J. Physiol. (1975), **245**, *pp.* 305–324
With 6 text-figures
Printed in Great Britain

VARIABILITY OF THE RELATIVE PREFERENCE FOR STIMULUS ORIENTATION AND DIRECTION OF MOVEMENT IN SOME UNITS OF THE CAT VISUAL CORTEX (AREAS 17 AND 18)

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(*Received 11 January 1974*)

SUMMARY

1. The responses to visual stimuli of single units in the cortex of cats anaesthetized with pentobarbitone were recorded extracellularly with glass micropipettes. All had receptive field centres more than 5° and most lay between 5 and 20° from the area centralis. Most units were in Area 18 but some were in the corresponding field representation in Area 17.

2. A quantitative method is described in which the visual stimuli (slits or light bars) were presented repetitively by mechanical means in each of four orientations of the stimulus and in two directions of movement for each orientation. The responses were analysed quantitatively and criteria are described for classification of units according to their preference for particular orientations or directions of movement of the stimulus.

3. Some units were studied continuously for up to 2 hr using the quantitative technique. In Area 18, of nineteen units, eighteen showed changes in their preference for direction of stimulus movement and, in seven of eleven units, the orientation preference changed. In Area 17 direction preference changed in eight of nine units and orientation preference in six of seven. In some cases both orientation and direction preference altered.

4. The relationship of these changes to alterations in the 'spontaneous activity' of the cortical units and to variations in the depth of anaesthesia are considered. Neither would appear to be the sole cause of the phenomenon.

INTRODUCTION

The ability to respond selectively to particular features of a visual stimulus is one of the characteristic properties of cells in the visual cortex. Hubel & Wiesel (1959, 1962, 1965), who first described these properties,

found that visual cortical units frequently show preferential responses to stimuli orientated at a particular angle in the visual field and that many are also differentially sensitive to the direction of stimulus movement.

Recently, we have had occasion to record from units in the cat visual cortex, particularly in Area 18, in a series of experiments which were originally directed to a study of the effects of lesions in Area 17 on units in Area 18 and which are described elsewhere (Donaldson & Nash, 1975). During this series of experiments we developed techniques for quantitative study of the responses of cortical cells to various stimuli and for their classification according to their preferences for orientation and direction. We then found, unexpectedly, that the orientation and direction preferences of many cells varies with time, whereas these properties have usually been believed to be fixed for any particular cell. The mechanisms of these changes are still unknown as is their significance for visual cortical function. In spite of this, we believe that the observations are sufficiently unexpected and interesting to be worth reporting at this stage, and they are described in this paper.

A preliminary report on some of the results has appeared (Donaldson & Nash, 1973).

METHODS

Preparation of animals

Twenty-five cats of either sex weighing between 1·8 and 3·5 kg were anaesthetized with intramuscular sodium pentobarbitone 30 mg/kg for induction and repeated I.V. doses of sodium pentobarbitone as required (usually about 3 mg/kg.hr).

A femoral artery and vein and the trachea were cannulated and the head was fixed in a stereotaxic head holder with ear bars and orbital bars which left the visual fields unobstructed.

Cortical pulsation was controlled either using a pressor-foot after cisternal drainage or with a closed chamber cemented to the skull (modified from that of Noda, Freeman, Gies & Creutzfeldt, 1971). The dura was excised under a dissecting microscope and the cortex was covered with paraffin oil at 37° C. Body temperature was maintained at approximately 38° C, and blood pressure was monitored continuously and normally remained within the range 100–160 mmHg (mean pressure). To reduce eye movements to the minimum paralysis was maintained either with repeated doses of gallamine (6 mg I.V. approximately each half hour) or by continuous infusion of gallamine at about 12 mg/hr. The animals were artificially ventilated and the expired CO_2 concentration was maintained between 4·0 and 4·5%. The intratracheal pressure was also measured throughout.

Preparation and alignment of the eyes

The pupils were dilated with atropine, the nictitating membranes were incised and retracted and corneal lenses were applied. The positions of the optic nerve heads were plotted on a tangent screen and checked from time to time during some experiments and always at the end of the experiment. We estimate the accuracy of plotting of the optic nerve projections to be about $\pm 1°$ and no apparent movement of their position greater than this was detected.

Electrodes and cortical recording sites

The electrodes were glass micropipettes with broken tips filled with 2 M-NaCl or 2 M-K citrate (occasionally with 3 M-KCl) whose DC resistance in the brain was 3–10 MΩ. They were driven through the 0·5 mm pore in the pressor-foot or chamber by a stepping drive and were advanced in steps of 2–10 μM into the cortex.

Most experiments were on Area 18 (Visual II) but fifteen units in Area 17 (Visual I) were also examined. The left hemisphere was always used. The electrodes were placed with reference to the lateral and post-lateral sulci and the interaural and mid-sagittal planes using the map of Bilge, Bingle, Seneviratne & Whitteridge (1967) and in such a way that all the receptive fields of the cortical units studied (in both Areas 17 and 18) lay below the horizontal meridian and to the right of the vertical meridian. All the field centres were *at least* 5°, and most lay between 5 and 20°, from the area centralis.

In a number of the earlier experiments the identification of the recording area as 17 or 18 was checked histologically. In these animals one or more glass electrodes were broken off and the ends left in the brain. The head was perfused with buffered formalin at the end of the experiment and the brain was later embedded in celloidin and sections 30 μM thick were cut in the plane of the electrode tracks and stained with cresyl violet and by Weil's method for fibres. The recording site was found from the glass left *in situ* and was identified as Area 17 or Area 18 using the criteria of Otsuka & Hassler (1962). In every case the histology confirmed the correct placement of the electrodes; so, in the later experiments, we felt confident in relying on the map of Bilge *et al.* (1967) to place the electrodes.

Visual fields

The receptive fields of the units were mapped on the tangent screen by listening to the responses to hand-moved targets of various sizes. In the later experiments when our interest was focused upon changes in the responses of units, the field position was mapped only to the extent necessary to ensure that the stimulus passed through the field centre and traversed the whole field.

