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INNATE AND ENVIRONMENTAL FACTORS IN THE DEVELOPMENT OF THE KITTEN'S VISUAL CORTEX

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SUMMARY

1. This is a study of the receptive fields of 771 cells recorded in the visual cortex of twenty-five kittens reared normally or subjected to various kinds of visual deprivation or environmental manipulation.

2. Kittens deprived of patterned visual experience, by dark rearing or diffuse occlusion of the eyes, have a majority of cortical neurones with little or no specificity for the orientation or axis of movement of visual stimuli. However, in such deprived animals, especially those younger than 3 weeks, there are a number of genuinely orientation selective cells. They are broadly 'tuned' (by adult standards), they are almost always of the simple type, are heavily dominated by one eye, and are found mainly in the deeper layers of the cortex, especially layer IV.

3. These innately specified orientation selective cells, together with other neurones that have only a crude preference for one orientation or axis of movement, tend to be grouped into a primitive orientation 'columnar' system.

4. There is no passive improvement in the specificity of cortical cells, indeed there may be progressive degradation, following prolonged pattern deprivation.

5. Normal visual experience, on the other hand, produces a very rapid increase in the general responsiveness of cells, in the proportion of orientation selective cells and in the distinctness of columnar organization. At around 4 weeks of age the experienced cortex is not markedly different from that of the normal adult.

6. Kittens were reared in a variety of restricted environments in an attempt to discover the relevant features of the normal visual world that

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are responsible for promoting this rapid development. An environment of randomly scattered spots leads to a specific selectivity for spots of the same size. If the spots are very small there is no improvement in the proportion of orientation selective cells, but with larger spots the number does increase. Intermittent exposure to an environment containing single, low-contrast vertical and horizontal contours also leads to a slight increase in the number of orientation selective cells and they are mainly sensitive to vertical or horizontal.

7. Exposure to high-contrast stripes, even for a very brief period, or to a pattern of large rectangles, produces a visual cortex in which almost all neurones are orientation selective and where the preferred orientations match those seen early in life. Visual experience of elongated contours seems to be the necessary condition for the normal development of the visual cortex.

8. Plasticity may be needed for the formation of cells with closely-matched receptive field properties in the two eyes, an essential feature for their suggested role in stereoscopic vision.

9. We tentatively propose a neuronal model for the development of the visual cortex. The model seeks to explain the adult columnar organization, in which neighbouring simple and complex cells have similar preferred orientations, despite the fact that the two cell types probably receive independent, parallel afferent input principally from slow-conducting and fast-conducting axons respectively. Genetically specified, predominantly monocular, simple neurones initially provide a 'conditioning' input to future complex cells and entrain them to respond to the same orientation. Both cell types ultimately gain matched input from the two eyes.

INTRODUCTION

The connexions between eye and brain provide central visual neurones in the cat with a variety of highly specific properties: they determine the size, shape and position of the receptive field on the retina, and they restrict the sensitivity of each cell to a limited range of stimulus attributes. The ability of visual neurones to detect behaviourally important 'trigger features' (Barlow, Hill & Levick, 1964) seems to rest on systematic elimination of spatio-temporal redundancy in messages from the receptors. This process reaches a remarkable level in the visual cortex, where Hubel & Wiesel (1962, 1965*a*) have described a high degree of stimulus specificity. Unlike the cells of the lateral geniculate nucleus, which relay visual signals to the cortex, cortical neurones are almost always orientation selective, responding to moving edges only if they fall within a narrow range of angles. Most neurones are binocularly-driven and their receptive field

properties are very similar in the two eyes. The fact that these binocular cells are often very selective for the retinal disparity of the two images during simultaneous binocular stimulation, and that there is variation in optimal disparity from cell to cell, has prompted the suggestion that they are involved in the analysis of the three-dimensional positions of objects in space (Barlow, Blakemore & Pettigrew, 1967; Pettigrew, Nikara & Bishop, 1968; Nikara, Bishop & Pettigrew, 1968). As well as possessing selectivity for the orientation and often the disparity of visual images, cortical neurones can exhibit specific sensitivity to both the direction and the velocity of movement, to the polarity of an edge, to the angular width of a bar, to its length and so on.

Nearly all of these properties of adult cortical cells seem to be modifiable early in life. Interference with the simultaneous, correlated use of the two eyes results in a reduction in binocularity in the cortex (Hubel & Wiesel, 1965*b*, 1970), and a small misalignment of the visual axes can lead to a corresponding shift in the average retinal disparity of the receptive fields (Shlaer, 1971). If a kitten is exposed exclusively to lines of one orientation its cortical cells generally develop a preference for just that orientation, (Hirsch & Spinelli, 1970; Blakemore & Cooper, 1970). Rearing in a stroboscopically illuminated environment, which precludes smooth retinal image movement, causes a deficit in the proportion of highly specific neurones (Cynader, Berman & Hein, 1973; Olson & Pettigrew, 1974). Visual experience of contours moving in one direction leads to a predominance of cortical cells preferring that direction (Tretter, Cynader & Singer, 1975). An early environment composed entirely of small spots produces many cortical neurones with a preference for spots or short lines rather than extended edges (Pettigrew & Freeman, 1973; Van Sluyters & Blakemore, 1973). Many of these changes in receptive field properties can only be caused by disturbances of visual experience early in life (see Blakemore, 1974).

All this neuronal plasticity in the first few weeks after a kitten opens its eyes surely makes one suspect that visual experience normally plays a crucial role in establishing the connexions of cortical cells. However, afferent terminations are present in the primary visual cortex at birth (Anker & Cragg, 1974), and there is especially rapid formation of intrinsic synapses in the cortex *before* three weeks – the age when the developmental 'sensitive period' begins. So, genetic instructions are adequate to guide afferent axons to the cortex and perhaps to promote a good deal of synapse formation. It is possible that they also pre-specify the characteristics of cortical receptive fields. Unfortunately there is disagreement about the degree of stimulus specificity that can be found in the cortex of a kitten that has never experienced a patterned visual environment. Hubel

& Wiesel (1963) recorded from a few neurones in very young kittens and concluded that 'much of the richness of visual physiology in the cortex of the adult cat – the receptive field organization, binocular interaction, and functional architecture – is present in very young kittens without visual experience'. Even long periods of binocular deprivation were said to leave about half of all cortical cells with clear binocularity and orientation selectivity (Wiesel & Hubel, 1965). On the other hand, Barlow & Pettigrew (1971) also recorded from young visually deprived kittens and claimed that 'diffuse binocular connexions and the mechanism for directional movement selectivity appear to be innately determined, but the mechanisms for disparity and orientational selectivity require visual experience'. Pettigrew (1974) has further supported this conclusion with a good deal of quantitative evidence, and Imbert & Buisseret (1975) have reported similar results.

We began the present study with the intention of defining the kinds of visual stimulation that could modify kitten cortical neurones. We were led to re-examine the effects of various types of total pattern deprivation and the results of all these experiments persuaded us to examine for ourselves the cortex of very young kittens. The outcome is thus a study of passive maturation of the cortex as well as an examination of the exact characteristics of the early visual environment that are necessary for the emergence of normal orientation selectivity.

METHODS

The animals and their experience

All our kittens were bred in an isolated laboratory colony, in a room where temperature and humidity were strictly controlled. An artificial day–night cycle of 18 hr light–6 hr darkness persuaded the resident adult cats to breed throughout the year. Queens in late pregnancy or with unweaned kittens were housed in large cages, but all the other cats and weaned kittens were kept loose in the room.

The experimental kittens were treated in a variety of ways, the details of which are described in the Results section, but the following remarks explain certain methodological procedures.

The darkroom. Many animals were housed for all or part of the time in cages in a totally darkened room with a double-door arrangement. A photographic plate left in the room for a day failed to fog, testifying to its light-tightness, and anyone entering the room took great care to ensure that no light was admitted. A room light was switched on for feeding and cleaning of cages, but beforehand every kitten was transferred in total darkness to a light-proof box in the darkroom, where they remained until the room lights were extinguished.

The only non-experimental visual experience that kittens living in the darkroom may have received was during their occasional removal from the room for weighing and examination to assess their state of health. This was always done with a thick black felt hood over the kitten's head but rarely the hood was very briefly removed to examine the kitten's eyes and nose. The only totally dark-reared animals (K139 and K165) in this series were never given even this chance of visual exposure.

Specific visual environments. Some kittens were taken from the darkroom for a certain period each day for exposure to controlled visual environments, using methods similar to those of Blakemore & Cooper (1970). The kitten, wearing a black felt hood, was fitted with a black ruff that restricted its visual field to about 130°. It was then placed on a transparent glass platform mounted in the middle of a plastic cylinder and the hood removed. The inside walls of this cylinder (diameter 46 cm, height 1 m) were plain white or were covered with a pattern of stripes or spots. The cylinder stood on a diffusing sheet of opal Perspex and was covered with a lid of the same material. It was illuminated from below and above. At kitten's eye level the bright parts of the patterned walls had a luminance of about 44 cd m^{-2} and the dark parts about 7 cd m^{-2}. The ruff prevented the kitten from looking at its own body and, incidentally, stopped it from lying down or rolling over. Nevertheless, observation through a peephole showed that kittens often went to sleep in the cylindrical chamber but that when they were awake they were frequently very active. All the lights were turned off before the kitten was removed and its head covered for the return to the darkroom.

Binocular lid suture. Some kittens were deprived of patterned visual experience, but not of all retinal illumination, by suturing together the eyelids, under Fluothane (Halothane) anaesthesia, according to the method of Wiesel & Hubel (1963). In the later experiments, before suturing the margins of the lids, we separated the conjunctiva from the edges of the trimmed lids, dissected a flap of conjunctiva from the upper and lower lids and sutured the edges of the two flaps over the cornea, using fine (1 metric) chromic collagen thread. This ensured that the eye was securely covered with an intact sheet of conjunctival tissue, so that even if a tiny 'window' developed between the lid sutures, no patterned light could reach the retina. On the rare occasions when windows did appear, we repaired them immediately.

Occlusion with nictitating membrane. For one animal (K190) we used another method of translucent occlusion described by Wiesel & Hubel (1963). This involves trimming the margin of the nictitating membrane, drawing it across the cornea and suturing it to a wounded region of conjunctiva along the upper lid. This provides a diffusing cover to the eye that only attenuates the light reaching the cornea by about 0·5–1 log unit (according to our estimates) as opposed to the 3–5 log units of attenuation provided by lid suture.

Surgical preparation and maintenance

In preparation for neurophysiological recording, we initially anaesthetized the kittens with Fluothane and then, after venous cannulation, with I.V. Brietal (methohexitone sodium) or Althesin (alphaxalone/alphadolone acetate). During the actual recordings the animal was paralysed by an I.V. infusion at 10 mg/kg.hr of Flaxedil (gallamine triethiodide) in 6 % glucose–Ringer solution. Anaesthesia was maintained by positive pressure ventilation through a tracheal cannula with a mixture of about 78 % N_2O/20 % O_2/2 % CO_2. Thoracic suspension minimized the mechanical resistance to ventilation and also reduced any respiratory pulsation of the brain.

Electroencephalogram and e.c.g. were monitored continuously and we checked repeatedly that the nitrous oxide mixture was always sufficient to produce a slow-wave e.e.g. that could not be desynchronized by a painful stimulus. Expired CO_2 was monitored with a gas analysis meter (Beckman LB2) using samples drawn through narrow-gauge tubing from inside the tracheal cannula. End-expiratory CO_2 was held at about 5·0 % by adjusting the tidal volume of the respiration pump. Body temperature was monitored and maintained at 37° C. In some experiments a cannula in the femoral artery allowed the measurement of arterial blood pressure.

The thin skull was always reinforced with a cap of dental acrylic before a tiny craniotomy and durotomy were made over the visual cortex. Kittens older than 4 weeks can usually be supported satisfactorily by miniature ear bars in a conventional stereotaxic instrument, but we adopted a different procedure for the youngest animals whose skulls were extremely delicate. We positioned four bolts in the acrylic cap over the skull in such a way that they could be used to fix the head to a metal plate, which had extensions that were clamped in the ear bar supports of the stereotaxic frame.

Optical quality. We performed cervical sympathectomy, which, in conjunction with the relaxant infusion, minimized residual drift of the eyes. The corneae were covered with contact lenses, the pupils dilated with homatropine, the nictitating membranes withdrawn with phenylephrine (neosynephrine), and optical quality improved with artificial pupils. We assessed the refractive state of the eyes by direct ophthalmoscopy and put an additional spectacle lens in front of each eye to focus it on a screen at a distance of 57 cm. We used a reversible ophthalmoscope to plot the projection of each area centralis on this screen.

Before about the fifth week the lens of the eye is rather cloudy and there is persistent hyaloid vascularization, which makes it difficult to see the fundus, let alone measure the refractive state. Yet our independent estimates of refractive error and of the projection of the area centralis usually agreed very closely. Only in the youngest kitten we recorded (9 days) were we quite unable to assess the position of the visual axis; but judging from the recording site and the projections of the optic disks, the receptive fields, as in all the other animals, were within a few degrees of the area centralis.

Recording methods and receptive field analysis

We positioned a sealed hydraulic microdrive over the craniotomy and advanced a tungsten-in-glass micro-electrode (Levick, 1972) into the cortex: in later experiments we used a stepping motor attached to the hydraulic system to drive the electrode in 2·5 μm pulsatile steps. Fairly low impedance electrodes (10–25 μm exposed tungsten, 2–3 μm diameter at the exit from the capillary; about 2 MΩ at 1 kHz) proved the most reliable, producing good recordings of background neural activity yet giving excellent, large amplitude action potentials from well-isolated single units. Responses were simply judged by listening to the discharges played over an audio monitor.

Once we had isolated a single unit, using a moving card with lines of many orientations to provide visual stimulation as the electrode was advanced, we systematically explored the visual field of each eye separately. Moving and flashing spots, slits, bars and edges were back-projected on the tangent screen by manipulating cut-out patterns on an overhead projector. A reflector cast an identical image on to sheets of graph paper on the projection table, where the receptive fields were plotted for permanent records.

We took a photograph of the kitten's eyes before the preparation, and another after paralysis, so that we could estimate any induced rotation of the eyes from the angles of the fissurated pupils. In this way we knew the correct horizontal and vertical axes for the visual field of each eye and were able to correct the positions and orientations of receptive fields accordingly.

Histology

After the experiment we gave an I.V. injection of Nembutal and perfused the animal through the heart with Ringer solution and then with buffered 10% formalin. The brain was removed and photographed, and a block taken from the

region of the penetration. It was frozen, sectioned at 40 μm and stained with cresyl violet, often with luxol fast blue counterstaining. We examined the sections to define the approximate position of the area 17/18 border and to reconstruct the penetration from electrolytic lesions (5–10 μA for 5–10 sec, electrode negative) made at several points along the track.

RESULTS

Here we shall report the detailed qualitative study of 771 cortical cells from twenty-five kittens, ranging in age from 9 days to 22½ weeks. Every cell that is described was held long enough for the receptive field to be thoroughly mapped (in both eyes if the cell was binocularly driven). We have excluded from this analysis only a handful of units, all of which, on the basis of their fibre action potential wave forms, brisk responses, and concentric, monocular receptive fields, were assumed to be afferent fibres from the lateral geniculate nucleus. A small number of units whose receptive fields had no orientation selectivity, and had clear antagonistic centres and surrounds *are* included because not only did they have cellular action potentials and usually clear binocular input but they also gave very prolonged injury discharges, not at all typical of axons, when the electrode was advanced (see Fig. 18).

To begin, we shall describe the kinds of receptive fields that were found, then we shall present the results of rearing kittens with or without various manipulations of their early visual environment; finally we shall discuss genetic and environmental influences on the cortex and those aspects of visual experience that seem to contribute most crucially.

Types of receptive fields

This study, together with previous work (Blakemore & Van Sluyters, 1974), has led us to the conclusion that, by means of the procedures to be described below, it is possible to classify the receptive fields of all cortical neurones in kittens of any age (whatever their rearing history) into five distinct and mutually exclusive groups. There is considerable variation in the detailed properties of all the cells falling into any one class, but neurones can be classified quickly and absolutely on the basis of a few simple tests. The receptive field types are as follows, in approximate order of increasing specificity:

Visually unresponsive. We occasionally came across spontaneously active cells that could not be excited by any visual stimulus we could devise and, even though we advanced the electrode with caution and constantly explored the visual field with a randomly patterned visual noise figure, we sometimes injured cells that had produced no previous action potentials while we were searching: we knew of their presence only

because of the injury discharge. Our failure to discover such neurones in the normal adult cortex leads us to believe that they are a distinct cell type and their occurrence in some kittens does not merely reflect our faulty technique or lack of ingenuity.

