BarlowHB (1982). David Hubel and Torsten Wiesel. Their contribution towards understanding the primary visual cortex. Trends in Neuroscience, 5, 145-152

Perspectives

David Hubel and Torsten Wiesel

Their contributions towards understanding the primary visual cortex

H. B. Barlow

Last year's Nobel Prize winners in Physiology and Medicine, David Hubel and Torsten Wiesel (see Fig. 1), published a paper 20 years ago that was a landmark in cortical neurophysiology[13]. And then a year later, in 1963[14,43,44], they published their first work on the development of the visual pathway in kittens, and this too opened a completely new field for physiological study. Even by that date many people felt their work was of sufficient merit for the prize, and it has been followed by 15 years of outstandingly successful collaboration producing a flow of important new results year after year. By now the award must be considered, not only one of the most richly-deserved, but also one of the hardest-earned.

Their work on visual cortex started when David Hubel joined Torsten Wiesel in Steve Kuffler's laboratory at Johns Hopkins in 1958. Hubel, working at the Walter Reed Research Institute, had developed a method of recording from single neurons in the cortex, whereas Wiesel had been continuing Steve Kuffler's own work on the retina. They published their first results on visual cortex in 1959[12], soon after Hubel's arrival in the laboratory, but it was not until 1962, after Kuffler had moved his laboratory to Harvard and at least 4 years after the work had started, that the major paper on the cat's cortex appeared. As far as cortical neurophysiology was concerned it was the dawn of a new day, for the preceding night had been illuminated chiefly by the murky glow of evoked potentials and electroencephalography. They reported three main results: first, they believed that neurons in primary visual cortex could always be excited by light if the appropriate patterned stimulus was found; second, the majority of neurons were binocular and could be excited through either eye; and third, they showed that cells of a given type were clustered according to a columnar microstructure. In their developmental work they showed both a high degree of ontogenetic determination of the features of the visual pathway, and striking plasticity resulting from abnormalities of experience. All of these findings were new, and all have been amply confirmed, though with certain qualifications and additions. If we consider these four problems, i.e. pattern selectivity, binocularity, columnar microstructure and development, we shall gain a fair idea of what they have achieved.

Pattern selectivity of cortical neurons

In 1962, many people were not at all convinced that it would be possible to make any functional sense of the activity of a single nerve cell in a sensory pathway, let alone in the cerebral cortex which contains some 10^{10} neurons. The claim they made, that the appropriate stimulus could be found for any single neuron in the primary visual cortex whose activity they could reliably detect, therefore had a major impact. Others had successfully recorded from cortical neurons, but had reasoned that light flooding the whole visual field, which made the whole field *look* bright, was the commonsense stimulus to use, to explore cortical neurons. Even at the retina and lateral geniculate nucleus (LGN) a uniform field is not nearly as effective as a small point of light because of lateral inhibition, and Hubel and Wiesel therefore explored the field with small spots in order to map the individual receptive fields of their cortical neurons. Examples of these maps are given in Fig. 2. Unlike the receptive fields at lower levels in the visual pathway, those of the cortical neurons were found to be elongated, and in consequence the patterned stimulus they responded to best was an oriented slit, bar or edge. Hubel himself says that they were aided in making this important discovery by the accidental observation that a fine dark line caused by a crack on one of their slides gave rise to a much larger response than the black spot that was intended as the stimulus.

Pattern selectivity in single cells was already known, and the behavioural importance of 'fly-detectors' in the frog's retina[1] was at that time being emphasized by Lettvin and his colleagues at MIT[26]. But selectivity for orientation was new, and so was the fact that all recordable neurons in the cortex were pattern selective. The implications were revolutionary; instead of thinking of the primary visual cortex (area 17) as a structure with myriads of cells each taking part in forming every visual image, one was forced to realize that each cell had its own very specific stimulus requirements, and consequently when it was active each cell 'said' something specific about the nature of the image in its particular region of the visual field.

Fig. 1. *David Hubel (left) and Torsten Wiesel (right).* (Photograph was taken at the Cold Spring Harbor Symposium in 1975 by Colin Blakemore.)

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Different cells differed from each other in many ways. Some preferred one orientation, some preferred another, and similarly with the size of the bar, and whether it was bright or dark, and the direction it was moved in. But there was also a major distinction into two types they called simple and complex. The former is the type shown in Fig. 2 and these cells responded to patterned stimuli in a way that could be roughly predicted from the shape and structure of their receptive fields, as plotted with a small spot of light turned on and off. Others, however, had larger receptive fields and often gave both 'on' and 'off' responses to a small spot over large areas. When tested with a bar or edge, however, these other cells also preferred one orientation, and often one direction of movement, just like the simple type. They named them complex and suggested that they were activated by a collection of neurons of the simple type that all shared the property of preferring one particular orientation, as shown in the lower half of Fig. 3. Since they had larger receptive fields they effectively generalized the detection of orientation over a range of positions; thus, they might provide a rudimentary example of the physiological mechanism for positional invariance – the ability to recognize the same feature anywhere in the visual field.

