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THE ORGANIZATION AND POST-NATAL DEVELOPMENT OF AREA 18 OF THE CAT'S VISUAL CORTEX

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SUMMARY

1. We made extracellular recordings from 1176 single units in area 18 of adult cats and kittens aged between 7 days and 10 weeks, and from 137 single units in area 17 in kittens aged between 12 days and 10 weeks.

2. All cells examined in area 18 of adult cats were visually responsive, 84% being orientation selective, 9% orientation biased and 7% non-oriented. Orientation columns and ocular dominance columns were identified. There was an over-all bias towards horizontal and vertical in the distribution of preferred orientations in the rostal part of area 18, where we were recording.

3. In area 18 of 7-day-old, visually inexperienced kittens the majority of cells (60%) were visually unresponsive; the remainder were either non-oriented (25%) or orientation biased (15%), and no orientation-selective units were found. Nevertheless there seemed to be a rudimentary columnar system, even in the youngest animals, in that orientation-biased cells tended to occur in clusters with neighbouring neurones having similar orientation preferences. In normal animals of 3 weeks and younger we found that the distribution of preferred orientations of a sample of neurones in area 18 with receptive fields scattered over much of the left lower quadrant of the visual hemifield was biased to oblique orientations.

4. As in adult cats, most cells in area 18 in young kittens were binocularly driven, and periodic alternation of dominance along oblique penetrations, characteristic of ocular dominance columns, was sometimes seen, even at the earliest ages.

5. Many of the developmental changes that we observed in area 18 occurred during the first 4 post-natal weeks. Orientation selectivity, orientation tuning, directionality and responsiveness of neurones matured rapidly over this period. The proportions of simple and complex cells were similar in kittens aged 4 weeks or more to those in adult cats, whereas prior to this most neurones that displayed an orientation preference appeared to be immature simple cells.

6. A laminar analysis revealed that very few units in the superficial layers (I, II and III) in area 18 are visually responsive in kittens during their first and second weeks, but orientation selectivity rapidly develops during the third week. By contrast, even in very young, visually inexperienced kittens, the majority of neurones found in deeper laminae (IV, V and VI) are visually responsive and a few of them

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already show an orientation preference; however, the subsequent appearance of larger proportions of orientation-selective cells in these lower layers is a more prolonged process than in upper laminae.

7. Comparison of the development of areas 17 and 18 suggests that, although the processes of maturation are generally similar in the two regions, there are some differences, which may be related to differences in the types of afferent input.

INTRODUCTION

A number of authors have described the post-natal development of the receptive field properties of neurones in area 17 of the visual cortex of the cat (Hubel & Wiesel, 1963; Pettigrew, 1974; Blakemore & Van Sluyters, 1975; Buisseret & Imbert, 1978; Fregnac & Imbert, 1978; Bonds, 1979; Albus & Wolf, 1984; Braastad & Heggelund, 1985), but much less is known about the normal maturation of cells in area 18. Albus & Wolf (1984) examined the properties of relatively small numbers of visually responsive neurones in area 18 in four kittens aged between 7 and 14 days, and found no major differences between areas 17 and 18 in the frequency of orientation-selective cells. Our aim was to study the development of the receptive field properties, laminar distribution and 'columnar' arrangement of neurones in area 18 by examining large samples of cells at various ages during the first 10 weeks of the kitten's post-natal life. As we were particularly interested in comparing the maturation of areas 17 and 18, we also obtained data on the development of neurones in area 17 using identical techniques.

The post-natal development of area 18 in the cat is of interest in view of the type of input that this cortical region receives from the lateral geniculate nucleus (l.g.n.). Several studies (reviewed by Stone, 1983) have shown that X, Y and W cells in the l.g.n. all project to area 17, whereas the afferents to area 18 from the l.g.n. arise principally from Y cells (although W cells may also send axons to this region): area 18 does not receive a direct input from geniculate X cells. X, Y and W cells are distinguished in the adult cat on the basis of physiological and anatomical criteria (see Stone, 1983), but there may also be differences in the way in which each class develops. Daniels, Pettigrew & Norman (1978) reported that X cells in the kitten l.g.n. develop normal receptive field properties in advance of Y cells, although Friedlander (1982) found that the *morphological* characteristics of at least some geniculate Y cells mature earlier than those of geniculate X cells in kittens. Blakemore & Van Sluyters (1975) suggested that the distinctive class of 'simple' orientation-selective cells found in area 17 in very young kittens might receive projections mainly from geniculate X cells, and that cortical cells dominated by Y cell inputs mature later during normal post-natal development. Little is known about the normal maturation of cortical cells with afferents arising from W cells, but it is possible that these neurones are not orientation selective at birth (Leventhal & Hirsch, 1980). It has been suggested, then, that at least some cortical cells receiving X cell inputs are innately orientation selective, whereas neurones innervated principally by geniculate Y and W cells require visual experience to develop orientation selectivity (Blakemore & Van Sluyters, 1975; Leventhal & Hirsch, 1980). Both areas 17 and 18 already have topographically organized input from appropriate cell types in the l.g.n. by the time

of birth (Henderson, 1982; Henderson & Blakemore, 1986). Differences between the post-natal maturation of the receptive field properties of cells in area 17 and area 18 might reflect differences in the types of geniculate input that each area receives.

Preliminary reports of this work have been published previously (Price & Blakemore, 1984; Blakemore & Price, 1985).

METHODS

Animals

Successful experiments were performed on three normal adult tabby cats (2–3 years old) and fifteen normal kittens aged between 7 days and 10 weeks, bred in an isolated colony (Table 1; all ages stated refer to post-natal age at the start of the experiment). Data on neurones in area 18 were obtained from the three adult cats and thirteen of the kittens, four of which were also used, in addition to the remaining two kittens, for a study of area 17 (Table 1). The eyelids of the two 7-day-old animals had not opened naturally by the time of the experiment and they were separated under anaesthesia.

Surgical procedures

Anaesthesia was induced in all cats and kittens with ketamine hydrochloride (20 mg kg^{-1} intramuscularly) and maintained, initially, with alphaxolone–alphadolone (Althesin, Glaxo) intravenously (I.V.), as needed, and later, during electrophysiological recording, with sodium pentobarbitone (1 mg $(kg\ h)^{-1}$ I.V. or more). Gallamine triethiodide was also infused (10 mg $(kg\ h)^{-1}$ I.V.) to produce paralysis. The state of anaesthesia of the animal was assessed by monitoring the e.e.g. (electroencephalogram) and e.c.g. (electrocardiogram), and the dose of infused anaesthetic was adjusted if necessary so as to maintain a state in which potentially painful stimuli did not desynchronize the virtually continuous slow-wave e.e.g. or alter the heart rate.

The rectal temperature was maintained between 37·5 and 38 °C. During paralysis, animals were artificially hyperventilated (at 33 strokes min^{-1}) with room air plus extra carbon dioxide, adjusted to maintain the end-expiratory carbon dioxide at a level similar to that measured in the lightly anaesthetized animal prior to paralysis (always about 5%).

The animal was placed in a stereotaxic frame (Eldridge, 1979*a*) that leaves the visual field unoccluded and which permits the head to be rotated to any desired angle. Complete stability of the head was achieved in all cats and kittens by cementing a bolt to the skull and attaching it to the stereotaxic frame. In order to give access to area 18 a small craniotomy was made over the lateral gyrus, a few millimetres lateral to the mid line, close to the interaural coronal plane (a.p.0), while penetrations into area 17 were made through a craniotomy placed further medial and caudal. The exact location of each track was subsequently determined in histological reconstruction (described below).

Optical preparation

Bilateral cervical sympathectomy was performed in all animals to reduce residual drift of the eyes during paralysis (Rodieck, Pettigrew, Bishop & Nikara, 1967). Atropine sulphate (2% w/v) and phenylephrine hydrochloride (10% w/v) were applied topically in both eyes; zero-power contact lenses were used to protect each cornea, and artificial pupils (4·5 mm diameter) were positioned in front of each eye as close as possible to the contact lenses. The refractive state of each eye was assessed by direct ophthalmoscopy, and additional lenses were used to focus on the retina images back-projected on a screen 57 cm from the cat or kitten. In animals of about 2 weeks or older the projection of the area centralis of each eye could be plotted on the screen by means of a reversible ophthalmoscope (Eldridge, 1979*b*). In very young kittens persistent hyaloid vascularization and the reticular network at the back of the lens made it impossible to assess the position of the area centralis with accuracy, and so only the optic disk of each eye could be plotted and the position of the area centralis was assumed to be 20 deg inferior and 30 deg medial to the projection of the centre of the optic disk in the visual field (Bishop, Kozak & Vakkur, 1962; Olson & Freeman, 1980).

Electrophysiological recording methods

Qualitative assessment

All recordings were made in the right cerebral hemisphere. A small durotomy was made, a tungsten-in-glass micro-electrode (Merrill & Ainsworth, 1972) was lowered so that its tip touched the surface of the cortex and the craniotomy was sealed with agar and a paraffin–petroleum-jelly mixture. A medio-lateral series of electrode penetrations, each track running through much of the thickness of the cortex, was made in area 18 in most animals, although occasionally penetrations were angled deliberately so as to cross the area 17/18 or 18/19 borders, and hence define them physiologically by finding the point at which the sequences of receptive field positions reversed. A number of penetrations was also made in area 17 at various ages.

Spikes were amplified and displayed on an oscilloscope screen and an audio monitor. Single units were isolated at regular intervals along electrode tracks. Our strategy was designed to obtain large samples of units from all cortical laminae in area 18 at each age, and we isolated and studied neurones at regular intervals along each track (approximately 25 μm intervals in kittens aged 21 days or less, 50 μm in older kittens and 100 μm in adult cats; the increase in the sampling frequency along electrode tracks with age was chosen to reflect the decreasing cortical cell density and the increasing thickness of the cortex). In order to study the columnar structure of area 18, multiple, closely spaced parallel penetrations were made whenever possible.

Once a single unit had been isolated we assessed its responses to stimuli of moderate contrast, such as moving or flashed bars or spots of light, that were manipulated by hand and back-projected on the tangent screen. The position of the centre of each receptive field was noted. We then assessed the ocular dominance (Hubel & Wiesel, 1962) of each neurone, and performed the remaining tests through the dominant eye.

In the adult cats, and all kittens aged 3 weeks or more, seven ocular dominance groups were used (Hubel & Wiesel, 1962). In younger animals we found it difficult, due to the generally weaker responsiveness of cells, to decide between groups 2 and 3 and between groups 5 and 6, and we classified cells into five categories equivalent to ocular dominance groups 1, 2–3, 4, 5–6 and 7.