Non-oriented. Cells with receptive fields of this type respond to moving stimuli but have no clear preference for any direction of movement or any orientation of edge. In general they prefer moving to stationary patterns

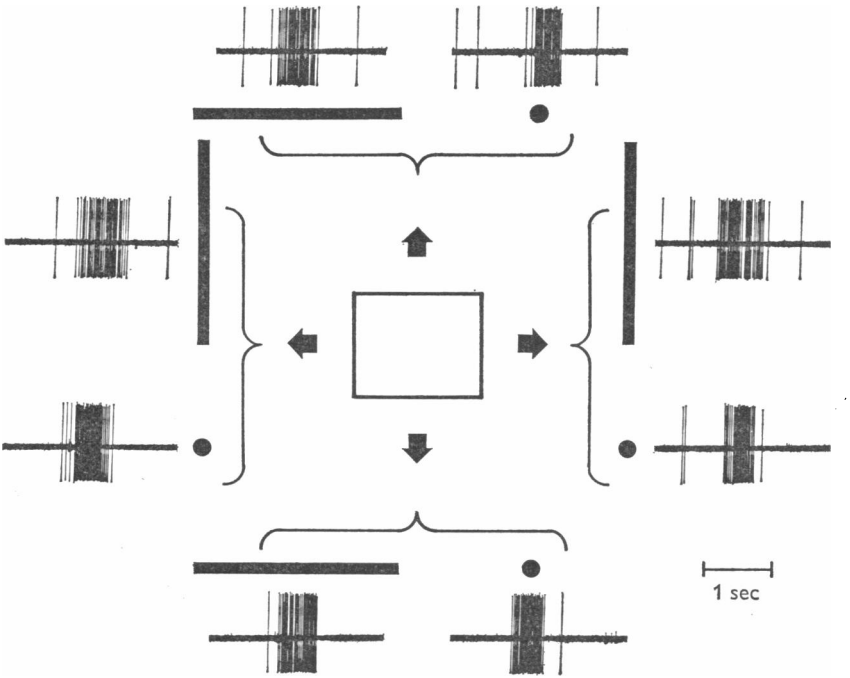

Fig. 1. Typical responses for a cell with a non-oriented receptive field recorded from a 13-week-old dark reared kitten (K48) who was regularly exposed to a striped environment from day 28 for a total of 76 hr. Filled arrows indicated the directions of movement of a 1 deg diameter dark spot or a $\frac{1}{2} \times 12$ deg dark bar across the receptive field. The response field (Barlow *et al.* 1967), which measured $7 \times 7\frac{1}{2}$ deg, is shown schematically in the centre. Responses are displayed (positive upwards) next to the stimulus which evoked them. In this, and the following figures, luminance of the dark part of the screen was approximately 5 cd. m^{-2} and of the light part of the screen approximately 20 cd. m^{-2}.

and in fact, many of them give little or no response to flashing spots anywhere within the receptive field. Some, however, produce clear ON or OFF responses from a central region, sometimes with antagonism from a surrounding area. Usually the surround is silent to flashing stimuli, even

for a large annulus. Often moving spots or bar-shaped targets of equal area (and therefore equal total flux) have equal effect on the cell.

A non-oriented receptive field is illustrated in Fig. 1: it belonged to a cell recorded from an animal reared in the darkroom but with regular exposure to a striped environment. The cell gave no response to flashed stimuli, but responded equally to movement in any direction, slightly preferring a moving bar to a small spot. It is most important to point out that this cell, and those illustrated in Figs. 2–4, came from animals that had enjoyed visual experience (albeit unusual) during the first few weeks of life. Consequently the responses were particularly brisk and reliable. Most neurones of these types recorded in visually deprived kittens are *not* this responsive and many of them are frustratingly variable in their sensitivity. This and the following examples illustrate the important properties of these types of cells without being typical of their responsiveness in all animals.

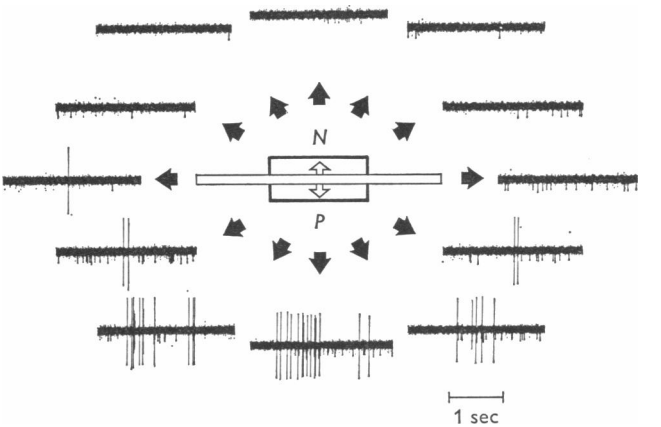

Fig. 2. Responses of a pure direction selective cell recorded from a kitten exposed to an environment of stripes (K31). A $\frac{1}{3} \times 9$ deg light bar was moved across the receptive field in the directions shown by the filled arrows. The orientation of the bar was always perpendicular to the direction of motion. For convenience, as in Figs. 3, 4, 7, 8 and 9, the receptive field is illustrated with the preferred axis of movement arranged vertically on the page. The size of the response field was $3\frac{1}{2} \times 1\frac{1}{2}$ deg. P = preferred direction, N = null direction.

Pure direction selective. Even in the normal adult cat some cells are better described as solely direction selective, rather than orientation selective (Blakemore & Van Sluyters, 1974; Palmer & Rosenquist, 1974). The receptive field has a clear axis, along which movement in one (preferred) direction excites, but in the reverse (null) direction does not cause a significant response. Moreover, the cell shows no preference for long

edges: it responds equally to spots, bars and edges of either contrast, and even to tiny dark or light tongues moving in the correct direction, just like the classical direction selective ganglion cells of the rabbit retina (Barlow *et al.* 1964). If the cell responds at all to flashed stimuli it usually gives

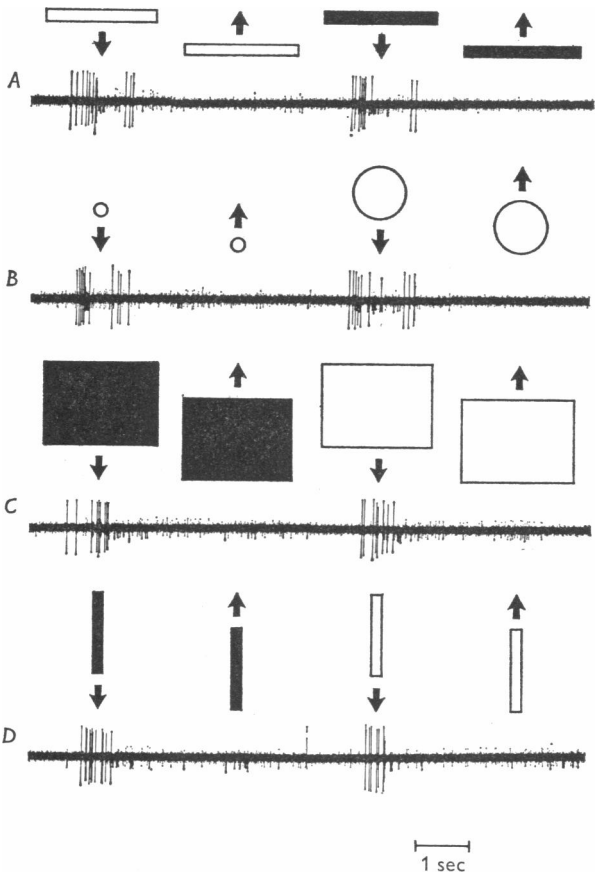

Fig. 3. *A*. Responses for $\frac{1}{2} \times 4$ deg light and dark bars moved down through the receptive field in the preferred direction and up in the null direction. *B*. Similar responses for $\frac{1}{2}$ and 2 deg diameter light spots. *C*. Responses for leading dark and leading light edges. *D*. Responses for $\frac{1}{2}$ deg wide dark and light 'tongues'. Same symbols and conventions as in Fig. 1. Same cell as in Fig. 2.

ON–OFF responses all over. The range of directions over which a moving spot excites such a cell (the 'tuning curve') is much the same as for a moving line. In our opinion, all these properties make it illegitimate to call such a receptive field orientation selective.

Figs. 2 and 3 show responses from a cell with a pure direction selective

receptive field, again recorded in an animal with experience in an environment of stripes. The directional tuning, shown in Fig. 2, was quite broad, the cell responding over a range of almost $\pm 90°$. Some tests of contrast independence and the irrelevance of target configuration for this cell appear in Fig. 3. Clearly this neurone remained direction selective for bars, spots and edges and seemed to exhibit little or no spatial summation across its 4 deg long receptive field, since small spots and even tiny tongues were as effective as long bars and edges.

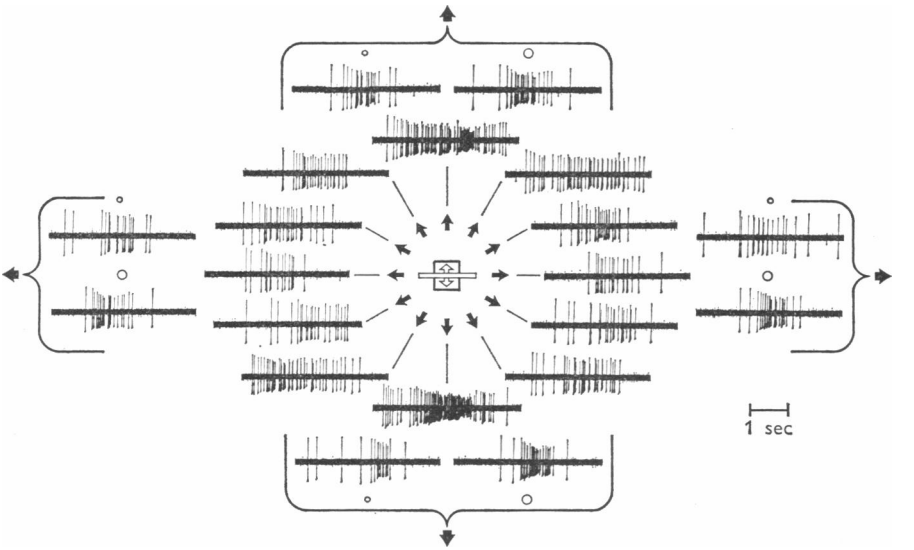

Fig. 4. Responses of an orientational bias cell, recorded from a kitten with binocular lid suture (K163), to a $\frac{1}{2} \times 6$ deg light bar moved across its receptive field in the directions indicated. The bar was always orientated perpendicular to the direction of movement. Enclosed in brackets are responses for $\frac{1}{2}$ and 1 deg diameter light spots moved through the receptive field both along and orthogonal to the preferred axis of movement. Same symbols and conventions as in Fig. 1. Response field size was $2\frac{1}{2} \times 3$ deg.

Orientational bias. In this case the cell again prefers moving to stationary stimuli and, like a non-oriented neurone, responds to stimulus movement in all directions. However, the response is not equal along all axes of motion; there is a preference for one axis and, thus, if an elongated border is being used, for one orientation of edge. In some cases one direction of motion along the best axis is obviously more effective than the reverse direction. The degree of axial selectivity varies enormously, from cells that are only just more reliable in their responses along the preferred axis compared with the orthogonal, to neurones that resemble normal orientation selective cells (described below) but produce a weak but secure discharge to a

stimulus orthogonal to the best orientation. Hence, these cells form a continuum between non-oriented properties and true orientation selectivity.

Some of these cells, for instance the one that provided the responses in Fig. 4, favour long lines over small spots and could be said to be selective for elongated contours. However, many orientational bias cells have no obvious preference for a line compared with a spot and in that sense look like bi-directional versions of the pure direction selective cell. It might be valid to dub such cells 'axial movement detectors' or as Pettigrew (1974) calls them 'axis-selective'. Interestingly, though this class of cell is rare in the mature cat's cortex, Van Sluyters & Stewart (1974*a*) describe very similar neurones in the adult rabbit's visual cortex and they call them 'double-direction selective'.

Orientational bias cells, if they respond to flashed stimuli at all, usually resemble complex cells (see below) in that they produce weak ON–OFF responses over the whole receptive field and show incomplete spatial summation. In a very small number of cases the receptive field has distinct spatially summating antagonistic ON and OFF zones, and in every way appears like an extraordinarily broadly tuned simple cell (see below).

Orientation selective. Our absolute definition of an orientation selective cell is that it should have a clear preferred orientation and no reliable discharge for movement of a contour along the orthogonal axis. Almost always a moving line is preferred to a moving spot and almost always the latter produces a broader tuning curve than the former, suggesting that the selectivity for orientation is generated in part by some mechanism other than that which creates a preference for motion along one axis.

The typical orientation selectivity of the adult cat's cortex has been described in detail by Hubel & Wiesel (1962, 1965*a*), who distinguish three types of such cells, all found in area 17. In brief, *simple* cells have receptive fields with a clearly spatially summating, elongated ON or OFF area with an antagonistic parallel zone (that usually produces the opposite response to flashes but is sometimes silent) on one side, or both sides, of the central region. The size and type of the central zone predict the optimum configuration of a moving target, but these cells often have a directional preference that cannot be accounted for by the field plotted with flashing stimuli (Bishop, Goodwin & Henry, 1974). *Complex* cells have somewhat larger receptive fields that do not show a simple arrangement of antagonistic regions. If flashed stimuli are effective at all, the type of response, usually ON–OFF, is the same all over the field. These cells have a clear preference for moving contours and give a prolonged discharge as the target moves across the whole receptive field. *Hypercomplex* cells resemble simple or complex cells in their responses to short bar-shaped stimuli (Dreher, 1972; Rose, 1974) and are only distinguished by par-

ticularly strong inhibitory zones at one end, or both ends, of the receptive field. Hence, they respond best to a moving corner or short bar and virtually not at all to a long line. Some further characteristic differences between these classes of cells are discussed by Pettigrew *et al.* (1968), Blakemore, Fiorentini & Maffei (1972), Bishop, Coombs & Henry (1973), Maffei & Fiorentini (1973), Watkins & Berkley (1974), Rose & Blakemore (1974) and Movshon (1975).

Unfortunately any scheme of classification artificially introduces apparently sharp boundaries between the properties of different cell types, but, short of a character sketch of every cell, some system of categories is useful, at least in considering the differences between animals of various ages and experience.

Sampling procedure

The method of selecting a sample of neurones poses a major problem in these experiments. The total number of cells recorded from any one animal is limited by the time taken to analyse each one and by the stamina of the experimenter as well as the preparation. But also, in principle, it is wrong to prolong experiments on very young animals that have been specially reared because even the brief visual stimulation given during the experiment could modify the properties of neurones (Pettigrew, Olson & Barlow, 1973; Blakemore & Mitchell, 1973; Pettigrew & Garey, 1974), especially after several hours. In addition, the arrangement of neurones, at least within the adult cortex, seems almost designed to frustrate the seeker after randomness; cells with similar preferred orientation and similar ocular dominance are clustered together in large slabs or 'columns' normal to the surface (Hubel & Wiesel, 1962, 1965*b*; Wiesel, Hubel & Lam, 1974), and cells of the same class, simple or complex, tend to occur together in a laminar distribution. Thus, a single surface-normal penetration should discover all cells to have about the same orientation preference: a single penetration exactly parallel to the surface might encounter mainly cells of one type alone.