Visual stimuli

The responses of units were studied quantitatively using an electromechanical device to present repeated stimuli of identical and controlled characteristics. A front-surfaced mirror mounted on the shaft of a rotary electromagnetic relay reflected the light beam from a slide projector on to the tangent screen and the beam of light leaving the mirror could be rotated about the axial ray by means of a Dove prism. A series of slides of transparent slits of various widths and lengths gave light bars of corresponding dimensions on the screen which could be rotated to any desired orientation (angle between the vertical and the long axis of the bar). A digital clock (Digitimer, Devices Ltd) controlled a linear ramp generator which delivered a symmetrical trapezoidal wave form to the stimulator so that the bar first moved across the screen in one direction ('forward'), stopped and remained stationary for a short time, usually 100 msec, and then retraced its path to its starting point at the same velocity ('reverse'). Movement was always normal to the long axis of the bar. The Digitimer also provided timing pulses to the data-collecting equipment.

The response of the units to repeated back and forth movement of the stimulus was examined over a number of sweeps in each of four orientations, viz: with the angle between vertical and the long axis of the bar (1) 0°, (2) 45°, (3) 90°, (4) 135° (clockwise, viewed from the cat's eyes).

Data collection

The glass electrodes provided excellent isolation of spikes of a single amplitude and only those with amplitudes above about 1 mV were studied. These were amplified and led to an oscilloscope and an audioamplifier and loudspeaker in the usual way. In addition they went in parallel to a pulse height analyser (PHA) which gave an output pulse of standard amplitude and duration (100 μsec). All subsequent analyses used these pulses which represented the time of occurrence of the unitary action potentials.

In the earlier experiments the PHA pulses and timing pulses were recorded on an analogue tape recorder and later analysed. Later, they were analysed 'on line' during the experiment using a PDP 12 computer (Digital Equipment Corporation).

A complete collection over 50 sweeps was made in each orientation in turn, for example, 50 sweeps at 0°; 50 sweeps at 45°, etc. Units were examined continuously for up to 2 hr; the number of examinations made of all the orientations varied from unit to unit.

Data analysis

1. *'On-line' during experiments*

Post-stimulus time histograms (PSTH) were constructed.

The 'forward' trigger pulse started each analysis sweep and spike occurrences were measured as integer counts of milliseconds from the trigger pulse. They were collected in bins 10 msec wide to form a PSTH with the trigger pulse as origin. The number of stimulus sweeps was preset, to 50, and the maximum total sweep time (forward plus reverse) was 4 sec. An oscilloscope display of a selected part of the histogram was available and proved invaluable in the control of the experiments. The histograms were plotted on an incremental plotter and were often also stored in digital form for further analysis. Interval histograms were also constructed, but will not be described in this paper.

2. *Analysis of 'analogue' magnetic tapes*

The analogue tapes from early experiments were analysed using an IBM 11/30 computer to construct PSTHS much as described above.

3. *Further analysis of PSTHS*

The choice of the methods and their aims will be described in Results and Discussion; the mechanics of the analyses are described here.

(*a*) *Estimation of the responses to visual stimulation.* The digital tapes were analysed off-line by a programme which listed beside the code name of each histogram file the value of the peak bin (P) in each direction (forward and reverse) and the 'response' value (R) for each direction which was derived as follows. The average bin contents for the histogram was found and subtracted from each bin in turn, and, if the result was positive, it was added to a running total. When all the bins had been examined the running total gave the sum of the amounts by which the average was exceeded. This value was called the 'response' and was calculated separately for the forward and reverse stimulus movements.

The values of 'peak' and 'response' were expressed as totals for 50 sweeps.

The (P) and (R) values to stimulation in the various orientations and directions were compared and used to classify the units as is described below (Results).

(*b*) *Polar diagrams of responses in various orientations and directions.* Each group of observations on a unit contained four sets of PSTHS each of which had parts representing forward and reverse stimulus motion. Thus such a group contained

eight peak (P) and eight (R) values. These values were calculated for each group, scaled and plotted as polar diagrams one for the 'P' and one for the 'R' value of each group. Fig. 3 is an example of a polar plot of 'R' values. The 'P' or 'R' value was plotted as the radial distance from the origin along the vector representing that direction of movement (the orientation of the stimulus bar was normal to this vector). These eight points were joined by straight lines to give a shape which represents the response properties of a given unit over a certain time. Comparison of successive polar diagrams for a unit makes it clear when changes have occurred.

(c) *Estimation of the variance of the response during the period of a PSTH.* The method by which the on-line programme collected data did not preserve the responses to the individual stimulus sweeps. However, the analogue tape records do contain this information and the variance of the responses making up a PSTH was estimated from these tapes.

RESULTS

1. *Definition of terms*

Information on the response of units to repeated movements of a visual stimulus to and fro across the receptive field was collected in the form of post-stimulus time histograms (PSTH). Since the stimulus moved across the field at constant velocity the PSTH also contains information on the spatial distribution of the response, which has not been analysed in any detail in the present experiments. Usually the PSTH showed two peaks which correspond to the movement of the stimulus forward and back respectively (for example, Fig. 2A). The criteria used to identify the PSTH bins to be included in the response to stimulation have already been described (Methods). The use of the contents of the peak bin to represent the response is self-explanatory, it is clearly an oversimplification whose disturbing effects became more severe as the response is spread over more bins, for example compare the narrow responses of Fig. 1B with the broad responses of Fig. 1A; the peak bin-size is clearly a much better index of the response in 1B than it is in 1A. Some criterion is required to define which bins of the histogram are to be included in the response to stimulation. The 'response' criterion (R) attempts to separate the stimulus-driven from the spontaneous or background activity which some units show by using the mean bin-content as an estimate of background activity. This value overestimates the background and thus reduces artificially the magnitude of the 'response', an effect which is most marked when the response is spread over many bins (in Fig. 1A, for example). However, in practice, these effects are small and will not influence any conclusions based upon comparison of R values for the same unit at various times. In order to classify units according to their direction- and orientation-selectivity quantitative criteria for the attribution of these properties to a unit had to be established. If possible, we wished to have a classification which would be comparable to that made by 'manual' methods. We found that, if we classified units as directional or orientated

using subjective criteria (listening to the response and so forth), during the experiment and then examined the P and R values given by the analysis, we were able to make an unequivocal decision that a unit had direction or orientation preference when the ratio of best to worst responses was 2:1 or more. The quantitative criteria are based on this observation and lead to the following definitions.