In later studies they investigated other cortical areas[15] and extended the work to monkeys[17] as well as cats. This part of their work is a superb example of what might be called the natural history approach to neurophysiology: they observed what their single cells responded best to and classified them, but they made little attempt to analyse the mechanism whereby pattern selectivity was achieved, or to fathom the significance of the types of selectivity observed. It must be said that their two major suggestions about mechanism have not stood up well. Their idea was that pattern selectivity was achieved by summation from a selected subset of inputs: geniculate afferents from a row of retinal neurons give a cortical neuron its orientational preference, they suggested, as shown at the top of Fig. 3. It now appears much more likely that inhibition plays the major role in making cortical neurons selective[34], just as it does in retina[4], for drugs antagonizing inhibitory transmitters remove pattern selectivity. Similarly their suggestion about the hierarchical arrangement of cortical neurons has been undermined by the discovery of parallel pathways in the visual system[37], by the demonstration that at least some of the complex cells are directly excited by geniculate afferents[36], and by the discovery of visual patterns that are ineffective for simple cells but effective for the

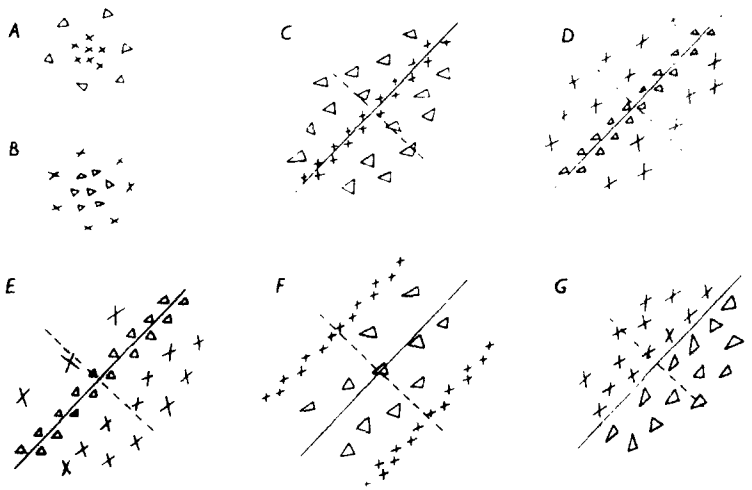

Fig. 2. *Examples of receptive fields plotted from isolated units in the primary visual cortex of the cat. When a spot of light was aimed at a position marked by a cross it caused a response when turned on, whereas for a position marked by a triangle the response occurred when it was turned off. Summation occurred when light fell simultaneously in regions marked alike, whereas light falling in an oppositely marked region reduced the response. The top left fields (***A** *and* **B**) *are from fibres arriving at the cortex from the geniculate. The remainder are from the simple type of cortical neuron, and the response to patterns of light could be predicted qualitatively from the arrangement of on and off areas of the receptive fields. (This is not true for complex cells.)* (From Ref. 13.)

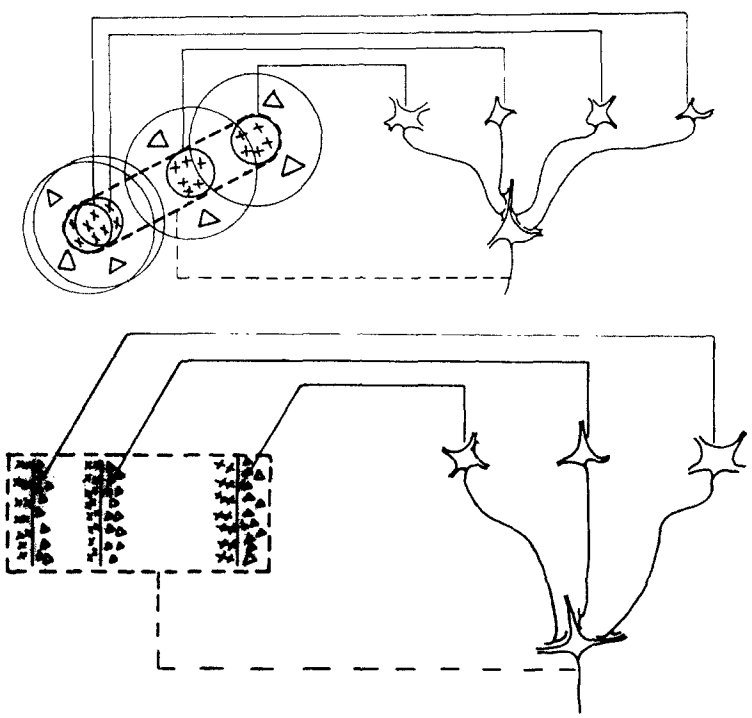

Fig. 3. *The mechanisms for the selectivity of simple and complex cells suggested by Hubel and Wiesel. At the top left the receptive fields of three retinal ganglion cells are shown. The messages from a large number of such cells, all lying in a row, are passed through lateral geniculate neurons and converge on a simple cell, which consequently has a linear receptive field. Below are shown the receptive fields of three simple type cortical neurons whose axons converge on a complex cortical neuron. Nowadays it is recognized that a simple cortical neuron often has very few excitatory geniculate afferents, and that inhibition plays an important part in their pattern selectivity. Also, there is often a direct geniculate input to complex cells and not only an indirect one as in this diagram.* (After Ref. 13.)