In practice, we developed the following strategy, which usually restricted the experiment to a single day and produced a total of about thirty units, but virtually guaranteed a fair and random sample, judging by its results in normal animals. We drove the electrode downwards and angled towards the midline, entering the cortex on the medial side of the crest of the post-lateral gyrus. This ensured: (*a*) that the electrode was in area 17 for much if not all of the penetration; (*b*) that it travelled obliquely through the cortex, which should reveal the sudden shifts in neuronal properties from one column to another and (*c*) that nearly always it passed through every layer of the cortex. We usually drove down to a depth of

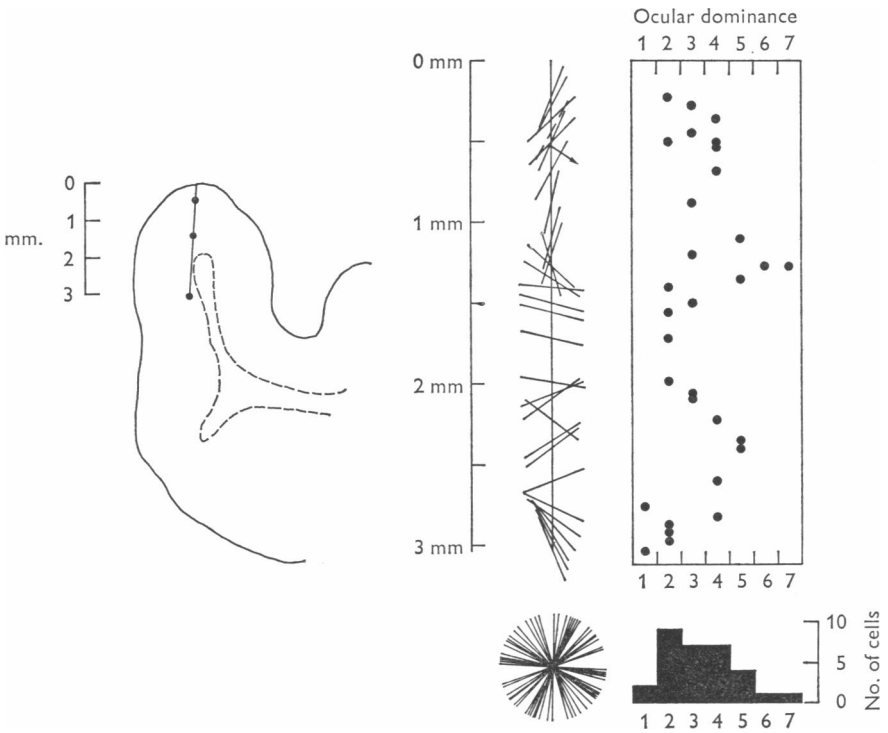

Fig. 5. Penetration reconstruction for a normal 5½ week old kitten (K145). The coronal section on the left shows the electrode track as determined from the three electrolytic lesions which have been marked on it. The penetration is schematically reconstructed on the right where each symbol indicates the position at which a unit was recorded, its receptive field type in the dominant eye, and, on the far right, its ocular dominance group. *Orientation selective* = continuous line at the preferred orientation; *orientational bias* = interrupted line at the optimal orientation; *pure direction selective* = arrow in the preferred direction. On the bottom right the results are summarized in a polar diagram of preferred orientations and directions, and an ocular dominance histogram (Hubel & Wiesel, 1962). Cells were classified into seven groups, according to their relative sensitivity to stimulation through the two eyes. Neurones in groups 1 and 7 are monocularly driven, responding only to stimulation through the contralateral or the ipsilateral eye respectively. Cells in all other groups are binocularly driven: those in groups 2 and 6 are strongly dominated by the input from the contralateral or ipsilateral eye respectively; those in groups 3 and 5 are slightly more sensitive to stimulation through the contralateral or ipsilateral eye respectively, while those in group 4 are equally responsive through either eye.

about 3–4 mm, studying every isolated unit, but often we further extended the area of the sample by ending the penetration with a number of rapid 250 or 500 μm advances, proceeding slowly at each stopping place until just one or two units had been isolated before the next advance. In the normal animal this procedure almost always produces an even range of preferred orientations and a typical ocular dominance distribution (Hubel & Wiesel, 1962) with a majority of binocular neurones and a slight preponderance of cells dominated by the contralateral eye. Fig. 5 shows the results of such an experiment in a normal 5½-week-old kitten. Even though in this case we did not make a series of advances to finish the penetration, the electrode obviously crossed many orientation and ocular dominance columns; the schematic reconstruction of the penetration shows the position of each unit, its preferred orientation or direction and, to the right in Fig. 5, its ocular dominance group. The results are summarized in the polar diagram of the range of preferred orientations and the ocular dominance histogram.

Experimental manipulation of early visual experience

Normal vision

We have studied seven kittens ranging from 19 days to 22½ weeks of age, reared completely normally, in the colony room, which was illuminated for 18 hr each day. Our results confirm Pettigrew's (1974) report that kittens older than about 4 weeks are virtually adult in their cortical physiology (Fig. 5). However, even the youngest visually experienced animal in our series (K243; 19 days), recorded before the start of the classical 'sensitive period' (Hubel & Wiesel, 1970; Blakemore, 1974) was surprisingly mature. Cells were not difficult to isolate; habituation and sluggishness were not major problems. Despite the very cloudy optics as well as the young age of the animal, the majority of neurones were distinctly orientation selective, narrowly tuned for orientation and obviously binocularly-driven. From place to place along the penetration there was distinct columnar clustering of cells according to preferred orientation and ocular dominance. Towards the end of the fourth week (K236; 26 days), when only the crudest kinds of visual behaviour are present, the visual cortex is almost indistinguishable from that of a normal full-grown cat.

The remarkable degree of receptive field specificity and cortical organization that we saw in even our youngest normally-experienced animals (which contrasts somewhat with the results of Pettigrew, 1974) made it essential to compare these kittens with animals deprived of visual experience, in order to distinguish between immediate innate factors, passive maturational changes, and active contributions from visual experience.

Binocular deprivation

We used a number of methods to deprive six kittens of patterned retinal images.

Dark rearing. Two kittens (K165 and K139) were kept in the totally dark room until recording at the age of 19 and 44 days. They were never removed from the darkroom for routine physical inspection and we are confident that they received no retinal illumination after natural eye opening.

Binocular lid suture. Three animals were binocularly deprived by suturing the lids of both eyes at or before the time of natural eye opening (about 6–10 days). Two of the animals, K207 (recorded at 47 days), and K36 (57 days), were simply kept in the illuminated colony room. The other kitten, K163 (recorded at 72 days) was housed in the darkroom and only brought out into the colony for an average of 1 hr each day to provide intermittent diffuse retinal illumination.

Nictitating membrane suture. For one animal we sutured the nictitating membranes across the corneae, in order to provide a more translucent diffuser than lid suture. The animal (K190) was kept in the dark but was exposed daily for about an hour in a cylindrical plastic enclosure, the inside walls of which were covered with white card and diffusely illuminated from above and below. This guaranteed fairly high diffuse retinal illumination without any possibility of even gross patterned images.

In addition, one kitten (K160) was studied at only 9 days of age, just as the lids showed the first signs of parting naturally.

In fact, there were no striking differences in the results for these animals that had been binocularly deprived in various ways. In every case the organization of the visual cortex contrasted quite remarkably with that of the normal kittens in this series. Some neurones were visually unresponsive, and of those cells that could be excited by visual stimuli, many were non-oriented. Perhaps even more impressive than the general paucity of stimulus specificity was the weakness and variability of responses combined with a marked tendency for rapid habituation, which Pettigrew (1974) has already described. This was only especially noticeable in animals that had been deprived for several weeks and was much less pronounced in the two youngest animals, less than 3 weeks old.

What we have said so far seems almost completely in line with Pettigrew's (1974) argument that, while binocularity and motion sensitivity are innately specified, visual experience is essential for the development of orientation selectivity. However, we have noticed a degree of inherent organization in the deprived cortex considerably greater than that described by Pettigrew (1974). Our results are summarized in Fig. 6,

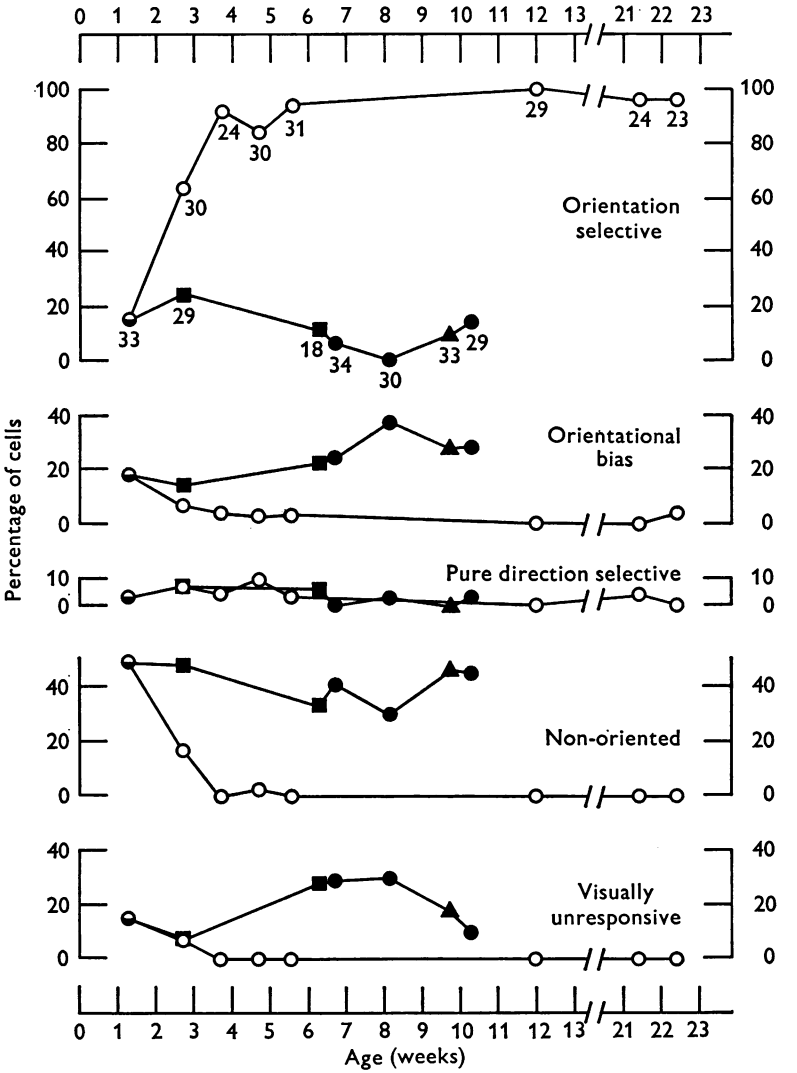

Fig. 6. Comparison of the effects of binocular deprivation with those of normal visual experience. The five pairs of curves show the percentages of each type of receptive field for 397 cells recorded from seven normal kittens (K243, K236, K246, K145, D3, K83, K82; open circles) and six binocularly deprived kittens (K165, K139, K207, K36, K190, K163; filled symbols) of various ages. In each case the two curves originate from points representing the data for the 9-day-old kitten (K160) recorded at the time of natural eye opening. For the binocularly deprived kittens: *Lid suture* = filled circles; *dark reared* = filled squares; *nictitating membrane suture* = filled triangle. The numbers beneath the data points for the top pair of curves indicate the total number of cells recorded in each animal.

where the percentages of the various classes of cells are shown for visually experienced (open circles) and binocularly deprived (filled symbols) kittens of various ages. The different kinds of deprivation technique are indicated by several symbols, described in the legend.

As well as having many non-oriented cells, deprived animals have a small proportion of pure direction selective neurones and a number of orientation bias cells, which, while responding somewhat to all directions

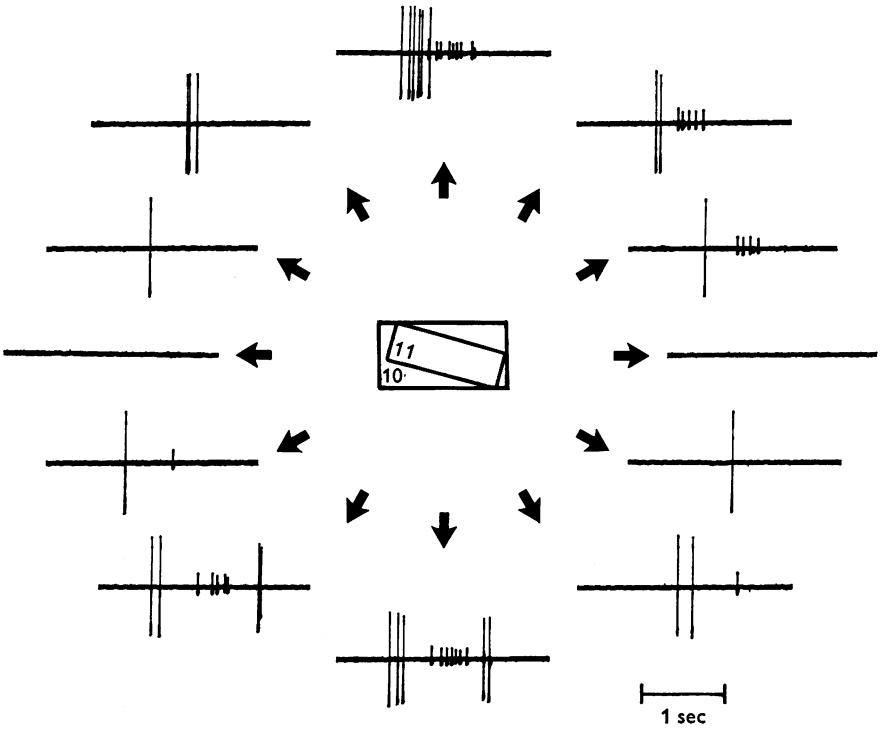

Fig. 7. Responses for two simultaneously recorded orientation selective cells in the 9-day-old kitten (K160). The stimulus (not shown) was a 3×16 deg light bar moved in the directions indicated by the filled arrows across the two receptive fields for the left eye, labelled '10' (large action potentials) and '11' (small action potentials). Response field '10' was 6×3 deg in size and '11' was $5\frac{1}{2} \times 2$ deg. Same symbols and conventions as in Fig. 1. For convenience of illustration, response field '10' is shown orientated horizontally.

of movement show a convincing preference for one axis of motion and often prefer a long contour to a small moving spot. Pettigrew (1974) has described just such cells and has argued that they do not satisfy rigid criteria for orientation selectivity: certainly they are immediately distinguishable from the normal orientation selective neurones of the adult.

However, we have also found a proportion of cells in the inexperienced cortex that pass the most exacting tests of orientation selectivity. The numbers of orientation selective cells were perhaps particularly high in the two youngest visually inexperienced animals (9 and 19 days) and, in a sense, this is the most satisfying indication that their organization is truly innate: these kittens had had the least chance of any form of patterned visual input. There is even an indication that the proportion of orientation selective cells decreases with the duration of deprivation: indeed, orientation selective cells can be so rare in older binocularly deprived animals, that even a fairly large sample from one animal occasionally contains no orientation selective cells, as we have previously reported (Blakemore & Van Sluyters, 1974). It is also of interest that, in binocularly deprived animals, the actual amount of retinal illumination does not seem to influence the degree of cortical specificity, since all the deprivation techniques produced concordant results.

What is our evidence that these neurones were truly orientation selective, and did not just possess a strongly developed preference for one axis of motion? First, of course, they produced no discharge for movement orthogonal to the best axis. Secondly, in every case the responses were stronger and the directional tuning narrower for a moving edge or bar than a moving spot. But, most important of all, the great majority of these orientation selective cells in all deprived animals were clearly of the *simple* type (with distinct, separate ON and OFF zones in the receptive field): the fact that they responded to flashed stimuli permitted what may be the ultimate test of orientation selectivity, the specificity for the orientation of a *flashed*, not a *moving*, bar. If a cell exhibits a strong preference for one orientation when a contour is flashed, this cannot depend on selectivity for a particular axis of movement. We tested our simple cells with flashed lines at various angles and confirmed their genuine orientation selectivity.

Figs. 7, 8 and 9 show a particularly fortunate example; in the 9-day-old kitten we recorded simultaneously from two orientation selective simple cells. First, in Fig. 7, the cells are stimulated with a broad bright bar, about 16 by 3 deg, moving in various directions. Both cells (K160R10, the large action potential, and K160R11, the small spike) fail to respond for a vertical slit moved horizontally but discharge reliably for a horizontal target (closer inspection shows that their exact optimal orientations are slightly different). The cells are broadly tuned ($\pm 60°$ for K160R10 and $\pm 45°$ for K160R11) but have quite clear optima. They both give reliable responses to flashed bars and are simple in character, even though the ON and OFF areas are unusually large (perhaps not surprising since the optics were so murky that we could not see the fundus with an ophthalmoscope!).