A *directional* unit is one whose P and R values for one direction of stimulus movement are each at least twice the corresponding value for the opposite direction of movement, in at least one orientation of the stimulus.

An *orientated* unit is one in which the sum of the P values for forward and reverse directions of movement ($P_f + P_r$) in the orientation in which ($P_f + P_r$) is maximum (the 'best') is at least twice that in the orientation whose value ($P_f + P_r$) is minimum (the 'worst') and the corresponding criterion ($R_f + R_r$) max $\geqslant 2$ ($R_f + R_r$) min is satisfied. In general only the units whose P and R values each satisfied the criteria have been classified as 'specific'. In practice they rarely disagreed. The present definition of orientation specificity attempts to minimize the effect of marked directionality on the decision about whether orientation specificity is also present by summing the response in both directions before calculating the ratio of best to worst responses.

2. *Experiment on the relationship of response size to spontaneous activity*

It soon became apparent from listening to the units between periods of visual stimulation that their spontaneous firing rate often fluctuated markedly while they were under observation. The fluctuations were sometimes periodic over a few minutes but often they took the form of unpredictable sudden or gradual changes of firing rate.

We arranged in one experiment for the stimulus to remain stationary outside the receptive field for 1·8 sec between the end of one complete stimulus cycle and the beginning of the next and to collect spikes during this period as well as during the time that the stimulus was in the receptive field. This gave samples of the response to stimulation and of spontaneous activity which were interleaved and which were collected over almost exactly the same period of time. Repeated observations were made over a period for each of several units as the spontaneous activity changed without any intervention by the experimenters. Also, on occasion, additional small doses of barbiturate anaesthetic were given which depressed spontaneous activity. The relationships between changes in response and spontaneous activity were then studied. It was found that changes in response size (to a constant stimulus) and in spontaneous activity showed no constant interrelationship. Thus, examples were found of parallel increases and decreases in the two parameters and others were seen where

one changed apparently independently of the other. Fig. 1 illustrates the behaviour of one unit in Area 18. In Fig. 1*A* the response has a peak height of about 20 spikes/bin and the spontaneous activity varies from 0 to 8 spikes/bin (mean about 3·5). A small dose of anaesthetic was then given and the subsequent behaviour of the unit is seen in Fig. 1*B*, recorded 12 min after *A*. The response has changed in character and the spontaneous activity has almost been abolished (range 0–5 spikes/bin, mean about 0·3). For this unit the response increased absolutely as well as relatively while the spontaneous activity declined. Thus it seems that the response magnitude is not simply a function of the spontaneous activity, and this conclusion was borne out by other units which were studied.

However, it is also clear from Fig. 1 that the response itself has changed, not only in magnitude and in its width but in its specificity. Thus, in *A*, the responses are rather poorly defined and the unit is non-directional whereas in *B* not only are they much more distinct but the second response is clearly much larger than the first (ratio 5·1:1) and the unit now shows a marked direction preference. Other units studied over a time in this experiment also showed this kind of change in the response. Because of this unexpected and interesting observation we carried out a series of experiments to find out if changes in specific properties over a time occurred at all commonly.

3. *Changes in the orientation and directional preference of units studied over a period*

In a number of cats histograms were recorded repeatedly in the four orientations in turn for periods of up to 2 hr on each unit. We were able to record seven or eight sets each of four histograms per hour, using the mechanical stimulator. On some occasions the effect of small doses of a rapidly acting barbiturate (hexobarbitone 2–4 mg/kg) was tested on the properties of units which had already been studied for a considerable time. For the rest, every attempt was made to maintain the experimental conditions and the state of the animal as constant as possible.

We shall use the term 'variability' to describe the behaviour of a unit which changes its preferred direction of stimulus movement and, or, preference from among the four stimulus orientations from time to time. The numbers of units studied over long periods were quite small (thirty in Area 18 and 9 in Area 17) but variability proved to be very common in these samples.

Variability in Area 18. An example is illustrated in Fig. 2 in which the responses to horizontal movement of a vertical bar are shown. The PSTH, *A* was recorded 15 min after the unit was isolated, and it shows non-directional responses. At 47 min, and 2 min after an additional dose of

anaesthetic, *B* was recorded and shows considerably diminished activity. In *C*, 11 min after *B*, the unit is seen to have recovered its response only in the forward direction and thus to have become directional for movement to the right. The polar plots of Fig. 3 show the response pattern of a unit in Area 18 at 4, 14 and 25 min after its isolation. It is clear that in *A* the unit has a preferred orientation for a bar at 135° which moves

