Figure 10. This form of stimulus was chosen because:-

(a) It was free from the spongy hill problem.

(b) It was relatively easy to mechanise.

(c) The shape of the hill was known to have some well defined peaks and valleys.

The response peak chosen was C1 (60 –90 ms), and the shape of the hill to be climbed was first mapped out using the normal averaging program, and the same apparatus, taking readings every 25°. This is shown in Figure 10.4.

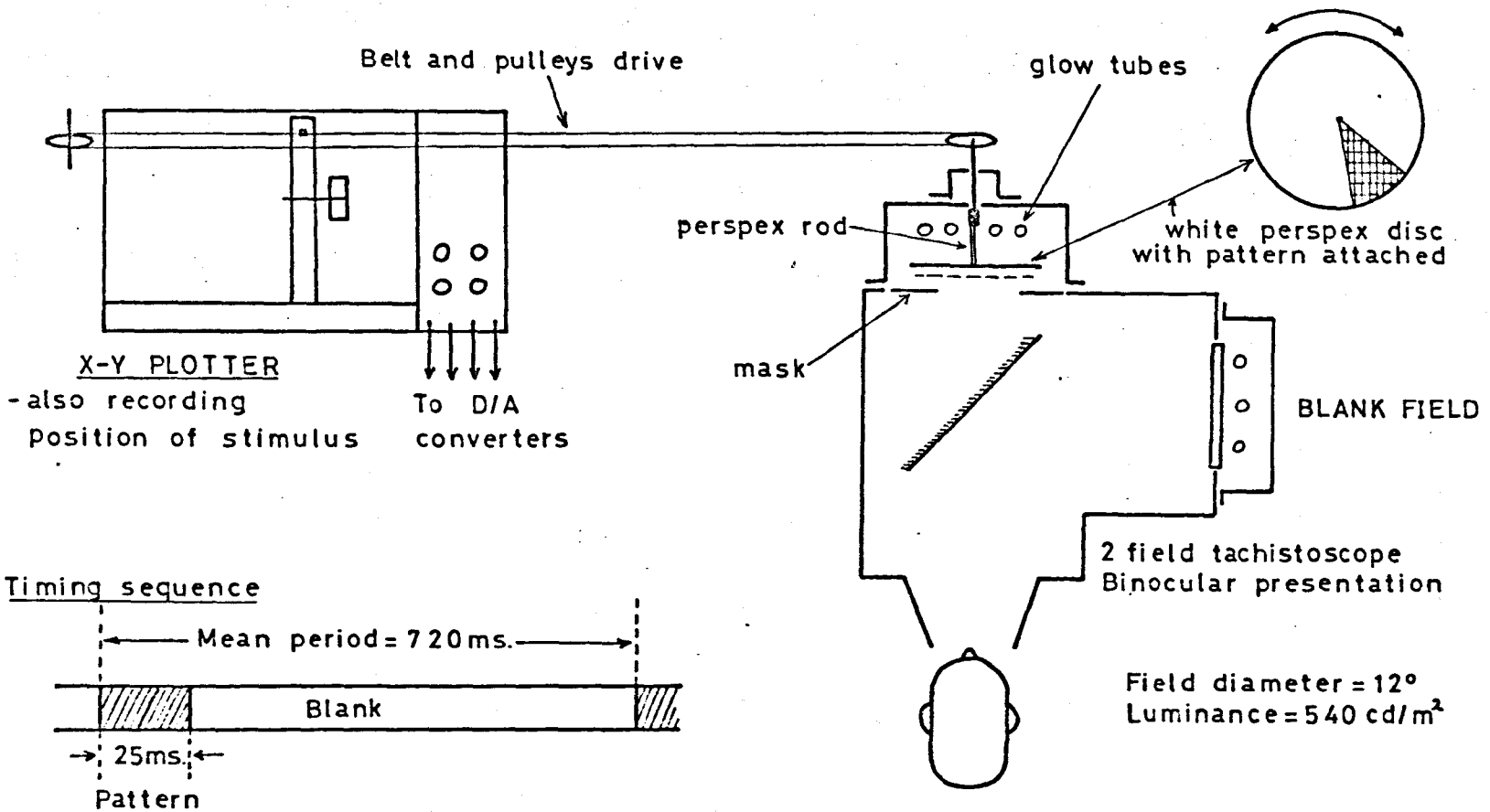
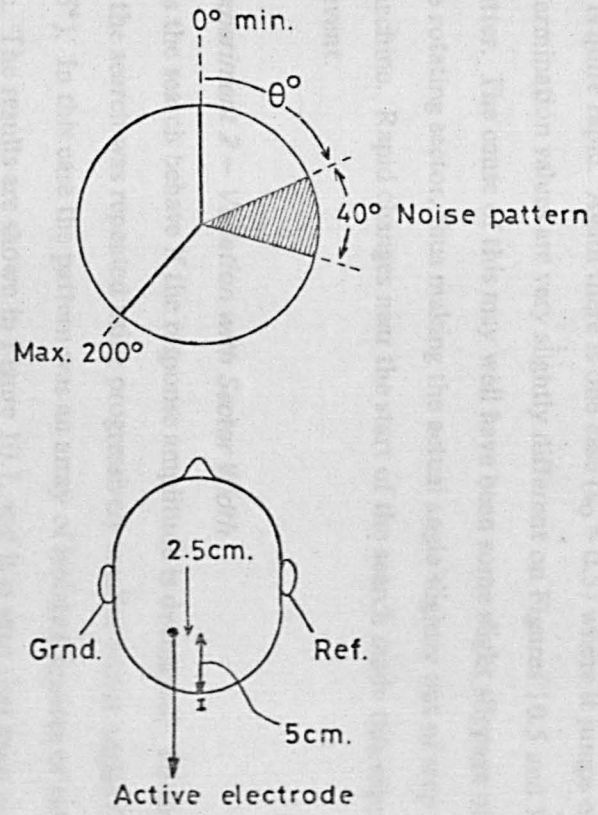