K160R10 is ON centre, while R11 is OFF centre. Note, therefore, that R10 (large spike) starts to discharge *before* R11 in Fig. 7, whatever the direction of movement of the bright slit.

In Fig. 8 the responses are shown for a small (0·5 deg diameter) white spot, a large spot (2 deg diameter) and a dark bar. Neither cell responds reliably for the moving spots. For the horizontal black bar both cells fire but now R11 before R10 (since R11 has an OFF centre field).

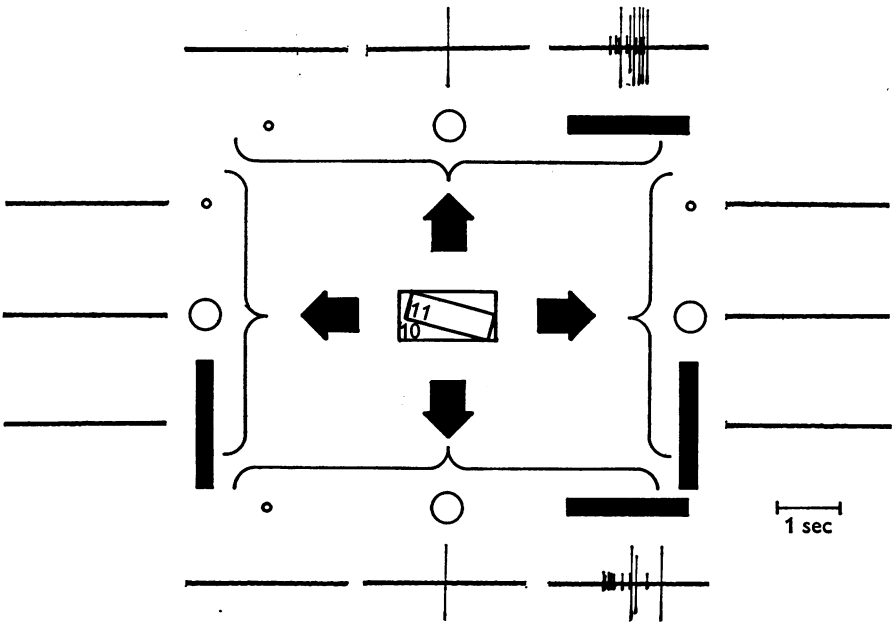

Fig. 8. Same cells as in Fig. 7. Responses for ½ and 2 deg diameter white spots and a 1 × 8 deg dark bar moved across the receptive fields both along and orthogonal to the preferred axis of movement. Same symbols and conventions as in Fig. 1.

Some responses to flashed stimuli are shown in Fig. 9. A horizontal white slit, positioned over the central zone of both fields produces ON responses from R10, OFF responses from R11. A vertical slit has no effect and neither does diffuse illumination, implying the presence of antagonistic flanks to the receptive fields.

The definite existence of orientation selectivity in the naive cortex prompts the question of whether columnar organization itself is also partly pre-specified. Hubel & Wiesel (1963) were quite convinced that a columnar arrangement can be found in very young animals and we examined this question in some detail. The very fact that the two simultaneously-recorded cells of Figs. 7–9 had close (though not identical) preferred

orientations is a hint that neighbouring orientation selective cells might have similar innately specified connexions.

This is a difficult problem to examine because the proportion of orientation selective cells in deprived kittens is never high and all of them are quite broadly tuned, making it difficult to assess their preferred orientations exactly. Nevertheless, the two youngest animals, with the highest

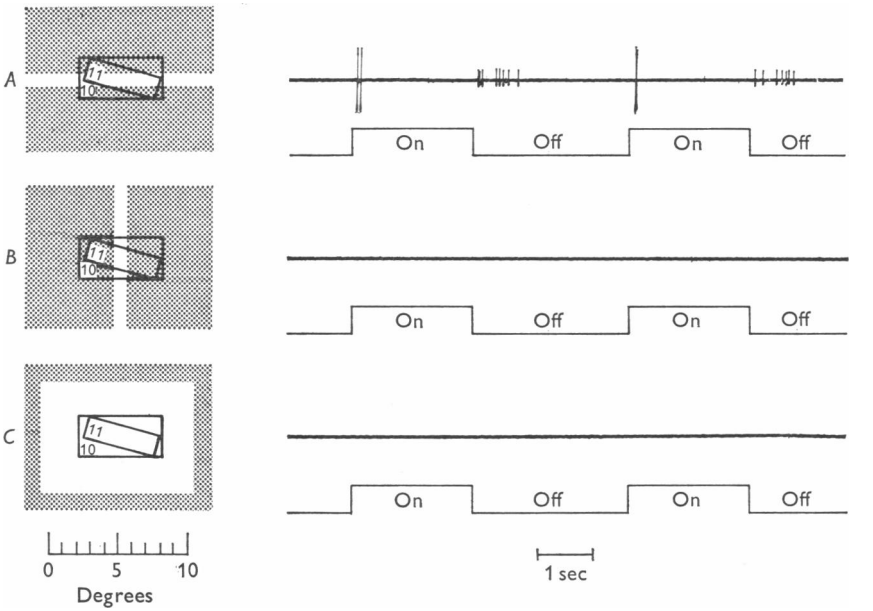

Fig. 9. Same cells as in Figs. 7 and 8. Responses to: *A*, a 1 × 14 deg light bar flashed on and off over the centres of the two receptive fields at approximately the optimal orientation for both cells; *B*, the same bar flashed on and off orthogonal to the preferred orientation; *C*, a full-field flash of light. The approximate times when the stimuli were flashed on and off are indicated below the responses. Same symbols and conventions as in Fig. 1.

proportions of orientation selective cells, are considered in Figs. 10 and 11. Each illustration shows a diagram of the penetration, and a schematic reconstruction of the series of units, indicating their positions, the receptive field types and, on the right, the ocular dominance groups.

In the 9-day-old animal (Fig. 10) the electrode passed briefly through the white matter as indicated on the reconstruction. In the 19 day kitten (Fig. 11) three deliberate advances of the electrode were made to increase the area sampled: these are shown as downward arrows at the side of the schematic penetration. In both animals there is just the slightest tendency for neighbouring orientation selective cells (continuous lines) to be similar

in orientation preference. Also orientational bias cells (dashed lines) tend to have optimal orientations close to those of nearby orientation selective neurones. More impressive is the quite orderly shift in ocular dominance from one region to another: this seems quite strong evidence for inherent organization into ocular dominance columns, at least as impressive as in

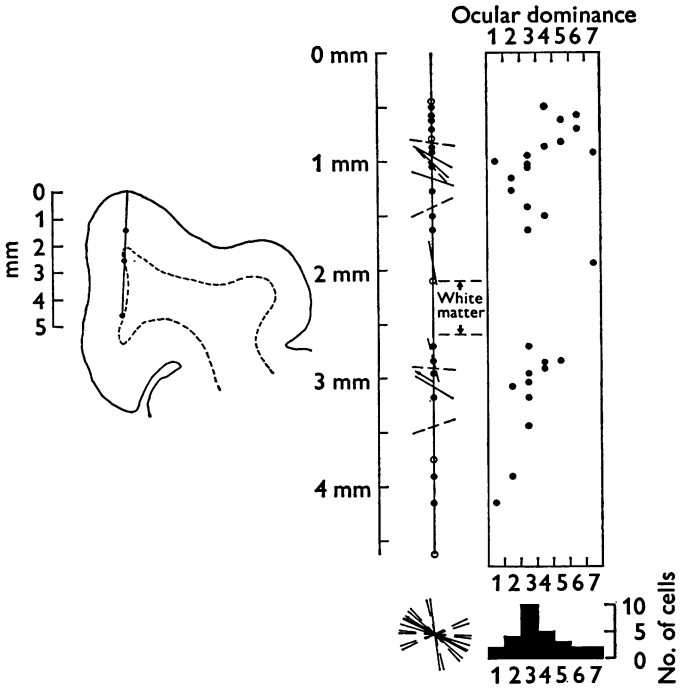

Fig. 10. Penetration reconstruction for the 9-day-old-kitten (K160). Same symbols and conventions as in Fig. 5. This penetration, as is shown in the coronal section, briefly passed through white matter. The points at which the electrode entered and left the white matter are indicated by horizontal interrupted lines beside the schematic reconstruction. In this, and the following figures: *orientation selective* = continuous line at preferred orientation; *orientational bias* = interrupted line at the optimal orientation; *pure direction selective* = arrow in the preferred direction; *non-oriented* = filled circle; *visually unresponsive* = open circle.

the normal 39-day-old (Fig. 5). Note that both these animals had a majority of binocularly driven cells, and the distributions of ocular dominance were quite normal, just as in all the binocularly deprived animals in this series. This confirms the previous observation of Wiesel & Hubel (1965).

Another important general finding now becomes evident in Figs. 10 and 11. The truly orientation selective cells, when they occur, tend to be in

extreme ocular dominance groups: they are often monocularly driven. This turned out to be a valid generalization for orientation selective cells in all animals without visual experience: *they were usually simple and often monocular.*

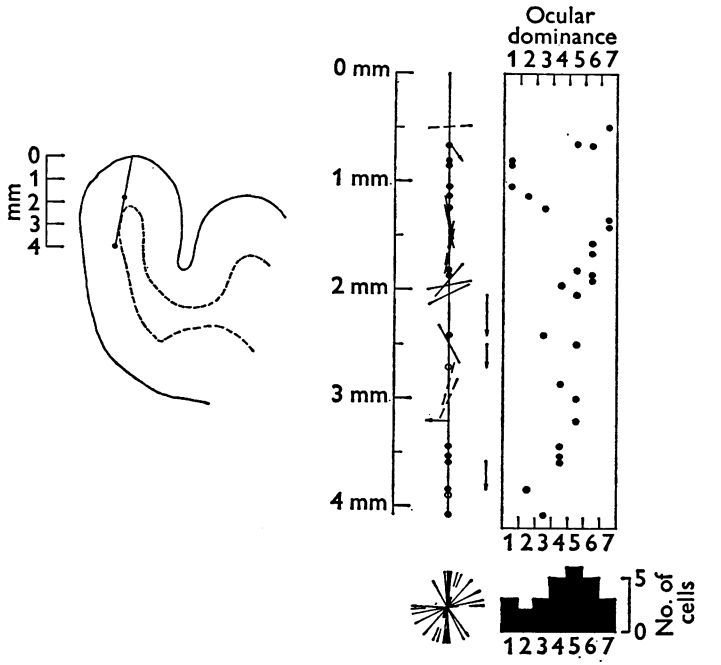

Fig. 11. Penetration reconstruction for the 19-day-old deprived kitten (K165). Same symbols and conventions as in Fig. 5. Towards the end of this penetration three deliberate advances of the electrode were made. They are indicated by downward arrows beside the schematic reconstruction.

Fig. 12 shows two ocular dominance histograms: the one on the left is for all orientation selective cells from the deprived animals, while that on the right illustrates the orientational bias cells from the same kittens. Certainly the latter were highly binocular and there was no tendency towards monocularity in the cell sample as a whole. However, the orientation selective cells were quite different: nearly half of them were monocularly driven and only two neurones were equally influenced by the two eyes. The histogram shows simple cells (open blocks) separately from complex (filled blocks) and hypercomplex (stippled): only four cells out of the total of twenty-four were not clearly simple.

We also had the impression that orientation selective cells in deprived animals were rarely found in the superficial layers of the cortex and we looked at this question of laminar organization more closely.

On the basis of histological reconstruction we were able to determine, with an accuracy of probably better than $\pm 100\,\mu m$ the position of the electrode tip when each unit was recorded. For soma recordings this is a fair estimate of the position of the neurone itself. (Judging by the usual criteria concerning the shape and duration of action potentials, together with the fact that many units produced lengthy injury discharges when the electrode was advanced and that we rarely isolated single units in the white matter, we conclude that almost all recordings were, in fact, from cell bodies.) So, taking careful account of the path of the electrode track, we were able to determine the approximate *surface-normal* depth of each cell recorded.

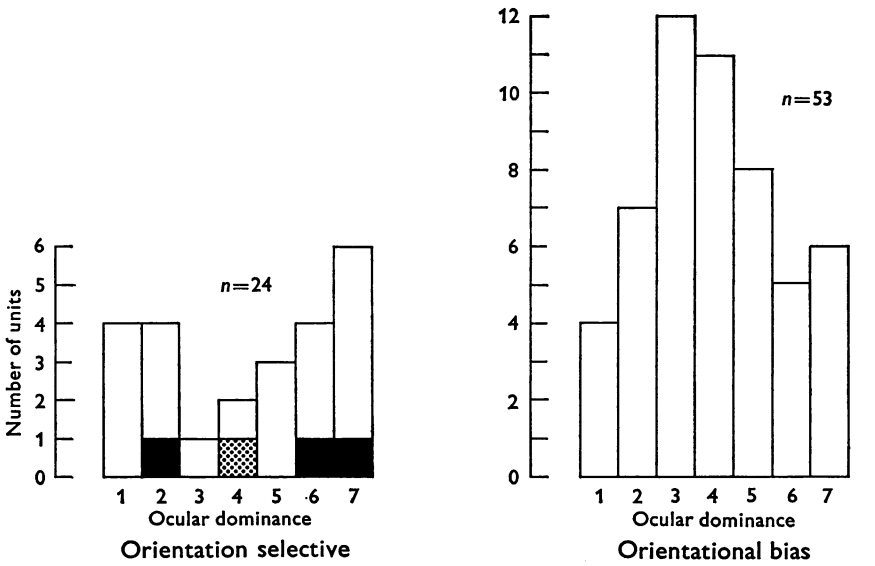

Fig. 12. Histograms, showing the numbers of cells, their ocular dominance groups and receptive field types classified on the basis of the responses from the eye dominating the cell. The dominance distribution on the left contains the twenty-four orientation selective cells recorded in the binocularly deprived animals. They are shown according to the following symbols: *simple cells* = open blocks; *complex cells* = filled blocks; *hypercomplex* cells = stippled blocks. The dominance distribution on the right contains the fifty-three orientational bias cells recorded in these same kittens. The classification of ocular dominance is described in the legend to Fig. 5.

The results for four representative binocularly deprived kittens (the two youngest and the two oldest) appear in Fig. 13. Because of slight variations in the thickness of the cortex with age (it increased from about 1·5–2·0 mm in the 9-day-animal to about 2·0–2·5 mm in its litter-mate aged 72 days) we have normalized the data for the total thickness of cortex. The

relative depth is shown for each cell, measured normal to the surface. The position and type of each neurone is plotted using the same symbols as in the penetration reconstructions (e.g. Fig. 10) except that oriented and directional cells are indicated only by horizontal lines and arrows: the actual preferred orientations and directions are not shown. On the right is the lamination scheme of Otsuka & Hassler (1962), as recommended by Garey (1971).

