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Modification of the Distribution of Receptive Field Orientation in Cats by Selective Visual Exposure During Development

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Summary. A novel procedure was used to rear kittens under conditions of controlled visual experience: one eye was exposed only to vertical lines while the other eye, simultaneously, was exposed only to horizontal lines. Stimuli were presented in a mask which the animals wore whenever they were in a lighted environment. At the conclusion of the rearing period elongated receptive fields of units recorded from the visual cortex of these animals were oriented either horizontally or vertically. This is in contrast to the full complement of receptive field orientations found in normal cats. Furthermore, units with vertically oriented fields were predominantly or exclusively activated by the eye which had been exposed to vertical lines, while neurons with horizontally oriented fields were predominantly or exclusively activated by the eye which had been exposed to horizontal lines. Normally, 80—90% of the neurons in the visual cortex of the cat are activated by both eyes. The consequences of this controlled visual experience provide evidence for highly selective modification of neuronal connectivity by environmental conditions prevailing during development. Sufficient control of the visual environment was achieved to allow direct comparison between single unit response characteristics and the specific stimuli presented during rearing.

Key Words: Visual cortex — Receptive fields — Visual deprivation — Neuronal plasticity — Cat

Introduction

Relating structure and function provides a starting point to investigate the processes and mechanisms underlying behavior. Study of the visual system, which lends itself well to both behavioral and physiological investigation, has led to considerable progress towards this goal. The discovery that neurons in the sensory pathways are often responsive to a relatively narrow range of stimuli led to the suggestion that information about specific stimulus attributes or features may be transmitted to the visual centers (Lettvin *et al.*, 1959). Feature-analyzing models of the perceptual process received further support from the finding that cells in the cat and monkey visual cortex respond optimally to elongated stimuli such as lines, bars, or edges (Hubel and Wiesel, 1962, and 1968). This might imply that

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analysis of incoming stimulus patterns involves activation of a particular set of orientation sensitive cells ("line detectors").

Manipulating the set of available "line detectors" should allow a direct, experimental test of their functional significance — something which has not yet been achieved. A particularly efficient procedure would be to observe the visual capabilities of an animal which has only one class of orientation sensitive cells; for example, the class responding optimally to vertical lines. Previous studies on restricted visual experience (Hubel and Wiesel, 1965b; Wiesel and Hubel, 1963, 1965; Ganz *et al.*, 1968) suggested that sensory deprivation might be an effective method for eliminating unwanted cell classes. The present paper describes a technique for realizing such a preparation. Elsewhere (Hirsch, in preparation), the results of behavioral studies designed to test the functional significance of orientation-sensitive cells are described. A brief report on the results of the physiological recording has appeared previously (Hirsch and Spinelli, 1970).

Previous studies (Wiesel and Hubel, 1963, 1965; Ganz *et al.*, 1968; Hubel and Wiesel, 1970) have demonstrated that restricting patterned visual stimulation during a critical period in an animal's development produces widespread changes in the function of cortical cells. The effect is greatest if the two eyes are subjected to different stimulus conditions during the appropriate time period. A rearing procedure in which the two eyes receive discordant stimulation was thus utilized in an attempt to restrict the effects of visual deprivation to one class of orientation-sensitive cortical cells, selected on the basis of their receptive field orientation.

Methods

Subjects

Nine kittens were reared under conditions of selective visual deprivation. They came from a total of six litters born in a closed laboratory breeding colony. VH-50 and HV-51 were littermates, as were VH-80, HV-81, and HV-82. Each of the remaining four kittens (VH-33, HV-40, HV-70, and HV-90) were from different litters. (HV and VH refer to the orientation of the lines to which each eye was exposed during rearing: HV kittens were exposed to horizontal lines with the left eye and vertical lines with the right eye, and the converse for VH kittens.)

Rearing Conditions

Kittens were placed into a completely dark room before their eyes opened. Beginning at three weeks of age they received *daily selective visual experience*. For each kitten this consisted of at least two 4-hour periods a day during which one eye was exposed to a white field containing three black vertical lines while, simultaneously, the other eye was exposed to a white field containing three black horizontal lines. These stimuli were mounted inside a mask worn by the animals. A lens (17 mm focal length, 17 mm diameter) was mounted in the mask in front of each eye. The stimulus lines were positioned at the focal planes of these lenses so that small changes in the position of the mask would not affect the sharpness of focus. Each black line subtended one degree of visual angle at the cat's eye and the centerpoints of the lines were six degrees apart. The mask provided approximately a 50 to 60 degree field of view for each eye. White diffusing plastic in the mask provided uniform illumination of the stimuli. Figure 1 is a photograph of a kitten wearing the mask; a more detailed description of the mask and procedures for assembling it are given in Hirsch, 1970, Appendix I.

The masks were put on and taken off inside the darkroom so that the animals would not receive any visual experience other than that provided by the mask. In order to insure that the cats would not pull or rub off the mask, they wore a neck ruff similar to that used by Hein and Held (1967). The animals became accustomed to the masks and were active and playful during the exposure periods. However, disease and skin lesions caused by the masks in some



Fig. 1. Photograph shows a kitten wearing one of the masks used to provide selective visual stimulation. The stimulus patterns are mounted on the inside surface of the black, rectangular sheet of plastic at the ends of the two white cylinders. One of the rubber straps which hold the mask in place can be seen; others are located at either side of the animal's head and under its chin. The neck ruff which the animals normally wore has been left off

cases forced suspension or termination of the exposure periods. Most of the animals were given daily selective visual experience until they were twelve weeks old. The cats were checked repeatedly while they were wearing the masks. Slippage due to rotation of the mask is estimated at a maximum of ten degrees, and in most kittens was less than five degrees. Eye movements were not measured during the exposure periods.

Three animals accidentally received some unplanned visual experience. One cat (HV-51) pulled off the mask after receiving 9 weeks of exposure and obtained at most 9½ hours of normal binocular experience. Another animal (VH-33), during the 12th week of exposure, broke the neck ruff and then pulled off the mask, receiving a maximum of 12 hours of normal visual experience. In both cases the animals were kept in the darkroom for several days after the accidental exposure until the electrophysiological recording could be done. HV-51 was given an additional 9 hours of exposure to the mask immediately prior to recording. A third cat (VH-50) wore the incorrect mask for one exposure period (6 hours, 15 min), thus viewing vertical lines with the eye previously exposed only to horizontal lines and horizontal lines with the eye previously exposed to verticals. This occurred when the cat was 7½ weeks old. The original exposure conditions were subsequently resumed until the animal was 12 weeks old.

The actual number of hours of exposure ranged from 633 hours given over a ten week period (VH-33) to 156 hours, 45 minutes, given over a five week period (HV-70).

Electrophysiological Recording

At the end of the rearing period, when most of the animals were between 10 and 12 weeks of age, the receptive fields of single units in the visual cortex were mapped. Prior to the electrophysiological recording the only visual experience which the animals received was the ex-

posure to the stimuli inside the masks (with the exceptions noted above). The recording thus provided a direct verification of the physiological consequences of the selective visual deprivation.