Fig.10.3 EXPERIMENTAL ARRANGEMENT FOR ROTATING SECTOR STIMULUS



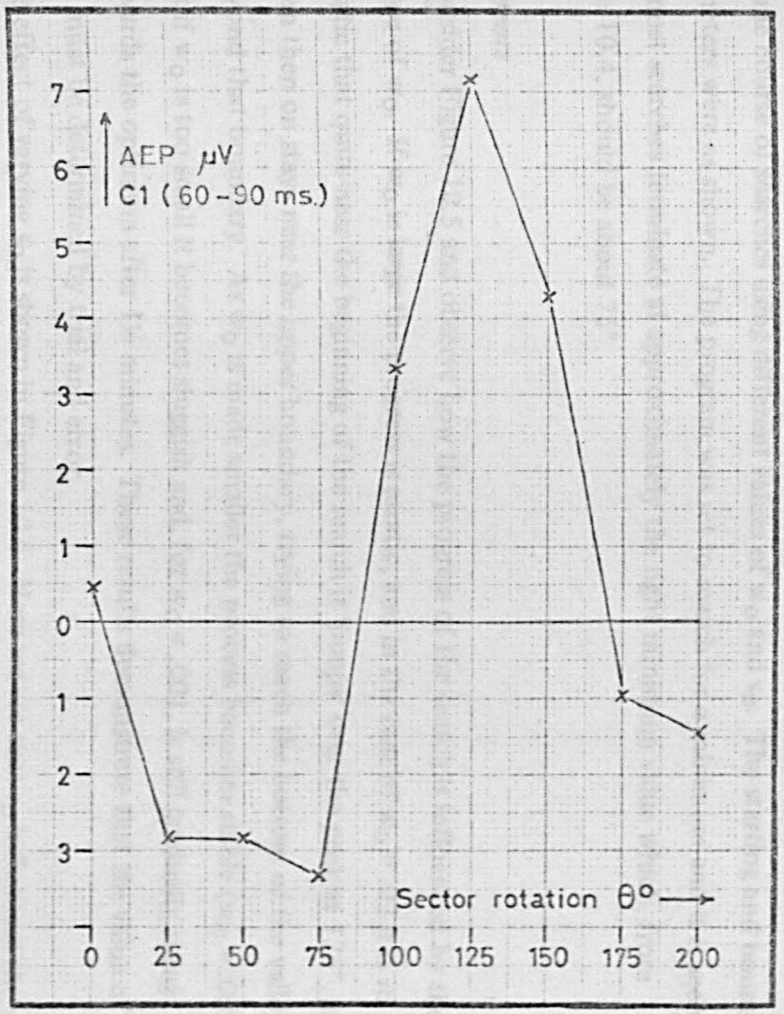


Fig. 10.4 Rotating Sector 'Hill'

This hill was then searched using the hill climber program, and Figures 10.5 and 10.6 show the time course of searches using different values of w_o and s_o. The starting and boundary parameters were as shown. The program was set to search for a minimum and it is seen that most searches terminate at approximately the right minimum value which, from Figure 10.4, should be about 75°.

Comments

1. Consider Figure 10.5 and observe how the progress of the search is influenced by the value of w_o. If w_o is large the progress is erratic, and in the case of $w_o = .02$ it is so erratic that quite near the beginning of the search it 'jumps' over the peak at 125°, and from then on stays near the upper boundary, trying to reach the bottom of the valley beyond that boundary. As w_o is made smaller the process becomes stable ($w_o = .002$), but if w_o is too small it becomes sluggish and, for $w_o = .001$, is still gradually rising towards the optimum after 1½ minutes. These results demonstrate that the value of w_o must be determined by trial and error.
2. The effect of varying s_o is shown in Figure 10.6. Here we see that s_o influences the variability towards the beginning of the search, which is understandable as the decay of s_n is quite rapid. Again there is one case ($s_o = 0.5$) where it jumps over the peak.
3. The termination values are very slightly different on Figures 10.5 and 10.6, particularly the latter. The cause of this may well have been some slight slippage of the belt drive to the rotating sector, thus making the actual angle slightly out of step with that in the machine. Rapid changes near the start of the search made this slippage difficult to prevent.

10.4.2 Experiment 2 – Variation with Sector Width

How does the search behave if the response amplitude is decreased? To answer this question the search was repeated using progressively smaller sector angles (30°, 20°, 10° and 5°). In this case the pattern was an array of isolated squares of side and separation 14′ of arc. The results are shown in Figure 10.7, and it is seen that even with a 5° sector (which was only a single radial row of squares) the search was successful.