We studied the responses to moving bars of light or edges of various orientations, and cells were classified as visually unresponsive, non-oriented, orientation biased, or orientation selective (a classification introduced by Blakemore & Van Sluyters, 1975, and used by several others). The preferred orientation of orientation-selective and orientation-biased units was determined, in all cases, by moving a bar across the receptive field: this method confounds direction and orientation selectivity, but previous studies have suggested that only a small proportion of cells are purely direction selective in areas 17 and 18, even in very young kittens (Blakemore & Van Sluyters, 1975; Albus & Wolf, 1984). A small proportion of cells in area 18 had 'hypercomplex' properties (Hubel & Wiesel, 1965), the response decreasing abruptly as a bar or edge was lengthened beyond some optimum value. However, 'end-inhibition' of this type, which is now thought to be no more common in area 18 than in area 17, did not seem to change consistently with age in its frequency of occurrence or its strength.

Conventions of measurement

Orientation. A vertically oriented bar presented on the tangent screen at any eccentricity has an orientation of 0 deg (or 180 deg), while a horizontal bar has an orientation of 90 deg. Clockwise rotation, as seen by the animal, is positive. If horizontal and vertical, as defined on the tangent screen, were to be transposed to a planar representation of the visual field, they would lie in a cartographic coordinate system with meridians passing through north and south poles and parallel lines of elevation.

Directionality. An assessment of the degree of preference of each neurone to the direction of movement of a bar of light at the optimum orientation was made by assigning one of the following values (referred to below as directionality values) to each orientation-selective or orientation-biased cell. 0, equal response to movement in either direction; 1, response to movement in both directions, but slight preference for one of the two possible directions; 2, response to movement in both directions, but distinct preference for one of the two possible directions; and 3, response to movement in only one of the two possible directions.

Responsiveness. Each cell was classified into one of four groups according to the strength of the best response; in the youngest kittens the tendency of neurones to 'fatigue' was overcome by

allowing sufficient time between presentations. 0, visually unresponsive; 1, weak response, detectable only on a proportion of stimulus presentations; 2, moderate response; and 3, brisk response.

Finally, the receptive fields of orientation-selective or orientation-biased units were explored with flashed stimuli to delineate any separate 'on' and 'off' subregions; units were classified as simple or complex (Hubel & Wiesel, 1962), as described in Results.

These qualitative methods were simple and rapid to employ, even in the youngest kittens, and they enabled us to examine large samples of neurones at all ages. However, we were concerned to discover the accuracy and reproducibility of results obtained with such methods. Independent assessment by the two authors of the properties of a number of units in animals at various ages were always in close agreement, but in addition we compared our qualitative judgements with data obtained using quantitative, computer-controlled techniques for a number of cells.

Quantitative assessment

Sinusoidally modulated, high-contrast (contrast = 0·7) drifting gratings were generated, under the control of a PDP-11/34 computer, on a Joyce display screen (mean luminance = 250 cd m^{-2}) 57 cm in front of the animal (at which distance the display subtended 22 × 24 deg), centred on the receptive field. A roughly optimum orientation and the better direction of drift were chosen and the spatial and temporal frequencies of the grating were adjusted to give the best response, judged by ear. Then the orientation (and direction) of the drifting grating were varied and the responses (number of spikes per second) measured by the computer. The full 360 deg range of possible directions was explored, usually in 20 deg steps; at each direction, responses to ten presentations, each of 2 cycles of the grating at the appropriate temporal frequency (usually 1·5 or 3 Hz), were accumulated and averaged by a program that produced a pseudo-random, interleaved sequence of directions. The spontaneous activity of the unit was measured during ten similar periods but with a blank field of the same mean luminance.

Ocular dominance was also assessed quantitatively for these cells by using a computer program that operated two motorized ocular occluders; stimuli of optimum spatial and temporal frequencies, orientation and direction of movement (or a blank field of the same mean luminance) were presented a total of ten times in pseudo-random sequence, separately to the right and left eyes. Analysis of data obtained using this method is described in Results.

Histology

Small electrolytic lesions were made at intervals along each electrode penetration so that the track could be identified in histological sections. At the end of the electrophysiological experiment, the animal was perfused transcardially with 1% (w/v) paraformaldehyde and 1·25% (w/v) glutaraldehyde in phosphate buffer at pH 7·2–7·4. Each brain was removed, allowed to sink in phosphate buffer containing 30% (w/v) sucrose, frozen and cut to give 50 μm sections, most of which were reacted to reveal cytochrome oxidase activity (Wong-Riley, 1979), and some of which were stained with cresyl violet.

RESULTS

We recorded from a total of 1176 units in forty-two penetrations into area 18 and 137 units in eight penetrations in area 17, in kittens aged between 7 days and 10 weeks, and in adult cats (Table 1).

Areas 17 and 18 were distinguishable in Nissl-stained histological sections (Garey, 1971), but location of the areal borders (and electrolytic lesions) was easier (especially for young animals) in material reacted to reveal cytochrome oxidase activity (Price, 1985). The dense band of high cytochrome oxidase activity that overlies layer IV in area 18 in cats and kittens in fact also extends superficially to cover the lower portion of layer III defined in Nissl-stained sections (Price, 1985), and this may be related to the finding that inputs from the l.g.n. to area 18 terminate not only in layer IV but also in deep layer III (Humphrey, Sur, Uhlrich & Sherman, 1985; Price, 1985). In this present study laminae were defined in cytochrome oxidase material, and where

the term 'c.o. layer IV' is used it refers to the full width of the dense cytochrome oxidase band that extends into the cytoarchitectonically defined layer III. This definition of layer IV seemed entirely appropriate in the present context since one of our aims was to study separately the development of cells in cortical laminae that receive dense or sparse input from the l.g.n.

TABLE 1. The ages (at the time of the start of each recording experiment) of animals used in this study. The numbers of single units examined in areas 17 and 18 are shown, as well as the numbers of electrode tracks

		Numbers of single units studied		Numbers of electrode penetrations	
	Age	Area 17	Area 18	Area 17	Area 18
Week 1	7 days	None	20	None	1
	7 days	None	41	None	2
Week 2	10 days	None	6	None	1
	12 days	None	22	None	1
	12 days	21	84	2	2
	13 days	None	87	None	2
Week 3	15 days	17	85	1	2
	19 days	None	92	None	2
	21 days	13	None	1	None
	21 days	19	110	1	2
Week 4		47	73	2	2
Week 6		None	123	None	4
Week 8		None	68	None	3
Week 10		None	69	None	3
		20	None	1	None
Adult		None	46	None	2
Adult		None	136	None	7
Adult		None	114	None	6

Qualitative and quantitative assessments of receptive field properties

A number of authors have described close agreement between receptive field properties determined using qualitative and quantitative methods (Blasdel, Mitchell, Muir & Pettigrew, 1977; Kato, Bishop & Orban, 1978; Albus & Wolf, 1984). To provide our own confirmation of this, we determined both qualitatively and quantitatively the orientation preference, orientation tuning and direction preference of thirty-seven single units and the ocular dominance of sixteen cells in areas 17 and 18 in four kittens aged between 12 days and 10 weeks.

To obtain quantitative estimates of the preferred orientation and direction, and the width of orientation tuning, the average spontaneous firing rate was measured over ten blank presentations without a grating on the screen (each equivalent to two temporal periods of the drifting grating) and a threshold value was established equivalent to this mean spontaneous rate plus two standard errors; any response (number of impulses averaged over ten presentations, each of two temporal periods)

greater than this threshold value was taken as a significant activation of the cell. The spontaneous activity of these cells was low and examination of peristimulus time histograms containing responses to gratings of optimum spatial and temporal frequencies revealed that, even when the response was clearly modulated in time with the drift of the grating, there was always an elevation in the *average* impulse frequency above the spontaneous level. In other words, the measurement of average impulse frequency revealed modulated as well as unmodulated responses. Average responses were plotted at each direction on polar coordinates (Fig. 1) and preferred orientation

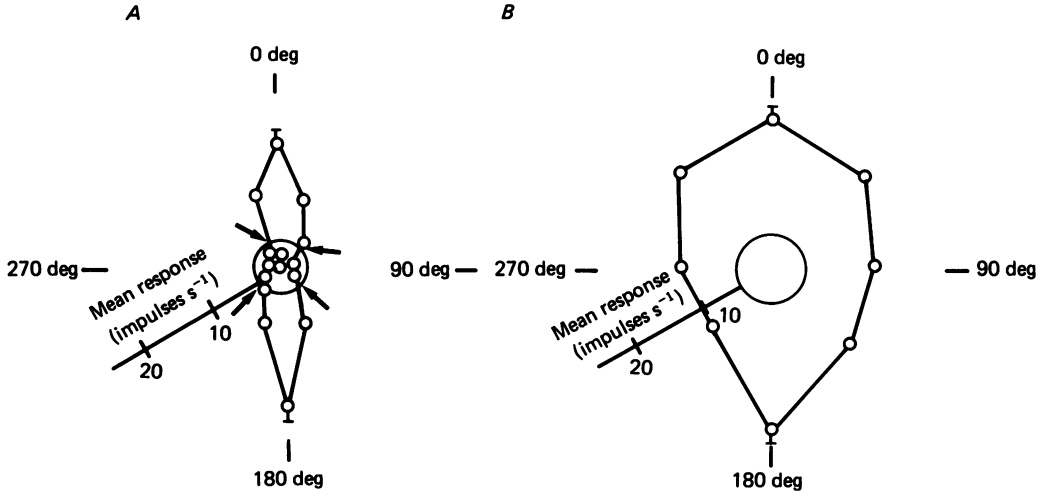

Fig. 1. Polar plots of response against direction of movement of a drifting grating. *A*, results from an orientation-selective cell from area 18 in a 10-week-old kitten. Each point plots the average discharge (+S.E. for responses at the optimum orientation) during two temporal periods of a grating drifting in the direction indicated by the radial axis of the polar coordinates. This cell responded equally to movement of a bar of optimum orientation (horizontal) in the two directions (and had, in fact, been given a qualitative directionality value of zero). The circle has a radius equal to the threshold value (average spontaneous firing rate plus 2 S.E.), and the range of orientations to which the cell responded (full-width of tuning) was measured between the two arrows: tuning was roughly the same in the two directions for this cell. *B*, results from an orientation-biased cell from area 18 in a 12-day-old kitten, whose response exceeded threshold for all orientations tested. This cell responded roughly equally to movement of a bar of optimum orientation (again horizontal) in either direction.

and full width of orientation tuning (defined as the total angular range of orientations over which the cell's response exceeded the threshold) were measured for each cell. These quantitative estimates were plotted against the independent qualitative estimates of these same properties obtained through judgement by ear of responses to stimuli manipulated by hand, and a close correlation was observed in both cases (Fig. 2). It is interesting that in making qualitative assessments, by ear, of the full-width of orientation tuning we appeared to be assigning the limits of the response at stimulus orientations where the firing rate of the cell was in fact very close to the mean spontaneous activity plus two standard errors.