The preparation, recording, and mapping techniques developed by Spinelli (1967) were used. To prepare the animal for recording, thiopental sodium was injected intravenously to obtain general anesthesia, and a small opening was made in the skin, bone, and dura above the visual cortex of one hemisphere. The animal subsequently was placed into a stereotaxic holder (Baltimore Instrument Company) which did not obstruct the visual field. All pressure points and incisions were infiltrated with a long-acting local anesthetic (Zyljectin). A skin flap was attached to a ring, and a mixture of agar and saline was used to minimize brain pulsations. Then, the animal was paralyzed with Flaxedil (gallamine triethiodide) and the general anesthetic was discontinued. The Flaxedil was infused continuously at a rate of about 10 mg/h. The animal was artificially ventilated by a Harvard apparatus pump (model 607, stroke volume 25–35 cc., respirator rate 20/min). Oxygen was administered to insure that the animal would remain in good condition. The animal's temperature was continuously monitored and maintained at 37 degrees \pm 1 degree Centigrade. To protect the cornea of the eye and to correct for accommodation, contact lenses were used. Atropine sulfate was given to maintain constant pupil size, and Neosynephrine was used to retract the nictitating membrane. Great care was taken to keep the contact lenses clean; the cat's eyes were examined routinely to assure that no deterioration had occurred. The recordings were made after the animal had recovered from the general anesthetic. In this manner the animal's condition more closely approximated the normal waking state.

The spike discharges of single units in the visual cortex were recorded with tungsten micro-electrodes. These electrodes make it possible to record the activity of a given cell for long periods of time. Solid state (FET) source followers were mounted directly above the electrode; their output was amplified and introduced into a Schmitt trigger. A standard pulse, produced whenever the potential change exceeded a pre-set level, was fed into a small general purpose computer (Digital Equipment Corp. PDP-8). In this way the occurrence of spike discharges of the cell could be recorded and stored by the computer.

The receptive field of a cell was mapped by moving a black spot (1 to 4 degrees in diameter) at a constant velocity of 10 degrees/second across a white tangent screen (reflectance: white — 75%, black — 3% incident light on the screen 20 lm/m²), positioned 57 cm from the cat. The spot was moved by a computer-controlled XY-plotter in a scanning pattern of 50 lines; each line was 25 degrees long and 0.5 degrees apart, thus covering a 25 by 25 degree square. The computer was programmed to store the responses generated by the unit during each 0.5 degrees of movement in separate memory locations. This produced 2500 data points for each map. During mapping, the screen was illuminated evenly by 3 tungsten filament lamps (20 lm/m²).

Spots were used in mapping, rather than line stimuli, because this method should reveal the shape of the receptive field with the least possible bias (Spinelli and Barrett, 1969). Using a line or bar in mapping assumes that all receptive fields will be elongated and that cells will respond optimally to line stimuli. Some hand mapping with line-shaped stimuli was done and all of the cells examined which responded to line-shaped stimuli also responded to the moving spot.

Using a white tangent screen (rather than a black one) kept the cat's retina in a light-adapted state. Thus, the effect of any stray light resulting from small imperfections in the optical system was minimized. Hand mapping, using both luminous spots and black spots indicated that many units in these cats responded more strongly to the black stimuli.

All units encountered during the recording were analyzed and, whenever possible, each was mapped at least 12 times. The mapping was first done with both eyes open and then for each of the two eyes separately. Under each of these conditions two vertical and two horizontal maps were made. For example, during a vertical map, the spot was moved at a speed of 10 degrees per second, from the bottom of the screen to the top, and then from the top to the bottom. Fifty such scans covered the field. Data were collected separately during upward and downward movement of the spot. In this manner two vertical maps were obtained. Horizontal maps were obtained in an analogous fashion.

An attempt was made to record the activity of units located in the region of the visual cortex receiving projections from the *area centralis* (Otsuka and Hassler, 1962). This was done

by making a small opening in the cranium and positioning the electrodes in accordance with stereotaxic coordinates (Spinelli and Barrett, 1969). The majority of units were recorded between stereotaxic coordinates Anterior-Posterior 0.0 mm to +1.0 mm and Medial-Lateral +0.5 mm to +1.0 mm. A few were recorded between +2.0 mm and +6.0 mm Anterior. To aid in verifying the electrode position, the projection of the optic disc onto the tangent screen was determined with the use of a reversible ophthalmoscope and the position of the *area centralis* was inferred (Bishop *et al.*, 1962a). The position of the receptive fields could then be compared with the estimated position of the *area centralis*.

Normally, the region scanned during mapping was positioned so that the projections of the pupils were near the vertical midline of the region and about 10 degrees above the bottom of the screen. To insure that the receptive field of the unit being examined was actually within the 25 by 25 degree region covered by the moving spot, hand-held stimuli were used to explore the receptive field. It was occasionally necessary to reposition the cat in order to bring the receptive field onto the scanned portion of the tangent screen.

After the electrophysiological recordings were completed, seven of the nine experimental animals were successfully revived. Intraperitoneal injections of cortisone (50 mg) were given to reduce shock, and 300,000 units of bicillin were given intramuscularly to control possible infection.

Analysis of the Data

The first problem in analyzing units was to determine whether they were cortical units or geniculate afferents. In normal cats a reliable indication that a unit is a cortical cell rather than a geniculate fiber is that both eyes can activate the unit. Since most, if not all, of the cortical units in these cats were expected to be monocular, it was necessary to rely on criteria other than binocularity for distinguishing cellular activity from the activity of geniculate fibers. These criteria include shape of the spike, background activity, and rate of firing (Bishop *et al.*, 1962b). Since few, if any, geniculate fibers have elongated receptive fields, the receptive field shape was used as a further criterion to distinguish between cortical and geniculate units. In addition, recording was restricted to the first two millimeters of cortex, where fibers tend to spread out more than in the underlying white matter, thus reducing the likelihood of encountering a geniculate afferent.

The record of a unit's activity was displayed on an oscilloscope screen as an integral contour display which permitted the shape of the receptive field to be readily visualized (Spinelli and Barrett, 1969). A level I integral contour display presented each of the 2500 points in the scanned region at which the cell fired at least once in response to the spot. At level II, all points at which the cell fired at least two times were displayed; any other desired level could be selected.

All the maps for a single unit were utilized to categorize it; the greatest weight was placed on maps obtained with the spot moving in the direction which elicited the strongest response. Units with elongated receptive fields usually responded best when the spot moved orthogonal to the receptive field axis. It may be helpful to explain why an elongated region of activity oriented at right angles to the direction in which the spot moved during mapping can be reliably interpreted as an elongated receptive field. Such a region of activity can arise only if the unit discharges on successive scans across the screen — in other words, every time the spot crosses the receptive field. In contrast, a region of activity extended along the direction in which the spot was moving during mapping can be caused in two different ways: either by an elongated receptive field oriented along the path of the moving spot, or by an after-discharge resulting from passage of the spot through a disc-shaped receptive field. It may also be noted that there are occasionally very narrow regular regions of activity which extend in the same direction as the spot moved during mapping (see, for example, Fig. 5, row 2); these presumably represent a sustained spontaneous discharge of the cell during mapping.