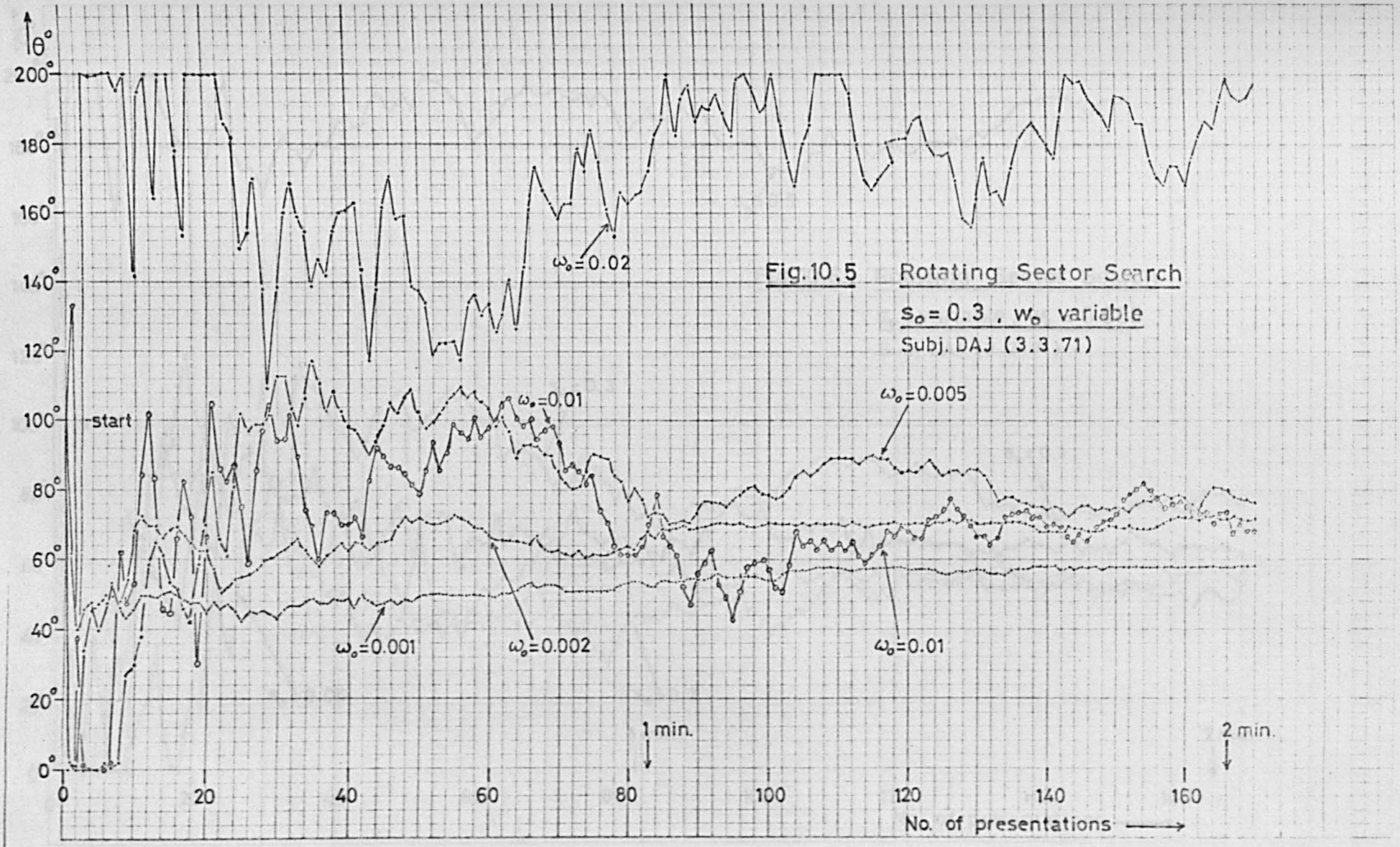


Fig. 10.5 Rotating Sector Search

s_o = 0.3 , w_o variable

Subj. DAJ (3.3.71)

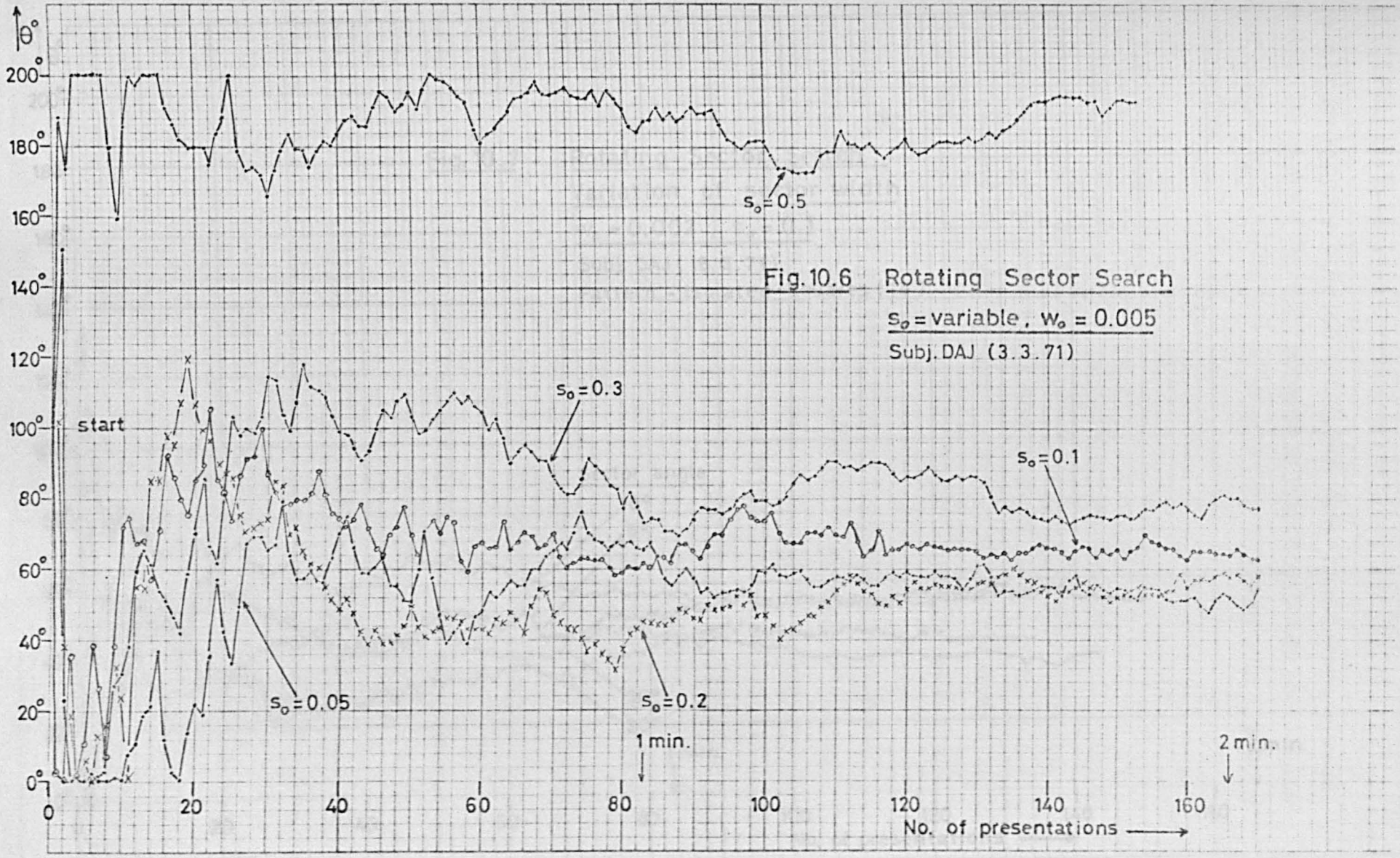
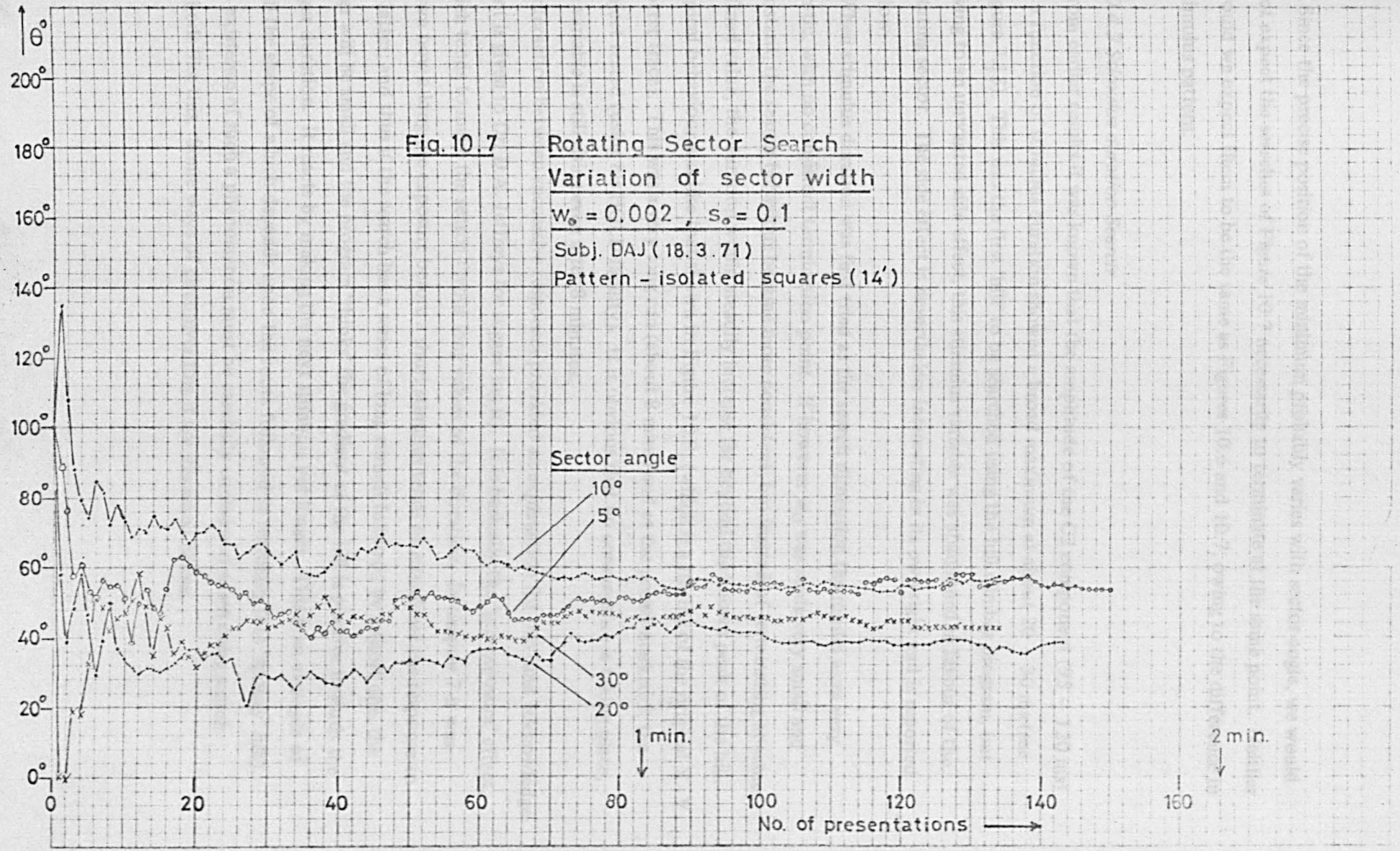