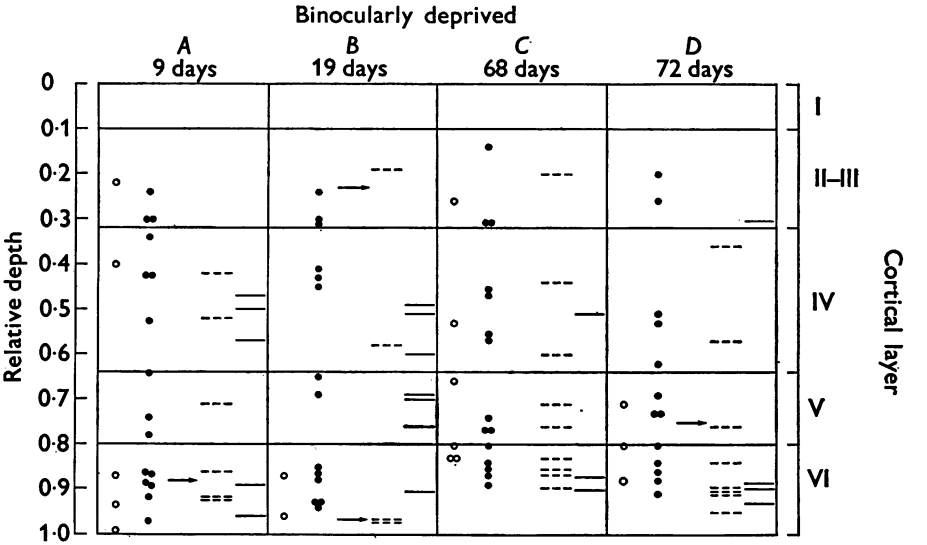

Fig. 13. Analysis of the relative cortical depth of 124 cells recorded from four of the binocularly deprived kittens: *A*, K160 recorded at 9 days; *B*, K165 recorded at 19 days; *C*, K190 recorded at 68 days; *D*, K163 recorded at 72 days. The data point for each cell is plotted against the relative cortical depth at which it was recorded, determined in the manner explained in the text. The receptive field type in the dominant eye is shown for each cell using the same symbols as in Fig. 5 except that all the pure direction selective, orientational bias, and orientation selective cells are indicated by horizontal lines and arrows, purely as a matter of convenience. On the right, the lamination scheme of Otsuka & Hassler (1962) is reproduced to provide an indication of the laminae in which cells were located.

The histograms of Fig. 14 re-plot the data for the four penetrations analysed in Fig. 13, showing the proportion of each type of neurone in each cortical layer. (Plotting *proportions* rather than the actual *numbers* of units eliminates spurious differences due to the unequal sample size from each layer.) This entire procedure has many possible sources of error, but nonetheless it provides a strong indication that innately-specified orientation selective cells were found mainly in the deeper layers, and especially throughout layer IV, where they constituted about a quarter of the

population. (In fact only one orientation selective cell was ever found above layer IV.) On the other hand, all the other types of cells were, in our sample, more evenly distributed throughout the cortex, with non-oriented cells being perhaps more prevalent in layers II and III, and visually unresponsive cells more common in layer VI.

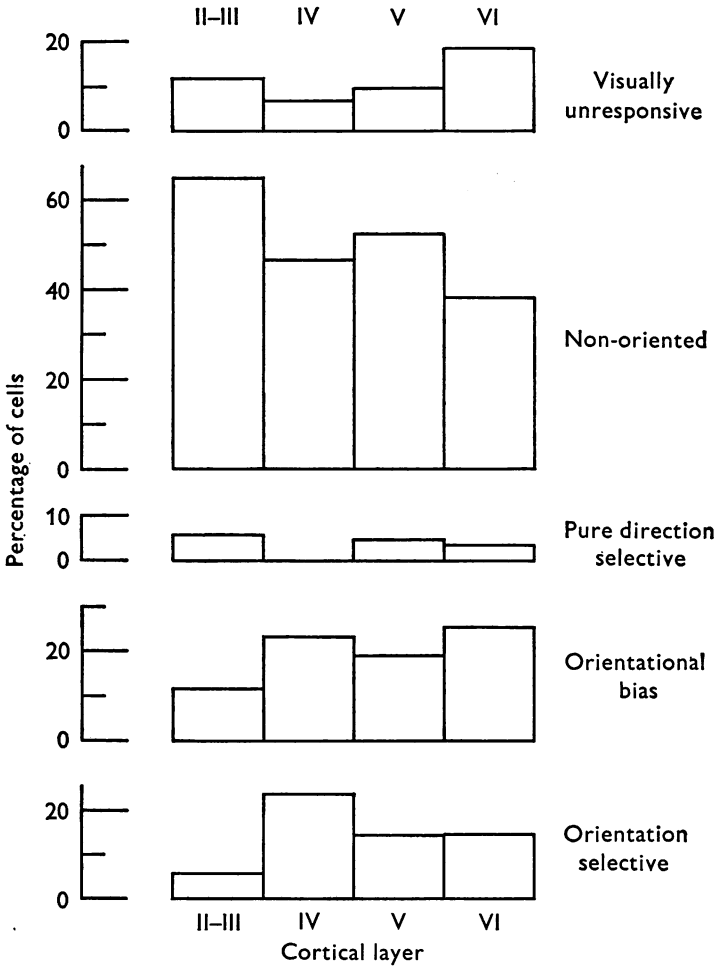

Fig. 14. Histograms, replotting the data from Fig. 13 to show the relative contribution of each cell type to the population of cells found in each of the various cortical laminae. This is accomplished by expressing the number of cells of a given type found in a lamina as a percentage of the total number of neurones studied in that lamina. The number of cells found in laminae II–III = 17; lamina IV = 30; lamina V = 21; lamina VI = 56; and the total number of cells sampled = 124.

Minimal exposure to single contours

We kept one kitten (K104) in the darkroom, did not suture the lids or the nictitating membranes, but exposed the animal for about 2 hr each day in the same diffusely illuminated white cylinder that we later used for the kitten that had nictitating membrane occlusion. This animal was originally intended to be a member of the binocularly deprived series, receiving quite strong, but entirely unpatterned retinal illumination. Having seen the close similarity between all the other deprived animals, despite enormous variation in mean retinal illumination, we were somewhat alarmed when we recorded from the kitten exposed in the diffusely-lit tube. Despite the fact that it was 12½ weeks old at recording, its cortical

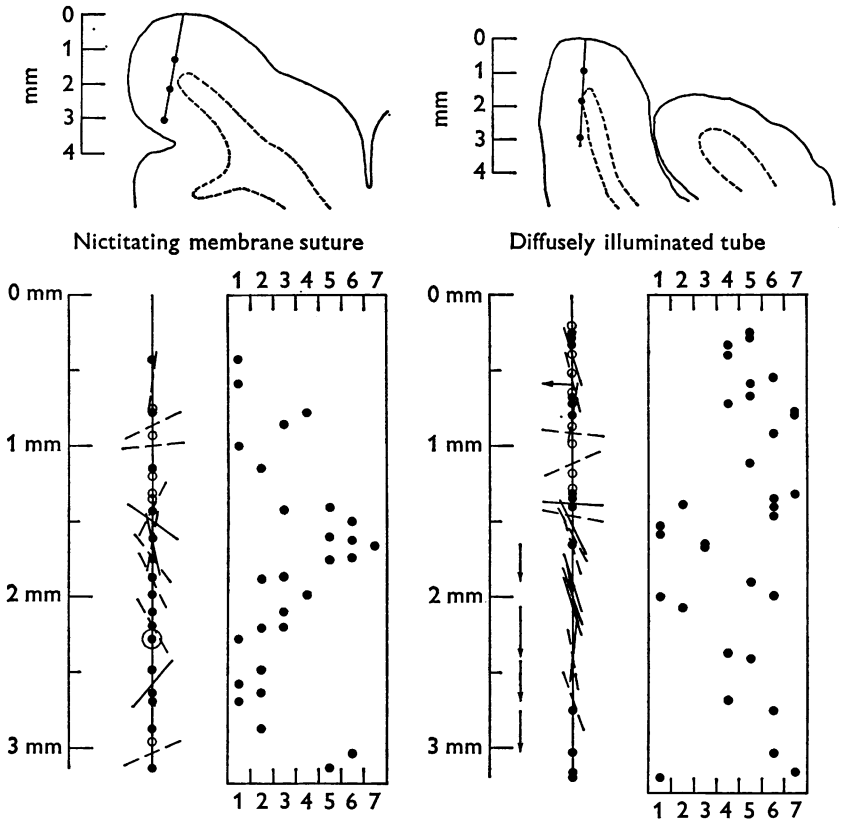

Fig. 15. Penetration reconstructions for the kitten reared with nictitating membrane suture (K190) and the kitten reared in the diffusely illuminated tube (K104). Same symbols and conventions as in Figs. 5 and 11 with the addition of: *afferent geniculate fibre, OFF-centre* = concentric circles with filled centre.

neurones were remarkably brisk and the proportions of orientation selective cells (18 %) and clearly orientational bias cells (21 %) seemed unusually high. Moreover, of the eight orientation selective cells, five were complex and only three simple, quite out of line with the massive preponderance of simple cells in other deprived kittens. Histological reconstruction showed very conspicuous aggregation of orientation selective and even biased cells, into orientation 'columns'. For the sake of comparison, Fig. 15 shows the penetrations in the animal with nictitating membrane suture and this animal, both of whom were exposed in the diffusely illuminated tube. They spent approximately the same amount of time in the cylinder and were not dissimilar in age at recording ($9\frac{1}{2}$ and $12\frac{1}{2}$ weeks respectively). Yet the animal without nictitating membrane suture seemed much more mature than the other.

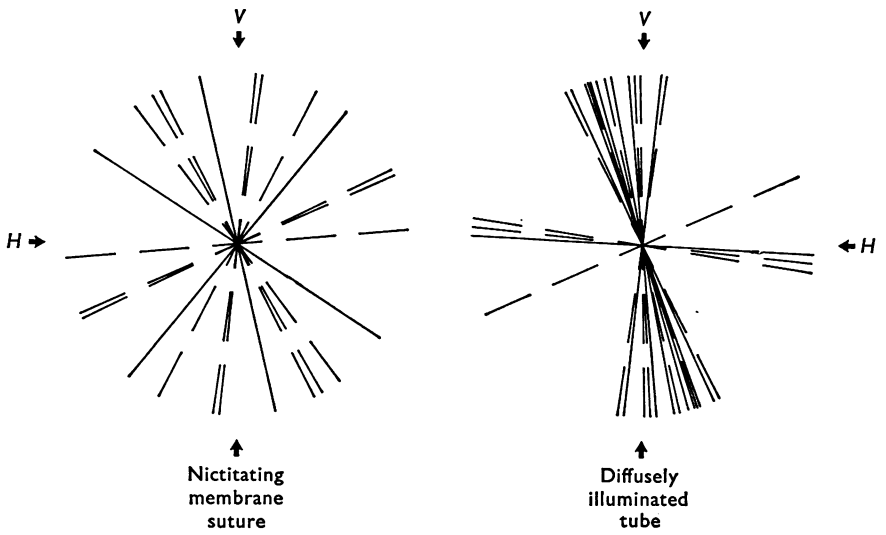

Fig. 16. Polar diagrams summarizing the preferred orientations in the dominant eye for all orientation selective (continuous lines) and orientational bias (interrupted lines) cells recorded in the two penetrations shown in Fig. 15. Horizontal and vertical coordinates are indicated by filled arrows marked '*H*' and '*V*'.

Another even more surprising fact became evident only after analysis of all the data from this anomalous animal. All the cells with orientation selectivity or orientation bias had preferences very close to horizontal or vertical, with the majority favouring the latter. Fig. 16 shows polar diagrams that summarize the optimal orientations for the two animals analysed in Fig. 15.

This quite convincing distortion in the distribution of preferred orienta-

tions, which was not present in any binocularly deprived animal, gave us a hint about the possible cause of all of K104's peculiarities. Close inspection of the diffuse cylinder revealed that it was not totally without pattern. There were two low-contrast but clear contours visible from the centre of the cylinder: the horizontal margin at the junction between the suspended transparent platform and the walls of the tube, and the even more distinct vertical seam where the sheet of white card lining the walls of the cylinder was joined together! We believe, then, that this animal had, in fact received minimal exposure to a contoured visual field: this would seem to explain not only the relative maturity of its neuronal responses and the clear columnar organization but also the predominance of vertical and horizontal preferred orientations.

Environments of random spots

Although our results so far indicate a degree of specificity in the inexperienced kitten's visual cortex that falls somewhere between the near adult levels reported by Hubel & Wiesel (1963) and the marked lack of specificity emphasized by Barlow & Pettigrew (1971) and Pettigrew (1974), we certainly agree with the latter authors that visual experience plays a crucial part in the total developmental process. So now it is inevitable to ask, what kind of visual experience is needed? Diffuse illumination is definitely not enough, but what kind of patterned images will and will not promote normal maturation? The results for the kitten accidentally exposed to single low-contrast contours suggest that elongated edges might be required, and to test this idea we tried to design an environment that would include a good deal of local contour but no long borders. We settled on an exposure cylinder lined with a pattern of randomly-scattered bright spots on a dark background. Pettigrew & Freeman (1973) used a slightly different technique that created spots of even smaller angular size and their results were basically quite similar to our own, which we have already reported briefly (Van Sluyters & Blakemore, 1973).

The random-spot exposure cylinders were identical in illumination and general arrangement to the chambers already described, except that it now became essential to restrict the kitten's movements to the central portion of the platform to avoid excessive variation in the *angular* size of the spots on the walls. This we achieved by placing the kitten in a smaller transparent cylinder (diameter 29 cm), inside the conventional cylinder (diameter 46 cm) which was lined with the spotted pattern. This limited the maximum and minimum straight-ahead viewing distances to about 32 cm and 8 cm respectively and thereby restricted the upper and lower angular dimensions of the spots. (If the kitten looked far up or down the tube the maximum distance increased to about 55 cm.)

Two kittens who were litter-mates (K102 and K103), were presented with small spots, 0·5 cm (1–3·5 deg) in diameter, and two more (K132 and K133), also litter-mates, experienced larger spots, 1·3 cm (2·5–9 deg) in diameter. In each case the spots were irregularly scattered over the dark background with a minimum centre-to-centre spot separation of about 7 cm (12–41 deg). All the kittens were dark-reared for the rest of the time. They were exposed for between 50 and 80 hr altogether and recorded at ages between 9 and 21 weeks.

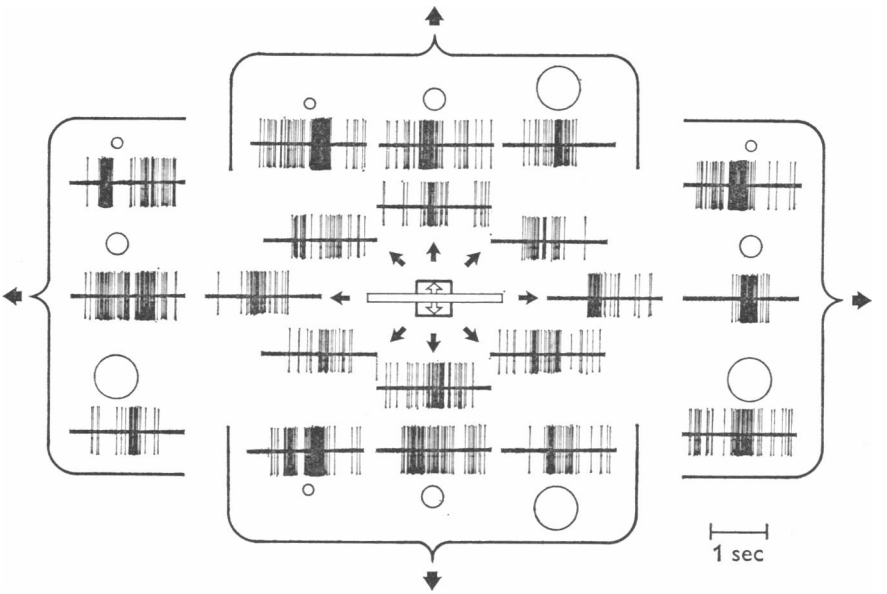

Fig. 17. Responses for a cell with a non-oriented, 'spot-detector' receptive field recorded from one of the 'small spots' kittens (K103). Same symbols and conventions as in Fig. 1. Responses are shown for a $\frac{1}{2} \times 6$ deg light bar moved across the receptive field in the directions indicated by the small filled arrows, and (enclosed in brackets) for $\frac{1}{2}$, 1 and 2 deg diameter light spots moved in the directions indicated by the large filled arrows. The response field size was $1\frac{1}{2} \times 1\frac{1}{2}$ deg.

As long as we used a long line stimulus to explore the receptive fields it was easy to classify cells from these animals into our five basic categories. However, nearly all the visually responsive cells had the curious property of showing little or even negative spatial summation along the length of the receptive field: hence they responded at least as strongly, and many of them more strongly, to a moving small spot as to a long line. In most cases the optimal spot size matched the average dimensions of the spots seen by the animal during rearing (about 2 deg for K102 and K103 and about 5 deg for K132 and K133). Figs. 17 and 18 show responses of a

non-oriented cell from a kitten exposed to small spots and recorded at the age of $10\frac{1}{2}$ weeks.