For each cell studied quantitatively we calculated a directionality index,

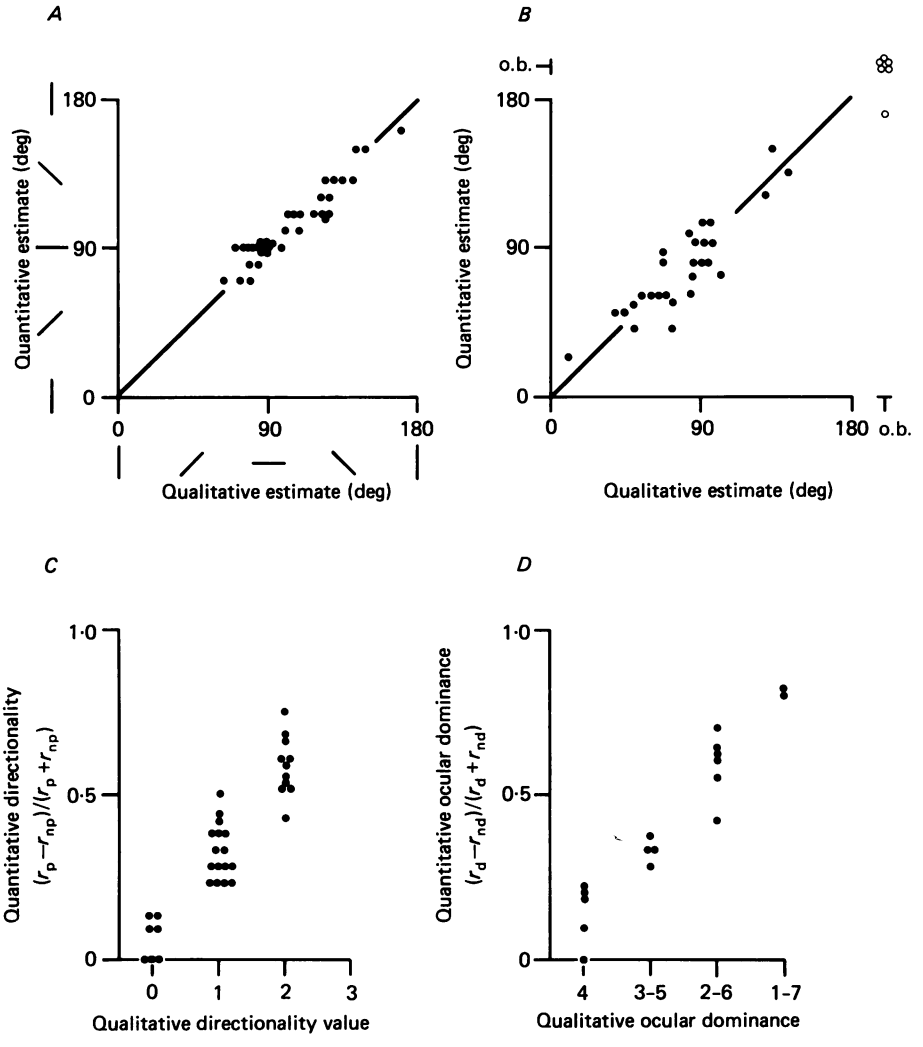

Fig. 2. These graphical comparisons demonstrate excellent agreement between quantitative and qualitative assessments of receptive field properties. *A*, preferred orientation, estimated quantitatively, is plotted against the qualitative measurement (correlation coefficient = 0·95). *B*, full-width of orientation tuning, estimated quantitatively, is plotted against qualitative measurement (correlation coefficient = 0·97). Cells classified as orientation biased (o.b.) by either method are indicated by open circles. *C*, quantitative directionality index, $(r_p - r_{np})/(r_p + r_{np})$, is plotted against the qualitatively determined directionality value (see Methods). *D*, quantitative ocular dominance value, $(r_d - r_{nd})/(r_d - r_{nd})$, is plotted against the qualitatively determined ocular dominance (see Methods).

$(r_p - r_{np})/(r_p + r_{np})$ where r_p = response in preferred direction, r_{np} = response in non-preferred direction, and an ocular dominance value, $(r_d - r_{nd})/(r_d + r_{nd})$ where r_d = response through dominant eye, r_{nd} = response through non-dominant eye, and compared these with the qualitatively determined directionality value and ocular

dominance (Fig. 2). This analysis showed considerable agreement between these two methods of classification.

The comparisons described above were made in normal kittens aged 12 days to 10 weeks, and even for units studied in a kitten as young as 12 days (Fig. 1*B*), at which age cells are weakly responsive and selectivity is poor, excellent agreement was found between quantitative and qualitative assessments of receptive field properties. In view of these findings we felt justified in relying on qualitative methods to obtain data from large samples of units and each age.

The development of area 18

Topography. It is known that area 18 contains a well-ordered retinotopic map of the contralateral visual hemifield in adult cats, with the vertical meridian represented at the border between areas 17 and 18 (Bilge, Bingle, Seneviratne & Whitteridge, 1967; Tusa, Rosenquist & Palmer, 1979; Albus & Beckmann, 1980). We found no violation of this retinotopic organization at any age, even in the youngest kittens. As electrodes angled away from the area 17/18 boundary passed progressively more laterally, the general trend at all ages was for receptive field positions to move peripherally, but this progression across the visual field was not absolutely strict; rather it resembled the 'random walk' described by Albus (1975) and Creutzfeldt (1977) in area 17 of the cat. Data obtained from area 18 in very young kittens suggested that, as in adult cats (Tusa *et al.* 1979; Albus & Beckmann, 1980) cortical magnification is higher closer to the area 17/18 border.

Cell types. In older kittens and in adult cats almost all units in area 18 responded to the kind of visual stimuli used in this study. However, especially in younger kittens, spontaneously active units that did not respond to any stimuli we presented were sometimes encountered. Very occasionally, an injury discharge was detected from a cell that had previously been silent, even during presentation of many different visual stimuli to the animal, just as the electrode was advanced from a sampling point. Such units were classified as visually unresponsive.

Visually responsive units were categorized as orientation selective, orientation biased or non-oriented (Blakemore & Van Sluyters, 1975); on the basis of their responses to stationary flashed stimuli most orientation-selective and orientation-biased units, at all ages, could be classified as either simple or complex. Cells with distinct antagonistic, spatially summating 'on' and 'off' areas were classified as simple cells (Hubel & Wiesel, 1962; Orban, Callens & Colle, 1975; Tretter, Cynader & Singer, 1975; Hammond & Andrews, 1978). Complex cells did not exhibit such subregions; many gave both 'on' and 'off' responses throughout the entire receptive field, although some did not respond at all to flashed stimuli and others gave responses of one type ('on' or 'off') but spatial summation was incomplete and the optimum bar was narrower than the receptive field (Hubel & Wiesel, 1962). In kittens aged 4 weeks or less, a number of cells gave only one class of response (either 'on' or 'off') to a small bar or spot of light flashed at all positions in the receptive field; although these 'unimodal' cells did not possess plottable antagonistic subregions, they did not respond to illumination of the whole visual field, and must therefore have had a silent adjacent antagonistic flank on one or both sides of the receptive field. Moreover, responses appeared to summate spatially in the 'on' or 'off' area. We have termed

such cells immature simple, because although they differ from typical simple cells seen in mature animals they have the fundamental defining characteristics of simple cells. We saw no such immature simple cells in kittens older than 4 weeks or in adult cats. Albus & Wolf (1984) have described similar 'unimodal' cells, displaying summation of response, in areas 17 and 18 in kittens during their first weeks post-natally, and although these workers placed such neurones into their own separate class ('unimodal' cells), they hint at a similarity between these orientation-specific unimodal cells and simple cells.

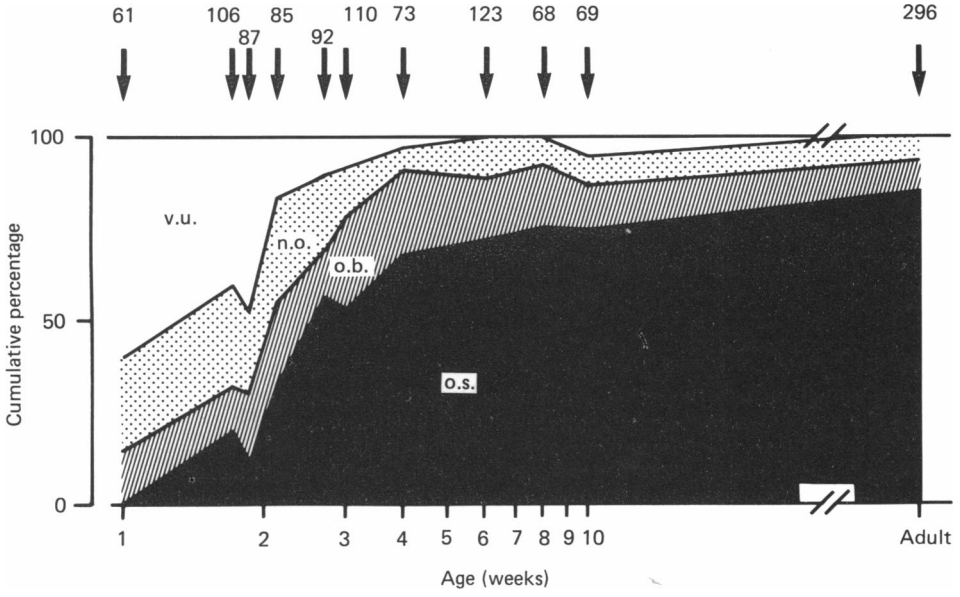

Fig. 3. This graph plots the cumulative percentages of orientation-selective (o.s.; filled area), orientation-based (o.b.; hatched area), non-oriented (n.o.; stippled area) and visually unresponsive (v.u.; open area) units in area 18 against age on a logarithmic scale. The numbers of units studied at each age are shown above the graph.

Changes in the proportions of cell types with age. Of sixty-one single units studied during penetrations through all laminae in area 18 in two kittens aged 7 days, 60% were unresponsive, 25% were non-oriented and 15% were orientation biased; no orientation-selective units were found. Of 296 cells examined in three adult cats 84% were orientation selective, 9% were orientation biased, 7% were non-oriented and no visually unresponsive units were detected (Fig. 3). Thus, at 7 days of age, just as the eyes were about to open, cells in area 18 were either unresponsive to visual stimulation or their properties were relatively non-specific. By 4 weeks of age virtually all neurones were visually responsive, but orientation selectivity appeared to continue to improve up to 10 weeks or more, in that there was a progressive increase in the percentage of orientation-selective cells, mainly at the expense of a corresponding reduction in the proportion of orientation-biased neurones (Fig. 3).

There was a progressive increase in the proportion of complex cells up to 4 weeks of age, while the over-all percentage of simple cells showed relatively little consistent change (Table 2). Most of the simple cells found in kittens aged 3 weeks or less had

immature properties, but in older kittens no such cells were found. After the beginning of the fourth week, the proportions of simple and complex cells remained relatively constant with age, so data from all animals aged 22 days or more were pooled for Table 2.