Fig. 10.6 Rotating Sector Search

s_o = variable, $w_o = 0.005$

Subj. DAJ (3.3.71)


θ°
200°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
0
20
40
60
80
100
120
140
160
No. of presentations
1 min.
2 min.
Sector angle
10°
5°
30°
20°
Fig. 10.7 Rotating Sector Search
Variation of sector width
$w_o = 0.002$, $s_o = 0.1$
Subj. DAJ (18.3.71)
Pattern - isolated squares (14')

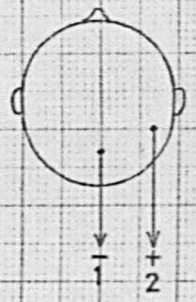
Since the precise position of the minimum probably varies with sector angle, we would not expect the searches of Figure 10.7 necessarily to terminate at the same point. Neither would we expect them to be the same as Figures 10.6 and 10.7, owing to the difference in stimulus pattern.

10.4.3 Stimulus duration Search

From earlier results it was known that the amplitude of the C2 component (95 – 120 ms) as a function of stimulus duration showed a broad maximum at about 20 – 30 ms (see Figure 7.13). This was the first 'hill' to be searched using the hill climber program, but owing to an unwanted side effect, this stimulus variable was abandoned in favour of the rotating sector. The side effect is nevertheless interesting in its own right and is reported below.

When stimulus duration was first tried as the search dimension the results were very erratic, with no consistent termination point. If however w_o was made very small and constant, the search behaviour became more consistent; but instead of terminating at some defined value, the duration would steadily increase far beyond the known peak of the hill. Typical behaviour was like that shown in Figure 10.8, (which is a tracing of the original X–Y plotter trace). This was a very long run (about 8 mins) and at the points marked R the subject rested (using his HOLD facility). It is obvious that no convergence is taking place, the variable is still rising even after 8 minutes.

Interaction between successive responses provided an explanation for this (and acknowledgement is given to Dr. D.A. Jeffreys for suggesting it). It is basically the 'pre-exposure' effect, which tends to make the search favour long values of the duration. In chapter 7 it was shown how a long pre-exposure before a short stimulus tends to attenuate the response to the latter; and thus if the search has a series of long stimuli followed by a short one, the latter will be small and the program 'thinks' the gradient of the hill is positive towards the longer duration. It reacts by making the next stimulus yet longer. This is an example of a hill the shape of which depends upon the route followed in searching it (a 'spongy' hill). The existence of such a phenomenon must be carefully considered when using search methods like this. Some ways of circumventing it are discussed below.



Stimulus - Lower 1/2 field
- Hollow square pattern
- Aperiodic, mean ISP 630 ms.

Subj. DAJ (3.12.70)

1 - 3 cm. above inion
2 - 10 cm. to right

$W_o = 0.00005$, $s_o = 0.2$
+ve search on C2 (97-123 ms.)

Fig. 10.8 Stimulus Duration Search

10.5 Discussion

1. The experiments with the rotating sector have demonstrated that an automatic search is possible with evoked potentials, and under the conditions used the search terminated reliably on the correct optimum. Nevertheless, it must be pointed out that several factors favoured a successful search, and it cannot be guaranteed that with more general conditions the method would be equally successful. The favourable aspects were:-
   1. The hill chosen had a deep valley ($-3\mu V$) adjacent to a large peak ($+7\mu V$).
   2. A well trained subject was used (DAJ).
   3. The search was in one dimension only.

The method shows promise however, and would be worth developing further. This is considered in chapter 11.

2. The spongy hill phenomenon could be a severe limitation on search experiments of this type. It can be overcome by allowing sufficient time between stimuli for the system to recover, but this would give long and inefficient experiments. However, to save time it may be possible to conduct several independent searches in parallel, making use of the recovery period between two stimuli of one search to present stimuli belonging to others.

Two interspersed searches (one for a maximum, the other for a minimum) were used by Wolfendale [170] in a psychophysical experiment. The purpose in this case was to prevent the subject detecting any trends in the sequence of stimuli.

SECTION D

GENERAL DISCUSSION AND CONCLUSIONS

CHAPTER 11: CONCLUSIONS, GENERAL DISCUSSION, AND SUGGESTIONS FOR FURTHER WORK

11.0 Summary of Results

Particular results have been discussed at the end of each chapter, where such discussion was most appropriate. In this final chapter we try to piece together some more general conclusions.

Major conclusions from each experimental chapter are summarised below. In all cases the findings refer to a restricted class of stimuli, i.e. a short pattern appearance (~ 25 ms) into an otherwise continuously illuminated diffuse field.