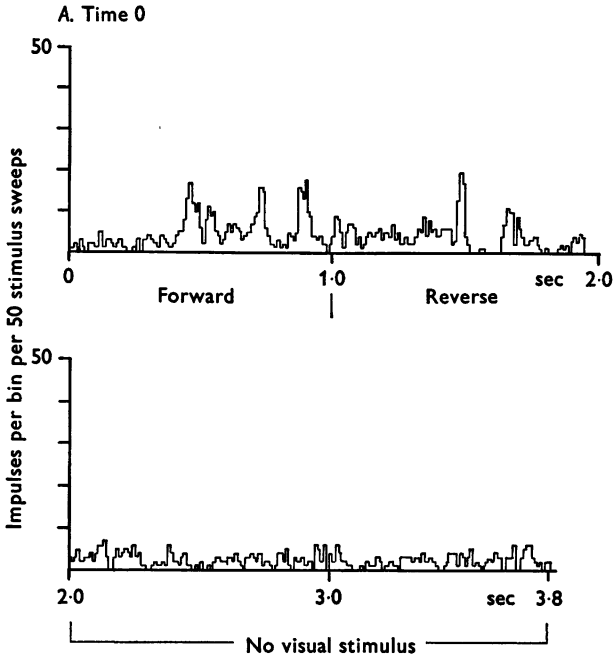


Fig. 1. The relationship of response to 'spontaneous' activity of a unit in Area 18. In *A* and *B* the upper PSTH shows the responses to a vertical bar moving horizontally across the field. The left half of each (0–1·0 sec) is the response to the bar moving from left to right (forward); the right half (1·0–2·0 sec) is the response to the bar moving from right to left (reverse). The lower histogram in each case is of the activity recorded for 1·8 sec after the end of each stimulus sweep-cycle while the stimulus was stationary outside the receptive field of the unit. Its contents are a sample of the 'spontaneous' activity of the unit.

A, unit shows marked spontaneous activity (mean about 3·5 spikes/bin. 50 sweeps) and has a broad ill-defined response and no directional preference.

B, the same unit 12 min later after a small additional dose of barbiturate. The spontaneous activity has decreased markedly (to a mean of about 0·3 spikes/bin. 50 sweeps). The response has changed markedly. It is now narrow and well defined with preference for the reverse direction.

The bin width is 10 msec in all the histograms.

along the up-right/down-left axis while in *C*, 21 min later, its preference is for 45° (up-left/down-right), that is for an orientation at right angles to its original preference. This change has involved not only increased firing in the up-left axis but also an absolute decrease in firing in the up-right axis which was originally preferred. Observation at 14 min (*B*) showed a state intermediate between these extremes. In contrast, Fig. 4 illustrates

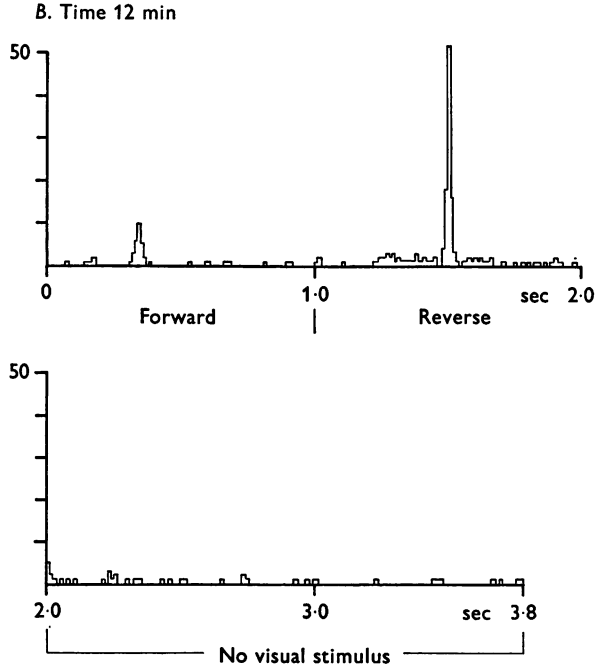


Fig. 1. For legend see facing page.

a sharply orientated unit whose specific preference did not change over 16 min although its overall firing increased slightly over the period (note the change in scale in Fig. 4*C*). The shape of the plot altered a little but not enough to alter the unit's classification by our criteria. In Area 18 (Visual II) eighteen of nineteen units showed variability in their preference for direction and seven of eleven for orientation.

A few units from the corresponding part of Area 17 were examined for variability and it was found that eight of nine showed alterations in direction preference and six of seven in orientation preference. An Area 17 unit which changed both orientation and direction preference is illustrated in Fig. 5. This unit changed from being orientated and directional (*A*) through an intermediate stage (*B*) to become non-orientated and non-directional (*C*) then to a new, though far from sharp, orientation

preference but without direction preference (*D*). It is notable that the bottom right quadrant which at first showed almost no response showed the largest response in the later observations. The overall firing rate in this unit was greatest when it was neither orientated nor directional (*C*).

All the responses described so far were recorded with both eyes open. In one cat, seven units in Area 18 were studied monocularly and of these five were held for long enough to study variability of the monocular

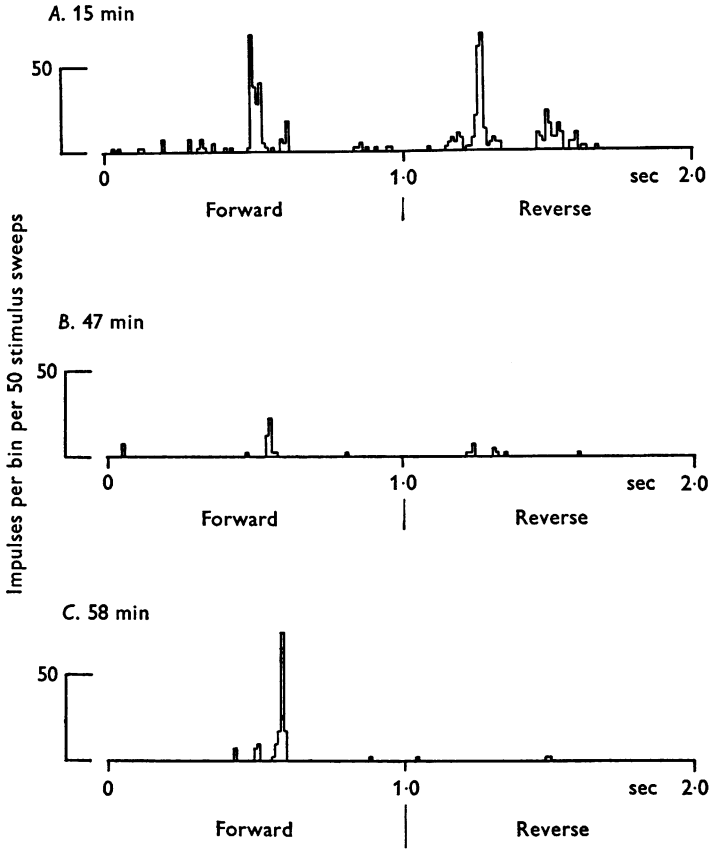


Fig. 2. Unit whose direction selectivity altered. The stimulus was in each case a vertical bar moving horizontally, from left to right during the 'forward' sections and right to left during the 'reverse' sections.