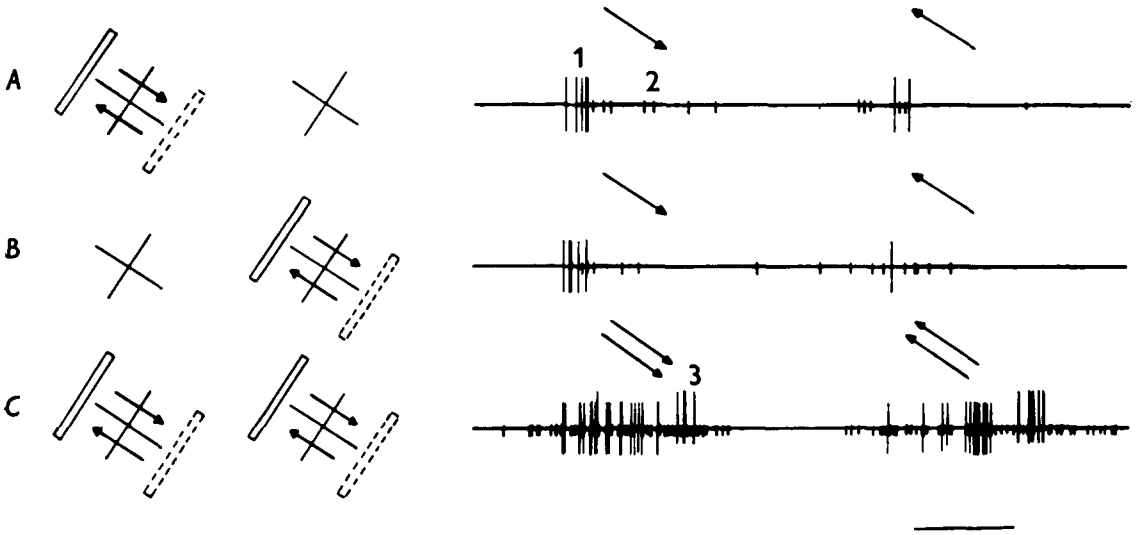

Fig. 4. *Binocular interaction in primary visual cortex of cat. Three different neurons could be discriminated at this position of the electrode.* **A** *shows the responses to a slit of light moved back and forth over the receptive field for the left eye,* **B** *for the right, and* **C** *for both together. Note that the responses in* **C** *are very much stronger than in* **A** *or* **B**, *and that the spikes numbered 3 could not be elicited at all through either eye by itself. Since the responses in* **A** *and* **B** *are approximately the same for neurons 1 and 2, these would belong to group 4 in an ocular dominance histogram.* (From Ref. 13.)

complex type[11]. But you must find your animal before you can skin him, stuff him or eat him, and Hubel and Wiesel's natural history of the cortex was the first and perhaps most important step.

Binocularity

The messages from objects in the right hemifields of each eye converge on the left LGN, and those from the left hemifields converge on the right geniculate. The geniculate neurons fed by each eye are, however, disposed in separate laminae, so that very few individual cells receive an input from both eyes. The axons of the geniculate neurons project to the primary visual cortex, and it is here that Hubel and Wiesel found cells responding to stimulation of either eye. Cats and monkeys differ somewhat in how this comes about, for in cats it appears that the geniculate afferents connect directly to orientationally selective cortical neurons, whereas in monkeys another neuron intervenes. These are the very numerous small granular cells confined to layer IV, that receive the direct geniculate input. They have monocular receptive fields and are not orientationally selective.

When the pathways from the two eyes had finally converged onto a single neuron, Hubel and Wiesel found that they had the same type of receptive field in each eye, and responded preferentially to the same type of stimulus – for instance, a horizontal slit of light of a certain size moving as shown in Fig. 4. The receptive field for each eye was also in approximately the same region of the visual field, so that it was reasonable to suppose that, with the eyes properly aligned in a conscious cat, an object in the external world would excite the same cell through both eyes. Not all cells had the same strength of connection with the two eyes, however, and they graded them into seven groups according to the balance of the excitatory connections from each eye. Thus arose the ocular dominance histogram shown to the left of Fig. 5. This displays the numbers of neurons in each group, from those responding only through the contralateral eye (group 1) through those responding only through the ipsilateral eye (group 7).