Pre-exposure Results (chapter 7)

1. Preceding a pattern appearance stimulus with an identical or different (pre-exposure) stimulus attenuated the AEP to the latter. The degree of attenuation depended in detail on the timing and nature of the pre-exposure, but was always greatest when the PE and test stimuli were identical. The results were somewhat inconclusive as to the origin or mechanism of the suppression other than that it was at least partially central.

In the light of the subsequently discovered significance of pattern AEP components, some of these experiments would be worth repeating, using the component separation technique.

AEP Variability (chapter 8)

1. The main conclusion was that the stimulus had a minimal effect on the observed variability, which seemed to be almost entirely due to independent noise sources.
2. Apart from one subject who showed α rhythm synchronised with the stimulus, attempts to show that the variability reduced when a response was present produced negative results. The hypothesis that there is a constantly active neural population which acts either in synchrony with a stimulus or randomly was not supported (at least for this sort of stimulus).
3. 'Running average' experiments indicated that long term pattern AEP changes were cyclic rather than steady decays.

Component Analysis (chapter 9)

1. AEP components at particular latencies were isolated by computer integration over short latency ranges. Two early components were defined C1 (52-80 ms) and C2 (85-113 ms).
2. Longitudinal (midline) and transverse scalp distribution studies showed C1 and C2 to be compatible with the hypothesis that they originate from independent spatially separate sources.
3. Distributions for ½ and ¼ field stimulation were in most cases good approximations to the appropriate sum of the constituent ¼ and ⅛ field distributions. This held for both C1 and C2.
4. The shapes of the distributions were in most cases compatible with surface negative dipole sources located in the retinotopically mapped striate cortex for C1, and extra-striate cortex for C2.
5. Some of the measured distributions disagreed markedly with the predictions.

Stochastic Searches (chapter 10)

1. A method was developed which reliably converged in one dimension under restricted experimental conditions.

Sections 11.1 and 11.2 consider the component analysis and stochastic search results respectively. Criticisms, limitations, and possible extensions to the work are included.

11.1 Component Analysis

Note that the results do not *prove* that C1 and C2 come from the striate and extrastriate cortex respectively, only that the observations are *compatible* with these sources. Unfortunately it is theoretically not possible to determine uniquely the distribution of volume generators from surface potential measurements. Some assumptions have to be made about the topography of the likely sources before a component can be assigned to a particular source.

However, if by further experiments we can confirm that an individual component comes with some certainty from a particular cortical region, then a study of this component

(as a function of selected stimulus variables) may be expected to reveal properties of the cortical source itself.

11.1.1 Some Criticisms

1. Eye movements were not restricted, other than by voluntary fixation. It is possible that the observed differences in scalp distributions could have been produced by changes in the pattern of eye movements when patterns were presented in different parts of the visual field. It may be possible to check this by presenting some composite patterns, e.g. non-adjacent octants, which would tend to have counteracting eye movement tendencies. Repeating some of the experiments using a stabilised retinal image would be the most satisfactory way of settling this point however.
2. Some results showed glaring anomalies (e.g. subj SH). Unusual cortical topography was considered in chapter 9 to be the most likely cause of these. If this could be proved to be the case by X-rays or other suitable methods, then the conclusions would be greatly strengthened.
3. Only four subjects were tested in detail, although Jeffreys [86] had earlier shown (by rough inspection of the AEP traces) that a group of 12 subjects showed similar features. The detailed component study should be extended to more subjects.
4. The dipole model was very crude and could easily be improved in three ways:-
   a. By using dipole sheets instead of isolated dipoles.
   b. By using a more exact cortical topography, taking into account curves, folds, cortical magnification, etc. Actual surface topography, determined by X-rays or other methods, could also be included.
   c. By taking into account the differing conductivities of cortex, skull, and scalp. This has already been covered by a number of workers [133,160].

The numerical integration power of modern computers should render the calculations involved quite tractable.

11.1.2 Extension Experiments

1. Eccentricity Mapping

In the reported experiments only 180° annular regions were tried (i.e. over ½ field). However by measuring annular region C1 and C2 distributions within one octant it may be possible to detect movement of the source along the cortex surface as eccentricity is changed. Thus we may expect that for C1 the source will move deeper into the cortex with increasing eccentricity. For C2 the expected movement will depend upon whether the stimulus is in the upper or lower ½ field. For the lower ½ field we may expect the source to move anteriorly along the top surface of the occipital lobe, whilst for the upper ½ field it should move deeper into the brain on the under surface of the lobe.

2. C3 Component

Attempts should be made to identify the source of C3. Does this come from a human Visual III region? Testing (as above) with various annular regions at different eccentricities may help to uncover the mapping direction.

3. Pre-exposure to Components

The differing effects of pre-exposure on C1, C2, and C3 should be investigated and may help to uncover features about the function of the source areas.

4. Pattern Complexity

Jeffreys [180] has established that in general the amplitude of pattern AEPs increases with the complexity of the stimulus pattern. MacKay [101] has suggested that this can be interpreted as evidence for 'lateral inhibition between high-order feature-sensitive elements'. We also know from single unit work in cats and monkeys that nerve cells in the cortical visual areas I, II and III are concerned with progressively more complex aspects of the structured visual field. If the same is true for humans then we may expect the dependence of at least C1 and C2 on pattern complexity to be different, with the higher order pattern features making a greater contribution to C2 than to C1.

A start was made at investigating this during the research, but before the computerised component isolation method was developed. It was inconclusive and was not pursued. The

main problem was how to quantify 'pattern complexity', and the initial attempt defined two sorts of feature – (A) contour types, and (B) relationships between contour types:-

viz.	*A-type*	*B-type*
	Straight edge	Spatial frequency
	Corner	Orientation
	Curved edge	Connectedness
		Depth information
		Regularity

Each feature may be expected to stimulate one or more neuron populations (channels) in the visual system, with the more complex features represented later in the analysis chain. Some ingenuity would be required here to devise series of stimulus patterns which vary one feature, but keep others constant. A careful study of the behaviour of the individual response components as a function of these features may yield interesting indications of the purpose of the cortical source.

5. Monocular Stimulation

If a particular cortical region contains neurons which are predominantly monocularly driven, then one may expect the AEP from that region to show a significant decrease if monocular rather than binocular stimulation is used. Normally AEPs are reduced slightly if only one eye is stimulated, and a careful study of the relative decreases of different components may reveal eye preference characteristics of the sources. There are already indications [87] that C1 is reduced more than C2 for monocular stimulation. This could indicate that the striate cortex contains a higher proportion of monocularly driven neurons. This is compatible with the monkey finding ([76]; [78] and see section 2.2.3) that simple cells in the striate cortex are predominantly monocularly driven.