TABLE 2. Percentage of the *total* sample of cells which were classed as simple, immature simple or complex at various ages. At all ages a number of oriented cells were insufficiently responsive to stationary stimuli to be classified. The total number of units (n) in each group is indicated

Age (weeks)	Simple (%)	Immature simple (%)	Complex (%)	Unclassified oriented (%)	n
1 (7 days)	0	3			
	3		0	12	61
2 (8–14 days)	2	8			
	10		3	20	193
3 (15–21 days)	5	14			
	19		18	32	287
4 or older (22 days or more)	11	0			
	11		48	31	629

Changes in directionality with age. In kittens in their first and second post-natal weeks no cell recorded in area 18 was completely direction selective (directionality 3), but in older kittens and in adult cats one-fifth of units responded to movement of an optimally oriented bar in only one direction (Table 3). After the fourth week no further changes were found in the distribution of directionality. Thus, the over-all trend was for cells in area 18 to increase their specificity for the direction of movement of an oriented stimulus until about 4 weeks of age.

Changes in responsiveness with age. At the time of eye opening the majority of cells (60 %) were visually unresponsive and the remainder were only weakly driven. There was a rapid improvement in responsiveness during the first 4 weeks after birth, and the percentage of weakly responsive units (responsiveness 1) decreased to approximately its adult value by the fourth post-natal week.

Orientation tuning with age. Data on cells that showed an orientation preference (that is, orientation-selective and orientation-biased units) were pooled for animals grouped according to their age in weeks. The mean value, and its standard error, for full-width of orientation tuning (measured as the total range of orientations over which a response was elicited by a moving bar) were calculated for each age group (Fig. 4). Orientation-biased cells were all assigned a full-width of orientation tuning of 180 deg (a minimal estimate, of course). In the 7-day-old kittens we found no orientation-selective cells, but some orientation-biased units. By 10 weeks the mean full-width had decreased to 78 deg, not significantly different from the value (84 deg) found in adult cats.

The full-width of orientation tuning was compared for simple and complex cells in adult cats; the mean full-width for simple cells was narrower ($76{\cdot}5 \pm 7{\cdot}5$ deg, $n = 23$) than for complex cells ($85{\cdot}0 \pm 4{\cdot}0$ deg, $n = 121$) but the difference was not

TABLE 3. Percentage of cells with each directionality value, for cells with an orientation preference in area 18 in kittens at various ages

Age (weeks)	Directionality value 0 (%)	1 (%)	2 (%)	3 (%)	n
1 (7 days)	50	50	0	0	6
2 (8–14 days)	58	28	14	0	51
3 (15–21 days)	36	30	19	15	156
4 or older (22 days or more)	26	21	33	20	484

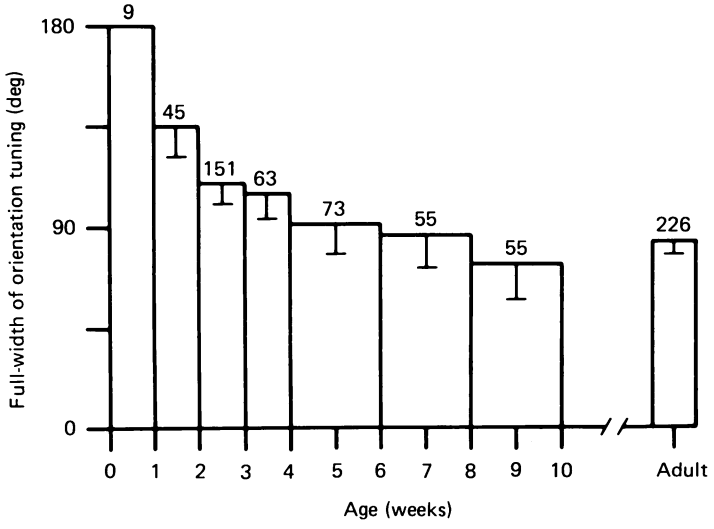

Fig. 4. In this graph, the mean full-width of orientation tuning (−S.E.) of all units with an orientation preference (orientation-selective and orientation-biased cells) in area 18 is plotted against age; orientation tuning is measured as the full angular range of orientations over which the cell will respond to a moving bar. All orientation-biased cells were given the value of 180 deg. The numbers of units studied at each age are indicated.

significant. The orientation tuning for simple (including immature simple) and complex cells was compared at all ages, and no significant differences were found, although at all ages complex cells had slightly higher mean values for orientation tuning than simple cells.

Ocular dominance. At all ages the majority of units encountered along penetrations into area 18 were binocularly driven. The distributions of ocular dominance were roughly symmetrical, but there were slight biases towards the contralateral eye in kittens and towards the ipsilateral eye in adult cats (Fig. 5). It seems possible that the ipsilateral eye gains relatively in influence with age.

Preferred orientation and direction. Distributions of preferred orientations at various ages are shown in Fig. 6. In kittens aged 7 days a very small proportion of cells

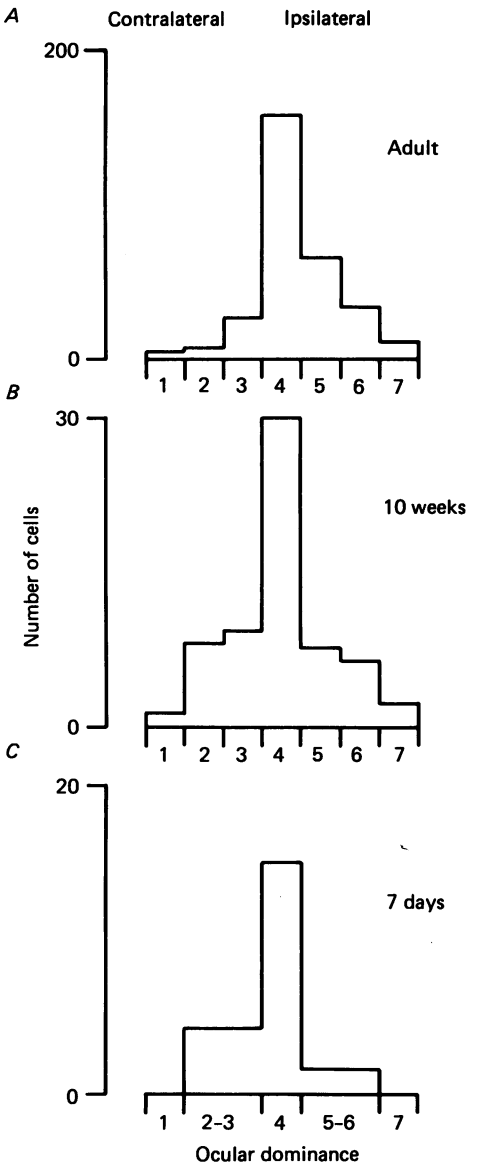

Fig. 5. Ocular dominance distributions for cells in area 18 of adult cats (*A*), a 10-week-old kitten (*B*) and 7-day-old kittens (*C*). Note that five groups were used in very young kittens (*C*), and seven in older kittens and adult cats (*A* and *B*) (see Methods).

was oriented and, generally, their preferred orientations were oblique (i.e. around 45 or 135 deg). In slightly older kittens, aged 10–21 days, a similar over-all pattern was seen, and relatively few cells had horizontal preferences (around 90 deg). As the percentage of oriented cells increased with age the distribution of preferred orientations changed, and in adult cats we found a clear bias towards horizontal orientations (90 deg) with a second small peak at vertical (0 or 180 deg). For kittens

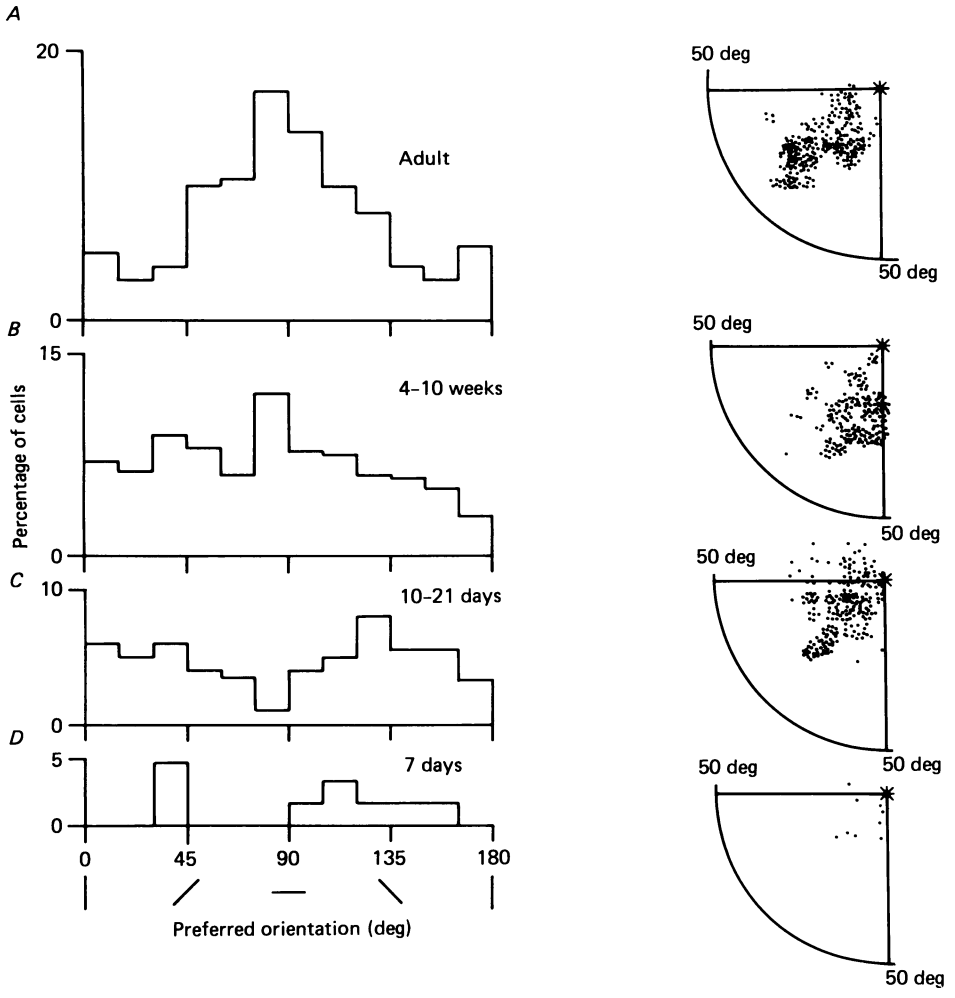

Fig. 6. The distributions of preferred orientation for cells in area 18 at various ages. The number of cells with a preference for each orientation is expressed as a percentage of the total of all cells in the sample. To the right of each histogram the positions in the visual field of the receptive field centres of the oriented units are shown (✳= projection of area centralis). Data are presented from adult cats (*A*) and kittens aged 4–10 weeks (*B*), 10–21 days (*C*), and 7 days (*D*). In adult cats and older kittens (4–10 weeks) a bias towards horizontal orientations is seen, while in younger kittens, in which relatively few cells are oriented, oblique orientations predominate. The cells studied in these animals were located rostral to a.p.0 in area 18 and their receptive fields were mostly centred in the left lower quadrant of the visual field.

aged 10–21 days (Fig. 6*C*), 4–10 weeks (*B*) and for adult cats (*A*) we obtained data to show that the biases in the distributions were statistically significant (in all cases $P < 0{\cdot}01$, χ^2 test). In each of these age groups the sample contained cells whose receptive fields covered a large proportion of the lower quadrant of the left visual hemifield (Fig. 6). In this respect the samples were comparable, although, in fact, we

did not find any evidence of a strong relationship between receptive field position and preferred orientation at any age.