The responses to spots $\frac{1}{2}$ or 1 deg in diameter (Fig. 17) are clearly stronger than those to a long bright slit, for all directions of motion. Surround antagonism, suggested by the inhibitory effects of long lines extending beyond the receptive field, is demonstrated more explicitly in Fig. 18. The cell gives brisk, sustained ON responses for a 2 deg diameter spot centred

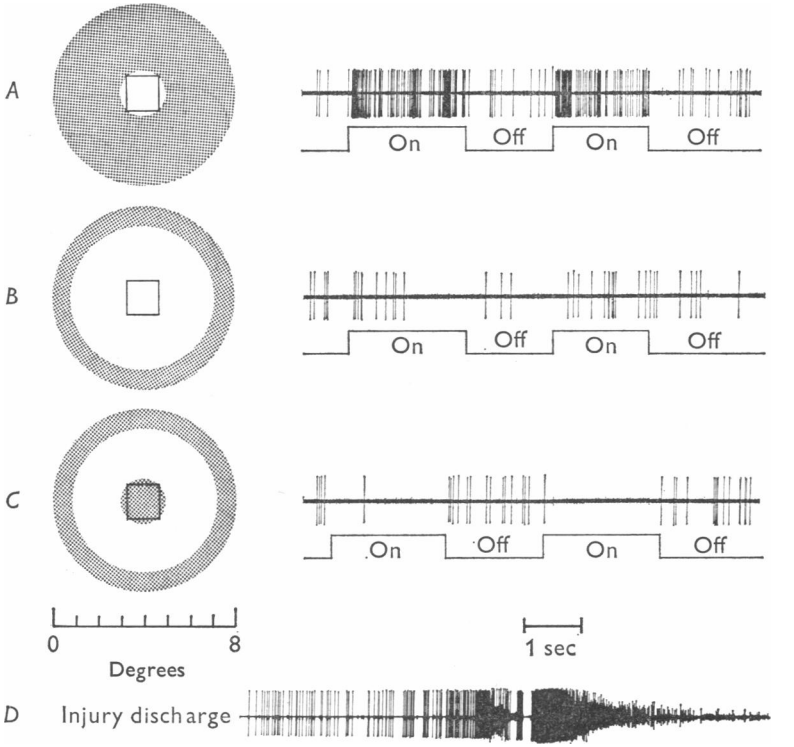

Fig. 18. (Same cell as in Fig. 17.) *A*, Responses to a 2 deg diameter light spot centred over the receptive field and flashed on and off. *B*, Responses to a 6 deg diameter light spot. *C*, Responses to a 6 external × 2 deg internal diameter light annulus. The approximate times when the stimuli were turned on and off are indicated below the responses. *D*, The prolonged injury discharge obtained from the cell when the electrode was slightly advanced. Same symbols and conventions as in Fig. 1.

on the field (Fig. 18*A*), but no reliable response to a large 6 deg flashing spot (Fig. 18*B*). If the central 2 deg is blanked, the surrounding annular zone yields weak OFF responses (Fig. 18*C*). Despite the cell wave form and clear binocularity (Group 3) of this unit, its properties are very similar

to those of an ON centre afferent geniculate fibre. However, as we advanced the micro-electrode, this unit produced an extremely prolonged injury discharge, illustrated in Fig. 18*D*, implying that it was indeed a soma recording.

Even the cells that seemed clearly orientation selective when tested with long lines (21 % in the 'small spots' kittens, 60 % in the 'large spots' kittens) usually had no preference for a line over a spot. Some were clearly inhibited by long contours and thus were classified as hypercomplex. Many, however, simply failed to exhibit the usual spatial summation as a

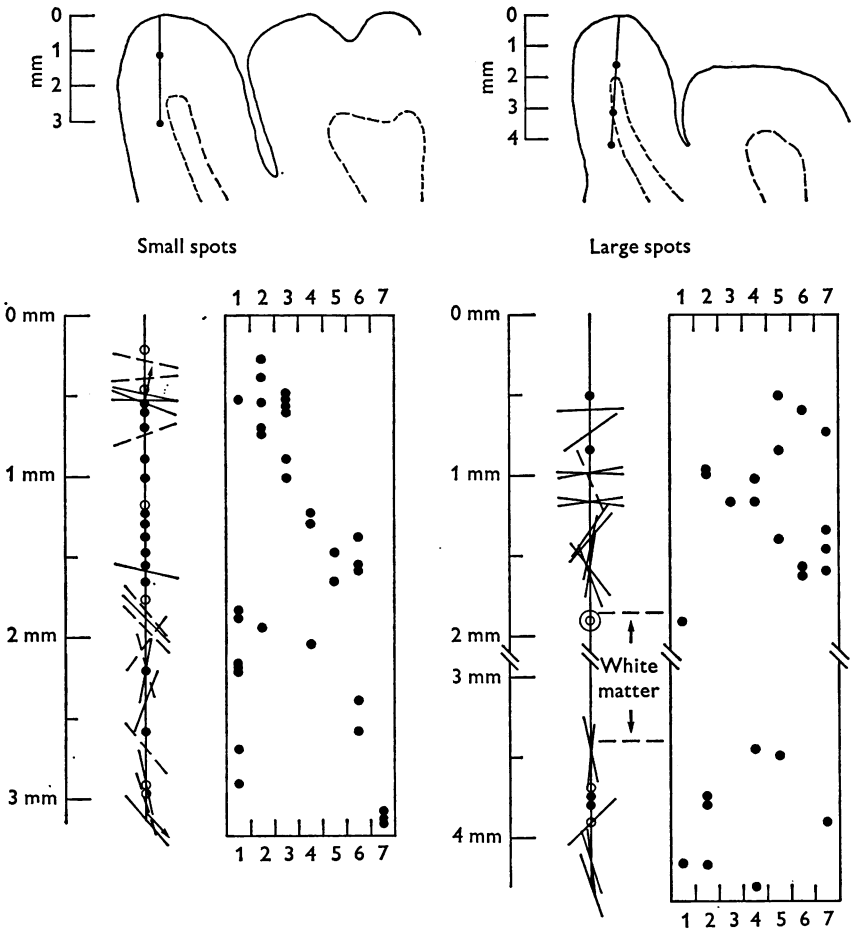

Fig. 19. Penetration reconstructions for one of the 'small spots' kittens (K103) and one of the 'large spots' kittens (K133). Same symbols as in Figs. 5 and 11 with the addition of: *afferent geniculate fibre, ON centre* = concentric circles with open centre.

spot was lengthened into a line and hence were really better described as 'narrowly-tuned axial movement detectors'. Of all the visually responsive cells, 76 % (thirty-two cells from forty-two) were at least as responsive to spots as to lines in the 'small spots' animals, and 85 % (fifty cells from fifty-nine) in the 'large spots' animals.

To return to our main theme, it is surely significant that the kittens reared in small spots had many fewer orientation selective cells (even when defined simply as having a preferred orientation for a long line and not responding to movement of an orthogonal contour) than those exposed to large spots. The more extended contours of the large-diameter spots seemed to promote the formation of orientation selectivity and with it clear columnar clustering, as shown in Fig. 19.

One other feature was rather unusual in these animals: cortical neurones were perhaps not quite so often binocularly driven as in normal adult cats or visually inexperienced kittens. (Binocularity was not obviously reduced in any of the other animals in this experimental series.) An environment of random spots may possibly be inadequate, in some way, to maintain cortical binocularity: we shall return to this question in a future publication.

Exposure to stripes

The results of early exposure to striped environments have been reported before (e.g. Hirsch & Spinelli, 1970; Blakemore & Cooper, 1970; Blakemore & Mitchell, 1973; Pettigrew & Garey, 1974) and we shall consider only those points that are relevant to the hypothesis that experience of extended contour promotes the emergence of orientation selectivity. A number of animals were reared in the manner of Blakemore & Cooper (1970), keeping them in the dark but presenting them with striped patterns in a cylindrical chamber for 1–2 hr each day.

Stripes of one orientation

We consider one typical kitten (K61) exposed briefly to vertical stripes, for only 6 hr in total between day 27 and day 29, and two others (K31, K8) exposed for 27 and 33 hr during the third and fourth weeks. Even the 'short term vertical' animal had a very high proportion of orientation selective cells (73 %: twenty-two cells from thirty) and the 'long term vertical' kittens were even more mature in this respect (91 %: sixty-nine of seventy-six cells).

Just as previously described, there was a very strong tendency for all orientation selective cells to prefer vertical contours, though the effect was slightly less pronounced in the short term animal: Fig. 20 (*A* and *B*) compares the distributions of optimal orientations for the 6 and 27 hr kittens.

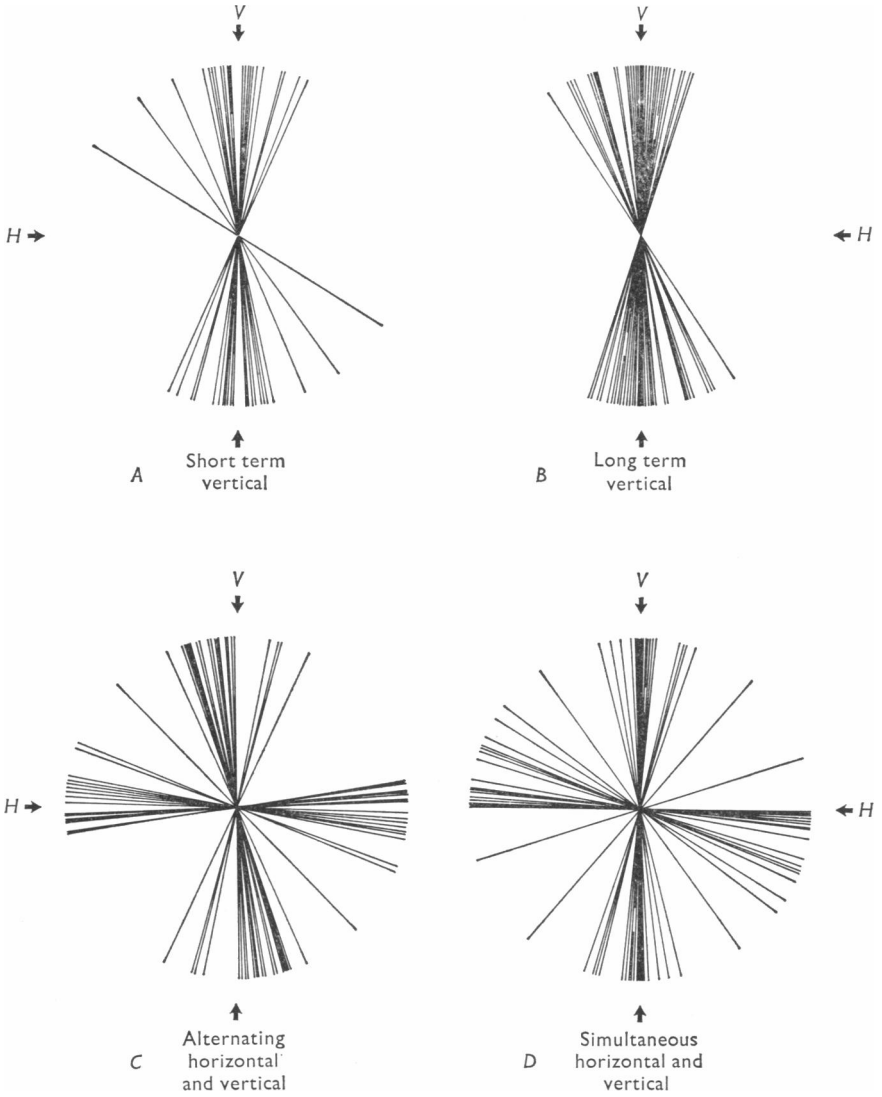

Fig. 20. Polar diagrams summarizing the preferred orientations in the dominant eye for all orientation selective and orientational bias cells recorded from animals reared in striped environments. *A*, 'short term vertical' kitten (K61); *B*, one of the 'long term vertical' kittens (K31); *C*, one of the 'alternating horizontal and vertical' kittens (K19) and *D*, 'simultaneous horizontal and vertical' kitten (K81). Same symbols and conventions as in Fig. 16.

Alternate and simultaneous exposure to horizontal and vertical stripes

Blakemore & Mitchell (unpublished) have found that periodic exposure to both horizontal and vertical contours tends to cause the establishment of two main types of orientation selective cortical cells, those tuned near horizontal and those near vertical. Two animals were exposed alternately to horizontal and vertical, one for 30 min at a time in each (K52), and the other for 3 hr at each exposure (K19). Both animals had a total of more than 50 hr of both horizontal and vertical experience and were recorded at about 9 weeks. Finally, we exposed an animal (K81) for a total of 53 hr to an environment containing both horizontal and vertical white stripes of various thicknesses and spacings, superimposed on the dark background. This created a mass of large black rectangles on a white ground.

All three animals had very high proportions of orientation selective cells (more than 90 %) and all showed a predominance of cells preferring angles near horizontal and vertical. Fig. 20*C* and *D* show the distributions of preferred orientations for one of the kittens exposed alternately (for 3 hr at a time) and for the animal exposed simultaneously to both.

The necessary environmental conditions for normal development

Briefly, our results can be summarized as follows:

(*a*) About one fifth of the cells that we can record in the young inexperienced cortex are truly orientation selective, though very broadly tuned by adult standards.

(*b*) Most of these are simple in properties, monocularly driven, and are found in deeper cortical layers.

(*c*) There appear to be at least the rudiments of a columnar organization, in that some neighbouring cells have similar orientation preference.

(*d*) There is little or no passive maturation of this system in the absence of patterned retinal images.

(*e*) Visual experience of dark-light borders seems to be the essential requisite for the emergence of a normal adult cortex, but only if the contours are elongated and are at least a few degrees in length.

In order to emphasize this final point, Fig. 21 reviews the outcome of our experiments. We have ranked the various procedures in the approximate order of increasing experience of elongated contour, shown along the abscissa, and the proportions of all cell types produced by these manipulations are shown above.

We have, for the sake of comparison, separated the results for the two very young, visually inexperienced animals (Fig. 21, column *A*) recorded before the beginning of the sensitive period (Hubel & Wiesel, 1970; Blakemore, 1974; Blakemore & Van Sluyters, 1974) from all the binocularly

deprived kittens (column *B*). Then come the other types of special visual environment in the order described above, ending with all the normal control animals except those recorded before 5 weeks of age (column *J*).

Though this serial ranking of the procedures is perhaps somewhat arbitrary and is, at best, only ordinal, the trend in the data is quite apparent. Across the spectrum of increasing visual experience there is a

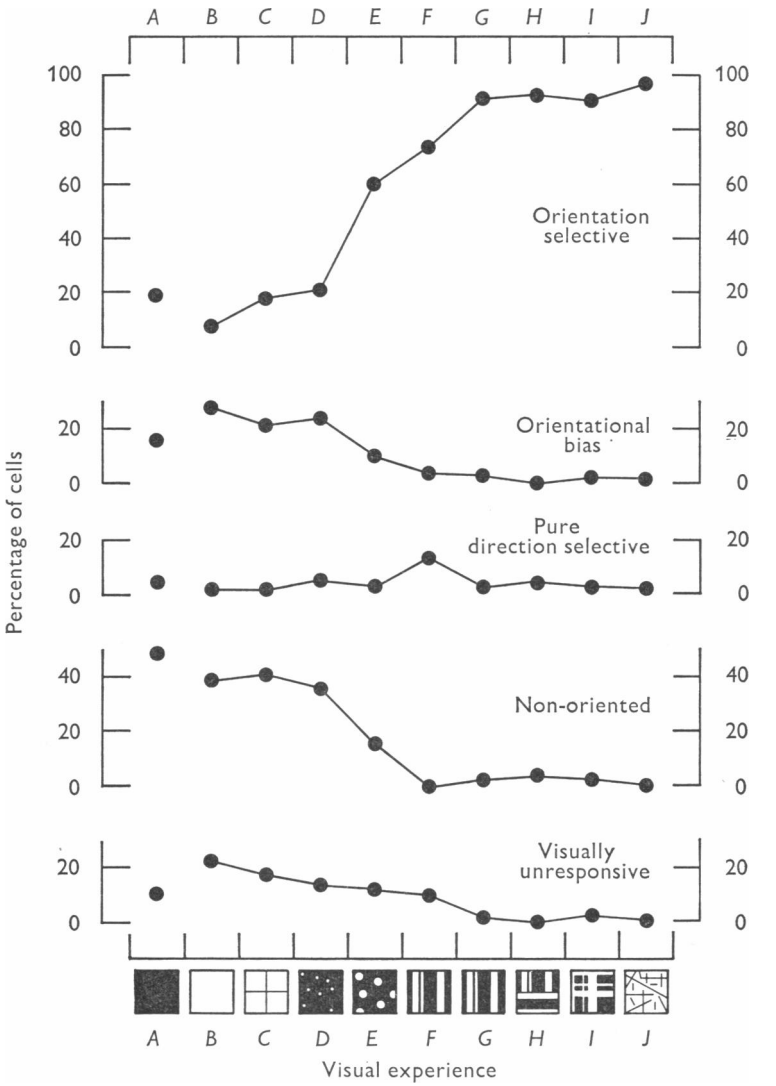

Fig. 21. For legend see facing page.

gradual increase in the percentage of orientation selective cells (with a notable increase in the fraction of complex and hypercomplex types). Concomitantly the proportion of orientational bias, non-oriented and visually unresponsive cells falls, while the number of pure direction selective neurones remains constant and low.