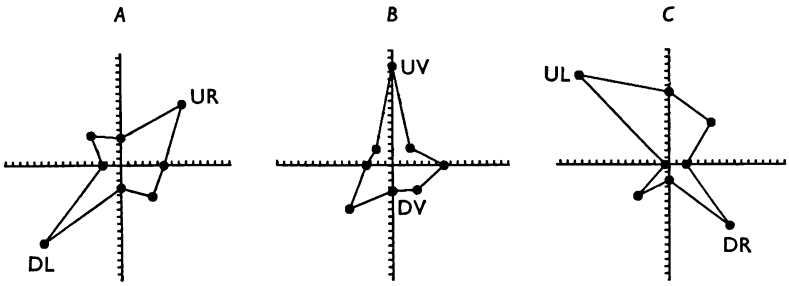
A, PSTH recorded 15 min after isolation of the unit – no direction selectivity.

B, Time 47 min and 2 min after a dose of anaesthetic – overall excitability much reduced.

C, Time 58 min – development of marked preference for forward movement with virtual absence of a response to the reverse direction.

Further explanation in legend to Fig. 1.

response from each eye in turn. The principal aim of the experiment was to determine if variability occurs in the response of a unit when it is driven monocularly, in case small movements of the eyes relative to each other (which might have occurred in spite of paralysis) might explain the variability of the binocular responses. Of the five units studied adequately 4 showed changes in orientation *and* direction preference of a monocular



Scale: 1 div. = 20 impulses per 50 sweeps

Fig. 3. Polar plots of a unit in Area 18 which showed progressive change in its orientation preference ('response' values are plotted).

A, 4 min after isolation.

B, 14 min after isolation.

C, 25 min after isolation.

The radial distance from the origin to each filled circle represents the magnitude of the response to a stimulus moving in the direction of the vector joining the origin to the circle. The long axis of the stimulus was always normal to this vector. The following examples illustrate the convention which is used in all the figures of polar plots.

In *A*, UR is the response to a bar whose long axis is at 135° to the vertical moving up and to the right. DL is the response to the same bar moving in the opposite direction, down and left. Similarly in *B*, a horizontal bar moving vertically gave UV when it moved across the field from bottom to top and DV when its direction was reversed. In *C*, UL and DR are the responses to a bar whose long axis was at 45° to the vertical, moving up-left and down-right. Only the horizontal and vertical axes are drawn in. The eight filled circles are joined up to give a shape which represents the response properties of the unit over a certain time.

response. As an example Fig. 6 shows responses from the left eye only and the right eye only at various times. These are remarkable in two respects. First, the right eye responses at 46 and 65 min show different orientation preferences. Secondly, the left eye responses at 34 and 75 min are similar and show no change in preference, but they are different from either right eye response. There seems no doubt that the response from the right eye has altered in orientation preference but how great the absolute difference in the preferred orientation between the eyes may be is uncertain

since there are no monocular records which are even approximately simultaneous for the two eyes nor is it certain whether the eyes may have adopted different attitudes after paralysis so that their vertical meridians may have occupied different angular positions with respect to the true vertical.

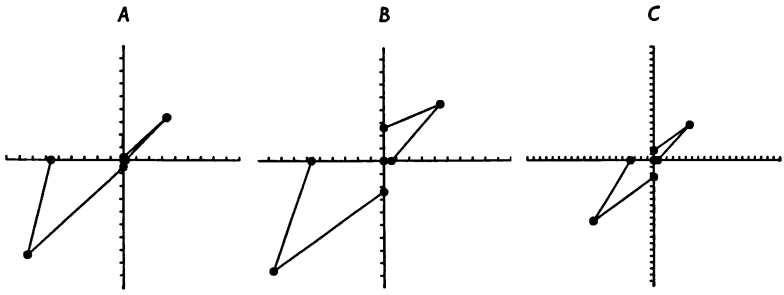


Fig. 4. Polar plots of a unit in Area 18 whose orientation preference remained stable although the magnitude of its response increased between *B* and *C* (note the change of scale). Response values plotted.
A, 4 min after isolation.
B, 12 min after isolation.
C, 20 min after isolation.
See legend to Fig. 3 for further explanation.

We have also studied for variability a few units in Area 18 of cats with an Area 17 lesion. These experiments are described elsewhere (Donaldson & Nash, 1975); variability was not abolished by the Area 17 lesion.

Table 1 summarizes the incidence of variability found to date.

4. *The variance of the 'response'*

Although the PSTHS contain no information on variance, it was possible to calculate the mean 'response' in each orientation and its variance from the analogue tape records which were available for nineteen histograms on nine units. The standard deviation of the fifty samples which make up a histogram was often large. Indeed, it is common experience that the responses of visual cortical cells are variable from trial to trial. However, the standard errors of the mean 'responses' (S.E. of mean) were usually less than one tenth of the mean for 50 sweeps, so the mean values are usually subject to only rather small variations. The values which are shown in the polar plots are the total numbers of impulses per 'response' which can be regarded as the means scaled conveniently for plotting (they are, of course, the means multiplied by 50). Thus, comparisons of serial

polar plots from the same unit are effectively comparisons of the various mean responses at different times. The changes in preference for orientation or direction are so large that it does not seem necessary to carry out calculations on their statistical significance. When the lists of individual responses were examined in those PSTHS whose S.E. of mean exceeded one tenth of the mean no sudden change of firing pattern was detected