As a display of the binocular connections in the cortex one can regard ocular dominance histograms either as brutally effective, or foolishly simplistic. They have been used extensively, both by Hubel and Wiesel and by others, and they have told us much of what we know about the columnar anatomy, the development and plasticity of the cortex. But their almost exclusive use is in many ways disastrous, because the binocular property displayed is only one of many binocular properties that ought to be taken into account. First, they only deal with the excitatory properties of binocular inputs; it is now clear that input from one eye can, and frequently does, inhibit the effects of input from the other eye, but this type of binocular interaction is not shown at all in the dominance histogram. Second, in some cases a neuron responds equally vigorously to input through either eye, and not much more vigorously to excitation through both, whereas in other cases it responds poorly or not at all through each eye alone, but vigorously to both together (see Fig. 4); the distinction between the OR-type interaction and the AND-type must surely be important, but both types would be placed in group 4 of the histogram. Third, no attention was paid to the precise positioning of the optimal stimuli in the two eyes, and Hubel and Wiesel therefore missed the significance for stereopsis of the binocular interactions that occur in area 17 (Refs 3, 9, 29, 31). In their 1962 paper they had suggested that the monocularly dominated groups 1 and 7 play a role in stereopsis by relaying monocular information elsewhere, and they subsequently[19] found disparity selectivity in cells of area 18, the second visual area. But it has now become clear that these so-called monocular groups in area 17 often have powerful inhibitory inputs from the non-dominant eye[9], and it is hard to see what role this inhibition could play according to their notion of the mechanism of stereopsis. On the other hand it finds a natural place in the rival scheme where disparity is analysed first in primary visual cortex (area 17), for it is the mechanism whereby selectivity for disparity is achieved.

Their treatment of binocularity is perhaps the least satisfactory aspect of their work. However, although ocular dominance is an unrefined measurement, it does have the merit of being easy to use, and it led to further important anatomical discoveries.

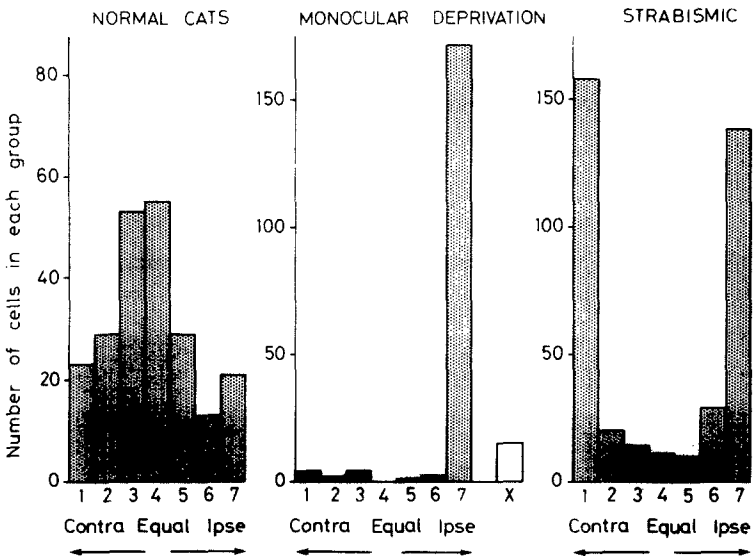

Fig. 5. *Ocular dominance histograms from primary visual cortex of young cats, showing the effect of monocular deprivation and surgically-induced strabismus. Group 1 has input from the contralateral eye exclusively, group 7 from the ipsilateral eye exclusively, and the intermediate groups have intermediate degrees of dominance. Cells with normal properties are shown stippled, whereas those in black had abnormal properties, lacking orientational selectivity; cells in the column marked X could not be excited at all. The centre histogram shows the results from the left cortex of five kittens aged 8–14 weeks in which the right eyes were closed by lid suture at 10–14 days. Note that all the cells with normal properties were strongly dominated by the ipsilateral eye that continued to give the kitten its view of the world. For the right histogram, four kittens were made strabismic by cutting an eye muscle. The misalignment of the eyes means that a given cortical region will usually not be stimulated by the same object in the external world so that cortical neurons would be unlikely to be stimulated by both eyes together. The result is that fewer neurons are found that respond best to combined stimulation of the type shown by the three cells of Fig. 4. Ocular dominance histograms do not take account of several important aspects of binocular interaction, but they show very clearly that the pattern of cortical connections can be modified by experience.* (From Refs 16 and 45.)

Columnar microstructure

Steve Kuffler always liked to see the structure that he was recording from, and his influence was possibly responsible for Hubel and Wiesel's constant determination to find the anatomical substrate for their physiological findings. One can find weaknesses in their suggestions about mechanism, and one can doubt the adequacy of their concepts about stereopsis and other aspects of visual performance, but when it comes to anatomy one can have nothing but respect and admiration both for their unremitting efforts and for the degree of success achieved. In the early 1960s there were many who thought of the cortex as a randomly interconnected porridge of cells, with a vaguely defined mapping of the major sensory inputs, and with a six-layered laminar structure whose significance no one understood. The precision of the topographical mapping of the visual field was confirmed by Hubel and Wiesel's single neuron records, but this had been anticipated by others such as Talbot and Marshall[38] and Daniel and Whitteridge using less refined methods[7]. The accuracy of these maps is of the order of 1 mm on the cortical surface, and when projected in the visual field this is not too far above the value of acuity, as judged by the minimum visible angle of separation of two points. The upshot of Hubel and Wiesel's work is to reveal a microstructure: within each square millimetre they found a regular arrangement of ocular dominance and of the axis of orientation preferred by the units. Within the topographic map they found new types of regularity and thereby they increased by an order of magnitude the amount of organized structure that could be recognized.