11.2 Search Techniques

The progress made in search techniques can only be regarded as a start. During the research it was soon realised that the noise represented a severe restriction on any search method, and until an efficient general method of searching in the presence of noise was developed, not

much progress would be made. The technique reported was preceded by several other unsuccessful methods. The main problem seems to be how to make the maximum use of each individual measurement, and it is significant that all the unsuccessful methods attempted to do some averaging to reduce the noise of a result *before* making a decision about it. The reported method did not.

Note the generality of the method; the stimulus space can be any number of dimensions and provided the desired response characteristic can be defined as the maximum of a continuous scalar function, any search can be conducted.

It was not without its problems however. One was the very real restriction of limited computer core storage. The program described almost filled that available on the PDP8.

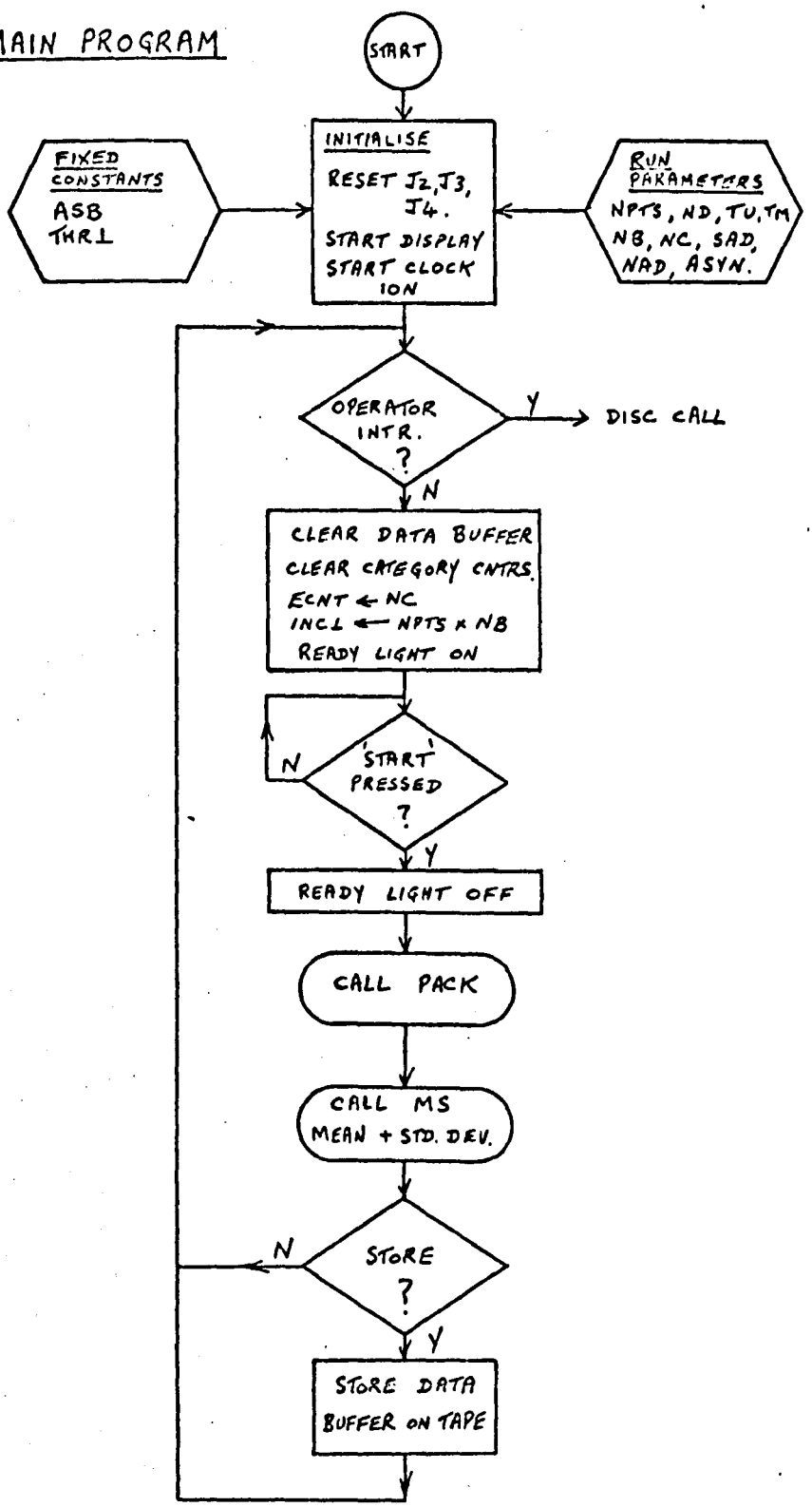
A more fundamental problem was that of translating the stimulus variables within the computer into real stimulus control. Variables such as time or simple stimulus position are relatively easy to mechanise, but when we consider somewhat more interesting variables such as the pattern features mentioned in the previous section, it is not so simple. A CRT display may be the answer here. If a suitable stimulus space specifying pattern content can be defined and mechanised it may yield some very interesting results.

11.3 Final Remarks

AEPs measured on the human scalp are always going to be at a disadvantage compared with more direct physical measurements made on the exposed brain.