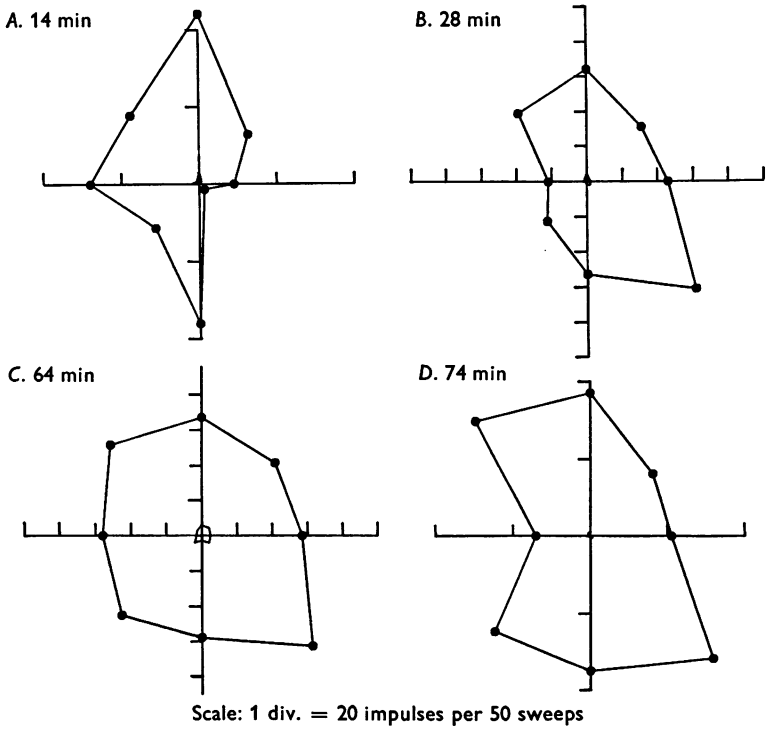


Fig. 5. Four sets of observations on the same unit in Area 17 at various times after its isolation. 'Peak' values. The small inner octagons (best seen in *C*) show the mean firing (for the 100 bins) in each orientation and direction.

A, 14 min after isolation.

B, 28 min after isolation and 5 min after a dose of anaesthetic.

C, 64 min after isolation.

D, 74 min after isolation and 4 min after a dose of anaesthetic.

which might have been attributable to the development of new specificity. Thus, the analysis has thrown no light on the time course over which changes in preference may occur. However, the lists do confirm the occurrence in some units of cyclic changes in excitability over periods of seconds or minutes of the kind which were often clearly audible during the experiments.

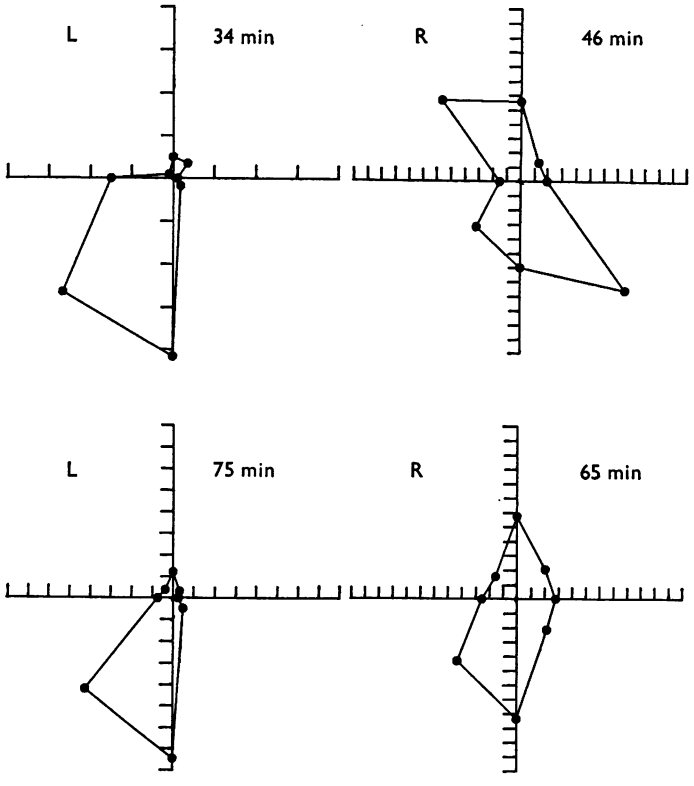


Fig. 6. Monocular responses. Polar plots of the responses of a unit in Area 18 to monocular stimulation via the left eye alone and the right eye alone at various times after its isolation.

Note the constancy of the left eye responses and the change in orientation preference between the right eye responses at 46 and 65 min.

DISCUSSION

The most interesting finding in this series of experiments is that, at least under certain conditions and measured by the criteria we have chosen, the specific properties of some visual cortical cells are variable, that is to say that their relative preferences for particular directions of movement and particular orientations of stimulus change from time to time. Since these properties have usually been regarded as fixed, at least in adult animals, it is important to examine first the possibility that the present results were caused by some experimental artifact and then to consider how the techniques used in the present work differ from those of other workers.

TABLE 1. Summary of units tested for variability in direction or orientation

Source	Direction preference			Orientation preference		
	Total no.	Variable	Non-variable	Total no.	Variable	Non-variable
Area 18 / Area 17 Binocular stimulation	19	18	1	11	7	4
	9	8	1	7	6	1
Area 18 Monocular stimulation	5	4	1	5	4	1
Area 18 Chronic lesion in area 17	6	5	1	6	4	2
Total	39	35	4	29	21	8

Note: some units are included in both orientation and directional groups.