Their early evidence for this microstructure came from the observation in the cat that two or more cells responding optimally to the same orientation were often recorded from simultaneously. They investigated this systematically by the technique of electrode track reconstruction. Mountcastle[38] had observed separate clustering of deep and superficial touch modality cells in columns perpendicular to the surface of the somatosensory cortex, and he and Powell[32] had developed the anatomical methods of marking an electrode track and locating individual cells along it so that their positions could be correlated with cortical landmarks, such as transitions from one area to another and the crossing of the six laminae. Hubel and Wiesel followed up this important work and found a more interesting microstructure, for the feature they found to be ordered in primary visual cortex, namely the preferred orientation of the cells, was a characteristic that was not present in the input at all but was created by the pattern selectivity of the cells themselves. Thus, the cortex seems to organize its own work in a columnar manner. Furthermore, the preferred orientation often changed in a regular way as the electrode advanced through the cortex, as illustrated in Fig. 6. They also found evidence of periodic alternation of eye preference in the cat's cortex, but it was not until they worked on monkeys that they found the anatomical basis.

The method of track reconstruction showed them that the clusters were arranged in columns running normal to the surface of the cortex from pia to white matter, for an electrode track running in this direction would often record from cells which all showed the same preferred orientation, whereas an oblique track would reveal the ordered sequences mentioned above. But it was difficult to obtain an idea of the cross-sectional shape of a column by this technique. In their Ferrier lecture[23] they recount four anatomical methods whereby they were able to show the alternating stripes of ipsi- and contra-lateral dominance, each about 0.5 mm wide, and occasionally joining up or ending abruptly (see Fig. 7). They also showed a periodic structure of orientational selectivity with a period of about 0.6 mm between repetitions of the same preferred orientation, and at first they speculated that these orientation columns were arranged as a stack of thin laminae also running through the depth of the cortex, but with the axis for orientation change at right angles to that for ocular dominance change (see Fig. 8). This is the picture that has got into the textbooks, but it is unlikely to be correct. It is probably more accurate to say, as they now do, that the two systems of columns are independent, rather than orthogonal, and if this is the case it would be possible to superimpose other independent organizations without running out of dimensions. Those who have looked at other properties, such as the preferred colour[27], directionality[30,41], or spatial frequency[40,42] of the neurons, have found almost as much evidence for clustering of these properties as for preferred orientation; some doubts have indeed been cast on the exactness of the columnar organization of orientation[25].

Hubel and Wiesel[20,21] point out that the organization their results reveal means that

each small region, about 1 mm² at the surface, contains a complete sequence of ocular dominance and a complete sequence of orientation preference. They named such sequences hypercolumns (see Fig. 8), and found that the whole cortex possessed this uniform arrangement, although the angular subtense of one such hypercolumnar distance, when projected into the visual field, varied from about 10 min of arc at the fovea to many degrees in the periphery. They have thus given us a very striking, though admittedly oversimplified, picture of a regular, almost crystal-like structure in which all the known machinery for analysing each region of the visual field is repeated regularly over the surface of the visual cortex.

They were no doubt fortunate that the anatomical techniques for performing these analyses turned up at just the right moment, but they have been in the forefront in developing them and demonstrating their usefulness. It is also interesting that in this, the area of their greatest success, they have avoided dogmatic adherence to their early views and have even acknowledged the contributions made by others. One feels that although the final picture is not yet complete, when it is Hubel and Wiesel's signature will be on it.

Development and plasticity of the visual system

The development of the visual system is a topic of obvious interest because of the clinical facts of amblyopia: a squinting eye, or one that is placed at a disadvantage compared with its mate in some other way during early development, often performs much worse, when it is subsequently tested, than can be accounted for by objectively measurable abnormalities. It was presumably for this reason that Hubel and Wiesel turned their attention to the problem so early; they published three papers on it in 1963[14,43,44], another three in 1965[15,45,46],