Results

A. Location of Units within the Visual Cortex

Since it was not possible to visualize the surface of the cortex through the small opening in the cranium, the relationship between the receptive field posi-

tions and the projections of the optic discs was used to verify the location of the electrode (Bishop *et al.*, 1962a). The projections of the optic discs onto the tangent screen were determined for all the animals and the mean position of the optic discs computed (relative to the projection of the pupils onto the same tangent screen). This was compared to the expected mean position of the optic discs (relative to the projections of the pupils) in normal adult cats (Bishop *et al.*, 1962a). The projections of the optic discs in the present study were some 8 to 9 degrees higher (relative to the pupils) than expected. In addition, the scatter of the points was greater than in normal adult cats.

The elevated location of the optic disc projections can be accounted for by assuming that the kitten's head, when held in the stereotaxic instrument, was tilted slightly relative to the standard position of an adult cat in a stereotaxic holder. Since the microelectrode which was attached to the stereotaxic instrument would be moved relative to the cortex by such tilting, an electrode positioned stereotaxically at the Anterior-Posterior zero line would actually enter the cortex at a position anterior to the zero line. It was computed that for an 8.5 degree tilting of the cat's head, this displacement would amount to approximately 4.2 mm. This leads to the conclusion that most of the units were recorded from a region of cortex located between 4 and 5 mm anterior of the Anterior-Posterior zero line and thus anterior of the region receiving projections from the *area centralis* (Otsuka and Hassler, 1962). As a result, most receptive fields were located in the lower half of the visual field. (These arguments are presented in detail with further supporting evidence in Hirsch, 1970, Appendix II.)

For units recorded within a few millimeters of the Anterior-Posterior zero line of the stereotaxic instrument, moving the microelectrode laterally shifted the position of the receptive fields in the contralateral visual field towards the vertical midline. This would be expected for electrodes located inside Area 17 (Hubel and Wiesel, 1962, 1965a). As pointed out, most recordings were made with the electrode positioned near the Anterior-Posterior zero line of the stereotaxic instrument. Gross examination of one brain at the end of recording indicated also that this region was located inside Area 17. On the other hand, for those units recorded from rostral positions (e.g., Anterior-Posterior +5.0 mm on the stereotaxic instrument) receptive field positions in the contralateral visual field shifted further out into the periphery when the electrode was displaced laterally. Presumably, these units were located inside Area 18 (Hubel and Wiesel, 1962, 1965a).

B. Electrophysiology

I. Classification of Receptive Fields by Shape

The receptive field characteristics of units in the visual cortex of the experimental animals were analyzed in order to evaluate the effects of the selective visual deprivation. A sample of 94 units was gathered from the nine cats whose rearing was described above. All but one of the 94 units were classified as cortical. On the basis of their receptive field maps all cortical units were assigned to one of the following classes:

1. units with diffuse receptive fields,
2. units with disc-shaped receptive fields,
3. units with elongated receptive fields.

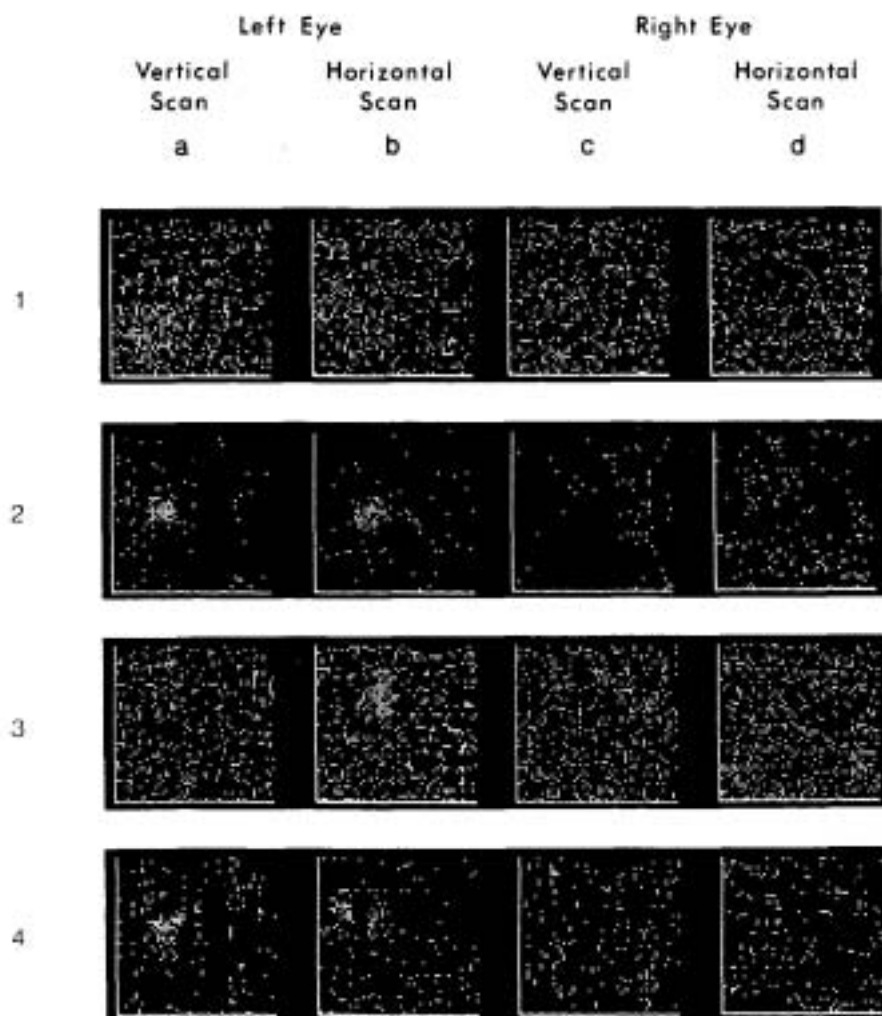


Fig. 2. Cortical neurons with diffuse, disc-shaped, and elongated receptive fields. Rows 1—4 illustrate integral contour displays of receptive fields of 4 units. In Columns a and b the units were mapped with only the left eye open; in Columns c and d the units were mapped with only the right eye open. The spot moved vertically in Columns a and c, and horizontally in Columns b and d. Row 1 illustrates a unit classified as having a diffuse receptive field. There is a slight concentration of activity in the lower left-hand corner of the field if the unit is mapped with the left eye opened. (Recorded from HV-82) Row 2 illustrates a cell classified as having a disc-shaped receptive field. The unit is activated only from the left eye and responds equally well to horizontal and vertical movement of the spot. (Recorded from HV-81) Rows 3 and 4 illustrate units classified as having elongated receptive fields. The unit in Row 3 responded only to horizontal movement of the spot (directionally selective), while the unit in Row 4 responded to both vertical and horizontal movement of the spot (not directionally selective). The receptive field, however, is clearly elongated only when the unit is mapped with the spot moving at right angles to the main axis of the receptive field. Both of these units are activated by only one eye. Furthermore, both are oriented vertically and are activated by the eye which had been exposed to vertical lines. The unit in Row 4 has two excitatory regions separated by an inhibitory region. (Recorded from VH-33). Level of integral contour displays: Row 1:I, Rows 2,3,4:II. Speed of spot during mapping: 10 degrees/sec. Incident light on screen: 20 lm/m²