The variability of direction and orientation preference

Is 'variability' an experimental artifact? Others have reported that the properties of some visual cortical cells may alter. Thus Horn & Hill (1969), Horn, Stechler & Hill (1972) and Denny & Adorjani (1972) have all reported changes in preferred orientation of visual cortical units some of which seemed to be related to tilting the head, and Bear, Sasaki & Ervin (1971) found that the shape of iso-response maps to flashing spots varied with time and with the state of light adaptation (Sasaki, Saito, Bear & Ervin, 1971). However, the changes associated with head tilt are much less common and much smaller than those reported here and the observations of Bear *et al.* are not really comparable. Changes in orientation-preference have been induced by conditioning of units in the cortex of visually inexperienced kittens (Pettigrew, Olson & Barlow, 1973) but plasticity of this kind has not been reported in the adult cat. However, changes in direction-preference apparently induced by alterations in stimulus contrast have been reported in adult animals (see Bush, Kuhnt & Michael, 1973). The observations which seem to resemble ours most closely are those of Poggio (1972) on Area 17 of the unanaesthetized monkey cortex where he found a few units which lost 'clear and specific sensitivity to stimulus orientation' over a period of minutes and then responded 'in a qualitatively indistinguishable manner to the same stimulus moving in any direction'. However, quantitative analysis was not used.

One might wonder whether the present variability might be only apparent and might in reality reflect eye movements. Bishop, Kozak & Vakkur (1962) found that under pentobarbitone and gallamine eye movements were reduced to below 1°, and Sanderson (1972) found that torsion move-

ments under similar conditions were either absent or less than 6° at most. The observations made during the present experiments did not reveal eye movements but these would probably have gone undetected if they were smaller than 1° and one cannot exclude entirely the unlikely possibility that the eye might move and then return to exactly the same position between observations. Also, Nikara, Bishop & Pettigrew (1968) found that very small relative movements of the eyes could change binocular facilitation into occlusion, in units near the area centralis in Area 17. Is it possible, then, that such relative movements could give rise to changes of the kind reported here? The experiment in which monocular responses were studied was carried out to test this possibility and it demonstrated that variability occurred in some units when there was no question of binocular interaction. More recent experiments (unpublished) have confirmed this result. Could this 'monocular variability' have been due to rolling of the eye about some axis? In the unit illustrated in Fig. 6 such an explanation would require the eye to have rolled through about 45° around its optic axis (since the field did not show any translation). All the evidence is that movements of such a magnitude do not occur in the paralysed cat. Similarly, to explain the changes seen in some of the binocularly stimulated units on the basis of eye movement, rotations of similar or even greater amplitude (again without any translation) would be required. Even the relative eye movements of 21° recently reported by Hubel & Wiesel (1973) in the paralysed cat would be insufficient to explain the changes described here.

Next, there is the possibility that some artifact of the recording technique might be responsible. Since the units were usually held for at least 1 hr, gross damage to the cell caused by electrode movement relative to it seems unlikely. In any event it is usually obvious that a unit is being disturbed by electrode pressure and such units were not studied further. In the early experiments using KCl-filled electrodes potassium leakage might have occurred. In all the later experiments, however, NaCl-filled electrodes were used and variability still occurred so depression due to potassium leakage does not seem to be a factor.

It is quite possible that the pressure-foot used in some experiments may have disturbed cortical circulation, but similar results were obtained in experiments using the chamber in which very little, if any, pressure was exerted. We cannot exclude the possibility that the cortical cells were disturbed by the insults of the experiment, in particular by the mechanical effects of the micro-electrode; but if these were the cause of the variability they must have acted in an extraordinarily selective fashion to increase the response in one orientation while diminishing it in another, sometimes while the general excitability of the cell increased and sometimes while it

decreased, and even, on one occasion (Fig. 6) to cause changes in the response from one eye while that from the other was apparently unaffected.

It did appear that changes were sometimes associated with deliberate alteration of the anaesthetic level. They also occurred independently of such deliberate changes but it is quite probable that the animals were on a gradually lightening level of anaesthesia between doses. Thus it is quite possible that anaesthetic effects have influenced the results but, equally, it would appear very difficult to explain the variability solely upon the basis of variations in anaesthetic level. Our experiments all used pentobarbitone anaesthesia and, at present, we do not know whether variability occurs under other anaesthetics. However, it may be that very light anaesthesia is necessary, especially in view of Poggio's (1972) observations on unanaesthetized monkeys.

If the variability is not artifactual, why has it not been observed before? Firstly, it is not yet known what proportion of units in the area centralis representation are variable although variability does appear to be present (unpublished observations). If the proportion of variable units is small, it is perhaps not surprising that all visual cortical cells have been thought to have fixed properties since the central units are those which have been studied intensively.

Secondly, most workers have used tungsten electrodes. In another series of experiments in which non-quantitative stimulation was used (Nash, 1973; I. M. L. Donaldson & J. R. G. Nash, unpublished results) we compared the populations of units in experiments using tungsten electrodes with those recorded when glass electrodes were used and found that the 'tungsten' population contained a much higher proportion of units with definite direction or orientation preferences (86%) than did the 'glass' population (34%). If tungsten electrodes *do* record from a different population of units than do glass electrodes, as our results might suggest, it may be that this population consists largely of non-variable units while the 'glass' population contains both fixed and variable units.

Thirdly, it is quite possible that variability might not be detected unless quantitative methods were used. Indeed, it seems likely that many of the units which we could not classify manually could not be classified because their properties changed from time to time, but it was only by using quantitative methods that we were able to demonstrate these changes. However, were one to persist for long periods with attempts to find the 'best' stimulus manually it is quite likely that, if the unit were variable, a state would eventually occur in which the unit behaved consistently over a few minutes. It would then be classified and very probably abandoned as having yielded at last to the experimenter's efforts to find the correct stimulus, and its earlier variability would pass undetected.

The origin of variability. At present, it is not at all clear what triggers the changes in preferred orientation or direction. Such evidence as there is from the lists of responses sweep-by-sweep might suggest that the change occurs rather rapidly, though one cannot be certain.

In the present experiments, 50 stimulus sweeps were presented in each orientation in turn. Factors which might contribute to the production of variability under these conditions are, firstly, a possible change in the rate of habituation of the response to repetitive identical stimuli and, secondly, the fluctuations of overall excitability which undoubtedly occur and might lead to apparent changes in orientation preference. While the present paper was in preparation Henry, Bishop, Tupper & Dreher (1973) reported quantitative studies of some nine cells near the area centralis representation. They found only minor alterations in the optimal orientation with time and concluded that these were manifestations of changes in general excitability of the units. The variability which appeared in the present experiments does not seem to be explicable simply as a manifestation of changes in general excitability although it sometimes accompanied such changes.