We conclude that the progressive refinement of the cortex mimicked by this set of experimental procedures is taking place in the normal kitten between the ages of about 2 and 5 weeks as it takes its fill of the normal visual world.

DISCUSSION

The visually inexperienced cortex

There appears to be a strong contradiction between the original observations of Hubel & Wiesel (1963) and those of Barlow & Pettigrew (1971), Pettigrew (1974) and Imbert & Buisseret (1975) on the level of specificity to be found in the visually inexperienced kitten's cortex. However those results are perhaps more different by repute than they are in reality. Pettigrew (1974) has reported very small numbers of cells in the deprived cortex that are orientation selective by the strictest criteria, and many that are definitely selective for a particular axis of movement. (His main concern was the importance of visual experience for the appearance of disparity selectivity, a property that Hubel & Wiesel, 1963, did not consider at all.) Moreover Hubel & Wiesel themselves (1963) did comment on the extremely broad orientation tuning, the general lack of responsiveness and the common habituation of cells in the very young cortex, and on the frequent occurrence of non-oriented cells in longer-term binocularly

Fig. 21. Comparison of the various forms of restricted visual experience employed in the present experiments. The five curves show the percentages of cells with each type of receptive field for 687 cells recorded from twenty-two animals allowed the following types of visual experience: (*A*), two very young, visually inexperienced kittens (K160, K165) whose data points are shown separated from the rest of the animals for the sake of comparison; (*B*), five binocularly deprived kittens (K163, K207, K36, K139, K190); (*C*), one kitten (K104) reared in a diffusely illuminated tube and given minimal experience of horizontal and vertical contour; (*D*), two kittens (K102, K103) reared in 'small spots'; (*E*), two kittens (K132, K133) reared in 'large spots'; (*F*), one kitten (K61) given 'short term' experience of vertical contour; (*G*), two kittens (K31, K8) given 'long term' experience of vertical contour; (*H*), two kittens (K52, K19) exposed alternately to horizontal and vertical contour; (*I*), one kitten (K81) exposed simultaneously to horizontal and vertical contour; (*J*), four normally reared kittens (K82, K83, K145 and D3) all of whom were older than five weeks at the time of recording.

deprived animals (Wiesel & Hubel, 1965). Perhaps our results will help to clarify the present situation by resolving some of these differences, both real and apparent.

Without doubt, there is a good deal of innately determined specificity in the naive visual cortex. As many as a quarter of all cortical neurones in an inexperienced animal can be truly orientation selective (Fig. 11). If one takes into account the fact that orientational bias cells and pure direction selective cells appear to have a preferred orientation when tested only with moving slits or edges, almost half of all deprived cortical cells have some form of orientational preference (though we fully agree with Pettigrew, 1974, that it is important to stress the functional difference between orientation and direction selectivity).

It is a little surprising that we find so many more truly orientation selective cells than did Pettigrew (1974). However, they are rather less common in deprived kittens older than about 5 weeks, and many of his samples came from such animals. Also, we find them more frequently in the deeper layers of the cortex and it is possible that, with the inevitably longer analysis time and smaller yield in his quantitative experiments, Pettigrew (1974) rarely reached the deeper layers of the cortex. Indeed, when Imbert & Buisseret (1975) deliberately restricted the depth of their penetrations they also failed to record any specified neurones in deprived kittens. But in more recent experiments Buisseret & Imbert (1975) have succeeded in finding a proportion of orientation selective cells similar to that which we report in very young, inexperienced kittens.

There is an alarming possibility that the stimulation imposed by us during the mapping of receptive fields might have influenced our results, for even very brief periods of visual experience are known to cause a radical improvement in the stimulus specificity of cortical neurones (Pettigrew *et al.* 1973; Blakemore & Mitchell, 1973; Pettigrew & Garey, 1974; Peck & Blakemore, 1975). Such a hypothesis might also explain why we usually found orientation selective cells only in the deeper layers of the cortex, some time after the start of the experiment. However, first, the process of environmental specification seems to require an interval of many hours of 'consolidation' before neuronal changes become apparent (Pettigrew & Garey, 1974; Peck & Blakemore, 1975). Secondly, we did occasionally discover an orientation selective cell early in the penetration (Figs. 13 and 14). Thirdly, we purposely avoided any chance of visual experience, even during the surgical preparation, and although we thoroughly analysed each unit, every effort was made to work as quickly as was practical, to preclude the possibility of inducing changes in the properties of cells. Finally, there were penetrations that re-entered the more superficial layers, deep down in the medial bank of the post-lateral gyrus and the proportion

of orientation selective cells found there was small, despite the fact that these were the last units recorded in the experiment (e.g. Fig. 15*A*).

Another word of caution is particularly noteworthy. In our experience, one can say nothing valid about the responsiveness or even the specificity of kitten cortical neurones without the most scrupulous attention to the physiological condition of the preparation and a detailed knowledge of that condition. Even a seemingly small decline in the animal's state of health (indicated by a gradual fall in blood pressure, a decrease in expired CO_2, a slight reduction in the amplitude of the e.e.g. and a lengthening of the QRS complex of the e.c.g.) can cause disastrous changes in the visual cortex, long before the condition is terminal. Cells can become totally unresponsive or non-specific, even in animals that have had normal experience, and large areas of cortex can seem silent. We cannot emphasize enough the importance of constantly monitoring the animal's condition properly.

The whole technique of sampling various types of neurones and drawing conclusions about the percentages of those types has recently been examined at length by both Stone (1973) and Levick & Cleland (1974). Stone reports that in the cat's retina, the proportions of the different kinds of ganglion cells that can be recorded depend mainly on the type, shape and impedance of the micro-electrode. In particular, he found that high impedance capillaries seemed much more effective in detecting small cells. Stone & Dreher (1973) used microcapillaries in the visual cortex of the adult cat and found that large numbers of cells could not be driven at all by visual stimuli. On the other hand we very rarely see any neurone that is not clearly orientation selective in the normal adult cortex. Could it be that the proportions of orientation selective, orientational bias, pure direction selective, non-oriented and visually unresponsive cells do not really change during development: do the orientation selective cells merely become larger and easier to record? We think that this is unlikely. Levick & Cleland (1974) were quite able to isolate small retinal ganglion cells using tungsten-in-glass micro-electrodes very similar to ours. In our own experiments, we used identical methods of recording in all animals and had no difficulty whatever in isolating non-specific cells in inexperienced animals. Also, the density of isolated units in each penetration was very constant throughout the series, suggesting that we did not miss any more cells in the normal adult than in the young kitten. So we believe that our results do give an indication of the relative effects, at least, of different kinds of visual experience.

The responsiveness and stimulus specificity of many cortical cells in the 9-day-old kitten (Fig. 10) is quite remarkable in view of Cragg's (1972) discovery that only 1·5 % of the adult complement of synaptic terminals

is present at day 8 and that dendritic spines do not appear at all until day 7–10. Unlike Pettigrew (1974), we experienced no difficulty in isolating units in the very young cortex and the majority of them were visually responsive. If kitten cortical cells do so well with so few synaptic connexions, one cannot help wondering what fraction of the 7000 odd synapses per cell observed in the adult cortex actually contribute significantly to the responsiveness or selectivity of the cell (see Creutzfeldt & Ito, 1968). In the very young kitten, incoming afferent fibres form early connexions mainly in the deeper cortical layers (Anker & Cragg, 1974), and it is not until later, in the second, third and fourth weeks, that large gains in synaptic density are made in the superficial layers (Cragg, 1972). This seems to fit very well with the occurrence of orientation selective cells deeper in the cortex of deprived kittens (Fig. 14) and with the virtually adult organization of the normal kitten's cortex at the age of 4 weeks (Fig. 6).

Although inbuilt factors are clearly important in the development of the visual cortex it would be quite wrong to underemphasize the role of visual experience. The two animals recorded at 19 days, one inexperienced, the other normal, were remarkably different (Fig. 6). While the inexperienced animal had the highest proportion of orientation selective cells of all our deprived kittens, it paled by comparison with the 19 day normal. The latter, despite only 8 days of vision through very cloudy optics, was impressively more mature. It is our feeling then, that the very earliest visual experiences, before the start of the 'sensitive period' at about 3 weeks, are already stamping strong impressions on the visual cortex. This conclusion contrasts markedly with that of Pettigrew (1974), who could distinguish little or no consequence of visual input before the fourth week.

Certainly, if binocular deprivation is prolonged beyond the age of about 3 weeks, there is no passive maturational improvement in cortical organization: indeed there may actually be degradation. No degree of diffuse retinal illumination seems adequate to promote further development (Fig. 6). Only the observation of quite long dark-light borders seems sufficient to promote normal development (Fig. 21). Even though early visual experience of an environment of small white spots produces a briskly responding cortex, it does not enlarge the population of orientation selective cells. Larger spots, some 5 degrees in diameter, are much more successful in promoting the development of orientation selectivity (Fig. 21). However, even small spots are not without influence on the selectivity of cortical cells: they seem to promote the emergence of an unusual preference for the very stimulus seen in early life (Figs. 17 and 18). Thus, experience of patterned stimuli without long edges is adequate to cause an increase in both excitatory input (hence increased responsiveness) and

inhibitory input (hence size selectivity) to cortical cells. But long contours are needed for the specific generation of orientation selectivity. Perhaps the ability to develop 'spot-selectivity' represents a power of adaptive plasticity that cortical cells are never normally called upon to use (Van Sluyters & Blakemore, 1973). It is also conceivable, however, that the process of developing partial or complete suppression of response for long contours might be important in the natural formation of hypercomplex cells (Hubel & Wiesel, 1965), and, indeed the generation of the somewhat weaker 'end inhibition' present even in most simple and complex cells (Rose, 1974). The natural, occasional early experience of short contours might bestow this property on cortical cells, while the common occurrence of long contours in the normal visual world would ensure that almost all cells also acquire true orientation selectivity.

The importance of environmental influences

What is the biological value of the influence of visual experience on normal cortical development, when genetic instructions are apparently capable of specifying quite exact properties for at least some cortical cells? One possibility is that some inherent *modifiability* of orientation selectivity could guarantee that the feature-detecting properties of cortical cells become matched to the frequency of occurrence of feature combinations in the kitten's visual environment (Blakemore & Cooper, 1970; Spinelli, Hirsch, Phelps & Metzler, 1972; Barlow, 1972; Blakemore, 1974). However, such a scheme seems less elegant when one considers that there is already a good deal of innate specification. And in fact, the average cat has little if any predominance of cells tuned to vertical and horizontal, perhaps the commonest orientations a kitten would encounter in an urban or laboratory environment (Pettigrew *et al.* 1968; Rose & Blakemore, 1974). So, environmental modification by rearing in stripes of a single orientation may illustrate a mechanism that does not in fact play a major part in determining the distribution of preferred orientations in most cats.

We have already suggested that an alternative adaptive function of orientational modification would be to ensure that the preferences of binocular neurones become closely matched in the two eyes, a necessary condition for their possible part in stereoscopic analysis (Blakemore & Van Sluyters, 1974; Blakemore, 1974). Our present experiments have provided further evidence that visual experience is certainly needed for matching the receptive field properties of binocular neurones. In our analysis of the characteristics of cells in the deprived and the experienced cortex we considered only the receptive field in whichever eye dominated the neurone (Fig. 6). However, in animals that had not had patterned visual experience, many binocular cells had rather different receptive fields

in the two eyes. Table 1 contains contingency tables which analyse interocular similarity of receptive fields for all binocular cells from the seven binocularly deprived kittens and from the two youngest normal kittens (19 and 26 days). Although in both normal kittens all cells had similar characteristics in the two eyes, a number of neurones from the deprived animals did not. In every case where there was an interocular difference, the field in the eye that dominated the cell was more 'specified' than that in the non-dominant eye. Cells that were orientation selective in both eyes were always of the same basic type (simple, complex or hypercomplex). However, such cells in the inexperienced cortex often had enormously different preferred orientations on the two retinae.

TABLE 1. Similarity of receptive fields in the two eyes

A. *Seven binocularly deprived animals*

	Receptive field in dominant eye			
	Orientation selective	Orientational bias	Pure direction selective	Non-oriented
Receptive field in non-dominant eye				
Orientation selective	9	—	—	—
Orientational bias	—	37	—	—
Pure direction selective	—	—	4	—
Non-oriented	2	6	1	77

B. *Two young normal animals* (19- *and* 26-*day*)

	Receptive field in dominant eye			
	Orientation selective	Orientational bias	Pure direction selective	Non-oriented
Receptive field in non-dominant eye				
Orientation selective	29	—	—	—
Orientational bias	—	3	—	—
Pure direction selective	—	—	2	—
Non-oriented	—	—	—	5

In Fig. 22 we show the range of interocular *differences* in preferred orientation for cells that were orientation selective (filled blocks) or orientational bias (open blocks) in both eyes, or selective in one eye and biased in the other (half-filled blocks). The distribution for the deprived kittens is very broad (S.D. of observation = 24·1°; n = 49), rather like that from kittens that have never had simultaneous binocular experience (Blakemore & Van Sluyters, 1974). On the other hand the distribution for two very young normal animals is much narrower (S.D. of observation = 10·27°; n = 40) and is not obviously different from that of the normal

adult (Blakemore *et al.* 1972). These two distributions are significantly different from each other ($P < 0{\cdot}001$; F test, d.f. 48, 39). The data for individual animals are pooled but the enormous breadth of the histogram is not accounted for by an increase in variance due to pooling: even the deprived animal with the smallest variance had a range of differences in orientation of 58° (S.D. of observation 18·32°; $n = 11$). Neither are the extreme ends of the distribution entirely devoted to orientational bias cells with preferred orientations that were vague and difficult to define. Some of the cells with the largest discrepancies in receptive field orientation were definitely orientation selective with clear optimal orientations.

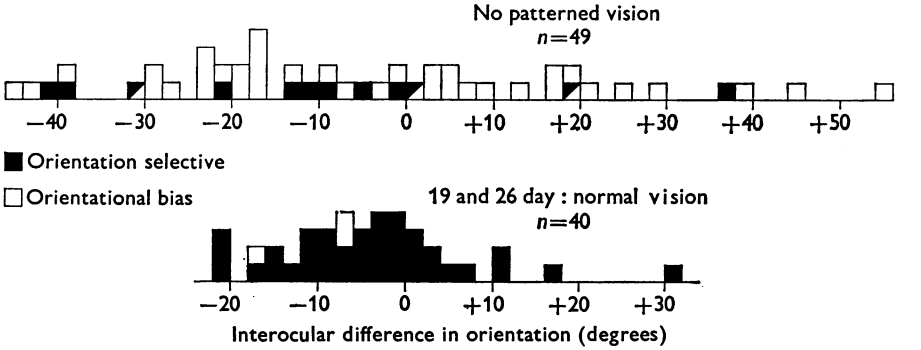

Fig. 22. Histograms, showing differences in preferred orientation in the two eyes for orientation selective cells (filled blocks), orientational bias cells (open blocks) and cells with an orientation selective receptive field in one eye and an orientational bias in the other (half-filled blocks). The upper histogram represents the data for forty-nine binocular cells recorded from seven kittens who had been totally deprived of any patterned visual experience (K160, K165, K163, K207, K36, K139 and K190). The lower histogram shows, for the sake of comparison, data for forty binocular cells recorded from the two youngest kittens who had received normal visual experience (K243, age 19 days; K236, age 26 days). In all animals the receptive field orientations were corrected for any torsional movements of the eyes following paralysis. Orientations clockwise from horizontal are negative, those anticlockwise are positive. To obtain the interocular difference in preferred orientation, the orientation in the left eye was algebraically subtracted from that in the right.

