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PATTERN EVOKED POTENTIALS AND SINGLE UNIT RESPONSES IN THE VISUAL CORTEX OF THE CAT

by

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Dissertation presented to the University of Keele
for the degree of Ph.D.

September 1975

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ABSTRACT

In this dissertation,experiments are described which investigated the properties of 51 cells in area 17 of the visual cortex of the cat. Simple and complex cells were distinguished by their responses to moving stimuli and the level of their spontaneous activity. Using these criteria, simple cells showed narrower orientation tuning; responded with fewer action potentials to an optimal moving stimulus; exhibited greater directional sensitivity and had smaller receptive fields. Simple and complex cells are affected similarly by changes in stimulus contrast and blurring of the retinal image by defocussing.

Experiments are also described in which attempts were made to record potentials at depth within the cortex which reflected the orientation preference and receptive field location of cells in the vicinity of the electrode (orientation column potentials). In the absence of clear results from these experiments, a study of the surface recorded pattern-related visual evoked potential (PRVEP) was made to establish the existence of such potentials in the cat visual cortex. In experiments where PRVEPs were recorded, the following questions were asked:-

1. How do PRVEPs compare with potentials evoked by equivalent blank stimuli?

2. How does the form of the stimulus pattern affect the PRVEP? Do discontinuous pattern elements evoke larger potentials?

3, Does a reduction in the pattern dimensions and contrast affect the PRVEP? How is the response changed by defocussing?

4. Is the PRVEP sensitive to pattern pre-exposure? How does the form and orientation of the pre-exposed pattern affect this sensitivity?

5. Is the retinotopic organisation of the cortex reflected in the distribution of components of the PRVEP over the cortical surface? Does this distribution differ from that of potentials evoked by blank stimuli?

6. How does the PRVEP relate to potentials evoked by pattern reversal?

PRVEPs in the cat showed a wide variety of waveforms in different experiments and were often similar to those evoked by equivalent blank stimuli. Increasing the discontinuity of the stimulus pattern elements did not have a marked effect on the PRVEP, in contrast to the results of analogous experiments in man. The cat PRVEP is attenuated by a reduction in pattern contrast and dimensions but is not as sensitive to defocussing as the human PRVEP. Pre-exposure of the stimulus pattern can cause a selective attenuation of some components of the PRVEP. This attenuation was dependent on the orientation of the pre-exposed stimulus and was different from that caused by pre-exposure of a blank field. Components of the PRVEP in the cat do not show a clear retinotopic distribution resembling the wide cortical spread of the later components of potentials evoked by diffuse stimuli. Potentials evoked by pattern reversal appear to contain components present in potentials evoked by both pattern appearance stimuli and blank stimuli.

In general the properties of the cat PRVEP has some similarities with CI of the human PRVEP but differs markedly in certain respects, notably the lack of a clear retinotopic distribution of its components on the cortical surface.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. P. Hammond and Professor D. M. Mackay for enabling the research reported in this dissertation to be carried out and completed.

My especial thanks are due to Dr. P. Hammond for his considerable patience and invaluable supervision.

I would like to thank Dr. D. A. Jeffreys for his co-operation and assistance in some of the experiments.

I thank Mr. B. Whitehouse for his expert technical assistance.

The support of the Science Research Council, through a Research Studentship, is gratefully acknowledged.

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1. INTRODUCTION

Recently, there have been many major advances in our understanding of the neural mechanisms underlying the processing of visual information by the brain. Despite these advances, the exact way in which the brain transforms the input to the retina into a picture of the visual world is still obscure. To attempt to solve this problem the neurophysiologist has at his disposal two main methods of investigation:

1. Recording the responses of single neurones with microelectrodes (single unit studies).

2. Recording the summed activity of a small volume of neural tissue with 'gross' electrodes (evoked potential studies).

So far, single unit investigations have revealed more about the functioning of the visual system than evoked potential studies. This must be due, partially, to an inability to interpret the components of the evoked potential in terms of the activity of single cells. In this present study attempts have been made to understand further the responses of individual cells and the reflection of their summed activity in the evoked potential.

1.1 PROPERTIES OF SINGLE CELLS IN THE VISUAL CORTEX OF THE CAT

The first extracellular recordings from single cells in the cat's visual cortex were made in 1952 by Jung, Von Baumgarten and Baumgartner. They classified cells into four groups according to their response to diffuse light stimulation:

A. No response to light stimuli

B. Activation at stimulus onset

C. Inhibition at stimulus offset

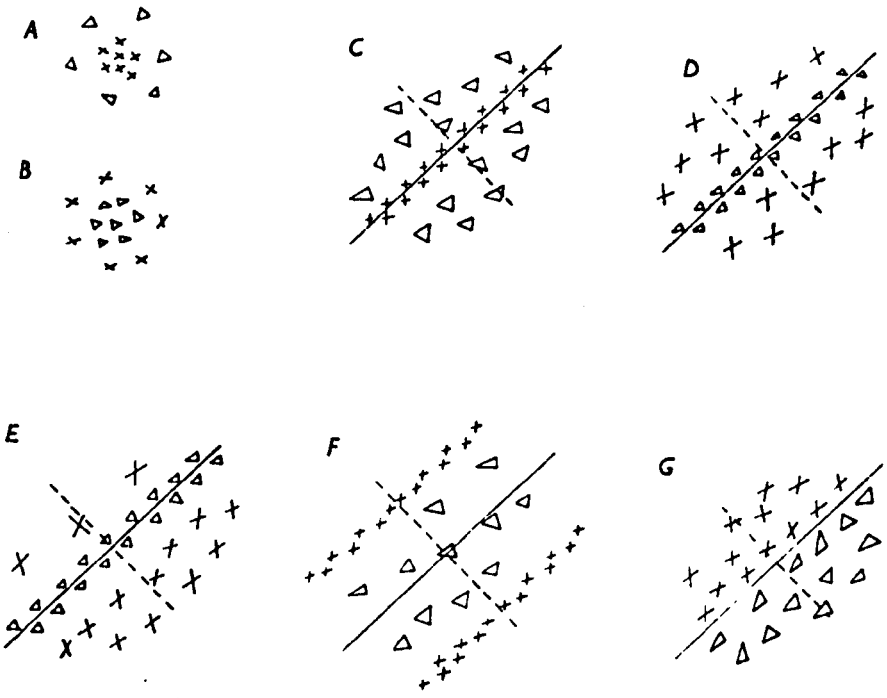
D. Activation at stimulus offset

Group A was later found to account for 50% of the cells recorded (Jung and Baumgartner, 1955). Hubel (1959), recording from the visual cortex of awake unrestrained cats, reported that diffuse illumination produced 'little or no response in most units' whilst many of the same cells responded briskly to restricted light stimuli. In 1960, Hubel concluded that those single units in the visual cortex which had been reported as responding to diffuse illumination (Hubel, 1957; 1959; Jung et al., 1952) were probably afferent fibres, and only those units in Group A (i.e. those cells unresponsive to visual stimuli) were cortical cells.

The arrangement of inhibitory and excitatory regions in the receptive fields of cells in area 17 of the cat visual cortex was investigated by Hubel and Wiesel (1959, 1962). They were able to distinguish two types of cell, simple and complex, whose receptive fields had different properties.

Using small spots of light it was possible to map simple cells into discrete excitatory and inhibitory areas which usually lay alongside each other in a parallel array. (See Fig. 1.) These cells responded optimally to an appropriately oriented slit of light covering either an excitatory area, when they would respond at stimulus onset, or an inhibitory area when they would respond at stimulus offset. These excitatory and inhibitory areas were mutually antagonistic; thus, a slit, inappropriately positioned

FIG. 1. Common arrangements of lateral geniculate and cortical receptive fields. A. 'On'-centre geniculate receptive field. B. 'Off'-centre geniculate receptive field. C - G. Various arrangements of simple cortical receptive fields. X, areas giving excitatory responses ('on' responses); △, areas giving inhibitory responses ('off' responses). Receptive field axes are shown by continuous lines through field centres; in the figure these are all oblique, but each arrangement occurs in all orientations (from Hubel and Wiesel, 1962).


A
B
C
D
E
F
G

or oriented, or diffuse illumination were ineffective. A simple cell could be distinguished as such if its receptive field was divisible into distinct excitatory and inhibitory regions and if it showed summation within and antagonism between these regions. Also, it was possible (according to Hubel and Wiesel) to predict a simple cell's response to movement from a knowledge of its receptive field map.

The receptive fields of complex cells were not so straightforwardly organised. Their receptive fields frequently could not be mapped since spots of light were often ineffective or evoked a response at both stimulus onset and offset throughout the receptive field. Even when it was possible to map excitatory and inhibitory zones there was no antagonism between or summation within these zones. These cells were similar to simple cells, however, in being selective for the orientation of slit stimuli, whether stationary or moving. Hubel and Weisel described four types of complex cell:

Type 1. Activated by slits. Non-uniform field (16%)

Receptive fields could be divided into excitatory and inhibitory areas but there was no summation within these areas except along the preferred orientation axis of the receptive field. These cells contrasted with simple cells in the following ways:

a) A slit stimulus produced a response at either ON or OFF over a wide variety of locations in the receptive field. The cell was non-specific for stimulus location.

b) There was no summation or mutual antagonism within the receptive field.

Type 2. Activated by slits. Uniform field (56%)

Responded at both stimulus onset and offset throughout the whole receptive field. This was in contrast to simple cells where a mixed ON-OFF response was merely a sign of a non-optimal stimulus.

Type 3. Activated by edges (20%)

Flashed spots or slits were ineffective - cells were only activated

by a correctly oriented light-dark edge. Reversing the contrast of an optimally oriented edge stimulus reversed the ON or OFF nature of the response. In contrast to simple cells, these cells had very large receptive fields.

Type 4. Activated by dark bars (8%)

These cells responded optimally to narrow dark bars at any position in the receptive field and differed from simple cells in the following ways:

a) There was no summation within the receptive field except along the preferred axis of the cell.

b) Stimulation of any part of the receptive field evoked responses only at stimulus onset: there was no antagonistic region.

Hubel and Wiesel (1962) reported that the two types of cell could also be distinguished by their response to stimulus movement: complex cells responding with 'sustained firing over substantial regions' of the retina whilst simple cells responded over 'a very narrow boundary separating excitatory and inhibitory regions.' For both types of cells they found that movement was a very powerful stimulus and assymetries of response to movements in different directions were common.

In 1968, Pettigrew, Nikara and Bishop, using different criteria, also classified cells in area 17 of the cat into simple and complex types. They reported that a simple cell had the following features:

1. Sharply defined responses to a moving stimulus.

2. A tendency for the response to be of low frequency and poorly maintained.

3. Little or no spontaneous activity.

They classified cells, with the following characteristics as complex:

1. A sustained response to a moving stimulus.

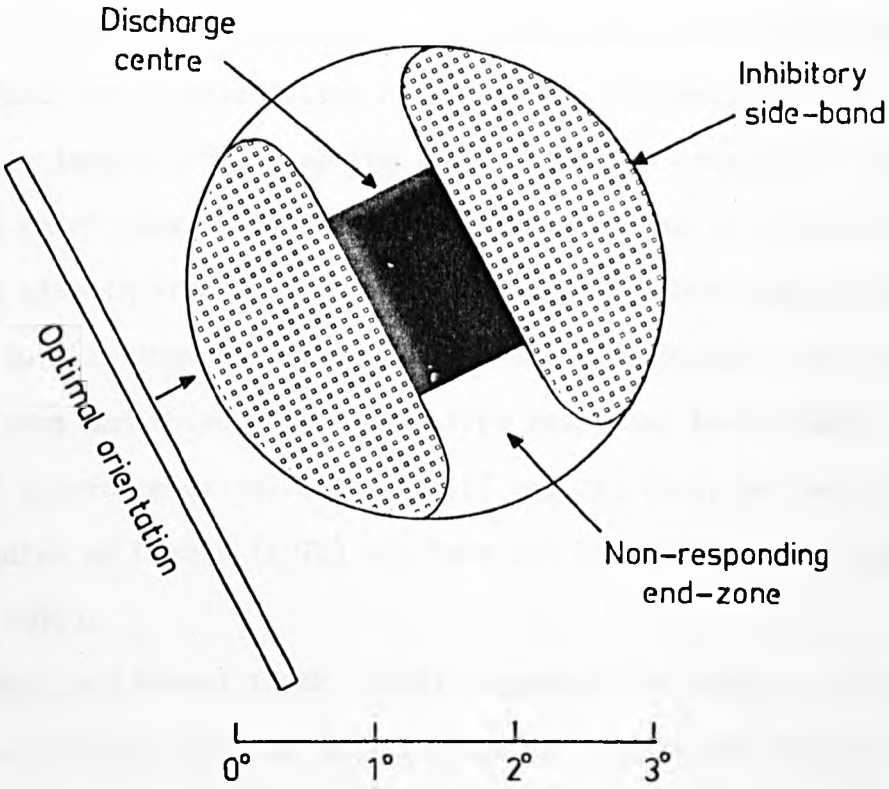
2. Brisk spontaneous activity in most cases.

3. A preference for fast oscillatory stimulus movements of small

amplitude compared with the total receptive field size.
Pettigrew and co-workers made no attempts to classify cells using flashed stimuli; indeed they reported that simple cells could rarely be driven with stationary flashed spots whilst moving stimuli always evoked a brisk response. In contrast to Hubel and Wiesel (1962) Pettigrew and co-workers reported that the simple cell response to a moving stimulus could not be predicted from a map of the excitatory and inhibitory areas within its receptive field. Using moving stimuli, Henry and Bishop (1971) have mapped the simple cell receptive field. (See Fig. 2). Typically, it consists of a central excitatory zone flanked by 1 or 2 powerful inhibitory side-bands. The excitatory areas for light and dark edges moving in different directions are often displaced within the excitatory zone. (Bishop, Coombs and Henry, 1971a). Bishop, Dreher and Henry (1972) have shown that the arrangement of the excitatory and inhibitory areas revealed by moving stimuli does not correlate with the areas responding to stationary stimuli; indeed there was often a spatial mismatch between the two. Bishop, Goodwin and Henry (1974) have reported the existence of direction selectivity for stimulus movements confined to regions as small as 4.3 mm wide within an ON area mapped with stationary slits of light. These results are difficult to reconcile with the interpretation of simple cell movement responses by Hubel and Wiesel (1959, 1962).

Probably all simple and complex cells in area 17 have receptive fields in both retinae. In some cells, however, the input from one eye may be inhibitory or 'subliminal' (Henry, Bishop and Coombs, 1969) which possibly accounts for earlier reports which concluded that only 84% of cells could be binocularly influenced (Hubel and Wiesel, 1962). Attempts have been made to establish that the disparities between the positions of the receptive fields in each eye could represent the mechanism underlying stereopsis (Barlow, Blakemore and Pettigrew, 1967; Pettigrew,

FIG. 2. Scale diagram of the receptive field of a simple striate neurone (after Bishop, Dreher and Henry, 1971).


Discharge centre
Inhibitory side-band
Optimal orientation
Non-responding end-zone
0°
1°
2°
3°

Nikara and Bishop, 1968). Hubel and Wiesel, however, have recently shown that for almost all cells in area 17 of the cat, the receptive field disparities are negligible (Hubel and Wiesel, 1973).

In 1965, Hubel and Wiesel in a study of the receptive fields of cells in areas 18 and 19 in the cat cortex described cells which were not only sensitive to orientation but responded optimally to slit stimuli of a certain length; the receptive fields were 'end-stopped'. This type of cell which they designated as hypercomplex has now been shown to be present also in area 17 (Dreher, 1972; Rose and Blakemore, 1974). Dreher (1972) has distinguished two types: those with complex cell type responses to movement and those with simple type responses to movement. The proportion of hypercomplex cells in area 17 may, in fact, be even larger than the studies of Dreher (1972) and Rose and Blakemore (1974) have revealed (Rose, 1974).

Hubel and Wiesel (1962, 1965) suggested the idea of a hierarchy in cortical receptive fields in which complex fields are formed by the convergence of simple fields and hypercomplex fields by the convergence of complex. Considerable evidence has now accumulated which does not appear to support this model.

Fukada (1971) and Cleland, Dubin and Levick (1971) have independently shown that retinal ganglion cells with X and Y type receptive fields (first described by Enroth-Cugell and Robson in 1966) have slow and fast conducting axons respectively. Stone and Hoffmann (1971) and Cleland et al. (1971) have shown that LGN cells receiving fast axons from the retina have fast axons projecting to the cortex. Those receiving slow axons have slow axons. These fast and slow geniculo-cortical afferents activate, monosynaptically, complex and simple cells respectively in area 17. (Stone and Hoffmann, 1971). Y-cells in the lateral geniculate

nucleus also project monosynaptically into area 18. Certain properties of the receptive fields of simple and complex cells are also hard to reconcile with the hierarchical model. Pettigrew, Nikara and Bishop (1968) found that simple cells had a lower spontaneous activity than complex cells and that simple cells preferred slower-moving stimuli (2°/sec for simple, 5-6°/sec for complex). The results of Movshon (1974) show that complex cells can respond to high velocities (40 deg/sec) at which simple cells respond poorly, if at all.

It would appear on this evidence that simple and complex cells are part of a 'parallel' processing system rather than the serial system envisaged by Hubel and Wiesel.

Hubel and Wiesel (1962) also suggested that simple cells were layer IV stellate neurones whose receptive fields were built up directly from the geniculo-cortical input. The stellate cells in turn projected onto pyramidal cells which had complex receptive fields. Recent intracellular studies have supported this model (Kelly and Van Essen, 1974; Van Essen and Kelly, 1973). It now seems unlikely that the specific afferents terminate exclusively on layer IV stellate cells. Globus and Scheibel (1967) have shown geniculo-cortical termination on pyramidal cells in the rabbit visual cortex and in 1970, Garey reported that specific afferents appear to project onto both stellate and pyramidal cells in the cat visual cortex. Also, there is now evidence showing that the geniculate input to the visual cortex is primarily excitatory (See Stone, 1972). It is unlikely, therefore, that the receptive fields of simple cells are formed only by direct geniculate input, particularly in the light of their intricate receptive field organisation. (Henry and Bishop, 1971; Bishop, Coombs and Henry, 1971a). They are more likely to be the product of intracortical neuronal interconnection. Bishop, Coombs and Henry (1971b) have put forward a model to explain the receptive field organisation of simple

cells. They suggest that simple cells are pyramidal cells and that stellate cells function as interneurons with the specific afferent terminating on both types of cell. The complicated responses to movement are caused by interaction between the stellate interneurons which have non-oriented receptive fields. These cells are encountered only on rare occasions in the visual cortex (Bishop and Henry, 1972) perhaps because of their small size and localised potentials.

SUMMARY

Hubel and Wiesel (1959; 1962) have distinguished, by their response to stationary flashed stimuli, two types of cell, simple and complex, in area 17 of the cat visual cortex. Other workers using slightly different criteria (e.g. movement responses, spontaneous firing) have also described cells as simple and complex (Pettigrew, Nikara and Bishop, 1968). The properties of simple cells distinguished by these two methods are not identical.

The roles and interaction of simple and complex cells in visual processing are not clear.

A more thorough understanding of the properties of these two types of cell is necessary to gain a clearer insight into the part they play in vision.

1.2 COLUMNAR ORGANISATION IN THE CORTEX

Cortical cells are laid out in chains lying normal to the surface of the cortex. The functional significance of this organisation was first suggested by Lorente de No in 1949 when he envisaged movement of information up and down the 'vertical organisation of cortical cells'.

The first physiological demonstration of columnar organisation was by Mountcastle (1957). He showed that cells recorded during a micro-electrode penetration normal to the surface of the somatosensory cortex belonged to one sensory-modality sub-group.

In 1962, Hubel and Wiesel demonstrated a columnar organisation in the cat visual cortex. They showed that cells with the same stimulus orientation preference and similar receptive field location in the visual field were grouped in vertical columns. This finding was investigated in more detail (Hubel and Wiesel, 1963) by plotting the mosaic formed by the intersection of the column walls on the cortical surface. The columns showed a variety of shapes from compact and round to long and narrow. The more compact were approximately 0.5 mm in diameter whilst the long and narrow columns extended for at least 2 mm along the cortical surface.

Blakemore (1970) reported finding columnar organisation linked with the binocular receptive field disparity of neurones in area 17 of the cat. He showed two types of column: one containing units with the same horizontal disparity (constant depth columns) and another containing units with a range of disparities (constant direction columns).

In the monkey striate cortex Hubel and Wiesel (1968) found two independent column systems, the first containing cells with similar stimulus orientation preferences and the second containing cells with the same eye dominance. There was also a less clear 'grouping' of cells with other stimulus preferences (e.g. stimulus colour and direction). The existence

of eye-dominance columns has since been demonstrated anatomically. (Hubel and Wiesel, 1969).

In the cat auditory cortex, columns of cells with similar 'best frequencies' have been noted by several investigators (Hind, Rose, Davies, Woolsey, Benjamin, Welkes and Thompson, 1960; Parker, 1962; Gerstein and Kiang, 1964; Oonishi and Katsuki, 1965). The column diameters, however, are small (100μ) and sharp transitions in column characteristics are not as marked as in the visual and somatosensory systems.

The functional importance of vertical organisation is indicated by the finding of Sperry, Minor and Myers (1955) who showed that cats were still capable of very fine pattern discriminations after widespread 'sub-pial dicing' of the visual cortex extending through to the white matter. This capacity survived removal of the superior colliculus.

The grouping of cells in the cortex with similar stimulus preferences has obvious advantages. For the cat visual system, it means that the analysis of contours with a certain orientation in a given area of the visual field can be carried out by a sub-group or column of cells with that orientation preference. Several workers have envisaged columns as 'functional modules' (Chow and Leiman, 1970) or 'basic cortical units' (Colonnier, 1966). It is tempting to suggest that the whole of the visual field is covered by functional sub-units ready to analyse contours falling on a particular part of the retina. Whether the visual cortex actually functions in this way is not yet clear.

1.3 EVOKED POTENTIALS AND SINGLE UNIT DISCHARGE

It is now known that cell spike activity is not a significant contributor to the surface recorded evoked potential. Early theories (Adrian and Matthews, 1934) were based on the hypothesis that axon spikes were added together in some way to generate slow-waves on the brain surface. These theories remained popular until Renshaw and co-workers (Renshaw, Forbes and Morison, 1940) demonstrated the absence of a relationship between slow-waves and unit spike activity for small groups of neurones. Li, McLennan and Jasper (1952) also provided evidence against early theories when they showed that it was possible to record normal surface slow-wave activity in the absence of cell 'spike' activity. They suggested and other workers have shown since, that postsynaptic membrane potentials are much more likely sources of surface-recorded evoked potentials (Eccles, 1951; Li and Jasper, 1953; Bremer, 1958; Li, 1963; Elul, 1968). Membrane potentials were found to be longer in duration than cell spikes having a time course similar to that of cortical surface potentials. The way in which these membrane potentials summate and contribute to the surface recorded evoked potential is complex and has been the subject of many investigations.

1.3.1 Responses to electrical stimulation

The experimental approach which has been employed most during the last 30 years in attempts to understand the relationship between evoked potentials and single unit discharge has involved electrical stimulation at a peripheral site (e.g. optic nerve, skin, thalamus, sensory radiation) and recording from the appropriate region of primary sensory cortex.

An electrical stimulus applied to the optic nerve evokes a potential with a characteristic waveform as illustrated in Fig. 3. (Bishop and O'Leary, 1938; Marshall, Talbot and Ades, 1943; Chang and Kaada, 1950; Bishop and Clare, 1952; 1953; Malis and Kruger, 1956; Landau and Clare, 1956; Doty, 1958; Storck, Battersby and Frumkes, 1972.) This potential has 5 basic components - 3 positive-going 'spikes' superimposed on a larger, slower positive-going wave which is followed by a negative-going wave. The first (C1) and third (C3) spikes (peak latency 1.5 and 2.8 - 3.0msecs. respectively) are of similar amplitude, both being significantly larger than the record spike (C2) which is seen as a small notch in the rising phase of C3. C2 has a peak latency of between 2.3 and 3.0msecs. The slower, larger positive wave (C4) upon which these spikes are superimposed has a peak latency of approximately 4.5msec. The late negative wave (C5) varies in amplitude and extent but reaches a peak at approximately 8 or 9msecs.

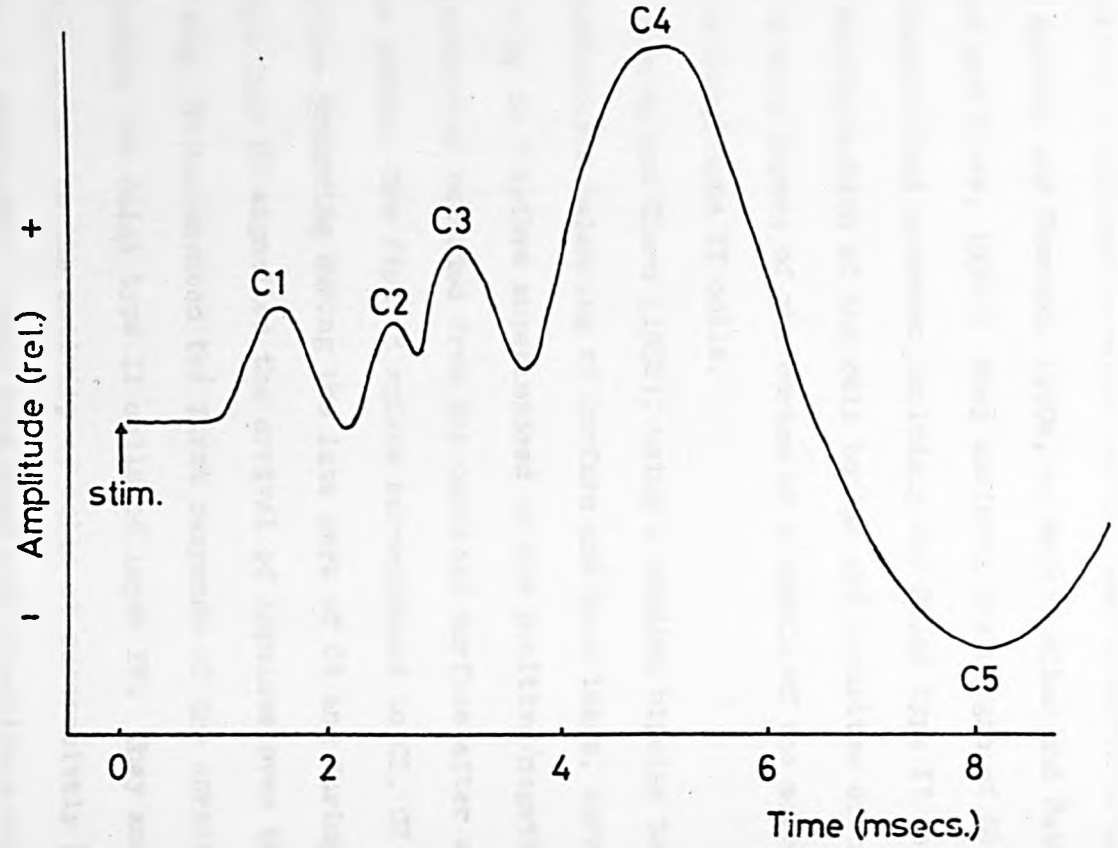
There have been many attempts to assign individual components of the potential to different groups of cells or fibres within the brain. The principal methods of analysis have been:

1. Depth recording within the cortex.

2. Sensitivity of different components to mechanical pressure, multiple shock stimulation and locally applied drugs. Components generated within the cortex are more sensitive.

Marshall, Talbot and Ades (1943), recording from the visual cortex whilst stimulating the optic nerve, concluded that C1 represented the

FIG. 3. Diagrammatic representation of the potential recorded from the surface of the visual cortex after electrical stimulation of the optic nerve.


C4
C3
C1
C2
+
Amplitude (rel.)
-
stim.
C5
0
2
4
6
8
Time (msecs.)

arrival of a sensory input and C2 the synaptic activation in layer IV. The remaining positive components reflected ascending cortical activity whereas the surface negative components reflected descending processes.

Chang and Kaada (1950) concluded that C1, C2 and C3 represented the activity of three systems of geniculo-cortical fibres with different conduction velocities, which they wrongly assigned to the neural processes underlying trichromatic colour vision, now known to be absent in the cat. (See Andrews and Hammond, 1970a, b; Meyer, Miles and Ratoosh, 1954; Landau and Clare, 1956.) They assigned the origin of C4 to the activity of intracortical neurones including the Golgi type II cells, and C5 to the depolarisation of the cell bodies and dendrites of the pyramidal cells in the deep layers of the cortex as a result of the synchronous discharges of the Golgi type II cells.

Bishop and Clare (1952), using a complex bipolar technique employing potentiometric balancing of surface and deep leads, were able to distinguish up to 5 spikes superimposed on the positive/negative sequence, of the potential recorded from the cortical surface after stimulation of the optic nerve. The first 3 spikes corresponded to C1, C2 and C3, the last 2 spikes occurring during the late part of C4 and during C5. They concluded that C1 signalled the arrival of impulses over the optic radiation and that C2 represented the first response of the cortical cells probably including the Golgi type II cells of layer IV. They assigned the following 2 or 3 spikes to the activity of cells at successively higher levels of cortical activation. They concluded that the slow surface positive wave (C4) appeared to be associated with the spikes, the early part of this component originating deeper in the cortex that the later. C5 appeared to originate in the lower third of the cortex probably in layer VI. In 1953, Bishop and Clare extended this interpretation, reporting that C4 reflected the response of the pyramidal cell basal dendrites and C5 the

anti-dromic conduction along the apical dendrites from the cell body towards the cortical surface. They also confirmed that C1 represented the discharge of afferent radiation axons and that C2 represented the activity of Golgi type II cells. The other spikes reflected the alternate activity of Golgi type II cells and pyramidal cells.

Li, Cullen and Jasper (1956), recording from the primary somato-sensory cortex whilst stimulating the ventralis posterior nucleus, recorded potentials with a waveform similar to those recorded in the visual cortex after stimulation of the optic nerve. Depth recording within the cortex showed that the initial spike components probably represented the activity of presynaptic afferent fibres. C4 reversed in polarity in the region of layer IV, suggesting that this component may signal the activity of Golgi type II cells and afferent terminals from specific thalamocortical projection fibres. C5 also reversed in polarity at a similar location, confirming the conclusions of Bishop and Clare (1953) and Chang and Kaada (1950) that this component represents conduction of the evoked potential from deep in the cortex to the surface.

Malis and Kruger (1956) reported that it was possible to record C1 and C2 from the surface of the white matter after removal of cortical grey matter. They suggested that C1 and C2 represent the activity of two fibre groups with different conduction velocities as seen in the optic tract (Bishop, Jeremy and Lance, 1953) and that C3 and C4 are the cortical responses to C1 and C2.

Schoolman and Evarts (1959) concluded that C3, C4 and C5 were cortical in origin and that C1 signalled afferent radiation activity. They were unable to draw any conclusions as to the origin of C2. They reported that the potential waveform was essentially the same in awake, anaesthetised and cerveau isole preparations.

Storck, Battersby and Frumkes (1972) recorded potentials, from the surface of the lateral gyrus, evoked by stimulation of localised sites in

layer A of the lateral geniculate nucleus. They found that C1 and C3 have a wider distribution in the cortex than C4 and C5. They suggested C1 signals precortical radiation activity whereas C4 and possibly C3 reflect the occurrence of post-synaptic intracortical events. They also were unable to draw any clear conclusions about the origin of C2. They reported that all the components of the potential were largest at anterior recording sites on the lateral gyrus when the anterior LGN was stimulated and, at more posterior stimulating sites, the components showed a peak response in more posterior parts of the cortex. This is an interesting finding in the light of the known retinotopic layout of the LGN (Bishop, Kozak, Levick and Vakkur, 1962) and the visual cortex (see section 1.4).

Watanabe, Konishi and Creutzfeldt (1966) made intracellular recordings of the responses of cells in area 17 of the cat visual cortex to electrical stimulation of the optic nerve. They reported that the average EPSP latency was 2.8msecs. which could be divided into two sub-groups of 2.4 and 3.8msecs. The average latency of the IPSP's could also be divided into two sub-groups with mean latencies of 3.4 and 4.6msecs. (The distinction of two latency groups was explained by two fibre groups with different conduction velocities in the visual pathway. (See Malis and Kruger, 1956 and Bishop, Jeremy and Lance, 1953.)) A comparison of these intracellular responses with the surface recorded evoked potential indicates that the EPSP's start during C2 but are mainly associated with C3 and C4. The IPSP's begin to develop during C4, reaching a peak during C5. No indication is given of the exact depth of the cells from which recordings were made or whether the cells could be expected to contribute to the surface potential.

So, most reports are in agreement that C4 and C5 signal post-synaptic cortical events because of their sensitivity to drugs, anoxia, mechanical pressure and increased rates of stimulation. C4 appears to be associated

with cortical layer IV which would make the stellate cells (Golgi type II cells in particular) likely candidates for the source of this component. C5 appears to be associated with C4 but originates deeper in the cortex. It probably represents the spread of activity from the somas of the vertically oriented pyramidal cells along the apical dendrites to the cortical surface.

It now seems that both C1 and C2 signal presynaptic activity of geniculo-cortical fibres with different conduction velocities, although early reports (Marshall, Talbot and Ades, 1943; Bishop and Clare, 1952; 1953) concluded that C2 was a post-synaptic event.