The results of a preliminary experiment using a different stimulation technique are relevant both to the relation of variability to changes in excitability and to the effects of habituation. In this experiment one stimulus-sweep was presented in each orientation in turn and then the sequence was repeated in the same order so that the four post-stimulus histograms were collected almost simultaneously, and thus during similar levels of general excitability, but with an interval of several seconds between stimuli in any one orientation. Variability of orientation-preference to monocular stimulation was found under these conditions. Although more detailed examination of the effects of habituation and general excitability is clearly required, these preliminary results do support the view that variability is not just a manifestation of changes in overall excitability and suggest that an uninterrupted sequence of repetitive identical stimuli is not essential to its appearance.

As to the site at which the variability occurs there is no firm evidence; one possibility is that variability may depend on changes in intracortical inhibitory mechanisms, such as those which have recently been proposed by Sillito (1974) to account for some aspects of the specificity of cortical cells.

Thus, the extent to which the appearance of variability depends upon the particular population of units which is examined and on the precise details of the experimental technique remains to be resolved.

We thank Mrs J. P. Donaldson for preparing the histological material, Dr P. G. H. Clarke for lending us his visual stimulator, Mr Bruce Nail for the use of his computer

programme for the IBM 11/30 and Mr I. R. Lloyd for skilled technical assistance. Our thanks are also due to the staff of the mechanical and electronic workshops of the Laboratory who constructed much of the apparatus.

We are grateful to the Medical Research Council for support and for providing the PDP 12 computer.

REFERENCES

BEAR, D. M., SASAKI, H. & ERVIN, F. R. (1971). Sequential change in receptive fields of striate neurons in dark adapted cats. *Expl Brain Res.* **13**, 256–272.

BILGE, M., BINGLE, A., SENEVIRATNE, K. N. & WHITTERIDGE, D. (1967). A map of the visual cortex in the cat. *J. Physiol.* **191**, 116–118*P*.

BISHOP, P. O., KOZAK, W. & VAKKUR, G. J. (1962). Some quantitative aspects of the cat's eye: axis and plane of reference, visual field coordinates and optics. *J. Physiol.* **163**, 466–502.

BUSH, F., KUHNT, V. & MICHAEL, D. (1973). Reaction of cortical neurones of the cat to moving stimuli of different intensities (EBBS abstract). *Brain Res.* **49**, 502–503.

DENNY, D. & ADORJANI, C. (1972). Orientation specificity of visual neurones after head tilt. *Expl Brain Res.* **14**, 312–317.

DONALDSON, I. M. L. & NASH, J. R. G. (1973). Variability of properties of units in cat visual cortex. *J. Physiol.* **230**, 40–41*P*.

DONALDSON, I. M. L. & NASH, J. R. G. (1975). The effect of a chronic lesion in cortical area 17 on the visual responses of units in area 18 in the cat. *J. Physiol.* **245**, 325–332.

HENRY, G. H., BISHOP, P. O., TUPPER, R. M. & DREHER, B. (1973). Orientation specificity and response variability of cells in the striate cortex. *Vision Res.* **13**, 1771–1779.

HORN, G. & HILL, R. M. (1969). Modifications of receptive fields of cells in the visual cortex occurring spontaneously and associated with bodily tilt. *Nature, Lond.* **221**, 186–188.

HORN, G., STECHLER, G. & HILL, R. M. (1972). Receptive fields of units in the visual cortex of the cat in the presence and absence of bodily tilt. *Expl Brain Res.* **15**, 113–132.

HUBEL, D. H. & WIESEL, T. N. (1959). Single unit activity in striate cortex of unrestrained cats. *J. Physiol.* **147**, 226–238.

HUBEL, D. H. & WIESEL, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cats' visual cortex. *J. Physiol.* **160**, 106–154.

HUBEL, D. H. & WIESEL, T. N. (1965). Receptive fields and functional architecture in two non-striate visual areas (18 and 19) of the cat. *J. Neurophysiol.* **28**, 229–289.

HUBEL, D. H. & WIESEL, T. N. (1973). A re-examination of stereoscopic mechanisms in Area 17 of the cat. *J. Physiol.* **232**, 29–30*P*.

NASH, J. R. G. (1973). The interaction between visual receptive areas. D. Phil. Thesis, Oxford.

NIKARA, T., BISHOP, P. O. & PETTIGREW, J. D. (1968). Analysis of retinal correspondence by studying receptive fields of single units in cat striate cortex. *Expl Brain Res.* **6**, 353–372.

NODA, H., FREEMAN, R. B., GIES, B. & CREUTZFELDT, O. D. (1971). Neuronal responses in the visual cortex of awake cats to stationary and moving targets. *Expl Brain Res.* **12**, 389–405.

OTSUKA, R. & HASSLER, R. (1962). Über Aufbau und Gliederung der corticalen Sehsphäre bei der Katze. *Arch. Psychiat. NervKrankh.* **203**, 212–234.

PETTIGREW, J., OLSON, C. & BARLOW, H. B. (1973). Kitten visual cortex: short-term stimulus-induced changes in connectivity. *Science* **180**, 1202–1203.

POGGIO, G. F. (1972). Spatial properties of neurons in striate cortex of unanaesthetized macaque monkey. *Invest. Ophthal.* **11**, 368–377.

SANDERSON, K. J. (1972). Does rolling of the eye occur in the anaesthetized paralysed cat? *Vision Res.* **12**, 1045–1050.

SASAKI, H., SAITO, Y., BEAR, D. M. & ERVIN, F. R. (1971). Quantitative variation in striate receptive fields of cats as a function of light and dark adaptation. *Expl Brain Res.* **13**, 273–293.

SILLITO, A. M. (1974). Effects of the iontophoretic application of bicuculline on the receptive field properties of simple cells in the visual cortex of the cat. *J. Physiol.* **242**, 127–128*P*.