Diffuse receptive fields have no clearly defined boundary and respond to stimulation over a wide portion of the receptive field. In some instances the resting activity of these units was quite low and they responded very little, if at all, to visual stimulation. Considerable averaging would have been necessary to determine to what degree, if at all, visual stimulation increased the firing rate of some of these units above the base rate; this was not done since units with elongated receptive fields were of primary interest. Whereas in normal animals units with diffuse receptive fields have relatively high background firing rates (Spinelli and Barrett, 1969), in this study many of the cells classified as diffuse had very low background firing rates. This suggests that these units may be similar to the non-responsive cells described by Wiesel and Hubel (1963, 1965) in visually deprived animals. It is also possible that some of the units with diffuse

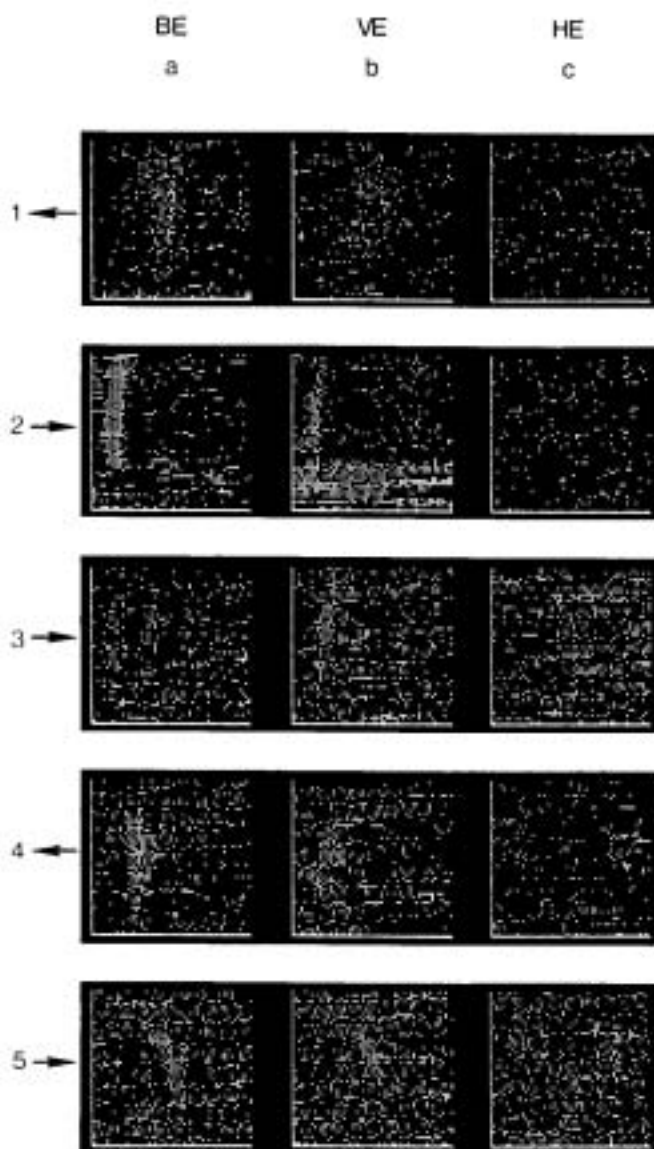


Fig. 9

fields may have been complex or hypercomplex cells (Hubel and Wiesel, 1962). Fifty-five of the 93 cortical units were classified as diffuse (Fig. 2, row 1).

Disc-shaped receptive fields were roughly circular; 6 cortical units were of this type (Fig. 2, row 2). These units responded to both the vertically and the horizontally moving spot. Furthermore, four of the units were activated by only one eye; the remaining two units were lost before sufficient mapping could be done to determine if they were also monocular. Although disc-shaped fields have been found for cortical units by several investigators (Baumgartner *et al.*, 1965; Spinelli and Barrett, 1969), it is possible that some of these units were geniculate fibers.

The remaining 32 units were classified as having elongated receptive fields. Sixteen of these units responded exclusively to movement of the spot orthogonal to the receptive field axis (directionally selective; Fig. 2, row 3), and the remainder showed stronger responses to movement of the spot at right angles to the field than to movement along the receptive field axis (Fig. 2, row 4).

The shapes of elongated receptive fields found in these animals ranged from somewhat elliptic to clearly edge or bar shaped, corresponding to the elongated receptive fields described by others. There was considerable variability between units in terms of the number of parallel, elongated excitatory regions within the receptive field. Four of the cells had three excitatory regions in the receptive field (Fig. 4, row 5; Fig. 6, row 4 — these had very clear fields; Fig. 4, row 2, and Fig. 6, row 1, have fainter excitatory regions). The remaining cells had either one or two excitatory regions within the receptive field. In many cases, a cell had two excitatory regions when the spot was moving in one direction, but only had a single excitatory region when the spot moved in the opposite direction. Presumably this was the result of asymmetries in the organization of excitatory and inhibitory regions within the receptive field. Twelve of the cells had two excitatory regions within the receptive field (for at least one scanning direction) and the remainder had only a single excitatory region. Maps from all but 8 of the 32 units with elongated fields are presented in Fig. 2 through 7; maps from 5 of the remaining cells were presented in a brief paper on this work (Hirsch and Spinelli, 1970, Fig. 2).

2. Monocularity of Units with Elongated Receptive Fields

The units with elongated receptive fields differed from those found in normal cats in several ways. First, 30 of the units with elongated fields were predominantly or exclusively activated by only one eye. In the normal cat only 10–20% of such

Fig. 3. Cortical neurons with vertically oriented, elongated receptive fields. Rows 1–5 present integral contour displays of receptive fields of five units. In Column *BE* the units are mapped with both eyes open, in Column *VE* they are mapped with the eye exposed to vertical lines open, and in Column *HE* they are mapped with the eye exposed to horizontal lines open. Note that all receptive fields are elongated, and activated by one eye — the eye exposed to vertical lines. The receptive field orientation is thus the same as the orientation of the lines to which the dominant eye was exposed during the rearing period. The direction in which the spot moved during mapping is indicated by the arrowhead. Row 1 unit recorded from HV-40. Row 2 unit recorded from VH-50. There was a sudden change in background activity during the mapping with the VE open which resulted in a solid region of activity in the lower portion of the field, the vertically oriented receptive field is nonetheless quite clear. When the change in activity subsided the unit was re-mapped and only the elongated receptive field was found to be present. Row 3 unit recorded from VH-50. Row 4 unit recorded from HV-51. Row 5 unit recorded from HV-81. The right eye was the dominant eye for this unit so the tilting of the receptive field may reflect counter clock-wise rotation of the right eye during recording. Level of displays: Rows 1,2,3,4,5:1. Other conditions as in Fig. 2