Chang and Kaada (1950) concluded that C3 represents the activity of afferent fibres, on the evidence that C1-3 all show similar sensitivity to drugs, anoxia etc. Most other workers (Marshall, Talbot and Ades, 1943; Bishop and Clare, 1952; 1953; Malis and Kruger, 1956; Schoolman and Evarts, 1959) however, conclude that this component originates within the cortex, signalling a post-synaptic event.

Electrical stimulation of a peripheral site, however, is a much larger and more synchronous stimulus than the visual sensory input. Even at low stimulus strengths (Chang and Kaada, 1950), the spiked waveform is still seen which is quite unlike the potential evoked by visual stimulation (see Doty (1958) for direct comparison). Therefore, what it can tell us about the way the brain works during normal sensory input is limited. In particular, records from the motor cortex in response to antidromic stimulation of the pyramidal tract (e.g. Humphrey, 1968) or stimulation of the specific projection nuclei (e.g. Creutzfeldt, Watanabe and Lux, 1966) cannot be generalised. The motor cortex is composed, almost totally, of pyramidal cells, (Mitra, 1955) which will be activated almost synchronously by electrical stimulation. It is almost certain that the varied elements in the visual cortex will not behave comparably during visual stimulation.

SUMMARY

Electrical stimulation of the optic tract evokes a potential on the surface of the visual cortex which has 5 components (C1-5). C1 and C2 represent the activity of 2 groups of afferent fibres with different conduction velocities; C3 is probably cortical in origin; C4 and C5 definitely signal post-synaptic intra-cortical events. Although investigations into the potential evoked by electrical stimulation have been numerous, studies of this nature can only yield limited information about the functioning of the visual cortex during normal sensory input.

1.3.2 Visual evoked potentials (VEP's)

Most observers report that the initial cortical response to punctiform or diffuse stimuli is surface positivity followed by surface negativity.

Marshall and Talbot (1942) found that the cortical reaction to diffuse photic stimulation was an initially positive wave followed by a negative wave. They confirmed their earlier finding (Talbot and Marshall, 1940) that these two waves arise from different sources.

Doty (1958) recorded a similar waveform, small in amplitude compared with the potential evoked by electrical stimulation of the optic nerve. The visual evoked potentials also had a much longer latency, the positive wave having a peak latency of between 30 and 40msecs; the negative wave 45-55msecs.

Burns, Heron and Grafstein (1960), recording potentials from the marginal gyrus evoked by diffuse photic stimulation, found that they were usually surface positive with an onset latency of 10-35msecs. Potentials with an initially negative component were usually confined to the anterior third of the marginal gyrus. Contralateral monocular stimulation evoked larger potentials than ipsilateral stimulation; binocular stimuli evoked potentials even larger. Since this simple relationship did not hold for single cell responses they concluded that the behaviour of individual neurones could not be predicted from the magnitude of the surface evoked potential.

Auerbach, Beller, Henkes and Goldhaber (1961) reported short-latency surface negativity (10-30msecs.) as the predominant cortical response to diffuse photic stimulation. This finding is not in agreement with Marshall and Talbot (1942), Doty (1958) and Burns and co-workers (1960). Their conclusions on the relationship between potentials evoked by monocular and binocular stimuli are, however, in agreement with those of Burns et al. (1960). They showed that the binocular potential was the sum of the ipsi- and contra- lateral potentials.

Fromm and Bond (1967) recorded from the posterior lateral gyrus of cats and found that cells fired less frequently during the surface positivity of both spontaneous and photically evoked activity. Creutzfeldt and Kuhnt (1967) devised a model for the genesis of the VEP which would have supported Fromm and Bond's findings. This model was based on results from earlier experiments by Creutzfeldt and co-workers (Creutzfeldt, Watanabe and Lux, 1966) on potentials recorded from the surface of the motor cortex after electrical stimulation of the specific projection nuclei in the thalamus. In this model they suggested that a 'highly synchronised afferent volley' (presumably a brief diffuse flash) produces EPSP's on the soma of the cell. This depolarisation spreads towards the cortical surface causing surface positivity. The subsequent surface negativity is caused by the rapid development of an IPSP on the soma due to the action of the recurrent collaterals. Three points concerning this model should be borne in mind:

1. The model is based on results from an electrical stimulation study of the motor cortex where the layout of the cells is quite different from the visual cortex.

2. The majority of cells in the motor cortex are pyramidal cells (Mitra, 1955) and can thus be expected to contribute in similar ways to the surface evoked potential (especially as electrical stimulation was used). This is not the case in the visual cortex.

3. The model relies on a 'highly synchronous afferent input' activating all cells alike. A diffuse flash is unlikely to produce this effect. Also, the model takes no account of the sequential activation of different types of cell.

The inadequacy of this model and the interpretations of Fromm and Bond (1967) were underlined by an extensive study by Creutzfeldt, Rosina, Ito and Probst (1969) of intracellular and surface potentials in the

visual cortex evoked by flash stimulation. Diffuse photic stimulation (duration 10 secs.) produced a wide variety of potential waveforms at the cortical surface (area 17). The mean evoked potential computed from a series of 18 experiments showed six components of which a surface positive component (peak latency 40msecs.) and a negative wave (peak latency 90msecs.) were the most prominent. Superimposed on the rising phase of the positive wave was a small positive-negative inflexion (latency 20-25msecs.). Following the late negative wave were positive and negative waves with latencies of 150msecs. and 200msecs. respectively. Intracellular potentials of cells and the activity of incoming fibres were recorded simultaneously with surface evoked potentials. ON-centre fibres showed excitation between 15-50msecs. after the stimulus. This was followed by a 50msecs. inhibitory period and and a 20msecs. period of excitation. OFF-centre fibres were inhibited during the period 15-90msecs. after the stimulus, By contrast, cortical cells showed a wide variety of responses to diffuse flash stimuli (see section 1.1) which were classified into two groups. The first group, a third of the total, showed primary excitation, the second showed primary inhibition. The most significant correlations noted by Creutzfeldt and co-workers (1969) between surface potentials and unit activity were:

1. Primary excitation of ON centre fibres and about a third of the cortical cells during the early part of cortical positivity.

2. Primary inhibition of the majority of cortical cells during the large surface positive component.

3. The late excitation of a large proportion of cortical cells with the late surface negativity.

These findings differ from those of Fromm and Bond (1967) and do not fit in with the model earlier proposed by Creutzfeldt and Kuhnt (1967). The lack of a clear correlation between unit activity and components of the surface potential highlights the difficulties involved in studies of this

nature. These difficulties are compounded by the use of a visual stimulus now known not to evoke a powerful response from cells in the visual cortex (see section 1.1). Cortical cells respond optimally to contours and light/dark edges in the visual field and not to diffuse stimuli. If a stimulus containing visual contours were used, it is possible that a more definite relationship between unit activity and surface-recorded VEP's might emerge.

SUMMARY

Diffuse photic stimuli evoke potentials with a positive/negative waveform on the surface of the visual cortex of the cat. Such stimuli are now known not to evoke responses from most single cortical cells. (See section 1.1). Understandably, attempts to correlate unit activity with the surface potential under these circumstances have not produced a clear result. It is possible that if a patterned stimulus was used, a clearer correlation between cell activity and the surface potential would result.

1.4 SURFACE MAPPING OF THE VISUAL CORTEX OF THE CAT USING EVOKED POTENTIALS

Although the link between single cell firing and the surface recorded visual evoked potential is not clear, it has been possible, using VEP's, to plot the retinotopic layout of the cat's visual cortex.

Early experiments on the retinotopic organisation of the visual areas were carried out by Talbot and Marshall (Talbot, 1940; 1942; Talbot and Marshall, 1942). Talbot, (1940) reported using punctiform stimuli subtending 20' of arc, that '. . . the left half of each retina projects to the left cortex and right to right; the lower field is forward on the brain, the upper field occipital. Central vision projects to the dorsal surface just forward of the apex of the tentorium. The vertical meridian of vision extends forwards about 15 mm. from here along the midline and backward along and just ventral to the sulcus lateralis posterior. The upper right quadrant of the field projects to the left gyrus compositus medialis, with the extreme right periphery around the lateral tip of the sulcus lateralis. The lower right quadrant projects to the medial wall of the left marginal gyrus, with periphery along the upper lip of sulcus splenialis. The right horizontal meridian follows the lateral limb of sulcus splenialis inward toward the midline then upward to the centre of gaze described above. The upper and lower left quadrants and their dividing meridian project correspondingly on the right cortex.'

In this same study, Talbot observed a seoond visual area, the existence of which he confirmed in a later report (Talbot, 1942). He reported that there existed a second area 'lateral to the midline localisation of the medial visual region.' This second visual region was 'oppositely disposed' and was confined anteriorly to the lateral gyrus, posteriorly to the suprasylvian. Talbot reported that whilst the responses were similar in latency and waveform in the two areas, they were quite independent.

The medial and lateral areas were designated VI and VII by Woolsey, Fairman and Baltimore (1946).

The existence of a point to point localisation on the surface of the visual cortex was questioned by Doty (1958, 1961). He found, using punctiform stimulation, that it was possible to evoke responses from a wide area of the cortex. He could find only extremely rough indications of a retinotopical organisation and questioned the validity of the studies of Talbot (1940, 1942) and Talbot and Marshall (1942).

The discrepancy between the findings of Talbot and Marshall and Doty was explained by Whitteridge (see discussion in Doty, 1961). He reported that only the early responses (latency 30-40 sec.) to flashed stimuli were well localised, and, using these early responses it was possible to replicate the findings of Talbot (1940, 1942). Whitteridge found that 'the late responses beginning after 70 secs. can be set up from points widely separated in the visual field and even in the ipsilateral visual field.'

Bilge, Seneviratne and Whitteridge (1963) confirmed Talbot's findings (Talbot, 1940) on the retinotopic layout of VI. They also confirmed the existence of VII but were unable to determine its retinotopic arrangement or extent.

In 1962, Otsuka and Hassler defined three visual areas, 17, 18 and 19 anatomically. Hubel and Wiesel (1965), in a single unit study, established the correspondence of areas 17 and 18 with VI and VII described by Talbot and also distinguished a third ordered projection of the contralateral visual field, VIII, which corresponded almost exactly to area 19. Bilge, Bingle, Seneviratne and Whitteridge (1967) recording surface potentials evoked by punctiform stimuli, showed that VII and VIII are both divided into areas representing the lower and upper visual fields. The upper and lower areas of VII join the vertical meridian of VI medially but laterally the horizontal meridian separates them from VIII. The area opposite the

representation of the area centralis separates the upper and lower halves of VII and VIII. The findings of Bilge and co-workers (1967) indicate that Talbot's maps of VII are an oversimplification. It appears that there are two parts of VII each lying along the vertical meridian separating VI from VII. Each VII then has a further VIII on its lateral side. Whitteridge (1973) has reported the arrangement of the horizontal meridian which separates VII from VIII as being 'on a small scale so that from 0-45° anteriorly and from 0-30° posteriorly are represented respectively just in front of and behind the area centralis.' Whitteridge (1973) reported that, anteriorly the horizontal meridian does not seem to be represented and that moving across the cortex in steps it is possible to move from VII to a corresponding position in VIII without 'touching the horizontal meridian at all.'

Woolsey (1971) found a cortical representation for VI and VII supporting the original map of Talbot (1940, 1942). He was unable to find any representation corresponding to VIII reported by Hubel and Wiesel (1965), Whitteridge (1973) and Bilge et al. (1967). It is possible that the complex arrangement of VII and VIII and the smaller scale representation of VIII (Whitteridge, 1973) may have led Woolsey to overlook the projection to VIII.

SUMMARY

The retinal projection of 3 visual areas (VI, VII, and VIII) corresponding to areas 17, 18 and 19 defined anatomically, can be mapped using the early components of potentials evoked by punctiform stimuli. The projection of VI is simple in comparison with the projections of VII and VIII which are less straightforwardly laid out than had been reported in earlier surface potential and single unit mapping experiments.

1.5 PATTERN RELATED VISUAL EVOKED POTENTIALS (PRVEP's) IN THE CAT

There have been relatively few studies of potentials evoked in the cat visual cortex by patterned stimuli.

Minke and Auerbach (1972) recorded surface evoked activity from the striate cortex of cats, and, with a microelectrode, simultaneously recorded the localised slow waves and spike activity from single cells, using low and high-pass filtering. Stimuli were used which were specific for the cell (i.e. a correctly oriented slit of optimal dimensions). Understandably, as the same recording electrode was used, they were able to correlate components of the 'local' potential with the spike activity for each cell. The surface potential also had a fixed but unique relationship between its positive and negative waves and the activity of the cell. Because of the unique nature of this relationship they were unable to draw any general conclusions about the contribution of cell activity to the surface evoked potential.

Berkley and Watkins (1972) used contrast reversal of a grating stimulus to evoke PRVEP's from area 17 of the cat. They reported a linear relationahip between the relative amplitude of the reveraal response and the log. of the spatial frequency of the stimulus. Acuity estimates obtained by extrapolation of this graph ranged from 5.0-5.9 c/deg in 4 cats.

Campbell, Maffei and Piccolino (1973) estimated the cat's contrast sensitivity from potentials evoked by a sine-wave grating stimulus reversing in contrast at 16 Hz. They reported a linear relationship between the potential amplitude and the log. of contrast. The slope of this function decreased with increase in spatial frequency. For this reason the results of Berkley and Watkins, who assumed a linear relationship between spatial frequency and contrast sensitivity, and Campbell and co-workers are difficult to compare directly but there is agreement between the estimates of acuity for high contrast gratings.

SUMMARY

Only a few studies have investigated PRVEP's in the cat visual cortex. Potentials evoked by contrast reversal have been used to estimate the contrast sensitivity and grating acuity in the cat. Minke and Auerbach using stimuli optimal for activation of individual cells could not find a clear universal relationship between optimal cell activity and the resulting surface potential. There have been no attempts to evoke pattern-related potentials using pattern appearance stimuli (see section 1.6) and to record unit activity under these circumstances.

1.6 PATTERN RELATED VISUAL EVOKED POTENTIALS (PRVEP's) IN MAN

Studies in human PRVEP's are now relatively well advanced compared with those in the cat. In man, the scalp-recorded PRVEP shows marked differences (i.e. waveform, scalp distribution etc.) from the potentials evoked by an equivalent non-patterned stimulus (Jeffreys, 1968; Spehlman, 1965; Clynes and Kohn, 1967). They are thought to reflect the activity of pattern sensitive neurones similar to those in the cat visual cortex.

Two types of stimulus have been used to evoke pattern-related responses:

1. Pattern onset and offset. In this method the stimulus is introduced into a previously blank field with no change in mean luminance. Brief pattern presentations are often referred to as pattern appearance stimuli. The technical difficulty of this method has been side-stepped by flash-presenting a patterned stimulus and electronically subtracting from that response, the response to an equivalent non-patterned stimulus (Rietveld, Tordoir, Hagenouw, Lubbers and Spoor, 1967) or subtracting the potential evoked by the defocussed pattern stimulus from the potential evoked by the focussed pattern stimulus (White, 1969). Neither of these methods is entirely satisfactory since it cannot be assumed, a priori, that responses to a blank stimulus and a patterned stimulus summate linearly.

2. Pattern reversal. The contrast of a regularly patterned stimulus is reversed to produce a pattern stimulus with no change in mean luminance.

The rate of stimulus presentation determines whether individual components resulting from a transient stimulus, or a harmonic composition of a steady state response, are investigated. (See Regan, 1972, p. 75).

Potentials evoked by transient pattern onset stimuli, have been investigated by Jeffreys (Jeffreys, 1969; Jeffreys, 1971; Jeffreys and Axford, 1972a; b). He found that a brief (25msecs.) pattern onset stimulus evoked a potential with three basic components: CI (peak latency 65-80msecs.) CII (peak latency 90-110msecs.) CIII (peak latency 160msecs.)

The polarity of the individual potential components varied with the recording site and with stimulus position in the visual field. Jeffreys and Axford (1972a; b) identified the sites of origin of CI and CII by analysing their scalp distribution when different parts of the retina were stimulated. A comparison of this distribution with that calculated from a knowledge of the anatomical layout of active sites and their orientation within the brain indicated that CI was striate in origin, whilst CII originated in the extrastriate cortex. Subsequent studies (Jeffreys, 1974) have revealed that CIII also originates in the extrastriate cortex but in a different region from that generating CII. Preliminary reports (Jeffreys, 1972; 1974) indicate that the generators of CII and CIII have different stimulus-related specificities from those generating CI. CII and CIII are more easily adapted by prolonged pattern stimulation, are more sensitive to defocussing of the retinal image and are more influenced by the presence of steady contours. These different properties suggest that CI represents a 'contrast' sensitive mechanism (striate in origin), whilst CII and CIII represent a 'contour' sensitive mechanism.

Halliday and Michael (1970) using a reversing checkerboard stimulus have also reported that the form and polarity of the PRVEP is dependent upon recording site and stimulus location but their findings contrast markedly with those of Jeffreys and Axford (1972a; b). From a study of the scalp distribution of potentials, Halliday and Michael concluded that the striate cortex buried deep in the calcarine fissure, plays no part in the generation of the PRVEP. In a later report (Michael and Halliday, 1971) they concluded that it is the extrastriate cortex on the inferior and superior surfaces of the occipital lobe which generates the response to upper and lower visual field stimulation, respectively. It is difficult to reconcile the results of Jeffreys and Axford with those of Halliday and Michael. Halliday and Michael attribute the PRVEP to surface positive activity on

the upper and lower occipital lobes near the occipital pole, whilst Jeffreys and Axford conclude that the PRVEP is generated by surface negative activity in and close to the calcarine fissure and on the upper and lower lobes of the occipital cortex close to the occipital pole.

The main differences are probably due to differing experimental methods. Jeffreys and Axford used brief (25msec.) pattern onset stimuli of 6° angular subtense. The pattern elements were hollow 14' squares of 3.5' line thickness. Component amplitudes were measured from the baseline. Halliday and Michael, however, used a 14°-18° field of 50' checks with pattern reversal, measuring the peak-to-peak amplitude of the 100msec. wave and the wave immediately following.

The relationship between potentials evoked by stimulus onset and offset has been the subject of several recent investigations.

Spekreijse and Estevez (1972) reported that potentials to stimulus onset were similar in form to those evoked by brief presentations of a patterned stimulus. Potentials at stimulus offset comprised of a weak negative deflection preceding a positive deflection, the weak negative deflection seeming to be 'rather luminance specific'.

Similar results were obtained by Spekreijse, van der Tweel and Zuidema (1973). They found that onset potentials were similar to those evoked by brief pattern appearance stimuli whilst the offset potential was seen as a 'sharp positive deflection followed by a decay'. In most subjects this was preceded by a weak negative deflection. They concluded that onset and offset potentials originated from different cell populations.

Estevez and Spekreijse (1974) considered that the responses to stimulus onset and offset should be viewed as 'contrast increase' and 'contrast decrease' responses. They concluded that whilst the reversal response contained contributions from both contrast increase and contrast decrease responses, the pattern-reversal potential lacked any components identified by Jeffreys as CII. They also suggested that the response

measured by Michael and Halliday (1971) seemed to be mainly related to contrast decrease, whilst those potentials recorded by Jeffreys and Axford were mainly due to contrast increase. As Spekreijse et al. (1973) have reported that the contrast increase and contrast decrease originated from different cell populations, this finding could account for the discrepancy between the results of Jeffreys and Axford and Halliday and Michael.

Jeffreys (1974) reported that the potential evoked by stimulus offset 'clearly consists of two successive positive peaks of latency comparable to CI and CII of the onset VEP'. He suggested that the source of the second component in the offset response originated in the extrastriate cortex resulting from surface positivity (as opposed to surface negativity in the onset extrastriate component). In a later report Jeffreys (Jeffreys, 1974) was able to confirm that the first component of the off response had a similar scalp distribution to the CI component of the pattern appearance response. The second component, however did not seem to be pattern specific, not showing the normal pattern evoked potential distribution on the scalp. This confirms an earlier report by Clarke (1973) that pattern disappearance VEP's did not clearly exhibit polarity reversal between the upper and lower half fields.

The relationship between pattern reversal visual evoked potentials and those evoked by pattern onset and offset is not yet clear. Jeffreys (1974) has reported that the reversal response is a composite waveform consisting of components corresponding to CI of the onset potential and the main (2nd) peak of the offset potential. This correlates with the interpretation of Estevez and Spekreijse (1974).

As the interstimulus interval is decreased, the components of the transient potential overlap to an increasing extent. At sufficiently high rates of stimulus presentation a steady-state is achieved in which no

individual response cycle can be associated with any particular stimulus cycle, so the harmonic composition and phase of the resulting potential is analysed. Steady-state potentials related to pattern have been investigated by several workers (e.g. Regan and Richards, 1973; Spekreijse, 1966; Campbell and Maffei, 1970; see Regan, 1972).

Regan and Richards (1973) found that using a reversing checkerboard as the stimulus (reversal frequency 6 Hz.) almost all the power in the response was confined to the 6 Hz. component (i.e. in the fundamental frequency). A log.-log. plot of amplitude versus check size could best be fitted by two lines of unity slope, the response decreasing at check sizes above and below 11'. This relationship was altered considerably by placing a +1D lens in front of the subject's eyes.

Campbell and Maffei (1970) found that the amplitude of the 16 Hz. component of the steady-state potential, evoked by a sine-wave grating reversing at 16 Hz., was linearly related to log. contrast. This relationship held over pattern contrasts of up to 0.3 log. units. Their results showed that at high frequencies, the response amplitude was markedly reduced. So, in contrast to the contribution that the higher spatial frequencies seem to make to the checkerboard reversal response (see Regan and Richards, 1973) (because of their sensitivity to defocussing, which attenuates the response to higher spatial frequencies) it would appear that the response to a square wave grating is mainly the response to the fundamental (because of the steep decline in response to higher spatial frequencies) and because of this it would be relatively insensitive to defocussing. It is not clear whether the response to a reversing sine-wave grating in these circumstances is a pattern specific response in the same way that the response to a reversing checkerboard is.

SUMMARY

In man, PRVEP's show marked differences from those evoked by luminance changes. The PRVEP to brief presentations of a patterned stimulus (a pattern appearance stimulus) is dominated by the potential evoked by pattern onset. The PRVEP to stimulus onset has 3 basic components: CI (65-80msecs.); CII (90-110msecs.); and CIII (160msecs.). CI appears to be striate in origin whilst CII and CIII are generated by two different regions of the extrastriate cortex. CI is thought to represent the activity of a 'contrast' sensitive mechanism whilst CII and CIII represent 'contour' detecting mechanisms. The offset potential only consists of a component similar to CI and a luminance related potential. Reversal and offset potentials are similar. It is possible that reversing gratings and checkerboards involve different pattern detecting mechanisms.

1.7 CURRENT PROBLEMS CONCERNING EVOKED POTENTIALS AND SINGLE UNITS IN THE VISUAL CORTEX OF THE CAT

The preceding sections have highlighted some current problems concerning evoked potentials and single unit responses in the visual cortex of the cat.

1. Receptive fields of single cells in the visual cortex of the cat are sensitive to patterned stimuli. Non-patterned stimuli are largely ineffective. Movement is a powerful stimulus.

2. Pattern-sensitive neurones are grouped according to their orientation preference.

3. The relationship between unit responses and surface recorded potentials evoked by diffuse photic stimuli is not clear. This could be due to insensitivity of cells to diffuse stimuli.

4. In man, potentials evoked by patterned stimuli are quite different in waveform and retinotopic distribution from those evoked by equivalent non-patterned stimuli.

5. There have been few comparable studies of PRVEP's in the cat and no attempts at correlating unit activity with surface slow wave activity under these conditions.

My expectation at the start of this thesis was that if cells with a given orientation preference and similar retinal location are grouped together in 'cortical columns' then during electrode penetrations normal to the brain surface it should be possible to record 'orientation column potentials' in response to localised grating stimuli of appropriate orientation, which had orientation sensitivity comparable to that of single cells. Such a potential would have formed a link between neuronal activity and the gross surface potential and might have also been a useful indication of the activity within a functional subunit of the brain.

Preliminary studies indicated that in certain circumstances it was possible to evoke pattern related potentials within the cortex which appeared to be related to the surrounding unit activity (see section 4.1). However, in other experiments in seemingly similar circumstances, it was not possible to record potentials related to patterned stimuli.

I then embarked upon an experimental programme aimed at finding the best experimental conditions under which it was possible to evoke pattern specific potentials from the cat visual cortex and to investigate their properties. Further investigations of the properties of single units in the cat visual cortex were carried out in parallel with these experiments. These results, and those from pilot studies of column potentials, are presented in this thesis.

METHODS

2.1 INTRODUCTION

The methods used in single unit experiments and evoked potential experiments were basically similar but differed markedly in certain respects. The methods section is therefore in two parts for clarity.

2.2 SINGLE UNIT EXPERIMENTS

2.2.1 Choice of Preparation

All general anaesthetics modify the responses of cells in the visual cortex to some extent. The extent to which this occurs varies with different anaesthetics, so the choice of anaesthetic is absolutely crucial. The anaesthetic chosen:

1. Must only minimally interfere with the responses of cells whilst maintaining an adequate depth of anaesthesia.

2. Must allow the easy maintenance of a constant depth of anaesthesia for the duration of recording from a cell if quantitative measurements are to be made.

3. Should not cause undesirable side effects e.g. cerebral oedema or chronic hypotension.

Preliminary investigations were made with four preparations before the most appropriate was chosen. Three experiments were carried out under sodium pento-barbitone (Nembutal-Abbot) anaesthesia. It was found that the excitability of cells in the cortex varied with the depth of anaesthesia - increasing depth caused the units to be sluggish and more difficult to drive. So, with periodic intra-peritoneal injections, the excitability of the units was not sufficiently constant to allow quantitative measurements to be made.

Two experiments were carried out under chloralase anaesthesia. It was found that although stable anaesthesia was easily maintained cell activity seemed to be considerably modified.

Trial single unit experiments were carried out using the rostropontine pretrigeminal preparation (Batini, Moruzzi, Palestini, Rossi and Zanchetti, 1959), a preparation which has been used by Burns and co-workers (Burns and Pritchard, 1962; 1964; 1971). It was possible using the technique employed by Burns to achieve a stable, unanaesthetised isolated forebrain but in all such preparations cerebral oedema was a problem. Oedema still occurred even when a ventricular drain (Burns and Pritchard, 1971) was used to release the build-up of cerebro-spinal fluid (CSF) caused by the disruption of normal CSF drainage. In single unit experiments cerebral oedema resulted in distortion and damage of the exposed cortex and for this reason use of this preparation had to be discontinued.

The anaesthetic finally adopted was a 75%/25% nitrous oxide/oxygen mixture supplemented with small amounts (< 0.8%) of halothane (Fluothane I.C.I.). This aneasthetic combination had the following advantages:

1. Provision of an adequate depth of anaesthesia for unit recording.

2. Simplicity of administration allowing a constant level of anaesthesia to be maintained for long periods.

3. Comparatively little effect on the excitability of cortical neurones.

4. Lack of undersirable side effects e.g. cerebral oedema. Excessive amounts of halothane did cause transient brain shrinkage, probably due to hypotension, but the concentrations necessary to cause this were usually considerably in excess of those required to maintain anaesthesia. Halothane even in these small concentrations did cause some bradycardia and hypotension particularly during surgery. This was countered by the intravenous administration of methyl amphetamine (0.03 - 0.06 mg I/V), methoxamine hydrochloride (0.2 mg I/V) or by premedication with atropine (0.06 mg subcutaneously).

Only results obtained under halothane/nitrousoxide/oxygen anaesthesia are presented in this thesis.

2.2.2 Surgical Preparation

Nineteen adult cats (weight 1.8 - 4.5 Kg) were used. Anaesthesia was induced and maintained for the duration of surgery with halothane (Fluothane I.C.I.) in oxygen. The right and left cephalic veins and trachea were cannulated. Blood pressure was monitored using a Devices CEC pressure transducer connected by a cannula to the left carotid artery. Clotting in this cannula was prevented by a continuous infusion of sodium citrate (3% at 0.3 ml/hr). Temperature was maintained at 37° - 38°C by means of a homeothermic blanket used in conjunction with a rectal thermistor (Electrophysiological Instruments Ltd.). The EEG was recorded differentially from 2 stainless steel screws in contact with the dura above the left visual and auditory cortices. The EEG was amplified by a Devices 3160 amplifier (bandpass 0.8 - 50 Hz) and continuously written out with the BP record on a 2-channel pen-recorder (Devices M2). The cats were mounted in a Narishige stereotaxic instrument modified to minimise obstruction of the visual fields. On completion of the surgical procedures and until the end of the experiment, the cats were maintained on a nitrous oxide/oxygen mixture (75%/25%) supplemented with small amounts ($< 0.8\%$) of halothane. End tidal carbon dioxide was maintained at 4.0% using a Palmer artificial ventilator (stroke volume approximately 30 mls., rate 27/min.) in conjunction with a carbon dioxide analyser (Beckman Medical gas analyser LB1). Eye immobilisation was achieved using gallamine triethiodide (Flaxedil, May and Baker). A continuous intravenous infusion of Flaxedil (20 mg/ml of 2.5% dextrose solution) at 1 ml/hr was preceded by an initial intravenous dose of 40 mg. Just prior to paralysis the EEG, carbon dioxide, blood pressure and pulse were all carefully assessed for use as criteria of adequate anaesthesia during paralysis when conventional methods are ruled out. Dilation of the pupils and retraction of the nictitating membranes were achieved by application of 1% (W/V) atropine sulphate and 10% (W/V) phenylephrine hydrochloride

(Macarthy's) eye drops, respectively (Bishop, Kozak and Vakkur, 1962). The corneae were prevented from drying by a pair of two-curve neutral contact lenses (Hamblin) selected from the following 3 pairs:

Base/peripheral curve: 8.0/8.5 mm
8.5/9.0 mm
9.0/9.5 mm

Each contact lens had a base diameter of 8.0 mm and a peripheral diameter of 12 mm. Selection of contact lenses for each cat was based on the data of Vakkur and Bishop (1963) and Vakkur, Bishop and Kozak (1963) (See Appendix I). The eyes were focussed, using a retinoscope in the plane of a matt-white translucent screen, 57.3" from the nodal point of the eye. The retinal landmarks (optic disc and area centralis) were plotted on a screen by back-projecting the narrow beam of an ophthalmoscope (Keeler) with a cube-cornered prism. A variety of circular artificial pupils were used with diameters ranging from 2 - 6 mm. Care was taken to ensure that the artificial pupils were centred over the area centralis of each eye.

2.2.3 Recording

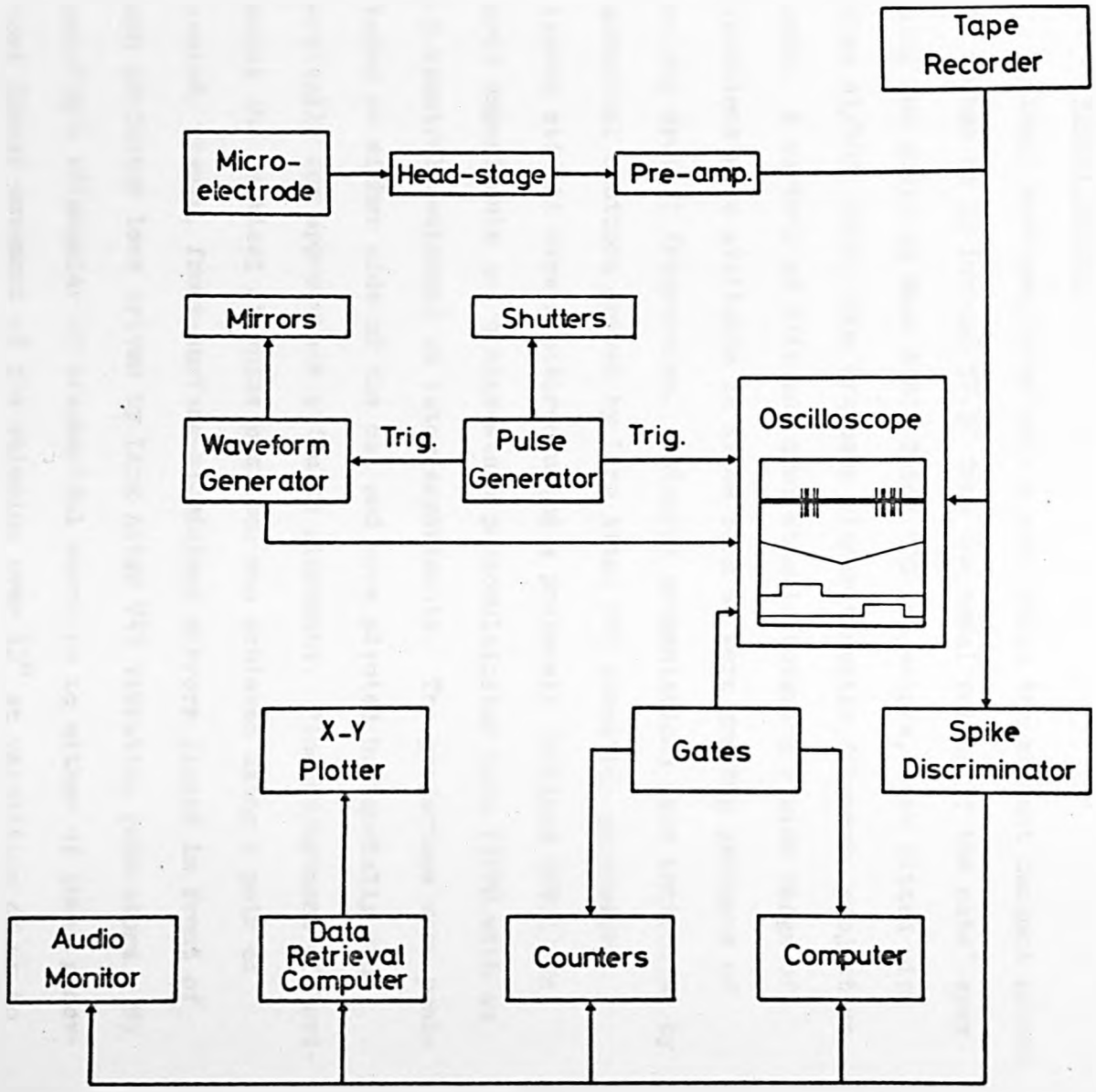
Extracellular spike recordings were made from single cells in Area 17 using glass micropipettes filled with either 2% pontamine sky blue dye (Gurr 6BX) in 0.5% sodium acetate (Hellon, 1970) or 4 M sodium chloride. With a tip diameter of between 1.5 and 2.0μ the impedance was typically 1.5 - 2.0 MΩ for sodium chloride-filled and up to 10 MΩ for the dye-filled electrodes. Dye-filled electrodes had the advantage of giving easy reconstruction of electrode penetrations but their relatively high impedance reduced the signal-to-noise ratio.