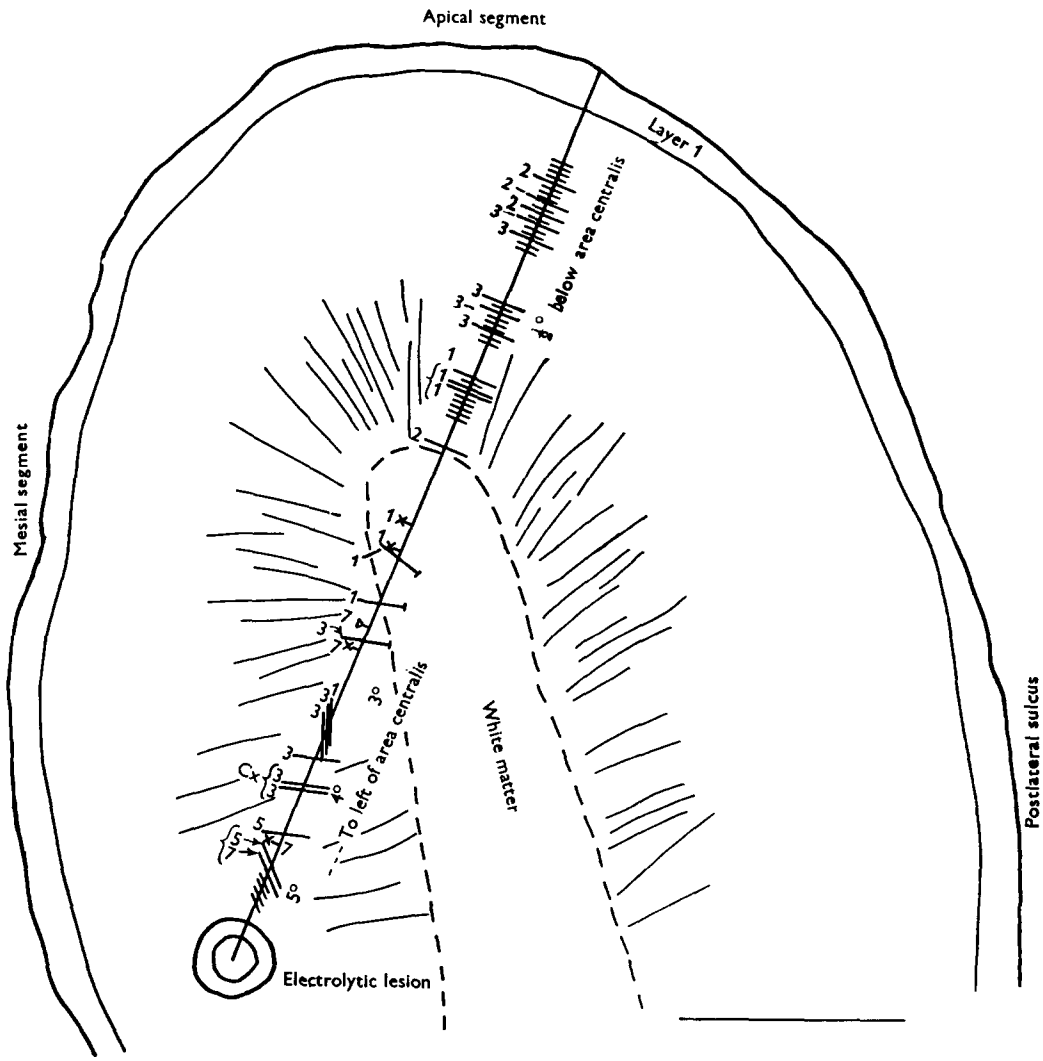

Fig. 6. *An example of the reconstruction of an electrode track in visual cortex of cat. The micro-electrode entered at the top and first passed down a column of cells which all had the same orientation, as shown by the angle of the longer line segments. The shorter line segments show the preferred orientation for eliciting hiss or crackle from unresolved units. The numbers show the ocular dominance groups of the cells; notice that for this part of the track they belong to groups 1–3 (i.e. all dominated by contralateral eye). For the remainder of the penetration the track passed obliquely through the cortex, and orientation and ocular dominance change. After the micro-electrode had been advanced just over 4 mm current was passed through it to cause an identifiable lesion. To record from a series of 21 neurons in an experiment like this would take at least 10 h, excluding time for setting up the preparation and of course the histology.* (From Ref. 13.)

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and another in 1970[18] which defined the critical age range within which development was modified by experience. These dealt with the cat; others on the monkey followed in 1974[22], and 1977[23,24]. The present state of the subject will be reviewed by N. Swindale in a future issue of *TINS*; here Hubel and Wiesel's main contributions will be outlined.

It is a curious paradox that, while they have consistently argued for a high degree of ontogenetic determination of structure and function in the visual system, they are also the authors of the best example of plasticity in response to changed visual experience. This is the result shown in part in Fig. 5. The left-hand ocular dominance histogram is from normal cats. The middle one shows what happens if the lids of one eye are sutured at an early age. When recorded from at a later date very few cells can be found still connected to this sutured eye and the great majority have switched their allegiance to the eye through which the kitten had seen the world. The right histogram shows results for kittens that had been given artificial strabismus by cutting an external rectus muscle. Here, there were cells connected to each eye, but few connected to both, so cells that had previously responded through both or either eye had now switched their allegiance almost totally to either one eye or the other. These results have been repeatedly confirmed. It has also been shown convincingly[33] that the orientation preference of cells can be modified, though I am not sure if Hubel and Wiesel have yet accepted this. At all events it seems well-established that cortical neurons become biased in favour of responding to patterns of afferent activity that occur frequently, and against those that occur infrequently or not at all. But there are some facts on the other side, and these are the ones Hubel and Wiesel emphasize.