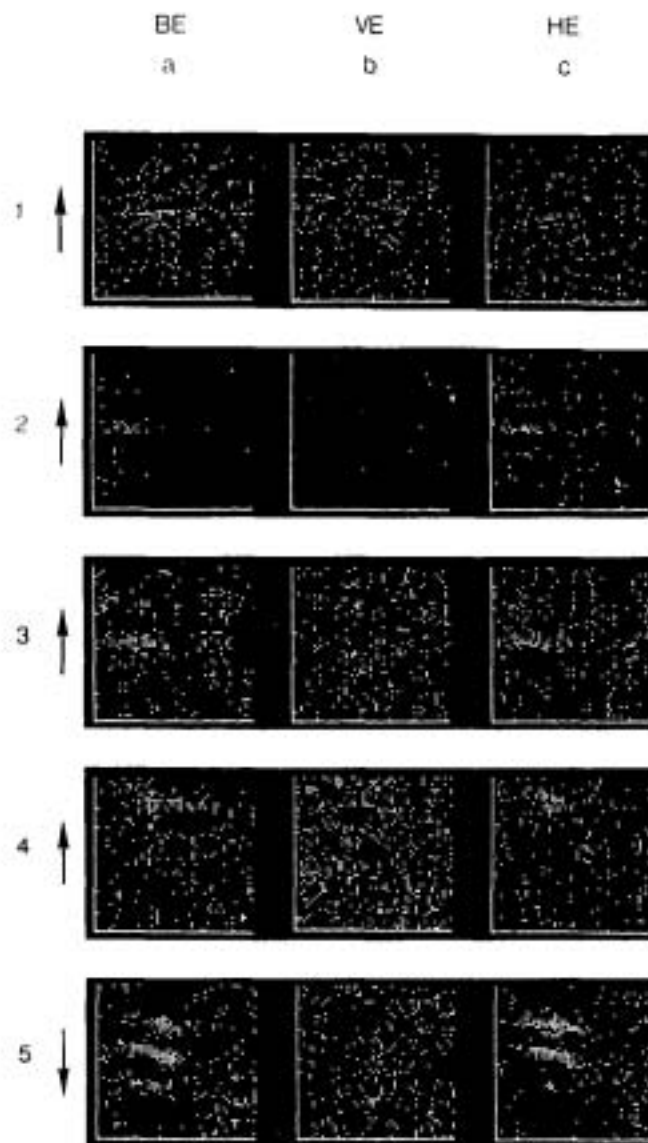


Fig. 4. *Cortical units with horizontally oriented, elongated receptive fields.* Conventions are as given in Fig. 3. Note that all receptive fields are elongated and that units are activated only by the eye exposed to horizontal lines during the rearing period. Rows 2 and 5 illustrate units having three parallel, elongated excitatory regions within the receptive field. The receptive fields in Row 5 are slightly tilted; the left eye was dominant for this unit so that the tilting may reflect clock-wise rotation of the left eye during recording. Row 1 unit recorded from VH-33. Row 2 unit recorded from HV-40. Row 3 unit recorded from HV-40. Row 4 unit recorded from HV-81. Row 5 unit recorded from HV-81. Level of displays: Rows 1,2,3,4,5:1. Other conditions as in Fig. 2.

units respond to just one eye (Hubel and Wiesel, 1962; Spinelli and Barrett, 1969; Pettigrew *et al.*, 1968; Barlow *et al.*, 1967). The remaining two units with

elongated fields were lost before sufficient mapping could be done to determine whether they were monocular, but there was nothing to suggest that they were not monocular also. Thus, as was anticipated, discordant stimulation of the two eyes resulted in a very sharp decrease in binocularity (Hubel and Wiesel, 1965b).

Although each unit was activated predominantly by one eye, occasionally faint inhibitory areas could be seen for the non-dominant eye (Fig. 4, row 4). As a further indication of this, some receptive fields were larger and clearer when the unit was mapped with only the dominant eye open than when it was mapped with both eyes (Fig. 3, row 3; and in Hirsch and Spinelli, 1970, Fig. 2, row 4). The reverse was true for a few cells, indicating the presence of subliminal excitatory regions in the non-dominant eye (Fig. 3, rows 2 and 5). Thus, there were interactions comparable to those described by Henry *et al.* (1969) for monocularly activated units found in normal cats.

3. Orientation of Receptive Fields

Perhaps the most interesting departure from the conditions found in normal cats was the distribution of receptive field orientations. Whereas normal kittens have a full complement of receptive field orientations at birth, the distribution of receptive field orientations in these cats was clearly bimodal. One group of cells had a mean receptive field orientation of 91.7 degrees from the horizontal axis, with a range of 85–103 degrees. (Median receptive field orientation: 90 degrees from horizontal.) Units in the second group had a mean receptive field orientation of -1.2 degrees from the horizontal axis, with a range of -13 to +7 degrees. (Median receptive field orientation: 0 (zero) degrees from horizontal.) These data are illustrated in Fig. 8. The two groups of units subsequently will be referred to as units with horizontally oriented fields and units with vertically oriented fields.

Examination of the data on receptive field orientation indicated that variations in receptive field orientation about the two principle axes were not randomly distributed. The receptive field orientation of cells activated by the right eye were all greater than or equal to 0 degrees (or, greater than or equal to 90 degrees). On the other hand, cells activated by the left eye all had receptive field orientations which were less than or equal to 0 degrees (or 90 degrees). This suggests that for some animals (and in particular for HV-81) the two eyes had rotated inward slightly (the right eye counterclockwise and the left eye clockwise). This may have been the result of the paralytic agent used during recording.

Differences between the mean receptive field orientations computed using maps made with only the dominant eye open and those computed from maps made with both eyes open suggest that this rotation of the eyes was greater when only one eye was open than when both eyes were open. (The mean orientation was 93.6 degrees and -2.0 degrees with only the dominant eye open, and 91.7 degrees and -1.2 degrees with both eyes open.)