Electrode penetrations were made through a small craniotomy (3 - 5 mm diameter) at the Horsley-Clarke coordinates A2 - P8, R2. The dura was always removed. Cortical pulsation was reduced either by use of a modified Davies chamber (see Davies, 1956) or by sealing the electrode

in with 2% W/V Imuno-Agar (Oxoid) covered with a layer of low melting point (39°C.) wax to prevent drying. The electrode was advanced slowly through the cortex using a hydraulic microdrive until one cell could be clearly discriminated from its neighbours and the background noise. Penetrations were rarely continued beyond a depth of 3 mm in order to minimise damage to the cortex by the shank of the electrode. To this end, the characteristics of the electrode puller (Palmer H104) were always set to pull pipettes with shank diameters less than 80μ, 2 mm from the tip. At the end of each experiment the cat was perfused with 10% formal saline. After 24 hrs. fixation the brain was sliced coronally at a known stereotaxic (Horsley-Clarke) position anterior to the recording site, and the posterior part of the cerebral hemispheres removed. The tissue was then sectioned in the coronal plane on a freezing microtome and, after noting the position of any dye marks, the sections were stained with cresyl violet (Nissl). Area 18 was usually marked by the presence of large pyramidal cells in layer II (Otsuka and Hassler, 1968). Where this was not clear the maps of Hubel and Wiesel (1965) were used as a guide.

Signals were fed into a high input-impedance head stage (Ancom 15B-2 operational amplifier with a differential FET input) amplified by an Isleworth Electronic A101 preamplifier (Bandpass 200 Hz - 5 kHz) and displayed conventionally on a Tektronix RM565 oscilloscope. Action potentials were fed to a window-discriminator permitting separation of positive or negative polarity spikes from the background noise. Z-modulation was used to intensify that portion of each spike above the threshold level, or, for photographic purposes, the entire spike. Standard 1μsec. pulses could be fed to suitably gated counters (Venner TSA 6634, Advance TC11A) and into a data retrieval computer (Nuclear Chicago DRC or Biomac 1000) for compilation of average response histograms (ARH's). (See Fig. 4.)

FIG. 4. Plan of apparatus used in single unit experiments.


Tape Recorder
Micro-electrode
Head-stage
Pre-amp.
Mirrors
Shutters
Oscilloscope
Waveform Generator
Trig.
Pulse Generator
Trig.
X-Y Plotter
Gates
Spike Discriminator
Audio Monitor
Data Retrieval Computer
Counters
Computer

The raw data were stored on magnetic tape using a Thermionics T3000 four channel FM tape recorder. In later experiments computer facilities (Digital Equipment PDP-8) were available for on-line analysis of mean spike counts and data could be stored on Dec-tape for subsequent off-line computations of means, standard deviations and standard errors.

2.2.4 Visual Stimuli

Stimuli were projected onto a matt white translucent tangent screen (46 inches by 33 inches) 57.3" from the nodal points of the cats' eyes using two modified Rank Aldis Tutor 500 projectors, each fitted with Atlas A1/205, 240v, 500w Trufocus planar tungsten filament projection lamps. A variety of slit and spot stimuli covering a wide range of dimensions were available in slide form as were grating patterns of various spatial frequencies. Stimulus presentations were controlled by mechanical shutters driven by Ling Altec V47 vibration generators. Flashed stimuli were monitored using a photocell (Mullard OCP71) in early experiments and a nine-stage photomultiplier tube (IP28 with an S-5 spectral response) in later experiments. The projectors were positioned on either side of the cat and were pivoted horizontally and vertically for appropriate stimulus placement. Fine adjustment of horizontal and vertical stimulus position was achieved using a pair of pivoted, planar, front-surface-aluminised mirrors placed in front of each projector lens driven by Ling Altec V47 vibration generators. By applying a triangular or trapezoidal waveform to either of these generators linear movement of the stimulus over 12^{o} at velocities of up to 125 deg/sec could be effected. The platform on which the mirrors were mounted could be rotated as could the slide carrier so that stimulus movement and orientation, respectively, could be controlled independently. In these experiments movement was used only in conjunction with slit stimuli and was always orthogonal to the stimulus motion.

Kodak Wratten neutral density filters allowed the stimulus intensity to be reduced in calibrated steps of approximately 0.1 log units over a range of 4 log units. A range of background adapting levels from -1.57 log cd/m^2 to +1.56 log cd/m^2 were available. In this study recording was carried out at high mesopic levels for the cat (Hammond and James, 1971) using a background intensity of 1.56 cd/m^2 in conjunction with 2-6 mm diameter artificial pupils.

2.3 EVOKED POTENTIAL EXPERIMENTS

2.3.1 Introduction to Methods

A variety of experimental techniques were used. The basic differences were:

1. Type of preparation.
2. Number of recording electrodes and the recording system.
3. Stimulus methods.

Type of Preparation

Preliminary investigations were made with three preparations before the most suitable was chosen. They were tried in the following order:-

a) Sodium pentobarbitone anaesthesia

Three experiments were carried out using sodium pentobarbitone anaesthesia (Nembutal, Abbot) but the preparation had two specific disadvantages:-

i) Even light anaesthesia caused some reduction of cortical activity.

ii) Periodic intra-peritoneal injections of anaesthetic caused fluctuations in cortical excitability.

b) Halothane/Nitrous oxide/Oxygen anaesthesia

Nitrous oxide and oxygen (75%:25%) plus small amounts (0.8%) of halothane (Fluothane, I.C.I.) was used successfully in single unit experiments (see Section 2.2) but because of the difficulty in maintaining constant depth of anaesthesia over very long periods (up to 30 hrs.) it was not suitable for evoked potential experiments.

c) The rostropontine pretrigeminal (Cerveau isolé) preparation

This preparation (Batini, Moruzzi, Palestini, Rossi and Zanchetti, 1959) has been used extensively by Burns and co-workers (Burns and Pritchard, 1962; 1964; 1971) in studies on the cat visual cortex. Two methods of isolation were used:

i) The 'Burns' Technique. A wire leucotome was passed behind the tentorium through the pons, rostral to the pretrigeminal nerve (see

section 2.3.2 for detail) to achieve the isolation. Thereafter the anaesthetic was discontinued leaving the cat in an unanaesthetised sleep-like condition with a spindling EEG. In several of these preparations, however, the isolation disrupted CSF drainage and cerebral circulation, resulting in cortical damage.

ii) The 'Llinas' Technique. RF current was passed through a parallel array of electrodes to produce a slab of coagulated tissue through the rostral pons. (For detail, see section 2.3.2.) This method minimised trauma to the brain tissue and was more successful than leucotomy.

The rostropontine pretrigeminal preparation had the clear advantage over anaesthetised preparations of giving long term cortical stability. Brain distortion caused by cerebral oedema was prevented by sealing in the electrode with low melting point (39°C) wax which was then capped with dental cement.

Number of Recording Electrodes

In early experiments a single recording electrode was placed over the border of cortical areas 17 and 18 representing the projection of the area centralis. Very different waveforms, however, were recorded from electrodes in this position in different experiments. A possible explanation for this was that a single electrode sampled different parts of a wider distribution of overlapping evoked potential components. So, to assess the distribution of these components, an array of up to 8 electrodes was used in later experiments. The electrodes were usually arranged in a para-sagittal row along the lateral and post-lateral gyrus at approximately L or R2, and a transverse row across the post-lateral gyrus and onto the suprasylvian gyrus (at AO-P4). To facilitate recording with 8 electrodes a multi-electrode amplification and recording system was used (Jeffreys and Axford, 1972a; b).

Stimulus Methods

Jeffreys has used a two-field tachistoscope to evoke pattern related

potentials in man (Jeffreys, 1971; Jeffreys and Axford, 1972a, b). A tachistoscope with a 9° field was used in early experiments but this was replaced in later experiments by one with 30° fields in order to stimulate the more peripheral retina which in area 17 is mapped on the medial edge of the hemisphere (Talbot, 1940; 1942; Woolsey, 1971; Whitteridge, 1973). It was thought that stimulation of the area would produce components in the evoked potential with a distribution different from those originating from A18, most of which is mapped along the lateral gyrus (Woolsey, 1971; Whitteridge, 1973), thus making it possible to identify separate A17 and A18 components.

A problem encountered using this stimulus was that potentials evoked by a slight intensity mismatch of the two fields, not sufficient to evoke a significant potential in man, evoked a large luminance-related potential in the cat which masked pattern related components in the response. In later experiments, in order to have greater control over luminance changes associated with the stimulus, patterns were generated on a CRT display. This also allowed easy presentation and control of pattern reversal stimuli.

2.3.2 Surgical Preparation

Fourteen adult cats were used. Surgical preparation was the same as for single unit experiments except as follows.

Electrodes were placed stereotaxically on the surface of the pia through small individual craniotomies made over the visual cortex. Each craniotomy was filled with low melting point (39°C) wax which was then covered with dental acrylic cement. After the electrodes had been sealed in the pretrigeminal transection was performed (Burns and Pritchard, 1971 or Llinas, 1969).

1. The 'Burns' Technique

A small hole was drilled in each side of the interparietal bone

6 mm lateral to the sagittal crest and 8 mm rostral to the external occipital crest. One arm of a 'U'-shaped stainless steel wire (0.025" diameter) loop was then passed through one hole and out through the other. The base of the 'U' was then pushed downwards at the angle of the tentorium (approximately 46^{o}-48^{o} to vertical) to the floor of the skull, passing through the rostral pons. Two further isolations, in the same plane as the first, but to either side, completed the transection.

2. The 'Llinas' Technique

The fore-brain was isolated by passing RF current through an array of electrodes inserted into the pons. Five steel needles (30 S.W.G.) insulated with polystyrene varnish to within 3 mm of the tip were arranged 1.5 mm apart in a fork arrangement. The electrode array is lowered at an angle of 46^{o}- 48^{o} from vertical, into the midbrain through a hole in the interparietal bone just caudal to the tentorium. Coagulation was achieved by passing 50-75 μA between adjacent pairs of electrodes at successive levels 2 mm apart through the brain-stem. The electrodes were removed and the tips cleaned after coagulation at each level. Eye movements and jaw closure during coagulation at lower levels were indications of correct electrode positioning.

After withdrawal of anaesthesia, the efficacy of the transection was assessed using EEG, blood pressure, pulse, end-tidal carbon dioxide and withdrawal reflexes.

Eye preparation and immobilisation and artificial ventilation to 4% end-tidal carbon dioxide were as described in section 2.2.2.

The cat's area centralis was directed to the centre of the stimulus by either tilting the stereotaxic instrument or inserting prisms between the cat's eye and the stimulus.

2.3.3 Recording

Silver/silver chloride recording electrodes were prepared in the following way. The tip of a silver wire (0.2 mm diameter) was fused in

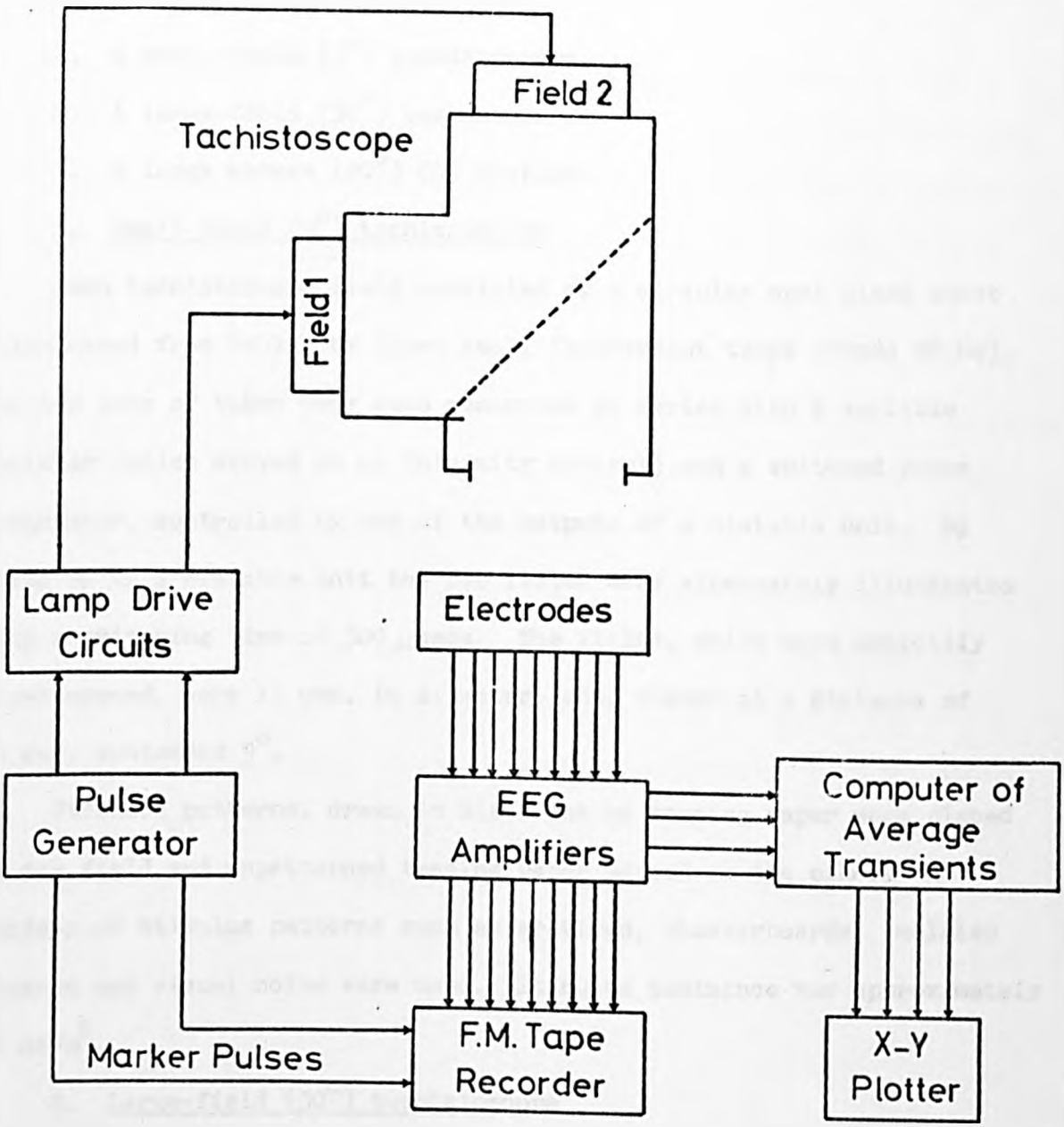
a bunsen burner for a few seconds to produce a small ball (0.3 - 0.7 mm diameter), which was then polished with fine emery paper and cleaned with ether. Two electrodes were then connected to a 1.5v battery and immersed close to each other in 0.1 N hydrochloric acid. Current was passed between them, three times in each direction, for 30 seconds. The electrodes were stored in the dark, immersed in 0.9% sodium chloride.

For single electrode experiments the raw EEG was fed into a high input impedance head stage (Ancom 15B-2 operational amplifier with differential FET input) and amplified by an Isleworth Electronics A101 amplifier (bandpass 0.2-50 Hz). The amplified signal was displayed on one beam of an oscilloscope (Tektronix 565). Responses were averaged by data retrieval computer (Nuclear Chicago D.R.C.) and written out with an X-Y plotter (Hewlett-Packard 7035B).

With multi-electrode arrays the evoked activity was amplified by a multichannel EEG amplifier (Beckman, bandpass 0.5 Hz - 50 Hz). The stimulus-locked responses from four electrodes were averaged on-line, using a CAT-400B averaging computer, the remaining responses averaged off-line. All the responses, together with marker pulses and a voice channel, were stored on tape using an FM tape recorder (Thermonix T8000) (see Fig. 5). The number of responses in any averaging run varied from 33 to 100 and for each stimulus two consecutive runs were carried out. All recordings were monopolar with the ear bars as the reference.

After fixation with 10% formal saline the brain was photographed allowing the electrode positions on the cortical surface to be established. The brain was sliced coronally at a known stereotaxic (Horsley-Clarke) position and the posterior part of the cerebral hemispheres removed and sectioned. Alternate sections were stained with cresyl violet (Nissl) and Luxol fast blue (myelin). Area 18 was distinguished from Areas 17 and 19 by the presence of large pyramidal cells in layer II (Otsuka and

FIG. 5. Plan of apparatus used in evoked potential experiments.


Field 2
Tachistoscope
Field1
Lamp Drive Circuits
Electrodes
Pulse Generator
EEG Amplifiers
Computer of Average Transients
Marker Pulses
F.M. Tape Recorder
X-Y Plotter

Hassler, 1968) and coarse myelinated fibres running transversely through the grey matter (Hubel and Wiesel, 1965). Where the borders were not clear, the maps of Hubel and Wiesel (1965) were used as a guide.

2.3.4 Stimulus arrangements

Three types of stimulus were used:

1. A small-field (9^{o}) tachistoscope.
2. A large-field (30^{o}) tachistoscope.
3. A large screen (20^{o}) CRT display.

1. Small-field (9^{o}) tachistoscope

Each tachistoscope field consisted of a circular opal glass sheet illuminated from behind by three small fluorescent tubes (Mazda MP-6w). The two sets of tubes were each connected in series with a variable resistor (which served as an intensity control) and a switched power transistor, controlled by one of the outputs of a bistable unit. By means of this bistable unit the two fields were alternately illuminated with a switching time of 300 μsecs. The fields, which were optically superimposed, were 11 cms. in diameter, and, viewed at a distance of 70 cms. subtended 9^{o}.

Stimulus patterns, drawn in black ink on tracing paper were placed in one field and unpatterned tracing paper placed in the other. A variety of stimulus patterns such as gratings, checkerboards, isolated squares and visual noise were used. Stimulus luminance was approximately 22 cd/m^{2}.

2. Large-field (30^{o}) tachistoscope

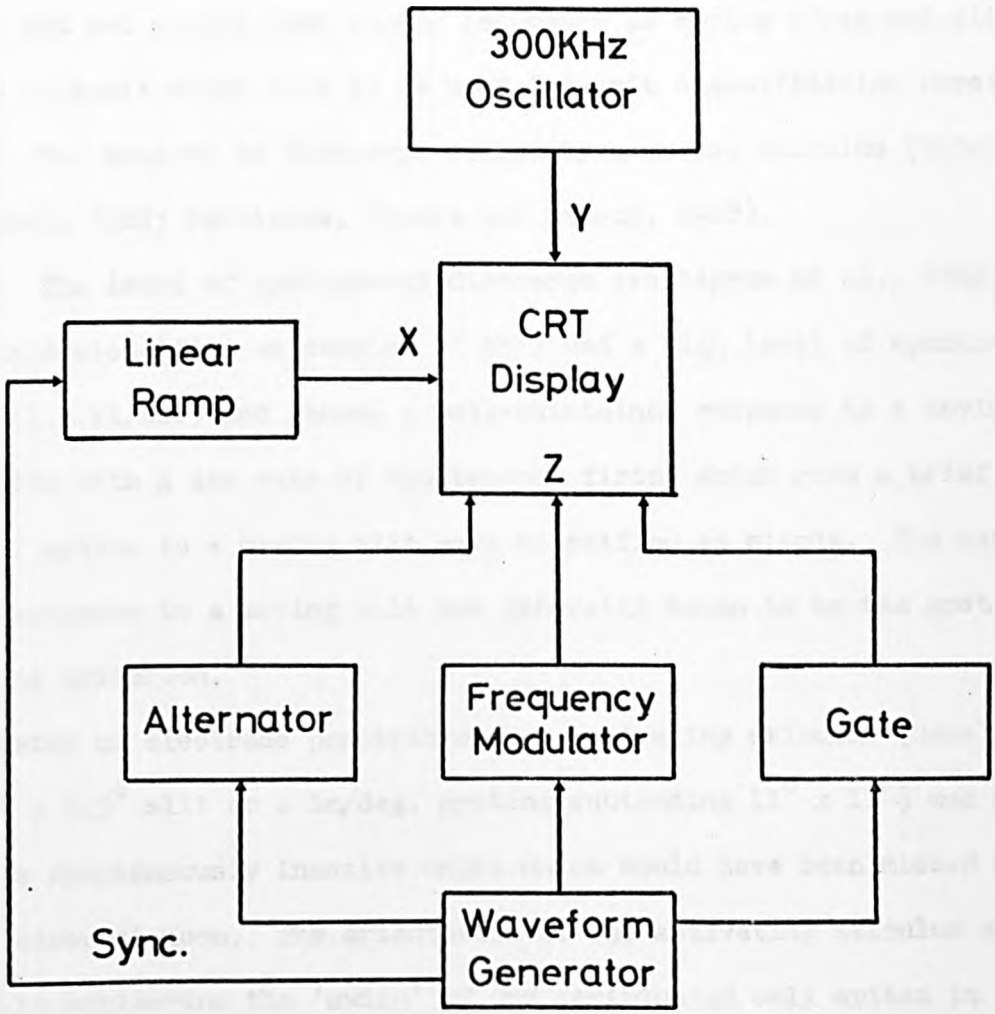
This stimulus was essentially the same as the small-field tachistoscope except that fields subtending 30^{o} were illuminated with fluorescent tubes (Atlas Daylight 15w) 45 cms. in length. The stimulus was 30 cms. in diameter and was placed 57.3 cm. from the nodal point of the cat's eye. Gratings, checkerboards and isolated squares were used as

stimuli. Switching times were typically 1 - 1.5 msecs. and maximum stimulus luminance was 50 cd/m^2.

3. Large screen (20^o) X-Y- display

Patterns were generated electronically on the screen of a CRT display (Hewlett-Packard Model 1300A - screen size 20 x 25 cms.). A linear ramp was applied to the X-input and the output of a 300 kHz crystal oscillator applied to the Y-input. This filled the screen with a raster of 100 lines/cm. which gave the impression of a blank uniformly illuminated screen. Grating patterns were generated by applying waveforms to the Z-input which were synchronised with the X-input (see Fig. 6). y varying the frequency, amplitude and type of waveform (sine, square or ramp), the spatial frequency, contrast and form of the pattern, respectively, could be varied. Gating this waveform or modulating its frequency from below (8c/deg) to above the cat's acuity gave pattern appearance stimuli. Pattern reversal stimuli were generated by applying a square wave stimulus to the Z-input, which, by means of externally controlled pulses, periodically reversed in phase (Stamps and Bourne, 1972). The screen of the display was masked-off except for the central 20 cms. and was placed 57.3 cms. from the nodal point of the cat's eye. Maximum pattern contrast was 0.7 and mean stimulus luminance was 50 cd/m^2.

FIG. 6. Plan of apparatus for generation of patterns on the CRT display.


300KHz
Oscillator
Y
CRT
Display
Z
X
Linear
Ramp
Alternator
Frequency
Modulator
Gate
Waveform
Generator
Sync.

3. RESULTS - SINGLE UNIT EXPERIMENTS

The results presented in this section are based on a sample of 51 units, all recorded from area 17 in the visual cortex of the cat.

In early experiments, units were classified as simple or complex on the criteria outlined by Hubel and Wiesel (1962) using stationary flashed stimuli. It was soon realised, however, that stationary flashed stimuli did not elicit such strong responses as moving edges and slits. So, the criteria which came to be used for unit classification were:-

1. The quality of discharge evoked by a moving stimulus (Hubel and Wiesel, 1962; Pettigrew, Nikara and Bishop, 1968).

2. The level of spontaneous discharge (Pettigrew et al., 1968).

Cells were classified as complex if they had a high level of spontaneous firing (i.e.>1/sec) and showed a well-maintained response to a moving bar.

Cells with a low rate of spontaneous firing which gave a brief burst of spikes to a moving slit were classified as simple. The nature of the response to a moving slit was generally taken to be the most important criterion.

During an electrode penetration, an activating stimulus (usually an $11^{\circ} \times 0.5^{\circ}$ slit or a 1c/deg. grating subtending $11^{\circ} \times 11^{\circ}$) was used to drive spontaneously inactive units which would have been missed under normal circumstances. The orientation of the activating stimulus was chosen by monitoring the 'swish' of undiscriminated cell spikes in the background noise as the electrode tracked through the cortex. The length of the activating stimulus probably accounts for the failure to record from hypercomplex cells now known to be present in area 17 (see Dreher, 1972).

When a unit could be clearly discriminated from the surrounding background activity, the spike-waveform, polarity and depth within the cortex were noted. Ocular dominance was estimated using auditory monitoring of the response to a moving grating or slit as a guide (Hubel

and Wiesel, 1962). When eye dominance had been established, the non-dominant eye was masked and the dominant receptive field plotted using the 'minimum response field' method of Barlow, Blakemore and Pettigrew (1967). An optimally oriented slit or edge was moved, sideways, into the receptive field until a response occurred. This was repeated with the other side, thus defining the axial limits of the receptive field. The non-axial limits were plotted by moving the same stimulus into the receptive field until a response occurred. This was then repeated with the opposite side. In this way a rectangle was built up which demarcated the cell's responsive area, the centre of which defined the receptive field centre. This method is now realised to be slightly crude, particularly in the light of receptive field detail outlined by Bishop and co-workers (Bishop, Coombs and Henry, 1971a; b) but it provided a useful first stage in elucidating receptive field properties. In some cases it was not possible to delineate both non-axial limits of the receptive field. When this was the case, the responsive area was estimated and a line drawn through its centre to indicate the receptive field position.

3.1 Location of Receptive Fields in the Visual Field

The locations in the visual field of the 51 units from which quantitative data were obtained is shown in Fig. 7. The areae centrales in each experiment have been superimposed and no allowance has been made for rotation of the eyes (on the evidence of Sanderson (1972)). 37 of the units (73%) had receptive fields located within 5° of the area centralis and 46 (90%) were located within 10°. 8 units (16%) had receptive fields with their centres in the ipsilateral half field. This is in agreement with the histological evidence of nasotemporal overlap of Stone (1966) and the physiological report of Blakemore (1969).

Fig. 8 shows the locations of the receptive field centres in the visual field with respect to recording site. It can be seen that the lower part of the visual field (i.e. below the area centralis) is represented more anteriorly in area 17 whereas the upper visual field is represented more posteriorly. It is also clear that it is possible to record from cells whose receptive fields lie within 5° of the area centralis in a wide range of locations in area 17. As these data are gathered from a number of experiments it is not clear whether this finding is due to the large representation of the area centralis and the lack of retinotopic mapping at the microscopic level reported by Hubel and Wiesel (1962), or to the wide variation in the position of the projection of the area centralis on the lateral gyrus (up to 4 mm), reported by Whitteridge (1973).

FIG. 7. A map showing the position of the centres of minimum response fields of cells on which quantitative studies were carried out. The left visual half-fields for the right and left eyes have been superimposed. A.C. = area centralis.

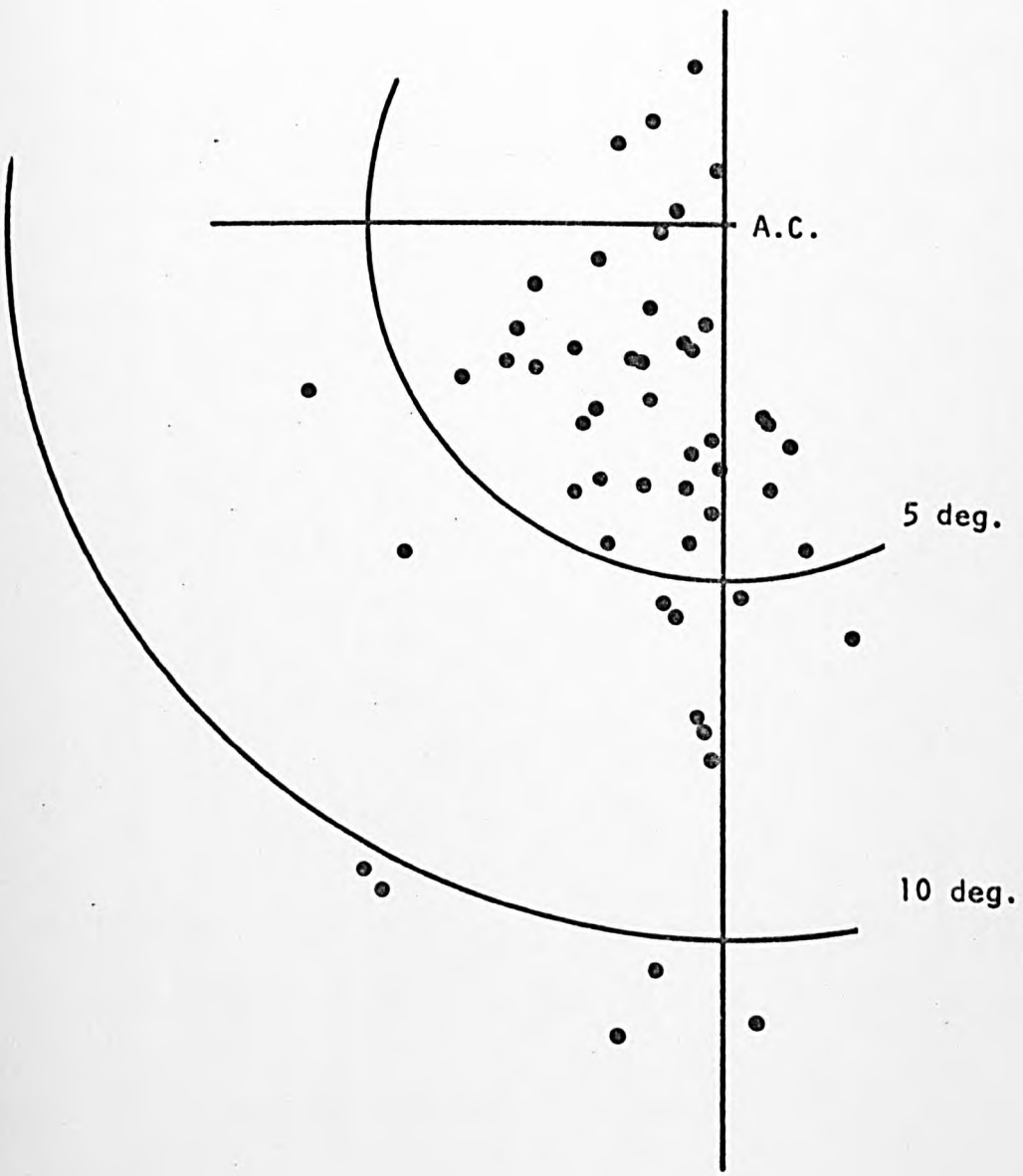
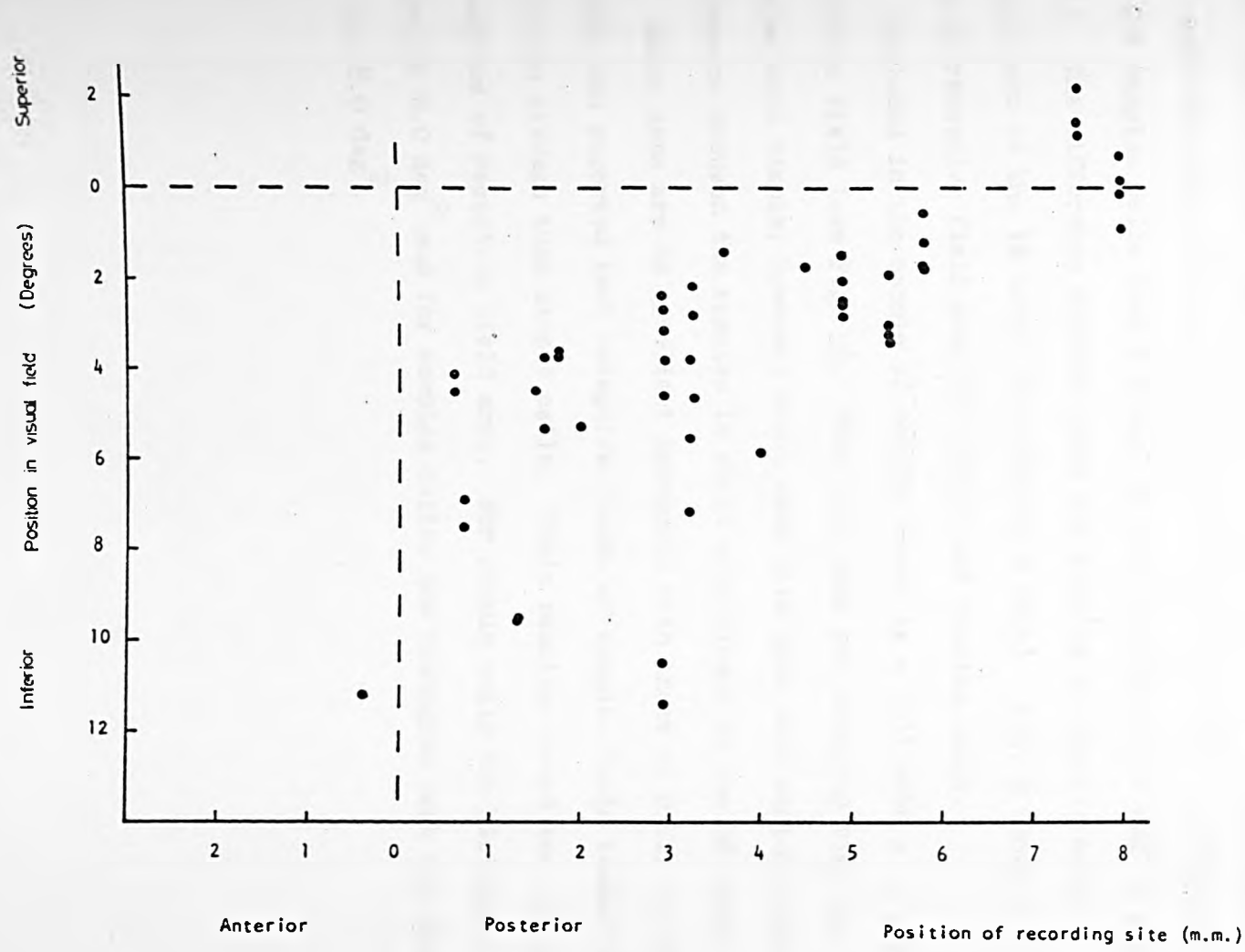

A.C.
5 deg.
10 deg.