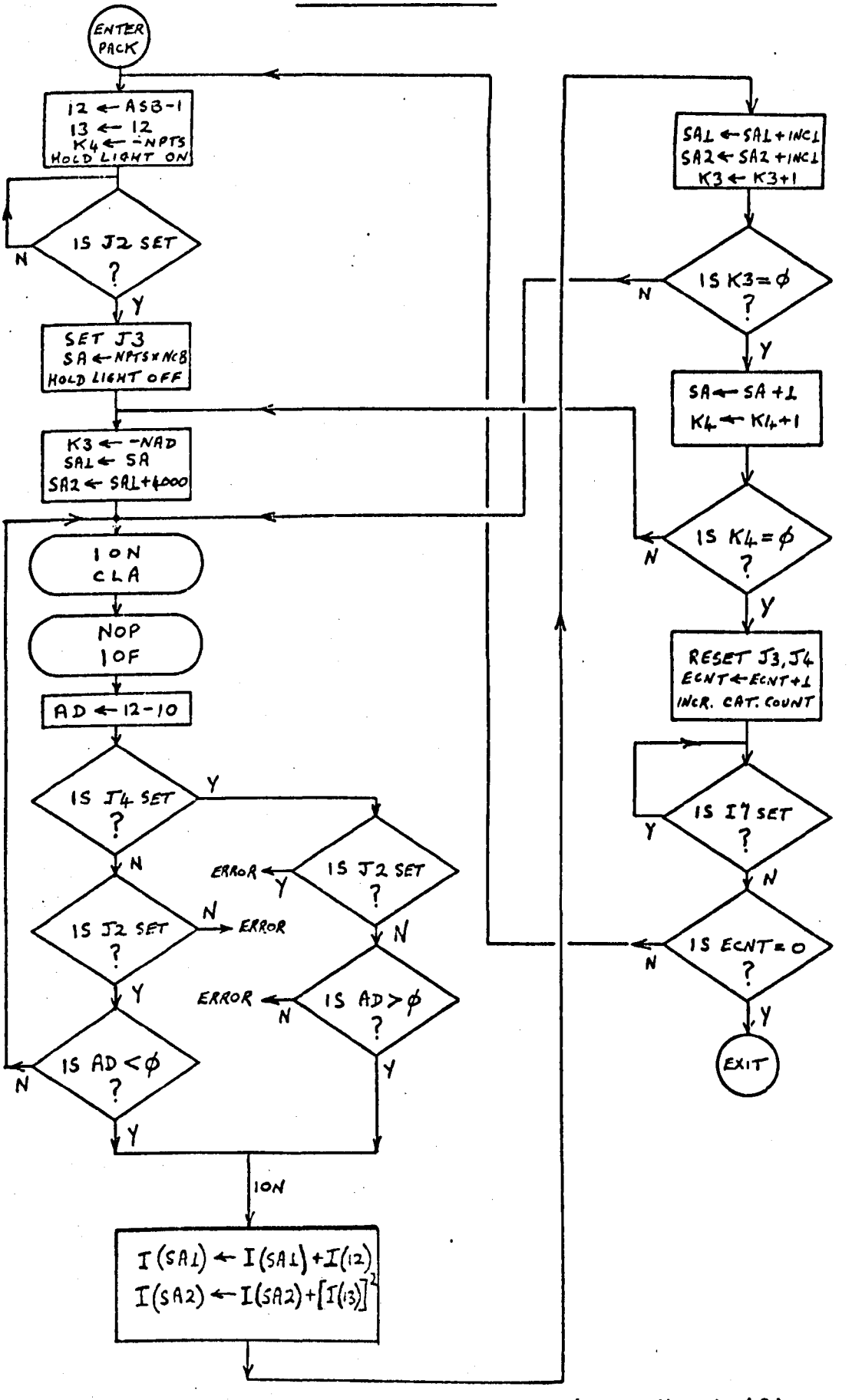
Nevertheless I believe that the work reported in this thesis is a significant step forward in AEP experimental techniques, and in our understanding of the probable source locations of AEPs to pattern appearance stimuli.

MAIN PROGRAM



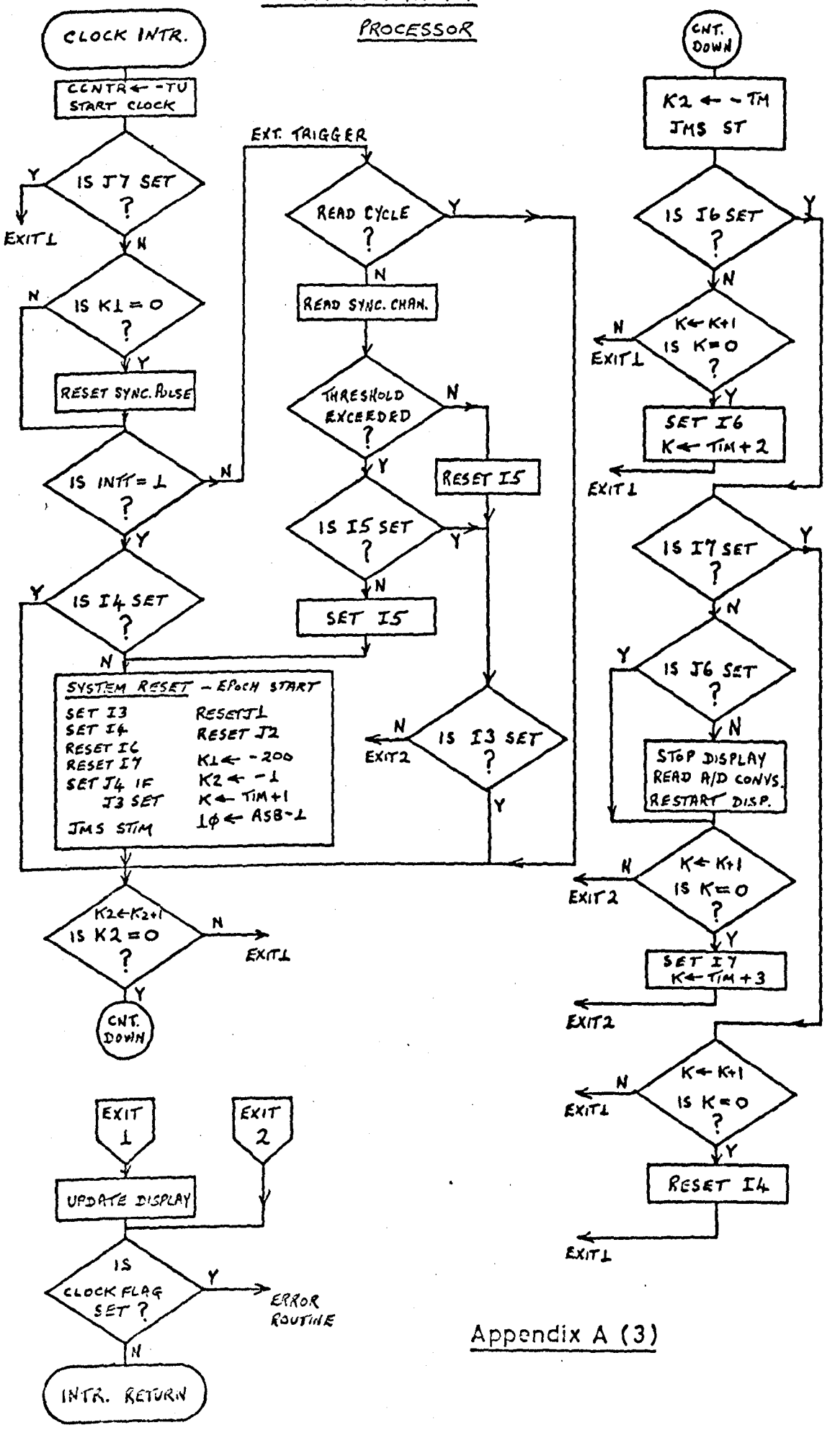
Appendix A (1)

'PACK' ROUTINE



Appendix A (2)

CLOCK INTERRUPT PROCESSOR



Appendix A (3)

APPENDIX B1: COMPUTATIONAL ERRORS FROM ROUND-OFF AND TRUNCATION

The following considers cumulative error that builds up as a result of a series of computational steps. It is concerned only with errors introduced by floating point arithmetic operations, and takes no account of error in the operands themselves.