Laminar analysis. We had a strong impression that the properties of cells were very different in the upper and lower layers in young kittens and that their time courses of maturation were dissimilar. We examined these differences by determining, from histological reconstruction, the lamina in which each recording site lay. This analysis confirmed a striking disparity in the development of orientation selectivity in the superficial laminae (above c.o. layer IV) and below (c.o. layers IV, V and VI), as shown in Fig. 7. In layers I, II and III in 7-day-old kittens 96 % of cells were visually unresponsive, and the only cell we recorded that could be driven was non-oriented; by contrast, the majority of units (64 %) in c.o. layer IV and layers V and VI at this early age were already visually responsive, 25 % of the sample being orientation biased and 39 % being non-oriented. However, there was a very rapid increase in the percentage of orientation-selective units in superficial laminae between 2 and 4 weeks of age, from 2 % to the adult value of about 100 % (the subsequent small fluctuations seen in Fig. 7*A* are presumably a reflexion of the relatively small sample sizes at some ages, especially at 4–8 weeks). By contrast, in the lower layers there was a much slower increase, lasting until about 8 weeks of age, in the percentage of orientation-selective cells (Fig. 7*B*).

The proportions of binocularly driven cells were similar in each cortical layer at every age, and the fraction of monocular cells was approximately the same in layer IV as in other cortical laminae, at all ages (see Fig. 11).

Over-all, this laminar analysis showed that, at the time of eye opening, visually responsive neurones are found almost exclusively in deeper cortical laminae (c.o. layers IV, V and VI), but that once the superficial layers (I, II and III) become responsive (mainly during the third post-natal week) they develop a high proportion of orientation-selective cells more rapidly than the deeper laminae.

The development of orientation columns in area 18. When we advanced the electrode obliquely across the radially arranged palisades of cells in area 18 in adult cats and older kittens, adjacent units usually had similar preferred orientations and orientation usually changed gradually and progressively along each electrode track as described for adult area 18 by Hubel & Wiesel (1965). Occasionally there were large shifts in orientation, which could occur at any depth in the cortex, rather than in a particular layer.

In the youngest kittens many cells were visually unresponsive or non-oriented and so it was often impossible to discern long progressive shifts of orientation preference, but where orientation-selective or orientation-biased cells were found lying close together they usually had similar preferred orientations.

We often made multiple, oblique, parallel (or nearly parallel) penetrations in a single coronal plane, at a quite rostral level in area 18, where the radial palisades of cells extend vertically in the parasagittal plane, and therefore run roughly in the coronal plane. By examining data from such parallel penetrations the preferred orientations of neurones at different depths within single or nearby radial palisades of cells could be compared. This was done by projecting each recording point from a histologically reconstructed electrode track up to the cortical surface along the

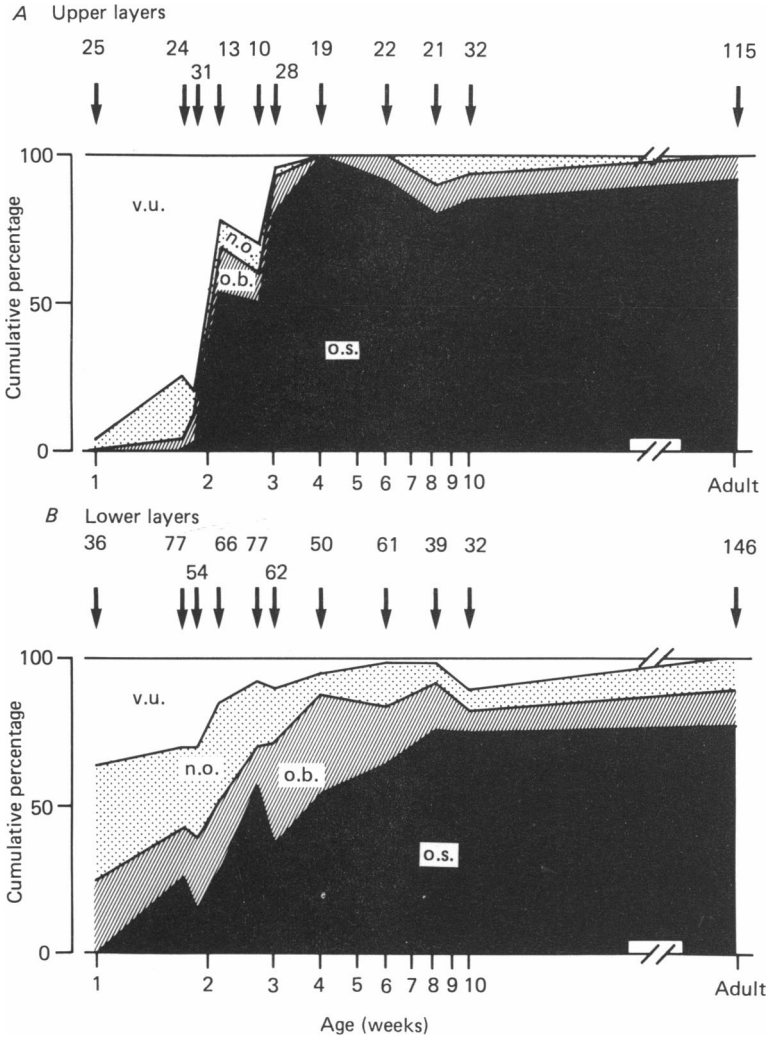

Fig. 7. Changes in the percentages of orientation-selective (o.s.), orientation-biased (o.b.), non-oriented (n.o.) and visually unresponsive (v.u.) units with age are plotted as in Fig. 3. The units were recorded in layers I, II and III (*A*) or c.o. layer IV, layers V and VI (*B*). The numbers of units studied at each age are shown above each graph.

radial palisade in which the recording was made; thus, progressive shifts in orientation along parallel electrode penetrations could be superimposed.

Fig. 8 shows the results of such an analysis in two adult cats. The progressive shifts in orientation along parallel oblique penetrations through area 18 coincided well, when superimposed in this way, indicating that orientation columns extend through much of the depth of the cortex. A degree of scatter of preferred orientations within the columns is suggested (as described in area 17 of the cat by Creutzfeldt, 1978), but at least some of this apparent variability within each column must be due to experimental error, particularly in estimating the optimum orientations and the precise locations of the single units from which we recorded.

We have strong evidence that such a columnar organization of the orientation domain is present in kittens by the third post-natal week (Fig. 9). Although we also made parallel oblique penetrations through area 18 in kittens in their first and second post-natal weeks, a full analysis of this type, based on a superimposition of data from the tracks, was less conclusive in view of the large proportions of visually unresponsive and non-oriented cells, especially in superficial layers. However, there was at least

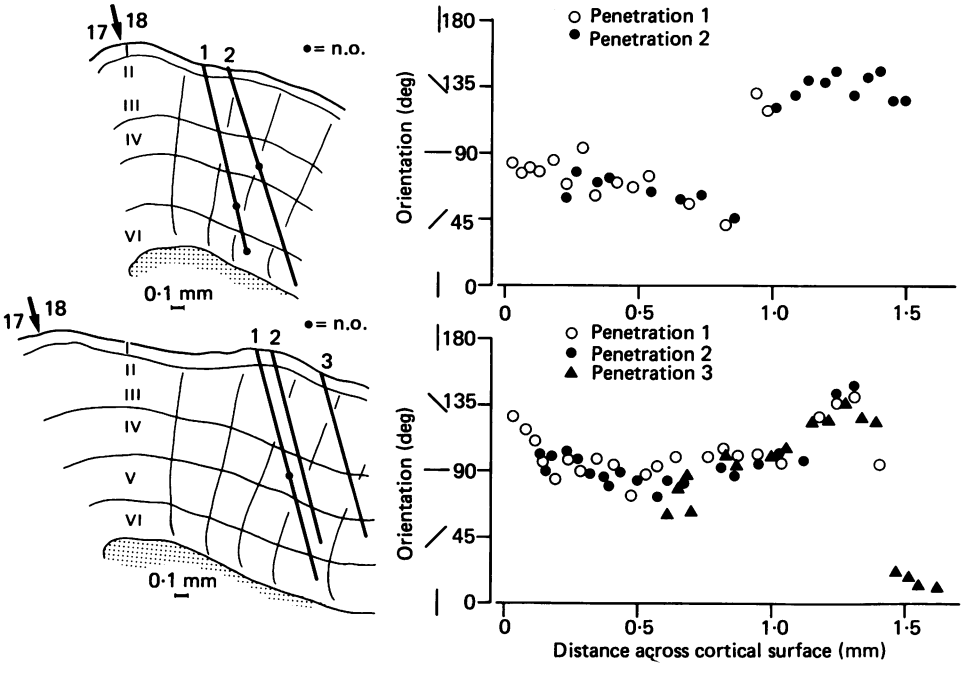

Fig. 8. Left panel: reconstructions of electrode penetrations angled laterally to pass through area 18 in a single coronal plane in each of two adult cats. The area 17/18 border (arrow), cortical laminae (defined in material stained with cytochrome oxidase) and radial palisades of cells, which run roughly perpendicular to the cortical surface, are indicated. Non-oriented cells (n.o.) are plotted. Right panel: graphs illustrating the shifts in preferred orientation along these penetrations. Each recording point is projected up the palisade in which it is located to the cortical surface, and preferred orientation is plotted against the distance across the cortical surface to each of these projected locations (zero being the point of entry of the most medial penetration). Each point is plotted, on the cyclical scale of orientation on the ordinate, at the nearest position to the preferred orientation of the preceding cell. The fact that the progressions of orientation along multiple parallel tracks superimpose, albeit with a degree of scatter, is evidence that orientation columns are present and extend through much, if not all, of the cortical depth in area 18 of adult cats.

a hint of a crude columnar structure even in these young kittens. Fig. 10 shows two electrode penetrations in a 12-day-old kitten, and although relatively few units were orientation selective or orientation biased, where such cells lay close together, or along a single or nearby palisade, their preferred orientations were often similar. It is possible that a rudimentary columnar organization for orientation is present at very early ages, even before the onset of patterned visual experience, but the full columnar structure appears during the third post-natal week.