FIG. 8. Position of the minimum response field centres of units in the superior and inferior visual fields in relation to recording site in the visual cortex (area 17). Ear-bar zero (Horsley-Clarke co-ordinates) defines recording site position zero.


Superior
Position in visual field (Degrees)
Inferior
2
0
2
4
6
8
10
12
2
1
0
1
2
3
4
5
6
7
8
Anterior
Posterior
Position of recording site (m.m.)

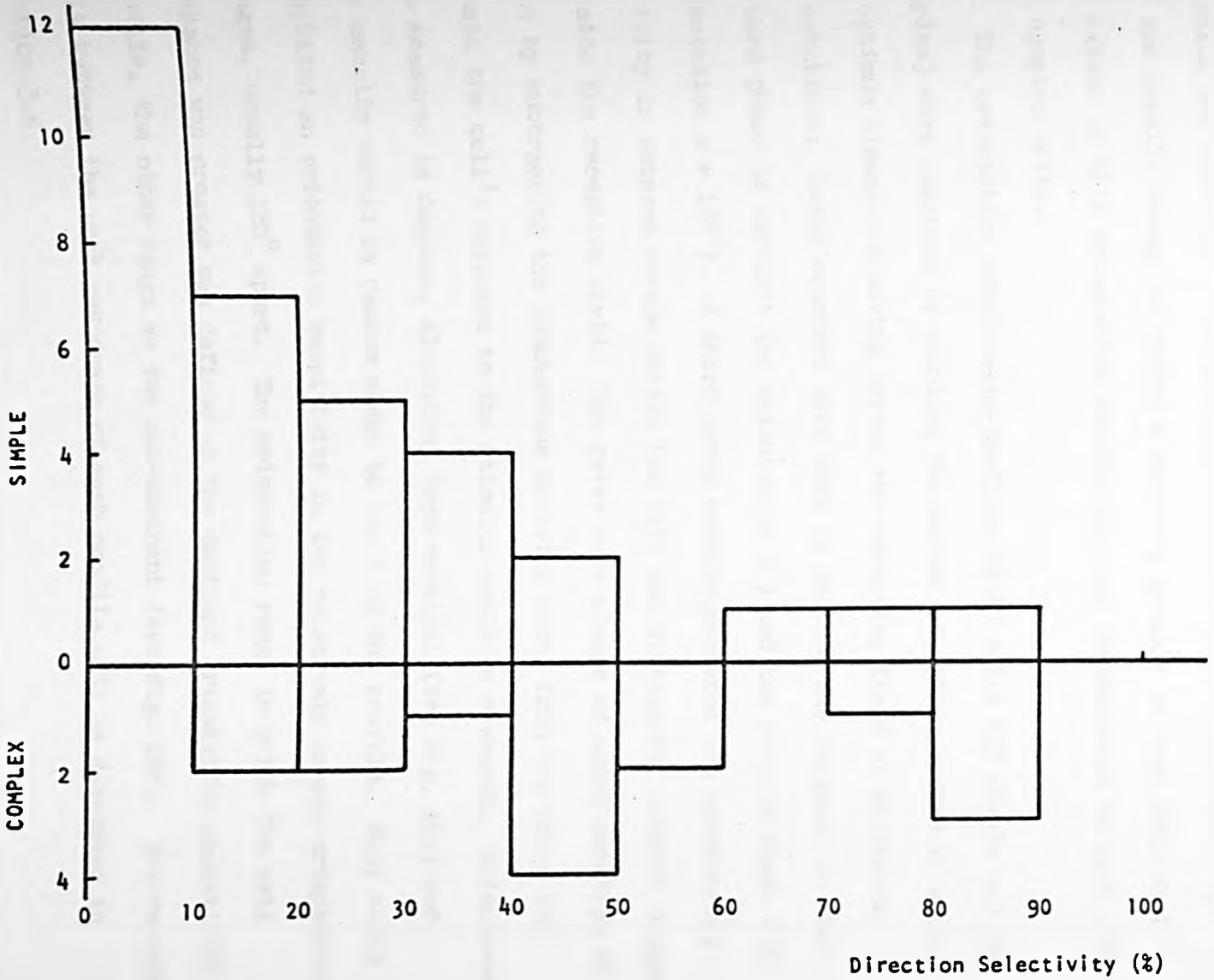
3.2 Size of Receptive Fields

The area of the receptive fields mapped by the 'minimum response field' method ranged from 0.12 deg^2 to 22.6 deg^2. For simple cells the range was from 0.12 deg^2 to 4.8 deg^2 (mean 1.7 deg^2 $\pm$ 1.07 (SD)) and for complex cells from 1.1 deg^2 to 22.6 deg^2 (mean 5.2 deg^2 $\pm$ 1.99 (SD)). The difference between these two samples is statistically significant at the 1% level (Mann-Witney U Test). Fig. 9 shows a histogram of receptive field area for simple and complex cells.

Included in the sample of complex cells is a cell with a very large receptive field (see Fig. 9). This cell does not unfairly bias the complex cell sample, however, since even with this cell excluded the difference between the samples is still significant at the 5% level.

These data are in excellent agreement with those of Hubel and Wiesel (1962), who reported that receptive fields of complex cells tended to be larger on average than simple cells. Their results showed two overlapping histograms of receptive field area. For simple cells the histogram peaked at 2.0 deg^2 and for complex cells, the histogram peak was between 4.0 and 8.0 deg^2.

FIG. 9. Histogram of receptive field areas for simple and complex cells. The mean receptive field area for simple cells was 1.74 deg^2 $\pm$ 1.07 (SD) and for complex cells, 5.19 deg^2 $\pm$ 1.99 (SD).


12
10
8
6
4
2
0
2
4
SIMPLE
COMPLEX
0
10
20
30
40
50
60
70
80
90
100
Direction Selectivity (%)

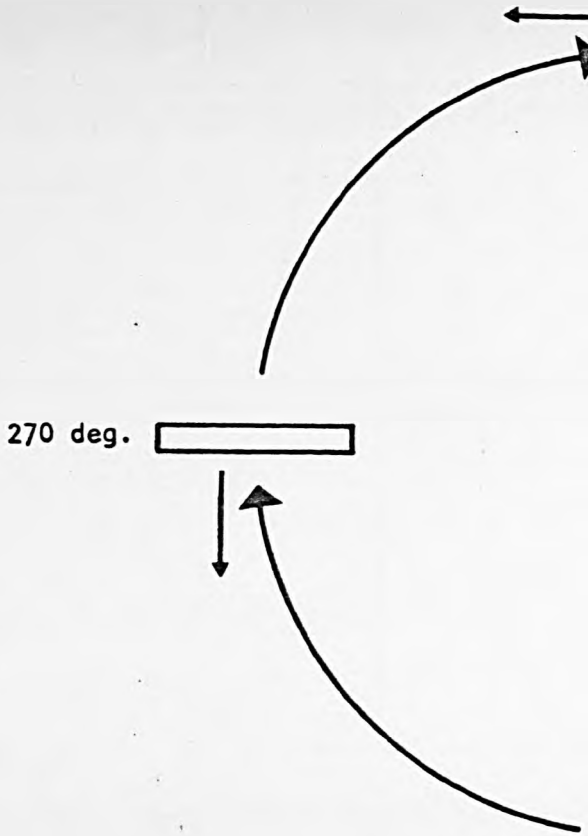
3.3 Orientation Sensitivity

Hubel and Wiesel (1959: 1962) showed that cells in the primary visual cortex responded to slits of light moved across or flashed on their receptive fields. To elicit a maximal response the orientation of the stimulus was critical - 'changing the orientation by more than 5° or 10° was usually enough to reduce a response greatly or even abolish it'. The extent of this orientation sensitivity was investigated in both simple and complex cells.

The orientation sensitivity profiles of 48 cells (33 simple and 15 complex) were measured by counting the number of spikes evoked by a slit of optimum dimensions moving across the receptive field at different orientations. Gated counters were used to measure the response to the forward phase of movement (at orientation x°) and the reverse phase (at orientation $x + 180^{\circ}$). A third gated counter measured the spontaneous activity in between sweeps whilst the slit was stationary, several degrees outside the receptive field. The gates were always of equal duration so that by subtracting the spontaneous activity count from the other two counts the cell's response to the stimulus could be measured. Orientation was measured in degrees, clockwise, from vertical (see Fig. 10a) and was usually varied in random steps to build up the profile. Many cells exhibited an orientation sensitivity in two relatively narrow orientation ranges, usually 180° apart. The orientation range in which the cell response was greater was defined as the dominant orientation sensitivity profile, the other range as the non-dominant (see Fig. 10b). The relationship between the peak responses of each profile will be discussed in Section 3.5.

For each orientation, histograms and averages were compiled using between 8 and 20 stimulus presentations. In all cells the same number of presentations was used at all orientations. The optimum slit velocity

FIG. 10a. Conventions of stimulus orientation and direction of movement. Short arrows represent the direction of movement of the stimulus.


270 deg.

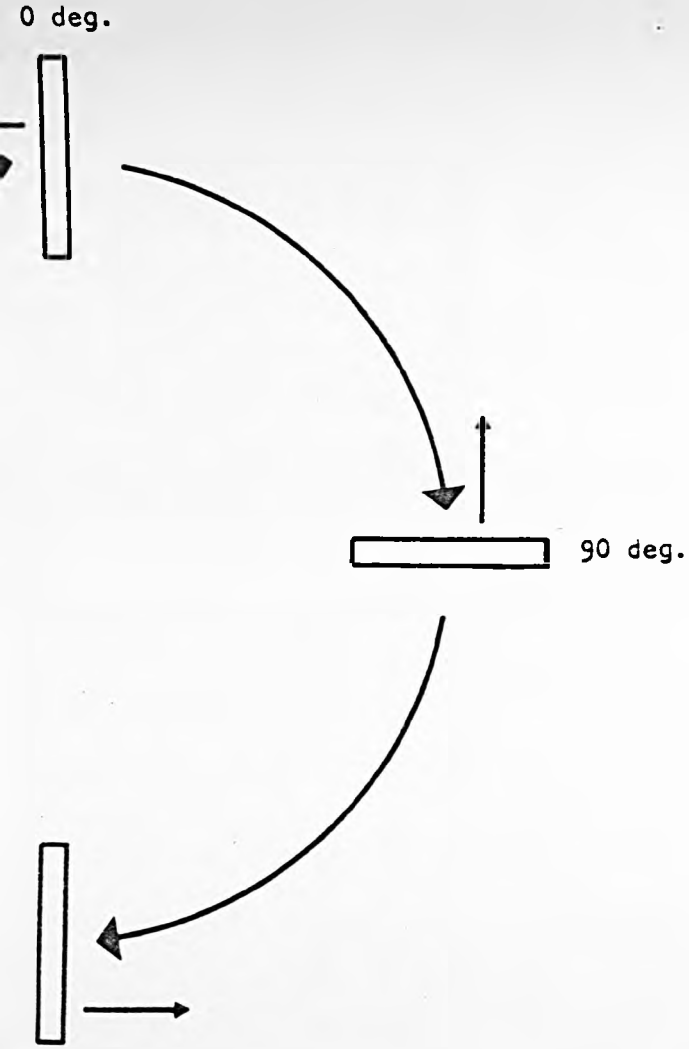
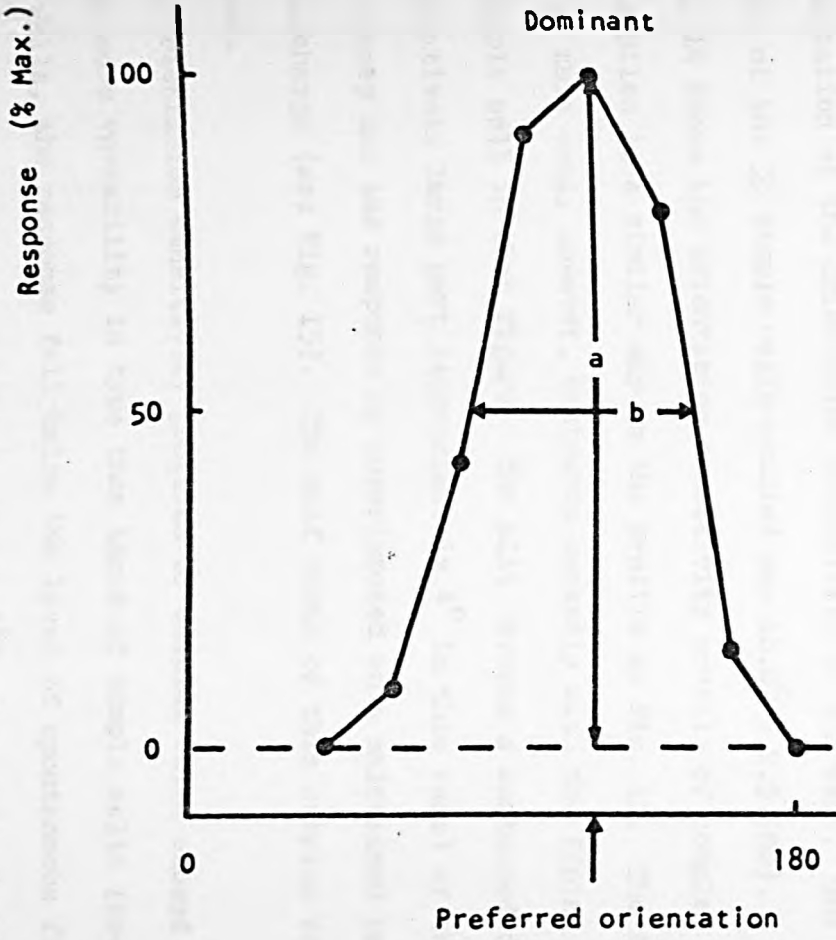
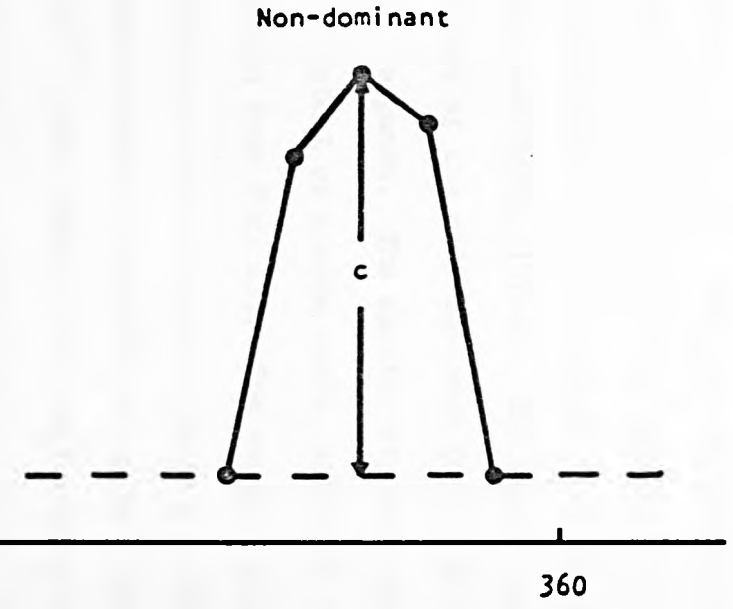

0 deg.
90 deg.
180 deg.

FIG. 10b. Schematic representation of the orientation sensitivity profile of a cortical cell. In the diagram, 'a' represents the maximum response amplitude of the cell. The half width at 50% maximum response amplitude, (b/2) was used as a measure of orientation sensitivity. The ratio of 'a' to 'c' expressed as a percentage, is the cell's directional sensitivity. The preferred orientation is the stimulus orientation at which the maximum response amplitude was elicited. The horizontal dashed line indicates the level of spontaneous firing.


Dominant
Response (% Max.)
100
50
0
a
b
0
180
Preferred orientation


Non-dominant
c
360
Stimulus orientation (Degrees)

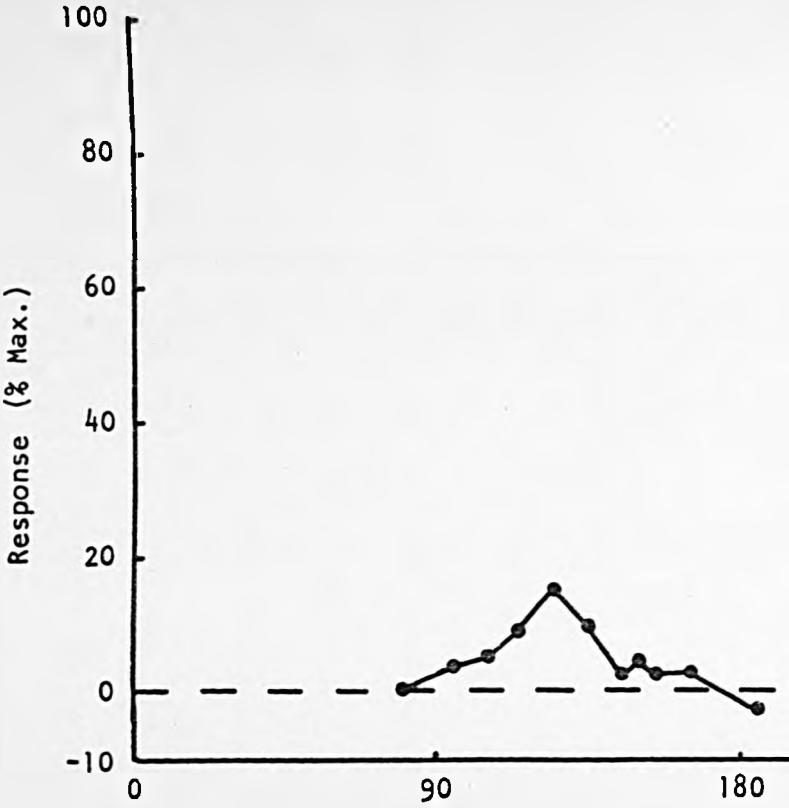
ranged from 1.07°/sec to 12.5°/sec and stimulus intensities were typically 1 log unit above threshold.

Fig. 11 shows the orientation sensitivity profile of simple cell 47-2-3 (Expt. 47, penetration 2, unit 3). The firing pattern of this cell to a slit of light moving across its receptive field, as seen in the average response histograms (Fig. 12) is typical of a simple cell response (see Bishop, Coombs and Henry, 1971a). The cell is virtually silent except for a small part of the slit movement (0.9° in this case) when the cell gives a brief response. The sensitivity profile of this cell shows a 'bell' shape, typical of simple cells, although the peak in some cells was more pointed (see Fig. 13). The curved 'tails' at the limits of the sensitivity profile were also typical of simple cells. The half width of the dominant orientation sensitivity profile at the 50% response level was 17.5°. This measure, the half width, was used as an indication of the orientation sensitivity of the cell. The mean half width of the 33 simple cells studied was 18.0° ± 2.5 (SD).

Fig. 14 shows the orientation sensitivity profile of complex cell 50-1-6 compiled in a similar way to the profile in Fig. 11. The firing pattern of this cell, however, contrasts markedly with the firing pattern of the simple cell in that figure. The slit evokes a sustained discharge over a relatively large part (approximately 4° in this case) of the stimulus sweep and the response is superimposed on a maintained background discharge (see Fig. 15). The half width of this complex cell is 25 degrees.

The orientation sensitivity profiles of complex cells showed considerably more variability in type than those of simple cells (see Fig. 16). In some cells, the response fell below the level of spontaneous firing in the 'null' (i.e. preferred orientation + 90°) orientation indicating supression at these orientations. In others, however, the firing remained above the level of spontaneous activity.

FIG. 11. Orientation sensitivity profile of simple cell 47-2-3. Stimulus dimensions were 11° x 0.5° and velocity was 4.25°/sec. The half-width of this cell was 17.5°. Maximum response amplitude was 18.8 spikes/sweep and the spontaneous firing indicated by the dotted line was 0.6 spikes/sec.


100
80
60
40
20
0
-10
Response (% Max.)
0
90
180

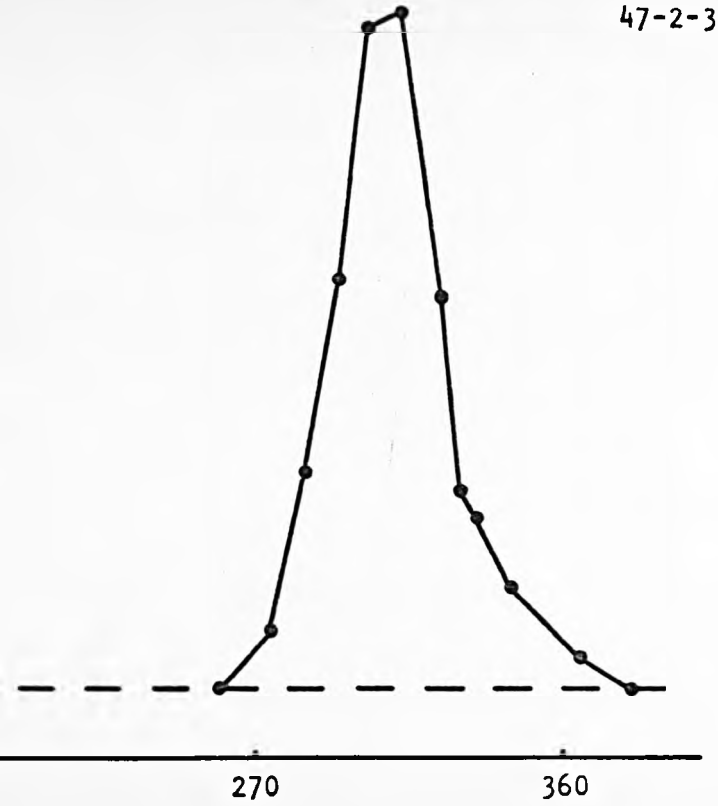

47-2-3
270
360
Orientation (Degrees)

FIG. 12. Average response histograms of simple cell 47-2-3 (the same cell as in Fig. 11) at various stimulus orientations through the dominant and non-dominant phases of the orientation sensitivity profile. Each histogram was compiled by 16 excursions of a slit (11° x 0.5°) through the receptive field. Stimulus velocity was 4.25°/sec. The histogram bin-width was 20.5 msecs and the vertical calibration represents 20 spikes/bin. Orientation is indicated by the numbers to the left of each histogram. The diagonal lines under each series of histograms represents the 10° stimulus movement, vertical arrows marking movement onset and offset.

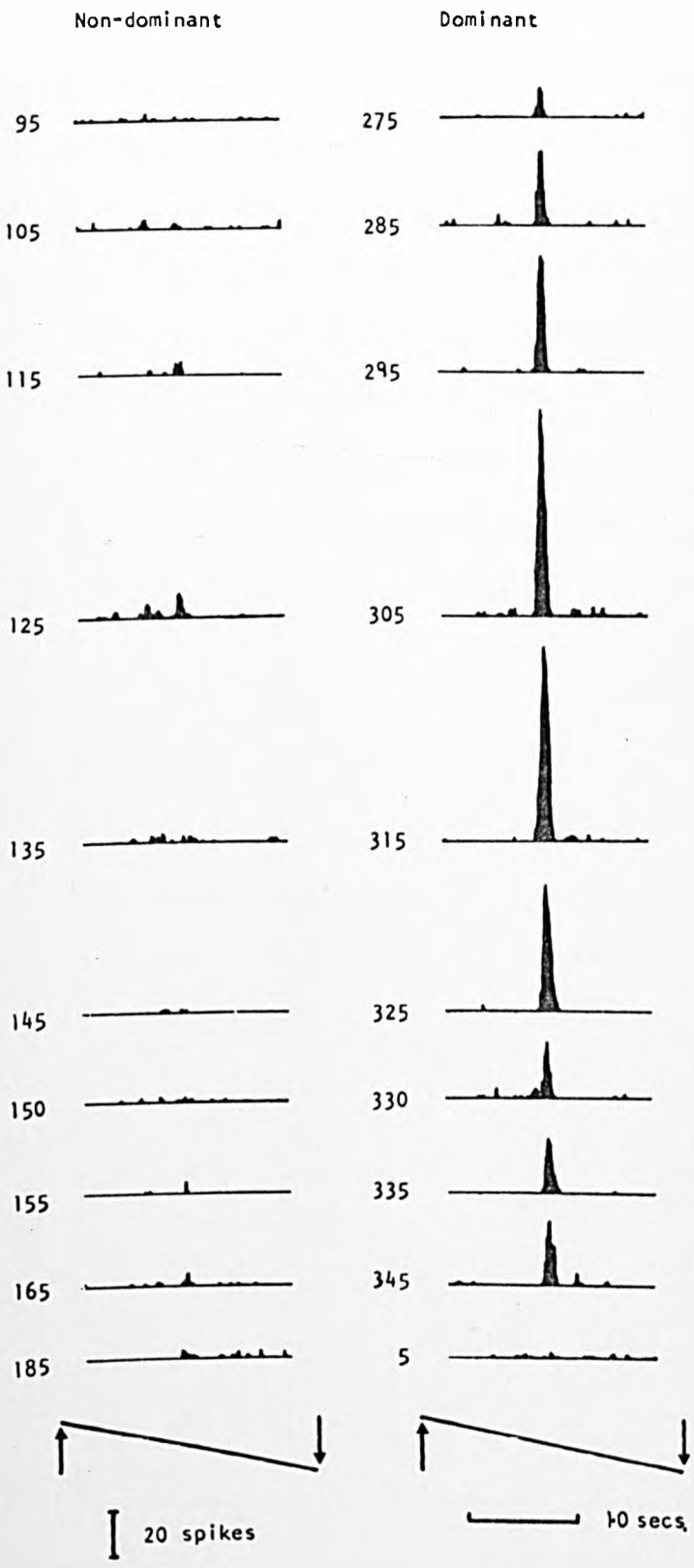
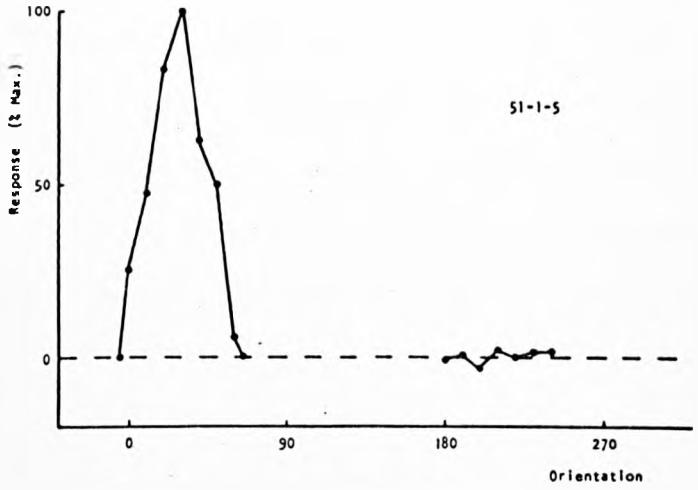
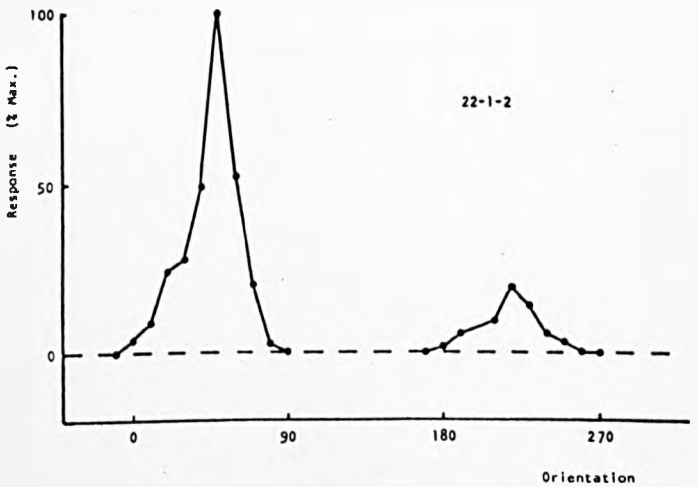

Non-dominant
Dominant
95
105
115
125
135
145
150
155
165
185
275
285
295
305
315
325
330
335
345
5
20 spikes
10 secs

FIG. 13. Orientation sensitivity profiles of 3 simple cells.
Unit 51-1-5: stimulus dimensions were 8° x 0.25° and velocity was 4.2°/sec. Maximum response amplitude was 8.4 spikes/sweep and the spontaneous firing (horizontal dashed line) was < 1 spike/sec.
Unit 22-1-2: stimulus dimensions were 11° x 4° and velocity was 3.2°/sec. Maximum response amplitude was 18.9 spikes/sweep. There was no spontaneous firing.
Unit 25-1-8: stimulus dimensions were 4° x 0.5° and velocity was 5.0°/sec. Maximum response amplitude was 12.0 spikes/sweep. There was no spontaneous firing.


100
50
0
Response (% Max.)
51-1-5
0
90
180
270
Orientation


100
50
0
Response (% Max.)
22-1-2
0
90
180
270
Orientation

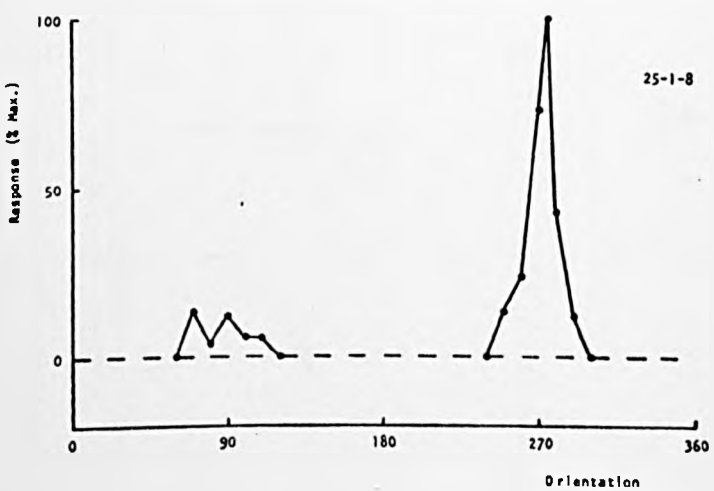
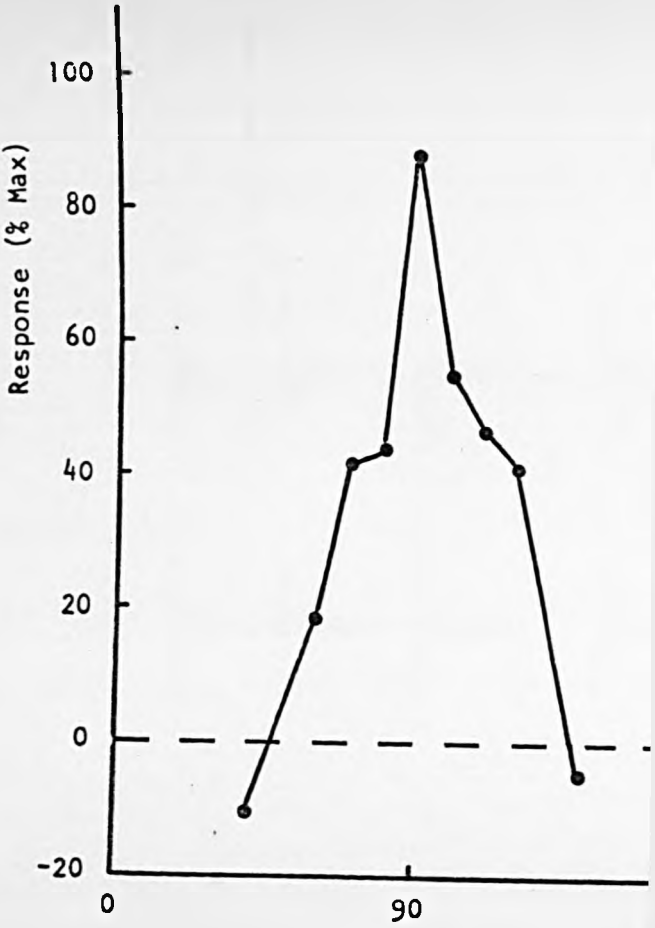

100
50
0
Response (% Max.)
25-1-8
0
90
180
270
360
Orientation

FIG. 14. Orientation sensitivity profile of complex cell 50-1-6. Stimulus dimensions were 11° x 0.5° and velocity was 3.9°/sec. The half width of this cell was 25.0°. The maximum response amplitude was 36.6 spikes/sweep and the spontaneous firing indicated by the horizontal dashed line ranged from 2.7 to 8.6 spikes/sweep.