4. Correlation between Receptive Field Orientation and Orientation of Lines Presented during Rearing

In normal cats, each eye can activate units with receptive fields of all orientations. By comparison, in this study, all of the units activated by a given eye had receptive fields of essentially the same orientation. Thus, each eye could either

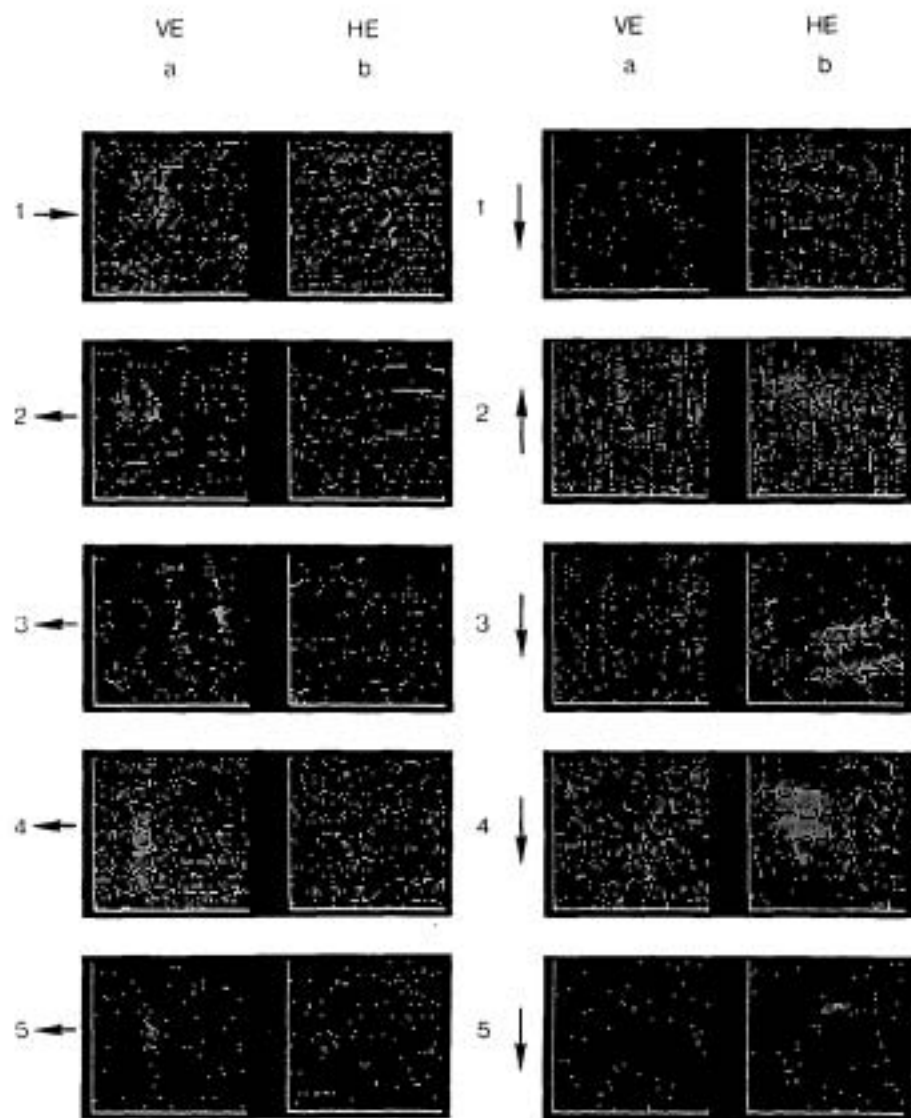


Fig. 5

Fig. 6

activate only units with vertically oriented fields, or it could activate only units with horizontally oriented fields. Furthermore, there was an almost perfect correlation between the orientation of the receptive fields and the orientation of the lines to which the eyes had been exposed during the rearing procedure. Cortical units activated by the eye which had been exposed to vertical lines were vertically oriented, and units activated by the eye which had been exposed to horizontal lines were horizontally oriented. This was true for 28 of the 30 units which had been recorded from long enough to determine that they were monocular. Such a distribution of receptive field orientations had an insignificant probability of occurring by chance ($p < .002$ — binomial test, Siegel, 1956).

Fig. 5. *Cortical units with vertically oriented, elongated receptive fields.* Conventions are as given in Fig. 3; Column BE has been omitted. Note that all receptive fields are elongated and that units are activated only by the eye which was exposed to vertical lines during the rearing period. Row 1 unit recorded from VH-33. Row 2 unit recorded from VH-33. Row 3 unit recorded from HV-40. The receptive field for this unit is tilted slightly. Since the right eye was the dominant eye this may reflect counter clock-wise rotation of that eye during recording. Row 4 unit recorded from HV-51. Row 5 unit recorded from HV-81. Level of displays: Rows 1,2,3,4:I. Row 5:III. Other conditions as in Fig. 2

Fig. 6. *Cortical units with horizontally oriented, elongated receptive fields.* Conventions are as given in Fig. 3; Column BE has been omitted. Note that all receptive fields are elongated and that the units are activated only by the eye which was exposed to horizontal lines during the rearing period. Rows 1 and 4 illustrate units which have three parallel, elongated excitatory regions within the receptive field. In Row 4 the inhibitory region separating the two top excitatory regions is not completely clear; it can, however, be seen clearly when the Level III integral contour display is examined which shows all of the points at which the unit fired at least three times. The receptive fields presented in Rows 1 and 3 are both tilted, but in opposite directions. For the unit illustrated in Row 1 the left eye was the dominant eye while the right eye was dominant for the unit illustrated in Row 4. Row 1 unit recorded from HV-51. Row 2 unit recorded from HV-51. Row 3 unit recorded from VH-70. Row 4 unit recorded from HV-81. Row 5 unit recorded from VH-90. Level of displays: Row 1:II, Rows 2,3,4,5:I. Other conditions as in Fig. 2

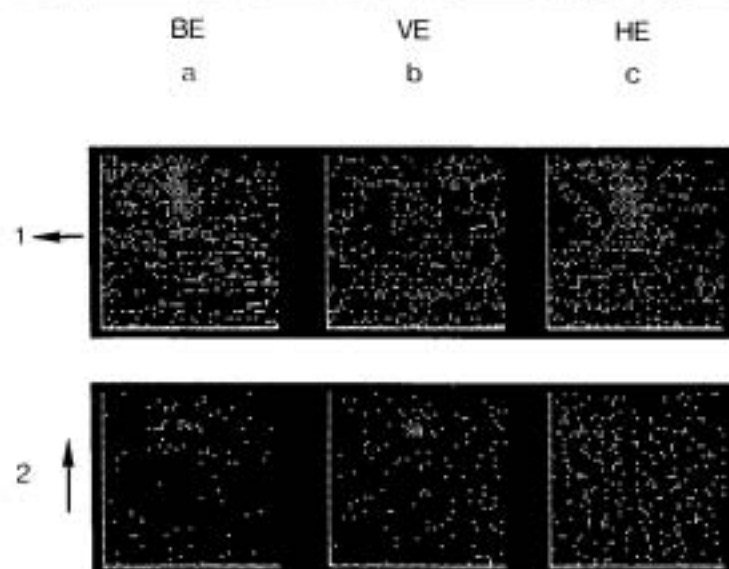


Fig. 7. *Cortical neurons with elongated receptive fields whose orientation does not correspond to the orientation of the lines presented during rearing.* Conventions are as given in Fig. 3. The unit illustrated in Row 1 has a vertically oriented field, but is activated by the eye exposed to horizontal lines during rearing. There is no receptive field when the unit is mapped with the eye exposed to vertical lines open. The unit was recorded from VH-50; this animal wore the incorrect mask for 6 hrs 15 min. During this period the eye which normally was exposed only to horizontal lines received exposure to a field of vertical lines. The unit illustrated in Row 2 has a small horizontal field when mapped with both eyes open, and a small disc-shaped field when mapped with the eye exposed to vertical lines. There is no receptive field when the unit is mapped with the eye which was exposed to horizontal lines. The unit was thus rather unusual (one other unit of this type was found: Fig. 4, Row 4). Level of displays: Rows 1,2:I. Other conditions as in Fig. 2