Visual experience is clearly required for the achievement of similar feature selectivity in the two eyes, and our previous results suggest that simultaneous binocular experience is needed (Blakemore & Van Sluyters, 1974). However, this raises an intriguing paradox. The two young animals of Fig. 22, even the 19-day kitten, had well matched preferred orientations in the two eyes, implying that they had received correlated binocular input. Yet it is current dogma that the kitten's eyes are extremely divergent

until at the least 4 weeks, and the deviation of at least the pupillary axes is obvious at a glance (Sherman, 1972; Pettigrew, 1974). We are led to propose, therefore, that the visual axes (or at least the receptive fields of many binocular cells) must be correctly aligned in visual space at least part of the time, even during the third week of life.

We suggest, then, that the influences of normal visual experience probably have three major functions:

(1) to enable genetically-specified simple cells to impose similar orientation selectivity on the cells around them and hence create the adult columnar system,

(2) to ensure that most cortical cells remain binocularly driven and, equally important, that they acquire similar preferred orientations in the two eyes, and

(3) to improve the crude innate orientational tuning, perhaps by some sort of inhibitory sharpening process.

Comparison with the rabbit

Before considering a model of cortical development that can account for these processes it is worth considering briefly a comparison with the rabbit, another well-studied species. In the rabbit's visual cortex, cells with simpler 'radially symmetrical' receptive fields are present at or near the time of natural eye opening, but the more complicated 'non-symmetrical' fields (orientation and direction selective) only appear between 10 and 25 days (Mathers, Chow, Spear & Grobstein, 1974). However, this maturation process is, apparently, entirely passive, since it is unhindered by visual deprivation (Chow & Spear, 1974). Even in the binocular representation of the visual cortex, prolonged monocular deprivation causes only the slightest shift in ocular dominance (Van Sluyters & Stewart, 1974*b*). Similarly, selective visual experience of stationary or moving contours at one orientation fails to modify ganglion cells (Daw & Wyatt, 1974) or cortical cells (Mize & Murphy, 1973).

This almost total lack of environmental influence in the rabbit's visual pathway contrasts strongly with the situation in kittens. The apparent uses that cats and rabbits make of their visual systems might provide an explanation for this remarkable difference. Rabbits have essentially panoramic vision, extremely complicated retinal processing and seemingly little increase in pattern abstraction between eye and brain. Their visual cortex has no obvious orientation columnar system, and in the limited binocular area, neurones often have very different receptive field properties in the two eyes (Van Sluyters & Stewart, 1974*a*). They can have incredibly large (and seemingly functionless) retinal disparities and totally discrepant preferred orientations or directions in the two eyes. How

different this is from the cat's cortex, where most cells are binocularly driven, they have very closely matched properties in the two eyes (Noda, Creutzfeldt & Freeman, 1971: Blakemore *et al.* 1972), and the range of receptive field disparities seems quite appropriate to the demands of stereoscopic vision (Barlow *et al.* 1967; Joshua & Bishop, 1970).

Conceivably, the resistance to developmental modification in the rabbit's cortex reflects the rigid specificity already imposed by immutable retinal processing. Modifiability might be so much more important in the cat because it is essential for the matching of receptive field properties in the two eyes and for defining the range of preferred disparities that will be naturally encountered (Shlaer, 1971; Pettigrew, 1974). Plasticity seems to be needed for this crucial business of ensuring that binocular cells will recognize the two similar images of single objects in space and encode their three-dimensional positions. It is this perfection of a mechanism for stereopsis, then, that seems to demand more information than genetic messages alone can carry. The kitten's visual system takes advantage of the fact that it is experiencing early in life the kinds of binocular stimulation that it needs to analyse. Modification of the narrowness of disparity-selectivity and the actual range of preferred disparities will match the binocular system to the geometric properties of its three-dimensional environment. Modification of preferred orientation will ensure that cells pick up closely-matched receptive field characteristics in both eyes, since they are habitually stimulated by the two very similar retinal images of single objects in space.

We suggest, therefore, that extreme plasticity might be a property of only highly binocular animals, with relatively few complicated ganglion cells (Stone, 1973; Cleland & Levick, 1974) and a well-developed cortical mechanism for stereoscopic vision.

A model for the maturation of the kitten's visual cortex

Finally, we present a very preliminary and speculative model of the organization of the naive kitten's cortex and the way that it might be changed during development. The model attempts to deal not only with our own findings but also with a number of other physiological and anatomical observations on the cat's striate cortex. In addition, it acknowledges the *Zeitgeist* of visual neurophysiology, which has cast some doubt on certain aspects of Hubel & Wiesel's (1962, 1965*a*) basic hierarchical model of the cortex.

The essence of the model is shown in Fig. 23 and the symbols used are explained in the legend. This represents a very simplified view of the cell types found in layers III–V of the visual cortex and some possible synaptic arrangements (Colonnier, 1966; Marty & Pujol, 1966; Garey, 1971; Lund,

1973; Szentágothai, 1973). There have been many laudable attempts to discriminate neuronal types according to the shape of the soma and the distribution of dendrites (Colonnier, 1966; Garey, 1971), the presence or absence of dendritic spines (Lund, 1973) and the distribution of the axon (Szentágothai, 1973). However, we shall follow LeVay's (1973) simple classification: (1) *Pyramidal cells P*, having apical dendrites that usually reach layer I, and many dendritic spines; (2) *Spiny Stellates SS*, found mainly in layer IV and having spines on their relatively regularly-arranged dendrites; (3) *Non-spiny or sparsely-spinous stellate cells NS* found in all cortical layers, having few if any dendritic spines, and axons of intrinsic distribution.

Synaptic terminals in the visual cortex (Colonnier, 1968; Garey, 1971) can usually be classified as belonging unambiguously to Gray's (1971) type I (asymmetrical, spheroidal vesicle, presumed excitatory) or type 2 (symmetrical, flattened vesicle, presumed inhibitory). Dendritic spines, on both pyramids and stellates, receive type 1 synapses almost exclusively (Colonnier, 1968; Garey, 1971; LeVay, 1973), while the somata almost always receive only type 2 contacts. The terminations of specific afferent fibres from the lateral geniculate nucleus, while they constitute only a tiny fraction of all synaptic endings (about 5 % of those in layer IV), end on the spines of both pyramidal and spiny stellate cells. They are all of type 1 (Colonnier & Rossignol, 1969; Garey & Powell, 1971). Pyramidal cells almost certainly also receive type 1 connexions from the terminations of other cortical neurones. Both pyramids and spiny stellates can have axons that leave the cortex (Szentágothai, 1973), but most have axon collaterals, which, after little horizontal spread, terminate in type 1 endings on the dendrites of other cortical cells (LeVay, 1973). Non-spiny stellate cells appear to distribute axons only within the cortex and they are probably inhibitory interneurones, since they end in type 2 synapses (LeVay, 1973). Since all the extrinsic input to the visual cortex probably has type 1 terminals (Garey & Powell, 1971), these smooth stellates, which include basket cells (Szentágothai, 1973) and *cellules fusiformes à double bouquet dendritique* (Colonnier, 1966; Garey, 1971), might be the origin of all presumed inhibitory synapses in the cortex.

Recently, Kelly & Van Essen (1974) have shown most elegantly that the majority of simple cells are stellate while virtually all complex cells are pyramidal. This would seem to support Hubel & Wiesel's hypothesis (1962) that simple cells, found mainly in layer IV, receive direct thalamic input and provide excitatory input to complex cells, thereby imposing similar orientation selectivity within the same column. However, there is now a good deal of evidence that both simple and complex cells can receive direct, monosynaptic input from the lateral geniculate nucleus.

Moreover, complex cells are more often driven by the large axons of (transient) 'Y' cells in the geniculate and simple cells by the smaller (sustained) 'X' axons (Hoffmann & Stone, 1971; Stone & Dreher, 1973).

The fact that complex cells respond briskly to a velocity of movement faster than can be detected by the majority of simple cells renders the straightforward serial model even more unlikely (Pettigrew *et al.* 1968; Movshon, 1975).

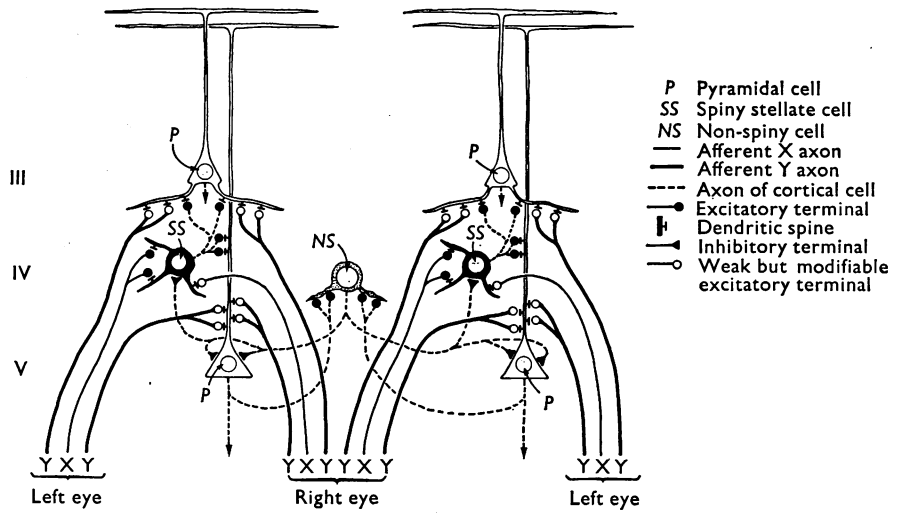

Fig. 23. A tentative model of the organization of layers III, IV, and V of the kitten's visual cortex. The symbols used to identify the various cell types and their connexions are shown on the right. The data that prompt us to propose this system for the maturation of the kitten's visual cortex, as well as some of its implications, are discussed in detail in the text.

Let us suppose, then, that X axons are distributed mainly to the spines of spiny stellate cells in layer IV, while Y axons end largely on the apical dendrites of layer *V* pyramids and the basal dendrites of layer III pyramids. Without visual experience, the only really secure geniculate terminations are those of X fibres on to spiny stellates and they endow the cells innately with orientation selectivity and simple properties. However, each such simple cell receives strong input from only one eye or the other and there is clear clustering of stellate cells according to ocular dominance. Further, imagine that the other X fibre terminals on to each spiny stellate cell (from whichever eye is non-dominant), and all the Y axon terminals from both eyes on to pyramidal cells are of a special, *modifiable* form. They are initially only very weakly excitatory, but those whose firing is regularly and reliably associated with post-synaptic impulse activity become

strengthened (Hebb, 1949; Brindley, 1967). To begin with, the Y cell axons ending on pyramidal cells represent a diffuse projection from one part of the visual field and do not encode any particular stimulus orientation. The pre-specified spiny stellate simple cells have excitatory endings on the dendrites of these same pyramidal cells. Initially, then, each pyramidal cell would be rather unresponsive and non-specific, showing, if anything, only a slight preference for the orientation that is innately specified for the stellate simple cell which provides its only really secure drive. These pyramidal cells, which are destined to become complex, at first appear to be non-oriented or orientational bias.

Now consider what might happen during normal visual experience. Each pre-specified simple cell fires most strongly when an object of the correct orientation appears in its essentially monocular receptive field. If both eyes are open, a very similar image will be present on the other retina, in a region determined by the angle between the visual axes, and the distance of the object from the cat. Thus the stellate cell will receive input through the weak, modifiable terminals from the non-dominant eye, at the same time as it is driven by the effective input from the other eye. In time this leads to the consolidation of an effective receptive field in the non-dominant eye, whose orientation closely matches that in the dominant eye and whose retinal position is appropriate to the average disparity of the retinal images. Similarly, the excitatory drive from the orientation selective stellate cells to the surrounding pyramidal cells will ensure that they too strengthen the direct input that corresponds to the same orientation, the same retinal position and the same disparity, although the axons carrying the information are Y rather than X. Thus, in time, pyramidal cells would shift from being almost completely non-specific to having the same preferred orientation as the simple cells in the same radial column, *even though they might have almost completely separate, parallel input.* An hierarchical arrangement between stellate and pyramidal cells is essential initially in order to provide the 'conditioning' input to putative complex cells, and may express itself in the properties of some complex cells even in the adult (Movshon, 1975).

This scheme, in which an initially specified input 'programmes' the properties of a largely unspecified synaptic input, has much in common with Marr's (1969) model of the organization of cerebellar cortex.

The model also incorporates a possible scheme whereby intracortical inhibition could improve the selectivity of cortical neurones for orientation (Benevento, Creutzfeldt & Kuhnt, 1972; Blakemore & Tobin, 1972). The excitatory terminations of axons and recurrent collaterals of pyramidal cells (and perhaps spiny stellate cells) end on the dendrites of non-spiny cells, which in turn distribute inhibitory endings mainly to the somata of

both pyramidal and stellate cells. This 'lateral' inhibition would be most effective within the same cellular column, but could spread tangentially, to some extent (Fisken, Garey & Powell, 1973) perhaps through the long axons of basket cells (Szentágothai, 1973). The inhibitory interneurones, which in this scheme would be non-spiny or sparsely spinous stellates, should have very broad orientation tuning (depending on the breadth of tuning of all the cells that contact their dendrites) and might have predominantly complex characteristics (or mixed simple and complex properties). Kelly & Van Essen (1974) did inject one complex cell that proved to be a small, presumably spine-free, stellate in layer II and another that was probably a *cellule à double bouquet*, but their sample did not include any basket cells.

This is only the simplest of possible systems of intracortical inhibition. It is likely that other inhibitory mechanisms are responsible for the creation or improvement of direction, velocity and disparity selectivities, as well as the 'end inhibition' of hypercomplex cells. Also, there is good evidence that most cortical neurones receive feed-forward inhibition, derived only di-synaptically from the afferent input (Watanabe, Konishi & Creutzfeldt, 1966; Toyama, Matsunami, Ohno & Tokashiki, 1974). Thus, although an important component of intracortical inhibition may be tri-synaptic feed-back of the kind described here, there is probably direct afferent input to at least some inhibitory interneurones.

This model (which we emphasize again is very tentative and is intended to be of heuristic value) has several other features, apart from accounting for our observations in the immature kitten and the adult visual cortex. It can, for instance, explain the loss of connexions from one eye during monocular deprivation (Wiesel & Hubel, 1963) and artificial strabismus (Hubel & Wiesel, 1965*b*). In the first case there would be no consistent input from the deprived eye, and hence no strengthening of those synapses. In the case of squint, the misalignment of the visual axes would prevent the non-dominant eye for the column in question from having the corresponding image within its field of input. Therefore its connexions would fail to mature, unless the angle of squint were small, in which case the disparities of receptive fields would become appropriate to that angle (Shlaer, 1971).

Modification of orientation selectivity is also accounted for, at least in part. As long as the experienced orientation falls somewhere within the very broad tuning curve of the pre-specified simple cell, then complex cells around it will adopt a preference for the experienced orientation. So too will the simple cell in its non-dominant eye. To explain a shift in preferred orientation even for the innately specified input to the simple cell from the dominant eye, one would have to propose that even that input includes

modifiable synapses, which can also be strengthened. But such a suggestion is probably needed anyway to account for the general increase in excitability, even of simple cells, despite the growth of inhibitory mechanisms.

It is perhaps relevant that Garey & Pettigrew (1974) found a convincing increase in the vesicle density in small type 1 terminals in layers III and IV after exposing deprived kittens to moving stripes. These may well be the terminals of the axons of spiny stellate cells, the ones that provide the 'conditioning' signal in our model.

In summary, then, both innate and environmental influences contribute to the maturation of the kitten's cortex. Genetic information lays down a synaptic field on which visual experience can play. The experience itself provides essential information that cannot be accurately forecast by genetic messages alone.

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