Response (% Max)
100
80
60
40
20
0
-20
0
90

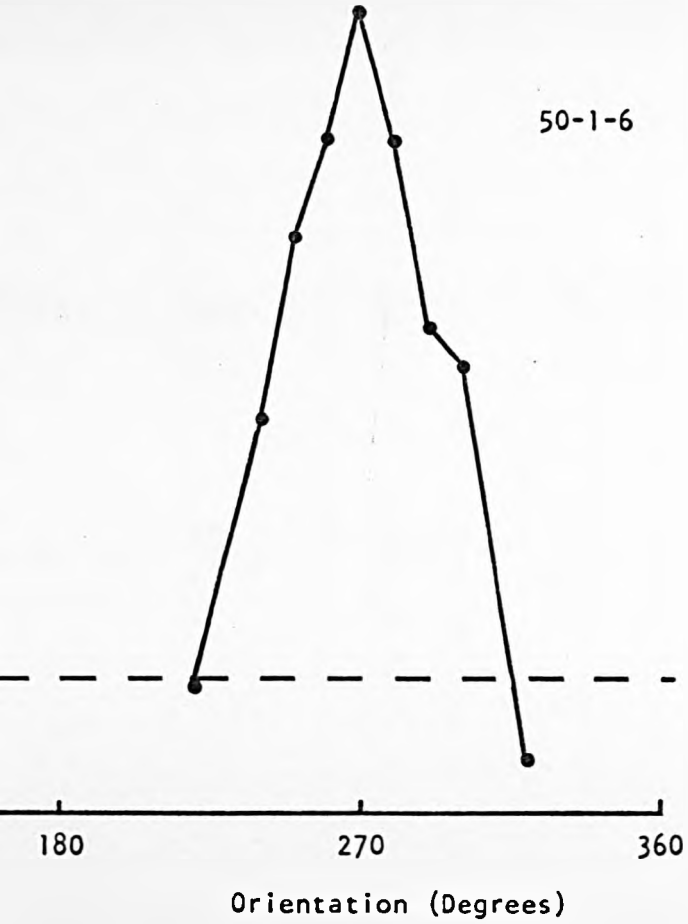

50-1-6
180
270
360
Orientation (Degrees)

FIG. 15. Average response histograms of complex cell 50-1-6 at various stimulus orientations through the dominant and non-dominant phases of the orientation sensitivity profile. Each histogram is compiled by 8 excursions of a stimulus, 11° x 0.5°, moving at 3.9°/sec through the receptive field. The histogram bin-width was 20.5 msecs and the vertical calibration represents 10 spikes/bin. Orientation is indicated by the numbers to the left of each histogram. The diagonal lines under each series of histograms represents the 10° stimulus movement, vertical arrows marking movement onset and offset.

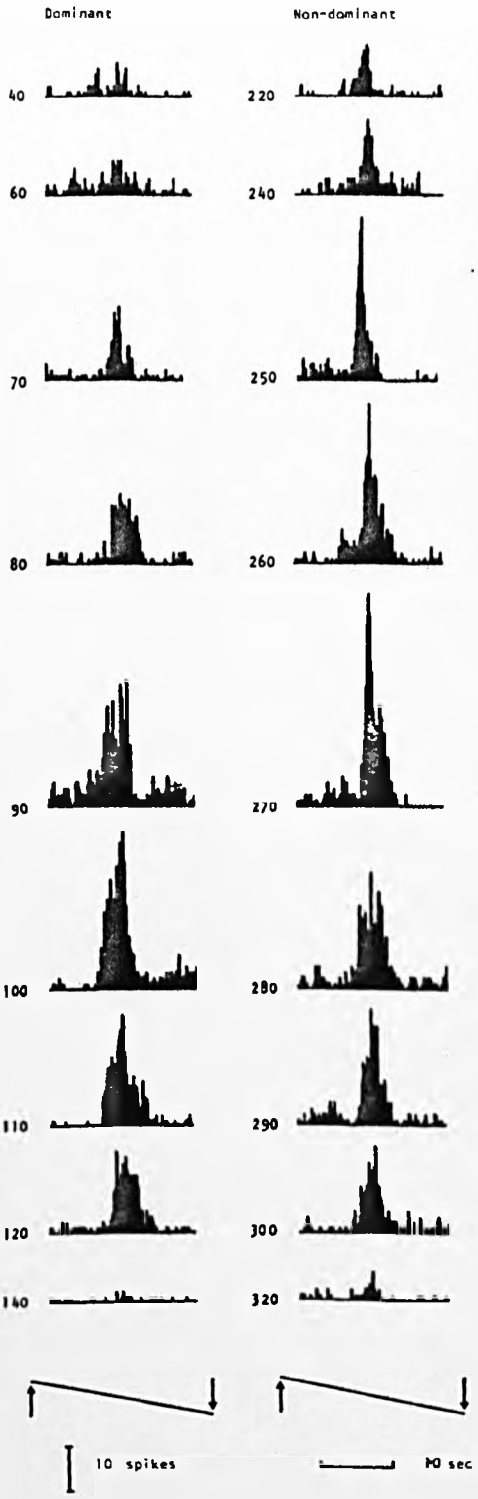
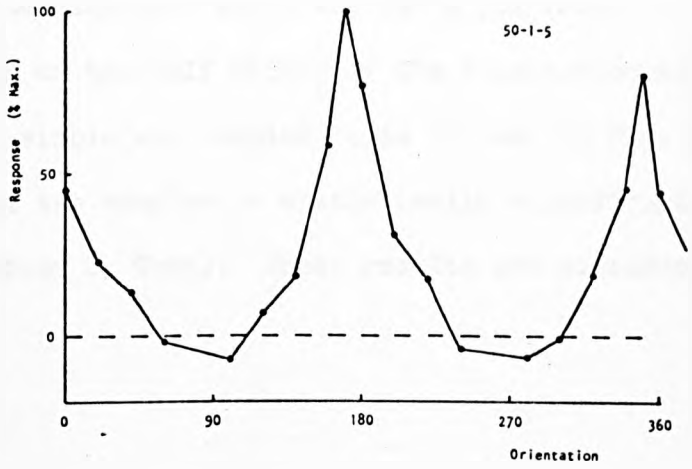
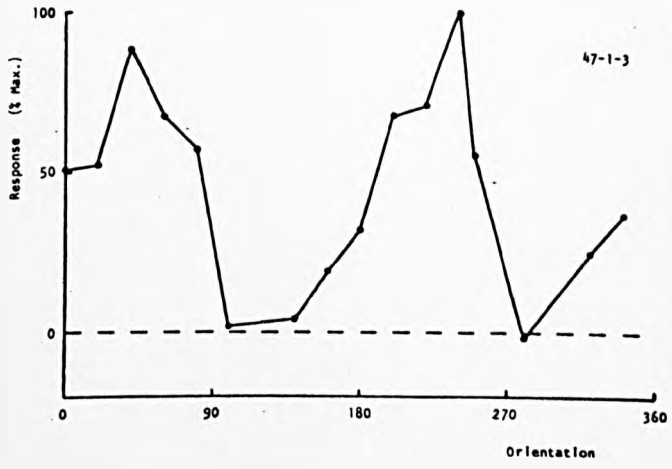

Dominant
Non-dominant
40
60
70
80
90
100
110
120
140
220
240
250
260
270
280
290
300
320
10 spikes
20 sec

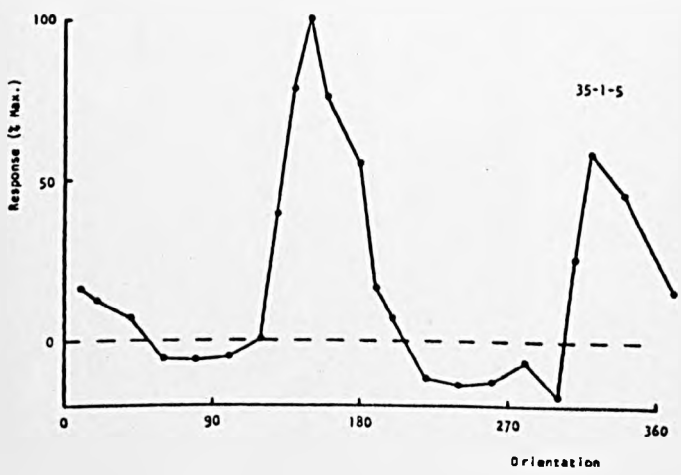
FIG. 16. Orientation sensitivity profiles of 3 complex cells. Unit 50-1-5: stimulus dimensions were 8° x 0.25° and velocity was 3.7°/sec. The maximum response amplitude was 40.5 spikes/sweep and the spontaneous firing (indicated by the horizontal dashed line) ranged from 1.3 - 3.9 spikes/sec.

Unit 47-1-3: stimulus dimensions were 11° x 0.5° and velocity was 6.0°/sec. The maximum response amplitude was 14.2 spikes/sweep and the spontaneous firing ranged from 0.4 - 2.7 spikes/sec.

Unit 35-1-5: stimulus dimensions were 4° x 1° and velocity was 6.6°/sec. The maximum response amplitude was 14.9 spikes/sweep and the spontaneous firing ranged from 5.3 - 14.5 spikes/sec.


50-1-5
Response (% Max.)
100
50
0
0
90
180
270
360
Orientation

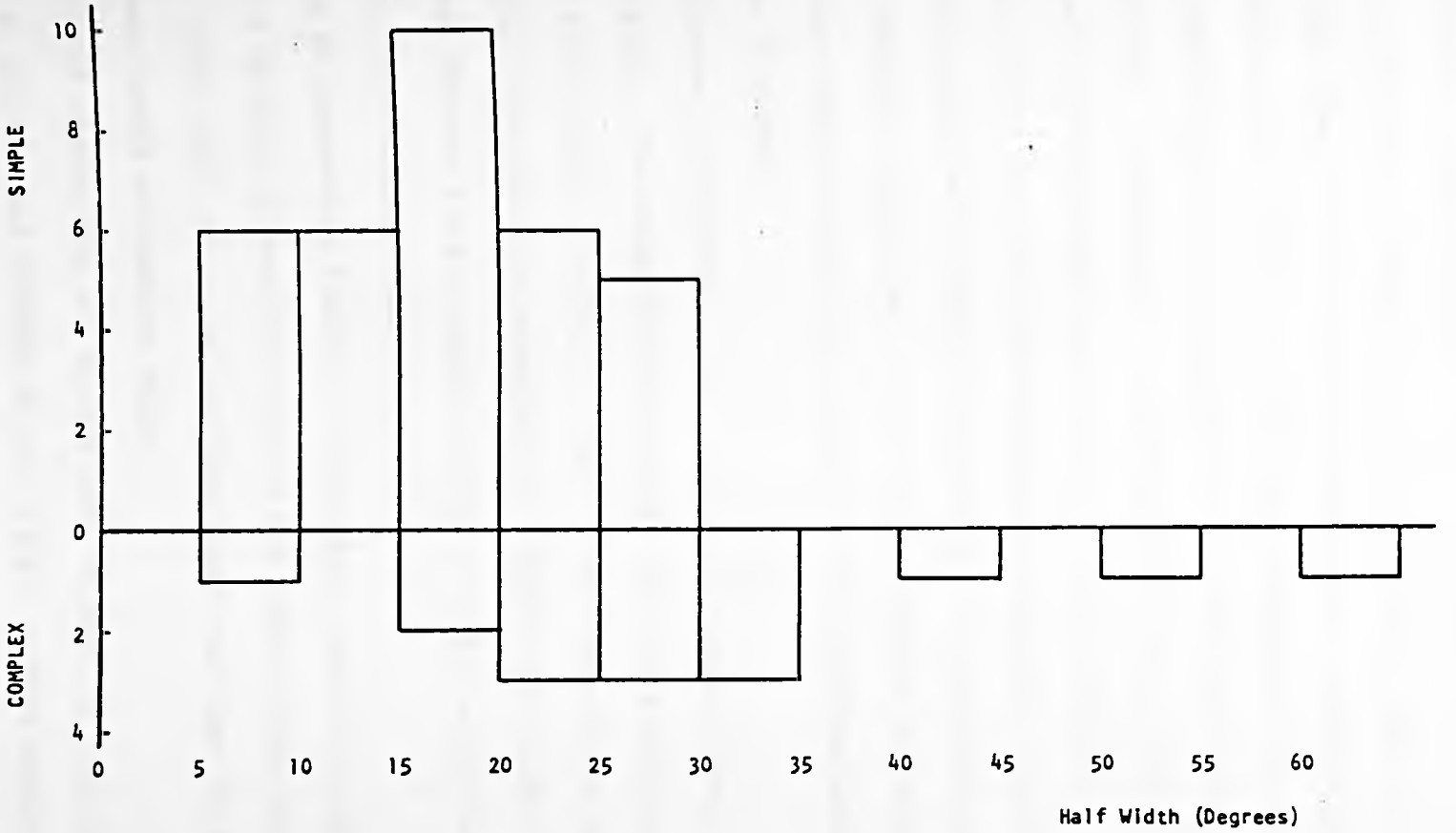

47-1-3
Response (% Max.)
100
50
0
0
90
180
270
360
Orientation


35-1-5
Response (% Max.)
100
50
0
0
90
180
270
360
Orientation

For the 15 complex cells whose orientation sensitivity profiles were measured the mean half width was $29^{\circ} \pm 3.1$ (SD).

A histogram of the half widths of the orientation sensitivity profiles of the simple and complex cells is seen in Fig. 17. The difference between the two samples is statistically significant at the 1% level (Mann-Whitney U Test). These results are discussed in Section 6.

FIG. 17. Histogram of the half-widths of orientation sensitivity profiles of 33 simple and 15 complex cells. The mean half-width for simple cells was $18.0^{\circ} \pm 2.5$ (SD) and for complex cells, $29.0^{\circ} \pm 3.1$ (SD).


SIMPLE
COMPLEX
10
8
6
4
2
0
2
4
0
5
10
15
20
25
30
35
40
45
50
55
60
Half Width (Degrees)

3.4 Directional Sensitivity

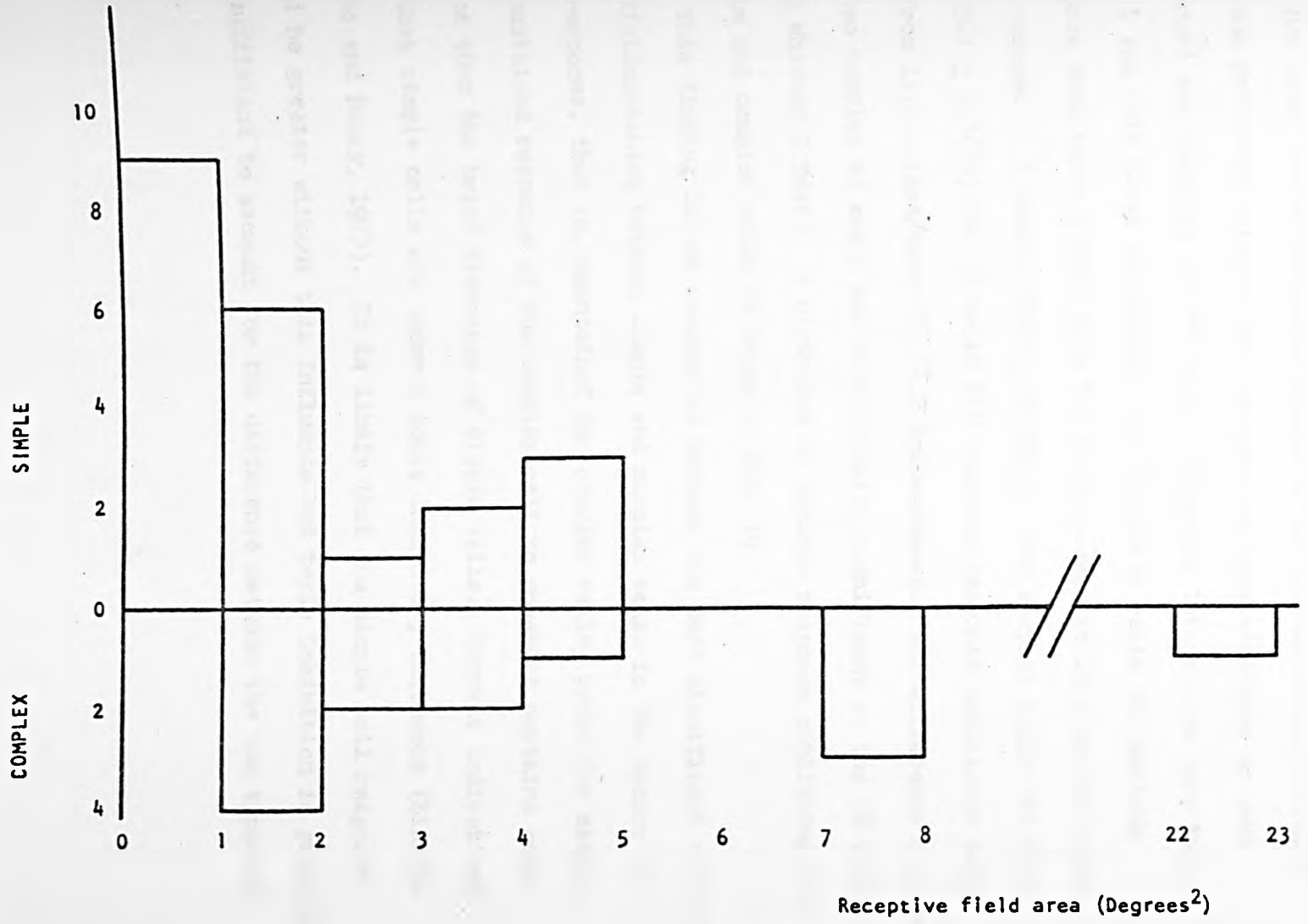
The directional sensitivity of 48 cells (33 simple and 15 complex) was estimated using methods similar to those described in Section 3.3. The maximum amplitude of the non-dominant orientation sensitivity profile expressed as a percentage of the maximum amplitude of the dominant orientation sensitivity profile gave a measure of the directional sensitivity of the unit. In most cells the orientations evoking maximal responses in the dominant and non-dominant sensitivity profiles differed by 180°. When this was not the case, and the non-dominant orientation sensitivity profile clearly peaked at a different orientation, the maximal responses of the two profiles were measured. When the non-dominant sensitivity profile was not clearly greater the response at the preferred orientation plus 180° was measured.

Fig. 18 shows a histogram of the directional sensitivities of simple and complex cells. The range of sensitivities for simple cells covered 0% to 81.1% with a mean at 21.3% ± 4.1 (SD). For complex cells the mean was 49.9% ± 13.9 (SD) with the sensitivities ranging from 11.6% - 88.6%. The difference between the two samples is statistically significant at the 5% level (Mann Whitney U Test).

This is an interesting finding. Directional sensitivity has been shown to be a property of many cells in the cat visual cortex (Hubel and Wiesel, 1959; 1962) but it has not been clear that there is a difference between simple and complex cells.

Directional sensitivity may be ascribed, in part, to tonic inhibitory influences in simple cells (Bishop et al., 1973). A slit moving in the non-preferred direction may cause an excitatory input which is insufficient both to overcome the inhibitory influence and to evoke a response. Any excitatory input to a complex cell is reflected as increased firing (provided it is not matched by an equal simultaneous inhibitory input) since the cell is spontaneously active.

FIG. 18. Histogram of the directional sensitivities of 33 simple and 15 complex cells. The mean directional sensitivity of the simple cells was 21.3% ± 4.1 (SD) and 49.9% ± 13.9 (SD) for complex cells.

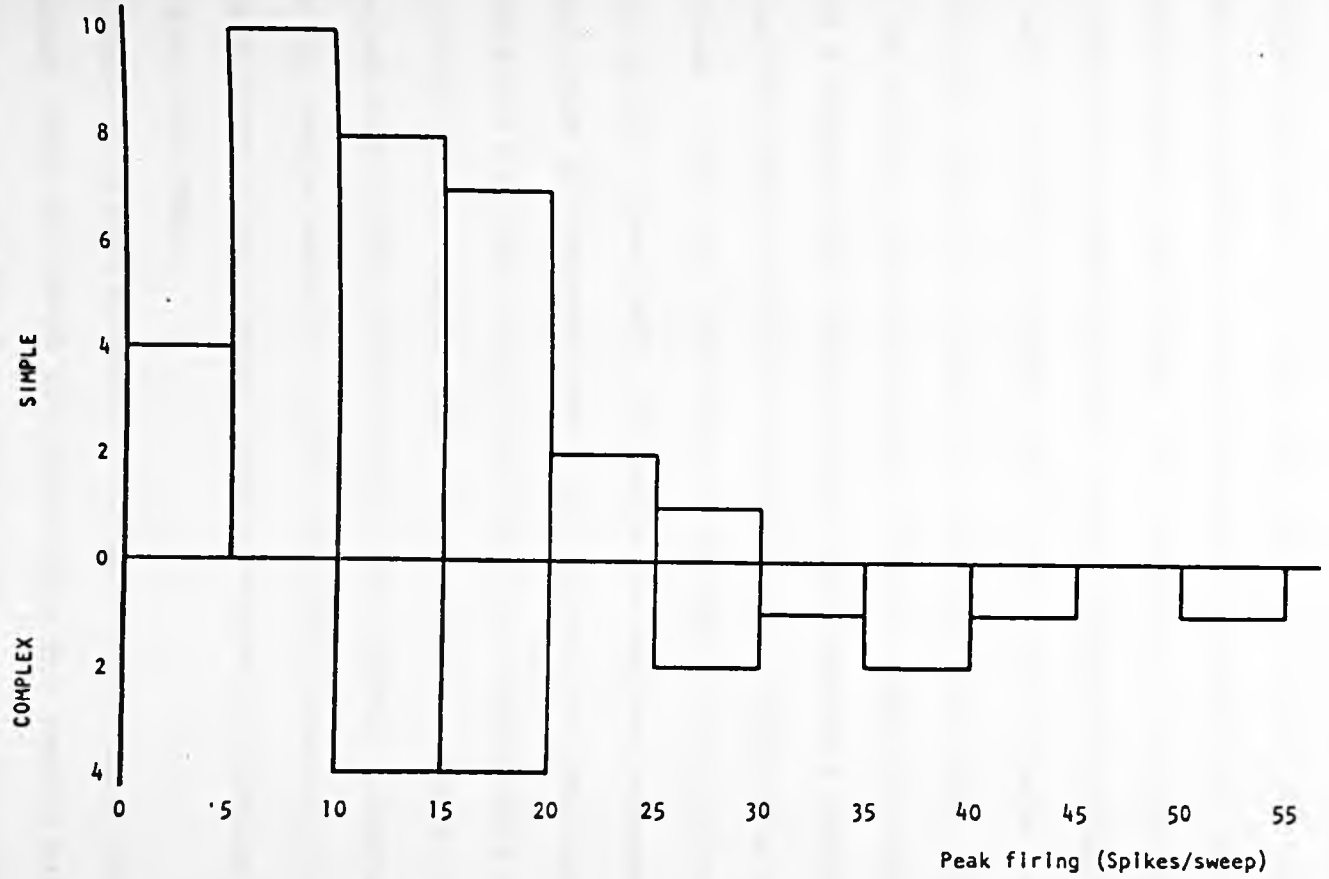

SIMPLE
COMPLEX
10
8
6
4
2
0
2
4
0
1
2
3
4
5
6
7
8
22
23
Receptive field area (Degrees^2)

3.5 Maximum Response Amplitude

The total number of spikes evoked by an optimal moving stimulus with the preferred orientation (maximum response amplitude or peak response) was measured for 48 cells. Stimulus intensities were typically 1 log unit above threshold. For 33 simple cells the maximum response amplitudes ranged from 3.0 spikes/sweep to 29.4 spikes/sweep and averaged 11.6 spikes/sweep $\pm$ 2.3(SD). For complex cells the mean was 25.1 $\pm$ 3.3(SD) for 15 cells with maximum response amplitudes ranging from 11.9 spikes/sweep to 54.2 spikes/sweep. The difference between the two samples of cells was statistically significant at the 1% level (Mann Whitney U Test). A histogram of maximum response amplitudes for simple and complex cells is shown in Fig. 19.

This finding is not unexpected because the most significant criterion for distinguishing between simple and complex cells is the nature of the response, that is, maintained for complex cells, brief for simple. The sustained response of the complex cell to movement contains more spikes than the brief discharge of simple cells. Current indications are that simple cells are under a tonic inhibitory influence (Bishop, Coombs and Henry, 1973). It is likely that the simple cell response would be greater without this influence but tonic inhibition is probably not sufficient to account for the difference between the two types of cell.

FIG. 19. Histogram of the maximum response amplitude of 33 simple cells and 15 complex cells. The mean maximum response amplitude for simple cells was 11.6 spikes/sweep $\pm$ 2.3 (SD) and for complex cells 25.1 $\pm$ 3.3 (SD).


SIMPLE
COMPLEX
10
8
6
4
2
0
2
4
0
·5
10
15
20
25
30
35
40
45
50
55
Peak firing (Spikes/sweep)

3.6 Effect of Stimulus Intensity

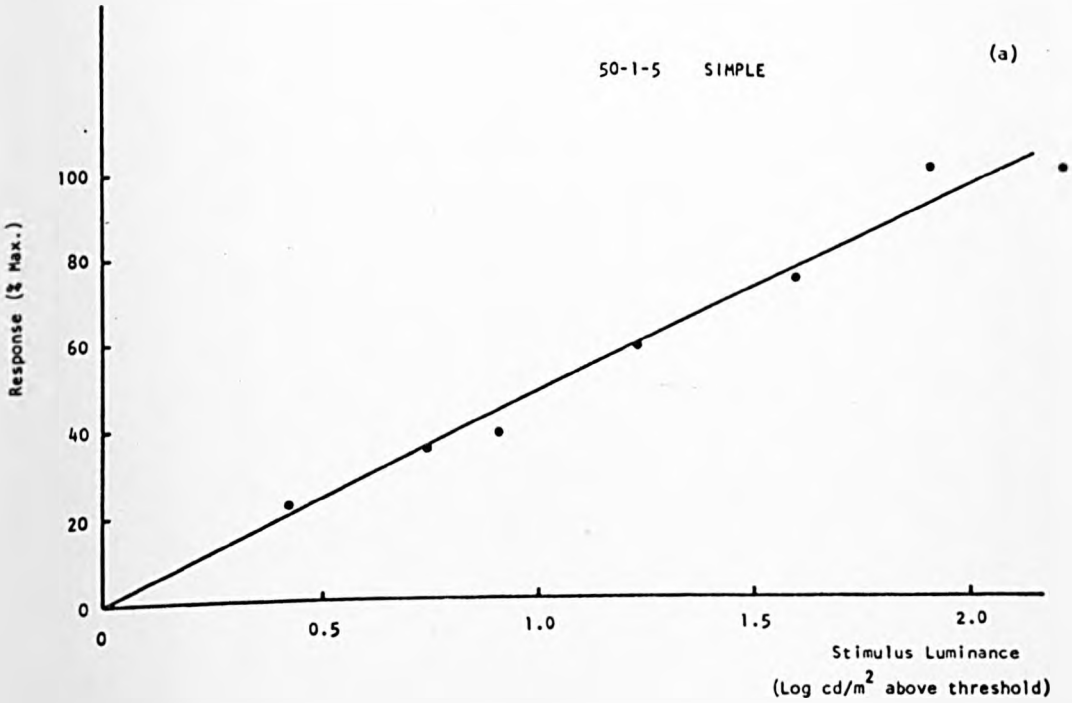
The effect of varying stimulus intensity on the response of simple and complex cells was investigated.

A moving slit of optimal dimensions, orientation and velocity was used. By varying intensity with neutral density filters, the response threshold was estimated from average response histograms or, more usually, auditory monitoring of cell firing. The intensity of the slit was then varied in random steps above threshold and the response was measured. For the 11 cells studied (4 complex and 7 simple) the response rose linearly with log. intensity, reaching a maximum beyond which the responses remained at the maximal level or declined. Fig. 20 shows the response of a simple and a complex cell plotted against suprathreshold intensity. (A cell in which the response fall-off at supramaximal intensities was very marked is shown in Fig. 21.) The intensity at which a straight line, fitted by eye to the linear part, intersects the maximum response level gives an indication of the range over which the cell can code intensity. The mean range was 1.29 log units $\pm$ 0.39 (SD) for complex cells and 1.38 log units $\pm$ 0.46 (SD) for simple cells. The difference between these two samples was not statistically significant. This finding indicates that both simple and complex cells are capable of coding intensity, the responses of both types of cells being linearly related to stimulus intensity over a similar, wide range.

This result is in good agreement with the results Pollen and Taylor (1974) obtained, when they found that both simple and complex cells had a linear relationship with the logarithm of intensity of a stationary flashed stimulus. They reported that at high light intensities, the response saturated but that the linear relationship held over a 1.0 - 1.5 log unit range.

Maffei and Fiorentini (1973) investigated the relationship between

FIG. 20. Effect of varying suprathreshold stimulus luminance on the response of 2 cells in area 17 of the cat visual cortex. (a) Simple cell, 51-1-5. Stimulus dimensions were 8° x 0.25° and the velocity was 4.2°/sec. Stimulus orientation was 30°. The 100% response level was 8.8 spikes/sweep and the spontaneous firing ranged from 0 - 0.5 spikes/sec. The range over which this cell had a linear relationship with the logarithm of suprathreshold intensity was 2.1 log/candles/m^2.
(b) Complex cell, 50-1-6. Stimulus dimensions were 11° x 0.5° and the velocity was 3.9°/sec. Stimulus orientation was 270°. The 100% response level was 36.0 spikes/sweep and the spontaneous firing ranged from 0.5 - 4.2 spikes/sweep. The linear range of this cell was 1.9 log. candles/m^2.


(a)
50-1-5 SIMPLE
Response (% Max.)
100
80
60
40
20
0
0
0.5
1.0
1.5
2.0
Stimulus Luminance
(Log cd/m2 above threshold)

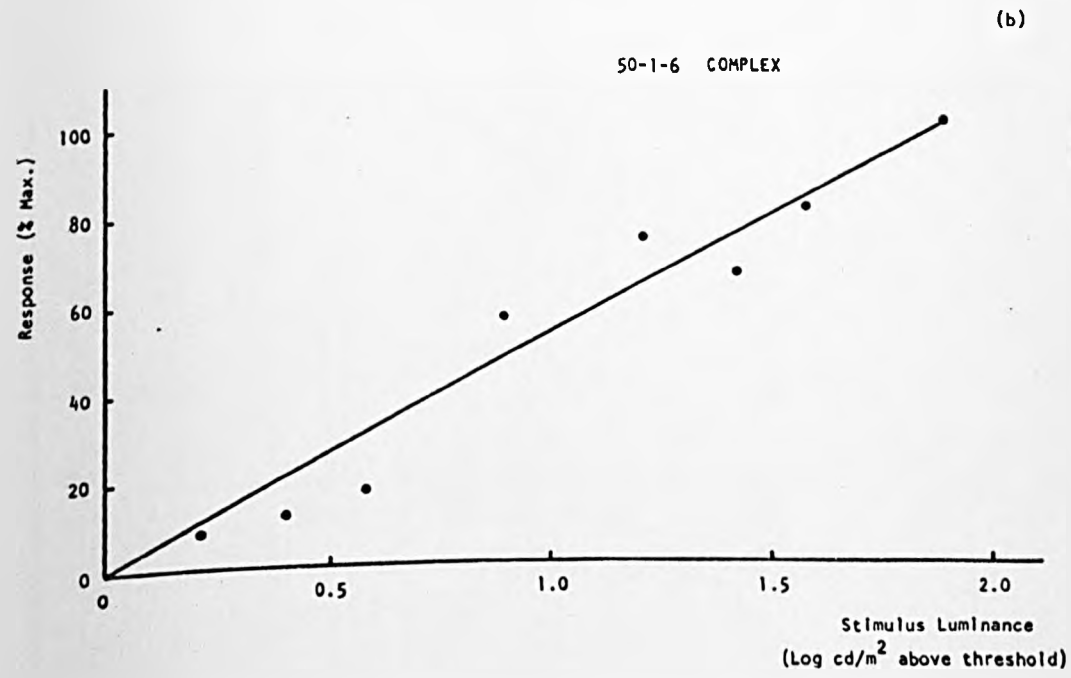
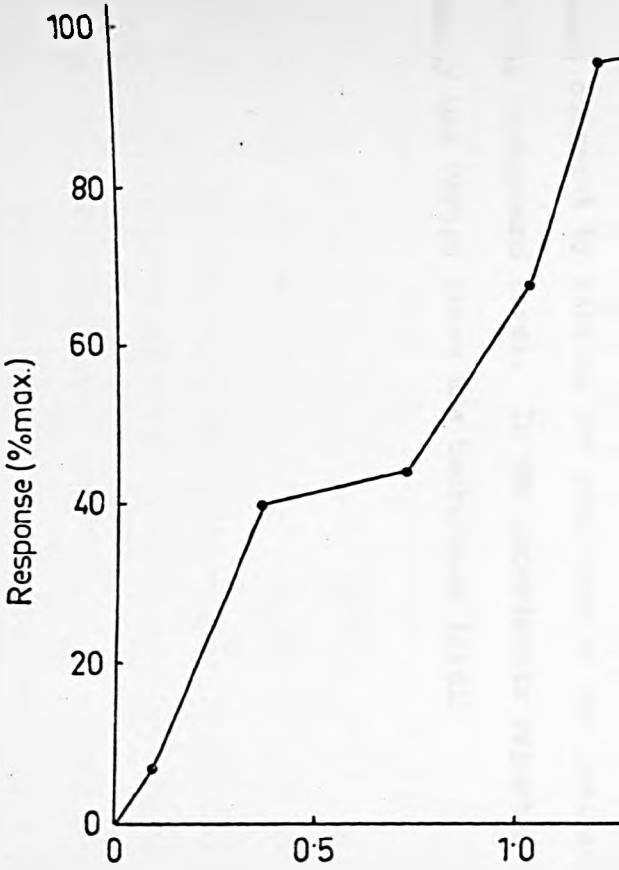
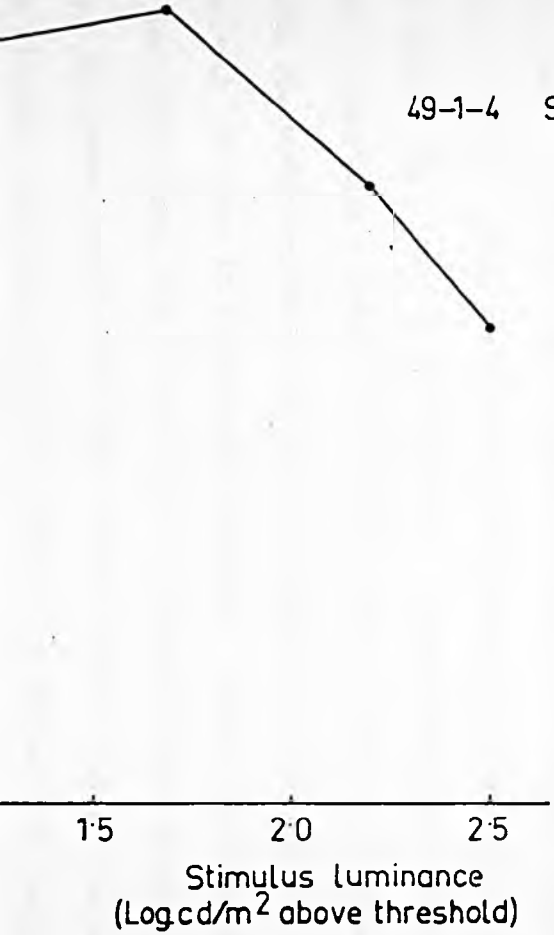

(b)
50-1-6 COMPLEX
Response (% Max.)
100
80
60
40
20
0
0
0.5
1.0
1.5
2.0
Stimulus Luminance
(Log cd/m2 above threshold)

FIG. 21. Effect of stimulus luminance on the response of simple cell 49-1-4. The 100% response level was 31.8 spikes/sweep and there was no spontaneous firing.