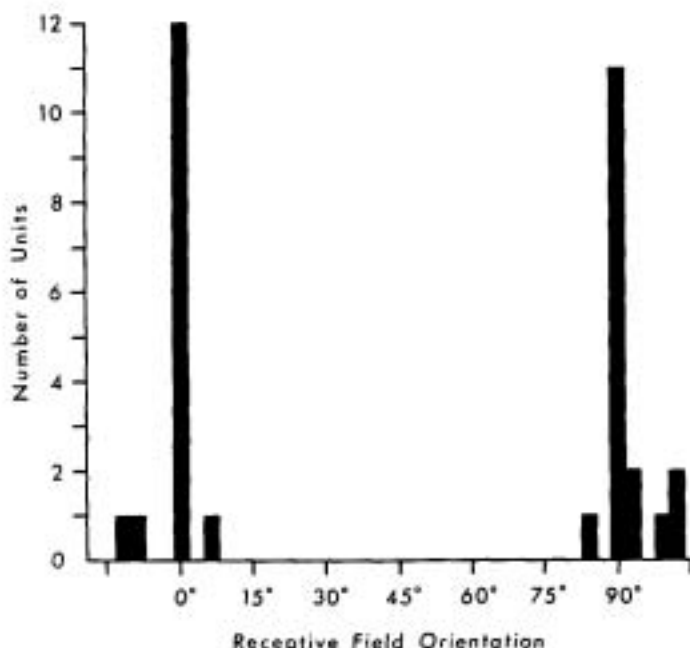


Fig. 8. Histogram of receptive field orientations. Receptive field orientations as estimated from the integral contour displays are plotted along the abscissa. The number of units which have a given receptive field orientation are plotted along the ordinate. It is evident that the distribution is bi-modal with no overlap between the two populations. Most of the deviations in receptive field orientation from the horizontal and vertical axis can probably be accounted for by inward rotation of the animal's eyes during the recording. The data represent 32 units classified as having elongated receptive fields

Two units with elongated receptive fields had receptive field orientations not correlated to the orientation of the lines present during rearing. One unit, 50-10, with a vertically oriented field, was activated by the eye exposed to horizontal lines (Fig. 7, row 1). It may be significant that this was the one cat that wore the incorrect mask for one exposure period, so that, in fact, the eye which activated this vertically oriented unit had been exposed to vertical lines for 6 hours, 15 min during the rearing. The second exception, unit 80-1, was a unit which when mapped with both eyes had a small horizontally oriented field; this unit was not activated at all by the eye which had been exposed to horizontal lines, but it had a disc-shaped receptive field when mapped with the eye which had been exposed to vertical lines (Fig. 7, row 2).

5. Size of the Receptive Fields

Most of the elongated receptive fields found in the present study were larger than the receptive fields found in normal cats (Hubel and Wiesel, 1959, 1962; Spinelli and Barrett, 1969). Although receptive field size is difficult to measure accurately, only a few cells in the present sample had small discrete receptive fields similar to those described in normal cats. This may be a consequence of the restricted visual experience received by the animals during rearing. An alternate explanation is that receptive fields were relatively large because the recording

site was located anterior to the region receiving projections from the *area centralis* (Hubel and Wiesel, 1962).

Discussion

A. Selective Effect of Restricted Visual Experience

The data demonstrate that by restricting visual stimulation during development it was possible to modify cortical cells selectively on the basis of their receptive field orientation. Control over the visual experience provided during the rearing was sufficient to allow detailed comparisons between the stimuli presented to the animals and the changes in the nervous system.

As expected, few, if any binocularly activated cells were found in the visual cortex of these animals. Also, cells with vertically oriented fields were activated by the eye exposed to vertical lines while cells with horizontal fields were activated by the eye exposed to horizontal lines. There were, however, virtually no units with fields oriented more than 5–10 degrees from the vertical or horizontal axis. A greater variation in receptive field orientation had been expected, since the data of Campbell *et al.* (1968) suggested that each set of lines presented during the rearing would activate a relatively wide range of units. Units responding differentially to vertical and horizontal lines should eventually come to be activated by only one eye — the eye from which they received the most effective stimulation. On the other hand, units not activated by either the horizontal or vertical lines (or activated equally by them) might be expected to survive the deprivation since almost 50% of the cells found in binocularly deprived animals respond normally to visual stimulation (Wiesel and Hubel, 1965; Ganz *et al.*, 1968). Thus, finding so restricted a range of receptive field orientations was surprising. (If inward rotation of the eyes of the animals accounts for much of the variation in receptive field orientation, then the range would be even more restricted.)

Before discussing the implications of these findings it is essential to consider whether the recording and mapping procedures may have introduced a bias which can account for the absence of cells with oblique and diagonal fields. Several points argue against this possibility. First, diagonal and oblique fields have been mapped using the present stimulating and recording procedures, both in normal adult cats (Spinelli and Barrett, 1969, Fig. 7) and in dark-reared cats of comparable age to those used in this study (Hirsch and Spinelli, unpublished observations). Secondly, 50% of the units with elongated fields found in this study responded to both the vertically and horizontally moving spot. It is therefore reasonable to assume that if cells with diagonal and oblique fields were present, the majority of them would respond at least to one of the scanning directions used. While it is possible that as a result of inadequate stimulation cells with diagonal and oblique fields become unresponsive and cannot be mapped with moving spots, successful mapping of units with elongated fields in cats reared without any patterned stimulation argues against this possibility. Moreover, although hand-mapping using line-shaped stimuli was not extensive, all of the units examined which responded to lines were also adequately mapped by the moving spot. It is thus unlikely that any significant proportion of the cells recorded had oblique or diagonal fields which were not revealed when the units were mapped with moving spots.

The absence of units with oblique and diagonal fields may also reflect non-random sampling of cortical cells by the microelectrode. Lack of stimulation may have affected the physical characteristics of cells with diagonal and oblique fields in a way that would reduce the likelihood of recording from them. For example, atrophy of cells with diagonal and oblique fields — or possibly, hypertrophy of cells with vertical and horizontal fields — might have such an effect. While there is little evidence for changes in cortical cell size after deprivation (Wiesel and Hubel, 1965), only direct anatomical verification that all cells are being sampled randomly can rule out the possibility of biased sampling by the microelectrode.

To summarize, it appears unlikely that cells with oblique or diagonal receptive fields constitute any sizeable proportion of the cells in the visual cortex of the animals reared in this study. The possibility that units with diagonal and oblique fields were altered by the rearing procedure, and thus were not represented in the sample of cells with elongated fields cannot be ruled out.