First, if both eyes are sutured one might naively expect both eyes to be disconnected; instead one finds a nearly normal ocular dominance histogram. They explained this by postulating competition between the eyes for dominance of cortical neurons, together with an effect of deprivation that placed an eye not receiving visual experience at a disadvantage relative to one that was. They also recorded from the cortex of young kittens[14] and monkeys[22] before they could have received very much, if any, visual experience, and found many of the properties of the adult. Thus, some cells are pattern selective, some receive connections from both eyes, and there is a clear indication of the columnar microstructure characteristic of the adult. Hubel and Wiesel concluded that cortical neurons required experience to maintain functional connectivity, but that experience had no positive effect in creating the pattern selectivity or the functional architecture of the cortex. The main trouble with this argument is that it is based to a disconcerting extent on the very incomplete view of binocular properties that is given by ocular dominance histograms. Many who have subsequently recorded from binocularly deprived cortex think that the ocular dominance histogram is almost the only normal thing about it, and that it does not reflect the general state of the cortex at all well. Of course if one hopes to get an adequate sample of cells a crude test of this sort is at first more or less a necessity, but here it seems to have been misleading. There is also strong evidence undermining their argument from the very young, visually inexperienced cortex, for this must be radically different from the adult cortex both structurally and functionally. First, at the age of eye-opening in kittens, when Hubel and Wiesel found cells supposedly like the adult, the cortex is anatomically immature and contains only a small fraction of the number of synapses of the adult[6]. Second, measures of acuity show that adult values are not reached until 2–3 months in kittens[10] or 5–6 months in monkeys[39]. Low acuity could of course result from deficiencies elsewhere in the system, but measurements on the cortex are now showing that the inexperienced neurons are not responsive to high spatial frequencies, and that whereas cells of the lateral geniculate develop this responsiveness without experience, those of the cortex fail to do so[5,8]. Thus, Hubel and Wiesel were correct in pointing out that the rudiments of pattern selectivity and functional architecture are determined ontogenetically, but it was rash to conclude that visual experience had no positive effect in enabling primary visual cortex to perform its adult functions.

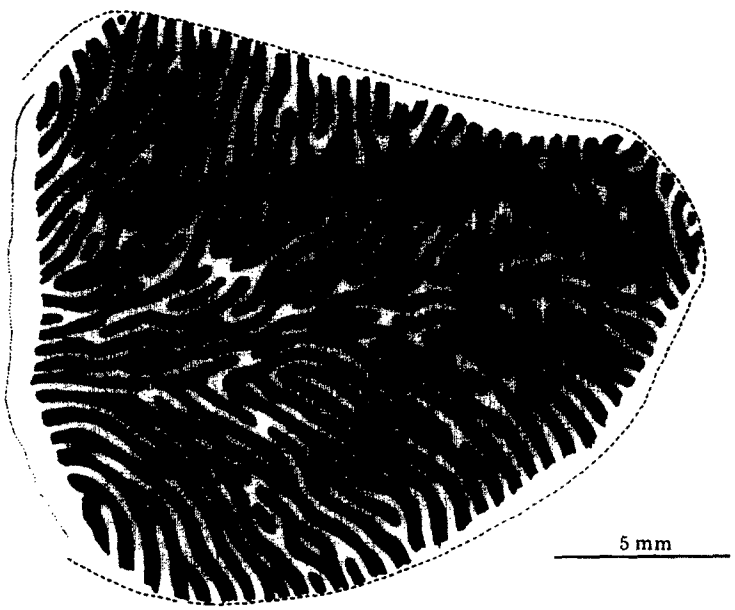

Fig. 7. *This shows a surface view of the primary visual cortex of rhesus monkey, with the portion dominated by one eye in black and that dominated by the other in white. The mid-sagittal plane is to the left, and visual cortex dips down here and is no longer visible. The dashed line is the border between areas 17 and 18; it corresponds to the vertical meridian in the visual field, with the fovea at the extreme right.* (From Ref. 23.)

As remarked before, on the nature/nurture controversy Hubel and Wiesel are in a paradoxical position – some of the best evidence on one side, and the most dogmatic statements on the other!

Unsolved problems

One of the glories of vision is that it is accessible for psychophysical as well as anatomical and physiological investigation. Overall visual performance is much better understood than any other high level function of the nervous system, and it is therefore peculiarly galling not to be able to say, at the end of an article like this, what aspect of this performance is brought about by the primary visual cortex. We know that Hubel and Wiesel's neurons must play an important part in processing information arriving at the primary visual cortex from the retina, and accordingly all the psychology texts include an account of their work: but what is the part they play? The answer is important for anatomy and physiology as well as psychology, for you could not give an ade-