100
80
60
40
20
0
Response (%max.)
0
0·5
1·0


49–1–4 Simple
1·5
2·0
2·5
Stimulus luminance
(Log cd/m² above threshold)

the response of cells in area 17 and the contrast of a moving grating with a sine-wave luminance profile. They showed that the response of simple cells was linearly related to the log.of the grating contrast over a wide range. Only occasionally was the response of complex cells linearly related and then only over a relatively narrow range. This finding does not seem to be in agreement with the results reported here although a direct comparison is difficult because of differing experimental conditions. Maffei and Fiorentini varied the contrast (defined as Lmax - Lmin/Lmax + Lmin) of sine-wave grating and for simple cells measured the peak-to-peak response amplitude whilst for complex cells the overall increase in firing was measured. In the experimental situation described here, the intensity of an optimal stimulus with a rectangular luminance profile was used and the cell's response to each sweep of the stimulus was measured. Also Maffei and Fiorentini changed the stimulus contrast by varying the amplitude of the luminance profile about the background level. In the experiments reported here the stimulus intensity was varied above the background level.

3.7 Effect of Defocussing the Retinal Image

Sensitivity to retinal image defocussing is an indication that a response is contour-related. Defocussing the retinal image is known to reduce the amplitude of the human pattern evoked potential (Jeffreys, 1974) and to change the relationship between check-size and the amplitude of the potential evoked by checker-board contrast reversal (Regan and Richards, 1973). The effect of retinal image defocussing on cells in the visual cortex was investigated.

The responses of 11 cells (8 simple and 3 complex) to an optimally oriented moving slit were measured for between 8 and 20 stimulus presentations. Average responses were computed and average response histograms were compiled. One of a range of lenses with powers between -6 dioptres and +6 dioptres was added to those already used to focus the cat's eyes on the tangent screen and the response measured. All the cells had receptive fields within 10° of the area centralis.

Responses after retinal image defocussing of $\pm$ 6 dioptres ranged from 5% to 88% of the optimal response, the response falling to less than 20% in only two cells. Simple cell 49-1-2 in Fig. 22 was relatively unaffected by defocussing the retinal image and still gave a response 77% of maximum with defocussing of +6 dioptres. Cell 47-1-3 in Fig. 22, a complex cell, showed marked attenuation of the response to retinal image defocussing of +6 dioptres. The major effect of defocussing is to reduce the rate of change of contrast of a visual contour, rather than reduce the overall contrast of the stimulus. This is indicated by the responses of unit 51-1-6 which were similar when both a wide and a narrow slit were used as the stimulus (see Fig. 23). The insensitivity to defocussing of the retinal image indicates that cortical cells can function over wide ranges of rates of change of contrast. This is also illustrated by Fig. 24, which shows the orientation sensitivity profile

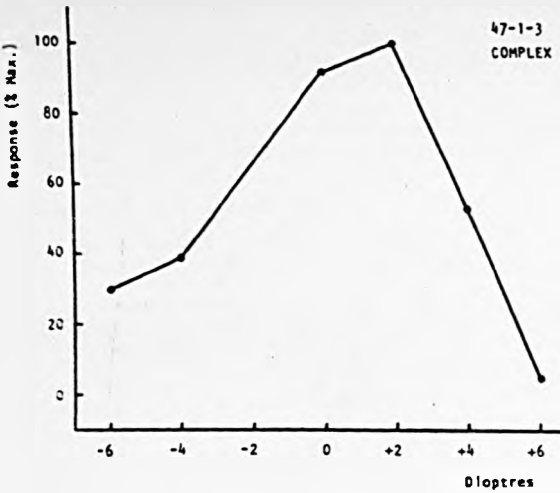
FIG. 22. Effect of retinal image defocussing on 4 cells in area 17 of the cat visual cortex.

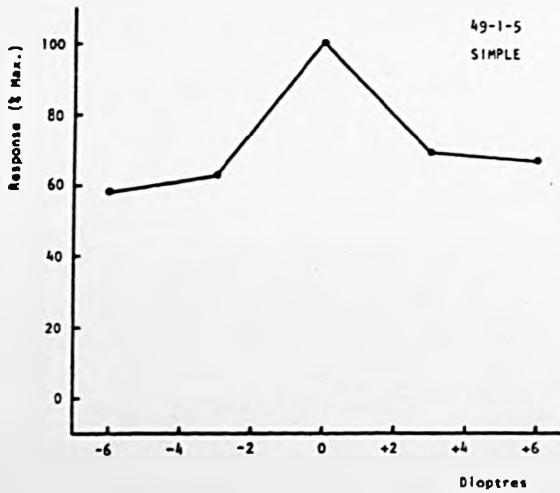
Cell 47-1-3 (complex): 11° x 0.5°slit, velocity 6.0°/sec, orientation 60°. 100% response was 24.6 spikes/sweep and the spontaneous firing ranged from 0.4 - 2.7 spikes/sec.

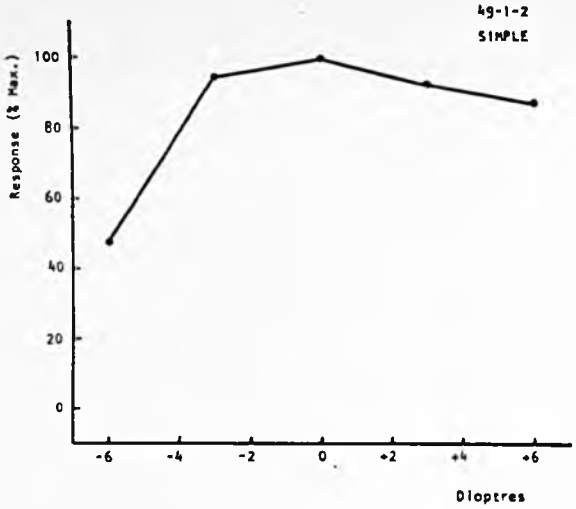
Cell 49-1-5 (simple): 11° x 0.5° slit, velocity 3.6°/sec, orientation 135°. 100% response was 6.9 spikes/sweep and there was no spontaneous firing.

Cell 49-1-2 (simple): 11° x 0.25° slit, velocity 3.8°/sec, orientation 145°. 100% response was 5.0 spikes/sweep and there was no spontaneous firing.

Cell 50-1-6 (complex): 11° x 4° slit, veolocity 3.9°/sec, orientation 180°. 100% response was 22.6 spikes/sweep and the spontaneous firing ranged from 0.5 - 4.2 spikes/sweep.


47-1-3
COMPLEX
Response (% Max.)
100
80
60
40
20
0
-6
-4
-2
0
+2
+4
+6
Dioptres


49-1-5
SIMPLE
Response (% Max.)
100
80
60
40
20
0
-6
-4
-2
0
+2
+4
+6
Dioptres


49-1-2
SIMPLE
Response (% Max.)
100
80
60
40
20
0
-6
-4
-2
0
+2
+4
+6
Dioptres

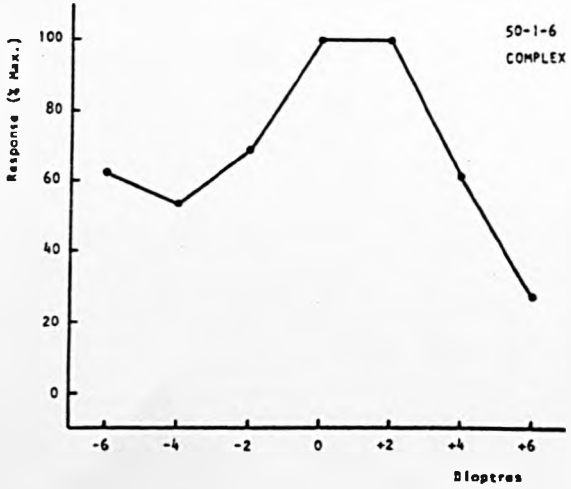
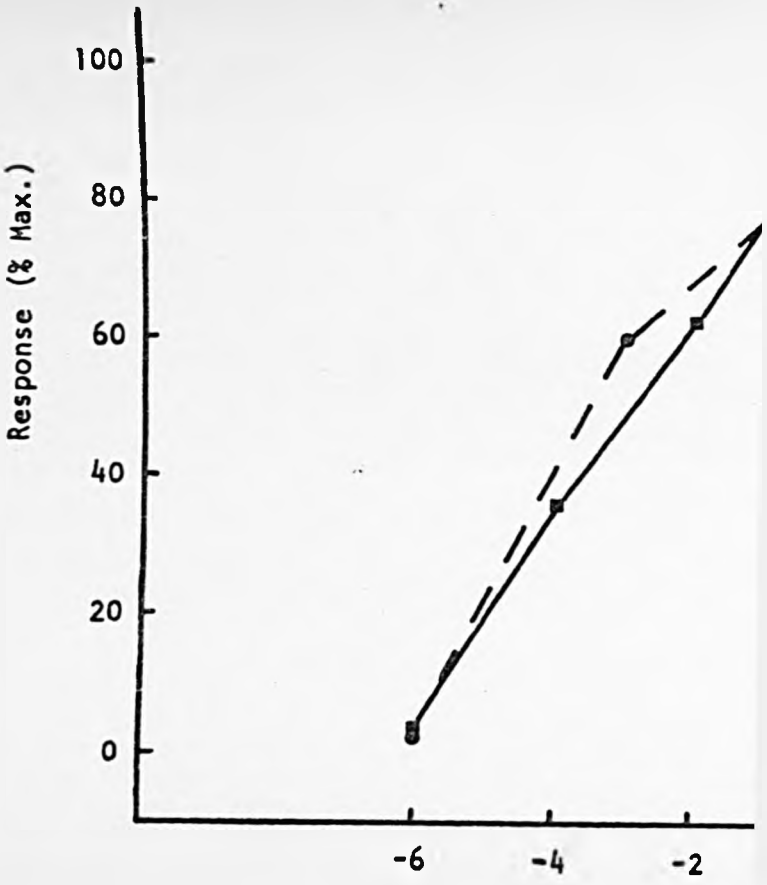
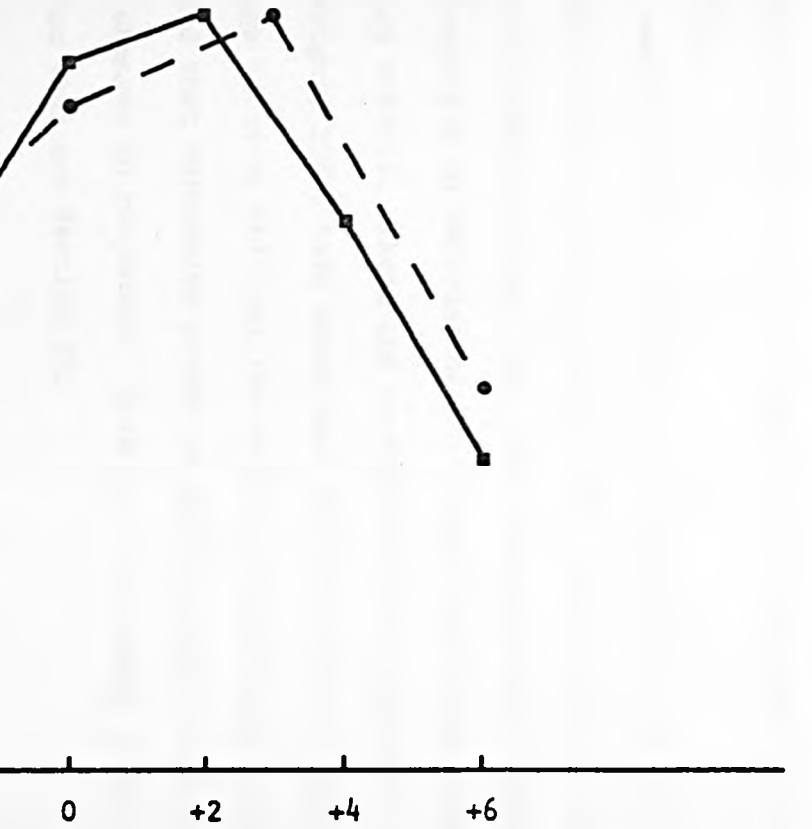

50-1-6
COMPLEX
Response (% Max.)
100
80
60
40
20
0
-6
-4
-2
0
+2
+4
+6
Dioptres

FIG. 23. Effect of retinal image defocussing on the response of cell 51-1-6 to slits of light with different dimensions. Continuous line: response to a slit 8° x 0.25°. Dotted line: response to a slit 8° x 4°. Stimulus velocity was 4.16°/sec in both cases. The maximum response amplitude with both stimuli was 15.6 spikes/sweep. There was no spontaneous firing.


Response (% Max.)
100
80
60
40
20
0
-6
-4
-2

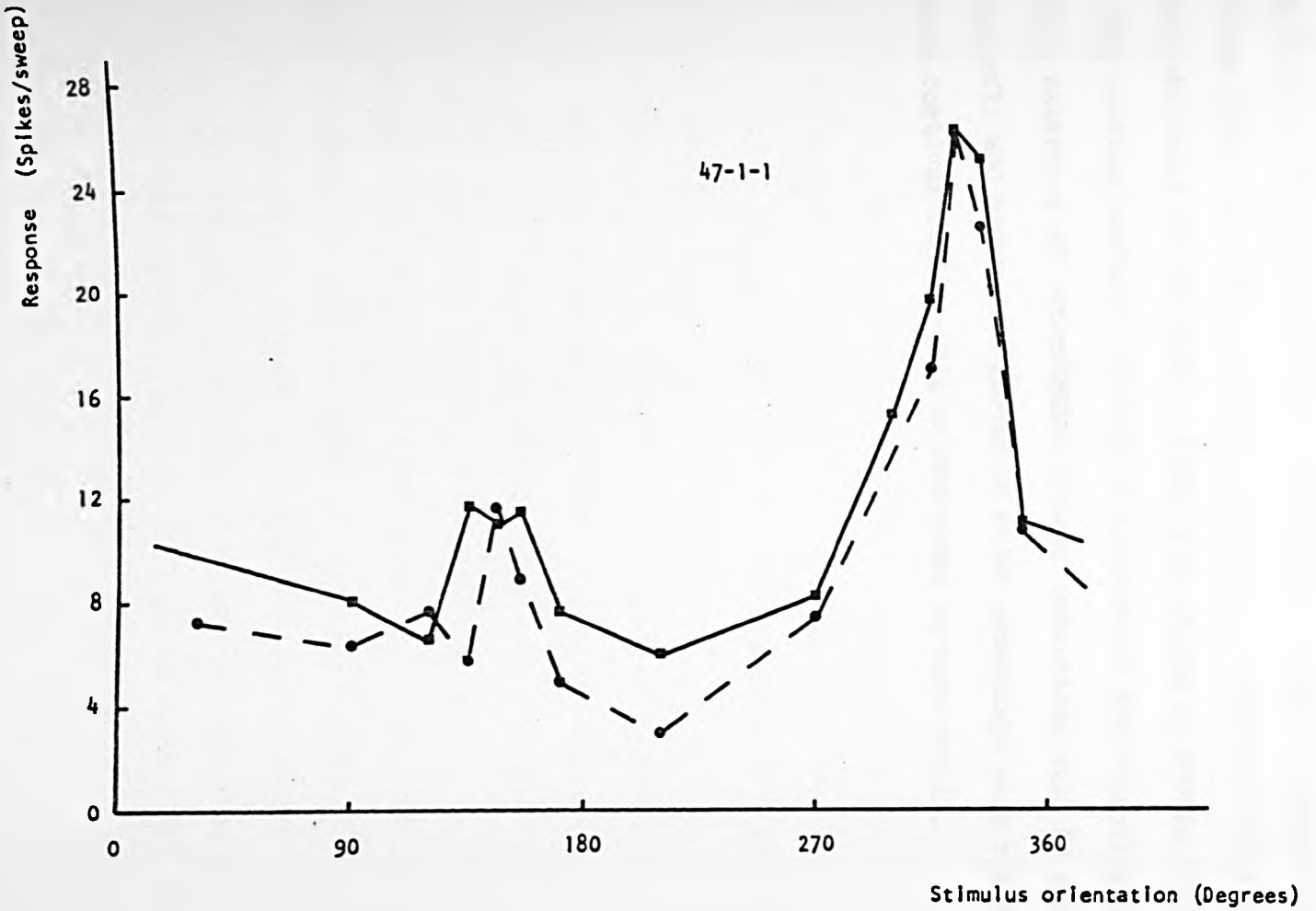
51-1-6



of a cell under normal conditions and with the retinal image defocussed by 4 dioptres. The profiles in the two situations are similar and the maximum response amplitude at the preferred orientation is identical in both cases.

These results are in agreement with those of Lee and Hill (1973) who found that cortical cells in the rabbit showed a wide variety of sensitivities to defocussing. They found that movement sensitive cells were less sensitive to defocussing than those cells which responded well to stationary stimuli. Ikeda and co-workers (Ikeda and Hill, 1971; Ikeda and Wright, 1973) have shown that for cat retinal ganglion cells retinal image focus is critical for evoking the greatest response. They reported that refractive errors as small as 0.25 dioptres produced detectable changes in responses. This does not appear to be the case in the cortex (but see Section 5).

FIG. 24. Orientation sensitivity profile of cell 47-1-1 for a focussed retinal image (continuous line) and for +4.0 dioptres of defocussing (dotted line). Stimulus dimensions and velocity were 11° x 0.5° and 4.2°/sec respectively.


Response (Spikes/sweep)
28
24
20
16
12
8
4
0
47-1-1
0
90
180
270
360
Stimulus orientation (Degrees)

4. RESULTS - EVOKED POTENTIAL EXPERIMENTS

As indicated in Section 1.7 initial experiments were designed to study potentials evoked within the cortex which were related to the orientation specificity and receptive field location of the cells close to the recording electrode ('orientation column' potentials). It became clear that the interpretation of the results of these initial experiments would be difficult without a knowledge of PRVEPs recorded from the cortical surface. The pilot experiments investigating the possible existence of 'orientation column' potentials will be dealt with briefly and those experiments in which potentials were recorded from the cortical surface will be described in more detail.

4.1 Orientation-column potentials

Results from a preliminary experiment indicated that it might be possible to record potentials at depth within the cortex which were related to the orientation sensitivities of the neurones surrounding the recording electrode.

Fig. 25 shows some of the results of this experiment (Expt. 9). A cerveau isolé preparation was used. The response to a blank flash was subtracted electronically from the potential evoked by a flashed grating stimulus to give the PRVEP shown in the figure. With increasing grating spatial frequency, the PRVEP decreased in amplitude indicating the pattern-related nature of the response (see Section 4.2.1). At 3.0 cycles/deg. the pattern and the blank responses were identical. Stimuli subtended 7° and the cortical recording depth was 1.20 mm. Fig. 25(a) shows the positions of the blank and patterned stimuli in the visual field.

A grating stimulus with an orientation of 90° evoked the largest potential with a peak-to-peak amplitude (first two components) of 1,010 μV. The same grating at an orientation of 0° evoked a potential with a similar waveform but with an amplitude of 650 μV. The microelectrode was advanced, normal to the surface of the brain to a depth of 1.45 mm when unit 9-2-1, a simple cell, was isolated. This unit responded optimally to a flash presented grating stimulus with an orientation of 90°, giving no response at an orientation of 0° (see Fig. 25(c)). This unit also gave no response to a blank stimulus. Both this and further units from the same penetration (such as unit 9-2-2) showed similar orientation preferences to the orientation of the stimulus evoking the largest 'orientation-column' potential. All the units had their receptive fields within the area covered by this stimulus. The cats optics showed no sign of astigmatism which could have accounted for these results.

FIG. 25.

(a) Pattern-related potentials recorded at depth to a grating stimulus at various orientations. Stimulus diameter 7^{o}; spatial frequency 0.74 c/deg; contrast 0.36; duration 40 msec. The vertical arrows mark the stimulus onset. The potentials are the averaged responses to 100 stimulus presentations.

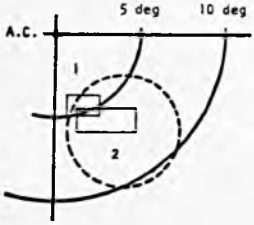
(b) Position of the grating and blank flash stimuli used in (a) in relation to 2 units from which recordings were made later in the normal penetration. The dotted circle marks the stimulus position and the rectangles, 1 and 2, delineate the minimum response fields of the units. Both units had a preference for stimuli with an orientation of 90^{o}.

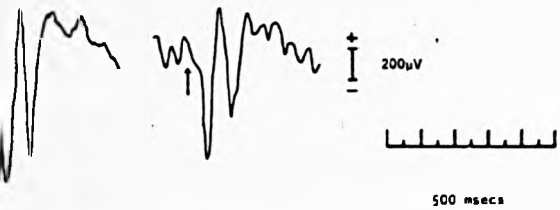
(c) Average response histogram (100 stimulus presentations) of unit 1 to a grating stimulus at optimal and non-optimal orientations with a spatial frequency 0.74 c/deg, duration 40 msec., constrast 0.36 diameter 7^{o}. The vertical arrows mark the stimulus onset.

(a)

Orientation (deg) 0 45

(b)





90 135

(c)

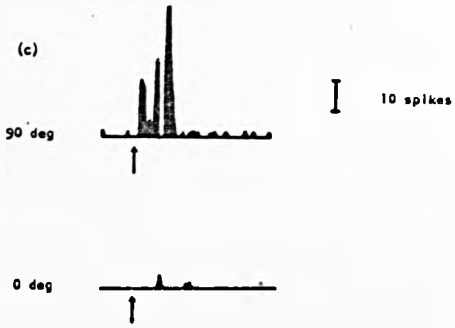
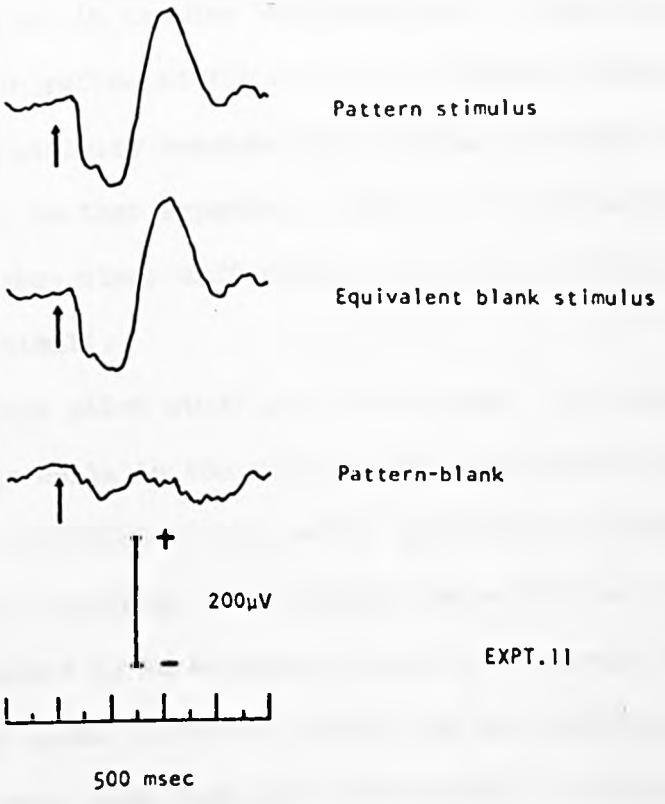


FIG. 26.

(a) Response (average of 100 presentations) to a grating stimulus with a spatial frequency of 0.42 c/deg, diameter 7°, contrast 0.36, duration 50 msec. The vertical arrow marks the stimulus onset.

(b) Response to a blank stimulus with an equivalent overall luminance to the grating stimulus in (a).

(c) Resultant potential when the response to the equivalent blank stimulus (b) was subtracted from the response to the grating stimulus (a).


Pattern stimulus
Equivalent blank stimulus
Pattern-blank
+
200μV
−
EXPT. II
500 msec

These initial results were encouraging but it was not possible to replicate them in subsequent experiments. Fig. 26 shows the results of another experiment where although it was possible to record normal unit activity, there were neither indications of orientation column potentials nor any clear distinction between PRVEPs or potentials evoked by equivalent blank stimuli. Recording conditions and experimental preparation in this experiment were identical to Expt. 9.

Two pilot experiments were carried out under nitrous oxide/oxygen/halothane anaesthesia but in neither experiment was it possible to record potentials which reflected the activity of nearby units. In both experiments unit activity recorded with microelectrodes showed no abnormality. Also, in neither experiment did cortical potentials evoked by patterned stimuli show clear differences from those evoked by equivalent non-patterned stimuli.

The results of this pilot study are paradoxical. In three experiments, even though the cells in the cortex were sensitive to patterned stimuli this was not reflected in the evoked potential recorded within the cortex. In order to attempt to establish the existence of PRVEPs in the cat it was decided to investigate potentials recorded from the cortical surface with gross electrodes making use of tachistoscopic stimulation methods which have been used extensively in studies of the human PRVEP.

4.2 Surface-recorded Evoked Potentials

4.2.1 Introduction

The results presented here are from a series of 14 experiments investigating surface-recorded PRVEPs in the cat visual cortex. In many ways this series is incomplete and represents a progression through several experimental methods (see Section 2) in an attempt to find optimal conditions for evoking PRVEPs.

The following tests were carried out on responses thought to be related to the pattern content of the stimulus.

1. Comparison of the responses to patterned and blank stimuli of similar space-averaged luminance. This included comparison between successive runs and subtraction of an equivalent blank response from a response to a patterned stimulus. Tachistoscopic stimulus presentation was also used, allowing pattern stimuli to be presented with minimal changes in luminance.

2. Investigation of changes in the form of the potential when different stimulus patterns were used.

3. Reducing the contrast and dimensions of the stimulus pattern until a pattern-specific response was no longer obtained.

4. Investigation of the effect of degrading the retinal image by defocussing.

5. Adaptation of the generators of a pattern-related response by pre-exposure to the patterned stimulus.

The retinotopic distribution of PRVEPs was also investigated and compared to that evoked by blank stimuli since, in man, the distribution of PRVEPs is systematic and quite different from that of potentials evoked by changes in overall luminance of the stimulus (Jeffreys, 1969).

4.2.2 Identification of Pattern-related components in the Evoked Potential

Fig. 27 shows the results from two experiments in which electronic

subtraction methods were used to reveal a pattern-related response. The two fields of the tachistoscope, one containing a pattern, the other an equivalent blank field were used alternately as the stimulus. The response to the patterned field was added to one channel of the averaging computer whilst the response to the blank field was subtracted from that channel to give the pattern-minus-blank response. Pattern and blank responses were also averaged on additional channels of the averager. Controls were carried out to ensure that any difference between the two responses was due solely to the difference between the stimuli. Responses to patterned and blank stimuli were similar when evoked by either stimulus field and,with both fields blank, subtraction did not give a potential. In experiments 26 and 31 a clear difference can be seen between the pattern and the blank responses as shown by the pattern-minus-blank potential. The form of the pattern, blank and pattern-minus-blank responses were not similar in the two experiments. This variation in the form of the response from different animals was a notable feature of the whole experimental series.

In other experiments there was no difference between the responses evoked by the patterned and blank stimuli. Fig. 28 (b) shows the position of 8 recording electrodes in relation to the visual areas in one experiment. The potentials recorded at these sites by stimulation of the lower visual half-field with a 30° diameter checkerboard stimulus (check-size 1°) are shown in Fig. 28 (a) (continuous line). The dotted line in Fig. 28 (a) is the response to an equivalent blank flash. It can be seen that there are only small differences in waveform between the pattern and the blank potentials. At recording site 3, the blank response and pattern response differ in their late components. At recording sites 2, 7 and 8, there are differences between some components (latency 20 msecs. and 50 msecs.) but the differences are small in relation to the size of

FIG. 27. Pattern responses from 2 experiments revealed using substraction methods. 'Pattern' and 'blank' potentials are responses to patterned and equivalent blank stimuli respectively. 'Pattern-blank' potential is the potential remaining after subtraction of the 'blank' potential from the 'pattern' potential. Time scales = 500 msecs; amplitude calibration 100μV. The recording electrode was on the cortical surface at the presumed projection of the area centralis at the Area 17/18 border.

Expt. 26. Stimulus onset at 100 msecs; duration 40 msecs. Grating pattern, spatial frequency 1.25 c/deg subtending 9° at 70 cms.

Expt. 31. Stimulus onset, 100 msecs; duration, 25 msecs. Grating pattern, spatial frequency 1.25 c/deg; subtending 30° at 57.3 cms.