Define – Absolute error, ey (of quantity y)

– Relative error, $\epsilon y = \frac{ey}{y}$

Suppose numbers are to base 'm', and 't' significant digits are used.

A maximum possible relative error (ϵmax) can be specified, depending on the rounding algorithm, as follows:-

For *truncation* – max absolute error = 1 x least significant digit.

$\therefore \epsilon max = m^{1-t}$

For *rounding* (up and down) – max absolute error = ½ x least significant digit.

$\therefore \epsilon max = \frac{1}{2} m^{1-t}$

Addition

If 'n' numbers are added sequentially:–

$y = (.....(((x_1 + x_2) + x_3) + x_4) + ... + xn)$

Thus $ey \leqslant [(n-1)x_1 + (n-1)x_2 + (n-2)x_3 + ... + xn]\ \epsilon max.$

Suppose all the x's are approximately equal and have mean value $\bar{x}$.

$\therefore y = n\bar{x}$

and $\frac{ey}{x} \leqslant [(n-1) + \frac{1}{2}n(n-1)]\epsilon max.$

if $n >> 1, \quad \therefore \epsilon y \leqslant \frac{n}{2}\epsilon max$ B1

Multiplication

If 'n' numbers are mutliplied sequentially:–

$y = (.....(((x_1 . x_2) . x_3) . x_4) . ... xn)$

Thus $e_y \leq (x_1 \cdot x_2 \cdot x_3 \cdot \ldots\ldots\ldots\ldots \cdot x_n) n \epsilon max$

$\therefore \epsilon y \leq n \epsilon max$ B2

Thus in general multiplication gives a greater error than addition.

The largest increases in relative error come when two nearly equal numbers are subtracted. For multiple divisions the resultant maximum error is roughly the same as for multiplication.

Hence it can be seen that for most operations (provided we do not take small differences), the maximum error is roughly proportional to the number of operations.

Application to Double Precision Arithmetic in the PDP8

The PDP8 word length is 12 bits, and thus double precision arithmetic will give 23 significant bits (one bit is used as a sign bit). Truncation is used.

Hence t = 23, m = 2, and $\epsilon max = \frac{1}{2^{22}} \approx 2.5 \times 10^{-7}$

If we allow $\epsilon y = 0.01$, then from eqn. B2

$n \geq \frac{0.01}{2.5} \times 10^7 = 40{,}000$

i.e. for a maximum relative error of 1% one would need 40,000 serial multiplications.

From the above considerations, it is concluded that the used of double precision arithmetic is unlikely to introduce significant error into any of the experimental computations.

APPENDIX B2: SINGLE PRECISION SUMMING ERROR

The process of computing the AEP involved the sequential summation of about 100 raw EP responses. Timing constraints dictated that this operation must use fixed point single precision arithmetic (11 significant bits).

If rounding up and down is used:–

$t = 11$, $m = 2$, and $\epsilon max = \frac{1}{2} \cdot \frac{1}{2^{10}} = \frac{1}{2048}$

and thus from eqn. B1, for $n = 100$,

$\epsilon y \leq \frac{100}{2} \times \frac{1}{2048}$

$\therefore \epsilon y \leq 2.4\%$

Note that if simple truncation were used the maximum relative error would be twice this value.

Dynamic Range and Overflow

A further consideration with this summing operation was the chance of overflow. Since fixed point arithmetic was being used, the summed value could not be allowed to exceed the range limits of a 12 bit binary word (i.e. ± 2048).

This can be expressed in terms of the following inequality:–

$$2048 \geq \text{Max AEP} \times \text{Amplifier Gain} \times \left[\begin{matrix}\text{A/D Conv.} \\ \text{'Conversion factor'}\end{matrix}\right] \times \left[\begin{matrix}\text{Max no. of responses} \\ \text{in AEP}\end{matrix}\right]$$

$$(V\mu V) \qquad (G) \qquad (\text{C units/Volt}) \qquad (N)$$

Typical design values were:– $V = 15\mu V$

$G = 5 \times 10^4$

$N = 100$

The value of C was chosen such that the inequality holds.

The dynamic range of the A/D convertor was fixed at ± 5 Volts, but the effective number of bits to which this range corresponded within the computer could be adjusted (i.e. the value of C). Suppose this number of bits is 'm':–

then $c = \frac{2^m}{10}$

and $2048 \geq 15 \times 10^{-6} \times 5 \times 10^4 \times \frac{2^m}{10} \times 100$

i.e. $m \leq 8.1$

In practice the A/D converter switch was set to provide a 9 bit conversion, which was then rounded (up and down) to 8 bits by the program.

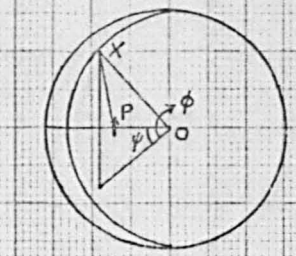
With 100 responses included in the AEP, the net effect was that a maximum AEP of $\pm$ 15μV was allowed before overflow occurred. If the number of responses was lower, this limit was higher, in direct proportion.

If overflow did occur, it was easily observed on the display, and the particular AEP could be rejected. No direct program action was taken on overflow.

Appendix C1

DIPOLE POTENTIAL – PERPENDICULAR DIPOLE

$\alpha = 0.75$



- UNIT RADIUS SPHERE
- UNIT DIPOLE (P) AT P PERPENDICULAR TO RADIUS
- $OP = \alpha$

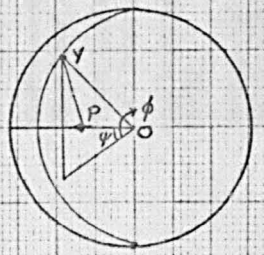
$$V_x = \frac{\bar{P} \cdot \overline{PX}}{|PX|^3}$$

$$V_x = \frac{\sin\phi}{(1 + \alpha^2 - 2\alpha\cos\phi\cos\psi)^{3/2}}$$

Appendix C2

DIPOLE POTENTIAL – RADIAL DIPOLE

$\alpha = 0.8$



– UNIT RADIUS SPHERE
– UNIT DIPOLE (P) AT P PARALLEL TO RADIUS
– OP = α

$$V_y = \frac{\bar{P} \cdot \overline{PY}}{|PY|^3}$$

$$V_y = \frac{\cos\phi \cos\psi - \alpha}{\left(1 + \alpha^2 - 2\alpha \cos\phi \cos\psi\right)^{3/2}}$$

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Note: EEGJ = Journal of Electroencephalography and Clinical Neurophysiology.

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