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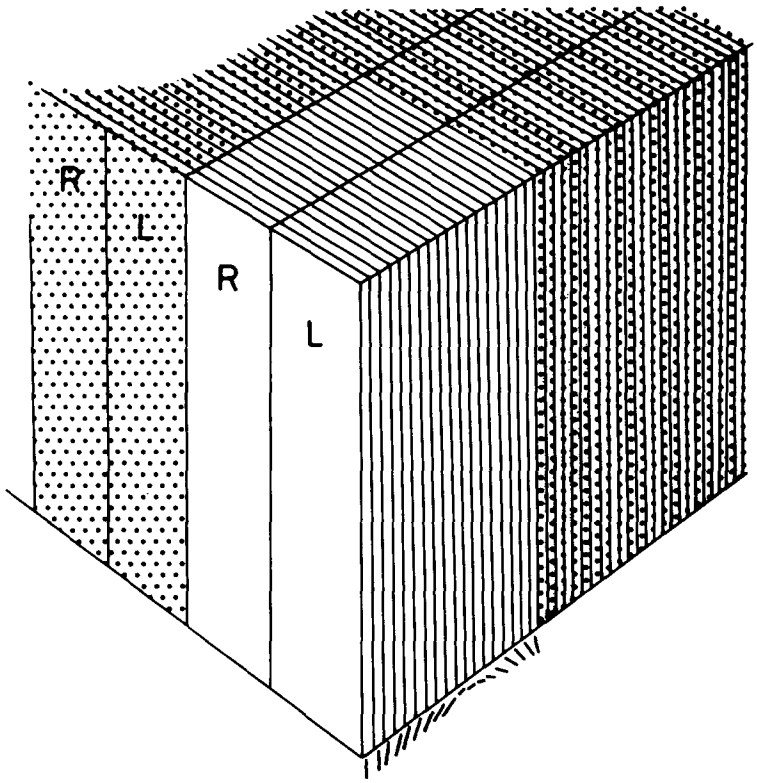

Fig. 8. *Diagrammatic representation of a hypercolumn in area 17 of monkey. It contains a pair of regions dominated by left and right eyes, and a complete (180°) cycle of orientation columns, as shown by the small line segments beneath each slice. The arrangement is not now thought to be as regular as this, and Hubel and Wiesel refer to the organization of ocular dominance columns and orientation columns as independent rather than orthogonal.*

quate account of the structure and function of the eye if you did not know it was an image-forming device. So what kind of an image does the primary visual cortex form?

The most hopeful answer at the moment is the one I have recently advocated[2], namely that it detects those local characteristics of the visual scene that enable it to be separated into its important objective sub-divisions, especially the segregation of figure from ground that Gestalt psychologists attached so much importance to. The cells of the cortex certainly respond selectively to orientation, texture, colour, movement and disparity, which are the main linking features enabling this segregation to be done. Having detected the presence of particular linking features in particular parts of the image one needs a mechanism for associating together all parts that share the same feature. This might be achieved in the multiplicity of secondary visual areas, possibly by use of projections from the primary area that are organized non-topographically according to the variables of the linking feature rather than purely according to position in the visual field. But this is speculative and awaits confirmation, refutation, or modification in the light of new experiments.

Two important problems that may be open to solution are the mechanism whereby cortical neurons achieve their pattern selectivity, and the mechanism for plasticity in the sensitive period. The mechanism of selective summation suggested by Hubel and Wiesel[13] (see Fig. 3) must play a role in pattern selectivity, for neurons obviously do not receive excitatory connections indiscriminately. But the importance of inhibition for orientational selectivity, motion selectivity, and disparity selectivity does support the notion that the restrictive logical function (equivalent to 'AND') is achieved by inhibition abolishing unwanted responses[4]. Possibly our brains use a form of NAND logic.

The mechanisms underlying plasticity in the critical period are obviously of enormous interest. Anatomically there is evidence of sprouting and spread of the active terminal afferents in the cortex, and withdrawal of inactive ones. Furthermore inactive cells in the LGN shrink and active ones swell. Such effects are very much like those of Nerve Growth Factor on sympathetic neurones, and it is tempting to advance a speculation involving similar substances in the CNS. Rauschecker and Singer[33] concluded from studies with successive types of visual deprivation in kittens that the condition for a geniculate afferent to establish and maintain a synaptic grip on a cortical neuron is the successful activation of the post-synaptic cell by the afferent's pre-synaptic terminals. It therefore seems possible that cortical neurons release a 'Synaptic Rewarding Factor' when activated, that this is picked up by the terminals which have just been depolarized, and transported in a retrograde direction to the cell body. There it would cause the observed cell growth, it would lead to the stabilization of the successful synapses, and it would enable the cell's axon to sprout. Such a mechanism would provide a functional link between experience and the known plastic changes that occur during the critical period.

These are some of the exciting possibilities that are opening up in cortical neurophysiology, but the more immediate task is to apply Hubel and Wiesel's own approach and methodology to other cortical areas. One cannot expect the identical pattern in other regions, but it will be most surprising if none of the lessons from their work can be applied elsewhere.

The acclaim for Hubel and Wiesel has come from a wide range of scientists, from psychologists to molecular biologists. Some of those following most directly in Hubel and Wiesel's footsteps have been more critical, both because the early reports have not always, upon repetition, seemed to tell the whole story, and because some of the early interpretations do not now fit all the facts. But it is hardly surprising if the first work in a field needs additions and corrections, and the importance of these amendments may have been inflated by the cries of outrage from the pioneers themselves, who have often been reluctant to accept new evidence. But time will tell, and the final judgement must be left to those who will make the important advances still necessary before the cortex begins to be properly understood. Among those who are carrying on Hubel and Wiesel's work few would deny that it is a constant challenge to match their overall record for innovation, reliability and thoroughness.

Reading list

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