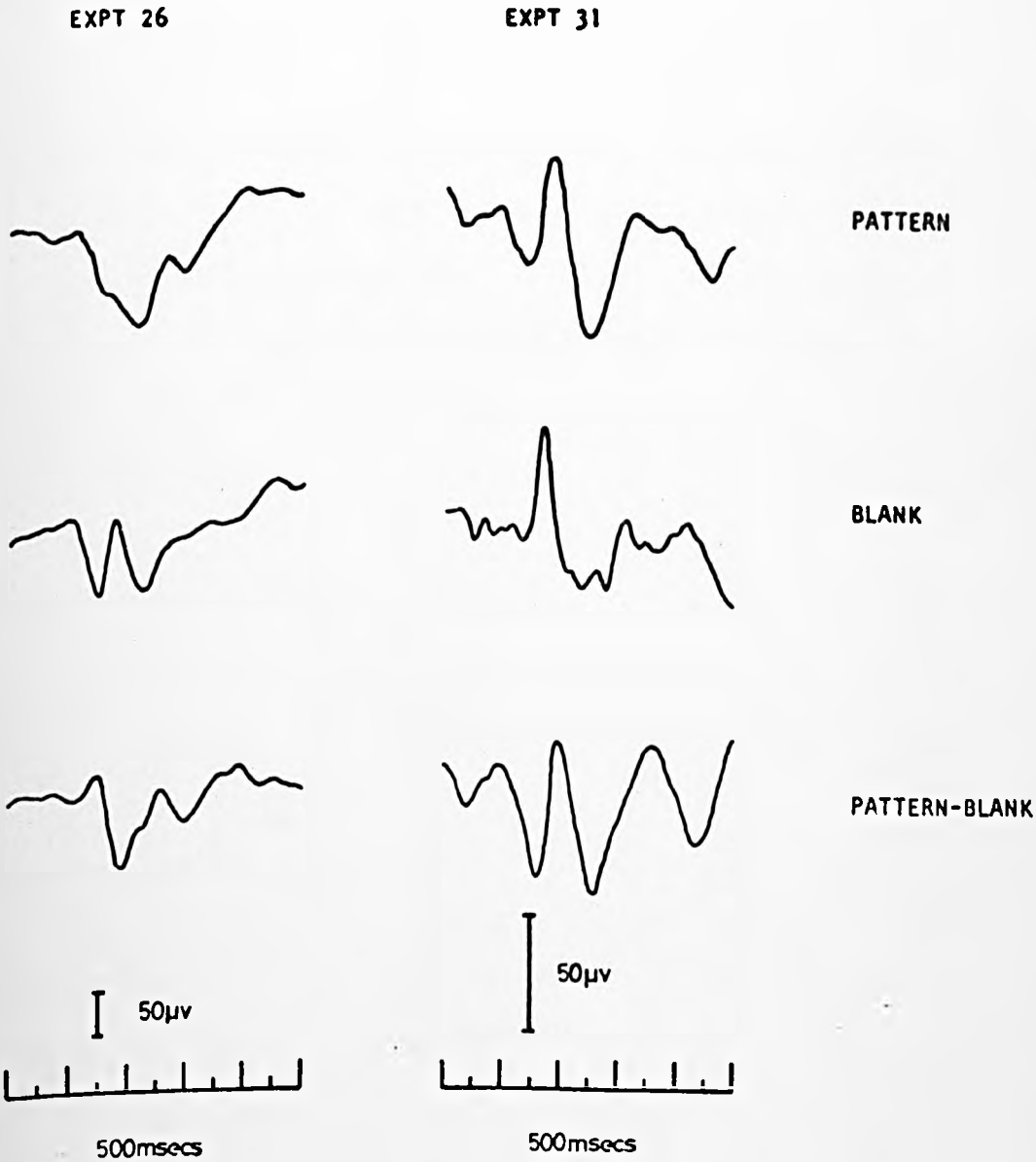
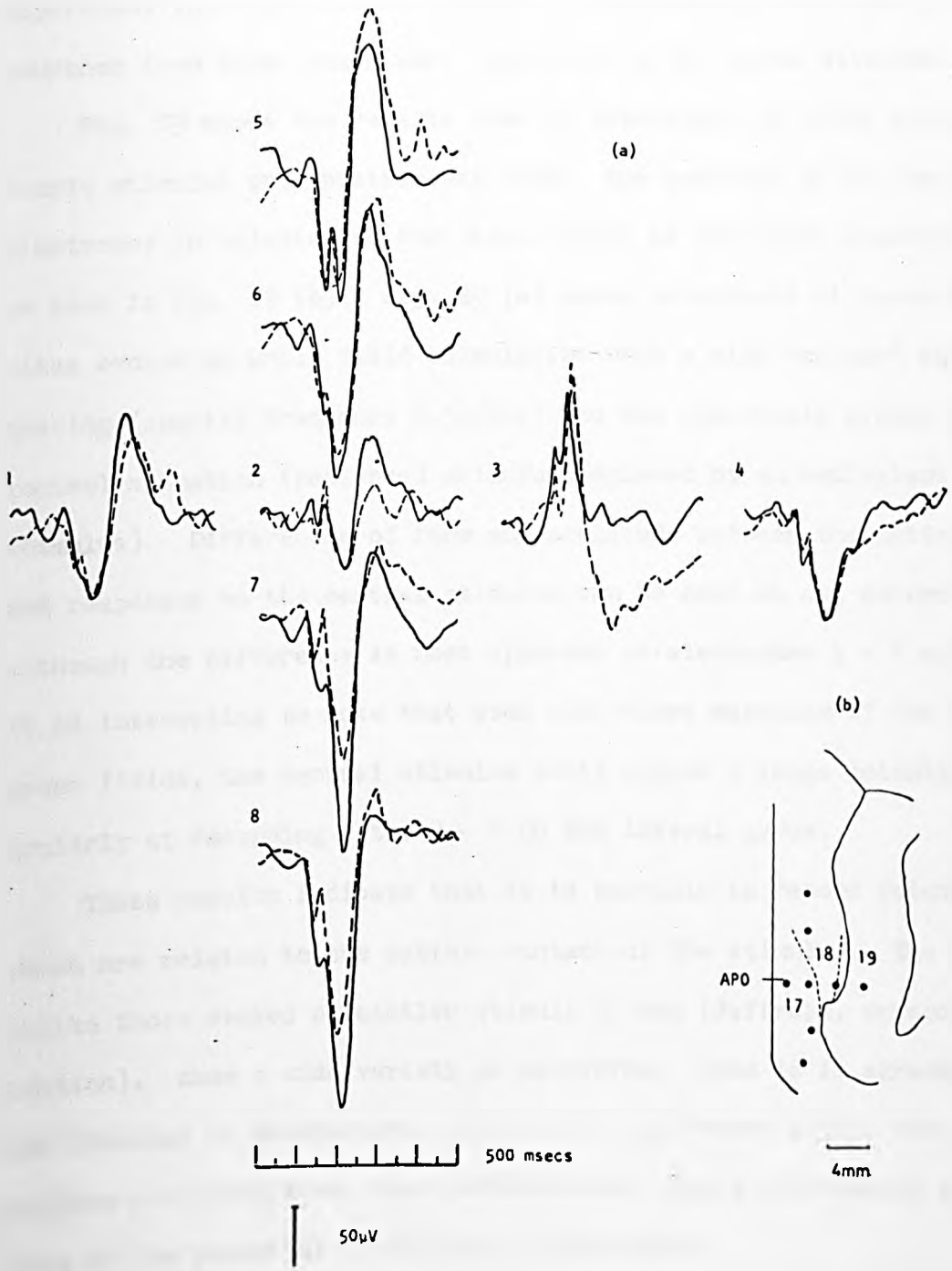

EXPT 26
EXPT 31
PATTERN
BLANK
PATTERN-BLANK
50μv
50μv
500msecs
500msecs

FIG. 28.

(a) Responses recorded from an array of 8 electrodes over the visual cortex of the cat to stimulation of the left eye. The continuous line is the response to a flashed pattern stimulus and the broken line is the response to a blank flash stimulus. Stimulus onset was at 100 msecs and the duration 25 msecs.
(b) Position of the recording electrodes used in (a) on the surface of the right visual cortex. Broken lines delineate the visual areas and AP0 marks the anterior/posterior zero (Horsley-Clarke co-ordinates). The horizontal line at AP0 is equivalent to 2 mm on the cortical surface.


5
(a)
6
1
2
3
4
7
8
(b)
18
19
APO
17
500 msecs
4mm
50μV

the whole potential and at all recording sites responses to the two stimuli have similar basic components. There is no evidence in this experiment that the pattern stimulus is activating different groups of neurones from those which were activated by the blank stimulus.

Fig. 29 shows the results from an experiment in which tachistoscopic stimulus presentation was used. The position of the recording electrodes in relation to the visual areas of the right hemisphere can be seen in Fig. 29 (b). Fig. 29 (a) shows potentials at those recording sites evoked by whole field stimulation with a high contrast square-wave grating (spatial frequency 0.5c/deg) and the potentials evoked in the control situation (patterned stimulus replaced by an equivalent blank stimulus). Differences of form and amplitude between the pattern responses and responses to the central stimulus can be seen at all recording sites although the difference is most apparent at electrodes 1 - 4 and 7 and 8. It is interesting to note that even with close matching of the tachistoscope fields, the central stimulus still evokes a large potential, particularly at recording sites 2 - 4 on the lateral gyrus.

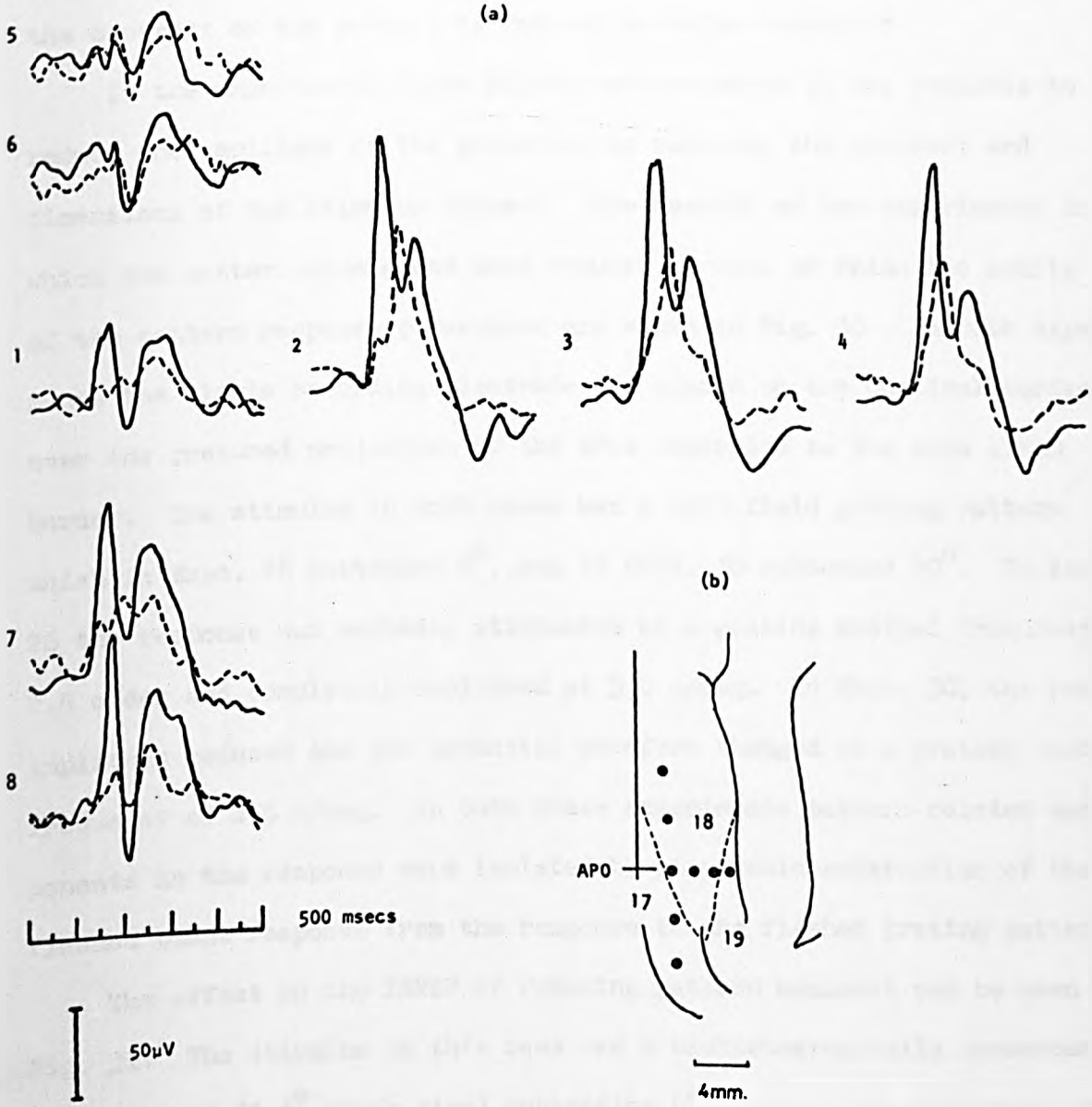
These results indicate that it is possible to record potentials which are related to the pattern content of the stimulus. The potentials, unlike those evoked by similar stimuli in man (Jeffreys, personal communication), show a wide variety of waveforms. This is in agreement with the findings of Creutzfeldt, Rosina, Ito and Probst (1969) who, using diffuse and punctiform visual stimulation, report differences in the form of the potential in different experiments.

Generally the cat visual cortex seems very sensitive to changes in stimulus luminance. In Fig. 29, even though the luminances of the two fields were closely matched the control stimulus evoked a potential with an amplitude of up to 60% of the potential evoked by stimulation with a high contrast patterned stimulus (see also Fig. 35). It is also interesting

FIG. 29.

(a) Responses recorded from the visual cortex to visual stimulation of the left eye using a tachistoscope. The continuous line is the response to full-field stimulation with a tachistoscopically presented patterned stimulus. The dotted line represents the blank control. The stimulus onset was at 100 msecs and duration was 25 msecs.

(b) The position of the recording electrodes used in (a) on the surface of the right visual cortex. Broken lines delineate the visual areas 17, 18 and 19, APO marks the anterior/ posterior zero (Horsley-Clarke co-ordinates) and the horizontal line at APO represents 2 mm on the cortical surface.


(a)
5
6
1
2
3
4
7
8
500 msecs
50μV
(b)
18
APO
17
19
4mm.

that in some experiments, potentials generated by flashed pattern and flashed blank stimuli often have similar waveforms (see Fig. 28).

4.2.3 Effect of Pattern Contrast and Dimensions on the PRVEP

Reducing the pattern element dimensions to beyond acuity should cause a reduction in the amplitude of the PRVEP to the noise level of the background EEG. A similar reduction in amplitude should occur when the contrast of the pattern is reduced to below threshold.

In the experiments where PRVEPs were recorded it was possible to reduce the amplitude of the potential by reducing the contrast and dimensions of the stimulus pattern. The results of two experiments in which the pattern dimensions were reduced to near or below the acuity of the pattern-response generators are shown in Fig. 30. In both experiments the single recording electrode was placed on the cortical surface over the presumed projection of the area centralis to the area 17/18 border. The stimulus in both cases was a full-field grating pattern which in Expt. 26 subtended 9°, and in Expt. 30 subtended 30°. In Expt. 26 the response was markedly attenuated at a grating spatial frequency of 2.5 c/deg and completely abolished at 5.0 c/deg. In Expt. 30, the response amplitude reduced and the potential waveform changed at a grating spatial frequency of 2.5 c/deg. In both these experiments pattern-related components in the response were isolated by electronic subtraction of the flashed blank response from the response to the flashed grating pattern.

The effect on the PRVEP of reducing pattern contrast can be seen in Fig. 31. The stimulus in this case was a tachistoscopically presented checkerboard (0.6° check size) subtending 9°. Recordings were made from a single electrode on the surface of the cortex at the projection of the area centralis to the border of areas 17 and 18. It is clear that decreasing stimulus contrast attenuates the pattern-related response.

FIG. 30. The results of Expts. 30 and 26 where the effect of reducing pattern dimensions of a grating stimulus was investigated. The figures beside the potentials indicate the spatial frequency (c/deg).

In Expt. 26 the stimulus subtended 9° and in Expt. 30, 30°.

In both experiments the potentials were recorded from a single electrode over the areas 17 and 18 border at the presumed central projection of the area centralis.

The vertical calibrations and time scales represent $100\,\mu V$ and 500 msec respectively.

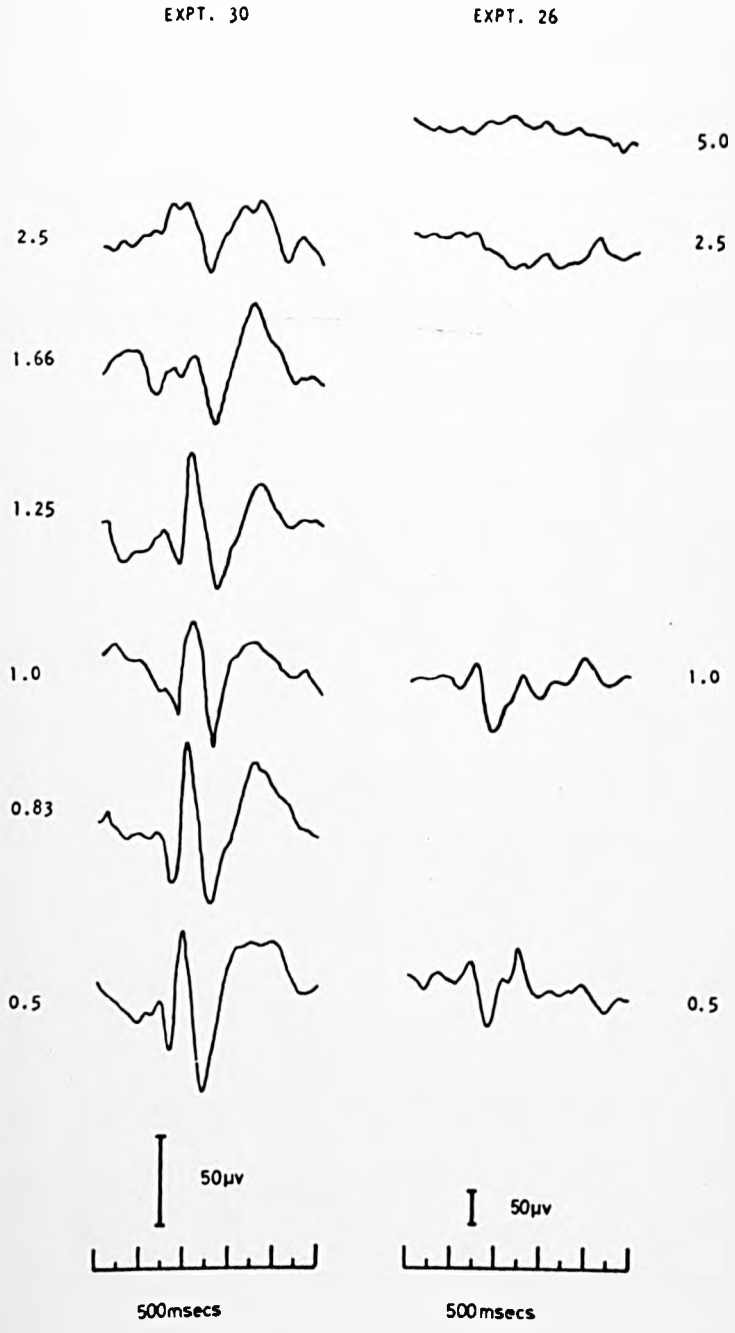

EXPT. 30
EXPT. 26
5.0
2.5
2.5
1.66
1.25
1.0
1.0
0.83
0.5
0.5
50µv
50µv
500msecs
500msecs

FIG. 31. Effect of decreasing stimulus contrast on a pattern-related response.

The stimulus was a tachistoscopically presented checkerboard (0.6° check-size) subtending 9°. The stimulus onset was at 100 msecs and the duration was 50 msecs.

The recording electrode was placed on the presumed cortical projection of the area centralis at the border of areas 17 and 18.

The time scale and calibration mark represent 500 msecs and 50 μV respectively.

DECREASING
50μv
500msecs

CONTRAST —

4.2.4 Effect of Retinal Image Defocus on the PRVEP

Using supplementary lenses to defocus the image of the patterned stimulus should cause a reduction in amplitude of the PRVEP (see Jeffreys, 1974).

In experiments where PRVEPs were recorded the effect of defocussing the retinal image was investigated. Fig. 32 (a) shows the results of one such experiment using a high contrast grating with a square-wave luminance profile and a spatial frequency of 0.5 c/deg. The pattern-related response revealed by subtraction methods, was not significantly affected by retinal image defocussing of up to +2.5 dioptres and even with defocussing of +8 dioptres a pattern-related response was still evoked although the potential waveform was changed.

Fig. 32 (b) shows the effect of defocussing on a pattern-related response in another experiment. PRVEPs were recorded from an electrode placed over the presumed central projection of the area centralis at the area 17/18 border. Retinal image defocussing of a checkerboard pattern (check-size 0.6 deg) of +3 dioptres reduced the amplitude of the response although the evoked potential still retained the same waveform. With defocussing of +6 dioptres, a potential was still evoked although its waveform was changed.

Pattern-related responses in the cat are relatively insensitive to retinal image defocussing. Jeffreys (1974) has reported that, in man, the addition of supplementary lenses has a more marked effect on the presumed extrastriate components (CII and CIII) of the PRVEP than on the component thought to originate in the striate cortex (CI). On this and other evidence, Jeffreys concluded that CI indicated 'contrast' sensitive processes whilst CII and CIII reflected 'contour' sensitive processes. The insensitivity of the cat PRVEP to defocussing is similar to the insensitivity of CI of the human PRVEP and could indicate the activity in the cat visual cortex of similar 'contrast' sensitive processes

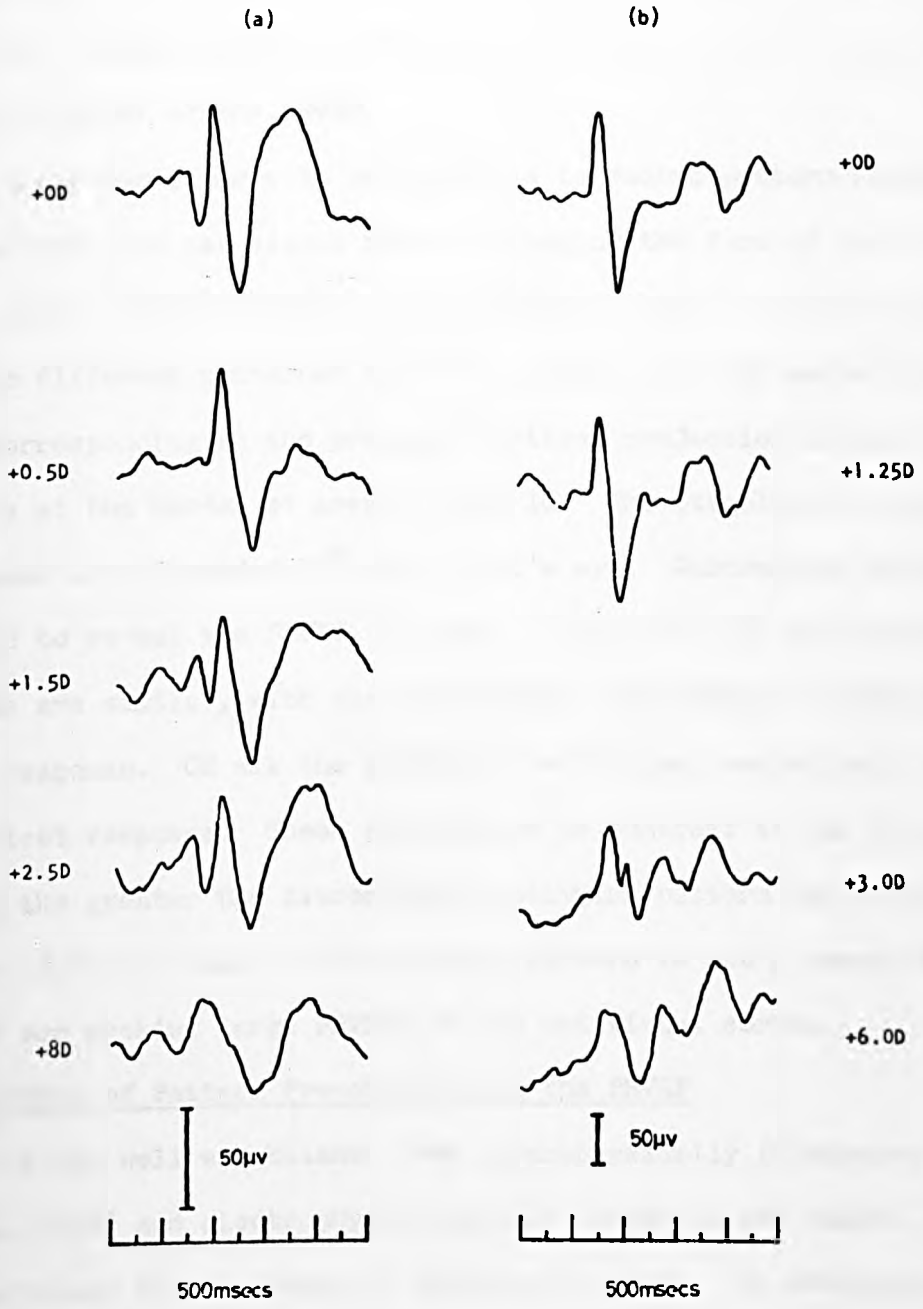
FIG. 32. Effect of retinal image defocus on PRVEPs. Values of supplementary lenses (in dioptres) shown alongside responses.

(a) Square wave grating stimulus (0.5 c/deg) subtending 30°. Stimulus on at 100 msecs for 1 msec. The PRVEP was revealed using subtraction methods.

(b) Checkerboard stimulus (0.6° check size) subtending a 9° field. Stimulus on at 100 msecs for 40 msecs, presented tachistoscopically.

In both cases the recording electrode was placed on the presumed central projection of the area centralis at the border of areas 17 and 18.

Time scale and amplitude calibrations represent 500 msecs and 50 μV respectively.


(a)
(b)
+0D
+0.5D
+1.5D
+2.5D
+8D
+0D
+1.25D
+3.00
+6.00
50μv
50μv
500msecs
500msecs

4.2.5 Effect of the Form of the Stimulus Pattern on the PRVEP

In man, individual components of the PRVEP show marked changes in amplitude when different stimulus patterns are used (Jeffreys, 1974). Generally the more pattern discontinuities (i.e. corners, edges) the larger the evoked potential. This applies in particular to the extrastriate component of the PRVEP.

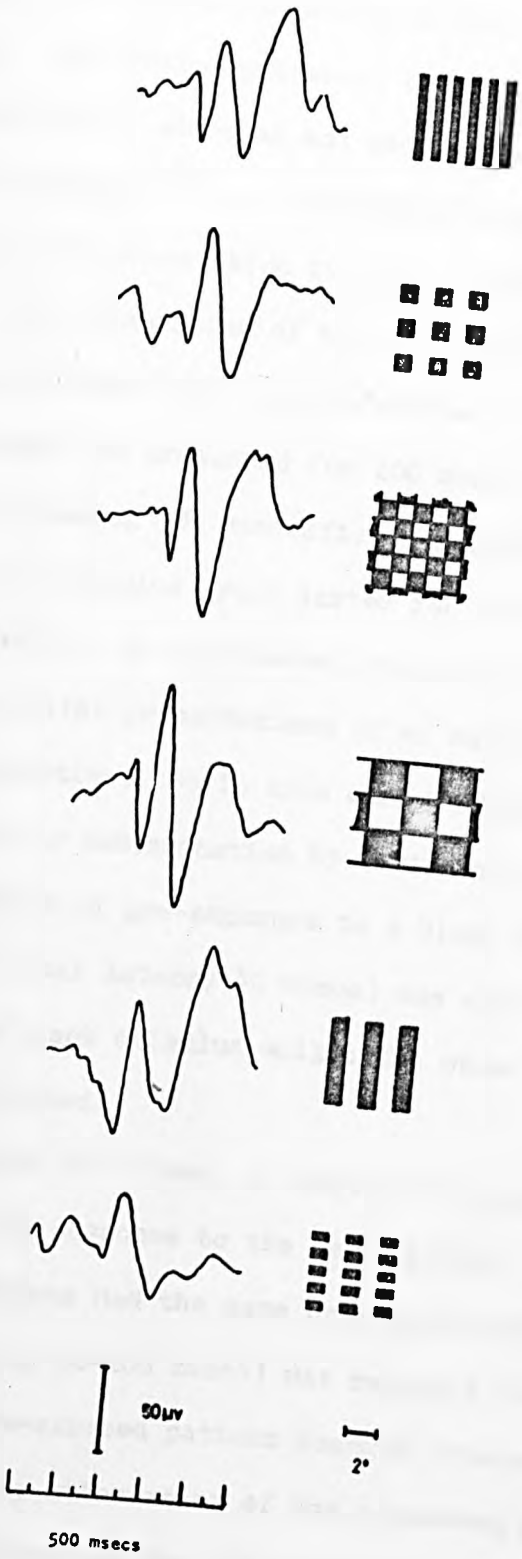
In experiments where it was possible to record pattern-related responses from the cat visual cortex, changing the form of the pattern did not have a marked effect on the response. Fig. 33 shows the responses to different patterned stimuli recorded from the surface of the cortex corresponding to the presumed cortical projection of the area centralis at the border of areas 17 and 18. The stimulus was presented for 2 msecs and subtended 30° at the cat's eye. Subtraction methods were used to reveal the PRVEP. It can be seen that all the potential waveforms are similar, with the checkerboard (2° checks) evoking the largest response. Of all the patterns the 0.5 deg. bar stimulus evoked the smallest response. These results are in contrast to the finding in man that the greater the discontinuous stimulus pattern the larger the PRVEP and indicate that a discontinuous pattern is not a powerful stimulus for evoking large PRVEPs in the cat visual cortex.

4.2.6 Effect of Pattern Pre-exposure on the PRVEP

It is now well established both psychophysically (Blakemore and Campbell, 1969) and electrophysiologically (Campbell and Maffei, 1970) that the visual system adapts to patterned stimuli. In addition, Jeffreys (1974) has shown that although all the components of the human PRVEP are sensitive to stimulus pre-exposure, CII and CIII (presumed to be extrastriate in origin) show greater sensitivity to pattern pre-exposure that CI (presumed to be striate in origin).

In only one experiment was it possible to investigate the effect of

FIG. 33. Variation of the pattern related VEP with the form of the patterned stimulus. The recording electrode was placed on the presumed central projection of the area centralis at the border of areas 17 and 18. The vertical calibration refers to the potential amplitude and represents 50 μV and the horizontal calibration refers to the pattern elements and represents 2^{o}.


50µv
2°
500 msecs

pre-exposure of the test stimulus on pattern-related responses. Recordings were made from a single surface electrode at the presumed border of cortical areas 17 and 18 corresponding to the central projection of the area centralis. Two grating patterns, one in each field of a tachistoscope, were used as the adapting and test stimuli. Each field of the tachistoscope subtended 30° and the spatial frequency of both gratings was 0.5 c/deg but the orientation of the adapting pattern could be varied from 0 to 90°. The orientation of the test pattern was 0°. The adapting pattern could be replaced by a blank stimulus of equivalent luminance. The adapting pattern was presented for 100 msecs, the test pattern for 1 msec duration following 500 msec after the offset of the adapting pattern. The whole stimulus cycle lasted for 1410 msecs. In this experiment test presentations of a patterned stimulus at durations of 1 msec evoked a response whilst presentations of an equivalent non-patterned stimulus were ineffective. So, in this case a flashed pattern stimulus evoked a PRVEP with no contamination by luminance responses. Fig. 34 (b) illustrates the effect of pre-exposure to a blank stimulus. The first positive component (peak latency 40 msecs) was clearly attenuated by pre-exposure to the blank stimulus whilst the other components of the potential were unaffected.

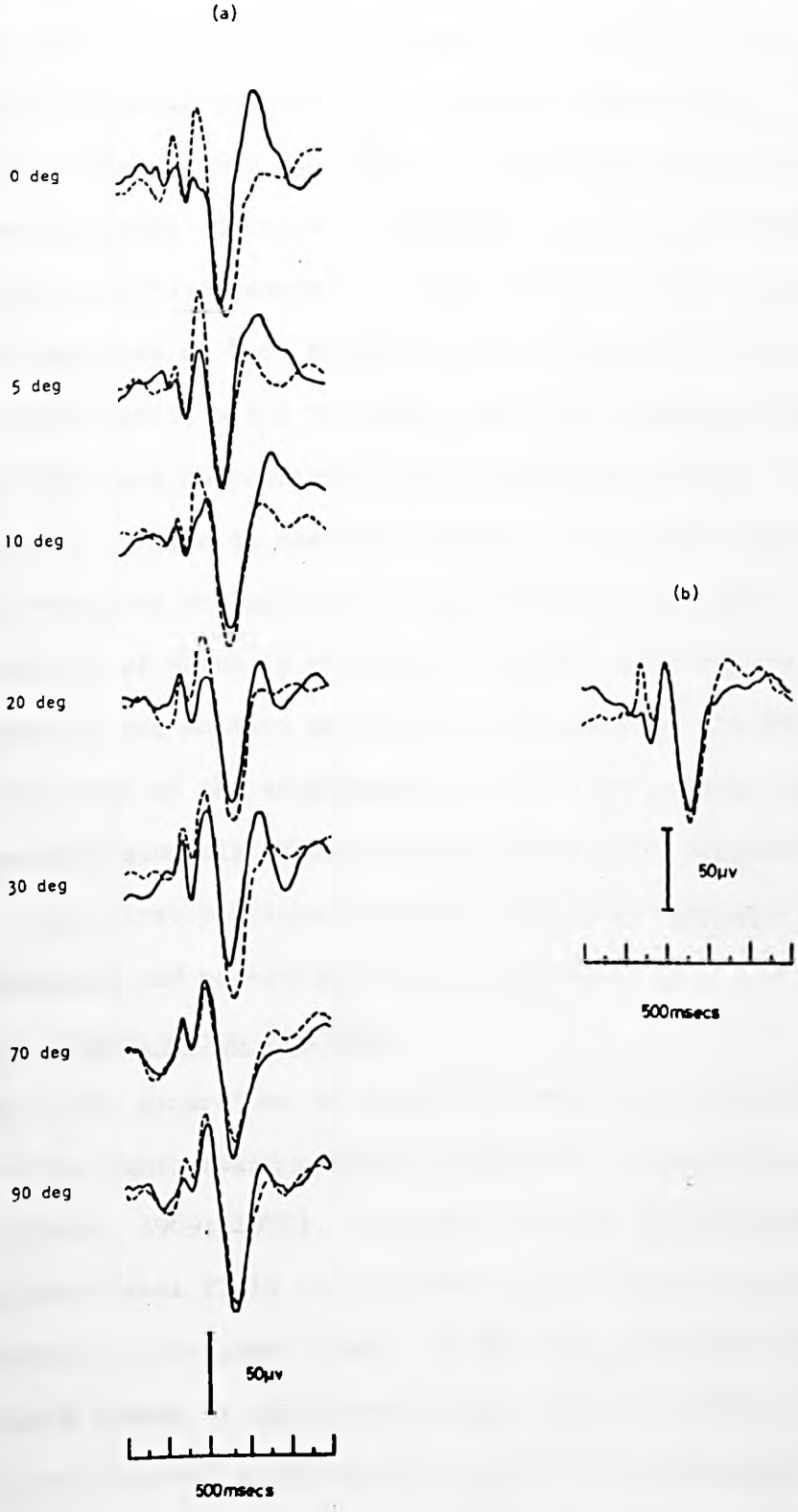
Fig. 34 (a) shows the effect of varying the orientation of the pre-exposed pattern on the response to the test pattern. When the pre-exposed and test patterns had the same orientation the second positive component (peak latency 90-100 msecs) was markedly attenuated. As the orientation of the pre-exposed pattern changed progressively from that of the test pattern the attenuation of the component became less marked until at 30° the influence of the pre-exposed stimulus on the response to the test stimulus was negligible. At the pre-exposed pattern orientation of 0°, the second positive component was also attenuated but this effect was less marked than that caused by pre-exposure to a blank field. The large negative component (peak latency 150 msecs) was also

FIG. 34.