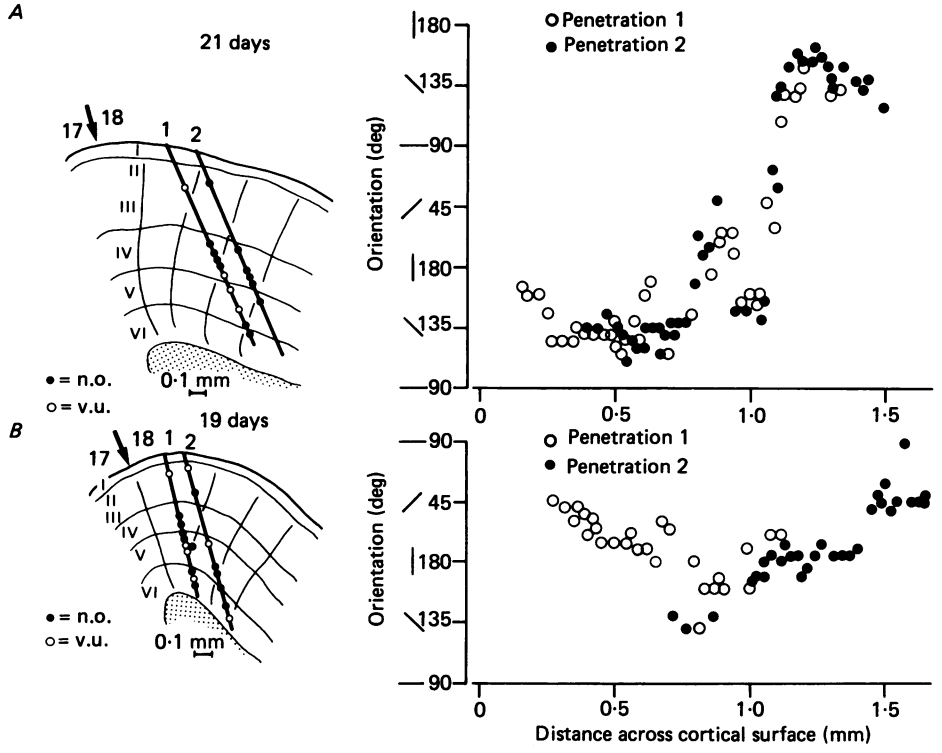

Fig. 9. Left panel: parallel, oblique electrode penetrations that passed laterally through area 18 in a 21-day-old (*A*) and a 19-day-old kitten (*B*) are reconstructed as in Fig. 8. Positions of non-oriented (n.o.) and visually unresponsive (v.u.) units are indicated. Right panel: the shifts in preferred orientation along these tracks are represented. A similar analysis has been performed to that in Fig. 8, and the progressions of orientation along the two tracks in each case coincide well, as in adult cats, with small degree of scatter. Orientation columns appear to exist in young kittens even in their third post-natal week.

Ocular dominance columns. The vast majority of cells in area 18 of adult cats are binocularly driven. In only about half of the oblique electrode penetrations made in a coronal plane in adult animals was there a convincing progressive shift in ocular dominance along the length of a track (e.g. Fig. 11*A*); in the other cases the ocular dominance fluctuated between groups 3 and 5 (e.g. Fig. 11*B*). Comparison of results from parallel tracks was rather unproductive because of the over-all paucity of monocularly dominated units in area 18: in some places there were clearly correlated variations of ocular dominance along parallel penetrations, indicative of a columnar pattern, but in other cases one or both tracks showed no obvious shift in dominance.

In view of the possibility that our failure to observe large and reliable variations in ocular dominance might have been due to our tracks running roughly parallel to ocular dominance 'stripes', we made a few penetrations that ran obliquely in a parasagittal plane through area 18, but the proportion of tracks revealing progressive shifts in ocular dominance was no different. We conclude that local clustering

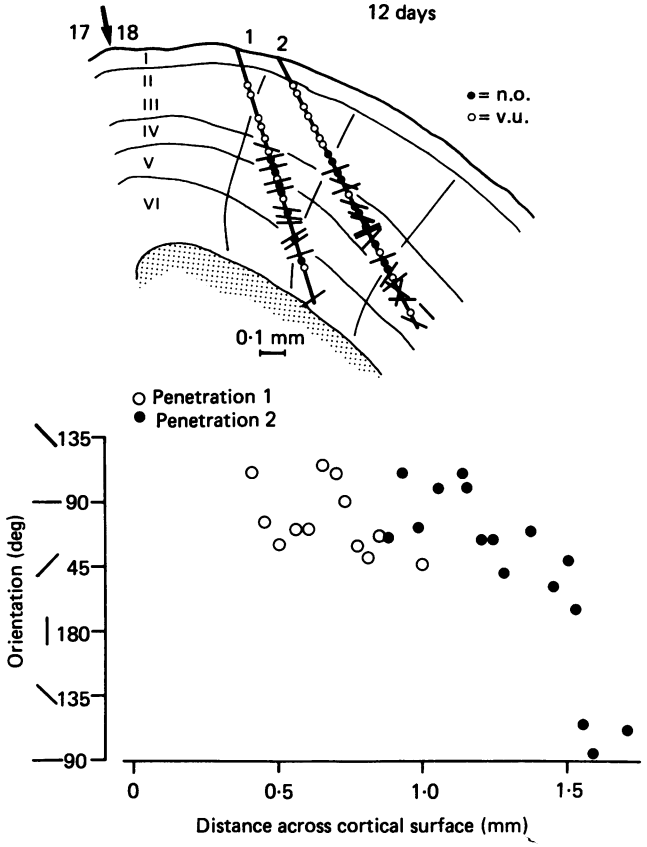

Fig. 10. Upper panel: reconstruction of two penetrations passing laterally through area 18 in the coronal plane in a 12-day-old kitten. Non-oriented units (n.o.) and visually unresponsive cells (v.u.) are shown, and those cells with an orientation preference are indicated by a short line corresponding to that preferred orientation. Lower panel: a graphical analysis, as in Figs. 8 and 9, is shown, but superimposition of the tracks produces little scope for comparison because of high proportions of non-oriented and visually unresponsive cells. However, it appears that orientation-selective and orientation-biased units in close proximity, or lying one above the other along a palisade, tend to have similar preferred orientations. Local scatter in orientation seems, though, to be greater than in older animals.

according to ocular dominance does occur in area 18 in adult cats but bands of iso-ocular dominance do not run exactly parallel to either the coronal or the sagittal plane at this level in area 18.

In kittens of all ages about half of the penetrations yielded progressive shifts in ocular dominance across the cortex (Fig. 11*C*, *D* and *E*) while in others we found a disordered scatter of ocular dominance values in the binocular range. 12 days was the youngest age at which such evidence for ocular dominance columns was obtained, and the large number of unresponsive units in younger animals prevented our detecting even a rudimentary organization for ocular dominance.

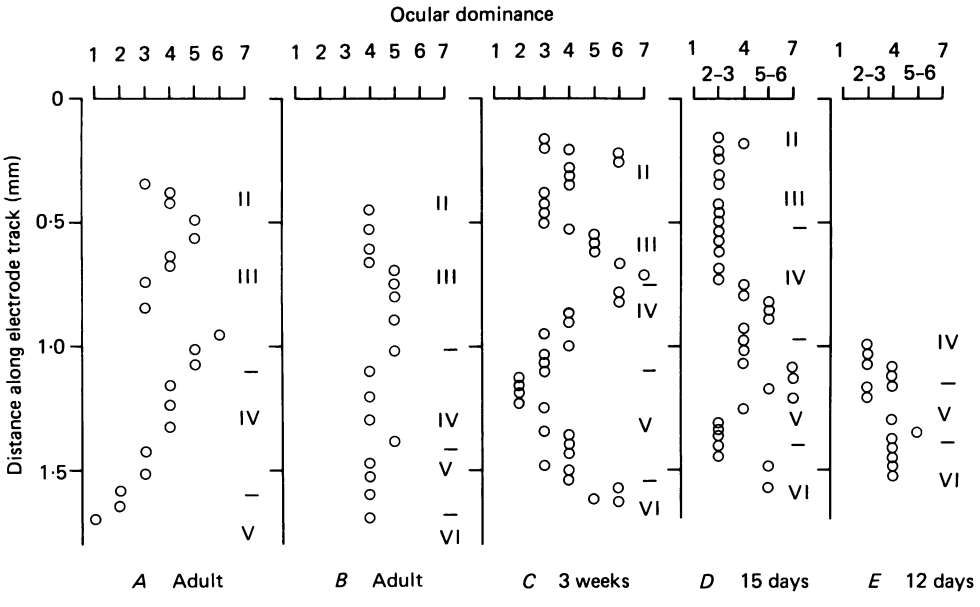

Fig. 11. The progressions of ocular dominance with depth along oblique electrode penetrations through area 18 in adult cats (*A* and *B*), a 3-week-old kitten (*C*), a 15-day-old kitten (*D*) and a 12-day-old kitten (*E*). The cortical laminae are indicated to the right of each graph. In the 12-day-old kitten (*E*) cells in superficial cortical laminae were visually unresponsive.

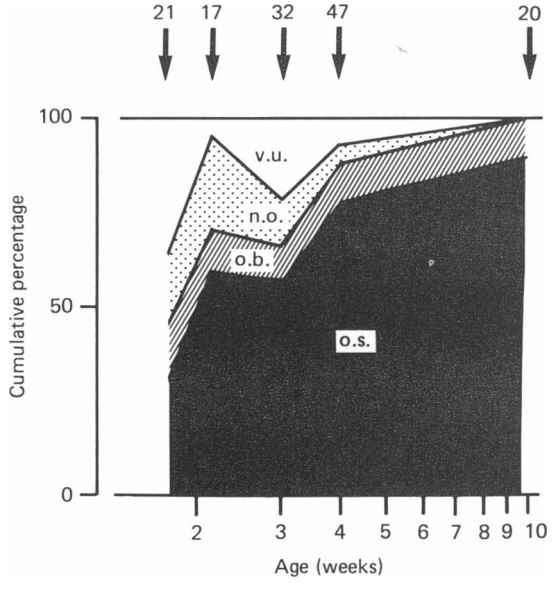

Fig. 12. Here the development of receptive field classes in area 17 is analysed, as in Fig. 3. Changes in the cumulative percentages of orientation-selective (o.s.), orientation-biased (o.b.), non-oriented (n.o.) and visually unresponsive (v.u.) units are plotted against age. The numbers of units studied at each age are indicated above the graph.