It may be helpful to review why single spots, rather than lines, were used in mapping. This was done in order not to bias the results in favor of finding units responsive to line-shaped stimuli. In studying a novel preparation it is best initially to use a measuring technique which makes the fewest assumptions, even if this may entail some loss in sensitivity. In addition, the likelihood of observer-introduced bias is very great when it is "expected" that cells with vertical fields will be activated by one eye while cells with horizontal fields will be activated by the other eye. Using an automated mapping procedure reduced the chance of such errors.

Elongated receptive fields of single units in the cat visual cortex have previously been mapped with both stationary spots (Hubel and Wiesel, 1962) and with moving spots (Spinelli and Barrett, 1969). The responsiveness to line-shaped stimuli can be predicted from maps made using spots. This is true for units which have discrete excitatory and inhibitory regions within the receptive field (simple cells), (Spinelli and Barrett, 1969; Hubel and Wiesel, 1962), and perhaps also for other types of units (e.g. complex cells, diffuse cells; Spinelli and Barrett, 1969). However, this technique may not be adequate for mapping all complex and hyper-complex cells. Thus, the automated technique was complemented, although not extensively, by using line-shaped stimuli to analyze units.

There is further evidence of considerable similarity between receptive field characteristics and the stimulus patterns presented during rearing. Fourteen of the units found had two or more elongated, parallel excitatory regions within the receptive field. The separation of these bars was remarkably constant (range: 3.8 to 6.0 degrees visual angle) and was quite similar (mean separation of 5.2 degrees visual angle) to the six degree separation of the lines presented during the rearing. Even more strikingly, four cells had three elongated parallel excitatory regions (Fig. 4, rows 2 and 5 and Fig. 6, rows 1 and 4). Such units have not to date been described in the literature. The receptive fields of these units have a remarkable similarity to the configuration of the stimuli mounted in the masks. It should be stressed that such a comparison is only possible if an organism's visual experience is as strictly controlled as was the case in this experiment. If an animal is free to move about relative to the stimuli being presented, then changes in size, orientation, and field of view would interfere with any direct comparison between stimulus parameters and receptive field characteristics.

To summarize, the effects of the rearing conditions were highly selective. The restricted range of receptive field orientations, the absence of units with diagonal and oblique fields, and the shapes of some of the receptive fields all point to this.

B. Modification of Neuronal Connectivity by Visual Experience

Hubel and Wiesel (1963) found that much of the organization which characterizes the visual cortex of adult cats is present at birth. Units recorded from newborn kittens responded optimally to line-shaped stimuli, although possibly with

less vigor and precision than in adult cats. Subsequent visual experience thus can either *modify* this organization, or, *add* to it.

Modification may involve selective disruption or damaging of the genetically determined connectivity. Alternatively, an animal's visual experience might alter the existing connectivity so that units acquire new and different response characteristics. On the other hand, there may be units whose connectivity has not been genetically determined so that their response characteristics can be specified in accordance with the organism's visual experience. This would add an environmentally determined component onto the organization which is present at birth.

Environmental conditions prevailing during an organism's development may help determine which units in the visual cortex maintain their connectivity. One may hypothesize: if groups of cells are constantly subjected to unequal activation, only that group of cells which is most effectively stimulated will survive. Similarly, if some of the afferents impinging onto a cell receive disproportionate activation, they will eventually gain control over the cell at the expense of any other afferents ending on the cell. In this manner, binocular units would come to be activated by only one eye, if the two eyes receive discordant stimulation during the animal's development. In the visual cortex of the animals raised in this study rather large "silent areas" were present. These may indeed be columns containing units which failed to maintain normal connectivity as a consequence of the conditions present during the rearing period.

A competitive or inhibitory interaction, as has been suggested, would account for the virtual absence of units with oblique or diagonal fields in the present study. It would also help explain the similarity between receptive field characteristics (number of excitatory regions and their separation) of some of the units found and the stimulus lines which had been presented to the animals during rearing. In effect, the more closely the response characteristics of a unit match the stimuli in the animal's visual environment, the greater the likelihood that the unit will survive. Such a competitive hypothesis can explain why Blakemore and Cooper (1970) did not find any units with vertical fields in a cat reared in a horizontal environment. Assuming that the animal's head was most often held in the upright position, then cells with horizontal fields would — on the average — receive more effective stimulation than units with vertical fields. In a similar manner one could account for the absence of units with horizontally oriented fields in a cat raised in a vertical environment. In summary, this *selectional hypothesis* suggests that the cells found in the visual cortex of adult animals are a *preserved subset* of the units present when the animal is born.

Environmental influence, however, may involve actual changes in the response characteristics of units in the visual cortex. Thus, a unit which initially is responsive to oblique or diagonal lines may, as a result of the animal's restricted visual experience, come to respond optimally to vertical (horizontal) stimuli. Although such a process may appear rather complex, it should be recalled that some units in the cat visual cortex alter their receptive field axis when the animal is tilted (Denney, 1968; Spinelli, 1968; Horn and Hill, 1969). Mechanisms for the modification of receptive field characteristics may thus be available.

Visual experience may add onto the organization of the visual cortex, rather than modifying it. The connectivity of some units may remain diffuse or uncom-

mitted until the animal receives visual stimulation. This *instructional hypothesis* has been tested in a further experiment (Spinelli and Hirsch, in preparation*). It is evident that this hypothesis can account for the presence of units whose receptive field characteristics closely match the stimuli presented during the animal's development. In fact, the instructional hypothesis receives its strongest support from the units which had three excitatory regions in their receptive field. The selectional hypothesis, on the other hand, must postulate that such units are present in normally reared cats. Failure to find them may mean that they constitute such a small fraction of the total number of units in the visual cortex that their inclusion in a small sample becomes probable only if the environmental conditions prevailing during development give them a great survival advantage.

To summarize, the unexpectedly high degree of correspondence between the stimuli present during the animal's development and the receptive field characteristics of single units in the visual cortex may thus represent the end result of a competitive interaction in which the survival of a relatively small group of units was strongly favored by the prevailing conditions of visual stimulation. The presence of considerable variability at the single unit level in the visual cortex (see, for example, Creutzfeldt and Ito, 1968) could greatly increase the range of response characteristics upon which environmental conditions can exert their selective influence. The range of possible effects may well be greater if response characteristics of some units are determined by the stimuli present during the animal's development, but even in this case there are no doubt limits on the capability of the system to modify itself. In order to verify that the response characteristics of single units are modified by visual experience it is necessary to control the stimulus conditions as strictly as was done in the present study. Only then are detailed comparisons of stimulus and receptive field characteristics possible.

* Note added in press: This aspect of the work is being pursued further. (Spinelli, D. N., Hirsch, H. V. B.: Genesis of receptive field shapes in single units of cat's visual cortex. *Federation Proceedings* 30, 615 Abs (1971)).

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