(a) Effect of a 500 msec pre-exposure of a patterned stimulus (0.5 c/deg square wave grating pattern) on the response to a similar test pattern. Figures beside the responses indicate the orientation of the adapting pattern. The test pattern orientation was 0° in all cases. The continuous line is the response with the adapting pattern at various orientations. The broken line is the response with the adapting field at 90°.

(b) Effect of a 500 msec pre-exposure of a blank field on the response to a patterned test stimulus, is the response after pre-exposure to a blank field (continuous line) and after pre-exposure to a pattern of similar dimensions but with an orientation of 90° (broken line).

The recording electrode was placed on the presumed central projection of the area centralis at the border of areas 17 and 18. The time scale and amplitude calibration represent 500 msecs and 50μV respectively.


(a)
0 deg
5 deg
10 deg
20 deg
30 deg
70 deg
90 deg
50μv
500msecs
(b)
50μv
500msecs

attenuated by pattern pre-exposure, although the effect is not clear. The attenuation of the component is probably responsible for the increase in amplitude of the late positive component when the pre-exposed pattern and stimulus patterns have similar orientations.

These results indicate that the pattern related response recorded in this experiment probably contained 3 components sensitive to pre-exposure. The first positive component (latency 40 msecs) was sensitive to the increased luminance of both patterned and non-patterned pre-exposure. The second positive and the major negative component (latency 90-100 msecs and 150 msecs respectively) both showed sensitivity to pre-exposure of a pattern similar to the test pattern. It is possible that these components represent the activity of groups of pattern-sensitive neurones, the activity of which is reduced by pattern pre-exposure. Since in this case the pre-exposed pattern is stationary on the retina, it is possible that some of the adaptation occurs in the retina, but this, however, would presumably affect only the very early components of the PRVEP, i.e. the first positive component which was markedly attenuated by both patterned and non-patterned pre-exposure.

4.2.7 Retinotopic Distribution of PRVEPs

In contrast to the generators of potentials evoked by blank stimuli, the generators of the human scalp-recorded PRVEP show a clear retinotopic organization (Jeffreys, 1969; 1971). Potentials evoked by patterned stimuli in the upper visual field are opposite in polarity to those evoked by stimulation of the lower field. In the cat, the early components of potentials evoked by punctiform stimuli are also distributed retinotopically over the cortex (Whitteridge, 1973) unlike the later components, and components of potentials evoked with larger areas of stimulation (Doty, 1958). Using an array of recording electrodes, the cortical distribution of PRVEPs was investigated.

In general cat PRVEPs did not show a clear retinotopic distribution. Fig. 35 illustrates the results of one experiment. A patterned stimulus, tachistoscopically presented in one quadrant of the visual field, evoked a large response over a wide area of the visual cortex. Stimulation of the ipsilateral quadrants of the contra-lateral visual field evoked potentials with a similar waveform and polarity as stimulation of the contra-lateral quadrants. Stimulation of the contra-lateral quadrants evoked potentials with a shorter latency than the ipsilateral quadrants but there is clearly no polarity reversal as seen in human PRVEP studies. Although in the control situation (patterned field replaced by an equivalent blank field) a potential was still evoked, it was not large enough to account for the lack of a retinotopic distribution and could not account for the absence of polarity reversal.

In this experiment potentials evoked by pattern stimulation (tachistoscopic presentation) showed a distribution similar to those evoked by flash-presented blank stimulation (see Fig. 36). With blank stimuli however, the latency of the potential was similar in all quadrants.

In general experiments using multielectrode arrays yielded similar cortical potential distributions of potentials evoked by both patterned or non-patterned stimulation of individual half fields or quadrants in contrast to similar experiments in man (Jeffreys, 1969; 1971). Stimulation of any quadrant of the visual field with patterned stimuli often yielded potentials of similar waveform and in this way are similar to the findings of Doty (1958) using large diffuse stimuli.

4.2.8 Responses to pattern-reversal stimuli

In four experiments pattern reversal stimuli were used to evoke PRVEPs (see Evoked Potentials - Methods) and it was possible to compare these potentials with those evoked by pattern appearance and by blank stimuli of similar contrast (0.7) at a mean luminance of 50 cd/m^2 (see

FIG. 35.

(a) Responses to pattern-appearance stimulation of the 4 quadrants of the visual field at each of four recording sites. The two circles to the left of the responses represent the two switching fields of a tachistoscope. Amplitude calibration = 50 μV; time scale = 500 msec.

(b) Map of the surface of the visual cortex showing the four recording sites from which the potentials in (a) were recorded and visual areas 17, 18 and 19. The short horizontal bar marks the ear bar zero (Horsley-Clarke co-ordinates) and represents 2 mm on the cortical surface.

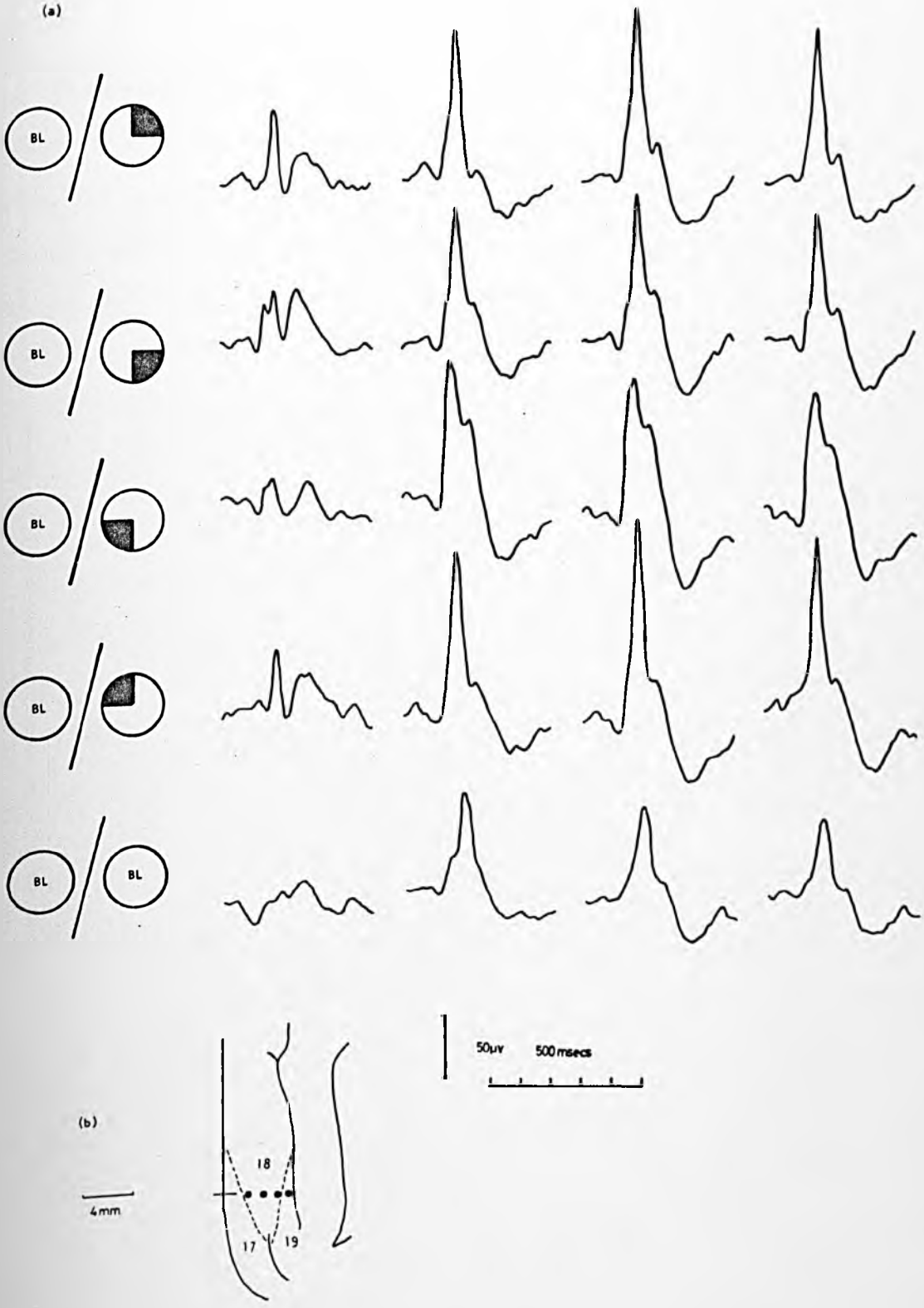

(a)
BL
BL
BL
BL
BL
BL
50μv
500 msecs
(b)
4mm
18
17
19

FIG. 36.

(a) Responses to flashed blank stimulation of the 4 quadrants of the visual field at 4 recording sites. Calibration = 50μV and the time scale = 500 msec.

(b) Map of the surface of the visual cortex showing the 4 recording sites from which the potentials in (a) were recorded and visual areas 17, 18 and 19. The short horizontal bar marks the ear-bar zero (Horsley-Clarke co-ordinates) and represents 2 mm on the cortical surface.

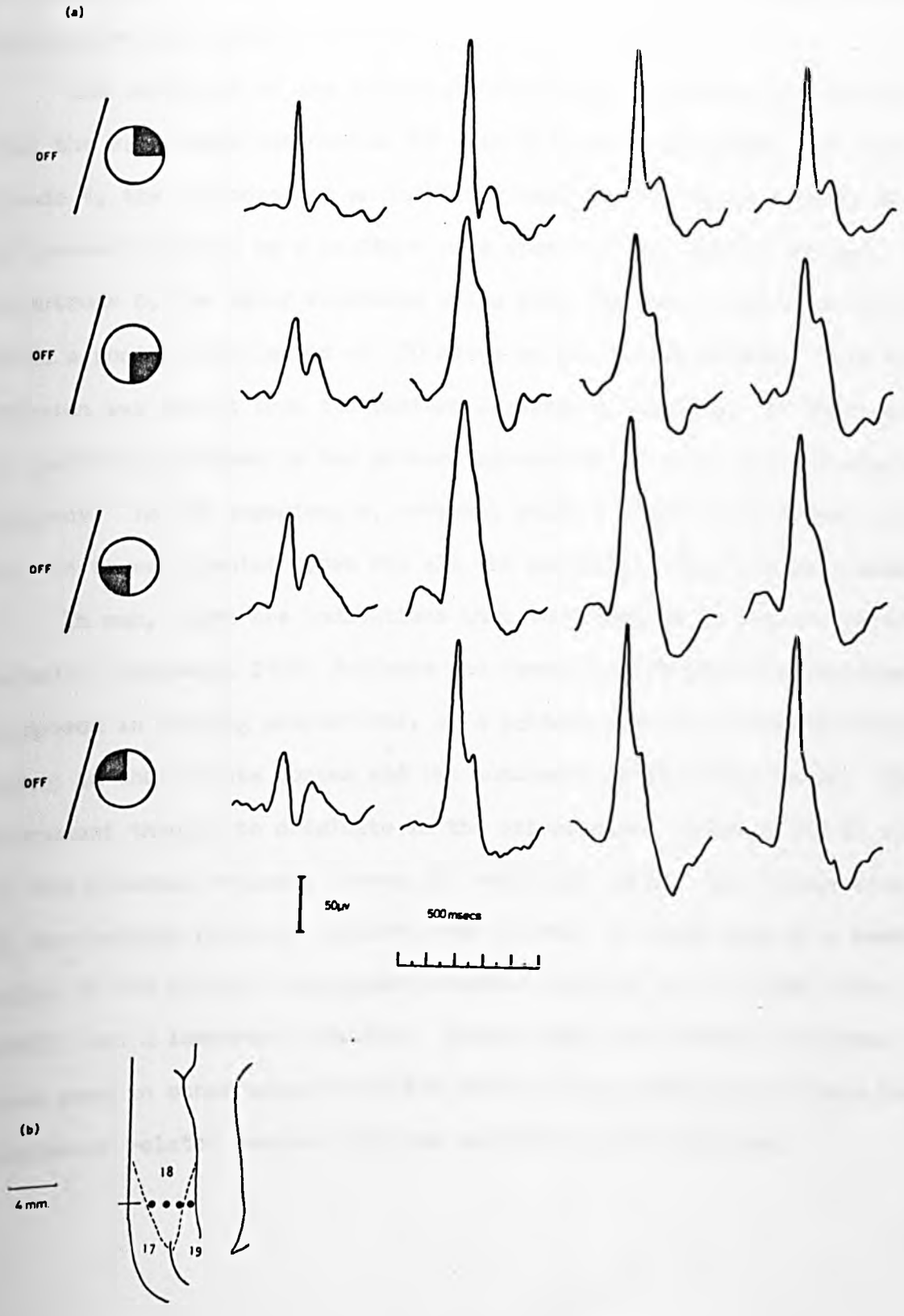

(a)
OFF
OFF
OFF
OFF
50μv
500 msecs
(b)
4 mm.
18
17
19

Fig. 37). The patterned stimulus was a grating (spatial frequency 0.71 c/deg.) and the flashed blank stimulus was 35 cd/m^2 above the mean background luminance.

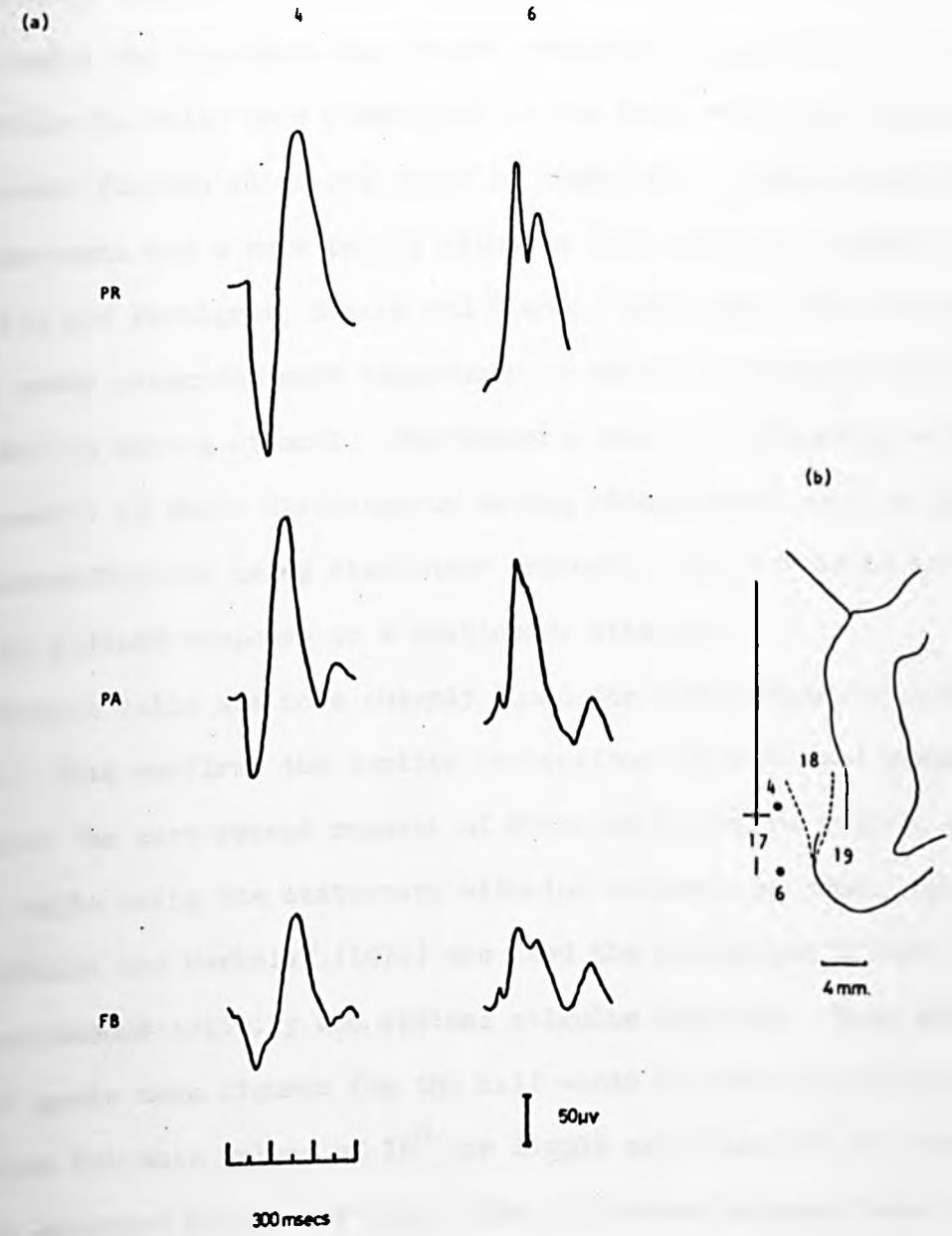
The waveforms of the potentials evoked by the three stimuli all had the same basic components but with different amplitudes. At electrode 4, the response was an initially negative one (peak latency 65-90 msecs) followed by a positive wave (peak latency 130-160 msecs). At electrode 6, the major component was a positive wave (peak latency 75 msecs) with a positive inflexion at 130 msecs on the falling phase. This inflexion was absent from the pattern appearance response. At electrode 6, potentials evoked by the pattern appearance stimulus had the shortest latency. In all experiments, reversal stimuli evoked the largest response of the three stimulus types but all the potentials had similar components.

In man, there are indications that the response to pattern reversal stimuli (Jeffreys, 1974; Jeffreys and James, unpublished observations) is composed in varying proportions, of a pattern specific component originating in the striate cortex and two luminance related components. The component thought to originate in the extrastriate cortex (CII) is absent in the reversal response (James and Jeffreys, 1975). The composition of the pattern reversal response seen in Fig. 37 could also be a combination of the pattern appearance response (similar to CI of the human PRVEP) and a luminance response. Similar pattern reversal responses were seen in other experiments but with varying contributions from the luminance related response and the pattern related response.

FIG. 37.

(a) A comparison of responses evoked by pattern reversal (PR), pattern appearance (PA) and flashed blank (FB) stimuli, recorded from two recording sites (4 and 6) on the cortical surface. Stimulus onset was coincident with the beginning of the potential and duration was 40 msecs. The spatial frequency of the grating pattern was 0.5 c/deg. Pattern reversal and pattern appearance stimuli had the same contrast and the blank stimulus was 35 cd/m^2 above the background. Amplitude calibration = 50μV; time scale = 300 msecs.

(b) Position of recording electrodes 4 and 6 on the surface of the visual cortex. The dotted lines delineate areas 17, 18 and 19 and the short horizontal bar indicates ear-bar zero (Horsley-Clarke co-ordinates) and represents 2 mm on the cortical surface.


(a)
4
6
PR
PA
FB
50μv
300 msecs
(b)
18
4
17
19
6
4 mm.

5. DISCUSSION

Single cells in area 17 of the visual cortex of the cat have been classified into simple and complex types using the response to a correctly oriented moving slit (Hubel and Wiesel, 1962; Pettigrew, Nikara and Bishop, 1968) and the level of spontaneous firing (Pettigrew, Nikara and Bishop, 1968) as the basic criteria. The 'quality' of the response to movement was the more significant criterion. Initially, as reported in Section 3, cells were classified on the basis of their responses to stationary flashed slits and spots of light but it soon became clear that movement was a more potent stimulus (see Hubel and Wiesel, 1962, page 113 and Pettigrew, Nikara and Bishop, 1968, page 380) and that cells never responded more vigorously to optimal stationary stimuli than they did to moving stimuli. Furthermore, the classification of cells by the quality of their discharge to moving stimuli went hand in hand with the classification using stationary criteria, when the cells gave a clearly defined response to a stationary stimulus.

Simple cells are more sharply tuned for orientation than complex cells. This confirms the earlier indications of Hubel and Wiesel (1962) and also the more recent reports of Rose and Blakemore (1974), who classified cells using the stationary stimulus criteria of Hubel and Wiesel, and Watkins and Berkeley (1974) who used the additional criteria of level of spontaneous activity and optimal stimulus velocity. Rose and Blakemore do not quote mean figures for the half width of orientation sensitivity profiles but mean values of 16° for simple cells and 19° for complex cells can be measured from their data. The difference between these values is less than the results presented here. Half-widths reported by Watkins and Berkley are 13.9° and 26.9° for simple and complex cells respectively which, although based on a smaller sample of cells, show greater similarity to the results of the present study. It is possible that the

difference between the values reported here and those reported by Rose and Blakemore could be due to their method of making the best straight-line fit to their orientation data. The difference between all three studies could also be explained by differences in experimental method (see below).

Simple cells have smaller receptive fields than complex cells and respond with fewer spikes to an optimal stimulus. These differences probably arise because of the criteria used to distinguish simple and complex cells. Obviously if complex cells are distinguished by a maintained discharge to stimulus movement, this is likely to result in a larger number of action potentials per response which occurs over a larger area of the retina. The converse is true of simple cells. They are characterised by their brief discharge to moving stimuli, which will result in an optimal response containing fewer spikes which occurs over a very localised area of the retina.

Hubel and Wiesel (1962) first reported that simple cells had smaller receptive fields than complex cells, the area of receptive fields peaking at about 2 deg^2 for simple cells and between 4 and 8 deg^2 for complex cells. These values are in good agreement with the results presented here, although the criteria used for distinguishing between the two types of cells in each study were different.

The difference in peak response amplitude of simple and complex cells confirms the finding of Rose and Blakemore (1974). Peak response amplitude measured from histograms illustrated in Rose and Blakemore's paper was approximately 17 spikes/sweep for simple cells and 38 spikes/sweep for complex cells. These values are somewhat larger than the values obtained in the present experiments. It is not clear how this discrepancy arises, although it could be due to anaesthesia techniques. Rose and Blakemore used an 80% nitrous oxide/18% oxygen/2% carbon dioxide

mixture following surgery under short acting barbiturates which could account for the increased excitability of the cells. This seems unlikely, however, since Bishop, Coombs and Henry (1971a) report response magnitudes of only 7-10 spikes/sweep for typical simple cell responses to optimal stimuli, under nitrous oxide/oxygen (70%:30%) anaesthesia alone, a value much lower than that obtained by Rose and Blakemore.

Directional sensitivity is a distinguishing feature of simple and complex cells which cannot be predicted directly from the criteria used in the categorisation of cells. Beyond a basic explanation that simple cells are clamped by tonic inhibition (see Henry and Bishop, 1973) which cuts off excitatory influences in the non-preferred direction, the explanation probably lies in the way in which movement responses are generated. To answer this question, a more detailed investigation of movement responses and their relationship to the receptive field 'map' is required.

The lack of distinction between simple and complex cell behaviour to changes in luminance is interesting. Although the sample of cells is small, it has been shown that simple and complex cells respond linearly to log. stimulus intensity, over a similar range. This is in agreement with the results of Pollen and Taylor (1974) for stationary flashed stimuli. These findings are, however, in contrast with those of Maffei and Fiorentini (1973) who report that simple cells respond linearly to stimulus <u>contrast</u> over a wide range whereas the behaviour of complex cells is irregular and non-linear. As noted in section 3.5, this discrepancy may be due to differences in stimulation techniques and measurement of response amplitude.

The insensitivity of both simple and complex cells to retinal image defocussing is interesting, particularly in the light of the results of Ikeda and co-workers (Ikeda and Hill, 1971; Ikeda and Wright, 1973) which show that, at the retinal level, responses are acutely sensitive to

defocussing. Their results were obtained using stimuli flashed on the centres of concentrically organised ganglion cell receptive fields so defocussing might cause light to scatter onto the antagonistic surround region of the receptive field. Small amounts of retinal image defocussing of a moving stimulus merely change the rate of change of contrast of the image of a moving edge on the retina (as explained in section 5.4) to which cortical cells are relatively insensitive. An investigation of image defocussing in those cortical cells which give clearly defined responses to stationary stimuli might give clearer results.

None of these findings support or deny a hierarchical model of cortical functioning (Hubel and Wiesel, 1962) in favour of a model based on parallel processing. Had complex cells been shown to respond non-linearly to changes in stimulus intensity in a way different from simple cells or had simple cells been more sensitive to defocussing than complex cells, this would have been difficult to reconcile with a hierarchical model. This, however, is not the case. The results of Pettigrew, Nikara and Bishop (1968) and the detailed study of stimulus velocities optimal for simple and complex cells (Movshon, 1974) are difficult to reconcile with a model based solely on the hierarchical principle as are the conduction velocity data of Stone and Hoffman (1971). In the light of the conflicting evidence, it seems likely that both parallel and hierarchical processing play a part in the neuronal organisation of the striate cortex of the cat.

Whether simple cells are stellate or pyramidal is still an open question although the evidence of Van Essen and Kelly (1974), however, gives considerable weight to the simple/stellate: complex/pyramidal hypothesis of Hubel and Wiesel (1962). Two points should be made, arising from the present study. Firstly, simple cells have been shown to possess considerable specificity of response, i.e. sharp orientation tuning,

direction selectivity, small receptive fields.It would seem unlikely that these cells are stellate neurones having no axon leaving the cortex to project to other cortical areas but merely projecting onto pyramidal/complex cells with more generalised properties. Secondly, it has been my impression during this study that it is possible to discriminate the responses of both simple and complex cells over many tens of microns during a penetration. This is not a property which would be expected of stellate cells in view of their shape and very localised dendritic trees. It is possible that both simple and complex cells are pyramidal neurones and that stellate cells function as interneurones (as envisaged in the model of Bishop, Coombs and Henry (1971b)).

This study was initially designed to investigate potentials within the visual cortex which were related to the preferred orientation and receptive field location of the units in the vicinity of the recording electrode. A positive result was obtained in only one out of four pilot experiments. In others (using both cerveau isolé and nitrous oxide/oxygen/halothane preparations) it proved impossible to correlate evoked potentials with the pattern content or orientation of the stimulus, despite the presence of normal unit activity. The difficulty in recording pattern specific potentials consistently from the cortex is surprising in view of the pattern specific responses of individual cells. It is implausible that the forebrain isolation or anaesthesia should depress the evoked potential without affecting unit activity. If post-synaptic activity (thought to be responsible for the generation of slow potentials - see section 1.3) were depressed cell activity would also be affected. In all experiments, the cat's optics were normal as far as could be judged by ophthalmoscopic examination.

The absence of a pattern-related response in some of the more recent experiments was also perplexing. For instance, in the experiment illustrated

in Fig. 28 the responses to a flashed pattern stimulus were not significantly different from those evoked by blank flashes. This particular preparation gave no indication of abnormality compared with others from which clear pattern related responses could be evoked. In other experiments responses evoked by tachistoscopic presentation of patterned or blank stimuli were similar indicating that pattern sensitive neurones were not involved. Perhaps a better understanding and evaluation of the ongoing EEG, used to monitor the state of the experimental animal, might reveal differences between those preparations which give pattern related responses and those which do not. Such an analysis might also account for the wide variety of waveforms and polarities of potentials seen in different experiments.

During the experimental series, considerable progress has been made in assessing optimal conditions for studying evoked potentials in the cat. It seems that the cerveau isolé preparation is essential, having the advantage of a stable unanaesthetised forebrain from which it is possible to evoke consistent potentials. Such preparations, however, suffer from cerebral oedema and general trauma to the CNS. Multiple electrode arrays allow simultaneous recording from several cortical sites and, thus, are useful for revealing foci of activation. A clear and consistent retinotopic distribution of pattern related potentials was not seen in these experiments. CRT displays are the most flexible and convenient method of displaying simple patterns (e.g. pattern appearance, pattern reversal and blank flashes). The tachistoscope is ideal for preliminary assessment of EPs to more complex patterns of high contrast but it is difficult to exactly balance the intensities of the two stimulus fields. Thus, switching between the two fields evokes luminance responses, due to the change in overall luminance, which contaminate the pattern responses.

In experiments where it has been possible to record PRVEPs, the potentials evoked by pattern appearance exhibited some properties similar to those of the CI component of the human PRVEP. This applied, in particular to their sensitivity to defocussing, partial adaptation following pattern pre-exposure and their relation to potentials evoked by pattern reversal stimuli. The cat PRVEP differed from CI of the human PRVEP in certain respects, notably in the lack of a clear retinotopic distribution of components over the cortical surface and showed none of the properties of the second and third components (C2 and C3) of the human PRVEP (see Jeffreys and James, 1975). Perhaps the pattern onset and offset potentials in the cat represent only the activity of contrast sensitive processes involved in the analysis of adjacent light and dark areas (represented mainly by CI in the human PRVEP) since contour detecting processes (represented by C2 and C3 of the human PRVEP) seem to have no direct correlate in the cat PRVEP.

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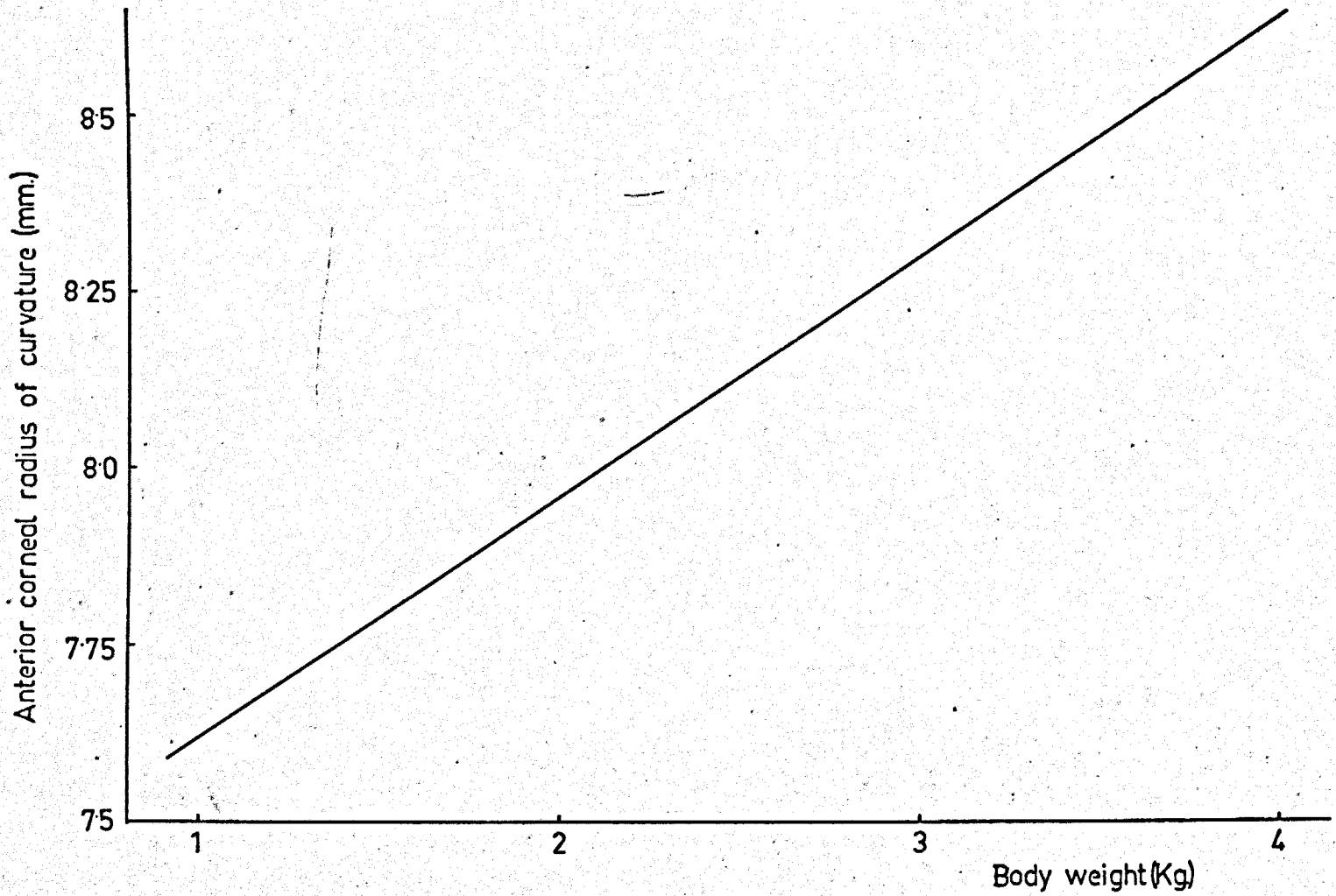
APPENDIX I

The calculated regression line on which selection of contact lenses was made. From the data of Vakkur, Bishop and Kozak (1963) and Vakkur and Bishop (1963) for fourteen cats in which body weight (x kg.) was compared with the anterior corneal radius of curvature (y mm.) of both eyes, the regression line $y = 7.28 + 0.34x$ (SD 0.38) can be calculated.


Anterior corneal radius of curvature (mm.)
8·5
8·25
8·0
7·75
7·5
1
2
3
4
Body weight (Kg)