The development of area 17

In order to make some comparisons between the development of area 18 and area 17, we obtained a sample of 137 single units from all laminae of area 17 in kittens aged 12, 15 and 21 days, 4 and 10 weeks. Cells were classified as visually unresponsive, non-oriented, orientation biased or orientation selective, exactly as for area 18, and changes of the proportions with age are shown in Fig. 12. At 12 days 29% of cells

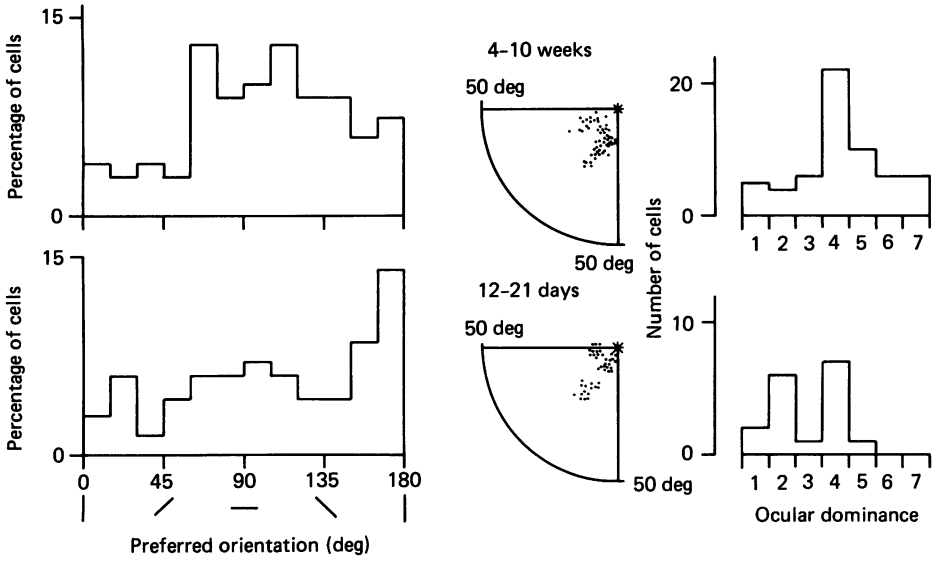

Fig. 13. Left panel: distributions of preferred orientation in area 17 in older kittens aged 4 and 10 weeks (above, $n = 62$) and younger kittens aged 3 weeks or less (below, $n = 49$). As in Fig. 6, the numbers of cells are expressed as percentages of the total sample. Centre panel: positions of the receptive field centres of orientation-selective and orientation-biased cells in area 17 in kittens aged 4 and 10 weeks (above) and kittens aged 3 weeks or less (below). Right panel: ocular dominance distributions of all cells in area 17 in kittens aged 4 and 10 weeks (above) and kittens aged 3 weeks or less (below).

in area 17 were orientation selective, 14% were orientation biased, 19% were non-oriented, and 38% were visually unresponsive; at this age 20% of cells in area 18 were orientation selective, 13% were orientation biased, 27% were non-oriented and 40% were visually unresponsive. Our data on the subsequent development of area 17 (Fig. 12) are similar to those found by Blakemore & Van Sluyters (1975), who used very similar methods for the classification of neurones. The time course of development of receptive field properties seemed generally quite similar in areas 17 and 18, although the percentage of orientation-selective cells in area 17 was slightly higher than in area 18 at all ages.

The distribution of preferred orientations in our sample from area 17 for kittens aged 3 weeks or less showed that, although all orientations were represented, there was a sharp peak for vertical orientations, and also a relatively large proportion of units responding best to roughly horizontal orientations (Fig. 13). The preferred orientations of cells in the sample from area 17 in older kittens (4 and 10 weeks) were

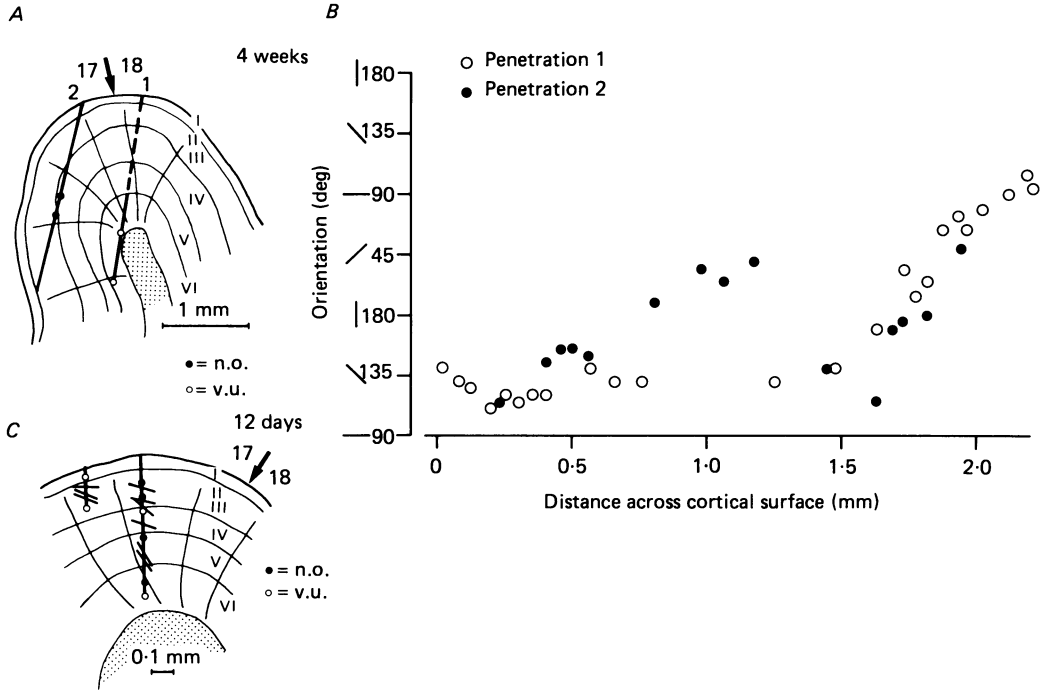

Fig. 14. Reconstructions of electrode penetrations in area 17. *A*, two roughly parallel tracks in a single coronal plane in a 4-week-old kitten (the dashed line indicates a portion of penetration 1 that lay within area 18). Non-oriented (n.o.) and visually unresponsive (v.u.) cells are shown. *B*, the progressions of preferred orientation along the two tracks shown in *A* are superimposed, as in Fig. 8. *C*, two penetrations in area 17 in a 12-day-old kitten are reconstructed, using the same conventions as in Fig. 10. At 12 days in area 17 some cells, even in superficial laminae, have clear orientation preference.

fairly similar in their distribution but with less of a bias towards vertical orientations (Fig. 13). In all these kittens the receptive fields of the units were scattered over similar parts of the left lower quadrant of the visual field to those sampled in area 18 (Fig. 13).

The distributions of ocular dominance for samples from area 17 for kittens aged 3 weeks and for older kittens are shown in Fig. 13; at all ages most units were binocular, although a slightly larger proportion of cells was monocularly driven than in area 18 (compare Figs. 13 and 5). As in area 18, there did appear to be some slight tendency for the ipsilateral eye to gain relatively greater influence with age; indeed, the ocular dominance distribution of cells in area 17 in very young kittens was quite strongly biased towards the contralateral eye, as Fregnac & Imbert (1978) have also described.

We obtained evidence of orientation columns extending through much, if not all, of the cortical depth in area 17 in kittens aged 4 weeks or more (Fig. 14). Preferred orientation changed usually gradually and progressively but occasionally in sharp jumps as the electrode was advanced, and, in a 4-week-old kitten, the sequences of orientation preference along two roughly parallel penetrations at different depths

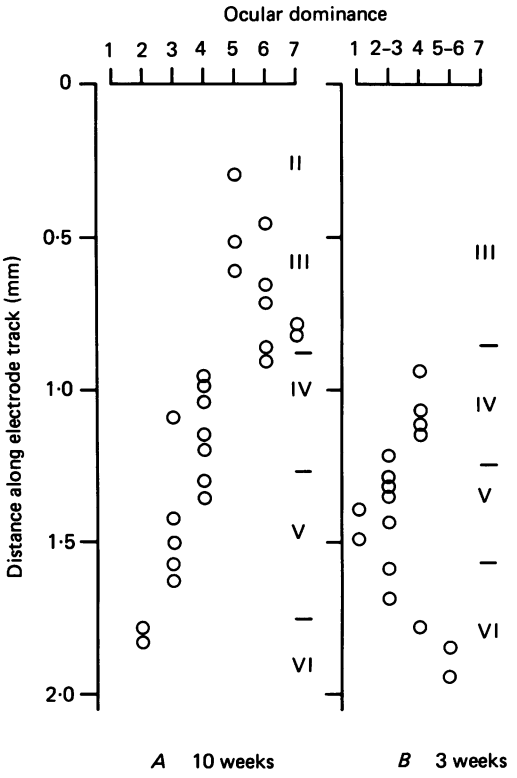

Fig. 15. Progressions of ocular dominance with depth along oblique electrode penetrations through area 17 in a 4-week-old kitten (*A*) and a 21-day-old kitten (*B*). Cortical laminae are indicated.

superimposed well (Fig. 14). Adjacent units had similar ocular dominances, and these changed progressively along electrode tracks in these older animals (Fig. 15). In younger kittens evidence for orientation and ocular dominance columns was less complete, although cells situated close together had similar preferred orientations (Fig. 14) and ocular dominances (Fig. 15). These data are consistent with the findings of Blakemore & Van Sluyters (1975) and Albus & Wolf (1984) and suggest that, even in very young kittens, rudimentary orientation and ocular dominance columns may be present in area 17.

DISCUSSION

Organization of area 18 in adult cats

In their original study of area 18 in the adult cat Hubel & Wiesel (1965) provided evidence for a columnar system for preferred orientation, extending through the full depth of the cortex. Our experiments, using a different approach (multiple parallel penetrations), fully confirmed this suggestion. We found no evidence that preferred orientation differs between superficial and deep laminae along individual radial palisades, as has been suggested by Bauer (1982) for area 17 of the cat. A study using

the [^{14}C]deoxyglucose method (Albus & Sieber, 1984) has suggested that iso-orientation bands form a rather complex network in area 18 and our results are compatible with this view, in that we generally found similar progressions of preferred orientation (changing sometimes slowly, sometimes quite rapidly and occasionally abruptly) along oblique tracks, whether they lay in the coronal or the parasagittal plane.

In our sample of 277 single units from area 18 in three adult cats we found that, while all orientations were represented, there was a clear bias for horizontal orientations and a minor one for vertical orientations, at least in the rostral parts of area 18, which represent the left lower quadrant of the visual field.

Although the majority of cells (84%) in adult area 18 were orientation selective, some were so broadly tuned that they were classified as orientation biased (9%) and others, found mainly in deeper cortical laminae, were actually non-oriented (7%); all cells we isolated in adult cats were responsive to visual stimulation. These findings are in general agreement with several previous studies (Donaldson & Nash, 1975; Dreher & Cottee, 1975). When Hubel & Wiesel (1965) investigated the receptive field properties of neurones in area 18 they classified none of the cells as simple and this formed a basis for their hypothesis of a hierarchical sequence of information processing from striate through extrastriate areas of visual cortex. Although the majority of orientation-selective neurones in adult area 18 are complex, we, in common with other workers (Orban *et al.* 1975; Tretter *et al.* 1975; Hammond & Andrews, 1978), found a population of cells with receptive fields qualitatively similar in organization to those of simple cells in area 17, i.e. with separate, spatially summating antagonistic 'on' and 'off' zones. The mean full-width of orientation tuning that we found for cells in area 18 was similar to that reported by Tretter *et al.* (1975), and there was no dramatic difference in the sharpness of tuning between simple and complex cells, in agreement with the results of Hammond & Andrews (1978).

We confirmed previous observations on the over-all binocularity of cells in adult area 18 (Hirsch & Leventhal, 1982; Sclar & Freeman, 1983). Hirsch & Leventhal (1982) have suggested that distinct physiological ocular dominance columns exist in regions of area 18 representing the central visual field (within 5 deg of the area centralis), but not in the representation of the peripheral retina. Most of our cells had receptive field eccentricities of more than 5 deg, and yet we saw distinct local fluctuations in dominance, suggestive of a columnar organization, in many penetrations. However, while our data suggest that some form of organization according to ocular dominance probably exists throughout area 18, we could not discern a regular and consistent spatial arrangement of iso-ocular dominance bands, even though the segregated bands of right-eye and left-eye geniculate afferents in layer IV of area 18 have been shown to run medio-laterally, perpendicular to the area 17/18 border (Shatz, Lindstrom & Wiesel, 1977). Unlike in area 17 (Shatz & Stryker, 1978), we did not find a higher proportion of monocular units in layer IV of area 18.

Development of area 18

The optical media of the kitten's eye are still very cloudy at the end of the first post-natal week, and clear only gradually as the animal matures. However, in

common with other authors (Bonds & Freeman, 1978; Bonds, 1979; Albus & Wolf, 1984) we do not think that poor optical quality was the reason for the generally low responsiveness and paucity of receptive field specificity in young kittens because nearby cells, recorded in single tracks, could have very similar or identical receptive field positions and yet have very different degrees of stimulus specificity.

A substantial proportion of cells (40 %) in area 18 are already visually responsive and the area is arranged retinotopically even at 7 days post-natally, before the eyelids have separated naturally, in agreement with anatomical results (Price & Blakemore, 1985*a*; Henderson & Blakemore, 1986). However, at that age we saw no strictly orientation-selective cells in any cortical layer, although 15 % of all units encountered did display an orientation preference and were classified as orientation biased. Albus & Wolf (1984) also found a proportion of neurones with a preference for one orientation in area 18 of visually inexperienced kittens.

The major phase of development of cell responsiveness, orientation selectivity and direction selectivity in area 18 seems to be virtually complete by about 4 weeks of age, with a further small increase in the proportion of orientation-selective cells and the general responsiveness of neurones up to about 10 weeks. By the end of the fourth week the percentages of simple and complex cells in the cortex were similar to those found in adults and the simple cells no longer had immature receptive fields (with only a single spatially summating zone responding to flashed stimuli). Complex cells appeared slightly later than simple cells during the first 4 weeks. It seems significant that in area 18, as in area 17 (Blakemore & Van Sluyters, 1975; Buisseret & Imbert, 1978), the majority of cells with some degree of orientation selectivity in very young kittens (even before eye opening) are located in deep cortical layers and have simple receptive field properties, even though such cells are presumably dominated by geniculate Y-cell inputs in area 18 but may well depend on X-cell input in area 17. In both areas, simple cells can apparently be innately pre-specified whereas the major population of complex cells appears after the onset of visual stimulation. Sharpening of the orientation tuning of neurones continued throughout the total 10-week period studied here, although much of the change occurred during the first few weeks post-natally.

In the rostral part of area 18 in adult cats we saw a clear bias of orientation preference towards horizontal orientations, and a smaller peak in the distribution for vertical orientations; we found a generally similar bias in kittens aged 4 weeks or more, but in kittens younger than 4 weeks, we found that relatively few units responded to horizontal orientations and there was a bias for oblique orientations. It seems possible that, while many orientation-selective or orientation-biased cells initially present in area 18 in kittens in their first few post-natal weeks prefer oblique orientations, orientation-selective or orientation-biased cells that mature later tend to acquire a preference for horizontal or, perhaps to a lesser extent, vertical orientations. Such a change from oblique to horizontal and vertical biases during development does not seem to occur in area 17 (see below).

Laminar and columnar development. Even in our youngest kittens, studied at the end of the first week and during the second, a rudimentary local organization of orientation preference seemed to be present in area 18, in that cells with similar preference were clustered together. However, full radial columnar organization

matures rapidly during the third post-natal week, and it seems likely that the early rudimentary organization, present almost exclusively in the deep layers, forms a framework for the future columnar development, as suggested for area 17 by Blakemore & Van Sluyters (1975).

A laminar analysis revealed that superficial cortical layers (I, II and III) in area 18 in kittens less than 2 weeks old are extremely immature, and mainly contain cells that are visually unresponsive. By contrast, many cells in deeper laminae of area 18 are visually responsive even at the time of eye opening, and some of them already display an orientation preference. It seems most unlikely that selective trauma could account for the abolition of visual responsiveness (but not spontaneous activity) in the upper layers of area 18. It is difficult to conceive of a mechanism that could reliably and precisely affect virtually the full depth of the superficial layers (without any histological evidence of damage) in all kittens younger than 2 weeks but in no animal older than 3 weeks. Furthermore, even along penetrations that ran at a very shallow angle to reach regions of the superficial layers that did not underlie the craniotomy and were therefore not exposed to the threat of local damage, we found hardly any responsive units in very young kittens until the electrode entered c.o. layer IV. Finally, the upper layers of area 17 were not disproportionately unresponsive, even in the same young kittens in which this phenomenon had been observed in area 18.

The difference in the responsiveness and specificity of neurones in superficial and deep layers in such young kittens may well be related to the fact that geniculo-cortical inputs are distributed mainly in deep laminae (IV, VI and also V) in new-born kittens (Anker & Cragg, 1974; Kato, Kawaguchi, Yamamoto, Samejima & Miyata, 1983; Henderson & Blakemore, 1986). A similar suggestion has been made for area 17, where innately specified orientation-selective simple cells are found predominantly in deeper layers (Blakemore & Van Sluyters, 1975). Area 18 is thought to receive no direct input from geniculate X cells, either in adults or in kittens (Henderson, 1982; Stone, 1983) yet it has a population of neurones with at least some degree of orientation specificity even at the time of eye opening and these cells are found exclusively in the lower cortical layers, which receive direct geniculate input. It seems quite likely, then, that orientation preference can be specified innately on the basis of input from Y axons.

During the third and fourth weeks there is a very rapid increase to adult levels in the responsiveness of neurones and in the proportion of orientation-selective cells in the superficial laminae; also, the full-width of orientation tuning of cells decreases more rapidly in these layers than in lower layers during the third and fourth weeks post-natally. The development of orientation selectivity in the deep laminae in area 18 proceeds at a much slower rate, over the first 8 weeks post-natally, than the rapid and relatively early maturation of the superficial laminae. Association projections from area 17 to area 18 are certainly present from birth (Price & Blakemore, 1985*a*, *b*) and they may terminate mainly in the superficial layers, as seems likely in the adult cat (Tretter *et al.* 1975). It seems possible, then, that the rapid early development of orientation selectivity in superficial laminae is influenced in some way by inputs from area 17 or other cortical areas. If different inputs do influence the development of upper and lower layers in area 18 there would need to be co-ordination of the two processes in order to ensure that neurones throughout the

depth of the cortex gained preferred orientations appropriate to the column in which they were located.

Even in our youngest kittens almost all responsive units were binocularly driven. This observation agrees well with the hypothesis that cortical cells receiving Y-cell inputs from the l.g.n. are innately binocularly driven (Blakemore & Van Sluyters, 1975; Leventhal & Hirsch, 1977; Fregnac & Imbert, 1978; Stone, 1983). Like Albus & Wolf (1984), we found evidence of at least a rudimentary arrangment of ocular dominance columns in kittens as young as 12 days.

Comparison of the development of areas 17 and 18

The youngest kitten in which we examined neurones in area 17 was aged 12 days, and had already had about 3 days of visual experience. At this age the majority of units encountered in area 17 were visually responsive, and 29% of all cells were orientation selective. The percentage of orientation-selective cells rapidly increased with age, and 90% of all cells isolated in area 17 in a 10-week-old kitten were selective, while all the rest were orientation biased. Our results, taken together with those of previous workers (e.g. Blakemore & Van Sluyters, 1975; Albus & Wolf, 1984), suggest that post-natal development follows a very similar time course in areas 17 and 18, but that neurones with an innately specified orientation preference are more narrowly tuned (indeed are orientation selective rather than just biased) in area 17 than in area 18.

There is general agreement in the literature that there is some degree of bias towards horizontal and vertical in the distribution of preferred orientations of cells in area 17 in adult cats (e.g. Pettigrew, Nikara & Bishop, 1968; Rose & Blakemore, 1974; Leventhal & Hirsch, 1975). For kittens, there is a striking difference between the results of Fregnac & Imbert (1978) and Leventhal & Hirsch (1977), who reported a very strong predominance of neurones responding to vertical and horizontal orientations in area 17 in kittens aged less than 3 weeks and in visually deprived animals, respectively, and those of Blakemore & Van Sluyters (1975) and Albus & Wolf (1984), who reported no clear biases. In our present sample there was a tendency for cells in area 17 of kittens 3 weeks old and younger more frequently to prefer horizontal and vertical orientations, and in older kittens the distribution of preferences was flatter with a slight bias towards horizontal. Our finding that the distribution of preferred orientations in area 18 in kittens aged 3 weeks or less is clearly biased towards oblique orientations might indicate a major difference between the organization of areas 17 and 18 in young kittens, and between the ways in which the immature distribution of orientation preferences changes to achieve its adult characteristics.

We found evidence suggesting some degree of local clustering of orientation preferences in area 17 in kittens aged 12 days, in agreement with results of Blakemore & Van Sluyters (1975) and Albus & Wolf (1984); rudimentary orientation clusters were also found in area 18 at this age. In general we found that a larger proportion of neurones in area 17 in kittens were monocularly driven compared with area 18, and this probably reflects the possibility that cortical neurones receiving inputs from geniculate X cells in kittens may have a strong tendency to be monocularly driven (Blakemore & Van Sluyters, 1975; Fregnac & Imbert, 1978).

Over-all, our conclusion is that in many respects areas 17 and 18 develop with similar time courses, but a number of differences between the maturation of the two areas are found and some of these may be explained by differences in the types of input that each area receives from the l.g.n. Association inputs from area 17 may also influence the development of area 18, especially of its superficial layers.

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